



Final Report

PVC Recovery Options Environmental and Economic System Analysis

Commissioned by VINYL 2010



Final Report:

PVC Recovery Options
Concept for Environmental and Economic System Analysis

commissioned by VINYL 2010

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Nomenclature and abbreviations

Al	Aluminium
AOX	Absorbable organic halogens
CaCl ₂	Calcium chloride
CaCO ₃	Calcium carbonate
Cl	Chlorine
Cu	Copper
DEHP	Di-(2-ethylhexyl phthalat)
DIDP	Di-isodecyl phthalate
DINP	Di-isononyl phthalate
HCl	Hydrochloride acid
HOK	“Herdofenkoks” coke from lignite
MEK	Methyl ethyl ketone (2-butanone)
MINP	Mono-isononyl phthalate
MSW	Municipal Solid Waste
MVR	Müllverbrennungsanlage Rugenberger Damm, Hamburg; engl. Waste incineration plant Rugenberger Damm, Hamburg
NaCl	Sodium chloride
NO _x	Nitrogen oxide
Pb	Lead
PCDD	Poly-Chlorinated-Dibenzo-Dioxines
PCDF	Poly-Chlorinated-Dibenzo-Furanes
PE	Polyethylene
ppm	Part per million
PVC	Poly Vinyl Chloride
REA	German flue gas desulfurization unit, engl. FGD
SNCR	Selective Non Catalytic Reduction
SO ₂	Sulphur dioxide
TEQ	Toxicity Equivalent
TOC	Total Organic Carbon

Executive Summary

Goal

The PVC industry supports an integrated waste management approach under the concept of Eco-efficiency. The concept of Eco-efficiency is promoted by the *World Business Council for Sustainable Development*, and it is further adapted here according to the goal of this study. The term Eco-efficiency comprises an efficient use of raw materials, a minimum impact of emissions and waste, and an overall balance of benefits and burdens in an environmental and economic way. In order to investigate different end of life treatment options and identify optimisation potentials for PVC-rich waste with respect to these criteria, this study was conducted. To this aim, an “Environmental and Economic System Analysis” of different processes and waste recovery options was performed. Mixed cable waste has been chosen as it represents a complex, large waste stream for PVC waste products and shows similarities with waste streams from other plasticised PVC applications. The environmental parameters were selected with reference to current international discussion. The study was performed in accordance with the Life Cycle Assessment methodology described in ISO 14040 ff. The economic parameters per option were based on gate fees. The gate fee was calculated by the operators under comparable boundary conditions.

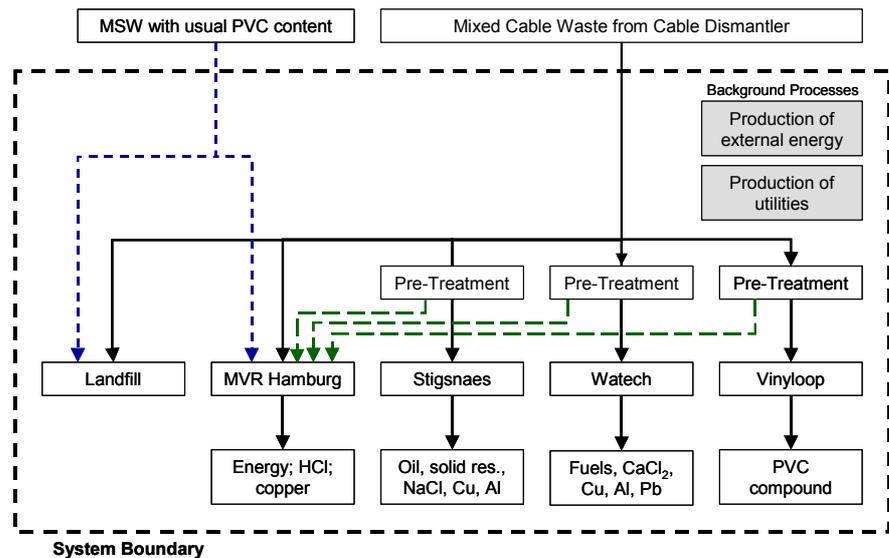
Scope

The function of the systems under study is “processing of 1 t mixed cable waste”. The technologies generate different quantities and qualities of recovered products (see below). The four investigated recovery technologies can be characterised as follows.

- **The municipal waste incineration** in the *MVR Hamburg* facility in Germany with the recovered products electricity, heat, HCl, and metal(s).
- **The feedstock recycling** with the *Watech* process of RGS90 A/S in Denmark. It uses pyrolysis followed by purification and extraction steps. The recovered products are CaCl₂, coke, pyrolysis oil (condensate) and metal(s).
- **The feedstock recycling process** of *Stignæs* Industrimiljø A.S. in Denmark is a hydrolysis followed by post-heating (pyrolysis) of the dechlorinated solid fraction. The recovered products are NaCl, hydrocarbon (C_nH_m) fractions, solid residue for the production of sandblasting material, and metal(s).
- **The mechanical recycling** with the *Vinyloop* process developed by Solvay S.A. uses solvents and is based on selective dissolution, separation and precipitation of the PVC compound. The recovered products are PVC compounds and metal(s).
- **Landfilling** was chosen as the reference option of this study; there are no recovered products.

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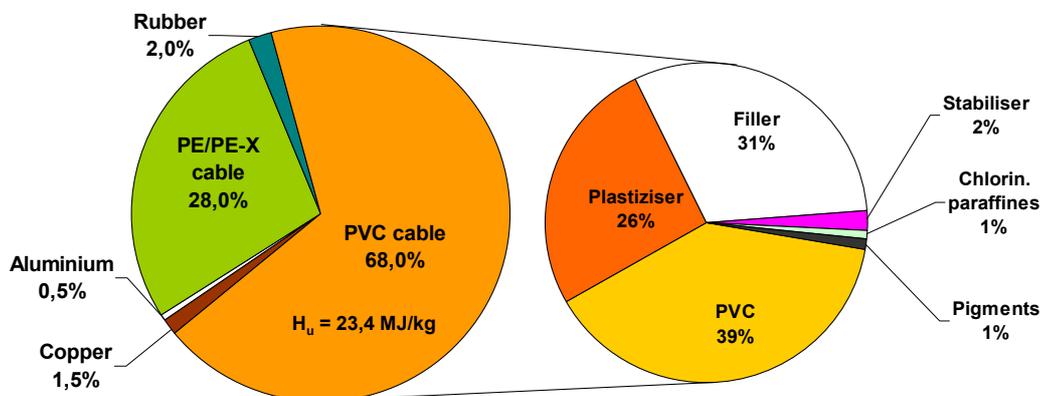
The method of “system expansion” is used to make the different options and the individual products comparable (for a detailed description of system expansion see chapter 2.3 of the Final Report). The data used were provided by the owners of the technologies (core process data of the individual recovery processes), or



System boundaries for the systems under study

otherwise taken from the GaBi databases (background data of materials, auxiliaries and energy production). The country specific situation was considered, and – if relevant – a parameter variation for an average European situation was calculated.

For this study the steering group of this project defined a reference composition of the cable waste. The largest part of the mixed cable waste is the PVC fraction (68%), which is made of PVC, filler, plasticiser, and other additives.



Composition of the mixed cable waste

Hence, the input to the system is 1 t of mixed cable waste. The system under study includes process specific pretreatment of the mixed cable waste, excluding collection and dismantling from the conductor materials.

Any relevant background processes, e.g. production of materials, energy and auxiliary materials to run the technologies are within the system boundaries. Outputs of the system are environmentally relevant substances (emissions, waste, wastewater) and marketable recovery products. According to the method of system expansion for comparison the alternative production routes are added. The study has been submitted to independent experts from EMPA (Switzerland) for a critical review.

Environmental assessment

The study focuses on the following environmental criteria:

- Primary energy consumption (non renewable resources)
- Global Warming Potential (GWP 100 years)
- Acidification Potential (AP)
- Characteristic emissions on inventory level, e.g. dioxin (PCDD), lead (Pb)
- Hazardous waste, municipal and inert waste, wastewater.

All elementary flows with a significant contribution to the selected environmental categories are considered within the calculations.

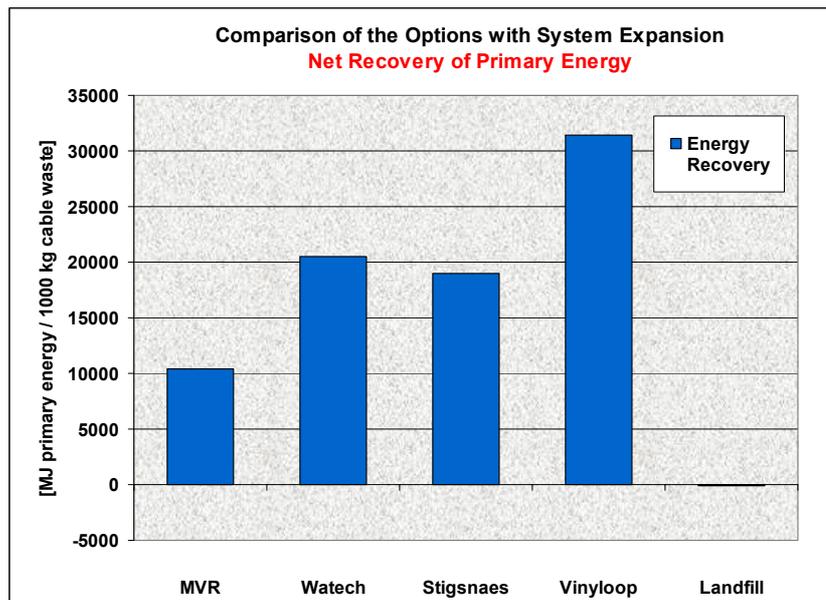
Economic assessment

The economic comparison of the different recovery options is based on the price the waste owner has to pay to the operator of the recycling facility for the cable waste. This “gate fee” is used as a baseline to assess the economic dimension. The boundary conditions for the calculation of the gate fee are 10 years depreciation time of the plant. Included were individual (and local) costs for pretreatment, utilities and effluents, labour and other direct costs, waste and wastewater treatment and revenues of the recovered products. The calculations are done without the consideration of grants. This leads to an individual “gate fee” of the processes to compare the economic dimension. The operators of the recycling facilities provided the „gate fees“. No comprehensive cost analysis was done within the scope of this study.

Environmental Results

In the Final Report (chapter 6), the investigated technologies were assessed with respect to the three impact categories, primary energy demand, global warming potential and acidification potential. The results were considered in comparison with landfilling as the reference option and presented in three different views (comparison of impacts, net recovery and life cycle view, all including system expansion). The net recovery of primary energy (see figure) is a good way of showing the results, but to get a comprehensive overview the other aspects under study should be considered as well.

All investigated options recover more **primary energy** by supplying different products than needed to operate the processes. Conversely, the reference case landfilling shows no recovery of primary energy (small burdens due to operation of the landfill). For instance, the net recovery of primary energy of the MVR plant is approximately 11000 MJ per ton of cable



Net recovery of primary energy with system extension
 waste. This means, if the recovered materials were to be substituted by “virgin” production processes (with electricity, steam and HCl produced by conventional processes), an additional demand of 11000 MJ/t of primary energy would be necessary. With the same rationale, all analysed recovery options reach the goal of energy recovery compared to landfilling.

