



An Evaluation of Shredder Waste Treatments in Denmark

Alternative Methods to Landfilling Auto Shredding Residue in
Compliance with the Strict Environmental Quota by the
European Union

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Abstract

This report, prepared for RenoSam and the shredder companies of Denmark, identified and researched alternative treatments of shredder residue, resulting primarily from the shredding of end-of-life vehicles, in order to help Denmark meet strict European Union recycling targets that will be implemented in 2015. Danish shredder companies are also motivated to reduce the amount of landfilled waste due to a two-phase landfill tax increase to be implemented in 2012 and 2015. Through extensive literature research, interviews with Danish shredder companies and landfills, and analyses of environmental and economic factors, the team investigated the implementation of alternative shredder waste processing methods and recommended several auto shredder residue treatment options to RenoSam and the shredder companies: co-incineration of shredder waste with municipal solid waste, construction of a joint plant implementing an independent shredder residue processing technology, and exporting of the shredder residue for processing at established shredder waste treatment facilities. Each shredder company will have to perform an economic analysis to determine which option is most viable. The analysis and recommendations presented in this report will aid Danish shredder companies in reaching the 2015 EU end-of-life vehicle recycling quota.

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Executive Summary

Historically, Denmark has been known for its progressive environmental stance and has been recognized as one of the most environmentally friendly countries in the world. Shredder residue, the resulting material from the shredding of automobiles, large household appliances and other industrial items, is currently landfilled in Denmark and poses an environmental challenge. Auto shredder residue (ASR) is a form of shredder residue resulting specifically from the shredding of automobiles. Denmark's environmental frame of mind has allowed them to implement and maintain strict environmental standards for landfilling shredder residue, enabling Denmark to work towards meeting high targets established by the European Union. In 2000, the EU instituted a directive stating that 95% of an end-of-life vehicle (ELV), or an automobile that is scrapped because of old age, abandonment, or excessive damage, must be reused and recovered by 2015. Currently, approximately 85% of an ELV is reused and recovered in the form of recycled materials and reused parts. The remaining amount, in the form of auto shredder residue, is landfilled. As a motivation for reaching the EU quota, Denmark has implemented a two phase plan for taxing landfilled shredder residue. As of January 1, 2012 a tax of DKK 160 per tonne of landfilled shredder residue will be applied, and as of January 1, 2015 the tax will be increased to DKK 475 per tonne. Due to this tax plan, there are incentives to find alternative processing methods instead of landfilling shredder residue. RenoSam, an association of municipal and inter-municipal waste management companies, aims to promote high environmental standards within the field of waste treatment and recycling. The essential goal of this project was to aid RenoSam in investigating alternative treatment methods for processing auto shredder residue.

Shredder residue is a highly heterogeneous mixture of residual ferrous and non-ferrous metals, plastics, rubber, foam, glass, wood, dust and other components that remain after vehicles are processed at a shredder facility. Shredder residue also contains heavy metals, automobile fluids, and other hazardous materials that can become entrapped in water, which flows naturally through a landfill, and leached into the ground. Mechanical and thermal pilot technologies have been implemented to either separate shredder residue into its component parts or thermally process it to yield a solid residue and a synthesis gas. However, due to ASR's highly heterogeneous nature, there have been a limited number of technologies developed. There are also environmental, economical, and legislative barriers surrounding alternative shredder technologies which create difficulties for further development.

In order to accomplish the goal of investigating alternative ASR processing methods, the team created a list of objectives that would enable us to give RenoSam an understanding of the current research and technological advancements that are being made in this sector of the waste treatment field as well as provide RenoSam with a list of alternative processing options. First, ascertaining the current international waste processing practices and treatments was essential in order to develop an initial understanding of the processes that are being implemented in the leading technological countries, such as the United States, Japan, and Germany. Concurrently, our team investigated and evaluated the current shredder waste processing methods in Denmark in order to determine the feasibility of implementing alternative treatments for Danish ASR, while keeping economic and environmental aspects in mind. These objectives were achieved by literature research, shredder and landfill facility tours, and analysis of the environmental impact and economic factors associated with current shredder waste processing practices in Denmark. We also contacted leading companies that have made advancements with alternative ASR treatment technologies, as well as experts on shredder residue processing. Environmental and economic aspects were closely analyzed and integrated into each of the objectives as they were the driving factors for proposing options for Danish shredder companies. The economics of the processes determined the feasibility of implementation and the environmental impact helped our team evaluate the efficiency of the processes. Finally, after analyzing numerous independent technologies, our team identified several alternative ASR processing options for further consideration by the shredder companies.

Our research on alternative technologies was concerned with mechanical and thermal treatment options. We focused on mechanical density separation for plastics and foams and thermal techniques of gasification, pyrolysis, and incineration. Argonne National Laboratory has developed an efficient plastics separation technology that can recover 90% of the plastic fraction at 95% purity. They have also developed various technologies for removing hazardous materials like PCBs and automobile fluids from the ASR fraction. It has been shown that the purified plastics fraction can be remanufactured into marketable products such as battery trays and steering wheel columns, thus replacing virgin plastic material. SiCon GmbH can create multiple marketable products from shredder residue including shredder granules, shredder fibers, and shredder sands. These products can be remanufactured into recycled plastic products, incinerated as fuel on a 1:1 ratio with powdered coal, used to treat sewage sludge, or utilized in the construction industry. In conjunction with conventional shredder processing, the SiCon process is able to recycle or recover 95% of an ELV. Co-

incineration is another promising method for processing shredder residue. This method combines ASR and municipal solid waste (MSW), commonly known as household garbage, to be incinerated for energy recovery. A solid residue is also formed which has promising applications for the cement industry.

Keeping the Danish landfill tax plan in mind, our team recommended several possibilities for shredder companies to pursue that will become economically feasible due to the implemented landfill tax. After analyzing the information collected, we recommended that shredder plants consider the co-incineration of shredder waste with MSW, constructing a joint plant using an independent shredder residue processing technology such as VW-SiCon, or exporting their shredder residue to be processed elsewhere. The companies will have to perform individual economic analyses when looking into these options. These courses of action will become economically feasible after the 2012 or 2015 landfill tax is implemented, depending on the economics of each option and shredder plant. By implementing one of these three shredder residue processing options, the Danish shredder companies should be able to reach the 2015 EU targets for reuse, recycling, and recovery of ELVs.

Chapter 1: Introduction

Each year, 30 million vehicles worldwide are scrapped because of age, abandonment, or excessive damage resulting from an accident (Ahmed et al., 2009). These vehicles are classified as end of life vehicles (ELVs) and are potential sources of recoverable, reusable, and recyclable materials. ELVs are sent to a dismantling station where the tires, batteries, fluids, mercury switches, and other reusable or hazardous components are removed and either resold or exported to treatment facilities. The remaining body of the ELV is transported to a shredding facility where ferrous metals and non-ferrous metals are separated and shipped for recycling. The remaining fraction is called auto shredder residue (ASR), a heterogeneous mixture of shredded materials consisting of the fluffs, fibers, rubbers, plastics, glass, wood, dusts, minerals and other residues that are difficult to separate with current processes (Ahmed et al., 2009).

Currently, ASR is landfilled in many countries because it is the most economical choice. However, ASR could be used to create beneficial industrial products while limiting harm to the environment. Impractical economic options and lack of research in relevant technologies have negatively affected major advances in generating strategies for reducing the amount of ASR landfilled, despite environmental problems caused by landfilling ASR. Denmark, a country that has expressed interest in the need for landfill reduction, is currently exploring practical alternatives. Much of Denmark's research into reducing the amount of landfilled waste is focused on analyzing different methods for recycling and reusing ELVs.

To accelerate research and development of shredder waste processing methods, the European Union Parliament introduced a directive that sets goals for ELV processing. By 2015 the European Union expects a 95% ELV recovery and reuse rate, an increase from the current target of 85%. Of the 95% target, thermal processes may account for 10% of the total amount and mechanical processes must encompass the remaining 85%. This 85% must reuse components in the ELV or recycle raw materials in order to create new products. The thermal portion of the target (10%) may be reached through reuse and recycling or by using energy recovery techniques. An additional factor that will help motivate Danish shredder companies to reach the 2015 goal is a two phase tax on landfilled hazardous waste, which includes shredder residue. As of January 1, 2012 a tax of DKK 160 per tonne of landfilled shredder residue will be applied, and as of January 1, 2015 the tax will be increased to DKK 475 per tonne, the rate of all other non-hazardous landfilled waste. Considering that 250,000 tonnes

of shredder residue were landfilled in Denmark in 2008 (Hjelmar, 2009), there is now an incentive to finding treatments that will process this large waste quantity.

A large amount of research has been conducted on mechanical and thermal ASR processing by technologically leading waste processing countries such as the USA, Germany, and Japan (Malkow, 2004). Many independent companies from these countries apply incineration, pyrolysis, gasification, or separation processes to convert ASR into usable materials. Some of these processes, if implemented, will allow Denmark to reach the 95% reuse and recovery target by 2015.

Despite all of the research that has been conducted internationally, Denmark has not implemented shredder waste processing methods to reduce the amount of landfilled waste. This is due to the legislative, economical, and environmental barriers surrounding the implementation of an alternative technology. RenoSam, an association of municipal and inter-municipal waste management companies, works to promote high standards for recycling, and is thus interested in a solution to these problems. The Danish tax on landfilled hazardous waste should motivate shredder companies to reduce the amount of waste that is landfilled. Despite the best efforts that have been put forth to create a functional solution to processing ASR, additional research must be completed on the environmental impacts and costs of implementing these processes into Danish shredder waste facilities.

This project assisted RenoSam in investigating alternative auto shredder residue treatments in order to help shredder companies reach the 2015 EU target. The team ascertained international waste practices and processing treatments by researching waste processing companies and understanding the technologies they are utilizing. The team then evaluated current shredder waste practices of Danish shredder companies in order to understand the feasibility of applying alternative ASR treatment technologies to the Danish system. The research focused predominately on the environmental impact of landfilling ASR and alternative treatment methods, but also included a limited economic analysis of the implementation of proposed treatments. After understanding the current technologies and practices, the team evaluated the various technological processing options with regard to environmental and economic impact. Finally, alternative options for processing shredder residue were recommended.

Chapter 2: Background

This chapter will provide an overview of the research that has been completed pertaining to ASR processing technologies. First, shredder residue will be introduced from a global perspective, followed by a discussion of ASR in the Danish context. Next, the stakeholders and their motivating factors in this project will be discussed. After that, environmental, economic, and legislative factors will be highlighted. Finally, thermal and mechanical technologies will be described, along with their environmental impacts and an overview of experimental plants.

2.1 Shredder Residue in Denmark

In Denmark, when an automobile reaches end of life status it goes through a dismantling process in which the tires, batteries, mercury switches, fluids, and other hazardous materials are removed from the vehicle. The remaining body of the vehicle is shredded and then mechanically separated into its constituent parts through various methods such as vibration sieving, ferrous and non-ferrous separation, and dry and wet separation. The dismantling and mechanical processes remove 75-80% of the automobile's mass in the form of ferrous and non ferrous scrap metal, tires, batteries, and other reusable or recyclable parts and materials (Ahmed et al., 2009). The material stream that is generated from ELV shredding consists of a highly heterogeneous ASR fraction of plastics, foams, glass, fibers, rubbers, and residual metals (Palfi, 2006). However, shredders in Denmark shred ELVs together with appliances, scrapped metal, and other potential sources of ferrous metals. The resulting shredder residue (SR) consists of roughly 10-45% ELVs, depending on the stockpiled shredder input (Stena & UniScrap, personal communication, April 16 & 19, 2010).

The components shredder residue that are not classified as ASR mainly consist of household appliances and scrap metal. The technologies that describe ASR processing can be applied to shredder residue in general as the similar material composition allows for the processing of SR (Harder, 2003). Some shredder processes recover a light and a heavy ASR fraction separately before combining and landfilling them. The light ASR fraction (SLF) is separated from the shredded residue stream with the use of air currents. The SLF consists of polyurethane foams (PUF), textiles, light plastics, dirt, rust, paint, and other light materials. An eddy current is used to separate out non-ferrous metals from the heavy ASR fraction, which consists of rubbers, plastics, wood, stones, sand, and glass. As the schematic in Figure 1 notes, a conveyor belt takes the shredded scrap to an air separation unit where the light

ASR fraction is separated from the air current by a cyclone. The heavy ASR fraction is separated by eddy current systems. The ratio between the heavy and light ASR fraction is about 1:3 by weight (Lundqvist et al., 2004). Since the resulting light and heavy fractions are landfilled together as ASR, this report will not distinguish between light and heavy residue fractions but instead, refer to either ASR or SR. However, among Danish shredder companies, there exists a difference in terms of the shredder residue fractions separated and recovered.

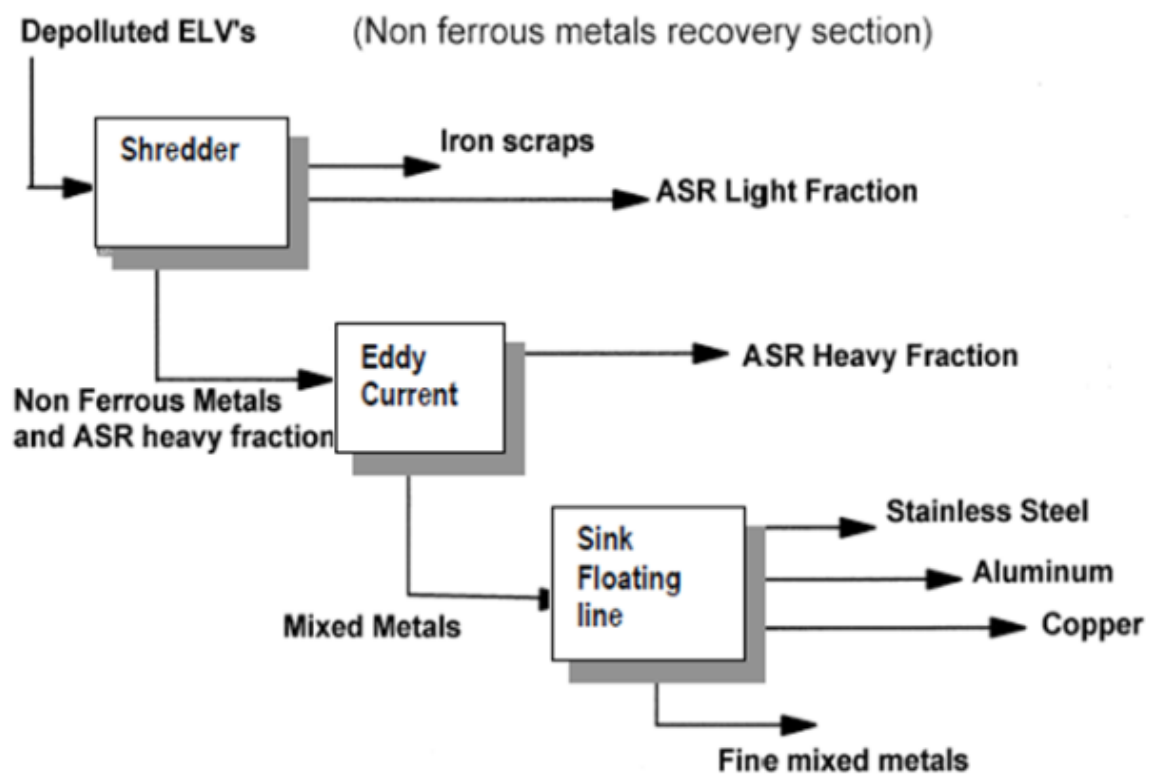


Figure 1: Shredder Process Layout (Lundqvist et al., 2004)

Globally, the majority of countries are landfilling shredder residue because there has not been a widely implemented method to process this waste cost effectively. In 2009, it was estimated that 30 million vehicles reached an end of life status, which accounts for a large amount of global waste. Europe accounted for 14 million of these end of life vehicles, producing about 2 million tonnes of ASR (Ahmed et al., 2009). Advanced methods of ASR processing would prevent millions of tonnes of waste from being landfilled annually. Instead, the ASR could be processed to recover recyclable material that would be used to create marketable products.

2.1.1 The Auto Shredder Residue Dilemma

In 2008, Denmark generated approximately 250,000 tonnes of shredder residue (Hjelmar, 2009). Reaching the 2015 target set by the EU Directive will mean reducing the amount of ELV waste landfilled in Denmark from the current 20% to 5%. A 75% reduction in the amount of landfilled SR would reduce the amount of shredder waste that is annually landfilled by approximately 190,000 tonnes.

The current Danish legislature regarding the treatment of ELVs was introduced in July of 2000. Denmark implemented the “Scrapage Package”, which is a set of laws that entails many of the issues addressed in the EU directive. This legislation will be discussed in section 2.2.1. These laws seem to be effectively decreasing the number of ELVs that are abandoned because of the financial incentive to bring the vehicle to a licensed dismantling facility. A summary of the laws can be seen in Figure 2.

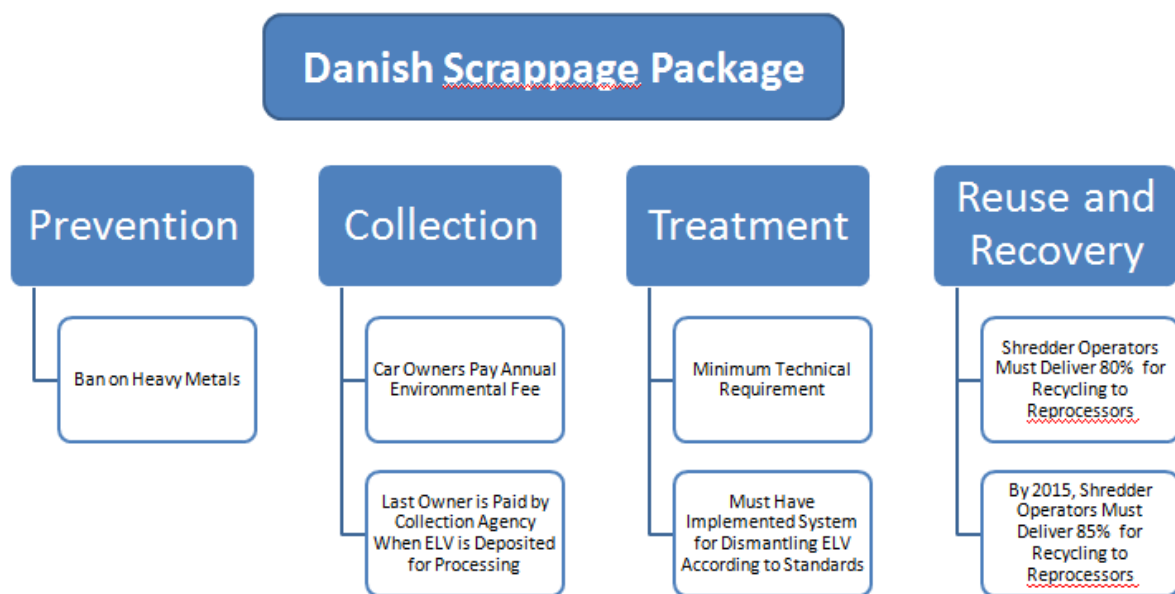


Figure 2: Danish "Scrapage Package" (Reformatted from Smink, 2007).

During a car's life span, the owner must pay an annual environmental fee of roughly DKK 90. The fee is paid to insurance companies as a mandatory tax, but is then transferred from the insurance agency to the recycling fund of Danish authorities. This tax helps offset the fee that is refunded to the last owner of the car whom, when the car is brought to a certified dismantling facility, is paid approximately DKK 1800 from the recycling fund. This financial incentive discourages Danes from improperly disposing of ELVs. There is also a statutory order that is given to all authorized car dismantling facilities stating how to dismantle and transport certain materials and products (Smink, 2006). In 2000, these

guidelines helped Denmark reuse or recycle 80% of ELVs by mass. Additionally, the “Scrapage Package” also includes the standards that were set by the European Union council in Directive 2000/53/EC (Appendices A & B). In order to meet these deadlines and minimize the impact of the impending landfill tax, Danish shredder waste companies must implement new processes to increase the percentage of waste that is sent to recycling facilities.

2.1.2 Auto Shredder Residue Composition

The composition of ASR is a very important factor in determining how to process the waste properly. Since the mixture of ASR is very heterogeneous and dependent on many different factors such as the year or manufacturer of the car, it is hard to identify the distribution of materials within the ASR. There have been many studies done on the contents of ASR and the tree diagram in Figure 3 illustrates the variety of materials found in it. A more in-depth analysis is shown in Appendix C.

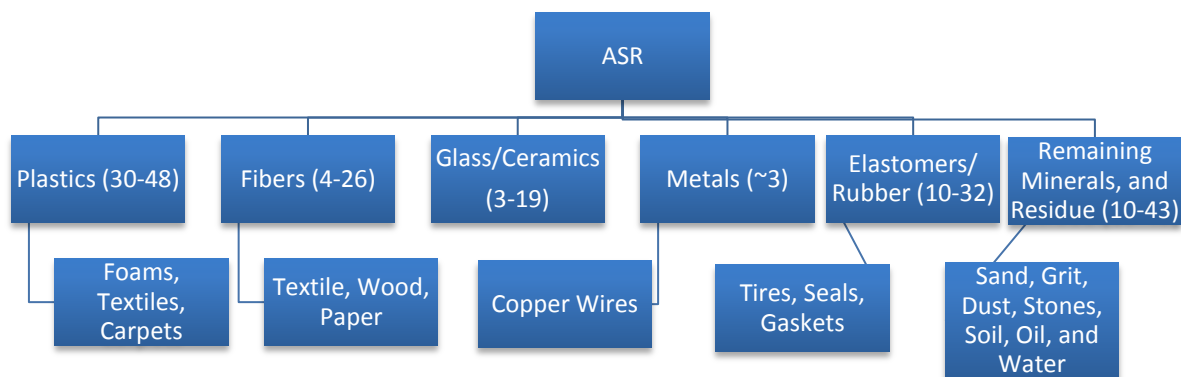


Figure 3: ASR Material Distribution, % weight (Modified from Hjelmar, 2009)

Plastics are the main component with fibers, elastomers, and mineral residue all contributing large portions to the ASR composition. There are several heavy metals that are difficult to extract, leading ASR to be labeled as hazardous waste. The EU Directive 2000/53/EC states that these heavy metals include lead, hexavalent chromium, mercury, and cadmium (European Parliament, 2000). Lead, a component in the metal alloys in the body of the car, is difficult to extract because it is alloyed with much more prevalent metals such as iron and aluminum. Chromium and cadmium are used as anti-corroding agents and are hard to remove because the treatment in which they are applied to metals is not easily reversible. Mercury light switches are used within older vehicles and, under the new laws, are removed

before the shredding process. However, even if the heavy metals are extracted before the ASR is landfilled, the shredder residue will still have to be treated as hazardous waste.

From the 20-25% of ASR created during the shredding process, approximately 50% of the landfilled waste contains a combustible fraction which can be thermally treated. The only exception is the remaining particulate bottom layer, or the char that remains from thermal treatments, which has a low combustibility due to its high content of heavy metals and other inorganic materials (Fiore, 2009). Table 1 details the ranges of thermal characteristics.

Table 1: Thermal Characteristics of ASR (Data from Fiore, 2009)

Analysis (% by mass)	Range
Combustible Matter	40-70
Humidity	2-25
Non-combustible inerts	5-40
Lower Heating Value (LHV) MJ/kg	13.4-25

The table shows that the heating value for ASR makes it a useful feed stock for thermal treatment and energy production and recovery. The non-combustible inert fraction can be collected from the treatment process and applied to other fields of industry.

2.1.3 Landfilling of Auto Shredder Residue

Landfills are organized sites for disposing waste as well as temporary storage and consolidation for waste material. In regards to shredder residue, Denmark allots specific cells to store hazardous waste in order to allow for easier access and recovery of the leachate, the liquid that drains through landfills. Usually, rainwater will percolate, or filter, through the porous landfilled material, and collect heavy metal residues, fluids, and other potentially hazardous materials which could enter into the groundwater and cause contamination. Impermeable bottom liners are implemented at landfills to collect leachate and prevent contaminants from entering the groundwater. These bottom liners usually consist of three layers: a geotextile layer, a polymer layer, and, in some cases, an additional drainage layer. There is also a compacted clay layer that acts as a last barrier for preventing leaching. It must remain moist to prevent cracks from forming that can lead deeper underground. These

systems also collect the leachate through well systems and send it to designated areas of the landfill for collection and testing. Figure 4 shows the setup of these landfill layers.

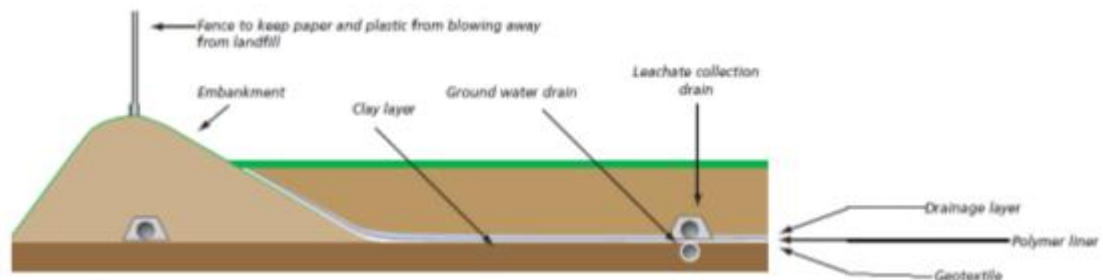


Figure 4: Cross Section Diagram of Landfill (Renovationselskab A/S, 2003)

After a landfill closes, several aftercare measures must be taken in order to ensure that negative impacts will not occur. An EU directive requires that every landfill must have a bottom filtering liner and be located close to the coastline to ensure that if any contamination does occur, the water underground can dilute the toxins to a safer level.

Landfill mining is a potential method for recovering recyclables and creating a profit, but there is a significant financial investment involved. Factors regarding landfill mining include the quality of the separated fraction, market price, and the total volume of material recovered. Some benefits of landfill mining include avoided liability through site remediation, reductions in landfill closure costs, reductions of long term environmental impacts, and the reclamation of usable land (Rosendal, 2009).

2.2 Motivation of Stakeholders

The principal stakeholders in this project are the waste processing companies, the landfill companies that receive the ASR, and RenoSam. RenoSam's primary motivation behind this project is to investigate alternative solutions to landfilling shredder waste. RenoSam wishes to help the shredder companies reach the increased recycling and recovery targets by researching new technologies. Lesser concerned stakeholders are the Danish citizens and the Danish legislature.

The shredder companies are the largest stakeholders in our research because any course of action they implement to meet the 2015 objective could pose a large change for their companies. The impact may require that the companies change their infrastructure significantly to gain the capacity for the new technology. They also have to fund the technologies they implement. A common practice in other European nations is for the car

manufacturers to pay a fee to have the car recycled and processed (Kanari et al., 2003), but this is not the case in Denmark.

The landfill-operating inter-municipal and municipal waste management companies of RenoSam constitute another important group of stakeholders in the project. If the waste processing companies started using a more efficient processing method, the landfill companies would receive less waste and thus less business. However, this is a much more environmentally friendly alternative to the status quo because less waste will increase the life of the landfill.

The lesser concerned stakeholders are the Danish legislature and citizens. The Danish legislature may amend legislation to ensure that waste processing companies reach the objectives of the Danish laws. The processing of shredder residue would positively impact Danish citizens because more recycled goods would be available to them, it is beneficial for the environment, and new processing plants would provide opportunities for employment.

2.2.1 Current Danish and European Legislation

One of the largest factors that influence Danish companies to seek alternative solutions for shredder residue processing is the landfill tax that will be implemented over the course of the next five years. In January of 2012, a tax of DKK 160 per tonne will be placed on landfilled hazardous materials. Until then, Danish waste processing companies will have paid no taxes for sending ASR to the landfills, since hazardous waste is exempt from the existing landfill tax. This legislation will motivate waste processing companies to reduce the amount of waste that they send to the landfills. In January of 2015, the fee will be increased to the same tax rate as non-hazardous waste, DKK 475 per tonne.

In addition to the Danish legislative incentives, the European Parliament and Council issued “Directive 2000/53/EC” in 2000. This directive attempts to make vehicle dismantling and recycling more environmentally friendly and sets clear targets for reuse, recycling, and recovery. Reuse refers to any part of the ELV that can be directly used or refurbished for use in a new vehicle. Recycling is processing ELV parts into raw material to be manufactured into new products. Recovery is reducing ELV material to its component parts and gaining the energy released. The directive must be followed by all signing members, including Denmark. The important points of the directive can be seen in Figure 5.

The articles of the EU Directive 2000/53/EC cover all of these points in addition to others which can be seen in Appendix B. For 2006, the EU called for an 80/85% recycling/reuse rate, and there have been varying levels of compliance with set standards. The most recent report on the directive was completed for the years 2005-2008. The results were inconclusive because many countries did not submit accurate information, if any at all. For the 2006 target it was reported that Denmark was not among the list of nations that met the recovery target of 85%, although they were able to meet the 80% reuse and recycling target (CEC, 2009).

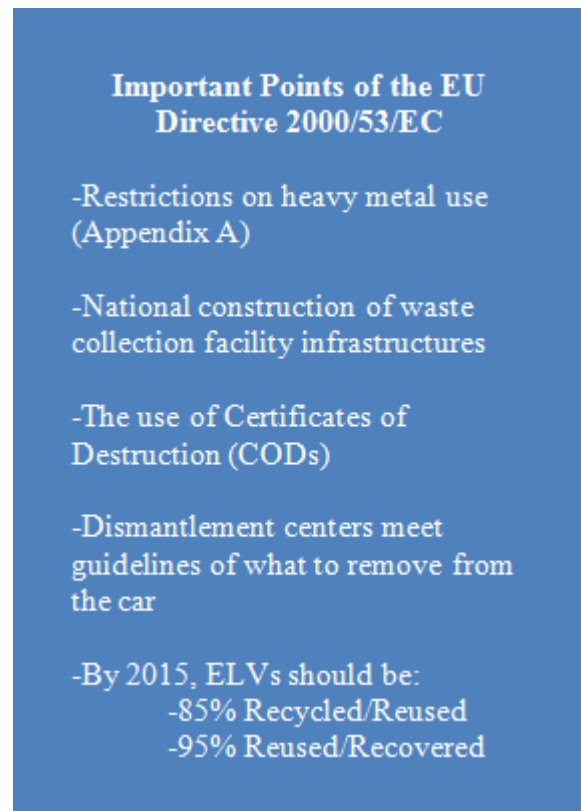


Figure 5: EU Directive Summary

2.2.2 Economic Factors

The economics of managing ELV dismantling, shredding, and alternative technologies for processing ASR depend primarily on the following factors:

- ELV processing costs
- Recycled material values
- ASR processing or disposal costs (landfilling costs and alternative technologies)
- Transportation costs
- Regional and local factors such as legislation

Much of the specific data pertaining to ELV economics is unavailable or kept secret within the specific company. Additionally, even though the economics are favorable overall (Staudinger et al., 2001), there is a low-profit margin gain because ELV management in Denmark is comprised of four competing, privately owned businesses.

The economic motivation provided by the Danish government to shredder companies in the form of a tax on landfilled shredder residue should incite shredder companies to accomplish the goal of reducing the amount of landfilled ASR. The overall economics of the situation are quite simple. If 75% of the landfilled shredder residue was recycled or

recovered, it would result in 187,500 tonnes not being landfilled. The landfill tax on this amount of material would be DKK 30 million in 2012, and increase to DKK 89 million in 2015. If the recycling and/or recovery cost is less than this amount, it will be economically beneficial to process rather than landfill the material. The resale price of the recycled and recovered materials, which is heavily dependent on market price and local factors, will provide additional economic benefits.

2.2.3 Environmental Impact of ASR

The processing of ASR will reduce the environmental impact because less hazardous waste will be landfilled, and leaching will be reduced. The leaching can be hazardous primarily when heavy metals are among the components that are landfilled, and could possibly result in groundwater contamination. This is not expected due to the current setup of Danish landfills, which has safeguards to prevent leachate from escaping. It is necessary for Danish landfills to perform percolate analyses four times a year, so these results are available. Analyses of percolate are designed to measure the contamination levels in the water that runs through the waste (R. Rosendal, personal correspondence, April 29th, 2010).

Additional environmental benefits can be achieved by recycling the materials recovered through the processing of ASR. These materials can be used as an alternative to manufacturing synthetics or mining metals. In addition, the use of recycled materials may result in energy savings when compared to the energy costs of manufacturing metals or plastics from raw materials. For example, one hundred kilograms of aluminum can be produced from only 104 kilograms of scrap and 20 kilograms of fuel, whereas producing the same amount of metal from raw ore would require one tonne of virgin ore and 230 kg of fuel. These benefits are also evident when recycling scrap steel. By recycling a tonne of steel rather than producing it from virgin ore, only half of the energy is used and a tonne less of carbon dioxide is emitted (Wenzel, 2009).

2.3 Auto Shredder Residue Processing

Recent legislative developments and the implementation of stricter EU regulations have placed a higher emphasis on energy recovery and environmental friendliness with regards to the disposal of automotive shredder residue. In Denmark, the prevalent thermal processing method for most types of waste is mass-burn incineration, with an emphasis on energy recovery from waste. However, due to its properties, ASR cannot be independently incinerated. Therefore, various mechanical and thermal pilot processes have been

implemented to separate and dispose of the ASR, but a large scale efficient process has yet to be introduced in Denmark.

2.3.1 Mechanical Processes

Mechanical separation processes are based on the different physical properties of the materials within ASR. The main fractions of ASR include plastics, fibers, rubber, and residual metals. The different properties of these fractions allow for mechanical separation methods including trommel size separation, vibration sieving, air classification, sink and float, eddy current separation, and magnetic separation (Jalkanen, 2006). A trommel is a screened cylinder that rotates and separates materials based on size. Vibration sieving separates different sized fractions of the ASR using differing mesh sizes. Air classification separates sieved fractions by size and density. The sink and float method separates fractions based on density. An eddy current separation system allows for non-ferrous metal separation by using a spinning eddy current rotor to repel the non-ferrous metals from the ASR stream. Iron is easily separated from non-ferrous materials with a magnet.

A sophisticated mechanical separation process was developed by the Huron Valley Steel Corporation of Michigan, one of the largest non-ferrous metal processors in the world. First, the ASR is washed to remove light materials like plastics, wood, and dirt. A light media separation system is used to separate metals and nonmetals since the metal sinks while plastics, rubber, glass, and extremely light metals float. This nonmetal stream is sent over an eddy current separator to remove any residual metals. Ferrosilicon is added to the metal fraction, making a heavy slurry so that heavier metals such as zinc, copper, brass, and stainless steel all sink while only aluminum floats, making it easy to separate out. The mixed heavier metals are sorted by size and sent through a series of eddy current separators which concentrate and separate the metals. Stainless steel is weakly magnetic so it can be separated out from the stream and sold. Zinc, copper, and brass are separated at imaging plants. At the first plant, zinc is targeted for separation so when the imaging system identifies a piece of zinc on the belt, it blows it away from the mixture. This process is repeated at the second imaging plant to separate copper and brass (Broughton, 2001).