Concerning the **GWP**, waste incineration in the MVR plant has the highest impact potential. The cable waste is incinerated and thus nearly all carbon content of the cable waste is converted into CO₂. Furthermore, the products (electricity and steam) account only for relatively low GWP savings in comparison to the other recovery processes, whilst the feedstock recycling processes applied by Stignsnaes and Watech recover most of the carbon in the form of coke, oil or other hydrocarbons. Best in this respect is the Vinyloop process, which shows a net recovery, as it prevents more GWP than is generated by the process.

All recovery processes show a net **Acidification Potential** benefit. The results are quite similar to Primary Energy. Landfill does not recover any products, but has only burdens due to the operation of the site.

In the reference case of landfilling, the input of 1000 kg of cable waste remains as municipal **waste** for disposal. The MVR incineration reduces the amount of waste to 419 kg in total and separates it into different fractions. The recycling options perform clearly better and are all in the same order of magnitude. Watech generates the smallest amount of waste (~6 kg).

Concerning **lead**, with incineration and landfilling almost 100 % of the input are found as part of waste streams. With the Watech process, nearly 99 % of the lead is concentrated in the recovered heavy metal fraction. With the Stignsnaes process approximately 97 % of the lead is found in the solid product, which is used on-site to make sandblasting products and separated there. Hence, the feedstock recycling processes perform best to separate the lead

from the other recovered products. With the Vinyloop process, approximately 99 % of the lead is reused as a stabiliser in the PVC product.

Some of these processes form trace amounts of **dioxins**, whilst with the Vinyloop process no formation of dioxins was detected. The Watech process showed trace amounts of formed dioxins, which are released via the stack. The MVR process directs the formed dioxins, together with other hazardous substances, into the hazardous waste stream (mainly filter ashes), which is securely disposed off in special underground facilities. The Stignsnaes process shows traces of dioxins in the oil product and in solid residue.

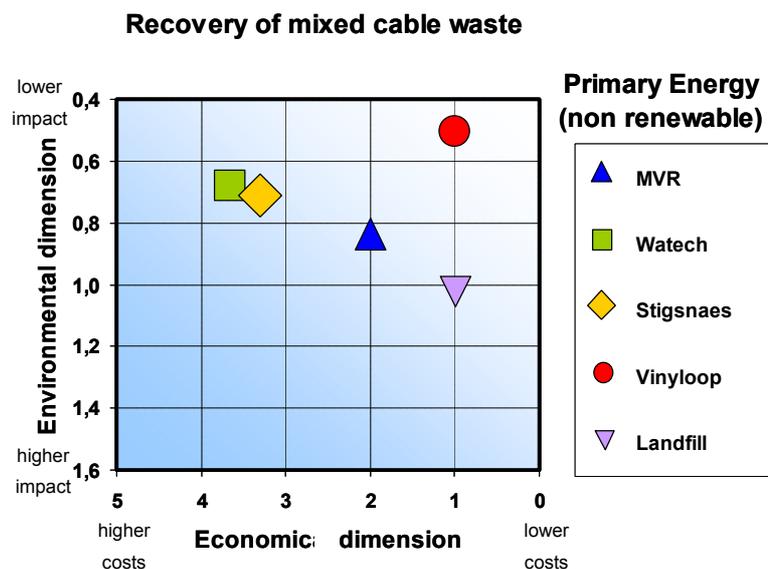
All recovery processes investigated recover **chlorine** from PVC - although in different ways - for industrial reuse. The recovery yields are highest for Stignsnaes, Watech and Vinyloop (all between 94 % and 99 %). The yield of chlorine recovery in the MVR waste incineration is around 53 %.

Eco-Efficiency

In order to illustrate the relation between the environmental effects and the costs of the investigated recovery options, economic and environmental aspects are presented in an Eco-efficiency diagram.

On the horizontal axis, the economic, and on the vertical axis the environmental assessment of the technology is displayed (high values = higher impact or costs, low values = lower impact or costs). The values are normalised with reference to the base case of landfilling (designated as 1 on each axis).

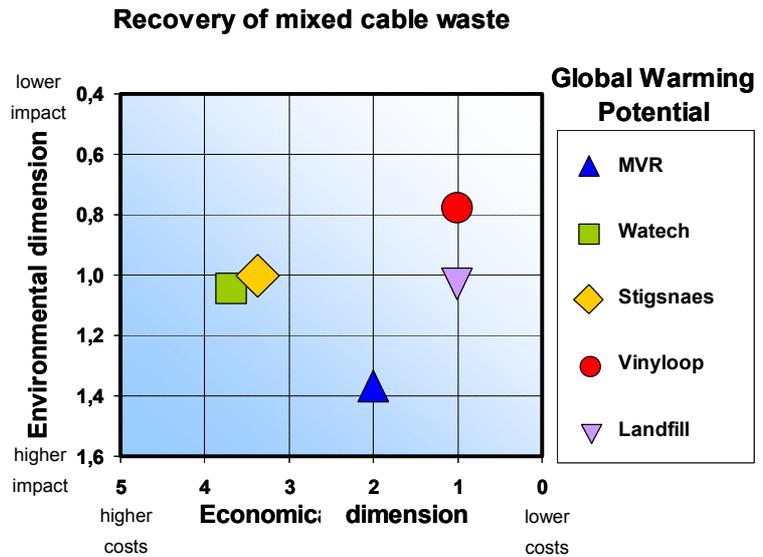
As already discussed above, regarding the primary energy demand, all recovery options perform better than landfilling from



Primary Energy (non renew.) with system expansion view
 an environmental perspective. However, with the exception of the Vinyloop process, all recovery options are more expensive than landfilling. The Vinyloop process shows the lowest primary energy impact in combination with a gate fee that is comparable with the reference option of landfilling.

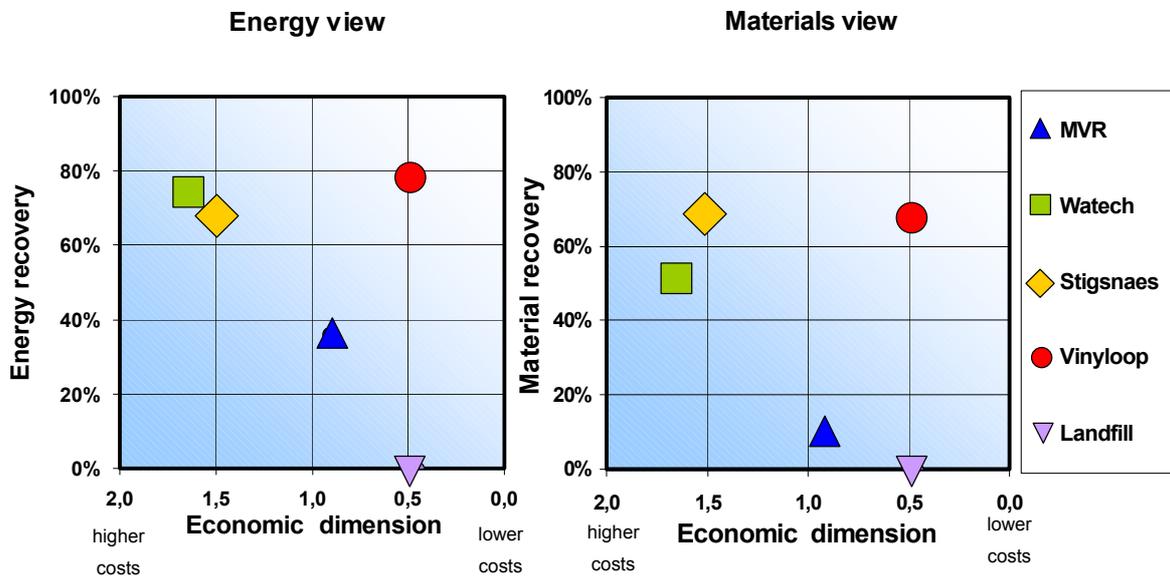
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Concerning the GWP, the Vinyloop process shows an environmental advantage while the economic dimension is comparable with landfilling. The Stigsnaes and Watech processes show a comparable GWP to landfilling but higher gate fees. The MVR incineration process increases both the costs and the GWP load in relation to landfilling, since carbon from the cable waste is converted into greenhouse-relevant exhaust gases.



Global Warming Potential with system expansion view

The results can also be presented from an energy and materials recovery perspective. The energy recovery diagram shows the energy content of all products recovered by the technology in relation to the energy content of the input cable waste. The materials recovery diagram shows the recovered share of mass in relation to the input cable waste on an elementary level.



Energy and Material Recovery without system expansion view¹

It indicates that all recovery options save material in comparison with landfilling. However, while the Stigsnaes, Vinyloop, and Watech processes achieve material recovery rates of 50–70 %, the MVR process turns almost all input into energy products and thus provides only

¹ 1,0 on the economic scale represents in this case the average of all processes

about 10 % material recovery. The economic valuations remain the same as above, of course. Note that it is not correct to combine the values of the energy and material recovery rates, respectively, because double counting would occur (e.g. oil counts for mass and energy). Therefore, the charts can only be interpreted independently from each other.

Conclusions

The results of the environmental and economic system analysis from this study are only valid for mixed cable waste with the described composition and for the specific conditions of the investigated recovery plants. The environmental assessment was conducted according to the applicable standards ISO 14040 ff. Differences in national environmental policies may also effect the conclusions from this study. In general, the following conclusions can be drawn:

1. When considering recovery options for an integrated waste management concept, an Eco-efficiency approach provides valuable insights in the environmental and the economic aspects of the investigated processes.
2. Compared with the reference option landfilling, all of the investigated recovery options have a positive effect on the demand of primary energy, due to the recovery of either energy or materials. The Vinyloop mechanical recycling process shows the best performance in this respect, followed by the Watech and Stignsnæs feedstock recycling processes, on a similar level, and with the MVR incineration process at 3rd place.
3. In addition to this criterion, the results for the other impact categories – global warming potential (GWP) and acidification potential (AP) – as well as the management of substance flows (lead and dioxin) also need to be considered. For example, the Watech and Stignsnæs processes are the only ones allowing to separate and recover lead.
4. The management of the polymer as a resource plays a decisive role for the environmental assessment. In landfills, the carbon content of the waste product is “stored”, although a long-term fixation is uncertain. Furthermore, landfilling incurs long-term risks and liabilities, which cannot be represented in the Eco-efficiency diagram. At least in Europe, landfilling of plastic waste does not represent a long-term disposal option from a legal point of view. Incineration processes such as MVR use the embodied energy of the polymer, while recycling processes such as Vinyloop, Watech, and Stignsnæs recover the material itself or its feedstock.
5. When taking the economic dimension (gate fees) into consideration, the Vinyloop process is shown to be competitive with landfilling, while all other recovery options entail higher costs – MVR, Stignsnæs and Watech in order of increasing gate-fees – mainly because of their low revenues for the recovered products.

The task for the decision-makers remains to arrive at an evaluation of the Eco-efficiency profile of each recovery option under consideration. This final evaluation will have to be based upon the system boundaries, conditions and specific demands of the technology, but will also need to take local and regional aspects into consideration.

We can herewith confirm after an in-depth critical review conducted according to EN ISO 14'040, chapter 7 that the compilation and valuation of environmental aspects of several end-of-life options for PVC cable waste in the report

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presented by PE Europe GmbH and dated 10th of April 2003 is in conformity with the actual series of standards EN ISO 14'040ff on environmental life cycle assessment (LCA). This part of the study is in line with the required structure of an LCA and fulfils the requirements on data quality, transparency, consistency, completeness and methodological soundness in dependency of the goal of the study.

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1 Introduction and Background

The PVC industry is currently involved in various activities developing technologies for mechanical and feedstock recycling and is investigating the potential of state of the art incineration with recovery of energy and chlorine as valuable products. A variety of such novel technologies are available as an alternative to standard incineration with energy recovery and landfill. It remains the question, what the most effective recovery option is hence the search for an answer about the most efficient option for a defined waste stream from an environmental and an economic point of view.

This question occurs normally in an early stage of the planning process. A consistent modelling of the projected facilities is the best possibility to get reliable results for optimisation and comparison of different options. This modelling is based on scientific common source – sink models. This allows adding other recovery options later on in a consistent way. Furthermore a variation of the level of detail is feasible, e.g. a more detailed assessment for options with good prospects.

ISO 14040 ff gives guidance and a good framework for comparisons and process optimisation from an environmental point of view. A common interpretation of environmental and economic facts is feasible with the eco-efficiency method.

Cable waste is the 2nd largest PVC waste stream from the durable sector in Europe and is chosen as input material for the calculations. Cable waste shows similarities with waste streams from other plasticised PVC applications like roofing sheets, flooring or coated fabrics. Cable waste in this context means cable insulation waste after dismantling and separation of most of the metal. The capacity of the existing mechanical recycling of cable waste is restricted because there is no bigger market for the recycling product out of this process. Therefore additional recovery options with marketable outputs are needed.

The following goal and scope definition is based on the structure given by ISO 14040 ff. It tries to give the necessary background information and settings for the study.

In Denmark another study on PVC recovery is planned. Therefore the Danish EPA has followed and accompanied this study. The Danish study is planned to focus on the socio-economic dimension of PVC recovery options. It may take this study as a basis and extends the goal and scope.

2 Goal and Scope Definition

2.1 Goal Definition

In accordance with the project group the following goals - intended applications, reasons for carrying out the study and intended form and forum - are defined. The goal of the study clarifies the scope of the study.

2.1.1 Intended application

The intended application describes the background how the results of the study may be applied.

- The evaluation of different processes and waste recovery options will be carried out to see, if the selected options make sense from an environmental and an economic point of view for this type of waste. An assessment of the options will clarify and quantify differences.
- The analysis of environmental and economic impacts opens the discussion towards eco-efficiency thinking on a more objective basis.
- The results can be used for identification of possible optimisation potentials of the considered recovery options from a system point of view.
- A major application will be the support of the decision making process. The results can be used to identify and justify, which concepts are the most favourable for the chosen input.

Reasons for carrying out the study

The reasons to carry out the study clarify the intention and motivation.

The PVC industry has adopted an integrated approach to deliver responsible cradle to grave management, embodied in the signature of a 'Voluntary Commitment of the PVC Industry'. The Voluntary Commitment' embraces the principles of Responsible Care®.

As part of this, the PVC industry supports an integrated waste management approach, which aims to maximise the efficient use of raw materials and utilise the best end-of-life treatment option per waste stream.

One of the commitments is to *“develop the use of high-quality mechanically recycled PVC in new products”, and to “continue investigating potential feedstock recycling processes and to complete assessments of environmental and economic benefits of these processes”*.

This results in an objective *“to recycle in 2010 200 ktons of post-consumer waste in addition to 1999 post-consumer recycling volumes and to any recycling of post-consumer waste as required by the implementation after 1999 of E.U. Directives on packaging waste, end-of-life vehicles and waste electronic and electrical equipment”*.

Therefore the identification and evaluation of promising recovery options for defined PVC waste streams is needed.

- The information enables to direct the efforts of industry and ultimately PVC waste streams to the adequate recovery options.

An inherent reason is the reduction of PVC disposed to landfills for resource saving aspects.

2.1.2 Intended forum and format

The presentation of the quantitative information and results depends on the forum, where the results are used or to which the results may be communicated.

- The forum of the study are experts and decision makers within the PVC industry
- A possible extension of the target group (e.g. public) will be considered within the structure of the study, to enable further steps using the same information base.
- The format of the study will be detailed descriptions, analysis and evaluations of the systems under study for the experts of the forum. Detailed LCI information of the process chains will be available.
- Comprehensive and comprehensible interpretation of the results for decision-making as well as for communication will be derived.
- The report will be split up in three parts. The environmental part will be done according to ISO 14040 ff. A separate economic section will be part of the report. A joint interpretation of the environmental and economic information will be the third part of the report. This procedure ensures most flexible use of different parts of the study for further use.
- The systems will be set up in the Life Cycle Engineering Software Tool GaBi. The implemented software and database models will be available to VINYL 2010 and allow further assessments in the future.

2.2 Scope of the Study

The scope of the study describes the different circumstances and boundary conditions, which are important to correctly interpret the results.

2.2.1 Function and functionality (functional unit)

Processing and recovery of 1 t mixed cable waste input (after dismantling)

The function of the systems under study is “processing of 1 t mixed cable waste”. The technologies generate different quantities and qualities of recovered products. The four investigated recovery technologies can be characterised as follows.

- The municipal waste incineration in the **MVR Hamburg** facility in Germany with the recovered products electricity, heat, HCl, and metal(s).
- The feedstock recycling with the **Watech** process of RGS90 A/S in Denmark. It uses pyrolysis followed by purification and extraction steps. The recovered products are CaCl₂, coke, pyrolysis oil (condensate) and metal(s).
- The feedstock recycling process of **Stignæs** Industrimiljø A.S. in Denmark is a hydrolysis followed by post-heating (pyrolysis) of the dechlorinated solid fraction. The recovered products are NaCl, hydrocarbon (C_nH_m) fractions, solid residue for the production of sandblasting material, and metal(s).
- The mechanical recycling with the **Vinyloop** process developed by Solvay S.A. uses solvents and is based on selective dissolution, separation and precipitation of the PVC compound. The recovered products are PVC compounds and metal(s).
- **Landfilling** was chosen as the reference option of this study; there are no recovered products.

The minimum requirement on each option is the processing and disposal of mixed cable waste (after dismantling), including its process specific pretreatment and transports. If there are other services provided by the options (e.g. recovery of marketable products) these benefits will be taken into account by the method of system expansion (see chapter 2.3).

2.2.2 Composition of the mixed cable waste

The composition of cable waste from the dismantlers varies in a wide range dependent on the origin and the age of the cable. Four types of cable insulation are found in a greater ratio: PVC compound, polyethylene (PE), cross-linked polyethylene (PE-X) and rubber.

For this study the steering group of this project defined a reference composition. The largest part of the mixed cable waste is PVC cable waste (68%), which is a compound of PVC, filler, plasticiser and others (see figure 2-1).

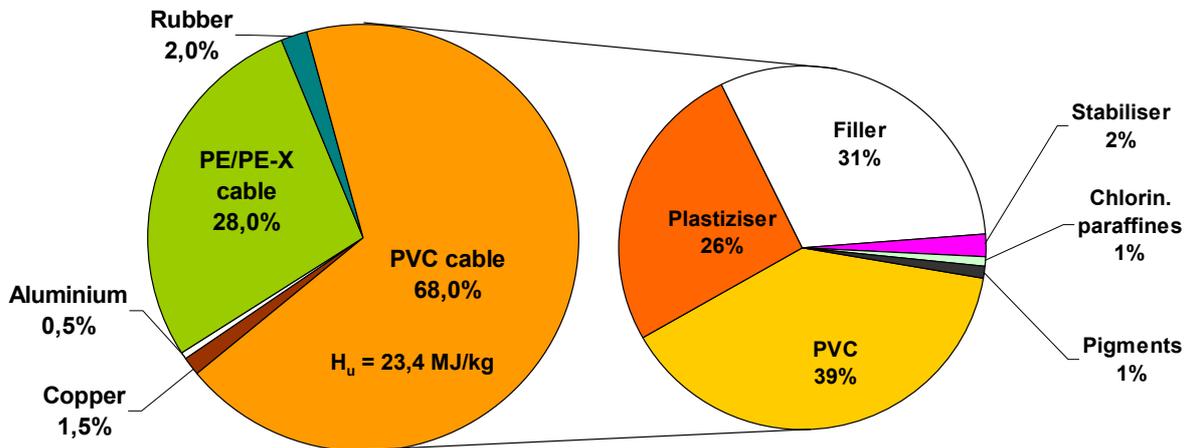


Figure 2-1: Composition of the mixed cable waste

Polyethylene (PE) and cross-linked polyethylene (PE-X) together are 28% of the mixed cable waste. Those are subsumed together in the following chapters as polyethylene.

The cable dismantler already separates the economic gainable copper and aluminium.

2.2.3 System boundaries

- Input: 1 t of mixed cable waste after dismantling
- The system under study includes process specific pretreatment of the mixed cable waste (but excludes collection)
- The study includes the four different treatment options: MVR waste incineration Hamburg, the feedstock recycling process of the Stignæs process, the feedstock recycling of Watech process and the mechanical recycling with the Vinyloop process.
- Reference option: landfill of 1 t mixed cable waste
- In landfill and MVR waste incineration the mixed cable waste is a share of the average input (see figure 2.2 and chapter 3.1.1)
- Any relevant background-processes, e.g. production of materials, energies and utilities (auxiliary materials) to run the technologies are within the system boundaries
- Infrastructure is not considered (not relevant in this context)
- Outputs of the system:
 - Environmental relevant substances (emissions, waste, waste water)
 - Recovered and principally marketable products.

Figure 2-2 shows the options included in the study and the system boundaries.