Huron Valley Steel Corporation's technology allows them to process aluminum, copper, brass, stainless steel, and zinc from ASR into different streams. The 35-acre plant has the capacity to manage the output of all 200 auto shredders that are in North America. The plant processes the output of 160 shredders, which amounts to 50% of the total ASR in the U.S, enabling the company to sell 225,000 tonnes of metal per year. Water consumption in

the process is environmentally friendly because all the water used for dust control is recovered, cleaned, and reused (Broughton, 2001).

2.3.2 Thermal Processes

Thermal processes are promising for handling the ASR fraction because the materials in the fraction have the potential for high heat content recovery and recovered materials and gases generated by these processes can be marketed for use in industry. The processes can range from pyrolysis, a thermal decomposition in an oxygen-free environment, to gasification, which regulates the amount of oxygen so complete combustion cannot occur, to combustion, in which the products are completely oxidized. Each process can be distinguished depending on the variability of the oxidizing and reducing media and the pressure and temperature (Integrated, 2004).

Co-incineration

Co-incineration is the method of completely combusting, or burning, two organic streams of high-calorific waste as an alternative to regular fuel in order to provide low energy costs to industrial boilers and power plants, and to provide district heating. Combustion is the complete oxidation of a substance to produce heat at elevated temperatures. This process is undergone without generating useful products like fuel gases, liquids, or solids. With regards to ASR, combustion is generally referred to as incineration because extremely high temperatures are utilized. Incineration is a thermal treatment method that involves the combustion of organic material. However, incineration has many operational disadvantages and results in the emission of harmful process residues including acidic gases, volatile organic compounds, and heavy metals (Malkow, 2004). Flame temperatures generally range between 800 °C and 1650 °C depending on the fuel, oxidant, stoichiometry, furnace design, and system heat loss (Integrated, 2004). Combustion produces heat, oxidized species such as carbon dioxide and water, ash, and pollutants such as chlorides, dioxins, and furans.

Experiments to co-incinerate municipal solid waste with organic wastewater sludge, plastics and other materials have shown that these methods are capable of reducing two waste streams simultaneously while recovering energy. Co-incinerating ASR and MSW has been experimented with and has resulted in a syngas and char being produced, but further testing must be completed to determine its applicability (Hjelmar, 2009).

Pyrolysis

Pyrolysis is a thermal process that degrades organic material in an oxygen-deficient environment to produce gas, a liquid tar, and a residual carbon-rich char. It is a method that is used to produce fuels and chemicals from organic feedstock such as wood, coal, plastics, tires, and municipal waste (Argonne, 2006). The system outputs are dependent on different ranges of temperature, pressure, and residence time. These ranges can also control pollution and conversion efficiencies. In regards to ASR processing, there are three types of pyrolysis: conventional pyrolysis, fast pyrolysis, and ultra-pyrolysis. Conventional pyrolysis applies temperatures ranging from 500 °C-900 °C, fast pyrolysis applies the same temperatures but in a short (few seconds) time interval, while ultra pyrolysis which must achieve temperatures up to 1900 °C. The resultant solid portion that is recovered from these processes mostly contains an inorganic fraction as well as a considerable amount of solid carbon or ash (Zolezzi et al., 2003).

Gasification

Gasification reduces the organic material content into a gaseous mixture of CO, H₂, CO₂, and light hydrocarbons by direct internal heating from the addition of oxygen and water to the system. The process is usually optimized to produce a resultant gas, or “syngas”, which consists of compounds from the organic gaseous mixture that can be used as a basis for producing many marketable feedstock gases like ammonia and methanol. The gasification technique additionally yields fuel gas which can then be utilized in a variety of ways, either energetically or as a raw material. Fuel gas applications include lime and brick kilns, metallurgical furnaces, driers, steam-raising boilers, fuel cells and fuel production, syngas, and methanol synthesis (Malkow, 2004). Gasification processes can vary considerably, but they are typically operated at temperatures and pressures ranging from 500 °C to 1000 °C and 5 atm. The amount of oxygen that is added to the system is limited so complete combustion does not occur. Gasification of solids, followed by combustion of fuel gases obtained by the gasification process, produces similar types of products that direct combustion of solids does, but pollution control and conversion efficiencies are improved (Integrated, 2004). A gasification case study of the Chinook Universal Gasification process can be seen in Appendix T. Circulating fluidized bed gasifiers (CFBG) and entrained flow gasifiers (EFG), two of the most widely used gasification processes, are described in Appendix U.

Pyrolysis and gasification co-processing

Increasing developments in the research regarding pyrolysis and gasification technologies are showing that these two processes may be applied as co-utilization and co-processing options. As Malkow notes in his review, pyrolysis and especially gasification are shown to be effective in reducing and avoiding corrosion and emissions. Except for mercury and cadmium, the processes retain alkali and heavy metals while sulfur and chlorine are trapped in the process residues. In addition, low temperatures help to decrease the levels of potentially harmful NO_x gases.

Although Malkow's review looked at the disposal of municipal solid waste, the pyrolysis and gasification techniques can be applied to a variety of waste including ASR. Pyrolysis and gasification are usually used sequentially since pyrolysis produces the fuels and solid residues which are then gasified for energy extraction or recovery. Many technologies exist which use these two processes and they usually differ only slightly in temperature or pressure in the kilns or chambers. The ConTherm Technology was developed by RWE Energie AG and is used at a 769 MW capacity coal-powered power plant in Hamm-Uentrop, Germany. The system carbonizes and decomposes waste to produce pyrolysis gas and coke. These products produce electricity and help fire the power plant, replacing around 10% of coal use. The ConTherm process also results in iron, stone, sand, metal, and glass, which are not combustible and are sent to the construction and steel industries for reuse (RWE Power, 2005).

The EDDITH process was developed by Thide Environment S.A. of France and the Institut Francais du Petrol (IFP). In 1998 the first thermolysis plant using this technology was built in Nakaminato, Japan. This demonstration plant only had a capacity of 10,000 tonnes/year. Several commercial plants in Japan exist including the Itoigawa plant which has been running since the middle of 2002. It has a 25,000 tonne/year capacity for municipal solid waste, uses fuel gas for the process heat, and solid fuel for a cement kiln. Another plant that has been running since 2003 exists in Izumo, Japan, with a capacity of 70,000 tonnes/year. The first EDDITH thermolysis plant in France is called the Arthelyse plant, in Arras. This plant, with a capacity of 50,000 tonnes/year, has been running since late 2003. The outputs of the Arras plant include industrial steam which is used in a nearby plant, ferrous and non-ferrous metals that are recycled, gravel and inert materials used in the construction industry, and solid fuel which is used as a coal substitute (Thide Environnement, 2004). A more detailed description of thermal processes can be found in Appendix D.

2.3.3 Environmental Impact of Thermal Technologies

An understanding of the impacts thermal processes have on the environment is critical for recommending an alternative solution as well as determining overall feasibility. The three main categories of environmental impacts are air emissions, char and slag management, and liquid residues (Integrated, 2004).

Air Emissions

Pyrolysis and gasification are perceived by experts as slight variations to incineration, but the major difference is that incineration does not produce useful products such as fuels or synthetic gases. The California Waste Management Board provides several additional differences between alternative thermal processes and incineration:

- Pyrolysis and gasification processes require lower amounts of air and oxygen, or none at all.
- The volume of output gas from a pyrolysis/gasification reactor is much smaller than incineration. Even though these output gases can eventually be combusted, the alternative thermal processes provide an intermediate step in which the reactors can be cleaned of certain pollutants while incineration has limited to no control over the combusted exhaust.
- Output gases from pyrolysis and gasifiers are typically in a reducing environment (products become more stable) compared to incineration where the exhaust is fully combusted to an oxidative form (Integrated, 2004).

In regards to cleaning the exhaust, there are several well established processes that can be implemented to remove the hazardous materials at the emissions level set by the EU in order to make certain that health and safety requirements are satisfied. Exhaust gas can include substances like aerosols, sulfur and nitrogen oxides, hydrocarbon gases, and carbon monoxide. The particulate material that is captured from the cleaning technologies contains hazardous material and must be landfilled. Appendix E provides a table of air pollution technologies that are used to control the outlet gas from the thermal processes.

Char and Slag Management

The runoff of inorganic and metallic ASR components produced from incineration, pyrolysis, and gasification methods solidifies into a fine particulate residue that is generally referred to as char. Proper management of the heavy metals can allow for more efficient

disposal of the recovered solid and can pose a lowered environmental threat (Integrated, 2004). Other processes vitrify the recovered ash and create a material called slag. This happens when the thermal system operates at a temperature that is higher than the melting point of the ash. The slag is a hard, glassy substance that contains non-volatile metals that were fused during vitrification and can be used in construction or other applications. However, caution must be used because the slag may still leach into the environment. For example, the slag formed from the PyroArc process (Appendix D) does not need to be landfilled since heavy metals are trapped during the vitrification process, creating a leach-resistant slag.

Liquid Residues

Liquid wastes are generated from thermal processes like pyrolysis, which use oils and scrubber solutions in the air pollution control technologies. Mechanisms for treatments of these wastes are available but costs can be high. Wastewater and other liquid streams are produced from similar gas cleaning systems for gasification and pyrolysis processes, and they can contain tars, oils, ash, and other constituents from the feedstock (Integrated, 2004). Many of these compounds can be toxic and should be treated individually, but there are also compounds commonly found in the waste stream that can be used in other industrial processes to form marketable products.

2.4 Summary

There are a number of mechanical and thermal ASR processing methods available to reduce the amount of landfilled waste in Denmark. Each process produces varying marketable outputs and has an overall positive impact on the environment when compared to current methods. This information will aid us in investigating alternative solutions to shredder waste and the overall environmental and economic impacts of the technologies. Additionally, these findings will support the shredder waste companies in their search for solutions that will allow them to meet the 2015 recycling/recovery targets.

Chapter 3: Methodology

The essential goal of this project was to assist RenoSam in investigating alternative treatments of recycling shredder waste from end of life vehicles and the resulting impacts of implementation. Our team developed an analysis of alternative shredder waste treatments and presented our findings to RenoSam and members of the Danish waste recycling and disposal community. We also distributed our report to Danish shredder waste companies and the landfill companies that receive shredder waste, while RenoSam posted our report on their website. The shredder companies will consider the proposed processes as options in meeting legislative waste reduction targets. Our team fulfilled these goals through the following objectives:

- 1) Ascertain current international waste processing practices and treatments**
- 2) Understand the current ELV shredder process, environmental impact, and costs from Danish shredder companies**
- 3) Evaluate the application of alternative technologies to process ASR in Denmark**
- 4) Recommend shredder processing course of action and present our findings in a conference setting**

The flow chart in Figure 6 shows the order in which our objectives were completed. We ascertained the current technologies and concurrently completed interviews with the Danish shredder companies, in order to focus our research on important topics. Using the results of these two objectives, we were able to complete an evaluation of the application of potential processes in Denmark. Finally, using this analysis, we recommended alternative processing options to the shredder companies.

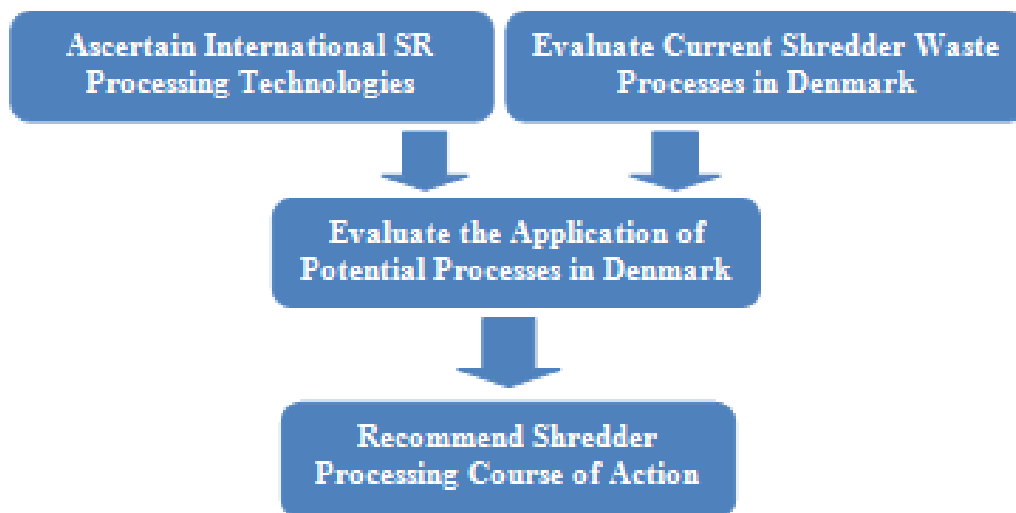


Figure 6: Methodology Flowchart

3.1 Ascertain Current International Waste Processing Practices and Treatments

In order to improve the shredder waste processing methods of Danish waste disposal companies, we first determined what processes shredder plants from around the world are currently using. We studied literature from the most technologically advanced shredder waste processing countries including Japan, Germany, and the United States. Documents our liaison provided us with allowed us to focus our research towards the authors referenced in these papers. Online databases such as ScienceDirect and JSTOR were indispensable resources in finding scholarly articles and reviews regarding ELVs and the processing of ASR. We gathered information on a substantial number of current international ASR processing treatments and collaborated with RenoSam to ensure that we had covered all of the appropriate technologies.

Our initial information on these technologies was generally limited to a detailed description of the process, a figure illustrating the process, and its material flow. The technologies were researched in greater detail by contacting the companies that have developed or implemented them. In order to obtain this information, we researched each process extensively to determine whether or not the information that we were looking for was publically available. If necessary, we contacted a representative for the technology, explained our project, and asked specific questions regarding information we sought. The few replies we received were very helpful and the information was incorporated into this report.

In order to compare the processes, we developed two spreadsheets containing information pertaining to each of the processes (Tables 2 & 3). These spreadsheets included

information on the material flow and the known economics of each process. Details on how the outputs can be recovered or recycled provided some environmental impact information. The research that was completed provided a substantial background that guided the developments of this project.

3.2 Understand the Current ELV Shredding Process in Denmark

It was important for our group to understand the shredder processes currently used in Denmark. This information allowed us to develop a more thorough approach to communicate with Danish shredder companies and work to find the optimal alternative solutions. Meeting with experts also allowed us to ask for their input regarding the scale and direction of the project so that our final recommendations would provide the greatest benefit to them. The main sources of information for determining how Danish waste companies were handling shredder waste were the waste companies themselves. Part of the research that we conducted included touring shredder companies, interviewing operators, and taking pictures of shredder waste processing technologies and landfills. The four shredder companies in Denmark are H.J. Hansen Genvinding, Stena Jern & Metal A/S, Uniscrap A/S, and AA. Espersen & Søn A/S. We interviewed representatives from all of these companies except for Espersen & Søn A/S, the smallest of the shredding companies. The landfills at which the shredder plants dispose of their waste are Odense Nord Miljøcenter (Odense Renovation A/S), AV Miljø (Amager-og Vestforbrænding), Glatved Deponi (RenoDjurs), and Kåstrup Losseplads (Skive Renovation 4S), respectively. We interviewed representatives from both Odense Nord and RenoDjurs. Due to high competition between the few shredder companies, we were unable to receive certain information regarding the specifics of their processes.

Based on the information that H.J. Hansen provided during our first shredder company visit, we decided that shredder companies would provide roughly the same types of information. Thus, we modified our set of questions to ask representatives from UniScrap and Stena (Appendix F). Additionally, we asked for shredder waste processing reports showing amounts of waste processed daily or annually as well as current technologies the companies were using or looking to implement to meet the 2015 EU quota.

In order for any of our suggestions to be implemented, they had to be economically sound. Therefore, there were several pieces of information that we wished to gain about shredder companies so that we could evaluate our researched alternative technologies. In order to analyze alternative ASR processes, there are several steps that we took:

- Talked to representatives from Danish shredder companies to determine what materials were currently being recycled from shredded ELVs
- Found out ELV material content and what percentage was currently being landfilled
- Found and interpreted leaching studies for landfilled shredder waste
- Determined the material flow of processes utilized by shredder waste companies in Denmark
- Focused analysis primarily on environmental impact by evaluating energy consumption, gaseous emissions, and resulting byproducts
- Considered the economics of technologies by analyzing the importance of manufacturing costs, gate fees, recycled product markets, incineration costs, transportation fees, and landfilling fees and taxes
- Understood current Danish Ministry of the Environment legislation
- Determined how shredder waste companies will attempt to fulfill the 2015 EU quota

This enabled us develop to our understanding of the Danish shredder waste status quo and advance our goal of recommending implementable technological options.

3.3 Evaluate the Application of Alternative Technologies to Process ASR in Denmark

It was critical that our group understood and evaluated the technological processing options that were available worldwide in order to be able to propose alternative shredder waste processing methods to RenoSam. We looked into a number of current mechanical and thermal processes that have been applied by technologically leading countries. These processes were analyzed for product recovery, environmental impact, and economic feasibility. By looking at what is recovered and recycled as well as the environmental impact of the various processes, the team was able to narrow down the multiple options and acquire a greater understanding of the various treatments. This allowed us to provide a comparison of alternative shredder treatments to RenoSam. Figure 7 shows the primary steps in our assessment of the shredder processing technologies.

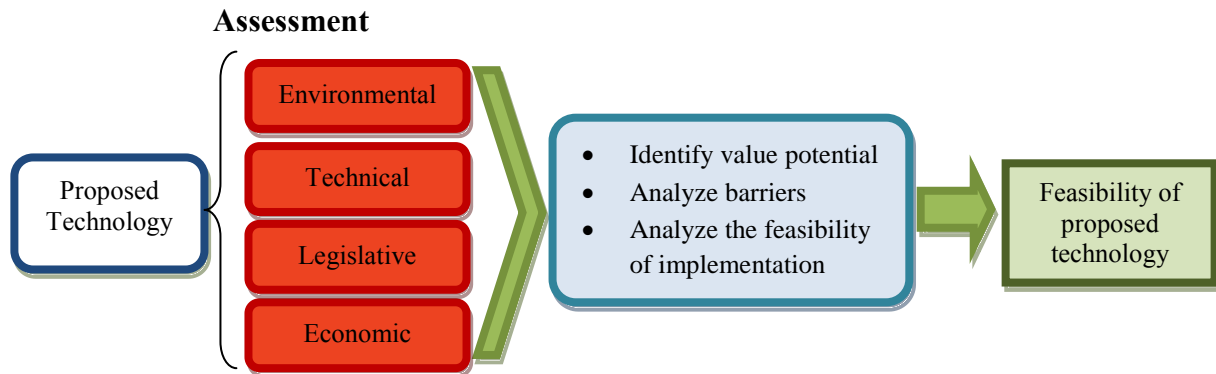


Figure 7: Assessment Flowchart (adapted from Ahmed et al., 2009)

The bullets below convey the key points in the assessment tools that we used to consider processing options:

- Environmental
 - Determine the recyclable and recoverable products that result from the process
 - Evaluate the overall environmental impact based on energy consumption, gaseous emissions, and resulting byproducts
- Technical
 - Evaluate the readiness and applicability of the process
 - Assess the feasibility of processes through current and past pilot plants
- Legislative
 - Determine whether the recycling/recovery targets can be met
- Economic
 - Analyze plant construction costs, gate fees, recycled product markets, incineration costs, transportation fees, and landfilling fees and taxes

The environmental assessment is comprised of several variables. One of the most important factors to consider was the leaching effects of hazardous material into the environment. Therefore, methods in which heavy metals are processed and disposed of were analyzed. Additionally, both thermal and mechanical processes require energy consumption and wastewater treatment, which present added environmental concerns. We compared the environmental impacts of current landfilling processes to the environmental impacts of the experimental ASR processes that are being researched.

Our group critically analyzed the material flow for ASR treatment processes. Understanding the material flow of each process enabled our team to tailor the most

applicable technologies for processing ASR. For example, since plastics make up the majority of the shredder residue, incorporating a process that extracts plastic from the ASR is a very important step in reaching the 2015 targets. By knowing the largest fractions of materials in the ASR flow, we were able to make sure that shredder companies extract the most prevalent materials in ASR.

3.4 Recommend Shredder Processing Course of Action

After completing the preceding steps, our team finalized evaluations on the technologies we believed would be optimal for processing shredder waste in Denmark. In addition to the environmental impact, economic considerations, and legislation, we also kept in mind RenoSam and the shredder waste companies' opinions of the suggested systems. Considering that they are the primary stakeholders in this proposition, their thoughts on the processes are paramount. In order to show our findings and receive feedback from the shredder waste companies and landfills, we presented our project at a conference that took place on May 6, 2010. There was a question and answer session that followed our presentation and we received feedback about our work. This allowed us to make suggested changes to the final report before we distributed it to RenoSam and the shredder waste companies.

3.5 Summary

The mission statement for this project was to assist RenoSam in investigating alternative treatments for recycling shredder waste, primarily from end of life vehicles. These alternative processes were determined mainly through researching mechanical and thermal processes on an international level. In parallel we analyzed the status quo of Danish shredder waste processing and disposal through research and interviews with shredder plant and landfill company employees. Having completed these steps, we evaluated the most promising processes with regard to the Danish waste processing system. Completion of these objectives allowed us to assist RenoSam in analyzing alternative solutions for the processing of auto shredder residue in order to meet the 2015 EU directive.

Chapter 4: Shredder Waste Processing

This chapter presents information obtained from literature reviews, personal correspondence, interviews and tours at shredder companies and landfills. The data focuses on accomplishing the first two objectives of this project: to learn about the current state of Danish shredder processing and ASR disposal, and to research the shredder waste treatments that are being developed globally. Although the focus of this report is on the Danish shredder processing sector, it was important to explore the system of ELV disposal and recycling in the United States to identify possibilities that would advance Danish ASR processing.

4.1 Current Shredder Waste Disposal Methods in Denmark

Municipalities are responsible for all of the waste generated within their territory and are therefore responsible for the shredder waste from the shredder companies within their jurisdiction. Since the municipalities are not allowed to make a profit they must adjust their prices accordingly (J. Simonsen, personal correspondence, April 29th, 2010). For economic and legislative reasons, the shredder companies landfill their waste at landfill facilities nearby in order to reduce transportation costs.

Currently only 6% of waste generated in Denmark is being landfilled (Hjelmar, 2009). Approximately 13-14 million tonnes of total waste are created in Denmark each year, of which 3.3 million tonnes is incinerated to generate steam for central heating (RenoSam & Ramboll, 2005). Landfill prices are rising for all of this waste because there are stringent EU regulations that just recently closed many landfills in Denmark, resulting in less landfill capacity. In addition, the advances that are being made in the field of shredder waste processing are resulting in the development of more efficient and inexpensive processes. Jacob Simonsen, the director of RenoSam, believes that market forces from the implemented landfill tax and rising landfill prices will drive the processing of shredder waste to a point that fulfills the EU 2015 target. RenoSam supports the landfill tax, even though some of their member companies will receive less business as a result. René Rosendal explained that the total amount of waste landfilled will be reduced, thus extending the overall life of the landfills. In the coming years, more landfills will be closing and, due to recent EU legislation, finding a site to build a new landfill is both difficult and expensive. By reducing the amount of waste that is currently landfilled, the landfill will be available for more business in the future. Shredder waste has to be landfilled separately from non-hazardous waste in a specified cell. However, there are currently studies taking place by the Danish EPA to

determine whether or not shredder waste should continue to be classified as hazardous waste. These reports should be published before 2012 by the Danish EPA (J. Simonsen, personal communication, April 27, 2010).

4.1.1 Shredder Companies in Denmark

The collective shredding capacity of the Danish companies is much greater than the demand. As a general rule, for every 500,000 people in the population, there should be 1000 horsepower of shredding capacity (S. Kriegbaum, personal coorespondence, April 19, 2010). However, between H.J. Hansen's 8000 hp shredder, UniScrap's 4000 hp shredder, and Stena's 2000 hp shredder, the shredding capacity in Denmark exceeds 14,000 horsepower. This means that they have the shredding capacity for 7 million people, although the population of Denmark is only 5.5 million. The resulting competition drives the shredder companies to research more technologically advanced processing methods.

The shredder companies in Denmark have a very similar process overall, using most of the same technologies with slight differences. H.J. Hansen's processes include magnetic separation and eddy current separation to separate the ferrous and non-ferrous materials, respectively (H. Larsen, personal correspondence, March 24th, 2010). A picture of the eddy current separation can be seen in Figure 8. The non-ferrous metals are separated into the second opening while the remaining waste fraction falls into the closer opening.



Figure 8: Eddy Current Separation

Then, vibration sieving (Figure 9) sorts the non-metals into particle sizes with increments of 20, 40, and 60 mm. The grid shakes up and down while slowly moving the material stream towards the other end. Debris that is larger than 60 mm is re-circulated through the shredder.



Figure 9: Vibration Sieving

Trommel separation is also used to sort the materials into varying sizes. Magnetic and optical imaging separations further extract ferrous metals and glass from the smallest fraction (<20 mm). Options for glass recycling are discussed in Appendix R. From the largest fraction (40-60 mm), additional plastics, rubber, and wooden components are removed and separated into a pile using a proprietary new pilot technology. The removed plastic, wood, and rubber fraction can be seen in Figure 10. H.J. Hansen is also currently experimenting with a heavy media plant for density separation.



Figure 10: Rubber, Plastic, and Wood Fraction

Magnetic separation removes approximately 73% of the vehicle by weight as steel. After subsequent runs through the shredder, an additional 5% of metal can be recovered. The remaining fraction is separated even further to yield about 2.3% plastic and metal. The final SR fraction (Figure 11), representing approximately 17.5% of the original shredded material, is sent to the Odense landfill. Each day, 1,300-1,400 tonnes of material is shredded and processed at the H.J. Hansen shredder processing plant.



Figure 11: Shredder Residue

Stena Jern & Metal in Roskilde uses many of the same processes, but in a different order (S. Hansen, personal correspondence, April 16th, 2010). After the initial shredding, the waste stream is sent through a trommel (Figure 12) that separates foams that are combined with the rest of the shredder residue. This process makes the resulting shredded stream a cleaner fraction.



Figure 12: Trommel Separator

During the shredding and the trommel step, a cyclone vacuums the fine dusts into filters for landfilling as shredder residue. After the first trommel, the waste stream is sent through a magnetic trommel that extracts the ferrous metal. The ferrous metal section is hand sorted so that electro-motors with large amounts of copper can be recycled (Figure 13). This hand sorting stage is very important because copper is a valuable metal and is considered a contaminant for scrap iron.



Figure 13: Copper Motors

The non-ferrous fraction from the magnetic trommel is then sent through another trommel that separates the waste by size. The large pieces are re-circulated through the shredder and the remaining fraction is sent through a metal sorting facility. This facility sorts out aluminum, stainless steel, and heavy metals such as copper, zinc, and lead. The resulting waste fraction from this plant is also landfilled. Stena's plant is able to handle about 700 tonnes of shredder waste per day.

UniScrap, in Grenaa, has mechanical separation systems that are similar to those found at H.J. Hansen and Stena. The shredder waste is fed into the inlet where it undergoes several mechanical processes including magnetic separation, eddy current separation, trommel separation, and optical imaging (S. Kriegbaum, personal correspondence, April 19th, 2010). UniScrap's separation process can recover 70-76% ferrous material (Figure 14), 6-10% of a heavier fraction that can be processed further for material recovery, 18% landfilled shredder waste, and a copper fraction between 0.2 and 0.3%.



Figure 14: Ferrous Fraction

The heavy fraction consists of a 50% usable non-ferrous material that ranges in sizes of 0-20mm, 20-100mm, and greater than 100mm, and 50% dirt and dust. The non-ferrous material is exported for recycling while the dirt and dust fraction is landfilled. UniScrap processes about 800 tonnes of shredder waste per day at the Grenaa facility.

Each of the shredder companies has developed a plan for reaching the 2015 EU targets. H.J. Hansen seemed confident that with the processes they are researching and testing they will be able to reach the set targets. Currently they are collaborating with Odense University in researching the formation of their own thermal process due to the expensive nature of international pilot processes. Additionally, the company is experimenting with a small-scale gasification type test plant. Stena Jern & Metal, a branch location of the Swedish corporation, is relying on Stena's research division based in Göteborg. Christer Forsgren, part of the Stena research team, is in charge of the investigations being completed into alternative shredder waste treatments. They are experimenting with multiple thermal processes, including microwaves. Stena Jern & Metal will most likely export their shredder residue to Sweden for processing when the new technologies become economically beneficial. Similarly, UniScrap is part of a larger corporation, Scholz AG, which is largely based in Germany. A fraction of their waste could be sent to a plant in Espenhain, Germany, which is

experimenting with technologies on alternative processing of shredder waste. Currently they are able to recycle or reuse 94% of a car, very close to the 95% EU 2015 target. See Appendix G for a more detailed description of the Espenhain plant. UniScrap's plan is to export the shredder waste to the Espenhain facility once it becomes economically beneficial to do so.

Since Denmark has no smelters, the shredder companies export the majority of ferrous metals to Turkey, Vietnam, Pakistan, and the United States, and non-ferrous metals to China, Japan, and Germany. Turkey receives a large portion of ferrous scrap because they are not very discriminating with regards to the quality of the scrap. The Turkish scrap market regularly receives metal from Eastern European nations, which are known for not having very pure irons, so a few impurities from aluminum and copper are acceptable to their smelting process (S. Kriegbaum, personal correspondence, April 19th, 2010).

4.1.2 Shredder Waste in Danish Landfills

Odense Nord Miljøcenter and RenoDjurs, the two largest landfills in Denmark, receive shredder waste from H.J. Hansen and UniScrap, respectively. On average, the Odense Nord Miljøcenter landfills 100,000 tonnes of shredder waste per year, but due to the recent global financial crisis, they only landfilled 65,000 tonnes in 2009 (about 35% of the total waste). There was a significant increase in the amount of shredder waste landfilled in 2001 and 2002 because shredder waste became classified as hazardous waste and was thus tax-free to landfill (F. Andersen, personal correspondence, March 24th, 2010). Over the period of 2001-2010, 775,000 tonnes of shredder waste was landfilled in then Odense Nord Miljøcenter. The shredder waste that is produced at UniScrap is sent to RenoDjurs for landfilling. In 2009, approximately 160,000 tonnes of waste was sent to RenoDjurs, including 27,500 tonnes of shredder waste (P. Madsen, personal correspondence, April 19th, 2010).

Landfill aftercare is very expensive and for Odense Nord, the aftercare period may take over 100 years, although funds are allocated for only 30 years of aftercare. If the landfill aftercare does take over 100 years, as preliminary studies suggest, the cost for the aftercare treatment will be around DKK 135 per tonne (F. Andersen, personal correspondence, March 24th, 2010). This will be a very large expense on the municipalities in which these landfills are located. The Odense Nord Miljøcenter is interested in the possibility of mining shredder waste for further processing to reduce the cost of this aftercare. The Odense Nord Miljøcenter and RenoDjurs are currently researching alternative methods of treating shredder waste with the Technical University of Denmark (DTU).

Finn Andersen, the operational manager at Odense Nord, provided a percolate analysis from the SR cell in their landfill (Appendix H). In 2009, 80,000 m³ of leachate was collected from the current landfill, and 50,000 m³ from Stige Island, the adjacent closed landfill. In 2008 however, due to heavy rainfall, there was 250,000 m³ total leachate from the two sites. Currently the leachate from both landfills is being treated to remove heavy metals at a small pre-treatment facility on site before being processed with other sewage at another location. Peter Madsen, a civil engineer at the RenoDjurs landfill facility, explained that RenoDjurs closed their older landfill in 2009 after 28 years of operation, and opened a newer and more efficient landfill site right next to it. The older landfill was forced to close because the landfill characteristics did not fall within the new European Union regulations on leaching; the landfill did not have a bottom layer filtering system for leachate. After recently testing the leachate at the older landfill it was found that there was only a small amount of pollution because the leachate was greatly diluted from the large amount of water present underground from the nearby sea. The waste landfilled at the new RenoDjurs landfill produced 7300 m³ of leachate in 2009, which was processed for removal of hazardous components at a nearby facility and then sent to a wastewater treatment plant for processing. In order to force leaching from the shredder waste at RenoDjurs, 20 m³ of water is spread on the shredder waste every day. Leachate samples from the shredder waste are analyzed and used in a research project conducted by RenoDjurs and DHI (Appendix I).

The practice of landfilling SR separately from all other waste is done for several different reasons. Shredder waste in Denmark is classified as hazardous waste and as such it must be landfilled in a particular manner. Another reason that SR is landfilled in its own cell is the possibility of recovering this material to process at a later time using a landfill mining process. This idea was introduced during our visit to H.J. Hansen and was confirmed by Mr. Andersen. The rapidly developing technologies for processing SR will soon develop a process that will make it economically beneficial to recover previously landfilled shredder waste. Once this happens, shredder residue may become a commodity as a market develops for recycled plastics and similar materials that can be recovered from this landfilled fraction of SR. RenoDjurs also has a separate cell for only shredder waste (Figure 15). As it can be seen in the picture, dirt that is added to the shredder waste to ensure that potentially harmful dust from the SR does not spread into the surrounding environment. The RenoDjurs landfill is similar to the Odense landfill, but instead of 3 filter layers, RenoDjurs has only a geotextile and a polymer layer. RenoDjurs also implements percolate wells to collect and control leachate produced from shredder waste.



Figure 15: Shredder Waste Landfill Cell

4.2 Alternative Shredder Waste Technologies

There are many different technologies that are currently being developed in order to process shredder residue. From a mechanical separation standpoint, plastics are the most important fraction to separate. This section presents a summary of the material flow and economics of several processes as well as a discussion of current plastics.

4.2.1 Technology Material Flows and Economics

In order to evaluate the processes, it was paramount to map out the material flow of each process (Table 2). This allowed us to complete economic and environmental analyses and determine which processes would be optimal to put in sequence.

Table 2: Abridged Material Flow of SR Treatment Processes

Process Name	Recycled			Fuel	Inerts	Overall Recovery (of ELV)
	Plastics	Metals	Others			
<i>Mechanical</i>						
Argonne (US)	27%	5-10%				94%
SiCon (DE)	36%	8%	33%		22%	95%
<i>Thermal</i>						
R-Plus & Sult (DE)		10%	20%	50%	20%	100%
SVZ (DE)		8%	12%	74%	6%	94%

The complete version of this table can be seen in Appendix J. The green columns show the percentages of materials that are recycled. The “Other Recycled” column shows the content that is processed into a recyclable material that cannot be described as a metal or plastic. An example of this is the shredder fibers that are created in the SiCon process, which are used to filter sewage sludge (Ujsaghy, 2008). The “RDF”, or refuse derive fuel, column shows the amount of material by weight of the shredder residue that is converted into energy or a material that is later burned in a furnace or other combustion device. This fraction of the shredder residue may be used to help reach the recovery goal in the 2015 EU target. The “inerts” are usually materials that are landfilled, but some processes are able to make these inerts safe enough to use in industry or to fill exhausted mines. The “Overall Recovery” column shows the total percentage of shredder material that is either recycled or recovered. Included in this percentage are the ferrous materials that are recycled during the shredding process, which will be assumed to be a constant 80%, and is the number that should be looked at when determining whether the process meets the EU 2015 target.