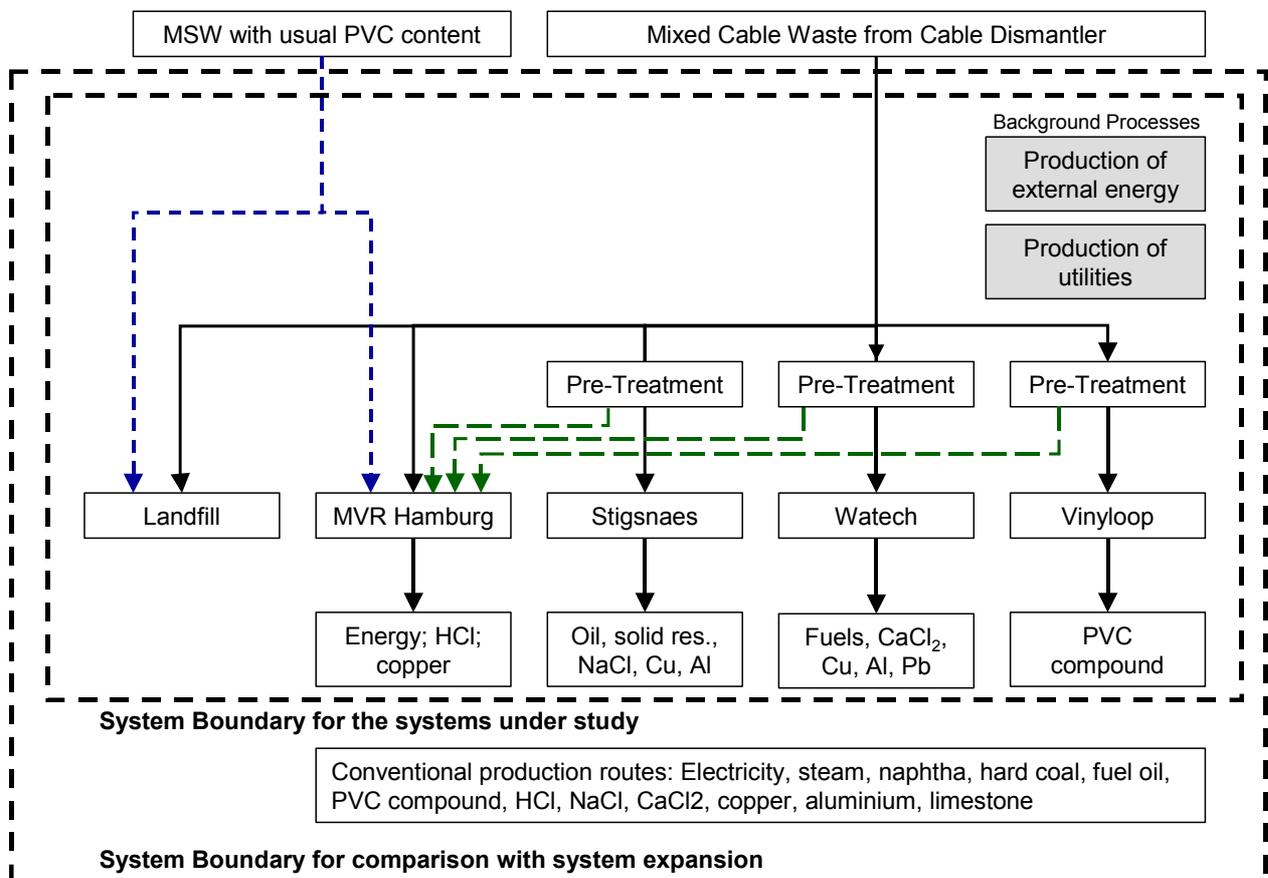


Figure 2-2: System boundaries

2.2.4 Data requirements, assumptions and limitations

To ensure reliable results the following points are handled as described:

Precision:

It is reported, which data either is measured or is modelled based on primary information or is data from the database. As the relevant data is primary data or modelled based on information of the owner of the technologies and the possibly sensitive data is analysed in a sensitivity analysis, no further description of the data precision is required.

Completeness:

All specific processes of the different options are considered and modelled representing the specific location. Any background processes are taken from the GaBi databases (GaBi 4, see software and database documentation).

Representativeness:

Geographical coverage: Specific national conditions are modelled. If a dominance analysis showed significant influences of the geography a scenario with an average European situation is modelled.

Time related coverage: The reference time is 2001/2002. If possible the annual average data are taken to compensate seasonal variation.

Technological coverage: Represents the specific technologies under study. For any required material-, energy-, utility-production “state of the art” technology is considered.

Consistency:

To ensure consistency only primary data of the same level of detail and background data from the GaBi databases are used.

Reproducibility:

The reproducibility is given for internal use since the owners of the technology provided the data and the models are stored and available in a database. Sub-systems are modelled by state of art technology using data of a publicly available and internationally used database. For external audience no full reproducibility will be given because of confidentiality reasons.

2.2.5 Selection of environmental parameters and impacts under study

All flows contributing to the selected categories in a relevant way will be considered within the calculations.

The study will focus on the following categories:

- Primary energy consumption (non renewable sources)
- Non renewable raw materials on inventory level
- Global Warming Potential (GWP 100 years)
- Acidification Potential (AP)
- Selected characteristic emissions of the technology on inventory level dioxins, lead and chlorinated paraffins will be traced back, others (Cd, Sb, PCBs) will be qualitatively assessed only
- Hazardous waste
- Municipal and inert waste

The impact assessment is based on the methods and data compiled by the Centre of Environmental Science of Leiden University [HEIJUNGS et al. 1992] [GUINÉE et al. 2001].

2.2.6 Critical review

It is planned to disclose this report to the public. Therefore the study has been submitted to independent experts from EMPA (Switzerland) for a critical review.

2.3 System Expansion

Within this study the system expansion is performed to make the different options comparable.

System expansion is conducted through the following way:

- The output products of all options under study have to be detected
- A set of products is defined containing the products from all options (products from MVR, Stigsnaes, Watech and Vinyloop)
- Production routes of generally applied processes are added to the system (see figure 2).

The product-output of all options is the same after modelling system expansion that means the service delivered by the options is comparable.

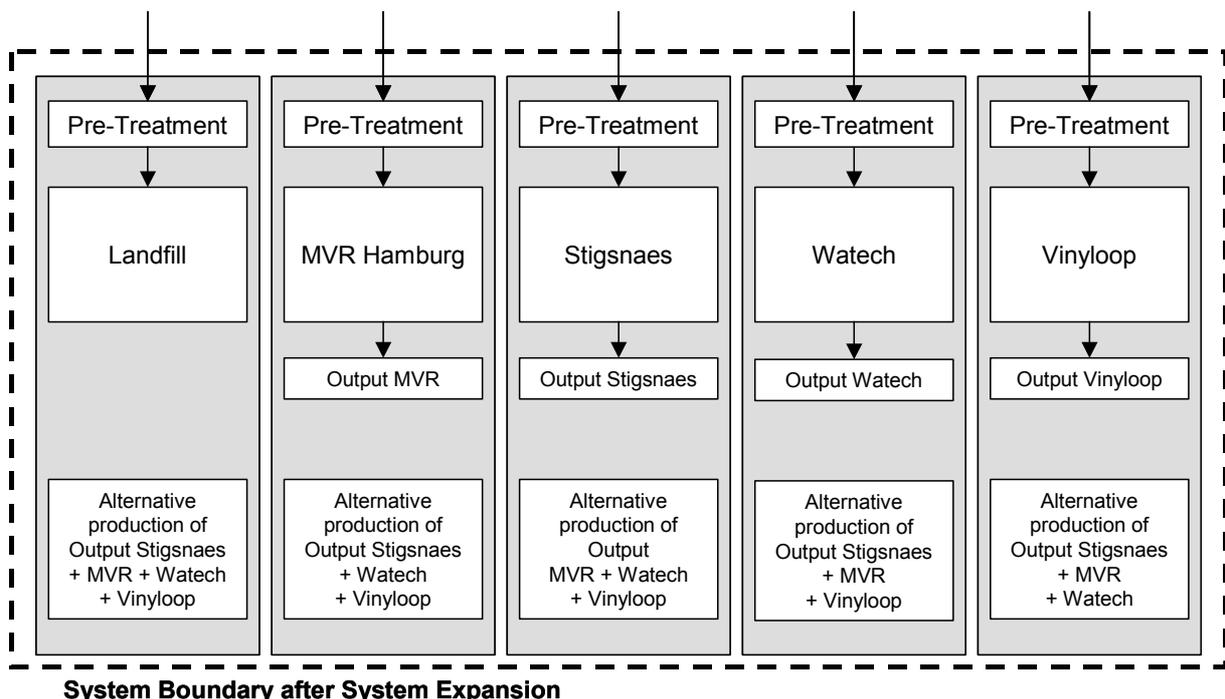


Figure 2-3: System expansion

2.4 Characterisation of the Technologies

In this chapter the four recovery options under study are described and characterised.

2.4.1 MVR Hamburg (municipal solid waste incineration)

General overview

The MVR in Hamburg is one of six waste incineration facilities in Germany with HCl-rectification. This type of plant is capable to treat PVC containing waste in co-combustion with municipal waste. Chlorine is recovered as hydrochloride acid in industrial quality.

The reclaimable output products of the incineration are:

- Electricity
- Steam
- Hydrochloric acid
- Metals (mainly steel and a non ferrous metal mix)
- Gypsum
- Slag

The products and the external process materials are shown in the figure below.

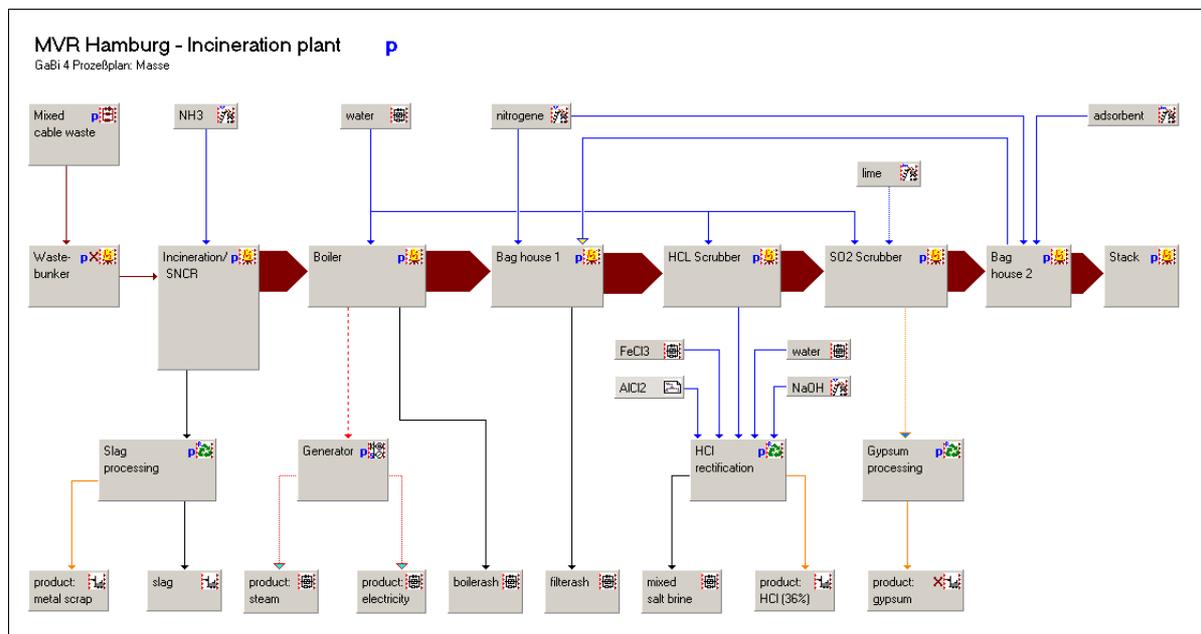


Figure 2-4: Mass Flows Analysis Model for the MVR Hamburg (Waste Incineration)

More information on the environmental affairs and effects of the MVR waste incineration is given in the environmental statement of MVR [MVR 2001].

Detailed Specification of the process:

The MVR plant consists of two incineration lines, each fitted with a grate and a steam generator. In addition, two natural gas-fired auxiliary steam generators are operated to safeguard steam supply to the industrial customers.

The grate slag is washed with additional water in the deslagging system to reduce the level of easily soluble salts. In the slag processing system, scrap iron and non-ferrous metals (aluminium, copper, brass) are separated from the slag to be used as raw materials in the corresponding metallurgical industry. The slag is sieved, crushed and cleared of unburned components to produce a tested and certified construction material.

A flue gas cleaning system is allocated to each line of incineration. Flue gas cleaning already starts in the boiler by spraying liquid ammonia into the combustion chamber using the Selective-Non-Catalytic-Reduction (SNCR) procedure. The SNCR reduces NO_x into elementary nitrogen and water. Furthermore, high temperature fly ash removal takes place. Flue gas leaving the boiler gets in contact with low contaminated mixture of blast furnace coke (HOK) and trass from bag house 2. Residual fly ash in the flue gas of the steam generator and the contaminated HOK is filtered out of the flue gas in bag house 1.

The flue gas then passes through a two-stage acid scrubber to wash out the halogen compounds HCl, HF, HBr and HI. A one-stage alkali scrubber follows to extract sulphur oxides. This is followed by a post scrubber stage consisting of a second bag house, with fresh active carbon being added to the flue gas before entering the bag house. A draft blower presses the purified exhaust gas through the stack.

Through the flue gas cleaning process a 10-12% crude hydrochloric acid is produced in the acid scrubber. This is then processed in a rectification plant operated independently from the incineration plant, to produce a hydrochloride acid with a concentration of at least 30% acid as given in DIN 19610 and EN 939. In several process stages, HCl acid is cleaned from disturbing components such as HCl halogen compounds, ammonia, fly ash and other inorganic and organic substances. The HCl gas is generated from the pretreated crude acid in a distillation process. The HCl acid 30% is produced using demineralised water.

2.4.2 Watech PVC feedstock recycling process

General Overview

The Watech process of the NKT Research Center A/S in Denmark can be understood as a pyrolysis followed by purification and extraction units.

The process produces by means of several process steps four reclaimable output products.

These products are:

- Organic condensate (a mixture of hydrocarbon products with up to 15% 2-ethyl-1-hexanol)
- Heavy metal product (depending on the input it contains lead, copper, cadmium, zinc and iron)
- Coke (a carbon rich, dry fraction of homogenous powder)
- Calcium chloride (36% solution)
- Polyethylene (separated in the pretreatment)
- Metal scrap (separated in the pretreatment)

External auxiliary supplies are:

- Limestone
- Water
- Electricity
- Propane

No wastewater is generated, as the water is recycled in the process or leaving the systems as part of the CaCl_2 product.

The objective of the process is to transform PVC-waste into recovered products, which can be used in other industrial applications to substitute virgin products of the same or comparable quality.

The process has been designed to a certain variation of input specifications. The process exists in a pilot plant size of app. 1,2 t_{PVC}/h . In average app. 300-400 t_{PVC}/a can be treated. Assessments and calculations are based on the design of an industrial scale plant of about 15000 t/a .

Materials which have been treated are: cables, flooring materials, cable trays, artificial leather, binders, mixed German building waste, and mixed Danish building waste.

Goal and Scope Definition

The plant was modelled in the Software Tool GaBi 4. All relevant mass flow to close the energy and mass balances of the individual steps was integrated. In Figure 2-5 the main mass flows are shown to enable an overview of the relevant mass transfers within the processes. The thickness of the arrows represents the relative amount of the mass flow.

Flowsheet Watech
 GaBi 4 Prozeßplan: Masse

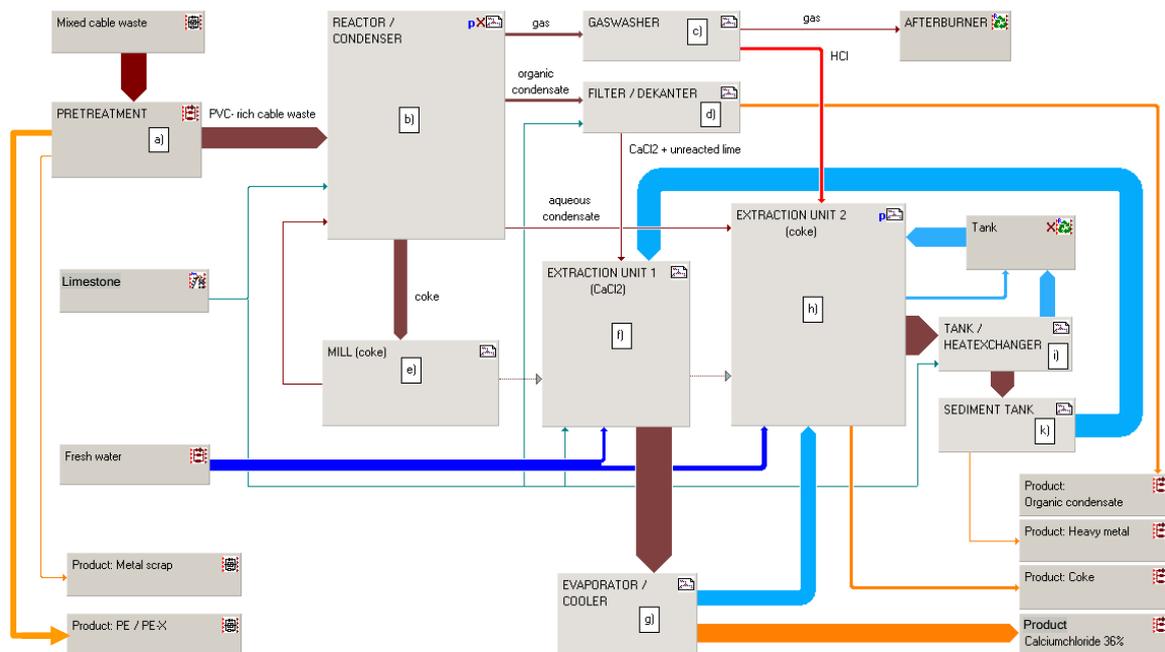


Figure 2-5: Mass flow Analysis model of the Watech Process

The main mass flows are the water cycles and the salt stream ending up in the product “calcium chloride, 36% solution”.

Figure 2-5 provides certain guidance for an easier understanding of the explanations in the next chapter.

Detailed Specification of the process:

Pretreatment on site (a)

The PVC cable waste is separated into a metal fraction, a polyethylene (PE) residue (containing some PVC traces) and a dry PVC-rich waste fraction. In the study it was assumed that app. 0,7% of the incoming PVC remain in the PE residue. According to different studies it is possible to minimise this amount further, but this does not affect the results of the study in a relevant way. The physical separation processes (mainly on flow-sink basis) just need electricity and water as auxiliaries. The metal fraction contains scrap of copper, aluminium and steel ready for commercial sale. The polyethylene residue itself can optional be separated in PE, which is a reclaimable material, and PE-X, a thermosetting

plastic that can be combusted in order to use its energy content. The PVC-rich waste fraction, which contains the main part of the synthetics (PVC, rubber, PE traces, PTFE etc.), is the basic material for the PVC-recycling process.

Reactor and Condenser (b)

The pretreated dry PVC waste is inserted in a combined reactor/condenser process in conjunction with limestone and water. In the reactor, a pyrolysis takes place under defined conditions concerning temperature and pressure. The arising solid product is coke.

The arisen non-solid product, the pyrolysis gas, is treated afterwards in the condenser. Hence the following condensed liquid products are gained:

- an organic- condensate in the upper phase,
- an aqueous condensate in the lower phase and
- furthermore uncondensed gas is separated

The needed energy can be provided by electricity or optional by combustion of internally produced products such as organic condensate. App. 85% of the needed energy is thermal energy and can be provided by combustion of the pyrolysis products such as organic condensate.

Gas washer and Afterburner (c)

In the gas washer, the purification of the uncondensed gas occurs. The process step is driven by the produced pressure in the reactor and thus needs no extra energy. One of the outputs of the gas washing process is dilute HCl, which is internally needed in the process and is used later for the metal extraction of the pyrolysis coke. The second output is washed gas, mainly containing CO₂ due to the decarbonisation of the CaCO₃ in the pyrolysis. In a downstream afterburner, the treated gas will be thermally treated and leaves the system via a stack.

Filter / Decanter (d)

The pyrolysis oil is admitted to a filter respectively to a decanter in addition to lime. The process step is driven as well by the produced pressure in the reactor. The main output is a purified, reclaimable organic condensate that can be used for instance as fuel or feedstock. The filter cake is a kind of slurry, containing mainly CaCl₂ and unreacted lime. This slurry will be collected in a tank and re-enters the process in the reactor.

Coke mill (e)

The coke that leaves the reactor has to be milled. A downstream sieve separates the coke depending on the size of the particles.

Goal and Scope Definition

If the coke particles have the desired size, they are directly transported to the extraction units; if not (particles too large), the particles will either be milled again or retransported to the reactor.

Extraction Unit 1 (f)

The aim of the extraction unit 1 is to extract CaCl_2 . The milled coke is mixed with water, about 80% of the demand is satisfied with recycled water circulating through the process. The generated slurry is fed with milled limestone in order to remove chlorine in form of CaCl_2 by using a filter press.

Evaporator / Cooler (g)

The filtrate that derived from the filter press contains 20% CaCl_2 . To achieve a CaCl_2 solution of 36%, the water has to be evaporated. The required demand of energy can be satisfied by electricity, but it is optional possible to use steam. The steam can be generated in an intern steam reformer unit, which can be fired with the internally produced organic condensate. The 36% solution of CaCl_2 leaves the process as product. The evaporated hot water feeds the filter press of the extraction unit 2 after recondensation.

Extraction Unit 2 (h)

The main task of the second extraction unit is to separate the usable product coke from the metal contents. The filter cake from the extraction unit 1 reaches the slurry tank where the cake gets mixed with recycled water and two streams of an aqueous solution with different content of HCl solutions.

Afterwards the extraction, the coke slurry passes through a filter press that decreases the moisture content of the slurry. Further on the filter cake gets flushed in order to remove the chlorides in the coke. The metal rich filtrate leaves this part of the process for a further treatment.

Heavy Metal Separation (i,k)

In this part of the process, the filtrate from the extraction unit 2 gets purified in order to separate the heavy metals. After energy recovery in a heat exchanger, the filtrate gets mixed with milled limestone, accordingly the heavy metals precipitate in a sediment tank. The liquid phase is going to be purified in a membrane filter before it returns to the recycling water loop. Finally, the solid fraction will be post-treated in a filter press to decrease the moisture content. The separated water reflows to the recycling water loop.

The output of this process sequence is a metal product containing different metals, but mainly lead.