Due to the fact that most shredder waste treatment technologies are in the testing stage, the economics for most processes are unknown or undisclosed. However, the gate fee for each process is very important when determining the feasibility of implementing the process. The known gate fees, plants sizes, and plant construction cost of selected processes can be seen in Table 3.

Table 3: Process Costs and Plant Capacities

Process Name	Gate Fee (€/t)	Plant Cost (€)	Plant Processing Rate (tonnes/yr)	Source
<i>Mechanical</i>				
R-Plus (WESA-SLF)	90	2.04 mil	16,000	GHK, 2006
VW-Sicon	20-50	6-12 mil	100,000	Krinke, 2006
Galloo	25		18,100	Schut and Lindqvist, 2004
<i>Thermal</i>				
Gasification	120-200		170,000-200,000 SVZ Plant	Hjelmar, 2009
Pyrolysis	120-150			Hjelmar, 2009
Co-Incineration	7-55			RenoSam, 2009
Sult	100			GHK, 2006
Ebara Twin-Rec	120			GHK, 2006

The “Gate Fee” column shows the estimated cost for processing a tonne of shredder waste in Euros. These fees in general include investment costs, processing costs, average profit, final disposal costs as well as income from sale of recovered metal fractions and energy. The “Plant Cost” shows an estimate of how much it costs to construct a processing plant of the size seen in the “Plant Processing Rate” column. Even though some plant costs are not included, some values in this column are provided so that examples of constructed plants can be shown.

4.2.2 Plastics Separation and Recycling

The main goal of recycling is to recover materials in such a way as to preserve their structural integrity and material value (Duranceau, 2009). Plastics separation and recovery has been a topic of research recently since they have a very high calorific content. Plastics have an energy value (45 MJ/kg) comparable to that of oil (48 MJ/kg), much higher than the energy values of coal (26 MJ/kg) or MSW (12 MJ/kg) (American Chemistry Council, 2010). Using recycled plastics is more cost-effective and less energy intensive than creating new plastics from raw material. At the end of their “useful life” plastics parts can be recycled into new parts. This recycling of the same plastic material can be applied multiple times and the plastic can still be used as a high-energy fuel source at the end of several “useful lives” (Duranceau, 2009).

One of the most developed and successful plastics separation technologies seems to be a two-step separation process utilized by Argonne National Laboratory. Argonne’s pilot plant consists of a 2 tonne/hr dry separation facility and a six-stage 0.5 tonne/hr froth

flotation system. The mechanical separation process divides the ASR into foams, residual ferrous and non-ferrous metals, and a polymer concentrate that consists of the plastics and rubber fraction. Since the polymers are incompatible with each other they have to be separated further to become marketable material and be recycled into new products. The froth flotation system is used to separate plastics from the mixture based on density differences. Argonne's technologies have been licensed to Salyp in Belgium where a successful full-scale commercial demonstration plant is in operation (Argonne National Laboratory, 2007). The separation plant and resulting plastic fraction can be seen in Figure 16.



Figure 16: Argonne's Plastic Separation (Argonne National Laboratory, 2007)

The main fractions recovered from the polymer mixture are polypropylene (PP), polyethylene (PE), acrylonitrile butadiene styrene (ABS), and high-impact polystyrene (HIPS). The PP and PE fractions are recovered at a greater than 90% yield and are more than 95% pure (Argonne National Laboratory, 2007). The plastic fractions are cleaned of any hazardous substances with a process developed by ECO2 Plastics. Instead of water, this environmentally friendly process uses a biodegradable solvent and liquid CO₂ to remove hazardous materials. The properties of the pure and clean plastic fractions have been proven to be very similar to the properties of various grades of commercially marketed virgin materials. Thus the fractions have been successfully used to make spare tire covers, steering column covers, battery trays, and knee bolsters (Figure 17) (Daniels, 2006). To gauge the full

commercial scale of the process and its products, a 20 tonne/hr plant is being constructed at a shredder site (Daniels, 2009). For a more detailed explanation of plastics separation processes refer to Appendix K.



Figure 17: Recycled plastic parts (Daniels, 2006)

A mechanical separation process developed by the German company SiCon GmbH separates ASR into four streams. The mixed plastics, rubber, metals, and remaining materials are separated by an automated process. Ferrous and non-ferrous metals are extracted from the ASR in the beginning of the process. The shredder fluff is separated into plastics, fiber, and sand. The plastics are recycled or manufactured into a fuel that burns with the same calorific as pulverized coal. The fibers created in this process can be used to filter sewage, or as a fuel source. The sand portion is landfilled. This technology is currently being employed in three VW-SiCon systems in Europe, operating with a total capacity of 200,000 tonnes/year. Another plant is under construction in Slovakia while a fifth plant's construction will start in the middle of 2010. The SiCon system can recover 80% of shredder residue and the process is environmentally friendly because it does not use any water (Recycling Today, 2010). The mechanical treatment of the process includes crushing, screening, and separation, based on characteristics such as density, size, magnetic content, and optical features. Products include hard plastics and rubber in the shredder granules fraction, foams and textile fibers in the shredder fibers fraction, and glass, rust, iron particles, and heavy metals in the shredder sand fraction. Uses for these fractions can be seen in Figure 18. In addition, residual ferrous and non-ferrous metals are recovered (SiCon GmbH Process, n.d.). SiCon has opened a shredder residue processing plant in Antwerp, Belgium that successfully processes 20,000 tonnes/year.

Plants are also in operation in Austria and France, and an additional plant will be built in 2009 in the Netherlands (SiCon GmbH Productions, 2008). Agreements are in place with various companies and plants so sale of the fractions generated by the VW-SiCon process is assured. More information on the process is presented in Appendix S.

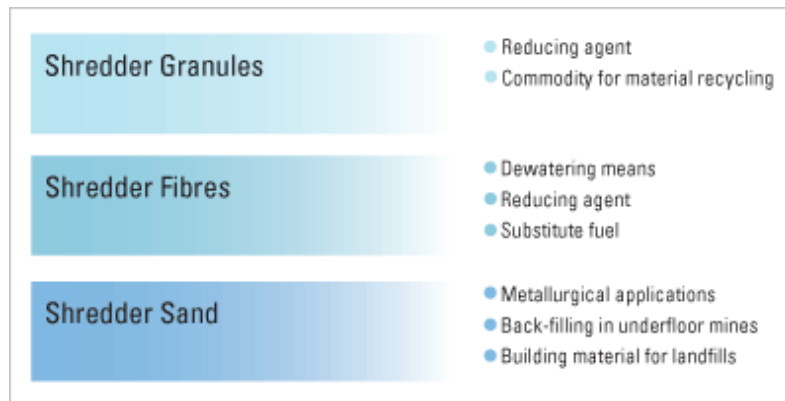


Figure 18: SiCon Products (SiCon GmbH Process, n.d.)

4.2.3 Co-Incineration and Combustion

Mr. Forsgren, the Environmental and Technical Director, and Ms. Gyllenhammar, the combustion Project Manager in the Technology and Environment Department from Stena, provided important information regarding their current research into the possibilities of ASR combustion and co-incineration. Research has shown that the SLF fraction may be able to replace coal in cement and lime kilns (Forsgren, 2010). Chlorine, zinc, and lead present in ASR are deposited and corrode the boiler during incineration. However, a recent Stena study has shown that ASR co-combustion with sewage sludge and MSW could reduce these effects (Gyllenhammar et al., 2010). The co-combustion was performed in a fluidized bed plant in Lidköping. Since no problems were found with the slag or bottom ash, the study concluded that co-incineration of ASR is a viable landfilling alternative. In addition, Sweden co-combusts 5-10% of ASR with MSW and industrial waste in grate boiler plants (M. Gyllenhammar, email correspondence, April 22nd, 2010).

4.3 American ELV Treatment

In the United States, 95% of vehicles are processed through a market driven recycling infrastructure that provides no additional tax burden to citizens and allows for more than 84% of the vehicle to be recycled (Bairley et al., 2007). Approximately 12.5 million ELVs (7.7 million cars, 4.6 million light trucks, and 0.2 million medium/heavy trucks) are recycled each year (Staudinger & Keolian, 2001). Therefore, a very efficient dismantling and shredding

process is implemented to ensure that the most material is recovered, reused, or recycled from each ELV. The five parameters that each dismantling facility is responsible for in an ELV are:

- Direct Reuse (body panels, door panel, trunk lid)
- Remanufacture (clutches, engines, transmissions)
- Recycle (fluids, batteries, catalytic converters)
- Energy Recovery (tires)
- Disposal (plastic fuel tanks)

Direct reuse of automobile parts keeps the amount of material and manufacturing energy for constructing new parts from virgin materials at a minimum. Remanufacturing specific vehicle parts is an attractive method because it provides a low cost replacement alternative for expensive new parts. Recycling parts such as batteries and catalytic converters allows for material recovery of precious metals including platinum or lead which can cause environmental hazards through leaching. Additionally, approximately 19 liters of fluids are drained per vehicle during the dismantling process (Greenway Recycling, 2009) which includes fuel and refrigerants that can be reused after purification. Tires contain a high calorific content for energy recovery which can be collected and used to power the dismantling process. Tires are a large resource potential, and details can be seen about its recovery potential in Appendix L. Plastic fuel tanks and other materials that have no recyclable, recoverable, or marketable value are broken down and disposed of in incinerators or other waste disposal methods.

In North America, there are more than 15,000 automobile dismantling facilities (Jody, 2009). Once a vehicle reaches end of life status in the U.S. it is sent to one of two types of dismantlers: high-value parts dismantlers or salvage/scrap yards. High-value parts dismantlers are retail or wholesale businesses that contain a large inventory of car parts for resale. The inventory is maintained on a nationwide computer database so car parts can be located quickly and efficiently and delivered to customers. Salvage or scrap yards are private family owned businesses that do not keep a detailed inventory report. Instead, the ELV is stored within the facility where the customers can find the parts themselves. Overall, this type of dismantler is not a very reliable source and contains less desirable ELVs compared to high-value dismantlers. (Staudinger & Keolian, 2001) Below is a list created by the University of Michigan's Center for Sustainable Systems in 2001 detailing the parts and materials removed from an ELV by dismantlers and their future use:

- Electro- mechanical parts: (clutches, water pumps, engines, starters, alternators, transmissions, motors for power windows) Refurbished and sold for reuse
- Structural body parts: (body panel, wheels, whole car seats) Removed to be used for repairing vehicles that have been damaged from accidents
- Aluminum and copper parts: Sold to nonferrous material processors or smelted into ingots for resale at a scrap market
- Gasoline: Recovered for reuse
- Vehicle Fluids: (engine oil, transmission fluids, ethylene glycol, windshield cleaning fluid) All are recycled
- Car Batteries: Recycled for their lead, sulfuric acid, and polypropylene content
- Tires: (burned for energy recovery, landfilled or stockpiled) Sent to scrap tire dealers
- Catalytic converters: Sent to recyclers for recovery of their precious metal catalysts (such as platinum or palladium)
- Air conditioning refrigerant gases: Recovered for reuse or destruction
- Air bags: Recovered for reuse or deployed and disposed of
- Fuel tanks: Steel tanks are flattened and sent to smelters for recycling. The plastic tanks are landfilled

Though remanufacturing automobile parts is an important part of the recycling infrastructure, there are several problems that must be taken into account. For example, dismantling bumpers was thought to be an economic incentive for the plastic recovery, but recycling problems were encountered with the amalgam of materials used to create bumpers and the paint on them. Nonetheless, some repair shops and dismantlers continue to collect the polypropylene from the bumpers. Another issue that arose was dismantlers tried to recover plastics and seat foam from vehicles for their marketable value, but they quickly found out that the operation was not economical. Storing foams and plastics required a lot of space that needed to be used for other dismantling processes and the amount of foams and plastics recovered from an average dismantled ELV was very small and, thus, difficult to market (Jody, 2009).

After processing, both types of dismantlers send their ELVs to a shredder facility. The remaining body of the ELV, called the “hulk”, is usually flattened before being shipped. At the shredder facility, the ELV is shredded and then separated into its ferrous and non-ferrous

components through the use of magnets, eddy current separators, and flotation system technologies. UM's Center for Sustainable Systems estimated that from 13.5 million ELVs, recovered ferrous metals accounted for 13.4 million metric tonnes (68% of the ELV weight fraction), recovered non-ferrous metals totaled 1.7 million tonnes (9%), vehicle fluids consisted of 1.1 million tonnes (6%), and tires weighed 0.5 million tonnes (2.5%). Figure 19 illustrates the fractions of the different recovered material from an ELV.

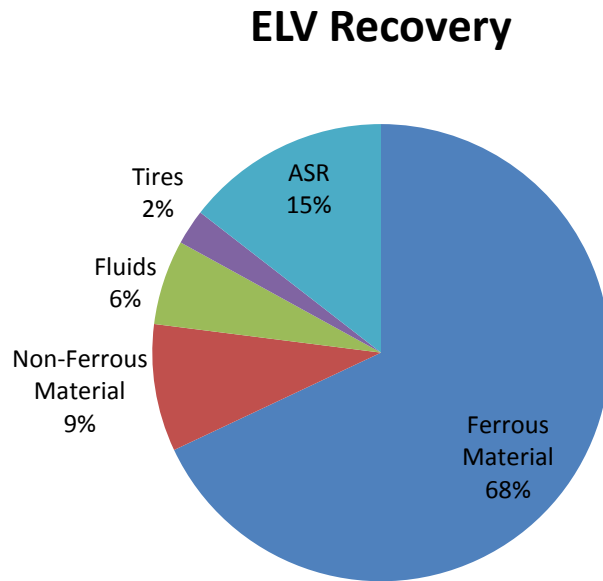


Figure 19: ELV Composition Resulting from Dismantling and Shredding (Data from Jody, 2009)

The ferrous metals are exported to smelters to be recycled while the non-ferrous material is separated further into a metal stream and an ASR stream. The non-ferrous metal stream consists of aluminum, brass, bronze, copper, lead, and other non-ferrous metals while the ASR stream consists of plastics, glass, rubber, foams, carpets, textiles, dirt, and other residues. The ASR consisted of 2.8 million tonnes or approximately 14.5% by weight of the 13.5 million ELVs (Staudinger & Keolian, 2001). The United States currently landfills ASR and is researching technologies to recover and reuse the plastics and other non-metallic material present in the fraction.

The United States Council for Automotive Research (USCAR) Vehicle Recycling Partnership (VRP) has entered into several agreements since 1991 called the Cooperative Research and Development Agreement (CRADA) with Argonne National Laboratory and the American Plastics Council in order to create methods to maximize the recycling of an ELV in the United States. The CRADA team's research is very broad and diverse and it includes:

- Establishing and publishing preferred practices for recycling
- Establishing efficient fluid removal processes
- Running a licensed Vehicle Recycling Development Center to establish procedures that optimize materials recovery in vehicle dismantling
- Researching separation technologies for commingled material streams
- Initiating efforts targeted at removing substances of concern from shredder residue, regardless of its source (Bairley et al., 2007)

The team also conducted a detailed study of car dismantling over several years. Their objective was to “evaluate the feasibility and viability of collecting and recycling automotive polymers from ELVs” (Jody, 2009). The plastic materials were recovered and restored to their original manufacturing specifications and marketable quality. The study concluded that reuse contributes significantly to recycling and the recovered materials from ELV dismantling are an acceptable alternative to new vehicle parts. However, the current economic incentives that are needed to balance the effort are not able to support the existing market in North America (Jody, 2009).

Ultimately, besides the items that can be dismantled from an automobile and sold without refurbishment, dismantling is not an economical choice. It requires costly manual labor and the small amount of materials that are recovered from an ELV are not a cost-effective choice. Furthermore, the storage space required for the recovered amount of material from over 15,000 car dismantlers in addition to the cost to transport the material to the storage facility would be costly and impractical. On the other hand, future automotive parts from hybrid vehicles that require expensive material for development may justify expanding the dismantling process to remove a more vast collection of parts. Otherwise, a problem could exist in which newer substances may arise in ASR that could require different processing requirements. Process improvements can enable ELV dismantling to be easier, more efficient, and cost effective ELV recycling.

4.4 The Future of ELV Dismantling and Processing

Automobiles are continuing to be designed in new and innovative ways. Hybrid and fuel cell powered vehicle sales are increasing as environmental awareness becomes more prevalent. New lightweight materials used in production will eventually end up in ASR and create new processing challenges. These materials include more aluminum, magnesium, plastics, and more catalysts from fuel cells (Jody, 2006). Therefore, insight into future

modifications is essential for the dismantling and shredding process in order to create an easier transition for processing shredder residue.

4.4.1 Light Weight Design Strategies for Future Vehicles

In order to build lighter vehicles, steel will be greatly reduced and replaced by plastics, aluminum, and magnesium. Parts such as the engine, frames, gears, and other components will be made by lightweight materials (Jody, 2006). As lighter weight materials are being implemented into vehicles, it can be expected that ASR will begin to consist of increasing amounts of lighter metals and plastics so proper alterations to the processing method will have to be applied. One major adjustment that will need to be implemented is an economical technology that can separate different aluminum types such as wrought and cast alloys. The technologies will also need to maintain the value of each separated alloy and continue to use the same process of shredding followed by separation (Jody, 2009).

New manufacturing techniques such as hydroforming and overmolding will be implemented and must be taken into account during the dismantling process. Hydroforming is a cost-effective method that uses high pressure hydraulic fluid to shape malleable metals such as aluminum. Overmolding is a process where a pre-formed plastic part is placed into a mold and then a second material, usually rubber or plastic, is injected into the mold forming a hard plastic that can replace certain metal parts in vehicles (GLS, 2004).

Newer battery designs for hybrid and fuel cell powered vehicles are also being investigated in order to manage energy more efficiently. Therefore, the use of easily recycled materials and the development of environmentally sustainable materials are critical for the future of ELV dismantling and processing.

4.4.2 Recycling of Hybrid Vehicles

In the United States, there were 9,600 hybrid vehicles sold in 2000 and in 2009 the number of units sold jumped thirtyfold to 290,272 (hybridCars, 2010). As oil prices rise, the number of hybrid vehicles sold is only expected to increase because they are able to obtain higher miles per gallon compared to a conventional vehicle. The vehicle's structure is generally downsized in order to meet the average power requirement of a conventional vehicle and also uses the energy stored in the battery to power an electric motor which is needed to meet extra demand for specific instances such as passing another vehicle (Jody, 2006). Hybrid vehicles may also have a regenerative braking mechanism that captures energy that is lost during braking. Currently, the leading batteries that are implemented in hybrid

vehicles are nickel metal hydride and lithium batteries. Other potential candidates include lithium ion, lithium polymer, magnesium-lithium, sodium nickel chloride, lead acid, and nickel zinc batteries. All of these batteries contain chemicals that would have negative impacts on the environment and would have to be dealt with accordingly after being extracted from an ELV (Jody, 2006). Zinc and aluminum are used to develop a sacrificial anode for zinc and aluminum air batteries. As the battery produces electricity, the anode is dissolved into the electrolyte and once the anode dissolves completely, it is replaced by a new anode. The resulting aluminum, zinc, and electrolyte mixture are removed from the vehicle and sent to a recycling facility (Jody, 2006).

4.4.3 Recycling Fuel Cell Vehicles

Fuel cells are designed to provide a cleaner and more efficient approach to generate energy, but several barriers limit their recycling. First, the availability of existing technologies that can process and separate the material is limited due to the complex structure of the fuel cells. A fuel cell consists of three subsystems: the fuel supply, the fuel cell stack, and the balance of the plant (Jody, 2006). The technology is still not proven in markets and thus currently lacks the necessary supporting infrastructure. Fuel cells also contain hazardous materials such as hydrogen, a specific electrolyte (i.e. phosphoric acid), and a catalyst. Finally, cost effectiveness of the materials recovery operation has to be assessed. The following description highlights some of the changes in material that fuel cell vehicles will have:

- A fuel cell power train will have an 80% reduction in the amount of iron used
- Bipolar plates, which are located in the fuel cell stack, compose 70-80% of the stack and contain phenolic-resin which is an increase of up to 18 times the current amount of phenolic-resin in vehicles. Current technologies cannot process this resin.
- The amount of precious metals such as platinum in a fuel cell ranges from 15 to over 200 times the amount that is found in the catalytic converter of conventional automobiles. Current technologies most likely could be implemented to recycle catalysts in catalytic converters. (Jody, 2006)

Ultimately, an in-depth analysis must be undergone to develop new technologies for the dismantling and processing of the fuel cells while using current technologies to process the rest of the vehicle.

4.4.4 Dismantling Cooperation

USCAR's VRP, which includes DaimlerChrysler Corporation, Ford Motor Company and General Motors, has worked together since 1991 on developing the most efficient ways to maximize vehicle recycling. Their cooperation offers each company the following benefits (USGS, 2009):

- Enables partners to have larger research budgets and optimize resources
- Creates environments for sharing technical expertise, ideas, and information. The Federal governments can also protect the disclosure of any proprietary information brought to CRADA by the partners
- Allows Federal and non-federal scientists to collaborate and offer non-Federal partners access to resources within the Federal government

Other benefits include sharing intellectual knowledge, agreements on patents, and government protection on disclosed information for several years.

The United States has a distinct advantage over Denmark in regards to cooperation. For example, if the Danish dismantlers were to have similar agreements, the dismantling process could be vastly improved. UniScrap, which receives their ELVs from multiple dismantlers, experiences a small explosion in their shredder at least once a month because the fluids are not always properly removed. Lapses in the dismantling phase such as this can lead to hazardous waste contamination or costly and dangerous explosions.

There are about 250 dismantlers throughout Denmark, but only 40 are part of the Refero network, an organization of environmentally approved access points where owners can leave their cars for scrapping (N. Remtoft, personal correspondence, April 29th, 2010). In Sweden, the Refero network is a collaboration between Stena and leading car manufacturers and importers. The Refero network in Denmark was created in 2007 but it is important to create a more inclusive national network so that dismantling procedures all over Denmark are consistent and fulfill strict environmental standards. The more efficient the dismantling process is, the more money dismantlers can earn for the parts they are able to reuse and recycle. Improved dismantling processes will also ease the burden on shredder companies to reach the 2015 EU targets for ELV reuse, recycling, and recovery.

4.5 Summary

Resulting from the research completed in this project, information regarding the current state of shredder waste disposal in Denmark and the United States, material flow and economics of alternative treatments, and other relevant information was obtained. This information was used to accomplish our first two objectives: to determine the status quo of shredder waste processing in Denmark and to research potential SR processing technologies for application in Denmark.

Chapter 5: Environmental and Economic Impacts of ASR Treatments

After accumulating data through interviews and literature review, an analysis of the possible ASR treatment methods was completed. This section discusses the environmental and economic impacts of auto shredder residue treatments and the effects of possible courses of action for Danish shredder companies.

5.1 Environmental Impact of Auto Shredder Residue Treatments

The ferrous and non-ferrous metals that are removed from the ELV during the shredding process are not considered hazardous to the environment, but the remaining ASR fraction contains hazardous components which can cause pollution to the soil and groundwater through landfill leaching. In regards to alternative ASR processing, both mechanical and thermal treatments have environmental impact concerns that must be analyzed before a full scale plant can be developed.

5.1.1 Landfilled ASR

ASR contains heterogeneous components that have different chemical behaviors once they are released into the environment via landfills. Foams can contain oils, moisture, minerals, and dust particles that could leach into the ground through water transportation. Even at low concentrations, heavy metals such as zinc, mercury, and lead pose a challenge in ASR because of their effects on the environment and human health. Lead is found in batteries, metal treating, and some fluids; zinc is used in protective metal coatings; and mercury is used in the headlights and mercury switches for older model vehicles. Even though the bulk of the heavy metals are removed during the dismantling process, the metals that were used as coatings can seep into the ASR fraction, causing a toxic leachate to flow through the landfill. Brake fluids, motor oil, coolants, and other fluids can contaminate the ASR if they are not properly removed from the ELV during the dismantling process.

In order to measure the amount of contaminants in shredder waste, landfill facilities have been specifically designed to filter leachate into a collection drain for testing and to prevent leaching into the surrounding groundwater. The bottom of the landfill can have two to three impermeable layers that consist of a drainage, polymer, and geotextile layer. The compacted clay, the last barrier for preventing contamination of leachate into the ground, is

present in all landfills and is kept moist at all times so cracks that lead further underground do not form. Figure 20 shows a detailed design of the Odense Nord Miljøcenter.

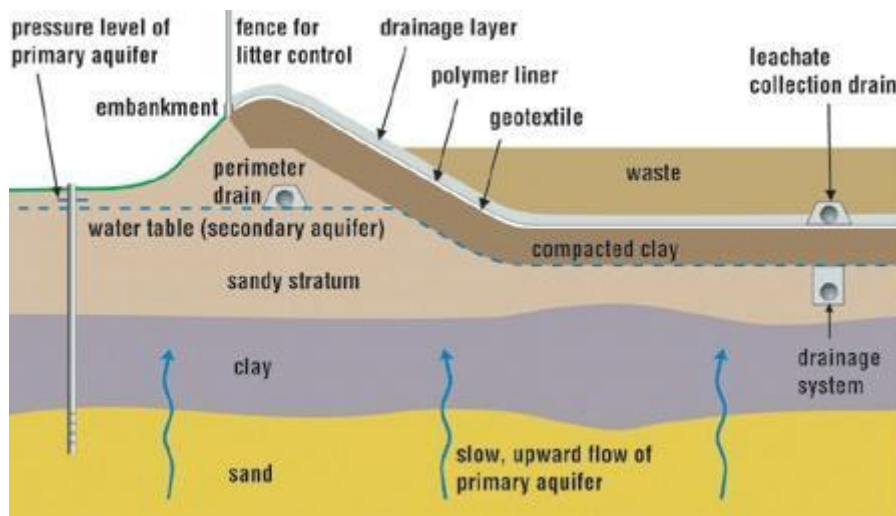


Figure 20: Odense Nord Miljøcenter (Odense Nord, 2008)

Drains have been implemented at the bottom of landfills to collect the leachate and then direct it to a collection site. Odense Nord has one large collection drain where all of their leachate is collected while RenoDjurs has a more advanced system. Several percolate wells were built at various points around the landfill to collect leachate and then direct it to a collection drain, but instead of one large drain, there are ten individual drains so different samples can be collected and tested from different areas in the landfill. The water flow from the primary aquifer, or an underground layer of water-bearing permeable rock, affects what kind of leachate system should be applied to the landfill. For example, the landfill at Odense Nord Miljøcenter has an upward aquifer flow resulting in an inwardly directed hydraulic gradient which ensures that leachate will not leak from the landfill into the groundwater.

Specific detection limits are monitored for concentrations of hazardous materials in leachate. If they exceed the “alarm limits” certain measures must be applied to lower the concentrations of the hazardous materials. Table 4 displays the range of material concentrations from shredder waste for the Odense Nord Miljøcenter and RenoDjurs landfills.

Table 4: Leachate Limits for Danish Landfills

	ASR Material					
	Mercury (Hg)	Arsen (As)	Chromium (Cr)	Iron (Fe)	Copper (Cu)	Nickel (Ni)
<u>Detection Limits</u>	0.05 µg/l	0.8 µg/l	0.5 µg/l	0.05 mg/l	0.04 µg/l	0.03 µg/l
<u>Alarm Limits</u>	N/A	15	17	N/A	4	38
<u>Leachate Range</u>	0.05-0.27	11-56	6.5-28	0.01-11	6.3-98	24-190

Leachate recycling is a good technique for managing the amount of leachate produced at a landfill. Once leachate is obtained and tested it can be cleaned of hazardous contaminants and then re-circulated back into the landfill for leaching. This method reduces the flow of leachate to a wastewater treatment plant. The washout of hazardous compounds in landfills also facilitates in the reduction in time of landfill aftercare (P. Madsen, personal correspondence, April 19th, 2010).

One of the best ways to prevent the leaching of hazardous materials from ASR is to reduce the amount of residue that is landfilled. Shredder waste processing technologies greatly increase the amount of material that is recycled or recovered, resulting in a large decrease in the amount of material that is landfilled. Some processes even promise that no waste will need to be landfilled with their technology. Considering some of the rates of recycling and recovery from processes seen in Table 5, the amount of waste that is prevented from being landfilled can be determined.

Table 5: Process Recovery Rates

Process Name	Overall Recovery
Mechanical	
Argonne	94%
SiCon	95%
R-Plus	100%
Galloo	90%
Salyp	97%
Thermal	
Sult	100%
SVZ	94%
TwinRec	85%
VTT Gasifier	96%
CTU Gasifier	97%

These processes could provide a reduction in the amount of waste that is landfilled in Denmark each year from 250,000 tonnes per year to anywhere between 0 and 40,000 tonnes. Considering that 250,000 tonnes of shredder residue per year are currently being landfilled, a significant portion could be recycled from implementing one or more of these processes.

5.1.2 Mechanical Treatment

The mechanical processing of shredder residue is the most common treatment for removing fractions from shredded materials. Mechanical separation of ASR poses a technological challenge due to its heterogeneous structure, density, and moisture content (Mancini et al., 2010). Cross contamination from residual oils in foams, mercury switches, and lead parts such as wheel weights present a barrier when processing and recovering ASR material to meet market specifications.

Not only does recycling and recovering materials reduce the amount of waste that is landfilled and provide income from reusable materials, it also results in an overall positive environmental impact. There is an environmental benefit of using recycled material rather than virgin material because it requires less energy and results in less gas emissions. However, each time that plastic is recycled it loses some of its structural integrity. The processing of recycled plastics is more difficult due to the presence of impurities and differences in molecular structure when compared to virgin plastics. Therefore, many recycled plastics are used for parts that do not require high strengths or critical manufacturing processes. For instance, the plastics fractions recovered with the Argonne process are used to make certain auto parts, but cannot replace all virgin plastic products. When a plastic's quality is too poor to be used to produce a part, it may be used in the energy recovery industry through incineration or another thermal process. The price to manufacture recycled plastic is two-thirds that of the same type of virgin plastic (Lundqvist et al., 2004). The price is lower because virgin plastic is produced from petroleum and the price for this diminishing natural resource is rising. The recycling of plastic is very important while considering shredder waste processing because it makes up such a large portion of the SR. Considering that 4% of the world's oil production is used as raw materials for plastic and another 4% is used to manufacture it, there are huge amounts of our limited petroleum supplies that can be saved by recycling plastics (Plastic Recycling Information Sheet, 2006). When recycling plastics, about 30% of the energy needed to create virgin plastic is used to create the same quantity. The energy required to manufacture varying plastics can be seen in Table 6 and a

plastic characterization of ASR from 150,000 ELVs can be seen in Figure 21. Using the data in this table and figure, the amount of energy saved by recycling plastics may be calculated.

Table 6: Plastic Manufacturing Energy Consumption (Gervet, 2007)

Plastic	Energy Consumption (GJ/tonne)
PVC	53
PE	70
PP	73
PS	80
PET	84
PC	107

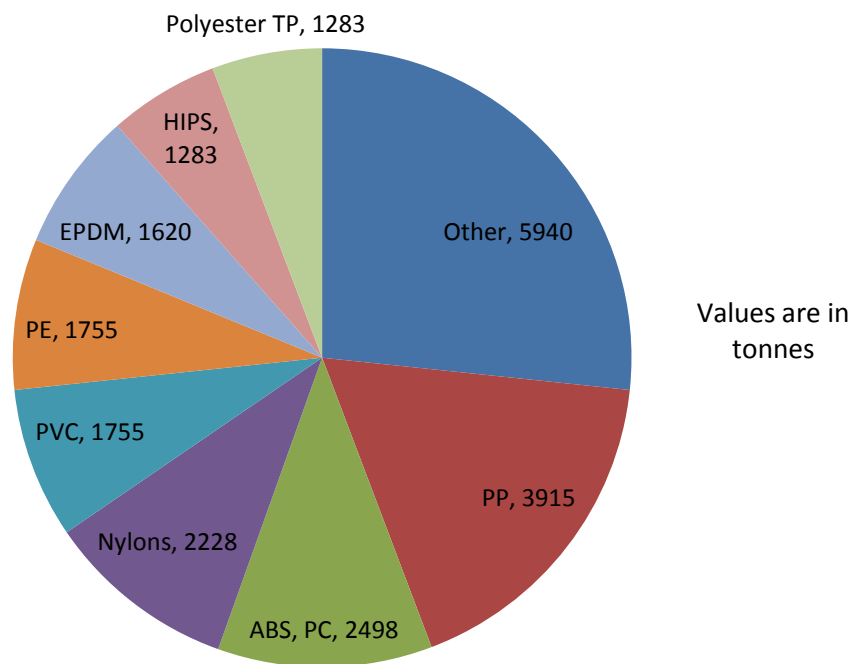


Figure 21: Plastic Break-Down of 150,000 ELVs (Daniels, 2008)

If plastic recycling rates similar to Argonne’s 90% are reached in Denmark, almost 20,000 tonnes of plastic can be recycled instead of landfilled each year. Just from the recycling of PP, PC, PVC, and PE, over 700,000 GJ of energy can be conserved. This could represent 0.06% of the energy that is produced in Denmark each year. The mechanical treatment and subsequent recycling or recovery of metals, plastics, and other materials in ASR shows promise for a vast amount of energy and material savings.

5.1.3 Thermal Treatment

ASR treated by pyrolysis followed by gasification is a promising technique that provides good potential for material recovery. The process could be designed to maximize useful gaseous products or material recovery in the form of char that could be used in the steel or cement industry. However, there have been limited and inconclusive experiments done on the char that is produced from sequential pyrolysis and gasification of ASR (Mancini, 2010). The presence of hazardous components such as heavy metals contained in the vitrified slag and chlorides from plastics in the gaseous output stream may create environmental hazards. Industries that produce cement, steel and iron could use this material, but further research is needed to determine whether the hazardous materials entrapped in the slag will leach into the environment. Therefore, the slag may need to be landfilled which would require testing for the concentrations of hazardous material within the various landfilled fractions.