2.4.3 Stignæs PVC feedstock recycling process

General Overview

Stignæs Industrimiljø A.S. in Denmark has developed a two-step PVC recovery process. The process can be understood as hydrolysis separating inorganic and organic parts followed by a post-heating of the organic fractions. The process produces the following reclaimable output products:

- Sodium chloride (industrial grade)
- Oil fraction (a mixture of hydrocarbon products)
- Solid residue (as a energy and material feedstock for a sandblasting product)
- Polyethylene (separated in the pretreatment)
- Metal scrap (separated in the pretreatment)

External auxiliary supplies are:

- Sodium hydroxide
- Hydrochloric acid
- Electrical energy

No freshwater input is needed, as water is formed due to reaction with NaOH.

The objective of the process is to transform PVC-waste into a feedstock of material and energy for a material production process of sandblasting.

The process has been designed to be able to provide the necessary organic and inorganic input for the sandblast material production. The inorganic content is material feedstock and the organic content is energy feedstock to heat the sandblasting process. The process exists in a plant size of app. 12 t_{PVC}/h . That enables (at 5000 operation hours) a maximum of 60000 t_{PVC}/a .

The plant was modelled in the Software Tool GaBi 4. All relevant mass flows to close the energy and mass balances of the individual steps were integrated. In Figure 2-6 the main mass flows are shown, to enable an overview of the relevant mass transfers within the process. The thickness of the arrows represents the relative amount of mass flow.

Goal and Scope Definition

STIGSNAES PVC Recycling p

GaBi 4 Prozelplan: Masse

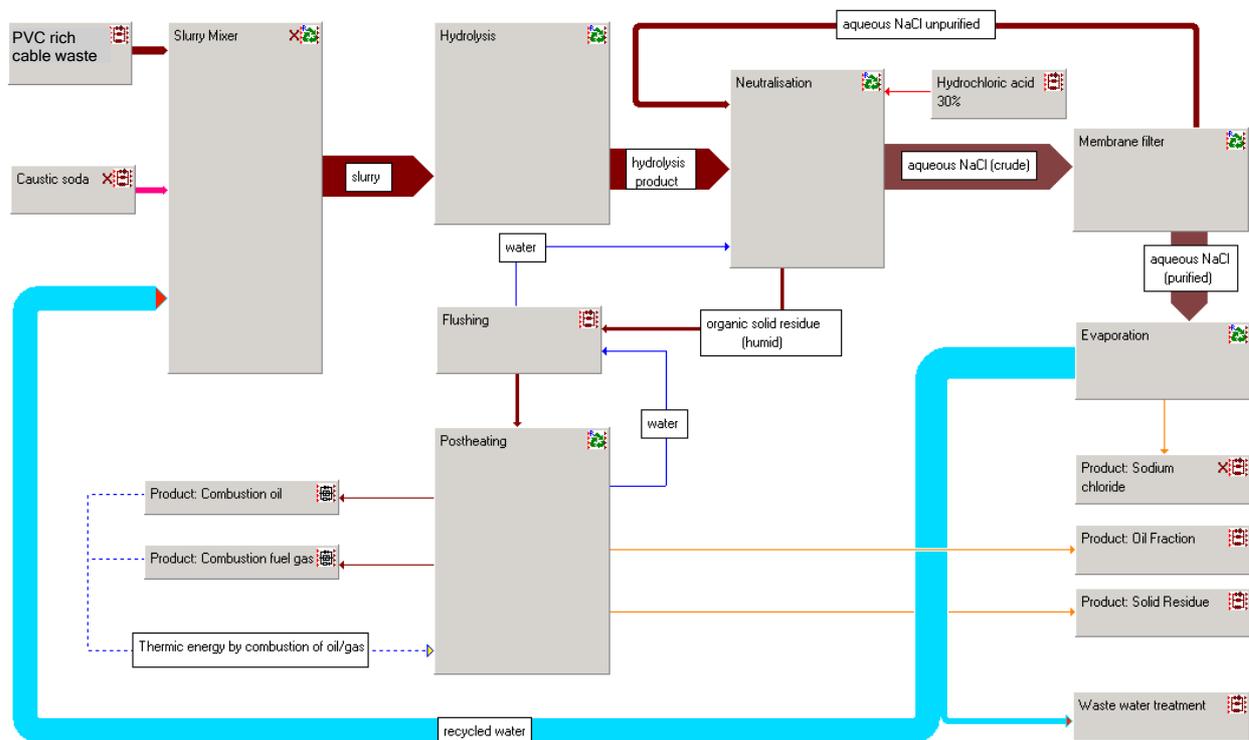


Figure 2-6: Mass flow Analysis model of the Stigsnaes Process

The main mass streams are as well the water cycles and the salt stream ending up in the product “sodium chloride”.

Figure 2-6 provides certain guidance for an easier understanding of the explanations in the next chapter.

Detailed Specification of the process:

Pretreatment at up-stream site

The PVC cable waste is pretreated into a metal fraction, a polyethylene (PE) residue - containing some PVC traces - a rubber fraction and a dry PVC-rich waste fraction. In the study it was assumed that app. 1% of the incoming PVC remain in the PE residue. This physical separation processes mainly on flow-sink basis needs only electricity and water as auxiliaries. The metal fraction contains scrap of copper, aluminium and steel ready for commercial sale. The polyethylene residue itself can optional be separated in PE, which is a reclaimable material, and PE-X, a thermosetting plastic that can be combusted in order to use its energy content. The PVC-rich waste fraction is the basic material for the PVC-recycling process.

Slurry Mixer

In the first stage of the process, cable waste is mixed with caustic soda and recycled water in a slurry mixer. The caustic soda is spent caustic from metal industry, hence no virgin caustic has to be added.

Hydrolysis Reactor

The originated slurry then is pumped via a feed pump into a tubular hydrolysis reactor. A complete dechlorination can be achieved under certain process conditions (high pH values) concerning temperature and time. The reactor is app. 3-4 km (!) long tube reactor.

Neutralisation

The hydrolysis products are passing through a neutralisation stage where aqueous hydrochloric acid is added. The hydrochloric acid may also be waste acid. The products are separated into solid (organic) sediments and a liquid phase. The liquid phase (mainly containing NaCl) passes through a membrane filter for purification. The residue, that has not passed the membrane filter, returns to the neutralisation stage.

Evaporation

The purified aqueous NaCl solution has to be consecutively evaporated in order to increase the NaCl concentration of the sodium chloride product (industrial grade). The thermal energy needed for the evaporation, is provided as waste thermal energy (off heat) by the nearby plant for sandblasting products. A pure salt product can be gained.

Post-heating Unit

The organic phase of the neutralisation stage is further treated in the post-heating process. In a flushing unit, residual NaCl is washed out of the solid residue with condensed water of the following post-heating unit.

The organics are treated thermally in a four stage post-heating process, reclaimable outputs are produced: A gaseous organic fraction is gained in the first stage. The gas is used to provide the needed energy for the further post-heating stages. An oil fraction is formed, that can be used as feedstock in industrial gasification processes, and a solid residue. The solid residue is used (after a further treatment) in the nearby Carbogrit plant to produce a sandblasting product.

The major part of the recycled water circulates through the process. The minor part is treated in a wastewater treatment plant.

Detailed specification of the process:

The Vinyloop process is a mechanical recycling process using an organic solvent to separate the PVC compound from the other materials in the PVC composite. It is a closed loop process. The solvent is completely recycled.

The batch process has the following main steps:

- Pretreatment and feeding
- Dissolving the composite
- Separation of the secondary material
- Precipitation of the regenerated PVC compound
- Drying and conditioning the product
- Recovery and recycling of the solvent in order to reuse

Pretreatment

In the first stage of the process, the cable waste is separated into a PVC rich fraction and a by-product fraction that contains among reclaimable copper and aluminium the major part of the non-PVC polymers such as rubber and polyethylene.

The feeding of the pretreated material to the Vinyloop process is done with a special device designed to introduce the composite in the dissolver without loss of solvent to atmosphere.

Dissolving the composite

A special solvent is chosen to dissolve the PVC compound selectively in a closed loop process under pressure and without air. A temperature of 100°C - 140°C adapted to the material and the type of composite helps to control the process.

Separation of the secondary material

The impurities are not dissolvable. They are separated in a filter from the PVC solution, all compounds of the PVC cable such as PVC, plasticiser, filler, stabiliser and pigments are found in this solution. It is possible to introduce additives like pigments or plasticiser to the solution at this stage.

The separation method is selected depending on the characteristics of the secondary material. It is washed with pure hot solvent to eliminate virtually the entire dissolved PVC compound and afterwards stripped with steam to recover all the solvent.

For this study it is assumed that the secondary material is combusted together with the by-product from the pretreatment in an incineration plant. (co-combustion with municipal waste)

Precipitation of the regenerated PVC compound

Following, the PVC solution is recovered in a precipitation tank, where steam is injected to completely evaporate the solvent. The PVC compound is recovered as an aqueous effluent. All the components of the original PVC formulation are recovered in the regenerated compound.

Drying and conditioning the product

The effluents from the precipitation step are sent to a decanter and split into cake and process water. The humid PVC compound is dried with hot air ready to be reused. The water from the process is treated up to the required purity level before being evacuated.

Recovery and recycling of the solvent in order to reuse

A multi-step decantation process regenerates the solvent. A primary condensation (using air or cooling water) is followed by a separation phase; both the biodegradable solvent and the water are recycled. A secondary condensation using pressure and low temperature recovers all the solvent that is technically and economically recoverable. The separated water returns to the precipitation tank, the solvent loops back to the dissolving stage. A final gas effluent treatment (afterburner) lowers the solvent concentration in the flue gas to meet all legal requirements constantly.

3 Mass Flow and Environmental Results

The following chapter describes the system modelling, the mass flows, the energy balance and the environmental profile of the considered recovery processes in detail. Additionally for Watech, Stigsnaes and Vinyloop scenarios were calculated and described.

The amount of output (products or output substances) is depending on certain conditions. These conditions are characterised (in this context) by so called parameters. The parameters that determine the amount of output are either depending on the amount of input or on the chosen technology, respectively the operating condition of the technology. Whether a parameter is considered technology dependent or input depended does not influence the environmental result, but enables an easier understanding of the given situation.

3.1 MVR Hamburg Municipal Solid Waste Incineration

3.1.1 System modelling of the incineration for the mixed cable waste

The following figure shows the Input – Output situation for incineration of the mixed cable waste (related to 1000 kg of mixed cable waste as input to the MVR Hamburg).

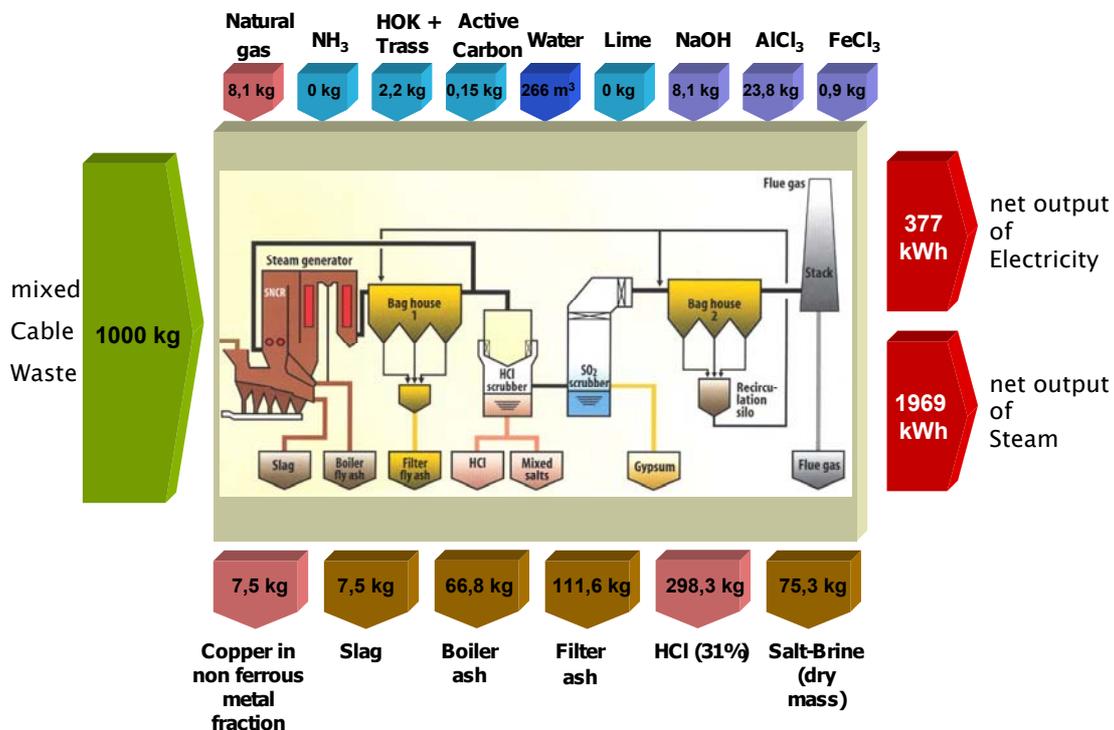


Figure 3-1: Mass flows of the MVR Hamburg incineration plant

Assumptions for the modelling of selected Input in the incinerator

For modelling the co-combustion of mixed cable waste with municipal solid waste, it is useful to define assumptions in order to guarantee the quality of the model. In the following, these assumptions are described.

In the model, a standard incineration for the municipal solid waste with a defined share of mixed cable waste is assumed. Some of the elements respectively tracked substances leaving the system are input dependent. That means, there is a linear correlation between input and output. For instance double input of chlorine means double output of chlorine.

This is not valid for all substances. Other input-output mass relations of substances are depending on the use technology in the process. The output of these substances is a function of the used technology and therefore constant for the same technology. One example for this kind of parameter is the output of chlorinated paraffins. No matter how sizable the input of chlorinated paraffins is the output of chlorinated paraffins remains constantly zero. The reason therefore is that the entire amount of chlorinated paraffins is destroyed in the combustion chamber of the waste incineration plant.

Hence, the singular view on a specific part of the input is valid, one parameter (input dependent) is linear the other one (technology dependent) is constant.

In the following the input dependent and the technology dependent parameters are described and the mechanism is explained.

Input dependent parameters:

- **Hydrocarbons:** The conversion rate of hydrocarbons is determined by stoichiometry (complete combustion): $H_mC_n + 3/2 O_2 \rightarrow nCO_2 + m/2H_2O$
- **Chlorine:** The PVC polymer matrix and possibly existing chlorinated paraffins are cracked in the combustion chamber. Following, a part of the released chlorine is immediately reacting with hydrogen. The composed HCl enters the flue gas stream and is carried through the process until it is separated in the HCl scrubber. The separated HCl is purified in the HCl rectification and leaves the process as HCl raw acid (industrial grade).

Due to the presence of CaO in the flue gas (deriving from the PVC-Filler $CaCO_3$), the remaining part of the chlorine is converted into $CaCl_2$. This is finally detectable in the filter ash residue and in the salt brine fraction.

- **CaCO₃:** The PVC Filler $CaCO_3$ is due to the temperature (at least 850° C) in the incineration and the small size of the particles separated in $CaO + CO_2$.
- **Sulphur:** The sulphur content of the mixed cable waste is completely transformed into SO_2 in the incineration. In the SO_2 scrubber, the sulphur dioxide is converted with

additional lime into gypsum ($\text{CaSO}_4 \cdot 1/2 \text{H}_2\text{O}$). Due to the presence of CaO in the flue gas (deriving from the PVC-Filler CaCO_3), a part of the SO_2 is already converted in the combustion chamber into gypsum. This gypsum is removed in the bag house from the flue gas stream.

- **Nitrogen:** In the incineration, the nitrogen content of the fuel is oxidised to NO_x , mainly NO_2 and N_2O (temperatures are too low for thermal NO_x).

Following, liquid ammonia is sprayed into the combustion chamber. This procedure reduces NO_x into elementary nitrogen and water.

- **Slag, boiler and filter ash:** The amount of slag, boiler and filter ash is dependent on the ash content of the waste.
- **Lead and aluminium:** Pb and Al are transported into the combustion chamber and are processed. An adhesion between these metals and dust occurs. The loaded dust particles are transferred to ~100% to the flue gas.
- **Copper:** Even in the areas of maximum heat in the incineration, the temperature is not high enough for smelting copper. Therefore the assumption is made that the main part of the copper is transferred to slag.
- **Chlorinated paraffins:** Chlorinated paraffins are part of the input. If they would not be destroyed within the process (thermal stability up to ~200°C) the amount of chlorinated paraffins in the output is dependent on the amount of chlorinated paraffins in the input.

Technology dependent parameters:

- **Carbon monoxide:** The formation of CO is the result of an incomplete combustion. A lack of air at certain spots in the combustion chamber promotes this process.
- **Dioxins:** The ultimate cause of the arising of dioxins and furans within the incineration process is the so-called De-Novo-Synthesis (new formation of Polychlorinated-dibenzo-Dioxins/Furans (PCDD/F) during the cool down phase in the boiler. Especially the temperature range (depending on technological size) between 250 and 350°C and the availability of certain elements is critical for this incident (detailed description in chapter 3.1.2)
- **Hydrocarbons:** The amount of HC emissions (result of incomplete combustion) is dependent on the air conditions within the combustion chamber.
- **Adsorbent:** The main task of the adsorbent is to catch dioxins. The demand of adsorbent, a mixture of coke and “trass” is dependent on the dioxin emission level.

- **Composition of slag, boiler and filter ash:** The composition of these residues is technology dependent, due to the fact that the influence of the composition of the PVC cable waste on the composition of the slag and the several ashes is marginal (combined combustion with mixed waste). The slag is used in the construction industry. In this study slag is handled as by-product without a value. That means that there has been no burden and no benefit allocated to the slag.
Boiler ash is adding to the category “municipal waste” due to the measured composition and boiler ash compositions out of in literature [ENVIRONMENT AGENCY 2000].
Filter ash is added to the category “hazardous waste”. For both ashes the further treatment is included in the study (operating effort and emissions).
- **Chlorinated paraffins:** As said before chlorinated paraffins are thermally stable to ~200 °C. Hence in the incineration they are completely destroyed in the combustion chamber (~850 °C). In low temperature processes chlorinated paraffins are not destroyed.

Boundary conditions of the incineration system modelling and allocations of utilities:

- **SNCR:** The NO_x emissions are reduced to 70 mg/Nm³. The necessary NH₃ demand is dependent on the nitrogen input from the fuel (input dependent) but the emission of unconverted ammonia (~10 mg/Nm³ after SNCR) is technology dependent.
- **Boiler and generator:** The efficiency of the steam production is 94%. The share of steam used to produce electricity is 11% and the rest (89%) is used as process-steam.
- **HCl-scrubber:** The output of the HCl-scrubber is a raw-acid with 10-12% HCl which is allocated to the chlorine input. The energy demand of the scrubber is allocated to the flue gas stream.
- **HCl-Rectification:** The amount of utilities and the energy demand of the rectification are allocated to the raw-acid that means they are input dependent.
- **SO₂-scrubber:** The demand of utilities is allocated to the sulphur input and the energy demand is allocated to the flue gas stream.

3.1.2 Dioxins arising from incineration of mixed waste

At the beginning of the 1990's, the thermal waste treatment had been regarded especially due to the dioxin/furan problematic as an emission source. Today, it is known, that waste incineration plants are a negligible source of emission for dioxins and furans due to effective

primary and secondary measures. Dioxins and furans are a class of 210 different chlorinated hydrocarbons with a principal structure as shown in Figure 3-2.

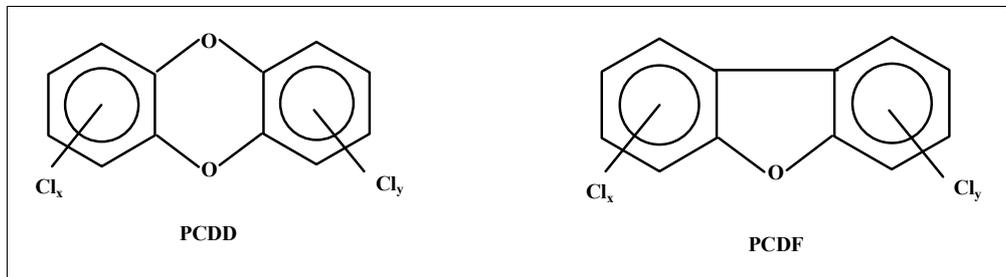


Figure 3-2: Principle dioxin (PCDD) and furan (PCDF) structure

The isomers have very different biological and toxicological behaviours. Isomers with chlorine-substitution in the position 2,3,7 and 8 have shown the strongest toxicological effect. The 2,3,7,8-Dibenzo-p-dioxin is also known as the “Seveso” dioxin.

Dioxins and furans are chemical and thermal stable. The thermal destruction takes place above 850°C. Thermal waste treatment plants for municipal wastes have to be operated in such a way that in the post combustion zone a temperature of 850°C is reached for at least two seconds.

With such a primary measure dioxins and furans are almost totally destroyed by passing the post combustion zone, independent of the chlorine input with the waste.

However, dioxins and furans can reform again downstream of the post combustion zone during the cool down phase in the boiler. Especially the temperature range between 250 and 350°C is critical for the so-called De-Novo-Synthesis (new formation of PCDD/F). The De-Novo-Synthesis is still, after many years of investigations, not totally understood.

It is known, that under the following conditions, dioxins and furans can be generated in the exhaust gas:

- Presence of elementary carbon C
- Availability of chlorine
- Presence of oxygen O₂
- Presence of copper Cu
- Sufficient resident time in the temperature range between 250 and 350°C

Due to these effects, the dioxin and furan emission in any waste incineration plant is in general above the regulatory level of 0,1 ng/m³ TEQ (standard conditions, dry). Therefore the

plants are equipped with secondary dioxin and furan abatement devices, mainly catalytic reactors or adsorption reactors.

The MVR plant is equipped with two adsorption filter devices. Activated coke is injected upstream of these two bag house filters for adsorption of dioxins and furans as well as mercury (Hg).

With these devices, the MVR plant reaches emission levels for dioxins and furans between 0,0003 and 0,0023 ng/m³ TEQ which is more than the factor 50 below the regulatory limit of 0,1 ng/m³ TEQ [MENKE 2002].