Current studies have shown that a co-incineration, sequential gasification followed by combustion, pyrolysis and ultra-pyrolysis are proficient techniques for processing ASR. Results from a study in which 14.2% SR was co-incinerated with MSW concluded that there was a high increase in heavy metal presence in the bottom ash (Pedersen, 2009) which could possibly lead to corrosion problems in the boiler. The effects of these metals could be reduced by lowering the amount of heavy metals sent to the shredder, or reducing the amount of chloride in the input waste because chlorides enhance the vaporization of the heavy metals. A study on the bottom ash resulting from co-incineration of ASR with MSW was also carried out and the results showed that there were no significant changes in the leaching characteristics of ash produced by co-incineration of shredder waste as compared to incinerating pure MSW (Hyks, 2009). This was surprising, as there were considerably higher concentrations of several metals in the shredder waste, including copper, lead, and zinc.

An in-depth thermal treatment analysis on three waste samples from different shredder facilities was developed at a full scale thermal treatment plant (Mancini, 2010). The treatment plant included gasification followed by complete combustion via incineration with three different compositions for testing: 70% ASR/30% SR, 30% ASR/70% SR, and 100% ASR. The exhaust gas compositions were measured at two separate locations: before bag filtration and at the chimney. Hydrochloric acid, nitric oxide, and nitrogen oxides were found in the flue gas before filtration, but the gasses were emitted below the EU limits at the chimney. The bottom slag and fly ash residues produced from combustion were also analyzed

according to plant regulations and leaching tests were performed as well. In regards to environmental impact, the results showed high chlorine and toxin levels in the flue gas, which can cause corrosion to the equipment, but the cleaning technologies implemented were able to reduce these toxins to below the EU limits. The test concluded that this process is useful for managing ASR while meeting the EU target and abiding by the legal limits for organic and inorganic materials emitted to the atmosphere. See Appendix M for an elaborated description of the process.

Another study on pyrolysis of ASR concentrated on assessing the most efficient parameters for obtaining products while limiting the environmental impact. Both fast and conventional pyrolysis converted more the 80% of the carbon with temperatures ranging from 500 °C to 800 °C. Conventional pyrolysis yielded a carbon content of 36.4% by weight of the feedstock at 800 °C and the carbon content measured for fast pyrolysis was more than 69% at 800 °C (Zolezzi et al., 2003). The hydrocarbon content in the emitted gas increased with higher temperatures due to the reducing environment. The study concluded that both conventional and fast pyrolysis processes are capable of recovering energy from ASR, provide more opportunity for material recovery, and grant a better environmental alternative compared to traditional thermal treatment processes such as incineration because of the reduced atmospheric emissions.

5.2 Economic Analysis of ASR Treatments

In order to determine what course of action each shredder company should look into, an economic analysis was carried out. From the information collected in this project, a general analysis of the economics of the options is presented, and the final analysis will have to be done by each shredder company with the information specific to the processes, current material resale market prices, current landfill prices, and local incineration costs. Some options and the economic factors to consider are shown in Table 7.

Table 7: Economic Factors for ASR Processing Methods

	Landfill Costs	Landfill Tax	Transportation Costs	Operating Expenses	Resale Value	Incineration Costs	Capital Costs
Landfill in Denmark	€€	€€€	€				
Landfill Elsewhere	€	?	€€				
Each Individual Company Processes SR	€	€		€	?		€€€
Export SR to be Processed Elsewhere			€€	€€	?		
Independent Company Processes SR			€	€€			
Co-Incineration with MSW			€			€€	

5.2.1 Landfilling Shredder Residue in Denmark

Landfilling shredder residue in Denmark is currently the cheapest option for shredder companies. However, due to several factors, more economically feasible options will be emerging. The most important impact on Danish shredder residue treatment will come from the landfill tax that is going to be implemented in 2012 and then raised in 2015. The effects of the tax on a base landfilling price of 200 DKK/tonne can be seen in Figure 22. In 2012, this tax will almost double the cost of landfilling shredder waste, and by 2015, the price for landfilling shredder waste will be over three times higher than current costs. Due to the tax increases, options that were previously impractical will become more viable.

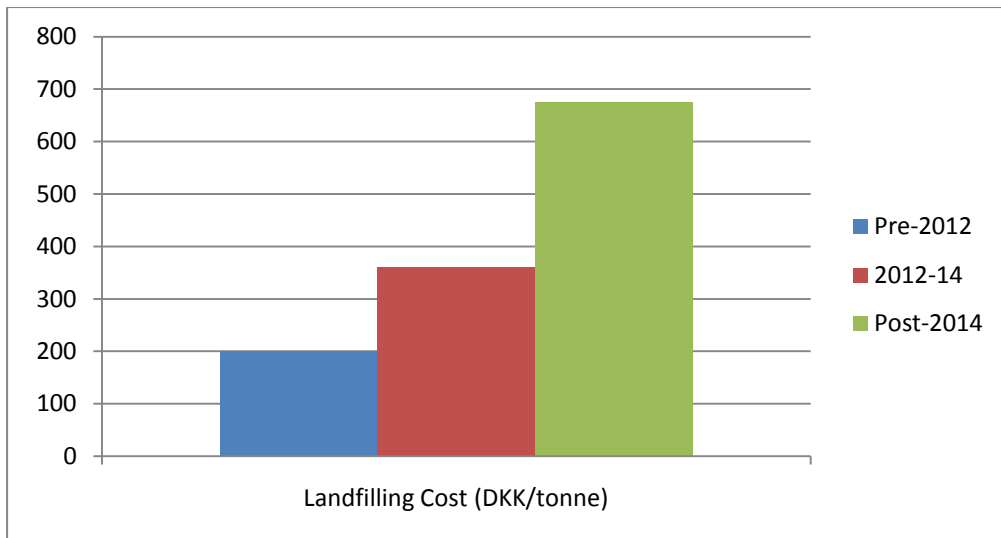


Figure 22: Cost of Landfilling SR in Denmark

5.2.2 Landfilling Shredder Residue Elsewhere

Landfilling shredder residue elsewhere is an attractive option because the landfilling taxes and fees in other countries are lower than they are in Denmark. In order to make the most economically efficient choice for this option, the company will have to balance the transportation costs and the landfilling costs in the destination country. For example, although Australia offers extremely low landfilling prices, the transportation cost to ship the waste there would be excessive. The landfill taxes in European countries are shown in Table 8. This added cost must also be taken into account when determining where to landfill ASR. Legislation in potential countries receiving the shredder waste may restrict the import of waste, so this should be investigated further. The option of landfilling shredder waste elsewhere may also be considered as a way of disposing of the remaining waste after shredding residue processing is completed.

Table 8: Landfilling Taxes in European Nations (UCD, 2009)

Country	Landfill tax euro/tonne		Description
	2001	2005	
Austria	44.0 7.2	65.0 21.0	Rising to 87 euros per tonne, from 2006. Rate for pre-treated landfill For construction bulk or ground excavation
Belgium Flanders	61.8		
Belgium Wallonie	27.5		
Czech Republic	10.0	13.0	Rising to 17 for 2007 onwards
Denmark	50.0	74.0	Landfill of MSW is banned, however in practice bulky waste still goes to landfill.
Finland	23.0 270.0	30.0	For MSW For hazardous waste
France	7-9.0 18.3	7-9.0	Introduced in 2002 Hazardous waste in HM landfills.
Germany	None		
Ireland	19.0	19.0	
Italy	1-10.0 5-10.0 10-25.0	10-50.0	Inert waste Other waste (MSW excluded) MSW, depending on region
Netherlands	86.0 14.0	86.0	per tonne of waste less than 1,100kg/m ³ for specific waste per tonne for non-municipal waste more than 1,100kg/m ³ (non combustible). Landfill of MSW is banned although where there is insufficient incineration capacity there is an annual exemption from the ban of 3 million tonnes.
Portugal	No		
Spain	No	10.0	In Catalonia only. Legislation in Madrid 10 e/t dangerous waste; 7 e/t domestic waste; 3e/t demolition and construction waste
Sweden	31.0	40.0	Rising to 47 from 2006
France	9.2		In 1999. The intention is that landfill of unprocessed waste would be banned from landfill by 2000
Switzerland	9.7 12.9 32.2		For residual landfill For reactor landfill (slag) For export to disused salt mines (untreated residues from flue-gas clean).
UK	19.0 2.0	26.0	Rising in 4.5 euro increments per annum to a maximum of 51 euros per tonne by 2010. For inert waste

5.2.3 Each Individual Company Processes SR

The option of each individual shredder company developing their own technology to process shredder residue is economically unfavorable. If a company hopes to do this, there are several economic factors that should be considered. The capital cost of developing and constructing the facility must be taken into account. Also, a gate fee may be estimated for processing each tonne of shredder waste, which would include the energy, upkeep, and other expenses in order to run the plant. The resale value of materials the process produces and the

landfilling of the remaining waste fraction must also be considered. Although it does not seem that this would be the most economically feasible option, it is a possibility that would reduce the amount of landfilled shredder residue.

5.2.4 Export SR to be Processed Elsewhere

Processing shredder waste elsewhere appears to be an option that UniScrap and Stena Jern & Metal are strongly considering. The research bases of both corporations are outside of the country and it would most likely be cheaper to export the shredder waste to the post-shredder technology plants rather than build a processing plant in Denmark. UniScrap's Danish shredder plant is a subsidiary of the Scholz Corporation, which has an SR treatment plant in Espenhain, Germany. The Scholz plant has completed tests to determine how much of an ELV can be recovered, and the results show 94% of the vehicle being recycled (Henkes, 2008). The UniScrap facility in Denmark has a small-scale pilot version of the technology used at the Espenhain plant. UniScrap will most likely continue to landfill their shredder waste in Denmark until an option such as sending their waste to Germany for processing becomes economically feasible. This will most likely happen after the first or second level of the new landfilling tax is implemented. Stena Jern & Metal is in a similar situation because Stena's base is in Sweden, along with their research and development department. Investigations into SR processing, taking place in Göteborg, should allow Stena to process their waste either in Sweden or possibly build a plant in Denmark to process it locally.

5.2.5 Independent Company Processes SR

A cooperative effort between the shredder companies is another option. Mr. Kriegbaum suggested that creating a joint shredder residue processing plant would benefit all of the shredder companies. If an outside company such as VW-SiCon leased their technology to the Danish shredder companies, a plant that was able to process the waste from all of the shredders in Denmark would reduce the cost for transporting waste out of the country to other facilities, or the cost of building individual facilities. A comparison may be drawn to the plastic recycling industry in Denmark a few years ago. There was a large boom in plastics recycling so plants opened all over Denmark. This resulted in far too much capacity for the amount of plastic being received, so many of the companies went out of business. Shredder companies want to ensure that the same thing doesn't happen to the shredder waste processing industry. If an independent company is able to utilize a process that is

economically beneficial for them and the shredder companies, this would allow them to develop the market for Danish shredder waste.

Some gate costs and other information regarding alternative shredder treatment plants can be seen in Table 3. Using the information provided in this table, a potential situation was posed. If a shredder company was investigating building a plant using VW-SiCon's technology, and it was able to process 100,000 tonnes per year of their shredder residue, it could be determined how long it would take for the plant to be worth the investment. The mean values were used for the gate fee and the cost of the plant. All of the values were converted to DKK at a rate of 7.5 DKK/Euro.

$$P_p = \left[(C_L * \sum M_M) - (C_G * M_{SW}) + \left(\sum R_M * M_M \right) \right] * t$$

P_p = Price of plant construction

C_L = Cost of landfilling (including tax)

$\sum M_M$ = Summed mass of materials recycled or recovered

C_G = Gate cost of process

M_{SW} = Tonnes of shredder waste

$\sum R_M * M_M$ = Sum of different material resales

t = Time (in years)

This formula was created by comparing the cost of continuing to landfill shredder waste in Denmark at the 2015 taxed rate of around DKK 675 to the cost of building a plant, plus the gate fee, minus the money not spent landfilling material, and the value of materials that are recycled or recovered. For the VW-SiCon process, the known values can be input (Krinke, 2006), assuming this is implemented post-2014 (because of the landfill tax):

$$67,500,000 = (675 * 95,000 - 263 * 100,000 + \sum R_M * M_m) t$$

$$67,500,000 = (37,825,000 + \sum R_M * M_m) t$$

$$\text{If } \left(\sum R_M * M_m \right) = 0, \quad t = 1.8$$

Unfortunately, the economic data for the resale of the different materials in the SiCon process are not available, so we assume that the resale of all the materials does not earn a profit. If this is the case, it will take less than two years for this plant to make its investment worthwhile for the shredder company.

A similar study may be made on the R-Plus plant, using the WESA-SLF process, keeping in mind that only 16,000 tonnes per year may be processed with it:

$$15,300,000 = (675 * 16,000 - 510 * 16,000 + \sum R_M * M_m) t$$

$$15,300,000 = (2,640,000 + \sum R_M * M_m) t$$

$$\text{If } \left(\sum R_M * M_m \right) = 0, \quad t = 5.8$$

Assuming that the summed material resale is about zero it would take about six years to cancel out the cost of the plant construction. The assumption that the material resale is about zero is not too unrealistic because the mineral fraction produced has a negative value.

Even though there are several differences between the technologies that SiCon and R-Plus developed, overall they are very similar. They both extract more of the ferrous and non-ferrous metals before using the organic fraction to create products. However, the created organic products are different. R-Plus creates a refuse derived fuel that is sold to furnaces. SiCon uses the organic portion of the SR to make two fractions: the plastic pellets that are manufactured into new parts, and the fibers that may be used as sludge filters or as RDF. SiCon seems to be a more promising option because recycled materials receive higher resale prices than material for energy recovery and SiCon plant's construction costs are offset by unrealized landfill costs in a third the time of R-Plus plant costs. Although there are many more factors, the scope of this project is not able to provide a more complete economic analysis.

5.2.6 Co-Incineration of SR with MSW

One of the most promising options may be the co-incineration of shredder waste with municipal solid waste. The infrastructure for waste incineration is already in place in Denmark and would result in lower start-up costs than the other processes. Currently in Sweden, 5-10% shredder residue is being co-incinerated with MSW and sewage sludge (M. Gyllenhammar, email correspondence, April 22nd, 2010). Since there is about a quarter of a million tonnes of SR landfilled every year in Denmark, if all of the shredder waste was to be co-incinerated with MSW at an SR fraction of 14.2% as in the 2009 Pedersen study, it would need:

$$\frac{100 - 14.2}{14.2} (250,000) = 1.51 \text{ million tons of MSW incinerated}$$

According to the Danish Ministry of the Environment, about 3.3 million tons of MSW are incinerated each year. Therefore, there is more than enough MSW to co-incinerate all of the shredder waste. However, a complication might occur because municipalities can decide whether a company within its jurisdiction is able to bring its waste to another municipality. This would be a problem if a shredder company had more SR than the local incineration plant was able to handle. There are currently talks in the Danish EPA about the liberalization of waste to be incinerated in Denmark. However, these legislative aspects are out of the scope of our project and must be taken into account by the shredder companies when considering the co-incineration option.

Another consideration is the use of the bottom ash. Currently, the bottom ash that is extracted from the incinerator after combustion of MSW is used in the Danish construction industry (O. Hjelmar, personal correspondence, April 13th, 2010). In order for this to remain the case, more tests with conclusive results must be performed to see whether or not there is a hazard caused by the use of the bottom ash resulting from the co-incineration of shredder and municipal waste. If it is not safe, this option might not be feasible because of the tax that would need to be paid on the hazardous bottom ash.

The current cost for incinerating waste in Denmark varies greatly depending on the age of the waste-to-energy plant. The gate cost at the waste-to-energy incineration plants can be seen in Figure 23. Due to the fact that all of these plants are publicly owned, their business plan consists solely of paying off the initial capital cost. Until this is accomplished, it is expensive to incinerate waste there. But, after this is done, the plants charge only the amount needed to keep the plant operating.

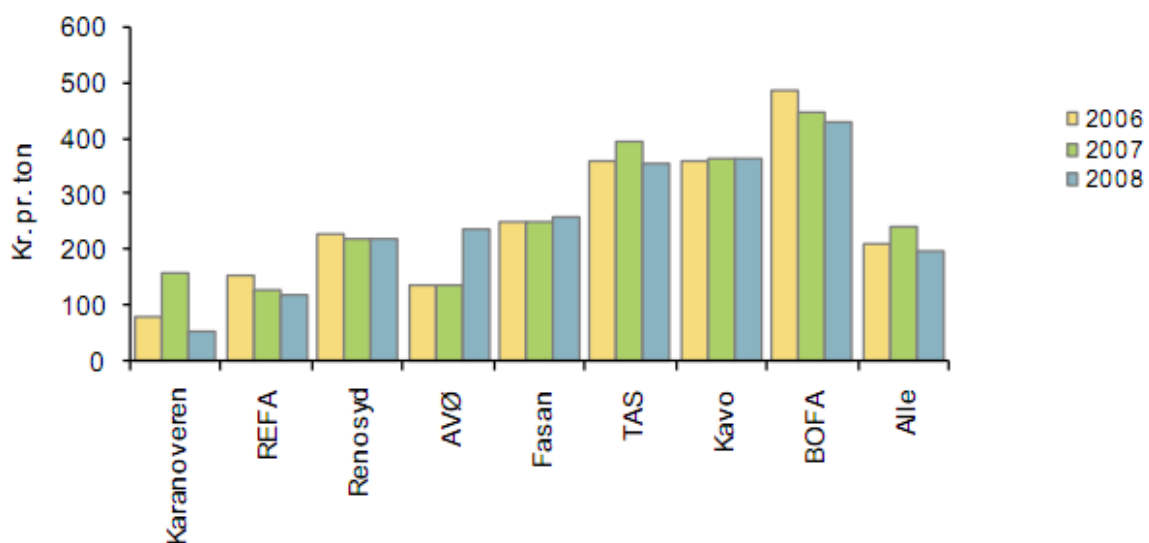


Figure 23: Waste-to-Energy Gate Costs (RenoSam, 2009)

5.3 Recycled or Recovered Material Resale

Material resale is the most important part of the recycling industry today. Market competitiveness drives the need for more efficient processes to recycle many different types of materials. For processing shredder residue, recycling materials is important due to both reducing the landfill costs and for re-forming the residue into marketable products. The most precious parts of shredder residue are the ferrous and non-ferrous metals. Most of these materials are recovered in the initial shredding process, but some still remain in the shredder residue. The resale price trend for scrap iron can be seen in Figure 24. The economic crisis drastically decreased metal prices that are now very slowly recovering, but this figure shows how temperamental the market can be for raw materials. This must be taken into account at the time the materials are being sold.

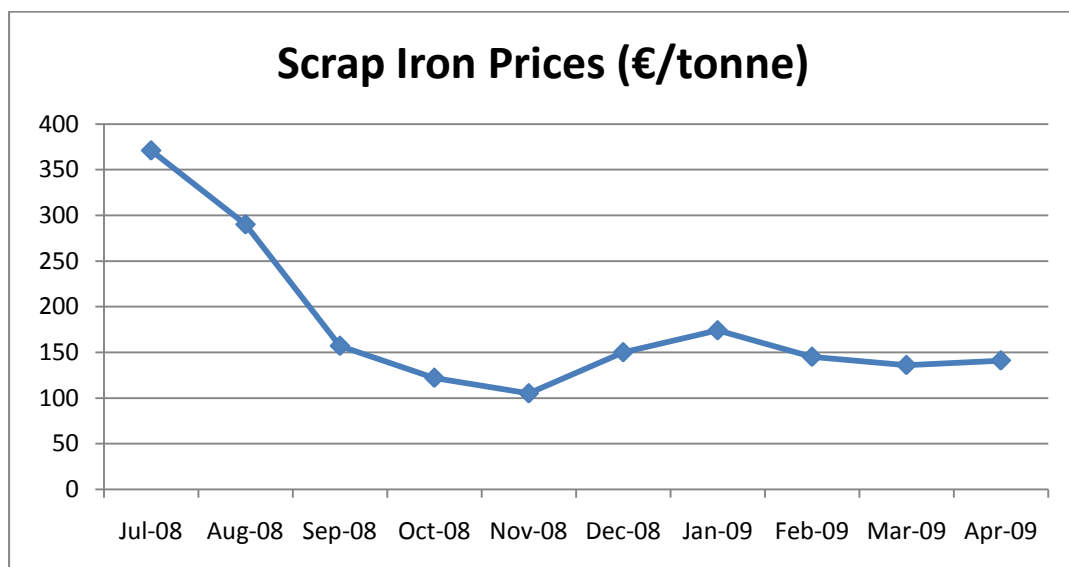


Figure 24: Scrap Iron Prices (Metal Prices, 2010)

Copper, steel, and aluminum are the most prevalent non-ferrous metals and are very profitable to recycle. The market prices for these materials vary due to demand and have been low recently because of the global economic crisis, but are rising once again. The market prices for these three metals can be seen in Table 9. Although the prices for these recycled metals are high compared to scrap iron, there is a relatively low concentration of them in ELVs.

Table 9: NF Metal Prices (Steel on the Net, Metal Prices and Benefits-of-Recycling, 2010)

Scrap Metal Type	Avg. Price(€/t)	Date
Copper	5223	Jan-10
Aluminum	562	2010
Steel	265	Mar-10

The largest fraction of shredder residue comes from plastic, making the resale of this portion important to recyclers. Unfortunately, there are many different types of plastic in an ELV, which are difficult to differentiate. Due to plastics' not being very compatible with each other, plastics must be nearly identical in composition to recycle efficiently, making it very important to separate plastics. However, plastic scrap processes developed by companies such as Argonne use sink float techniques in series with other processes to separate these fractions. The amount of each of these plastics that could be recycled from Denmark's yearly 150,000 ELVs can be seen in Figure 21. Although 27% of the material is grouped into an "other" fraction, the majority of the plastic scrap is made up from polypropylene and other recyclable plastics. For the plastic recycling processes, high prices are paid for recycled plastic and can be seen in Table 10. These values were obtained from the online scrap price provider, WorldScrap, on April 26, 2010.

Table 10: Plastic Scrap Prices (WorldScrap, 2010)

Plastic Type	(€/t)
ABS	1000
Polycarbonate	1300
Polypropylene	870
PVC	750
Polyethylene	830

The resale of plastics from these 150,000 ELVs would result in the ABS, PC, PP, PVC, and PE selling for about €11.3 million. Scrap values for the other identified fraction were not available, and the "other" fraction is often used as a feedstock because of its high calorific values. With these values added in, the market for recycled plastics may well reach almost €13 million or about DKK 100 million per year in Denmark.

Although the resale of recycled materials provides millions of Euros worth of economic stimulus for the industry, the largest economic impact from processing shredder residue is the money saved by not having to pay the landfill cost and tax.

5.4 Summary

The analysis completed in this section shows several important facts. The environmental impact of landfilled ASR is not currently a problem due to the advanced design of landfills. However, the aftercare of this waste is a large economic burden and the limited space remaining in landfills makes it a problem for the future. The environmental

impact resulting from the shredder waste treatments is not large when compared to the energy and material that is saved during the recycling process. The economics, although they currently drive shredder companies to landfill shredder waste, will most likely cause shredder companies to choose an alternative ASR processing route in the near future. The economics of these alternative routes were discussed in brief, but a full analysis will have to be done by each individual company. There was also an analysis determining some of the material resale prices for shredder companies that are interested in developing or implementing their own processes. Due to plastics being the largest part of the shredder residue, separating and recycling the plastics or recovering their high calorific content is one of the most important parts of any potential process. The high resale value of plastics in combination with their prevalence in ASR makes it possible for the plastics recycled from ELVs in Denmark to generate income in excess of €10 million (DKK 75 million) per year. The results of our analysis guided us to conclusions about shredder residue treatment options in Denmark.

Chapter 6: Conclusions and Recommendations

From our research into alternative shredder residue treatments, interviews with shredder company and landfill employees, and correspondence with experts on thermal and mechanical technologies, we were able to develop three conclusions and two recommendations on what shredder companies and others in the Danish waste management industry should consider, based on legislative, economic, and environmental factors.

In this study, we concluded that there are many currently available technologies that will allow Danish shredder companies to meet the 2015 EU targets for recycling and recovery. The mechanical processes that we researched focused on plastic separation and the creation of recycled products. The thermal technologies that we investigated focused on the generation of products used in energy recovery because of the high calorific value of the organic content in ASR. Some technologies are being implemented on an international scale and have been proven to be economically feasible, while others are still in the pilot stage.

It was further concluded that the environmental impact of the researched thermal and mechanical treatments is favorable in comparison to landfilling. By recycling or recovering the materials using these processes, more energy or materials are regained than are spent in the process or would be spent to manufacture an equivalent amount of virgin materials. Overall, recycling is better than recovery because mechanical treatments are more environmentally friendly than thermal processes. Mechanical processes recycle the material and reduce the need for virgin materials and the associated energy consumption, while preventing harmful greenhouse gas emissions.

Our third conclusion is that currently, the most economically feasible option is to keep landfilling the shredder residue in Denmark. However, after the landfill taxes are implemented in 2012 and 2015, it will become more economically feasible to process SR rather than landfill it.

Based on these conclusions, we make two recommendations. The first recommendation is that the Danish shredder companies should investigate the application of alternative shredder residue processing courses of action presented in our analysis chapter. Each process has advantages and disadvantages and there are fluctuations in material flow, cost, applicability, marketability of products, and required inputs. In particular, we suggest that the shredder companies consider the following options: co-incineration, having an independent company build an SR processing plant in Denmark, or exporting their SR to be

processed elsewhere. This report did not produce a full economic analysis, but it did present factors that will have to be taken into account when completing an analysis.

The co-incineration of ASR and shredder residue with MSW is the most promising of future alternative treatments. Denmark has an extensive infrastructure of waste-to-energy and incineration plants. At this time it is more than three times cheaper to landfill rather than incinerate shredder residue, but when the landfill tax is implemented in 2015, incineration of ASR will become a slightly cheaper alternative. It is necessary to continue researching the effects of co-incineration of ASR with MSW, but recent studies have shown that co-incineration of either 5-10% of shredder residue with MSW and sewage sludge or 14.2% SR with MSW is an effective and promising option (M. Gyllenhammar, personal correspondence, April 22nd, 2010 & Pedersen, 2009). Thus, all the shredder companies could transport their shredder residue to nearby incineration facilities, at minimal transportation costs, and co-incinerate the waste to help heat homes and provide energy.

The second option is for an international company with a well-developed and commercialized process, such as the VW-SiCon process, to construct a shredder residue processing plant in Denmark. In this scenario, multiple Danish shredder companies would transport their shredder residue to this plant. Transportation costs would be kept to a minimum as they would not have to export the waste. The processing plant would allow all of the shredder companies to significantly reduce their landfill costs and to reach the 2015 EU targets. Construction of a full-scale ASR processing plant would have to start soon so that by 2015, a plant is ready to start processing shredder residue.

The third option is for the shredder residue to be exported out of Denmark for processing elsewhere. This option is most attractive for Stena because it is a branch of a larger organization in Sweden that is developing SR processing technologies and for UniScrap because they are a subsidiary of Scholz AG, a German-based company with an established post-shredder technology at their Espenhain plant. However, for H.J. Hansen and Espersen & Søn, this option is not as appealing because they are independent companies. They are likely to choose an alternative option or develop their own process. Nonetheless, many full-scale plants are being constructed or starting operation in nearby countries, such as the SR processing plants in the Netherlands and the UK, so the shredder companies could also look into exporting their shredder residue to these sites.

The second recommendation is for further research by institutions in Denmark on several topics. One of the most promising options for alternative SR treatment in Denmark is co-incineration, but this option has not been studied very extensively. Future studies should

determine whether the bottom ash is hazardous or acceptable for use in the construction industry. This study could further the development of co-incineration of MSW and SR. Further research must also be done on the impact of the changing composition of vehicles. With the increasing prevalence of hybrid vehicles, more dismantling will have to be done because of new components such as nickel metal hydride (NiMH) batteries and electric motors. By increasing collaboration with auto manufacturers to determine vehicle composition and what the best course of action for the shredding community will be, an efficient process may be maintained.

The recommendations presented in this report will help guide Danish shredder companies in deciding their best course of action in regard to the future of ELV shredding. By considering the options of co-incineration, a private company building a shredder processing plant, or exporting shredder residue to be processed, each shredder company will be able to find the solution that best fits their needs. By researching and implementing one of these options, each shredder company can reduce costs, provide benefits to the environment, and help Denmark reach the targets set by the European Union.

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Appendix A: EU Directive Material Restriction

Appendix A contains the allowable use of certain materials in accordance with the EU “Directive 2000/53/EC of the European Parliament and of the Council”. There are time limits on some of these, as can be seen in the “Scope and Expiry Date of the Exemption” column. The right column marks components that are marked by car manufacturers for removal prior to ELV shredding.

Materials and components	Scope and expiry date of the exemption	To be labelled or made identifiable in accordance with Article 4(2)(b)(iv)
<i>Lead as an alloying element</i>		
1. Steel for machining purposes and galvanised steel containing up to 0,35 % lead by weight		
2(a). Aluminium for machining purposes with a lead content up to 1,5 % by weight	1 July 2008	
2(b). Aluminium for machining purposes with a lead content up to 0,4 % by weight		
3. Copper alloy containing up to 4 % lead by weight		
4. Bearing shells and bushes	1 July 2008	
<i>Lead and lead compounds in components</i>		
5. Batteries		X
6. Vibration dampers		X
7(a). Vulcanising agents and stabilisers for elastomers in fluid handling and powertrain applications containing up to 0,5 % lead by weight	1 July 2006	
7(b). Bonding agents for elastomers in powertrain applications containing up to 0,5 % lead by weight		
8. Solder in electronic circuit boards and other electric applications		X ⁽¹⁾
9. Copper in friction materials of brake linings containing more than 0,4 % lead by weight	1 July 2007	X
10. Valve seats	Engine types developed before 1 July 2003; 1 July 2007	
11. Electrical components which contain lead in a glass or ceramic matrix compound except glass in bulbs and glaze of spark plugs		X ⁽²⁾ (for components other than piezo in engines)
12. Pyrotechnic initiators	Vehicles type-approved before 1 July 2006 and replacement initiators for these vehicles	

Hexavalent chromium

13(a). Corrosion preventive coatings	1 July 2007	
13(b). Corrosion preventive coatings related to bolt and nut assemblies for chassis applications	1 July 2008	
14. Absorption refrigerators in motorcaravans		X

Mercury

15. Discharge lamps and instrument panel displays		X
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Cadmium

16. Thick film pastes	1 July 2006	
17. Batteries for electrical vehicles	After 31 December 2008, the placing on the market of NiCd batteries shall only be allowed as replacement parts for vehicles put on the market before this date	X
18. Optical components in glass matrixes used for Driver Assistance Systems	1 July 2007	X

Figure 25: Material Selections (European Parliament, 2000)

Appendix B: Summary of EU ELV Directive

Summary of EU Directive Articles:

- 4.1) Central governments shall encourage car manufacturers to design cars easier to recycle and disassemble, as well as encouraging products for recycled products.
- 4.2) Restrictions shall be placed upon the metals that are used in cars, particularly hazardous heavy metals. A graph showing acceptable uses of these restricted heavy metals can be seen in Appendix A.
- 5.1) Nations shall ensure that there are an adequate amount of waste collection facilities within their territory and that a system is established to process ELVs.
- 5.2) Member states shall take measures to make sure that ELVs are transported to authorized treatment facilities.
- 5.3) Nations shall set up a system containing certificates of destruction (CODs) that will show proof that a vehicle at the end of its life has been properly disposed of.
- 5.4) Nations shall prevent the last owner of an ELV from having to pay a fee in order to have it properly processed.
- 5.5) Nations shall allow that other nations recognize their own CODs and what they entail.
- 6.1) Nations shall ensure that all ELVs are processed in accordance with set technical regulations.
- 6.2) Nations shall require that all treatment facilities obtain a permit to display their compliance with set standards.
- 6.3) Nations shall ensure that these facilities fulfill these standards for removing certain materials from the vehicle in the processing stage.
- 6.4) Nations shall ensure that the centers that receive the permits fulfill the set technical regulations.
- 6.5) Nations shall encourage the use of new, certified environmental management systems.
- 7.1) Member states shall encourage the reuse of components that are suitable for reuse, and the recovery of materials that are not suitable for recycling.

- 7.2) Nations should be reusing or recovering 85% of ELVs by mass, and reusing and recycling 80% by 2006. By 2015, 95% of ELVs by mass should be reused or recovered, and 85% should be reused or recycled.
- 7.3) The EU parliament shall set higher standards for the years following 2015.
- 7.4) European standards for dismantling shall be increased by 2001.
- 7.5) Nations shall ensure that in the process of reusing or recycling parts a safety or environmental hazard is not produced.
- 8.0) The EU parliament shall set dismantling codes no later than 2001.
- 9.0) At three year intervals, nations shall give reports to the council providing information about the compliance and results of this directive.
- 10.0) By 2002, nations should have adopted legislature in order to fulfill the standards laid down by this directive.
- 11.0) The committee will meet again to complete definitions regarding several open areas in the directive.
- 12.0) These articles shall go into effect in 2002 for cars that are manufactured on this date or later, and in 2007 for cars of all creation dates.

Appendix C: Content of Auto Shredder Residue

<i>Material</i>	<i>Reported content in ASR (weight per</i>					
	a	b	c	d	e	f
Source of information:						
Plastics	30-48	20	21.5	41		33
Polymers						
Plastics (foam, PUR)						15
Plastics (including coatings, textile)					83.1	
Elastomers (including rubber)	10-32	20	5.3	21	2.6	18
Rubber (long pieces, no tires)						
Rubber (tires, seals and gaskets)						
Fibres (textile, wood, paper)	4-26	25	53.7	10		10
Textiles, carpets, leather, PUR						
Textiles (small pieces)						
Paints, lacquer	3-10			5		
Metals	~ 20		8.1		13.5	3
Metals (Wires, Al plates)						
Cu wires						
Glass, ceramics, electric materials	3-16		3-5	19		
Dust, soil, etc.	10-20		excl.			
Wood						
Minerals (glass, sand, grit, dust, etc.)		35				
Minerals (stones, up to 100 – 500 g)						
Other (residues)			7.9	4	0.6	21
Oils, water	15-17					

a: Keller (2003)
b: Galvagno et al. (2001)
c: Das et al. (1995)
d: Mirabile et al. (2002)
e: Lanoir et al. (1997)
f: Ambrose et al. (2002)

LF: Light fraction
HF: Heavy fraction

Figure 26: Auto Shredder Residue Content (Ahmed et al., 2009)

Appendix D: Thermal Case Study/Pilot Plant Results

Fuel Rod Formation Using an Extrusion Apparatus

The purpose of this thermal process is to derive a solid fuel from ASR by using an extrusion apparatus. Since ASR has a high heat value it is possible to convert ASR into a residue derived fuel (RDF). The National Kaohsiung First University of Science and Technology's primary method of evaluating the process was to first "analyze the physical and chemical properties of ASR to evaluate its potential for RDF" and examine the "extrusion conditions and evaluation indicators for ASRDF (automotive shredder residue-derived fuel) formation". The ASR samples, which consisted of various particle sizes, all had reusable and non-combustible parts removed prior to being shredded. The ASR was separated into seven piles with mesh numbers 4, 5, 7, 10, 18, and 25 (H.S. Tai, 2006). They were packed into the fuel rod (Figure 27) and experimented under temperatures and pressures of 100, 120, 140, 160°C and 100, 120, 140, and 160 atm. Some of the smaller non-combustible and organic material cannot be separated and is burned in the rod. The extrusion apparatus was packed to capacity of ASR because compact material burns more efficiently and produces more heat per unit weight than un-compacted material.

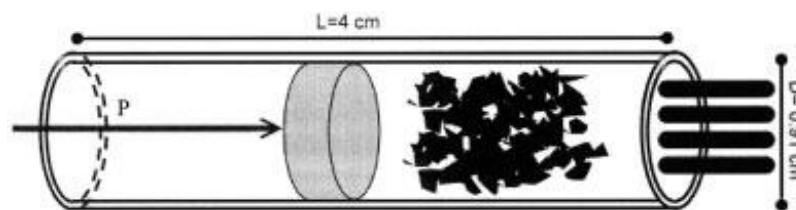


Figure 27: Fuel Rod Extrusion Apparatus (Tai et al., 2006)

The quality of the fuel rod was established by observing the color and consistency, density and the heat value of the resulting ASRDF. In general, a fuel rod with an external surface that appeared to be consistently covered, more compact and solid, and had fewer internal voids was considered useful. The heat value was measured using an adiabatic calorimeter and the appearance of the fuel rod was determined by the skin-core effect. Further analysis by the skin core effect conveyed that a better appearance and a higher density can be achieved through producing fuel rods under higher extrusion temperature and pressure conditions. The skin core effect helps explain this phenomenon by stating that the conditions the plastics and foam were subjected to caused the volume reduction and surface carbonization. The skin core effect can also account for the decrease in heat content values as the temperature and pressure are increased. Heavy metal content was measured by submerging an ASR sample into nitric acid or hydrogen peroxide and then analyzing the

sample for specific metals by the method of atomic absorption spectrometry. Hazardous products such as chlorine in the ASR are the greatest concern to the environment when it is combusted. Besides the negatives affects to the atmosphere, the hazardous by-products shorten the life of the incinerator, and cause health risks to plant workers.

The analytical results from this process concluded that a conversion of auto shredder residue into residue derived-fuel is feasible. The only exception to this process was the bottom layer which is not very combustible and contains a high inorganic content that is not useful for the thermal analysis. The ASR showed a moisture content of <2%, ash was approximately 80%, and combustibles were nearly 80% by weight (H.S. Tai, 2006). Nitrogen and sulfur emission concentrations were very low, but the main concern was the chlorine levels which constituted between 1.32% and 2.79%. The high chlorine levels were produced from chlorinated plastics within the ELV and if they are not treated properly they could potentially produce hazardous by-products such as polychlorinated dibenzo-p-dioxin (PCDD), polychlorinated dibenzofuren (PCDF), and gaseous hydrochloric acid. Furthermore, not only do these products shorten the life of the incinerator, but the health-risk impact on plant workers significantly increases with exposure to the aforementioned by-products. The Institute of Occupational Safety and Health in Taiwan created a study to illustrate the importance of properly treating ASR combustion by-products:

“For all selected exposure groups, their PCDD/F exposures were dominated by the particle phase contents. Congener profiles of the gaseous+particle phase PCDD/Fs were found with more fractions of high chlorinated congeners than low chlorinated congeners. The lifetime average daily doses (LADDs) and their resultant excess cancer risks (ECRs) found for sinter plant workers were higher than those residents living at the residential area and rural area, but were lower than those living at the nearby of the selected sinter plant, urban area, industrial area. Considering ECRs of the sinter plant workers were still higher than 10(-6) suggesting the need for adopting proper control measurements for reducing workers' PCDD/F exposures, particularly for those sinter zone workers.”

Particle size has no significant effect on the chemical composition of the ASRDF and the overall heat content recovered is between 5000 kcal/kg and 6000 kcal/kg. ASR is also very stable during storage and it is unlikely to have any odor or attract pest problems.

Furthermore, another factor to consider when producing RDF is the die swell ratio which calculates the expansion ratio of the fuel rod as it expands from its release of the extrusion apparatus. This is possible to calculate by applying the following equation:

$$s = \frac{d}{D}$$

The die swell ratio, s , is calculated by dividing the resultant rod diameter, d , and the die diameter, D .

Shear stress on the fuel rod is produced at the wall of the die and is calculated by the following equation:

$$T_W = \frac{r\Delta P}{2L}$$

The shear stress, T_W , is calculated from the die radius, r , the pressure drop, ΔP , and the length of the die, L . The die swell ratio decreases with increasing shear stress and high temperatures (Shih, 2008).

Sekundarrohstoff-Verwertungszentrum Schwarze Pumpe

Another option for recycling ASR is high-temperature gasification that is carried out by the Sekundarrohstoff-Verwertungszentrum (SVZ) pump. It is equipped with the recently developed BGL-gasifier that produces gas and vitrified slag which concentrates hazardous waste such as heavy metals, facilitating their disposal. The ASR is preprocessed into pellets and the process is shown in Figure 29. The waste feed inlet stream of the SVZ pump process can be a liquid, solid, or another highly viscous material. The different compositions of the inlet feed can be observed in Figure 28. This material is then fed into an entrained-flow-gasifier (EFG) and a BGL-G slag bed gasifier (Figure 32) where the core of the thermal process takes place. The EFG uses unburned coke, waste oils, and other liquids in the gasification process to facilitate the partial oxidation process that uses steam and oxygen at temperatures between 1300 °C and 1600 °C and a pressure of 25 bars. Hazardous components including dioxins, furans, polycyclic aromatics, and biphenyls are cracked into their base components of H₂, CO, CH₄ and CO₂. Residues from the BGL-G are considered vitrified slag and can contain heavy metals. Therefore, considering the residue's liquid molten characteristics, the slag is not leached into the environment. Instead, the slag could be granulated and used for road undercover, dyke barriers, or cavity filling in under-surface mining. The main purpose of the SVZ pump is the "complete transformation of organic compounds into feedstock synthesis gas, or 'syngas'" (Buttker, 2005). The resulting syngas can be used for large scale production of basic chemicals such as methanol, ammonia, and formic acid.

PARAMETER		SR, pretreated	SR, untreated
water	Ma.-%	17	17
crude ash	Ma.-%	37,9	41,1
calorific value	kJ/kg	15565	15281
bulk density	g/cm ³	0,10	0,18
particle size distribution			
< 1 mm	Ma.-%	8,11	25,17
1 - 6,3 mm	Ma.-%	3,09	18,79
6,3 – 10 mm	Ma.-%	1,99	5,13
10 - 25 mm	Ma.-%	17,69	13,72
25 - 60 mm	Ma.-%	33,57	20,14
60 - 200 mm	Ma.-%	22,59	8,27
> 200 mm	Ma.-%	12,96	8,79

Figure 28: Inlet Compositions (Buttker, 2005)

In an experimental run to analyze the efficiency of the SVZ pump, 930 tons of shredder waste was supplied by a German shredder company. The plant flow can be seen in Figure 31. One third of the SR was partially refined to increase organic content and the remaining amount was left untreated. The shredder was processed with MSW, but this did not affect any part of the process. This process was being analyzed as a general gasification process for more wastes than just shredder residue, but this process can be used for ASR since the materials are comparable. The SR was processed over the course of 3 days, but the measurements were taken during a 24 hour period under steady-state conditions. Before being fed into the gasifier, the SR underwent agglomeration, or the process of converting SR into pellets that are more convenient and suitable for the gasifier. The process yielded the following results (Buttker, 2005):

- Approximately 74% of the SR was processed in the gasification
- Approximately 12% of water was discharged during the conditioning step and transferred to the waste water treatment facilities of SVZ
- Approximately 6% of the input was inert material that will be landfilled
- Approximately 8% of the input are ferrous and non-ferrous metals, which were recovered separately

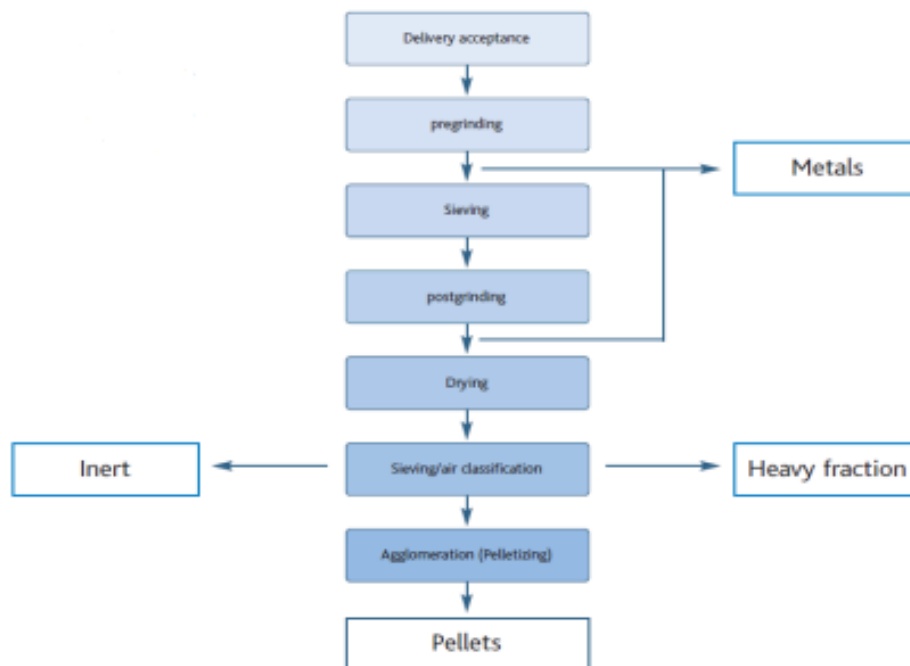


Figure 29: Flow Chart for Pelletizing SR (Buttker, 2005)

During the 24 hour measuring period, roughly $750,000 \text{ m}^3$ of crude synthesis gas was generated, but in order to meet the requirements of methanol synthesis the gas needs to be appropriately refined. Figure 30 illustrates the composition of clean synthesis gas.

Cleaned synthesis gas (%)

H ₂	Vol.- %	59,1
CH ₄	Vol.- %	11,6
CO	Vol.- %	23,5
CO ₂	Vol.- %	2,1

Figure 30: Synthesis Gas Composition (Buttker, 2005)

Based on the results from SVZ's pilot plant, the following conclusions could be made:

- The BGL-G gasifier can recycle approximately 70,000 tons of SR pellets per year
- Since the BGL- G gasifier in the SVZ is usually operated in parallel with two fixed bed high-pressure gasification reactors, an additional capacity of about 35,000 tons per year for pre-treated SR is available.
- As a result, approximately 105,000 tons per year of pretreated SR could already be recycled within existing facilities and for delivered SR this approximation corresponds to a recycling capacity of about 146,000 tons per year

- With the planned parallel operation of the BGL-gasifier with 3 fixed bed pressure gasifiers, the annual capacity for delivered SR could be increased to an overall value of 170,000 tons per year
- With the possible installation of a second BGL-gasifier at SVZ in the medium term, a further increase of the recycling capacity for delivered SR of up to 200,000 tons per year may be possible

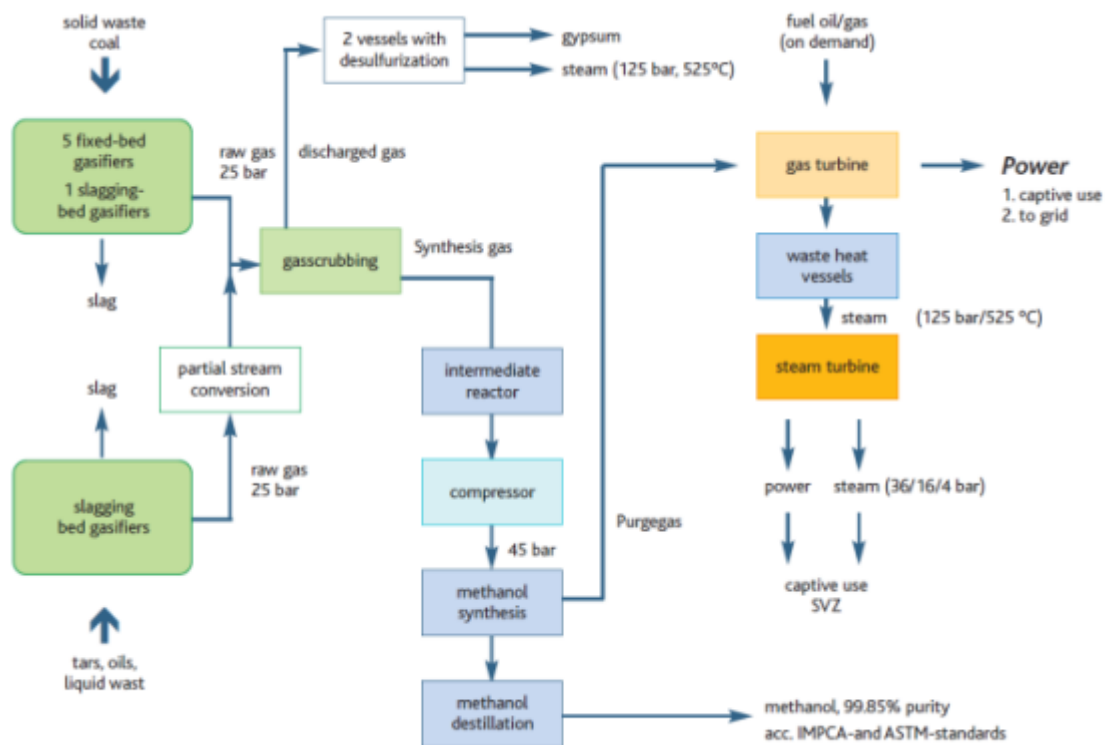
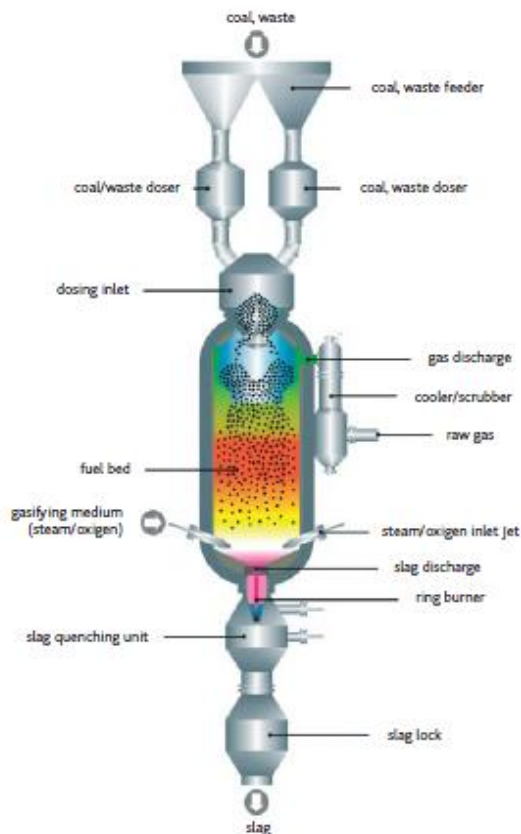


Figure 31: SVZ Process (Buttke, 2005)



BGL-G Gasifier

SYSTEM PARAMETERS:

- Reactor diameter: 3.6 m
- Pressure: 25 bar
- Double Jacket watercooled
- Feedstock input injected from perimeter
- Liquid-slag discharge

SPECIFIC PARAMETERS:

- Feed rate: 27-32 t/h
- Cycle times: 6-9 /h
- Gas amount: 35,000 m³/h
- Final gasification temperature: 1600 °C
- Oxygen amount: 6000 m³/h
- Steam amount: 6-9 t/h
- Slag discharge: ≤ 7.5 t/h
- Crude syngas gas temperature: 500-700 °C
- Temperature after scrubber: <200°C

Figure 32: BGL-G Gasifier 2 (Buttke, 2005)

ConTherm Technology

This technology, developed by RWE Energie AG, is able to process MSW and ASR as well as post-consumer plastics. The shredded fuels are pyrolysed at 500-550 °C in rotary kilns (from TECHNIP) and the gas is combusted in a pulverized coal (PC)-fired boiler. For metal recovery the residues obtained from the process are screened and sorted. In 2002 the first ConTherm power plant was scheduled for building at a 769 megawatt (MW) PC-fired power station in Hamm-Uentrop, Germany (Malkow, 2004).

EDDITH Process

This process was developed by Thide Environment S.A. of France and the Institut Francais du Petrol (IFP). This technology includes a rotary drier fueled by hot air, a rotating tubular pyrolysis reactor (kiln) which is externally heated by reusing waste heat (flue gas), a combustion chamber that is equipped with a low NO_x burner to improve efficiency, and char separators for metal recovery. The waste is fed to the drier where preheated air from the flue gas heat exchanger reduces the waste's moisture content by about 10%. The fuel is brought into the kiln by a piston where it is thermolyzed at 450-550 °C. The char produced is

separated and its materials filtered while the flue gas is used as a source of heat to preheat air for its use in the heat recovery steam generator (HRSG).

One tonne of waste processed with the EDDITH process results in:

- 400 kg of gas with 12 MJ/kg calorific value
- 240 kg coke
- 51 kg metals
- 61 kg inerts
- 10 kg salts (mostly CaCl_2 and NaCl)

In 2002 there were two demonstration plants being built in Japan while in 2003 a 3 tonne/hour plant was scheduled to start operation in France, processing 50 kt annually (Malkow, 2004).

Serpac Technology – P.I.T. Pyroflam process

This process uses an inclined reactor that has two interconnected chambers for the pyrolysis and gasification of waste, and finally the combustion of collected gases in a boiler. Waste is pyrolyzed in the first chamber at 600-700 °C while char gasification with air at 800 °C occurs in the second chamber. The fuel gas flowing back towards the first chamber provides the necessary heat. Organic matter in the fuel is evaporated while heavy metals remain in the char. To generate steam the yielded gases are combusted at 1100 °C in an attached boiler. Metals can be recovered from the char. There is currently a plant in operation at the airport in Budapest, Hungary that is treating industrial waste (Malkow, 2004).

PKA Technology

As seen in Figure 33, starting with the pre-processed, screened and shredded waste, pyrolysis occurs in an externally heated rotary kiln at 500-550 °C for 45-60 minutes. The gas is funneled into a converter unit where at 1000 °C the hydrocarbons and organic volatiles are decomposed to give a homogenized CO/H_2 -rich fuel gas. The char is processed by separating the ferrous and non-ferrous metals, reducing its moisture content to less than 10%, and grinding it to smaller than 2mm before it can be used as a fuel, a sorbent, or a raw material in brick production. Gasification of the char at 1400-1500 °C in a high-temperature smelting reactor produces a combustible gas and a vitrified slag. The slag is granulated and used in the cement and construction industry while the gases, after being quenched and cleaned, can be used in gas engines. There are several pilot plants using this technology in Germany and the

Netherlands while the Japanese Toshiba Corporation will market the technology (Malkow, 2004).

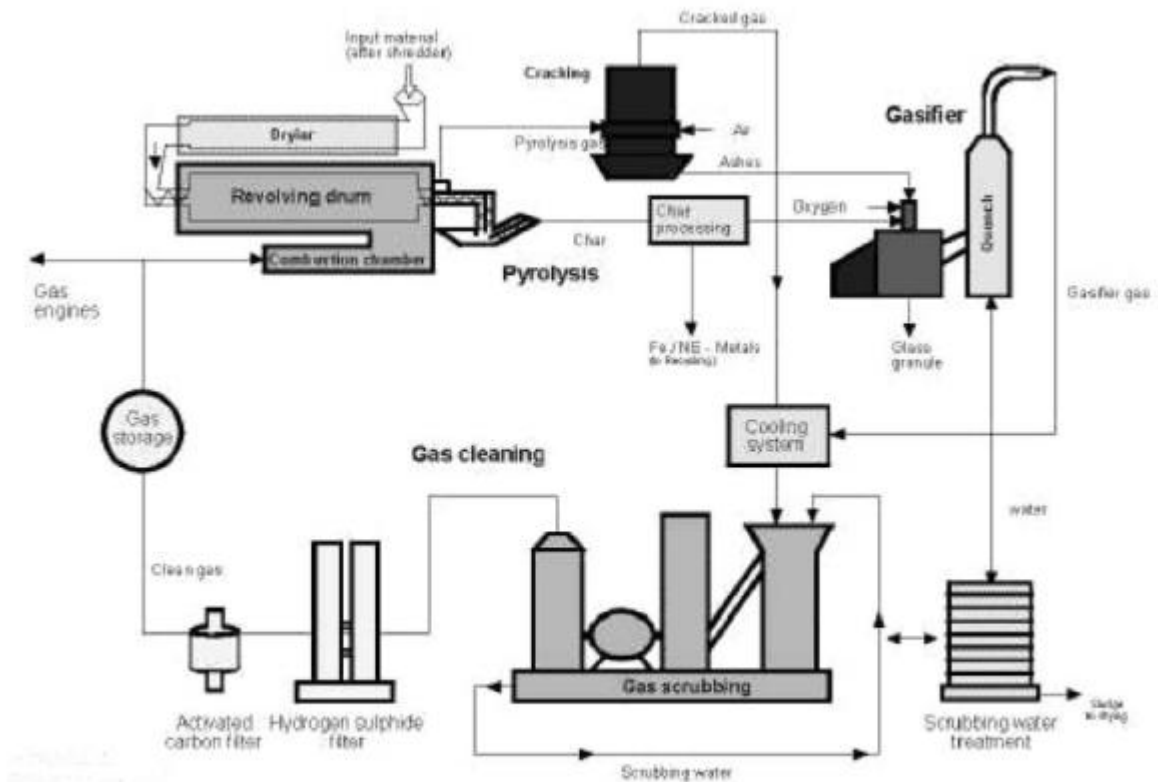


Figure 33: PKA Technology Schematic (Malkow, 2004)

PyroMelt Technology

Waste, including light ASR fractions within an 8-18 MJ/kg lower heating value range, is shredded to pieces smaller than 15 cm and then pyrolyzed at 1200 °C in a drum. The lower heating value (LHV), or net calorific value, refers to the amount of heat released by combusting a specified amount of a fuel. A majority of the gas is combusted with air to provide heat for the drum while the flue and pyrolysis gases are funneled to the heat recovery steam generator (HRSG). Using recycled fractions of pyrolysis oil, a fuel that could be used instead of petroleum, the pyrolysis gas is cleaned and depolluted using a scrubber system and cooled before combustion. After the char is cooled down to 50 °C using water it is shredded to less than 5 cm and ferrous and non-ferrous metals are separated on a fluid bed. Oxygen enrichment of the exhaust gas at 1350 °C creates a ceramic matrix which is quenched with water and granulated (Malkow, 2004).

SIEMENS Schwel-Brenn technology

This technology is classified as a discontinuous carbonization-incineration process. As shown in Figure 34, the recirculation of flue gas indirectly heats the rotating drum where waste is dried and pyrolyzed at 450 °C for an hour in an oxygen-depleted atmosphere. The residue particles greater than 5 mm are “removed for recycling into ferrous, non-ferrous and inert materials while the finer carbon-enriched (30%) fraction is ground to 0.1 mm and combusted together with the gas in the slagging furnace at 1300 °C with excess air to raise steam to 400 °C at 40 bar”. This process generates electricity at a 24% efficiency rate. The treatment of 1 tonne of MSW with this process creates 550 kWh of electricity. There are a few pilot plants operating in Germany while there are several plants in Japan including an ASR-fuelled plant in Fukuoka that was launched in 1998 (Malkow, 2004).

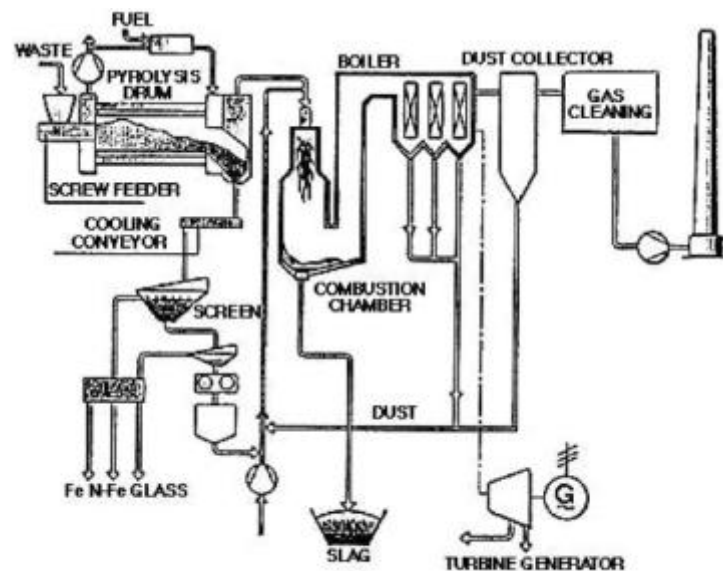


Figure 34: Schwel-Brenn Technology Diagram (Malkow, 2004)

Noell-KRC Conversion Process

This process involves two thermal treatment steps, pyrolysis followed by gasification. Waste is pyrolyzed for an hour in an externally heated rotary kiln at 550 °C and then the residues are gasified in a slagging entrained flow using oxygen at 1400-2000 °C and 2-50 bar of pressure. The gas has many subsequent uses including heating the kiln, syngas, and combustion in a boiler or engine. There are several demonstration and reactor plants operating in Germany (Malkow, 2004).

THERMOSELECT Process

This technology, shown in Figure 35, utilizes pyrolysis then fixed bed oxygen-blown gasification in slagging mode so that there is joint mineral and metal residue vitrification. The vitrification process permanently traps harmful chemicals in block of solid glass-like material. Waste is first pyrolysed at 600 °C then at 800 °C. The products are gasified at 1200 °C and 2000 °C in the top and bottom reactors to ensure that dioxin pollutants are destroyed and the residues are vitrified. The syngas obtained at the top of the reactor is rich in CO and H₂ but must be cleaned by acid/alkaline wet scrubbing and activated carbon to remove contaminants like NH₃ and heavy metals. The cleaned syngas is then used to heat the degassing channel, raise steam in an engine or turbine, or as a chemical feedstock; it can also serve in hydrogen production. Combustion residues from the bottom part of the reactor are homogenized at 1600 °C with a burner and metallurgically separated into ferrous and non-ferrous metals on a slag which is then quenched and granulated. The Thermoselect process can reach up to 40% electrical efficiency. There is a 150 t/day plant operating at Kawasaki Steel Corporation's Chiba Works in Japan and a 300 t/day plant in Karlsruhe, Germany. There are also multiple plants in the planning, construction, or commissioning stages (Malkow, 2004).

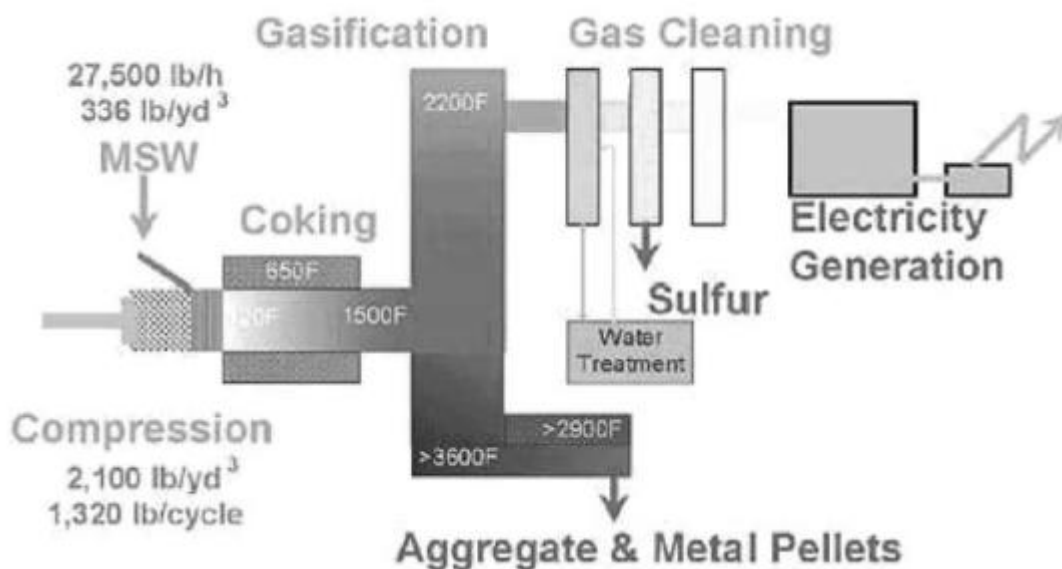


Figure 35: Thermoselect Schematic (Malkow, 2004)

Von Roll RCP Technology

The recycled clean products (RCP) technology by Von Roll/Inova utilizes a grate-type pyrolysis chamber, a melting and Holderbank-Smelt-Redox (HSR) furnace, a circulating fluidized bed (CFB) reactor with an aerocyclon and a fluid ash cooler along with a HRSG. As can be seen in Figure 36, the waste is dried, pyrolyzed by partial oxygen combustion, and entered into a melting furnace where it is combusted at 1400 °C with oxygen. The HSR process is used to separate and recover metals and slag in a second furnace. In the CFB the gas is burned under 1000°C and then steam is raised in the HRSG. A 16 MW pilot plant with a 6 t/day capacity is in operation in Bremerhaven, Germany but Switzerland is planning a 50 kt/year ASR-fuelled plant (Malkow, 2004).

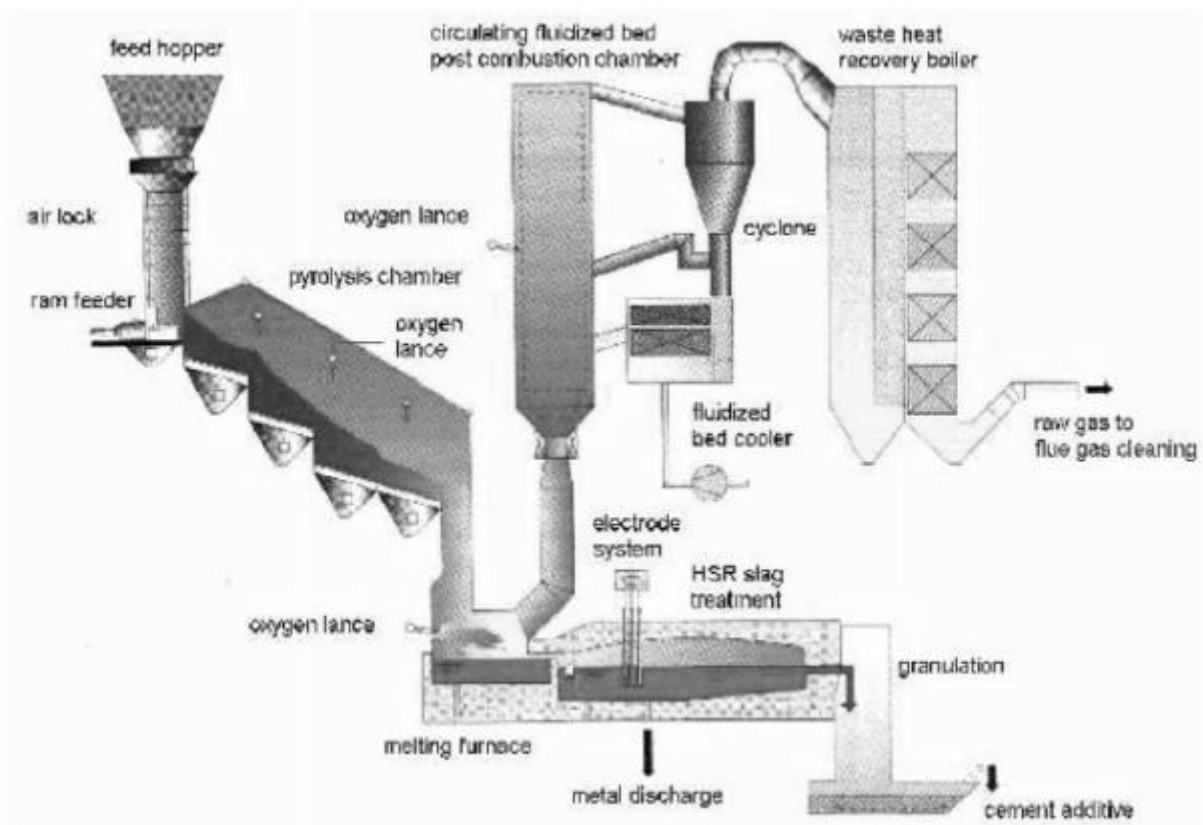


Figure 36: RCP Process (Malkow, 2004)

Compact Power Process

This process was developed by the UK's Compact Power Ltd. It incorporates pyrolysis, gasification, and high temperature combustion to process a variety of wastes and recover gas and other materials such as carbon. After being pyrolyzed through heated tubes, the waste is gas combusted in a cyclone at 1200-1250 °C. This provides heat for the tubes, guarantees vitrification, and most importantly allows for steam-raising in a HRSG. A 500

kg/h pilot plant has been in operation in Bristol, UK while another plant is planned for installation in Scotland (Malkow, 2004).

The following provides a comparison of some of the pyrolysis and gasification techniques discussed above:

Shredded fuels are pyrolysed in a rotary kiln at a range of temperatures from 400 to 850 °C. The ConTherm technology process pyrolyses shredded fuels at 500-550 °C and combusts the gas in a coal-fired boiler. Solid residues are screened and sorted for metal recovery. A similar but more efficient system involves EDDITH technology. Preheated air reduces the moisture content of the ASR by 10% in the rotating kiln. The resulting char is separated and filtered while the flue gas is used to preheat the air. The Serpac technology process has an inclined reactor with interconnected chambers. Waste is pyrolysed then the char is gasified with air at 800 °C in the second chamber. As with the EDDITH process, the flue gas flows towards the first chamber to provide necessary heat. Heavy metals remain in the char and metals can be recovered from it. The gases collected are combusted to generate steam.

The process employing PKA technology also involves pyrolysis in an externally heated rotary kiln and yields easily reusable and recoverable materials. The resulting gas is gasified at 1000 °C to decompose the organic volatiles. Ferrous and non-ferrous metals are first separated in the char and it is then gasified to yield a combustible gas and a vitrified slag which can be used in the cement and construction industries. The combustible gas is cleaned and depolluted with a scrubber system, and is then used in gas engines. PyroMelt technology is fairly similar to the PKA technology. Light ASR fractions are shredded to small pieces and pyrolysed at 1200 °C. The gas is combusted with air to provide heat for pyrolysis as in the previously mentioned processes. In addition, the pyrolysis gas is cleaned using a scrubber system. The char is shredded and a fluid bed is used to separate the ferrous and non-ferrous metals.

The Schwel-Brenn technology also recirculates flue gas to indirectly heat the rotating drum where waste is pyrolysed. Larger residue particles are separated for ferrous and non-ferrous metal recycling while smaller particles are combusted with the gas in a slagging furnace at 1300 °C, thus generating steam. This process has a 24% efficiency rate for electricity generation. A more efficient technology involves the Thermostelect process, which can reach up to 40% electricity efficiency. ASR is pyrolysed at two temperatures and subsequently gasified at two temperatures, thus destroying dioxin pollutants and vitrifying the

residues. The syngas, after cleaning, is used to raise steam in a turbine or it can be used in hydrogen production. Similar to the other processes, the solid residues are separated into ferrous and non-ferrous metals.

The gas from the Noell-KRC Conversion process is also used to heat the kiln, as syngas, or for combustion in a boiler or engine. The Von Roll RCP technology incorporates a Holderbank-Smelt-Redox (HSR) furnace. The ASR is pyrolysed by partial oxygen combustion, then combusted in a melting furnace. The HSR separates and recovers metals and slag while the gas is burned for steam-raising in an HRSG. The Compact Power process also employs combustion. After pyrolysis the waste is combusted in a cyclone, providing heat for the tubes and steam-raising in an HRSG. The combustion in a cyclone additionally guarantees vitrification (Malkow, 2004).

Appendix E: Air Pollution Control Technologies

Contaminant	Control Technology
Particulate Matter (PM) and Aerosols	Inertial Separation, Baghouse, Scrubbers, Electrostatic Precipitators (ESP)
Volatile Metals (vapor state)	Carbon Filters (or condense to PM or aerosols and use PM separation techniques)
Dioxin/Furans	Limit chlorine mass input in feedstock, Cold-quenching and/or Catalytic/thermal Combustion
Carbon Monoxide (CO) and Hydrocarbon (HC) gases	Process Design, Catalytic/thermal Combustion, Re-burning, Carbon Filters
Oxides of Nitrogen (NO _x)	Flame Temperature Control/ Low NO _x Combustors, Fuel Nitrogen Management, Selective Catalytic Reduction, Water Injection, Re-burning
Oxides of Sulfur (SO _x)	Limit sulfur mass input. Scrubber
Acid Gases	Scrubber

Figure 37: Air Pollution Control Technologies (Integrated, 2004)

Appendix F: Interview Questions

Shredder Facility Interview Questions

1. What is the process that ELVs undergo before reaching your shredder plant?
2. What is the process that ELVs undergo once they reach your shredder plant?
3. How much ASR do you output each day?
4. What environmental factors (i.e. energy usage, wastewater production) do you take into consideration when conducting your business? Which of these are required by Danish law?
5. How are you planning to meet the 2015 recycle/reuse rate? How will the taxes impact your company economically?
6. Has your company done any research into alternative ASR treatment technologies such as pyrolysis and gasification? If, so can you provide our team with information regarding your research and project work? If no, if your company had the chance to research alternative treatment technologies then what would you predominately research?
7. Has your company done any research into mixing MSW and ASR for co-incineration?
8. If your company were to implement a new process, would you buy the rights to the technology outright, or contract with another company that constructed the technology?
9. How much metal do you export and where?
10. Are there any additional handouts or information you could provide our team?
11. Upon completion, would you like a copy of our report?

Landfill Facility Interview Questions

1. What are the pre-treatment steps your company applies to process the leachate? What are the different materials (percents?) that are extracted from the leachate and what is done with it? Are you able to provide us with any percolate tests?
2. Has your facility compiled any research on leachate recycling?
3. Is shredder waste landfilled in a special cell? If so, what sort of filtering system have you developed for leachate runoff?
4. Do you process the shredder waste any further after you receive it from the shredder facility or is it directly landfilled?
5. Was the landfill facility affected by the economic crisis (i.e. less amount of shredder waste received last year)?
6. How much shredder waste do you landfill each day...each year? Do you have information on these numbers from previous years?
7. After incinerating shredder waste, a hazardous slag is produced and captured in a screen. This slag consists of three different components: a mineral part, an iron part, and a hazardous residue. Have you investigated the vitrified slag process via pyrolysis?
8. Has there been any research or do you have any information on storing CO₂ underground that results from the gasification process? Have you heard of using the CO₂ to extract oil from deep wells underground?

9. Do you know of anyone locally, regionally or internationally investigating alternative shredder waste treatment technologies?
10. Is there any additional information or handouts you can provide our team with?
11. Upon completion, would you like a copy of our report?

Appendix G: Scholz Shredder Waste Processing Plant

Scholz Recycling AG & Co. KG is a leading steel and metal scrap recycling company in Europe, based in Essingen, Germany. The company focuses on the complete recycling of scrap iron, alloyed steel, and non-ferrous metals with a large emphasis on using railways and waterways for transport and incorporating advanced technologies geared towards environmental protection. Recycling of metals is very important from an economic and environmental standpoint because natural resources are diminishing, extraction and transport prices of primary raw materials are steadily increasing, and manufacturing virgin ores is very energy intensive. Thus, 50% of the world's annual steel production is manufactured from metal scrap, helping to save 600 million tonnes of coking coal, 200 million tonnes of iron ore, and 130 million tonnes of CO₂. (Competence in Scrap, n.d.)

Scholz AG has developed a high-tech post-shredder technology (PST) that is being utilized at their Leipzig-Espenhain plant in Germany. In 2006 and 2008 they conducted two large-scale tests on over 1200 ELVs to determine how much material can be recycled and recovered from pre-series vehicles using the PST (Henkes, 2008). The results were very promising as 93-94% of the ELVs by weight were reused, recycled, or recovered. In 2006, 729 ELVs were tested at the Espenhain plant while 501 ELVs were put through the machinery in 2008. Here are the results from the two tests:

- 2006
 - Recycling and reuse 86.4%
 - Energetic recovery 7.3%
 - Total recovery rate 93.7%
- 2008
 - Recycling and reuse 82.3%
 - Energetic recovery 9.7%
 - Total recovery rate 92.0%

In 2008 the total recovery rate was a little lower, but 200 fewer ELVs were used and although the recycling and reuse decreased by 4%, energy recovery was 2.5% greater (Mehlhorn et al., 2009).

The 2008 test on behalf of BMW was conducted along with Galloo Plastics of France. For the test, 501 BMW pre-series vehicles from 2007 were dismantled by BMW and the pressed hulks were then transferred to Scholz's Espenhain plant, as seen in Figure 38.



Figure 38: ELV Hulks (Henkes 2008)

The dismantling process included the removal of all fluids and toxic substances, batteries, catalytic converters, bumpers, front and rear lights, and body parts intended for reuse. From a starting weight of 761.8 total tonnes, the empty weight of the ELVs was 718.8 tonnes and after dismantling, 646.4 total tonnes was shredded (Henkes, 2008).

The PST at the Espenhain plant has been in operation since 2005 and Henkes notes that at the time of the 2008 test it still seemed to be the only technology in Europe able to automatically generate both plastics and metal fractions from heavy and light shredder fractions. The Scholz plant classifies the heavy shredder fraction as mainly consisting of non-magnetic metals, metal-bearing composites, and plastics composites. The light shredder fraction is classified as including fibrous material, paints, polyurethane foams, plastics, rubber, and glass. The aim of the test was to recover the non-alloy steel content through shredding, use PST to recover residual metals from the heavy and light shredder fractions, recover the secondary fuel fraction, and recover recyclable plastics from the enriched plastic-rubber fraction (Henkes, 2008). The following amounts of products were recovered after the shredding process:

- 382.6 tonnes of directly recyclable steel scrap
- 145.6 tonnes of heavy shredder fraction
- 110 tonnes of light shredder fraction
- 4.0 tonnes of copper-bearing composites which were extracted by hand
- 1.4 tonnes remained as mainly rubber, textiles, and non-metallic composite materials

Figure 39 presents the treatment process and some material flow for the shredder light fraction.

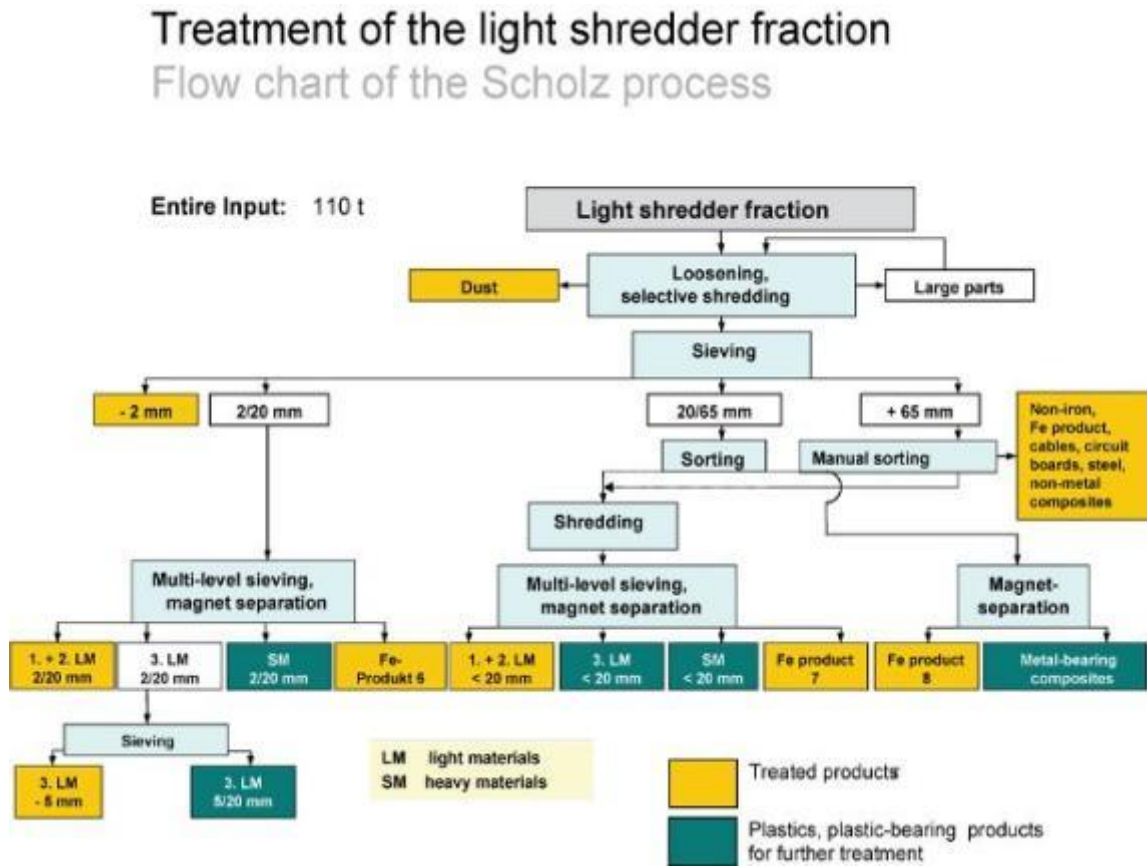


Figure 39: Flow Chart of Scholz Process (Henkes, 2008)

By using shredding, sieving, magnetic separation, and sorting and classification technologies, the Scholz PST allows for the recovery of the following products from the SLF (Henkes, 2008):

- Directly recyclable metals
- Metal-bearing composites (including cables and circuit boards for further treatment)
- Substitute fuels (non-metal composites varying in particle size)
- Plastics and plastics composites for further treatment
- Mineral products (< 2mm)

Figure 40 shows the fractions obtained when the light shredder fraction is processed (Mehlhorn et al., 2009):



Figure 40: Fractions from Scholz SLF-Processing (Mehlhorn et al., 2009)

Figure 41 details the heavy shredder fraction processing methods.

Treatment of the heavy shredder fraction Flow chart of the Scholz process

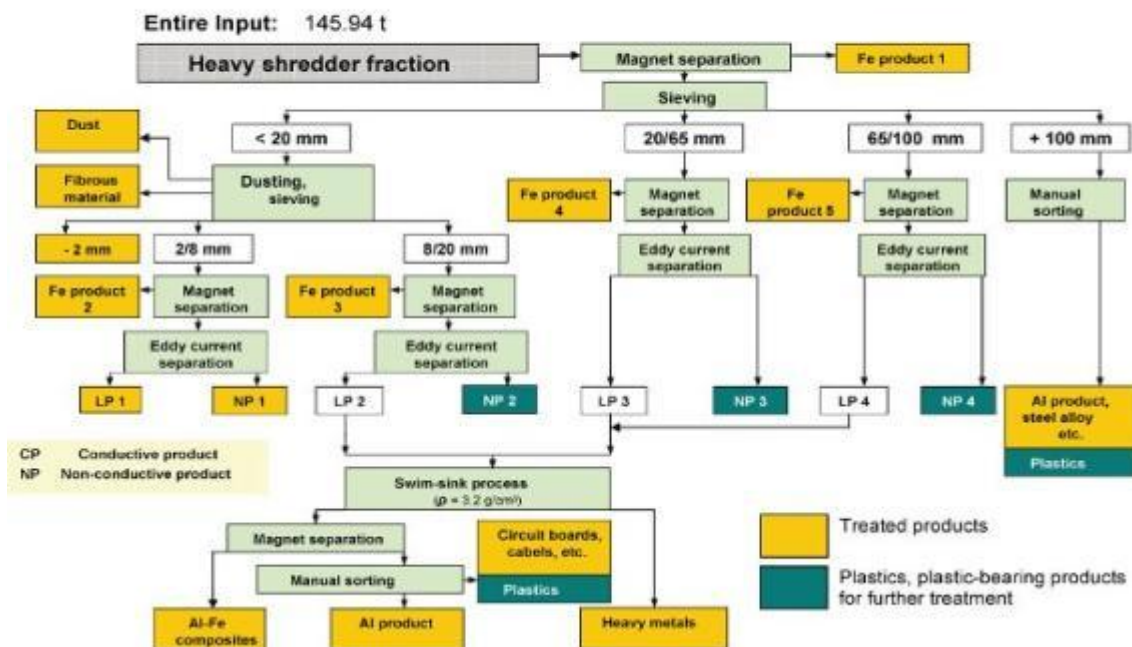


Figure 41: Flow Chart of the Scholz Process Heavy Fraction (Henkes, 2008)

The products recovered from the heavy shredder fraction with the use of sieving, magnetic separation, and eddy current separation include:

- Metals (directly recyclable Fe, Al and Cu metals, steel alloys, Al-Fe composites)
- Metal-bearing composites (Cu-Fe products, cables, circuit boards, and composites suitable for further treatment)
- Substitute fuels
- Plastics of various sizes
- Dust and fibrous material (<20 mm)
- Mineral particles (<2 mm)

67.5 tonnes of plastics and rubber are recovered through this heavy shredder fraction separation process, but some metal deposits are present as well. Since the heterogeneous plastics fraction has a high calorific value it would be beneficial to purify and sort the various plastics fractions. Thus, Scholz cooperated with Galloo Plastics S.A. in France to separate as much residual metal as possible and sort the plastics fractions. As seen in Figure 42, the materials were separated with sink-float technology, first at a density of 1.5 g/cm³ and then, following eddy current separation, at a density of 3.2 g/cm³ (Henkes, 2008).

Treatment of plastics residues

Flow chart of the Scholz process

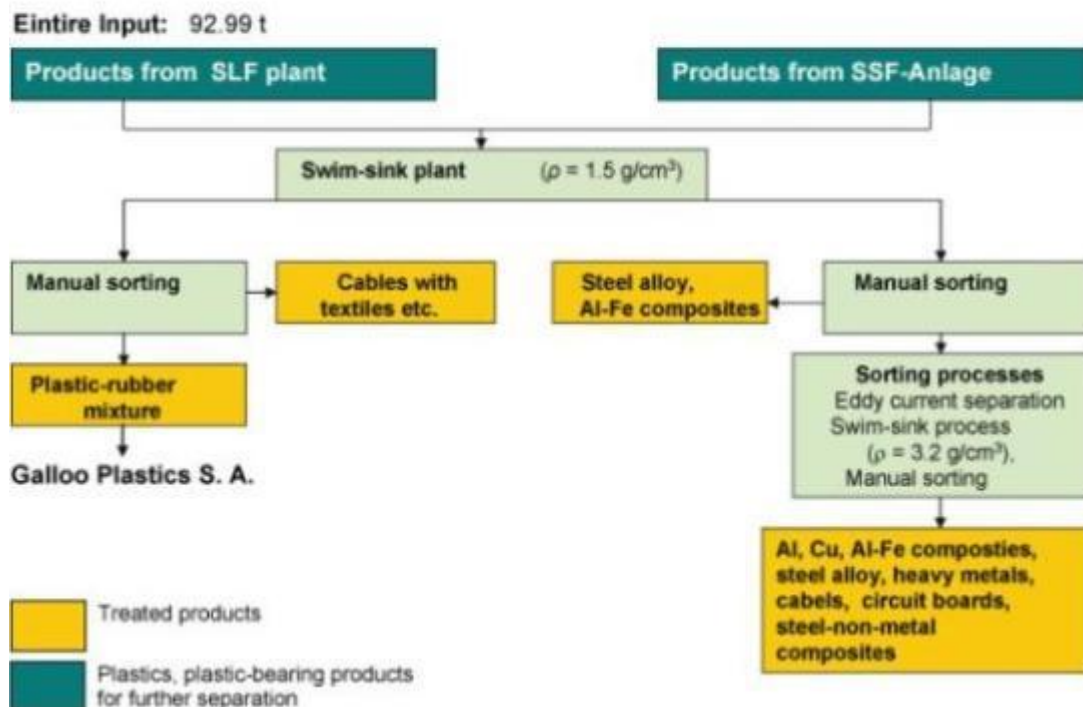


Figure 42: Treatment of Plastic Residues in Scholz Process (Henkes, 2009)

The pie chart in Figure 43 details the mass balance and percentages of products resulting from the Galloo Plastics separation process.

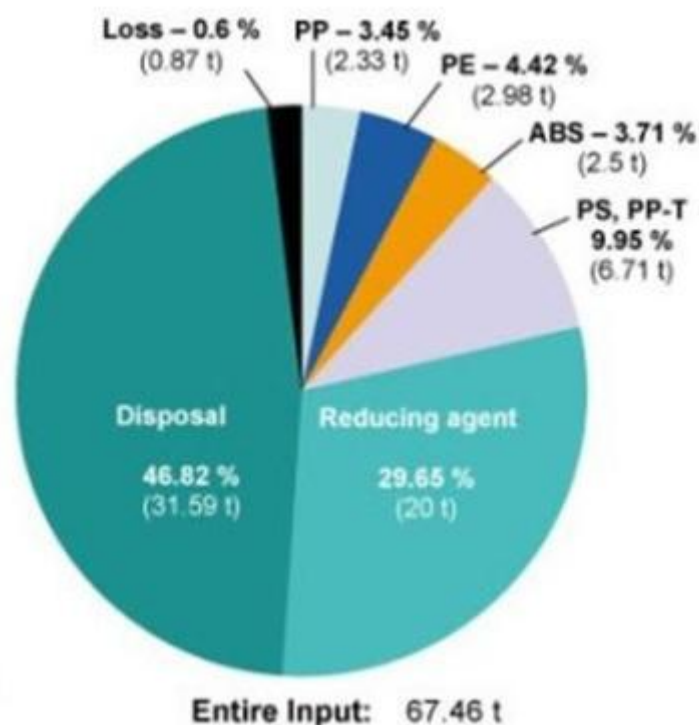


Figure 43: Products Resulting from Galloo Process (Henkes, 2008)

The main resulting fraction, almost 46%, is chlorinated plastics with a density between 1.25 and 1.5 g/cm³. The next largest fraction contains a product with polyolefin that can be used as a reducing agent in foundries. The remaining single-variety plastics fractions can be treated further and recycled, or granulated and used in blast furnaces. However, the large chlorinated fraction presents somewhat of a problem since the chlorine concentration does not fall within the allowable limits for conventional waste incineration plants. The 3-8% chlorine content in this fraction comes from PVC-bearing plastics that are used in vehicles and so this waste will still have to be landfilled. However, this fraction represents only 4% of the total vehicle weight (Henkes, 2008).

The 2008 ELV test at the Espenhain plant seems very promising as 565 tonnes of metal were recovered overall, representing 78.6% of the vehicle's weight. Some product uses include substitute fuels in waste incineration plants for energy recovery and reduction of the Cu fraction for use in firing cement works (Henkes, 2008). Scholz's research and development is continuing as the company has invested more than €100 million in shredder

technologies since 1995 (Mehlhorn et al., 2009). Scholz is investing in sink-swim technology and pyrolysis equipment to further treat the troublesome chlorinated plastics fraction (Henkes, 2008).

The technologies in use at the Leipzig-Espenhain plant are very environmentally friendly and help to reduce the world's CO₂ emissions. The plant recycles 235,000 tonnes of steel scrap and 33,500 tonnes of Al yearly, saving 330,000 CO₂ equivalents of green house gas emissions. Each tonne of recycled steel scrap saves 1 tonne of CO₂ equivalents, one tonne of iron ores, and 600 kg fuel, mainly coal. A tonne of recycled aluminum saves 9.9 tonnes of CO₂ equivalents while a recycled tonne of copper saves 3.5 tonnes of CO₂ equivalents in green house gas emission. Figure 44 shows the proportions of the three main shredded material fractions in 2008 (Mehlhorn et al., 2009):

Proportions of Mass 2008
 Condrotor SCHOLZ Recycling AG & Co. KG, Espenhain

Product	Proportions	
	<i>in %</i>	<i>in t/a</i>
Steel Scrap	72,8	200.654
Shredder-Heavy-Density-Fraction	11,2	30.870
Shredder-Light-Density-Fraction	16,0	44.100
Loading Material*	100,0	275.624

*ELVs in total 14,7 % from the whole loading material

Figure 44: Shredded Material Fractions (Mehlhorn et al., 2009)

Appendix H: Odense Nord Miljøcenter Percolate Analysis

Table 11: Odense Nord Miljøcenter Percolate Analysis

Prøvenr.:	24715240				
Prøve ID:			Detekt.		RSD
Prøvemærke:		Enheder	grænse	Metoder	(%)
Prøvens farve	gulbrun			*VISUEL	
pH	8.2	pH		DS 287	
Konduktivitet	970	mS/m	0.5	DS/EN 27888	5
Iærstof, totalt	6100	mg/l	20	DS 204	10
Suspenderede stoffer	38	mg/l	0.5	DS/EN 872	10
Ammoniak+ammonium-N, filtreret	190	mg/l	0.005	SM 17 udg. 4500	5
Total-N	200	mg/l	0.05	DSEN111905 Auto	10
Total-P	1.9	mg/l	0.005	DS/EN I 6878aut	10
Chlorid	2000	mg/l	1.00	SM 17 udg. 4500	5
IOC, totalt organisk kulstof	400	mg/l	0.50	DS/EN 1484	20
VOC, flygtigt org. kulstof	<0.50	mg/l	0.50	DS/EN 1484	10
NVOC	400	mg/l	1.0	DS/EN 1484	10
BI5	140	mg/l	0.50	DS/EN 1899-1	10
COD, kemisk iltforbrug	1300	mg/l	5.0	ISO 15705	10
Arsen (As)	23	µg/l	0.80	ISO17294m-ICPMS	15
Chrom (Cr)	6.5	µg/l	0.5	ISO17294m-ICPMS	15
Jern (Fe)	11	mg/l	0.050	ISO17294m-ICPMS	15
Kobber (Cu)	6.3	µg/l	1.0	ISO17294m-ICPMS	15
Kvikselv (Hg)	0.27	µg/l	0.050	ISO17294m-ICPMS	15
Nikkel (Ni)	190	µg/l	1.0	ISO17294m-ICPMS	15
Blødgørere					
Diethylhexylphthalat (DEHP)	0.76	µg/l	0.50	MK0250-GC/MS	12

Oplysninger fra prøvetageren:

Prøvetagningsmetode	Stikpr.	
Nedbør	0.0	mm
Vandtemperatur (slut)	10.8	gr C
pH (målt i felten) slut	8.1	pH
		DS/ISO 5667
		*
		DS 287

*) Ikke omfattet af akkrediteringen.

Appendix I: RenoDjurs Percolate Analysis

Table 12: March 2010 RenoDjurs Percolate Analysis

Sted:	Enh. A / -				Reg. nr.:	777008	A16493	A40355	A29467	A42704	A45720	A47807	A51858	0
Type:	Shredder affald				Dato.:	2009.04.08	2009.06.18	2009.08.25	2009.10.09	2009.11.23	2009.12.14	2010.01.14	2010.02.10	1900.01.00
					Prøve nr.:	77700801	A1649305	10533813	10545544	A4270401	10549466	A4780701	A5185801	0
					Prøvested	Enh. A	Shredder A	Shredder A	Shredder A	Shredder A	Shredder A	Shredder A	Shredder A	0
sort.nr.:	Parameter	Enh.	dtg.	Test	Alam-Perkolat	FA1 - C ₁	Data	Data	Data	Data	Data	Data	Data	Data
1	pH	pH	-	DS 287:1978	-	-	7,4	7,6	7,9	7	7,6	7,8	7,6	7,9
2	Ledningsevne	mS/m	0,1	DS/EN 27888	-	-	630	310	100	300	740	250	620	830
3	Total-N	mg/l	0,05	DSENI11905 Auto	-	-	270	120	23	20	290	65	220	230
4	Total-P	mg/l	0,01	DS/EN 16878aut	-	-				1,4	< 0,005	< 0,005	< 0,005	< 0,005
5	Ammonium, filtreret	mg/l	0,01	SM 17 udg. 4500	-	-				< 0,006	< 0,006	< 0,006		
6	TOC, totalt organisk kulstof	mg/l	0,5	DS/EN 1484	-	-				560	< 0,5	< 0,5		
7	COD, Kemisk iltforbrug	mg/l	5	ISO15705/LC500	-	-	5700	1700	140	2000	4000	950	2200	1400
8	Chlorid	mg/l	1	SM 17 udg. 4500	-	15000	550	280	81	240	1000	330	730	820
9	Sulfat	mg/l	0,5	SM 17 udg. 4500	-	17000	750	98	21	41	110	53	50	310
10	Natrium (Na)	mg/l	0,5	ISO17294m-ICPMS	-	-				210	< 0,5	< 0,5		
11	Calcium (Ca)	mg/l	0,5	ISO17294m-ICPMS	-	-				560	< 0,5	< 0,5		
12	NVOC, ikke-flygtig, kulstof	mg/l	0,1	SM 5310 A+B	-	-				550	< 0,1	< 0,1		
13	AOX, som Cl	mg/l	0,02	DIN EN ISO 9562	-	-				0,07	< 0,015	< 0,015		
14	Benzen-C10	µg/l	2	GC/FID	-	-	180	71	< 2	21	370	73	280	100
15	C10-C25	µg/l	8	GC/FID	-	-	520	220	22	82	880	230	520	270
16	C25-C35	µg/l	10	GC/FID	-	-	< 10	< 10	< 10	14	18	< 10	52	< 10
17	Sum (Benzen-C35)	µg/l	#	GC/FID	-	-	700	290	22	120	1300	300	860	380
18	Naphthalen	µg/l	0,01	MK2260-GC/MS	-	-	0,12	0,23	< 0,01	0,041	1,4	0,24	0,89	< 0,01
19	Phenanthren	µg/l	0,01	MK2260-GC/MS	-	-	2	0,12	< 0,01	< 0,01	0,033	0,015	0,022	< 0,01
20	Anthracen	µg/l	0,01	MK2260-GC/MS	-	-	0,18	< 0,01	< 0,01	< 0,01	0,018	0,021	< 0,01	< 0,01
21	Acenaphthen	µg/l	0,01	MK2260-GC/MS	-	-	0,12	< 0,01	< 0,01	< 0,01	0,14	< 0,01	0,049	< 0,01
22	Fluoranthen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
23	Pyren	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
24	Benzo(a)anthracen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
25	Chrysen/ Triphenylen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	0,019	< 0,01	< 0,01	< 0,01
26	Benz(b)+k(1)fluoranthen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
27	Benzo(a)pyren	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
28	Indeno(1,2,3-cd)pyren	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
29	Benzo(g,h,i)perylen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
30	Dibenzo(a,h)anthracen	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
31	Fluoren	µg/l	0,01	MK2260-GC/MS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	0,48	0,04	0,19	0,074
32	Acenaphthylen	µg/l	0,01	MK2260-GC/MS	-	-	0,073	< 0,01	< 0,01	< 0,01	0,031	0,052	< 0,01	< 0,01
33	Sum PAH (16 EPA)	µg/l	#	MK2260-GC/MS	1,5	-	2,5	0,35	< #	0,041	2,7	0,38	0,95	0,074
34	Diethylnexylphthalat (DEHP)	µg/l	0,1	MK2265-GC/MS	-	-				< 0,1	< 0,1	< 0,1		
35	Cyanid, total	µg/l	1	DS/EN ISO 14403	-	-				3	6	6	8	8
36	Arsen (As)	µg/l	0,8	ISO17294m-ICPMS	15	3000				11	54	19	60	56
37	Chrom (Cr)	µg/l	0,5	ISO17294m-ICPMS	17	1500				13	25	8,2	28	24
38	Chrom-VI	µg/l	0,1	SM3500D/VKI	17	-				< 0,1	< 0,1	< 0,1		
39	Kobber (Cu)	µg/l	0,04	ISO17294m-ICPMS	4	60000				9,7	52	11	98	14
40	Bly (Pb)	µg/l	0,03	ISO17294m-ICPMS	-	15000				1,8	19	6,3	24	4,3
41	Zink (Zn)	µg/l	0,5	ISO17294m-ICPMS	-	60000				100	34	9,8	160	64
42	Cadmium (Cd)	µg/l	0	ISO17294m-ICPMS	-	1700				1,3	0,6	0,2	1,2	0,22
43	Nikkel (Ni)	µg/l	0,03	ISO17294m-ICPMS	38	12000				24	100	31	130	120
44	Kviksølv (Hg)	µg/l	0,05	ISO17294m-ICPMS	-	300				< 0,05	< 0,05	0,067	< 0,05	0,18

45	Tørstof	mg/l	20	DS 204:1980	-	-	7300	2500	630	2500	5900	1800	4500	4100	
46	Gledelab, total	mg/l	20	DS 204:1980	-	-									
47	B15	mg/l	0,5	DS/EN 1899-1	-	-	2800	690	20	1100	1800	320	580	250	
48	Ammoniak+ammonium-N, filtreret	mg/l	0,01	SM 17 udg. 4500	-	-				14		< 0,005	< 0,005		
49	Alkalinitet, total	mmol/l	0,01	DS/EN 1 9963	-	-									
50	VOC, flygtigt org. kulstof	mg/l	0,1	MK4261DS/EN1484	-	-				7,7		< 0,1	< 0,1		
51	Hydrogencarbonat	mg/l	3	DS/EN 1 9963	-	-				1400		< 3	< 3		
52	Nitrat	mg/l	0,5	SM 17 udg. 4500	-	-									
53	Sulfid-S	mg/l	0,02	DS 278:1/1976	-	-				140		< 0,02	< 0,02		
54	Magnesium (Mg)	mg/l	1	ISO17294m-ICPMS	-	-									
55	Kalium (K)	mg/l	0,2	ISO17294m-ICPMS	-	-				62		< 0,2	< 0,2		
56	Jern (Fe)	mg/l	0,01	ISO17294m-ICPMS	-	-				1,3		< 0,01	< 0,01		
57	Mangan	mg/l	0,01	ISO17294m-ICPMS	-	-									
58	Vanadium (V)	mg/l	0,5	ISO17294m-ICPMS	-	-									
59	PCB nr. 28	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
60	PCB nr. 52	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
61	PCB nr. 101	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
62	PCB nr. 118	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
63	PCB nr. 138	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
64	PCB nr. 153	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
65	PCB nr. 180	ug/l	0,01	MK2260-GCMS	-	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
66	Benzen, ug/l	ug/l	0,2	GC/FID	-	-				< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
67	Toluen, ug/l	ug/l	0,2	GC/FID	-	-				< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
68	Ethylbenzen, ug/l	ug/l	0,2	GC/FID	-	-				< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
69	m+p-Xylen, ug/l	ug/l	0,2	GC/FID	-	-				< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
70	o-Xylen, ug/l	ug/l	0,2	GC/FID	-	-				< 0,2	< 0,2	< 0,2	< 0,2	< 0,2	< 0,2
71	Chrom-6, ug/l	ug/l	0,1	ISO17294m-ICPMS	-	-				< 0,1	< 0,1	< 0,1	< 0,1	< 0,1	< 0,1
72	Chrom-3, ug/l	ug/l	0,1	Beregning	-	-				13	23	8,2	< 0,1	24	
73	Fortynding, ml/l	ml/l			-	-									
74	LAS	ug/l	100	HPLC	-	-									
75	Nitrifikat.hæm 1 konc/std.slam	%	20	ISO/9509	-	-									
76	Nonylphenoldiethoxylater	ug/l	0,1	MK0250-GC/MS	-	-									
77	Nonylphenoler	ug/l	0,1	MK0250-GC/MS	-	-									
78	Nonylphenolmonoethoxylater	ug/l	0,1	MK0250-GC/MS	-	-									
79	Sum Nonylphenoler+ethoxylater	ug/l	0		-	-									
80	Olje + fedt (total)	mg/l	0,1	DS/R209 mod.	-	-									
81	Suspenderede stoffer	mg/l	0,5	DS/EN 872	-	-									

Appendix J: Material Flow of Shredder Waste Treatments

Table 13: Material Flow of Shredder Waste Treatments

Process Name	Plastics	Metals	Fer. Met.	NF Met.	Foam	Org. Frac.	Gypsum	Coke	Gases	Inerts	RDF	Shredder Granules	Other Recycled
Argonne	27%	9.5%											
CTU Gasifier		6%	3%	3%			13%			67%			13%
EDDITH				5.1%				24%	40%	7.1%	24%		40%
Galloo	9%	30%	12%	18%							13%		
R-Plus		5%				60%				35%	60%		
Salyp	18%	19%	10%	9%	3%						46%		3%
SiCon		8%	5%	3%						22%	36%	36%	33%
Sult		10%	7%	3%		50%				20%	50%		20%
SVZ		8%								6%	74%		12%
TwinRec		8%									52%		25%
VTT Gasifier										49%	38%		

Process Name	Shredder Fibers	Glass	Water	Dust	Sludge	Overall Recovery	
Argonne							Jody, 2006.
CTU Gasifier				14%		86%	Nielsen et al, 2006.
EDDITH							Marty, 2002.
Galloo						90%	Schut, 2004 and Hjelmar, 2009.
R-Plus						92%	GHK, 2006.
Salyp						86%	Schut, 2009.
SiCon	31%		1.5%	1.5%	1.0%	95%	Ujsaghy, 2008 and Hjelmar, 2009.
Sult			20%			100%	GHK, 2006.
SVZ			12%			70%	Buttker, 2005.
TwinRec		25%				85%	GHK, 2006.
VTT Gasifier				13%		82%	Nielsen et al, 2006.

Appendix K: Plastics Separation Processes

A Cooperative Research and Development Agreement (CRADA) was established between the U.S. Department of Energy's Argonne National Laboratory, the United States Council for Automotive Research's (USCAR) Vehicle Recycling Partnership (composed of DaimlerChrysler, Ford, GM), and the American Chemistry Council's Plastics Division. The aim of this research partnership is to research and implement sustainable recycling solutions for materials in shredder residue (Daniels, 2006). This collaboration allowed Argonne to develop a two-step mechanical separation and froth flotation process for the recovery of pure single-plastic fractions from shredder residue. The process has enormous environmental and economic potential. If all the polymers from landfilled shredder residue were recovered in 2007, the market value would have been around \$500 million and saved billions of MJ of energy. The main benefits of the Argonne process include:

- Saving raw material by recycling plastics from the waste stream
- Capable of processing polymer concentrate with mixed wood and rubber fractions
- Reduces greenhouse gases and uses no hazardous materials
- Recovered plastics are a fully compatible replacement for virgin plastics
- Using recycled instead of virgin plastics results in cost savings over 25%
- Manufacturers can purchase plastics recovered from the Argonne process for half the cost of virgin plastics

A typical shredder residue stream contains between 25-40% of recoverable polymers made up of a few dozen plastics and half a dozen types of rubber. Thus, a mechanical separation process is necessary to concentrate and separate the polymers from the rest of the shredder residue (Argonne National Laboratory, 2007).

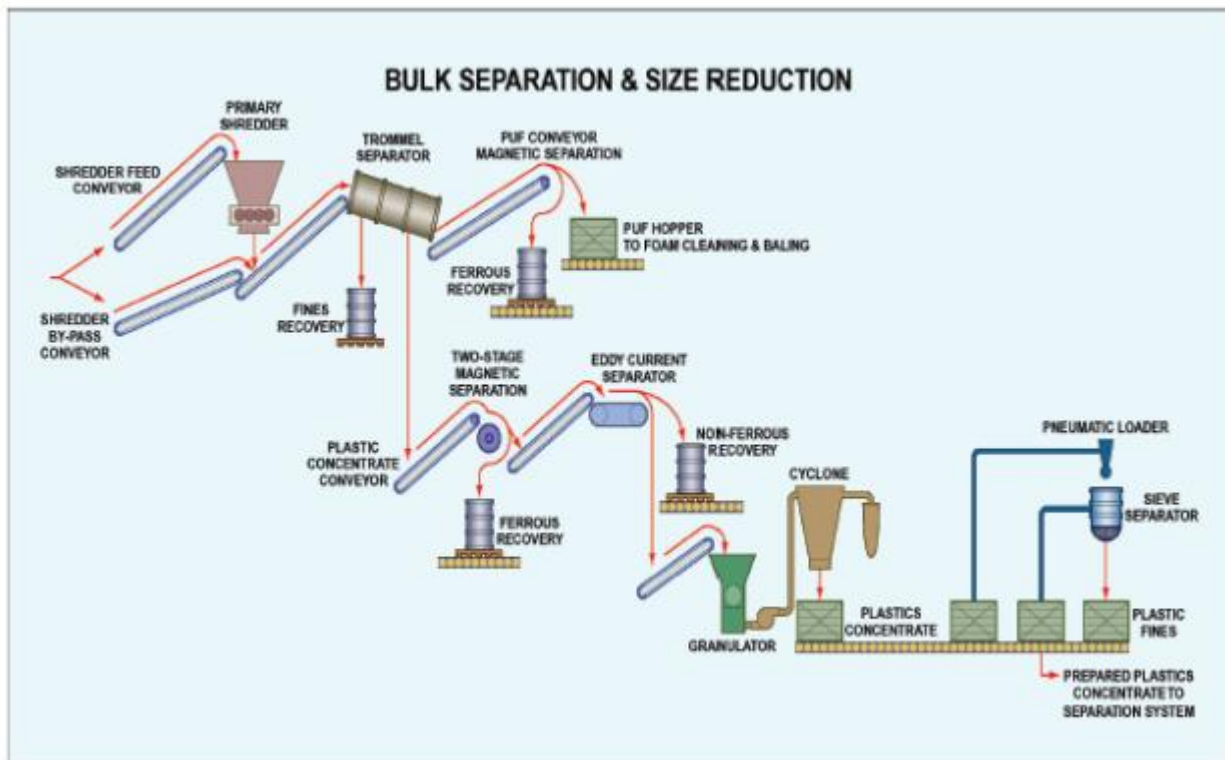


Figure 45: Argonne Bulk Separation and Size Reduction (Jody & Daniels, 2006)

The physical separation concentrates the shredder residue into four fractions: foam, ferrous and non-ferrous metals, polymers, and fines (Figure 45). Larger pieces of metals, rocks, and foam are screened by a trommel separator and separated from the residue stream. The remaining shredder residue is then shredded to smaller pieces and put into a two-stage trommel. Small particulates are removed first and in the second stage a fraction containing plastics, rubber, residual metals, and small foam pieces falls through the slots in the trommel. A larger fraction consisting mainly of polyurethane foam (PUF) exits the trommel and is passed over a magnetic pulley and an eddy current separator to recover residual ferrous and non-ferrous metals. The polymer-rich fraction is treated in the same way to recover and separate residual metals. The polymer-rich fraction is then granulated to an average particle size of 0.5-1 cm and put on a vibrating screen for further processing. The cyclone and air classification removes small residual PUF pieces, dust, and other fines (Jody & Daniels, 2006).

The fractions recovered from the mechanical separation process are all able to be reused or recycled in some way. Figure 46 shows the material flow of 10,000 lbs of ASR in Argonne's mechanical separation plant. The bulk separation of the residue results in a polymer concentrate that is about 45% of the ASR weight and 10% by weight PUF fraction. The remaining 45% by weight is grouped into an oxides fraction and includes metals, small

pieces of glass, dirt, and some organics. Argonne has a patented PUF cleaning system which allows for the use of the foam in producing carpet padding for automobiles. The oxide fraction has use in the cement industry. The polymer concentrate is processed at the froth flotation plant to recover and separate the plastics (Argonne National Laboratory, n.d.).

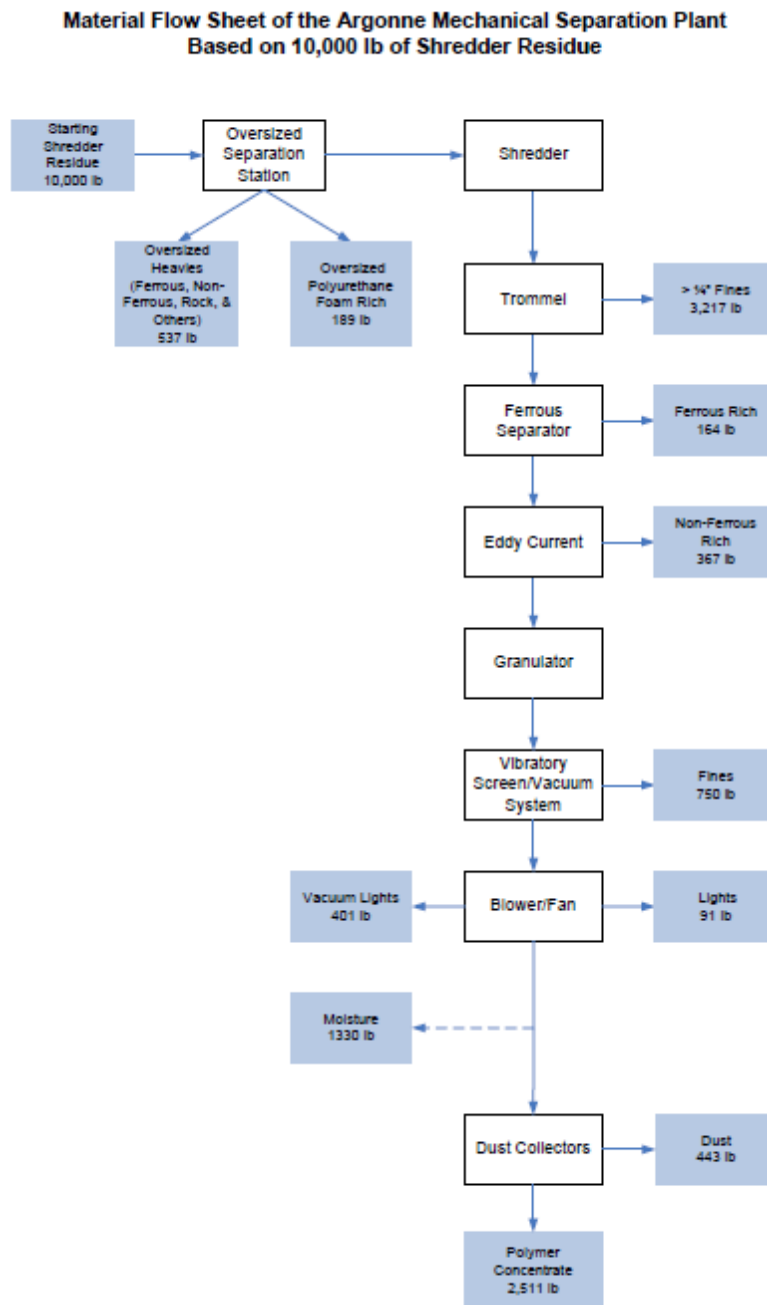


Figure 46: Material Flow of Argonne Mechanical Separation Plant (Gallon & Binder, 2006)

Argonne’s polymer recovery process involves a six-stage froth flotation system which enables the recovery of polyolefins (polypropylene and polyethylene), ABS, HIPS, nylons, and other plastics (Figure 47). The froth flotation technology was adapted from the minerals processing industry to allow for separation of ABS from HIPS. The separation tanks work to

recover plastics fractions based on their different densities. The plastics mixture is placed in a solution that will selectively enhance the hydrophobicity or hydrophilicity of a targeted plastics fraction. One part of the polymer concentrate sinks while the other floats, thus enabling simple separation. Since ABS and HIPS have the same density, surface modification is used to enable air bubbles to attach to the hydrophobic HIPS molecules, thus lowering their apparent density and causing them to float while the hydrophilic ABS molecules sink. Therefore, HIPS molecules are easily separated from the ABS fraction (Argonne National Laboratory, 2007).

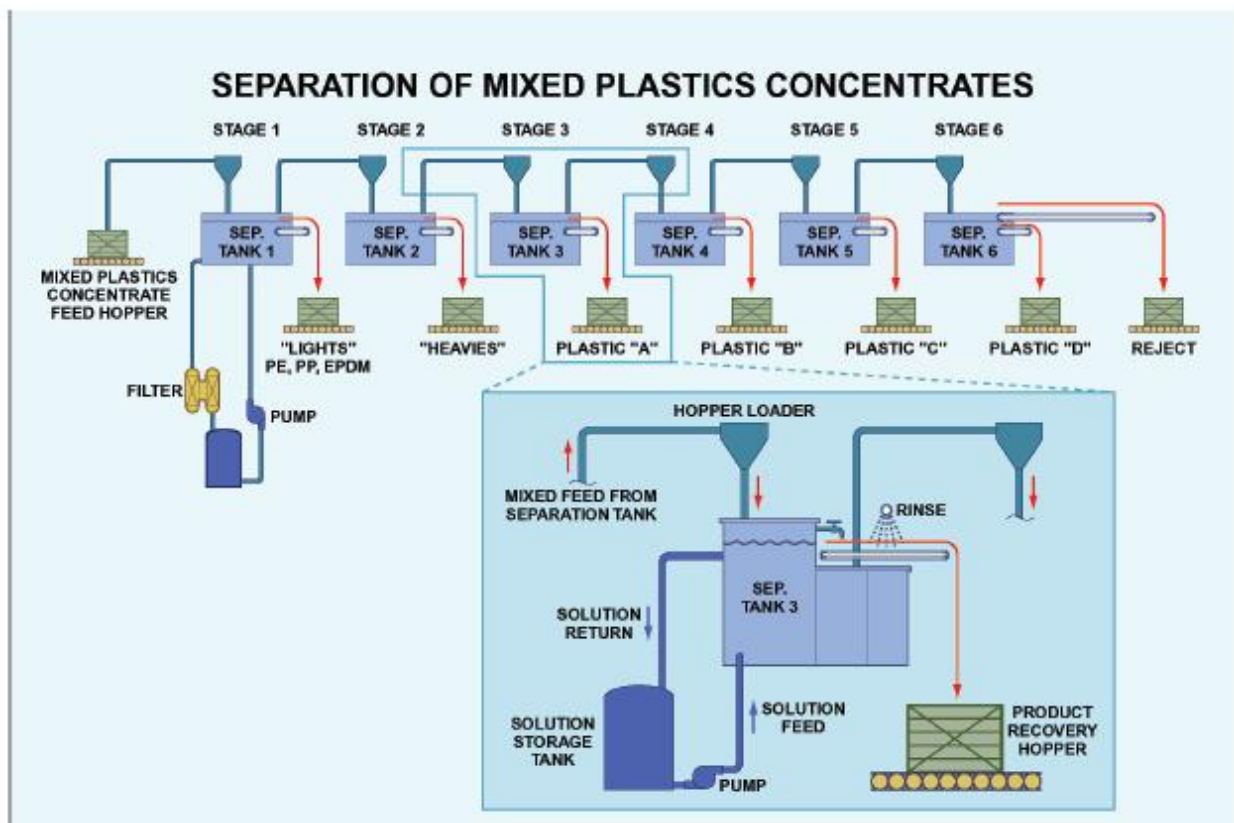


Figure 47: Argonne Plastics Separation (Jody & Daniels, 2006)

The material flow of the polymer concentrate through the froth flotation system can be seen in Figure 48. The recovery of pure fractions allows for the recycling of plastics into reusable products for the automobile industry instead of using virgin plastic materials. The whole Argonne process is environmentally beneficial as a Life Cycle Assessment of the process performed in 2006 concluded that using the plant results in “environmental benefits for primary energy demand, CO₂, SO₂, and VOC (volatile organic compounds) emissions and for the impact categories AP (acidification potential), EP (eutrophication potential), GWP100 (global warming potential), and POCP (photochemical ozone creation potential)” (Gallon & Binder, 2006).

**Material Flow Sheet of the Argonne Plastic Separation Plant
Based on 10,000 lb of Shredder Residue**

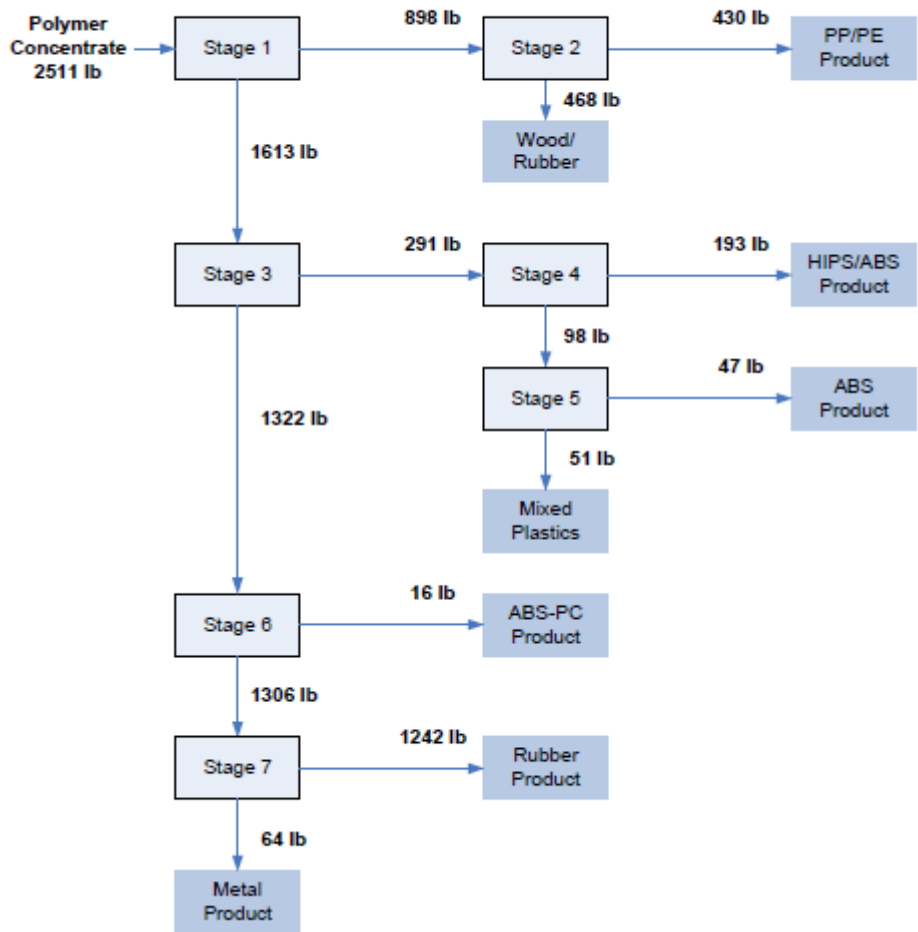


Figure 48: Material Flow of Argonne Plastic Separation Plant (Gallon & Binder, 2006)

Other plastics separation processes include Galloo Plastics, MBA Polymers, and EnviroPlastics' Plastic Conversion Technology (PCT). The Galloo Group is based in France and operates various recycling facilities, including 15 shredding operations in France and Belgium. They use a bulk separation process at three sites to recover residual metals still present in the shredder residue (Figure 49). The main fractions recovered from the process include a mineral fraction (40% by weight of the input), a light SR fraction (30%), a heavy SR fraction (15%), and a plastics fraction (10%). The remaining residues, representing about 5% of the input feed, include residual metals, PVC, and rocks.

The plastics fraction collected from the three bulk separation processing sites is sent to the Galloo Plastics recycling unit in France which has a commercial process for recovering polyolefins (PP and PE) as well as some polystyrene and ABS. Density and gravity separation processes are used to separate the different plastics fractions. To recover the polyolefin and polystyrene fraction, "static hydrodynamic" separation tanks are used and the

recovered plastics fractions are then compounded and pelletized. Special filters are in place to eliminate residual contaminants and clean the plastic fractions. Based on a 2002 test performed with 200 Peugeot and Renault vehicles, the Galloo Plastics process can recover about 50% of the polyolefin fraction. However, 20,000 tonnes of polyolefin pellet are produced at the plant every year and utilized by Peugeot Citroen. For instance, the polypropylene fraction is used to make wheel wells and battery cases for Peugeot cars (Jody & Daniels, 2006).

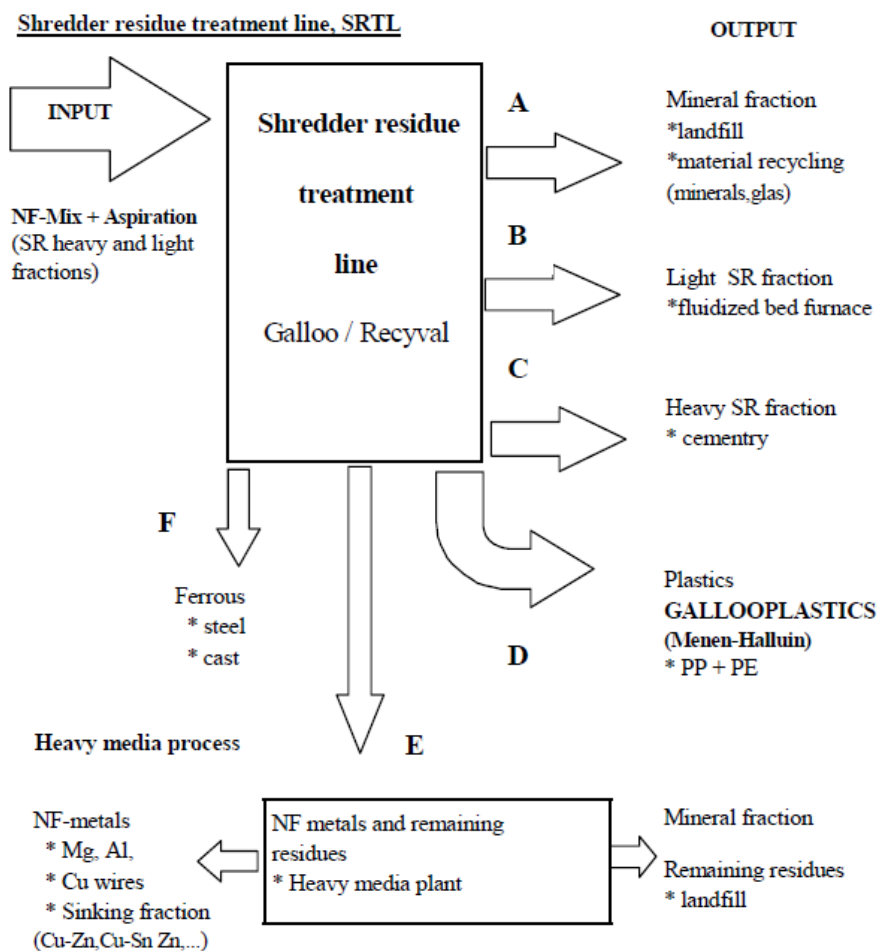


Figure 49: Galloo Shredder Residue Treatment Line (Lundqvist et al., 2004)

MBA Polymers is a California based plastics separation and recycling company that has collaborated with the American Plastics Council and Argonne National Laboratory. MBA Polymers developed a commercial-scale plastics separation and recovery process using physical and froth flotation separation techniques. Extensive research and large-scale test runs have been performed on automotive plastics from shredder residue. An important test run was an 18,000 kg test using plastics concentrates from Salyp. The concentrate was processed at MBA Polymer’s California processing line. The test yielded five fractions:

polyolefin “A”, polyolefin “B”, filled PP, ABS, and HIPS. Thus, the technology has been proven to be able to separate polyolefins, ABS, and HIPS from plastics concentrate. The recovered fractions represented about 48.5% of the plastics-rich polymer concentrate. Testing of the recovered plastics fractions revealed that their properties are “encouraging” and thus the “products could be used in some type of durable goods applications without modification”. MBA Polymers is expanding as it has created a joint venture for a plant operating in China and in Austria (Jody & Daniels, 2006).

SiCon GmbH, in addition to its VW-SiCon process, is developing other technologies including polyfloat for plastics separation. Developed in collaboration with Leiblein GmbH, the process allows for the separation of pure and marketable plastics fractions (SiCon GmbH Plastics, n.d.). The technology, shown in Figure 50, separates plastics fractions based on density by using a fluid density system. The plastics are 99% pure and the fraction yields are over 98%. The company builds polyfloat turnkey systems up to 5,000 kg/hr that include storage, feeding, drying, and electronic control (Henricks, 2009).

PROCESS OVERVIEW

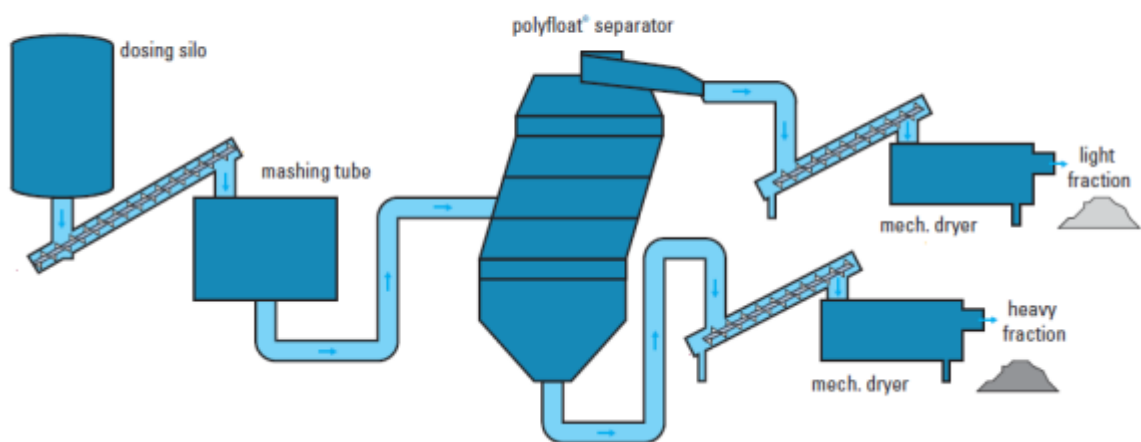


Figure 50: Polyfloat Process Overview (Henricks, 2009)

EnviroPlastics is a Washington state based company which utilizes a Plastic Conversion Technology (PCT) for plastics recovery. This promising technology will allow for the recovery of a foam and rubber stream that is converted into energy in the form of synthetic oil. A second, plastic-rich stream can be sent to a plastics compounder for recycling. The Plasti-Stract process will allow the PCT to remove plastics from ASR, while eliminating contaminants using a combination of two liquefied gases under pressure. Using sink/float technology the plastics concentrate is separated into three streams: polyolefines (PP and PE), ABS/HIPS, and mixed plastics. EnviroPlastics is constructing their system in

Wisconsin. Founder and President Gary de Laurentiis believes “the PCT process can extract all the plastics from ASR” (Sandoval, 2009).

Appendix L: Tire Recovery

Dismantler

During the ELV dismantling process, tires are removed and either stockpiled for remanufacturing or landfilled. Recently, ongoing research into recycling non-reusable tires from ELVs has reduced the amount of tires landfilled and developed awareness for the potential of the benefits that can come from recycling tires. A tire is considered non-reusable once it cannot fulfill its two primary functions: transportation in total safety (Michelin, 2004). The primary challenge for recycling tires is creating an efficient management system for collecting and recycling tires that will produce effective solutions which all countries can agree upon.

A tire is an inert material that remains stable for long periods of time, and because of their constant chemical and physical properties it is not considered a hazardous material. Therefore, besides the negative appearance that large stockpiles of tires can have, there has not been any motivation to encourage research into recycling alternatives for tires until recent European legislation. Since 2003, there have been 3 directives passed in Europe concerning landfilling tires, tires from ELVs, and tire incineration (Michelin, 2004):

- No whole tires in landfills as of July 2003, no shredded tires in landfills as of July 2006
- 85% of mass of ELV recycled as of 2006
- Older cement kilns will no longer be allowed to burn tires after 2008

Various systems have been implemented in many countries to facilitate end of life tire (ELT) recycling. In Denmark, a tax based system has been instituted that requires tire producers to pay a tax to the government who then are responsible for creating a system and paying the recyclers. Countries like Sweden, Norway and France have created a system in which the producers of tires are responsible in recycling the non-reusable tires. The producers must pay part of their sales income into a fund that specifically finances ELT recycling. A free market system has been applied in Germany and Italy where the tire distributor can work with an ELT recycler of their choice.

Current research has found that recycling tires can provide opportunities for recovering energy and material. Compared to coal, a tire can produce a comparable amount of heat energy at 30-34 MJ/kg and one tonne of tires can yield the same energy as a 0.7 tonnes of oil. There is a low amount of sulfur in tires (approximately 1%), but compared to

coal (5% sulfur content) tires are a beneficial fuel substitute in regards to the impact on the environment (Michelin, 2004).

In the United States and Japan, fuel derived from tires has been developed and used to produce electricity in power stations, industrial boilers, produce steam, in incineration units, as supplemental fuel, and mixed with domestic waste. Cement kilns require a vast amount of energy and ELT tires have been used because the carbon and steel in the tires can be integrated into the production of raw cement (Michelin, 2004).

In terms of material recovery, whole ELTs have been implemented to fill material in roads, retain structures, noise-abatement walls and shock absorbers along jetties and quaysides. Cut tires can be used as a supporting layer for railroad tracks to absorb noise and vibration and shredded tires can be applied as draining layers or light filling material in road construction. Tires in the granulated or powdered form can be molded into refuse containers, used to make surfaces for sports stadiums or playgrounds, or added to road surfaces to reduce tire to road contact noise and prolong the life span of the road surface (Michelin, 2004).

ASR Application

The use of fibrous constituents is a topic that has been researched by the Vienna University of Technology. They have created new technology by making the observation that ASR fluff fibers are similar to tire fibers in fiber length and width. Though further testing on a larger scale must be completed, the results have concluded that ASR fibers can be used as a substitute for tire fibers. Alternatively, a newer post shredder technology (PST) concept has evolved where the ASR is sieved and then used in making asphalt for road pavement. The fibers from the ASR compare with bitumen fibers, one of the main components in asphalt (Bartl, 2009). Mixing ASR with domestic waste for co-incineration in a cement kiln to produce raw cement is another avenue that should be researched. Ultimately, fibers that are similar with well-established marketable fibers can be derived from ASR fluff and may be suitable for all applications that ELTs are used for, but non-fibrous particles cannot be avoided and large scale testing must be done to prove the applicability of these technologies.

Appendix M: Gasification/Incineration Method from Mancini Report

The ASR feedstock entered into a rotary kiln with oxygen at temperatures ranging approximately at 850°C at the entrance to 1120°C in the afterburner chamber at the exit (Figure 51) (Mancini, 2010). Inorganic and metal material produced a melt which emptied the kiln into a slag removal and discharged. In order to maintain partial combustion for gasification and to enhance the conversion of solids to gases, the oxygen was controlled by two fans – the first located at the rotating chambers entrance to direct air to the bottom of the kiln and the second located at the afterburner chamber in order to control heat and oxygen flows during treatment.

The slag produced in the afterburner chamber is collected at the bottom of the chamber and removed at regular intervals and the flue gases emitted at the top of the afterburner chamber enter a boiler where their energy is used to generate steam. The gases are properly cleaned by dust collector to comply with legal limits set by the European Union. Dust collectors generally comprise of a blow, dust filter, a filter cleaning system, and a dust removal system. First, a cyclone mechanism removes dust from the flue gas and transports it to a filter to be removed. Then the gas enters into a fabric filter, commonly known as a baghouse, which uses filtration that can collect dust up to 99% efficiency. A mechanical shaker is usually implemented at the top of the bag to create waves in the bag and shake off the dust into a collection chamber at the bottom of the system.

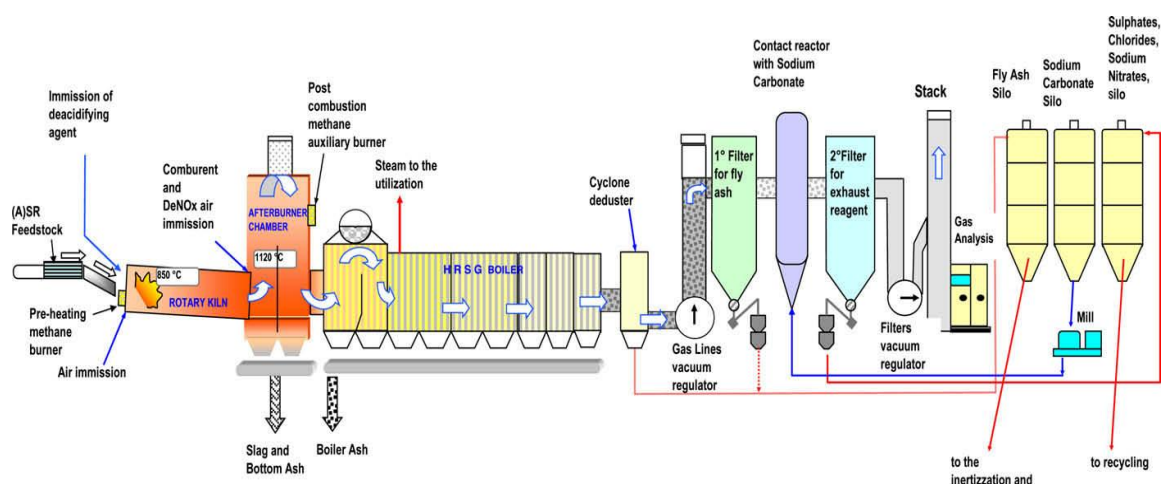


Figure 51: Sequential Gasification and Combustion for Co-processing of ASR (Mancini, 2010)

The steam measures approximately 43 bars and 430 °C and it is used to power a turbine which produces electricity for the thermal process. Ash, which produced from residuals contained in the flue gases, from the boiler is collect at regular intervals (Mancini,

2010). An induced draft fan then extracts the flue gases from the boiler into a cyclone where dusts that are contained in the flue gas are removed by the cyclone mechanism. The gas stream then is sent into a dual bag filtration system that is aimed to remove fly ash that is remaining from the cyclone, acid gases and sulphur oxides. A second induced draft fan is located after the second filtration system to remove flue gases and emit them into the atmosphere at the strict European Union limits (Mancini, 2010).

The full scale experiment was tested for up to 40 hours of continuous shredder residue feeding at an average rate of 2400 kg/hr. The experiment had three different compositions for testing: 70% ASR/30% SR, 30% ASR/70% SR, and 100% ASR. All three streams were analyzed since there is an emphasis on co-incineration in this report. The exhaust gas compositions were measured at two separate locations: before bag filtration and at the chimney. Hydrochloric acid, nitric oxide, and nitrogen oxides were found in the flue gas before filtration. Pollutants detected in the exhaust included H₂O, CO₂, CO, NO, NO₂, NO_x, HCL, HF, SO₂, NH₃, and N₂O. Samples from the exhaust were also tested for other hazardous materials which included Cd, Tl, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, and Hg. The bottom slag and fly ash residues produced from combustion were also analyzed according to plant regulations and leaching tests were performed as well.

The results from the experiment showed that all three ASR compositions had a high percentage of undefined material. Very fine material, < 20mm, constituted more the 50% of the undefined part. In regards to ASR fines, the undefined portion consists of organic fractions, iron oxide, and inert materials like sand, small amounts of glass, stainless steel, copper, aluminum, zinc and lead. Each of the streams contained similar amounts of the inert fraction, but 70% ASR/30% SR stream contained the greatest amount of plastics at 24% (Mancini, 2010). However, the 100% ASR stream which is similar to the aforementioned stream in content has a much lower percentage of plastics and is much more similar to the 30% ASR/70% SR stream. These results represent the highly heterogeneous nature of ASR and indicate the difficulty in identifying a strict definition for the composition of ASR. It also explains the complexity in developing a process for co-incineration since there are always fluctuating amounts of different materials. Appendix P shows detailed tabled results for material composition from the experiment as well as experiments from other reports from 1995 to 2007. Appendix O conveys three tabled results from the experiment and literature research concerning an elemental analysis, the metallic contaminants and other contaminants that were present in the three ASR samples. Larger material size was found to produce lower residual ash content and a higher calorific value (Mancini, 2010). In regards to environmental

impact, the results showed high chlorine levels, particularly in the form of HCl, dioxans, furans, and other chlorinated compounds, which can cause corrosion to the equipment.

Contamination levels of metals such as Pb, Cu, Ni, Hg and Zn were measured, thus methods for lowering concentration levels would need to be established throughout the entire ELV process. Cu wires are generally intertwined with other materials and can be recovered more efficiently during the dismantling and shredding process. Other pollutants such as PCB's found in plastics are regarded as one of the most problematic and hazardous materials in ASR and are a concern when developing marketable materials or fuel with ASR. Mineral oils representing values higher than 0.1% in ASR distinguishes ASR as hazardous waste which limits landfill disposal. Finally, ASR release Persistent Organic Pollutants (POPs) which are organic compounds that are resistant to environmental degradation by chemical, biological and photolytic processes and must be taken into account during the combustion process (Mancini, 2010).

In regards to PCB, Argonne has successfully developed a proven process to remove PCB's from plastics. A Soxhlet method was chosen because of its simplicity and because it is an approved method by both U.S EPA and European protocols (Jody, 2009). A Soxhlet method is used when a compound, such as PCB, has a limited solubility in a solvent, and the impurity, or the contaminated plastic, is insoluble in the specific solvent. Argonne tested two solvents, hexane and toluene; hexane proved to be more efficient by extracting larger samples of PCB in less time. Furthermore, sample sizes as small as 30 grams proved to be adequate, thus smaller fines resulting from gasification processes are applicable with this method (Jody, 2009).

Appendix N displays a table with the characterization of solid residues that were collected from the different locations throughout the plant with the hazard waste limits set by the Directive. The main components present in the solid residue predominately included ferrous and non-ferrous metals, char and granulated or powdered inorganics. The highest concentrated metal in the residue was lead and zinc and copper. Lower concentrations of chromium, cadmium, selenium and arsenic were found, but their concentrations varied between the different collected solid residue streams.

From the total ASR processed slag constituted about 18% and ash from the exhaust represented approximately 3% (Mancini, 2010). Based on regulations, the slag was classified as non-hazardous and leaching tests were done on the collected bottom and fly ash from various sections of the plant and each of those streams were classified as hazardous.

Appendix Q illustrates the exhaust emissions from the three different compositions. The analysis conveys that nitrogen oxides, sulfur oxides, hydrochloric acid and other various organic compounds are the primary pollutants of concern. Peak fluctuations from graph to graph are a result from different experiments changing operational conditions (i.e. varying oxygen levels) and altering feed compositions. No significant amounts of metals were found in any of the flue gas emissions and carbon monoxide and dust emissions were well below the legal limits.

In terms of energy recovery, a combustion rate of 2.5 kg/hr was able to produce 9 to 11.5 tons of steam with an electric energy production varying between 2.5 and 2.6 kW. Shredder residue produced calorific values over 13000 kJ/kg. Combustion analysis and energy recovery tests yielded 11 MW of thermal energy input to the plant, a production of 3.2 electric MW and an internal energy consumption of 0.5 electric MW. The potential of achieving approximately 0.9 MW h/ton of processed ASR which would grant 36 GW h of electric from 40,000 tons of treatable ASR (Mancini, 2010).

Ultimately, the technical, legislative, commercial and financial parameters surrounding alternative processes for ASR treatment create difficulties for development, thus the reason for so few effective processes currently implemented. This study provides a clear example for an effective and applicable process for treating ASR while limiting the environmental impacts. It also supports the application of co-incinerating ASR and household waste which appears to be an effective alternative to landfilling ASR. High NO_x concentrations in the exhaust can be controlled by proper combustion air management and all other organic contaminants were measured below the required legal limits. Even though further research should be undergone to acquire more concrete results, this study provides a useful environmental analysis for ASR treatment methods.

Appendix N: Characterization of Solid Residues

Parameters	Directive 09/04/2002 Hazard waste limit	U.M.	Present experiments							Lee (2007)					
			Slag	Slag (boiler entrance)	Bottom ash	Fly ash (boiler)	Fly ash (boiler ash belt)	Fly ash (boiler clapet)	Fly ash (ash propeller)	Fly ash (bag filter)	Media bottom	Cyclone	Boiler	SDR	Bag filter
Residue at 105 °C	-	%	99.96	99.87	75.90	98.78 ± 1.53	99.76	99.96	99.8 ± 0.2	99.74					
Residue at 600 °C	-	%	99.60	97.23	86.48	92.07 ± 3.98	92.94	93.40	93.06 ± 1.57	85.01					
Bulk density	-	kg/dm ³	1.11	1.01	0.92	1.71 ± 0.83	1.20	1.20	1.105 ± 0.25	0.95					
TOC	-	mg/kg	<1,000	4,800	49,000	46350 ± 14071	25,800	14,700	74750 ± 15910	97,800					
Aromatic solvent	1.000	mg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5					
Chlorinated solvent	1.000	mg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5					
As	1.000	mg/kg	3.80	43.92	22.53	52.52 ± 13.86	31.82	24.35	39.64 ± 4.89	51.38	11.5	12	38.4	10.7	20.4
Cd	1.000	mg/kg	1.59	128.27	2.55	151.87 ± 63.52	50.38	5.71	197.45 ± 55.24	297.09	<1	7	110	16	105
Cr (total)	-	mg/kg	35.3	109.1	306.2	273.77 ± 7.90	325.8	419.1	49.63 ± 2.19	58.2	11.75	9.7	10.2	6.5	5.4
Cr VI	1.000	mg/kg	5.89	0.46	0.91	7.05 ± 1.07	2.47	<0.15	1.605 ± 0.97	2.48					
Cu	250.000	mg/kg	3,333	747	32,424	2148 ± 1049	13,334	53,570	1343 ± 961	1,209	30500	2800	3400	1200	4600
Hg	1.000	mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1					
Ni	1.000	mg/kg	169.2	92.1	265.5	257.89 ± 8.25	258.1	363	53.26 ± 6.42	73					
Pb	30.000	mg/kg	188	1.814	3.824	21032 ± 9457	6.000	6.447	10323 ± 652	21.478	570	1400	12,000	4700	9600
Se	30.000	mg/kg	0.56	1.59	3.78	17.37 ± 10.15	7.24	3.90	12.88 ± 7.66	11.34					
Zn	250.000	mg/kg	7.123	325.928	14.727	268,856 ± 22,053	180.493	38.855	703,725 ± 51,854	655.567					
PCB	1.E + 06	µg/kg	38.54	29.08	5.15	5.41 ± 0.32				8.94					
PCDD/PCDF	1.E + 09	ngTE/kg	1.017	1.006	28.761	98.28 ± 107.62				27.176					

Figure 52: Characterization of Solid Residue (Mancini et al., 2010)

Appendix O: Elemental Analysis and Contaminants in Slag

Elemental analysis.

Parameters	U.M.	Fluff #1	Fluff #2	Fluff #3	Saxena et al. (1995)	Shen et al. (1995)	Rausa and Pollesel (1997)	Patierno et al. (1998)	Galvagno et al. (2001)	Kondoh et al. (2001)	APAT (2002)	Mirabile et al. (2002)	Hwang et al. (2008)
Ash	wt.%	54.4 ± 6.9	20.2 ± 15	44.7 ± 4.9	43.2	58.1	12.1	-	-	23	-	36.2	-
C	wt.%	33.7 ± 0.3	64.3 ± 1.1	36.3 ± 1.3	39.7	29.70	56.6	17.5	37.2	60.2	48.11	49.5	20.2
H	wt.%	4.2 ± 0.2	7.9 ± 0.3	4.67 ± 0.2	4.6	4.00	7.9	2.1	4.8	6.6	6.07	5.3	1.3
N	wt.%	-	-	-	0.92	0.90	2.7	0.5	-	1.7	-	4.5	0.8
O	wt.%	-	-	-	11.8	-	21.4	17.4	1.5	7.8	-	6.9	-
S	wt.%	0.63 ± 0.10	0.62 ± 0.02	0.28 ± 0.03	0.25	0.30	0.2	0.25	0.4	-	0.3027	0.2	0.7
Cl	wt.%	1.822 ± 0.411	4.660 ± 0.978	0.943 ± 0.155	-	-	-	0.005	2	2.5	-	0.5	3
F	wt.%	0.20 ± 0.003	0.009 ± 0.006	0.017 ± 0.002	-	-	-	-	-	-	-	-	-

Table 5

Metallic contaminants.

Parameters	U.M.	Fluff #1	Fluff #2	Fluff #3	Galvagno et al. (2001)	APAT (2002)	Mirabile et al. (2002)	Grilc and Fabjan (2005)	APAT (2006)	Jalkanen (2006)	Hwang et al. (2008)
As	mg/kg	15.9 ± 3.9	4.10 ± 0.5	8.4 ± 1.2	-	4.17 ± 0.81	-	10-20	0.01 ± 0.01	-	-
Cd	mg/kg	22.2 ± 8.5	15.2 ± 2.5	12.9 ± 2.8	45	22.9 ± 4.0	62.50	31-60	31.3 ± 24.5	-	-
Cr (total)	mg/kg	209 ± 38	37.2 ± 1.3	257 ± 0.14	162.5	149 ± 22	360	727	136 ± 59	6000	-
Cr VI	mg/kg	4.9 ± 1.1	1.6 ± 0.7	4.1 ± 0.5	-	-	-	-	<0.05	-	-
Cu	mg/kg	2.856 ± 2.249	5.747 ± 8.800	8.831 ± 4.757	15.400	25.867 ± 7.485	19,994	1533-4376	12.284 ± 8.741	17,000	2500
Hg	mg/kg	0.213 ± 0.067	0.113 ± 0.023	0.12 ± 0.02	3	<1	-	<1	<0.05	-	-
Ni	mg/kg	257 ± 108	33.0 ± 6.1	166 ± 27	112.5	69.2 ± 17.2	797.5	443-650	260.38 ± 127.82	950	-
Pb	mg/kg	2.458 ± 258	2.167 ± 394	2.205 ± 117	3217.5	2.007 ± 768	4635	6480-11,590	6.191 ± 4.446	6000	3400
Se	mg/kg	2.2 ± 1.6	2.4 ± 1.8	0.54 ± 0.2	-	-	-	-	<0.01	-	-
Zn	mg/kg	19,439 ± 1,974	6,646 ± 1,195	12,881 ± 5,354	5,050	3,493 ± 242	22,175	20,470-32,820	6,833 ± 4,288	17,500	33,100

Table 6

Other contaminants.

Parameters	U.M.	Fluff #1	Fluff #2	Fluff #3	APAT (2002)
IPA	mg/kg.	12.2 ± 1.4	7.34 ± 1.3	5.58 ± 1.6	5.83 ± 2.67
PCB	mg/kg	13.2 ± 2.0	24.3 ± 5.7	7.93 ± 1.7	44.45 ± 34.06
PCDD/PCDF	ngTE/kg	7.0 ± 2.9	4.68 ± 1.1	3.02 ± 0.5	56.75 ± 44.64
Mineral oil	g/kg	21.5 ± 5.2	20.3 ± 7.1	22.3 ± 3.5	-

Figure 53: Elemental Analysis and Contaminants in Slag (Mancini et al., 2010)

Appendix P: Materials Contained in Fluff Feedstock

Material	Fluff #1 (70% ASR)	Fluff #2 (30% ASR)	Fluff #3 (100% ASR)	Saxena et al. (1995)	Das et al. (1995)	Lanoir et al. (1997)	Sakai et al. (2000)	Maurino (2000)	Staudinger and Keoleian (2001)	Galvagno et al. (2001)	Mirabile et al. (2002)	Ambrose et al. (2002)	Marco et al. (2002)	Kakimoto et al. (2004)	Zolezzi et al. (2004)	Boughton and Horvath (2006)	Forton et al. (2006)	Harder and Forton (2007)	Nourredine (2007)	de Marco et al. (2007) ^b	de Marco et al. (2007) ^c
Fine material < 10 mm, fine material < 20 mm ^a	30.3 56.03	64.98 78.52	53.5 69.58	-	-	-	62	-	20	35	-	13	6.1	4.88	-	15-20	-	25-75	-	75	6.1
Foam	0.29	0.07	0.26	43	4.4	35.3	-	-	-	-	-	15	3.3	-	-	-	8.9	-	-	-	-
Fabric, fibres	2.4	10.6	12.27	7	42	-	-	-	-	25	-	-	11	1.61	10-40	-	-	-	10	8	10.5
Soft plastic, hard plastic	0.11 24.71	0.11 8.37	0.26 13.35	8.6	19.3	11.7	21	60	31	20	41	33	29	6.06	19-31	20-30	14	15-20	41	7.5	27.6
Rubber/elastomers	8.19	0.95	1.42	2.7	5.3	2.6	12	10	8	20	21	18	9.7	2.34	10-30	10-20	2.3	-	21	4.1	35.1
Wiring/ceramic and electric material	0.67	0.16	0.44	-	2.1	4.7	-	2	-	-	3	5	0.7	-	-	-	1.5	-	3	0.4	0.7
Ferrous metals, non-ferrous metals	0.11 0.25	0.29 0.18	1.1 0.29	6.4	-	8.8	5.6	3	-	-	-	3	-	-	-	2-7	2.7	-	-	-	-
Glass	0	0	0	2	0.128	-	-	25	12	-	16	-	-	0.8	-	5-10	-	-	16	-	-
Wood, paper, cardboard	6.93 0.14	0.53 0.22	0.63 0.41	4.4	10.8	-	-	-	-	-	-	3	5.6	0.47	2-5	-	0.8	15-20	-	-	-

^a Including the <10 mm fraction.

^b Light ASR

^c Heavy ASR

Figure 54: Materials Contained in Fluff Feedstock (Mancini et al., 2010)

Appendix Q: Stack Emissions for Gasification and Incineration

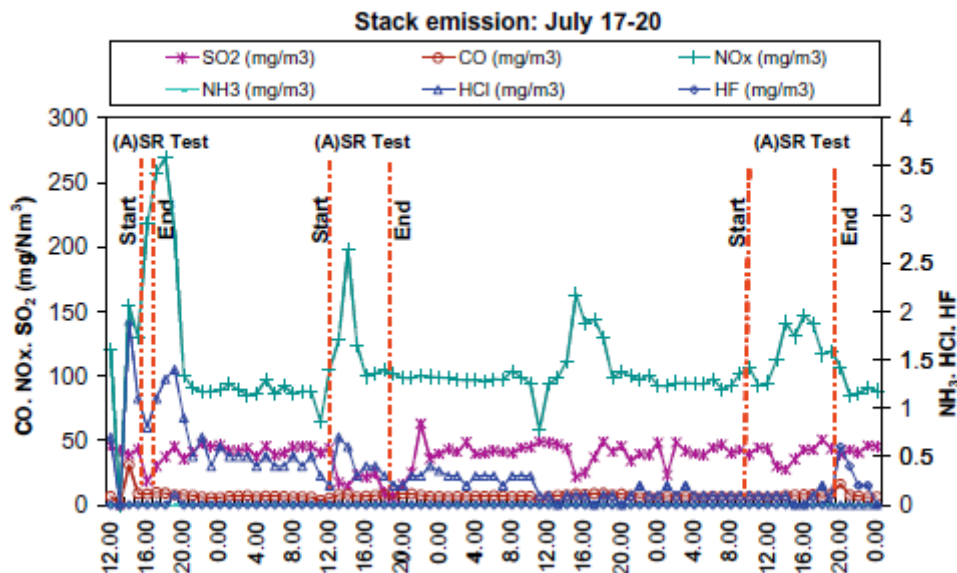


Figure 55: Stack Emissions for 70% ASR/30% Household Waste

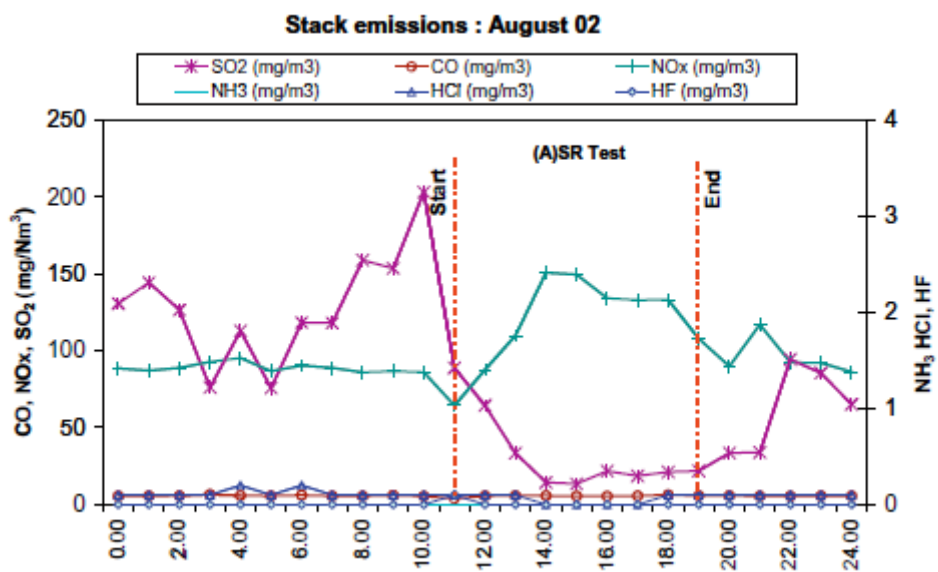


Figure 56: Stack Emissions for 30% ASR/70% Household Waste

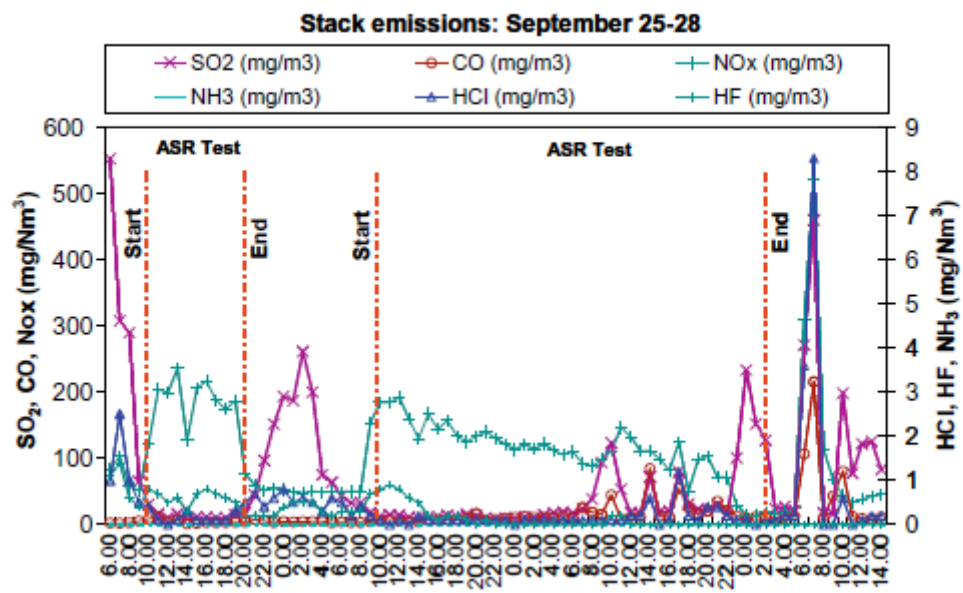


Figure 57: Stack Emissions for 100% ASR

Appendix R: Glass Recycling

Approximately 495,000 tonnes of automotive glass is generated each year from dismantling ELVs. Automotive glass accounts for approximately 3% of an ELV which means that recycling as much glass as possibly is critical in reaching the 95% reuse and recovery goal. Recycling automotive glass can be challenging though because of its complex chemical composition which includes:

- Silicon dioxide 69-74%
- Sodium oxide 12-16%
- Calcium oxide 5-12%
- Magnesium oxide 0-6%
- Aluminum oxide 0-3%
- Additives such as iron can also be measured from window tinting (Lundqvist et al., 2004)

After glass is removed from an ELV it is processed to produce a cullet, which is a result from being crushed and refined to remove the metal wiring (for defrosting) and the plastic interlayer's that are used to keep the glass together as a safety measure if it were to break (Lundqvist et al., 2004).

Trienekens Rohstoff GmbH & Company in Nivenheim, Germany is the largest recycling facility in world and they process 35,000 tonnes of glass a year which is approximately half of what all five facilities that comprise the company jointly processes (Lundqvist et al., 2004). They process recycled automotive glass to be used in the following applications:

- Mineral wool industry
- Bottle glass industry
- Grinding products, construction material, glass beads, side rails
- Foam glass

Energy savings from glass is small when compared to other materials. Recycling 1kg of glass will result in the same amount of energy saved as recycling 180g of newspaper, 150g of steel or 12g of aluminum (Lassesson, 2008). Figure 58 compares the energy savings between glass and 3 other materials.

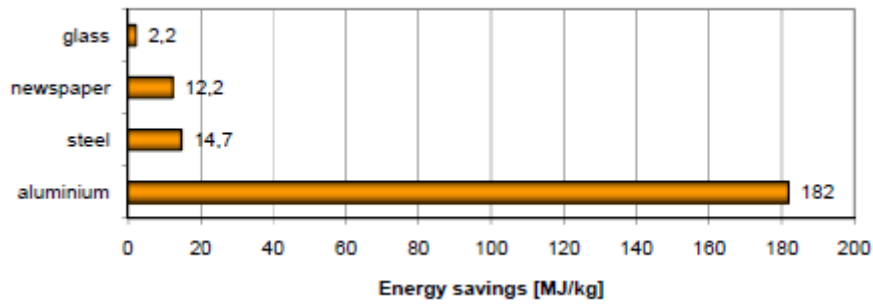


Figure 58: Energy Savings from Recycling (Lissesson, 2008)

Since energy savings from glass is very small compared to the energy saved from other materials, a thorough economic analysis should be conducted weighing the cost benefits of economics versus environmental benefits. Glass can be used in a number of marketable ways and the techniques that are implemented must be as efficient as possible to maximize these markets.

Appendix S: VW-SiCon process

Formed in 1996, SiCon is a very small company that focuses on shredder residue (Fischer, 2006). In 2008, SiCon had a team of only 12 people, but its strong partnership with Volkswagen, as well as with car manufacturers, shredder operators, and the metal recycling industry, allows it to expand its customer list and ensure the sale of products on the market (SiCon GmbH Productions, 2008). The joint venture with Volkswagen started in 1998, when VW chose SiCon's system for mechanical processing of shredder residue. The first full-scale commercial plant using the VW-SiCon technology was opened in Belgium in 2005 (Fischer, 2006). In addition to the VW-SiCon process, the company is developing other shredder residue treatment processes including FinesTuning for treating the SLF sieve fraction, ReEnvision for the production of hydrogen and syngas from shredder residue, and polyfloat to separate plastics fractions. SiCon's poolyfloat process is discussed further in Appendix K under the plastics separation section (SiCon GmbH Productions, 2008).

The VW-SiCon process employs a multitude of mechanical treatments. It is very important that dismantlers execute their job properly and remove all fluids, especially, oils from the ELVs before sending them to a shredding facility. After magnets remove the ferrous fraction and the residual metals are removed from the ASR, the remaining residue stream undergoes a combination of crushing, chopping, hammering, blowing, mixing, and screening. This stage ensures that the ASR is separated according to optical characteristics and properties such as density, particle size and shape, and magnetic content. The separated granule, fiber, and sand fractions are transported in clear plastic tubes to refinement units. The homogeneous products are then collected in trays, ready for further treatment or sale as marketable products (Fischer, 2006). The SiCon process is environmentally friendly as a 2006 Life Cycle Assessment study conducted by Volkswagen AG concluded that, compared to dismantling with mechanical recycling, the VW-SiCon process is 6-29% better with regards to environmental impacts such as global warming potential or acidification potential (Krinke et al., 2006).

SiCon involves potential customers in the development and testing process to ensure that the recovered products meet their specifications and will be useful. The recovered metal fractions are sold to smelters. The shredder granulate is a mixed plastics fraction that has a low chlorine and metal content. Thus, it can be used instead of heavy oil as a reducing agent in blast furnaces. In addition, the polyfloat technology allows for the separation of the mixed plastics and further use as a raw material for making new plastics products. The shredder

fibers fraction is a mix of textile fibers and seat foam that is mainly used instead of coal dust in the treatment of sewage sludge. Research has also shown that the properties of the fraction may allow the use of fibers as a fuel. The shredder sand fraction makes up a substantial fraction of the ASR and includes glass, fine iron particles, rust, fine copper wires, and dust. The fraction can be used to fill old mine shafts. A potential use being researched involves separating the shredder sand fraction at high temperatures. The sand melts while oil and other contaminants burn. This leaves residual metals and melted black glass, which can be used in countertops and floors (ARN, n.d.). Figure 59 shows the SiCon machinery in the top-right picture, the refined shredder granules in the middle right, and shredder fibers in the bottom right picture.



Figure 59: Products from the SiCon Process (Fischer, 2006)

Although SiCon has implemented its process into plants in Austria, Belgium, France, and Germany, the most recent development is occurring in the Netherlands. In 1995, Auto Recycling Nederland (ARN) was formed by car dismantlers, car manufacturers and importers, car dealers and workshop, and damage repair companies. Of the 300 dismantlers in the Netherlands, 253 are ARN member companies, processing 85% of all Dutch ELVs. This

extensive network enabled the Netherlands to recycle and recover 85.6% of their ELVs in 2008. ARN acquired a licensing contract from VW and SiCon designed the production plant that is being constructed in Tiel (Beck, 2009). After numerous setbacks and delays, construction work started on July 1, 2008. The plant is expected to be operational by the middle of 2010 at the Tiel, Netherlands site. Initially, only 35,000 tonnes of just ASR will be processed. However, the plant is expected to start full operation of shredder residue processing in 2011, with a capacity of 100,000 tonnes/year. The process should allow the Netherlands to achieve about a 90% recycling and recovery rate by 2011 with further developments being researched and implemented to enable 95% recycling by 2015 (ARN, n.d.).

Appendix T: Chinook Gasification

Chinook Sciences, Ltd. recently partnered with European Metal Recycling Ltd. (EMR) with plans to use Chinook's universal gasification system for ASR processing. The joint venture is called Innovative Environmental Solutions UK Ltd. and is to process 120,000 tonnes of ASR a year using the patented RODECS gasification system, beginning operations in 2010. Chinook Sciences, founded in 1998, is based in New Jersey and is a leader in the development of advanced gasification technology. Its' RODECS system is the only industrial-scale universal gasification system. EMR is a leading recycling company and Europe's largest recycler of automobiles. The system's gasification of ASR is projected to provide electricity to power 21,000 homes and to reduce greenhouse gas emissions by 300,000 tonnes (Chinook Energy, 2008).

The RODECS gasification system is perfect for the waste-to-energy industry because it can process a variety of heterogeneous material with no pre-processing necessary. Chinook's ActivePyro, a non-incineration system, implements the RODECS gasifier to break down organic material. The temperature range of the processing chamber varies from 450-600 °C, depending on the waste input. In this temperature range non-ferrous metals are not oxidized and no slag is produced. The syngas generated by gasification is heated at a range of 1200-1400 °C to destroy most of the harmful substances. The syngas can then be fully combusted to generate steam in a boiler or it can be used to create liquid alcohol (Chinook Energy Technology, 2008). The system has a double-loop cycle to keep pollutants released from the waste stream under control during the whole gasification process. Figure 60 illustrates the schematics of the process, showing the various input feeds as well as the products (Chinook Energy, 2009).

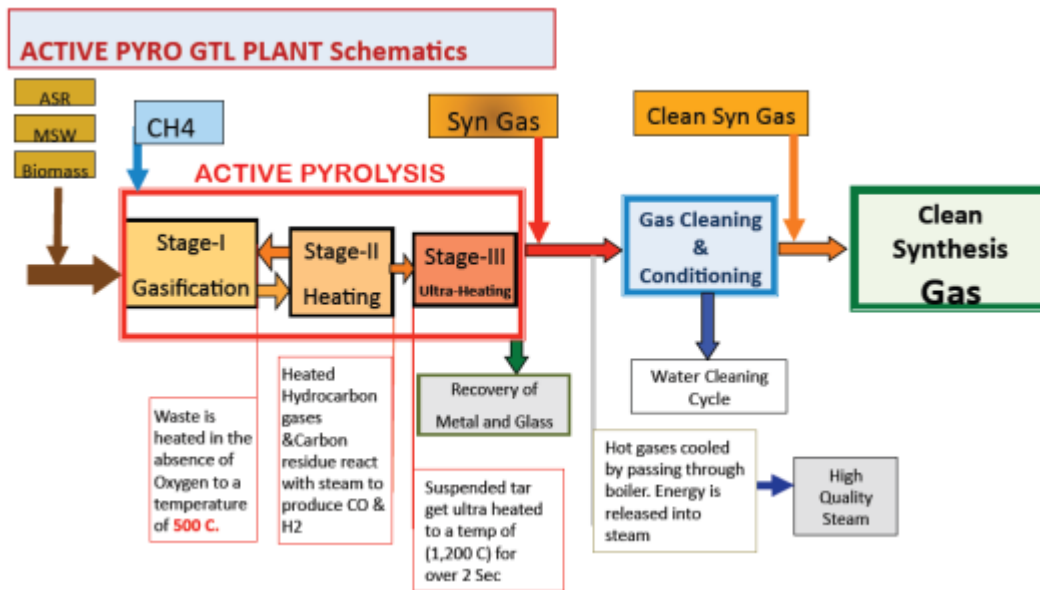


Figure 60: Chinook Plant Schematics (Chinook Energy, 2009)

The RODECS system is able to process scrap metal, MSW, electronic waste, industrial waste, and has been successfully tested for ASR processing. The double-loop cycle ensures that Chinook’s process is able to comply with various emissions standards world-wide. Figures 61 and 62 show that the Chinook’s emissions values are much lower than the US and UK standards. The technology also has a large negative carbon footprint in comparison to landfilling of the shredder residue (Chinook Energy, 2009).

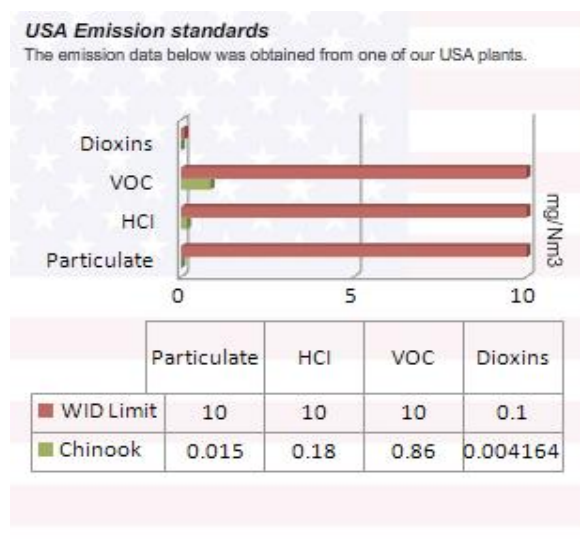


Figure 61: US Emissions From Chinook Process (Chinook Energy, 2009)

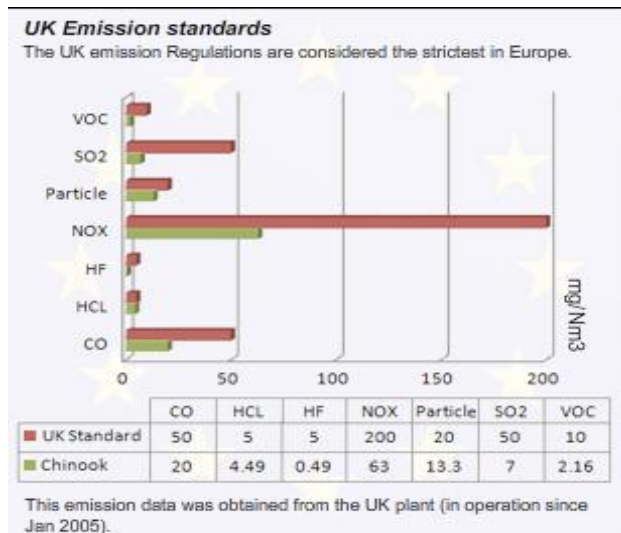


Figure 62: UK Emissions from Chinook Process (Chinook Energy, 2009)

Chinook Energy is developing two energy plants in Europe and has a facility in the United States. The plant in the Eastern US has a capacity of 160,000 tonnes of ASR per year. The facility has a long-term agreement with a major automobile recycler for a steady supply of ASR (Chinook Energy, 2009). The joint venture with EMR in the UK resulted in a proposal to build a processing plant which would recover metals, aggregates, and some plastics. The full capacity is projected to be 190,000 tonnes/year. About 138,000 tonnes of post-processing material, including wood, foam, and plastics, would be processed with the RODECS gasification system. The process would generate 30 MW hours of electricity and less than 6,000 tonnes are expected to be sent to the landfill. In addition, EMR is developing a plastics reprocessing plant with MBA Polymers to be operational in 2010 (“EMR Plans”, 2009).

Appendix U: Types of Gasifiers

Circulating Fluidized Bed Gasifiers (CFBG)

Air, oxygen, and steam are used to operate these gasifiers and control the high turbulent mixing zone to enhance the heat and mass transfer which quickens the gasification process. A fraction of the fluidized material is circulated throughout the gasifier bed which aids in maintaining steady state conditions and also removes some residual bottom ash. Additionally, the fast fluidization in the gasifier increases the residence time of the ash so more can be removed at the end of the reaction for slag production or possible land uses, but uses vary depending on the material in the ash. The remaining ash is extracted from the bubbling system. Ultimately, a CFBG is optimized to produce syngas. Technologically advanced gasifiers can produce a clean syngas that can be converted directly into electricity for generating heat or used in the chemical industry as base components for producing methanol and ammonia. Less efficient gasifiers produce syngas that potentially contain hazardous material, therefore additional cleaning is required and in some cases a desulfurization process may be implemented. Activated carbon can also be implemented since it has a very large surface area from its porosity. Small particles are required in the feed for a CFBG because they allow for a large gas-solid contact surface. High gas velocities and solid dispersion within the gasifier promote the contact of gas and allow for the heat and mass transfer to take place.

Entrained Flow Gasifiers (EFG)

The EFG is a more complex system and requires a much smaller inlet particle fraction and moisture content than the CFBG and it results in a higher quality effluent syngas. There are two types of EFG's: slagging and non-slagging. For the purpose of treating ASR, a slagging EFG should be implemented because ASR produces ash that can be melted in the gasifier and removed as a vitrified slag. Non-slagging gasifiers are used when there is a little or no ash component in the input feed and, thus the walls of the gasifier are kept clean of slag. A slagging entrained gasifier is "fuel flexible" and requires a fluxing material like ASR that can be treated to obtain certain slag properties at different temperatures (van der Drift et al., 2004). Advantages to this system are that there is little pretreatment of the input material, a lower energy consumption because of the smaller particle sizes, and a lower inert gas consumption which is used to pressurize and compact the material before entering the gasifier.

The disadvantages though outweigh the advantages since it is unknown if the material is completely converted to gas, the stability of the system is questioned, and further research for new developments are required (van der Drift et al., 2004).