The evaluation of the dioxin and furan emission situation from adding up to 5% cable waste to the average municipal waste, we need to have a closer look to the following three process steps at the MVR plant.

1. Post combustion zone

Dioxins and furans are almost completely destroyed, even if the chlorine content is increased. From a theoretical standpoint, the addition of cable waste does not lead to increased dioxin and furan levels at this process stage.

2. Boiler section

All conditions for the De-Novo Synthesis are given, regardless of the additional PVC-scrap. The carbon and the chlorine concentration are increased approximately by the same percent factor as the percentage of additional PVC-scrap in regard of the normal waste mass input flow. From these elements no measurable increase of the dioxin and furan level is expected.

Only copper has been considered separately, as copper is known as a major driving element for the reformation of dioxins and furans. Copper has to be present in its elemental form and in fine distribution in the flue gas, for instance as dust.

The PVC scrap is shredded before it will enter the waste incineration plant and any copper from cable material will be added in pellet form (2 mm length, diameter dependent on cable material, typically 0,98 mm for a 0,75 mm² cable, no hair-wire).

It is unlikely that such large pellets enter the flue gas. It is more likely that these pellets are separated directly after the incineration grid.

Thus no significant increase of the dioxin and furan level is expected due to the addition of cable waste, when the flue gas passes the boiler section.

3. Secondary abatement systems (filters)

In general, activated coke for the adsorption of mercury and dioxins/furans is added in excess in order to reach the regulatory limits in all cases. Normally mercury is the leading parameter for the additive injection. Thus the dioxin/furan removal is always uncritical.

Even if the dioxin and furan level would be increased in the boiler section by adding cable waste, no additional additives have to be injected to ensure the dioxin and furan removal below the regulatory limit of 0,1 ng/m³ TEQ.

Taking these three facts into consideration, one has to come to the conclusion, that the dioxin and furan question is not related to the additional input of cable waste, especially in the range of the planned percentage of addition to the municipal waste.

This means that the dioxin and furan situation is technology related. As the technology remains unchanged the addition of cable waste has no additional effect to the environmental burden of the plant.

This result of the theoretical evaluation is practically proven by measurements, which have been conducted on site [MENKE 2002]. Mixed PVC containing waste incinerated in addition to municipal waste in the MVR in Hamburg. Emissions have been measured directly after combustion, after filter 1 and at the stack. The report shows that the copper content did not increase because of co-incineration of PVC scrap. The report also shows the measured dioxin and furan emission levels. As expected from theory, the co-incineration of PVC scrap did not lead to significant changed dioxin and furan levels after the combustion or the first filter. After the second filter as well, the critical dioxin and furan emission are not influenced by the addition of PVC scrap.

In summary it can be stated that the additional input of chlorine containing cable waste like the mixed cable waste of this study does not influence the environmental burden concerning dioxins and furans in a plant like the MVR Hamburg.

3.1.3 Mass flow of chlorine, lead, dioxins and chlorinated paraffins

The elements chlorine and lead as well as the organic halogen compounds dioxin and chlorinated paraffins could be environmental relevant. Hence, it is reasonable to take a closer look at these compounds. In this study, the amount of these substances in the single products respectively residues are shown in the mass flow charts below. The thickness of the arrows represents the amount of the substances.

In the MVR waste incineration plant, more than 50% of chlorine input can be recovered in the HCl product. About 47% of the chlorine, mainly deriving from the filter ash and the salt brine fraction will be disposed in special underground facilities (abandoned mines), which are legally allowed and approved to be a safe deposition site of the incineration residues.

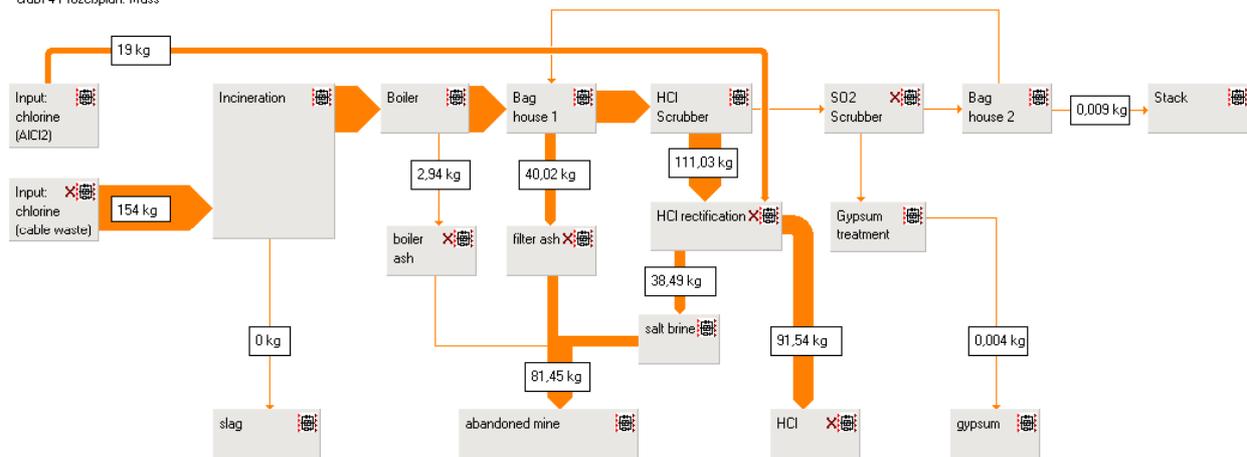
Mass Flow and Environmental Results

There is an additional input of chlorine via $AlCl_3$ into the rectification. It is mainly needed to separate other halogens from the HCl raw acid to ensure the industrial grade quality of the hydrochloric acid.

So one mainstream of the chlorine is converted into a new product and the second mainstream is transferred into residues under controlled process conditions, which enable to dispose the residues without direct environmental impact in underground dumpsites. Small amounts are found in the products gypsum and slag. The concentrations are below legal demands. Hence the products can be used in further applications. Only about 0,5% of the chlorine reaches the stack as emission.

MVR - mass flow chlorine

GaBi 4 Prozeßplan: Mass



	Input		Output						
	mixed cable waste	Auxiliary materials	Slag	Boiler ash	Filter ash	HCl	Salt brine	Gypsum	Flue gas
chlorine [kg]	154	19	<i>not exp.</i>	2,94	40,02	91,54	38,49	0,004	0,009
chlorine [%]	89	11	0	1,7	23,1	52,9	22,2	0,002	0,005

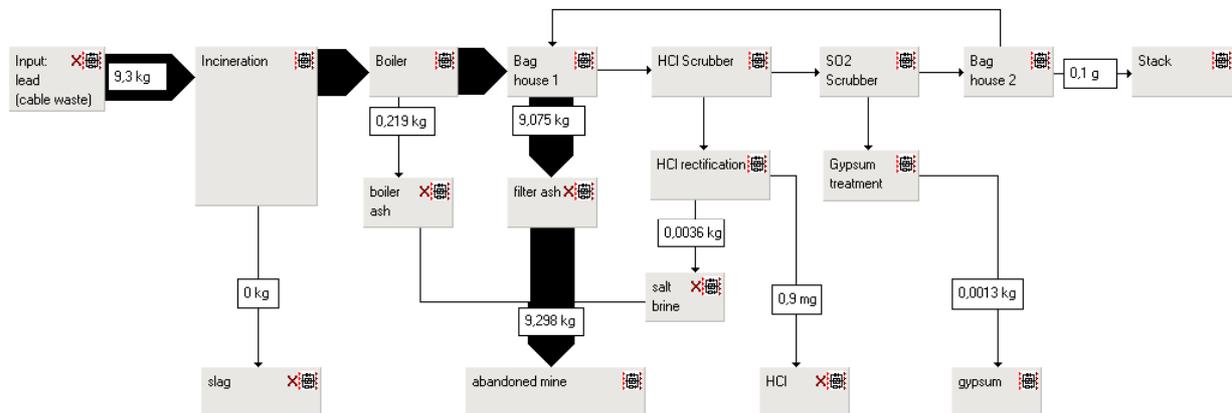
Figure 3-3: Mass flow of chlorine for the MVR waste incineration process (input dependent)

Lead and dioxin (both more than 99%) are mainly directed into in the filter and boiler ashes that are vitrified (to prevent elution) and also disposed in the underground dump facilities. The adsorbent in the bag filters is chosen to ensure a minimum emission rate of dioxins and heavy metals. Small amounts are found in the products gypsum and slag. These concentrations are also uncritical (see chlorine).

Mass Flow and Environmental Results

MVR - mass flow lead

GaBi 4 Prozeßplan: Mass

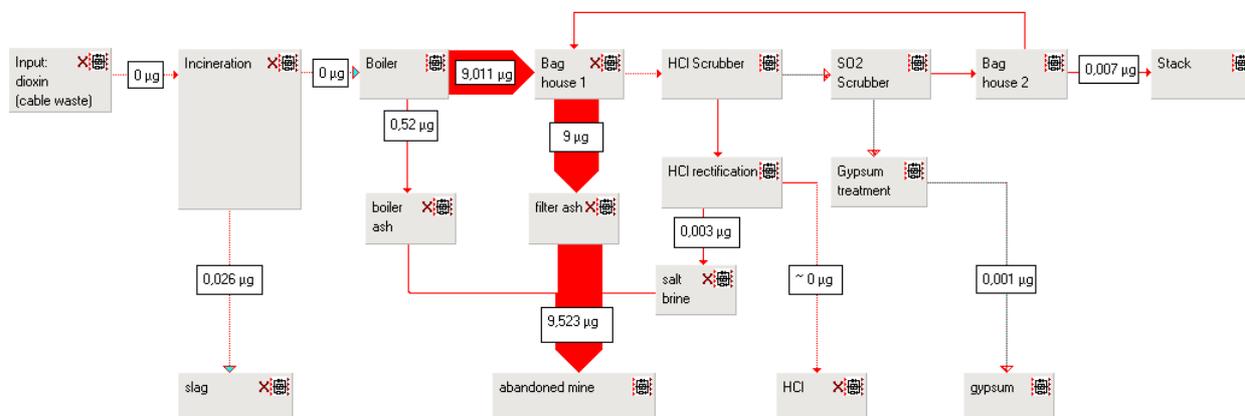


	Input		Output						
	mixed cable waste	Auxiliary materials	Slag	Boiler ash	Filter ash	HCl	Salt brine	Gypsum	Flue gas
lead [kg]	9,3	not measured	not exp.	0,220	9,075	$0,9 \cdot 10^{-6}$	0,0036	0,0013	0,0001
lead [%]	100	0	0	2,37	97,58	0,000	0,039	0,014	0,001

Figure 3-4: Mass flow of lead for the MVR waste incineration process (Input dependent)

MVR - Mass flow dioxin

GaBi 4 Prozeßplan: Mass



	Input		Output						
	mixed cable waste	Auxiliary materials	Slag	Boiler ash	Filter ash	HCl	Salt brine	Gypsum	Flue gas
dioxin [kg]	not expected	not expected	$2,6 \cdot 10^{-11}$	$5,2 \cdot 10^{-10}$	$9,0 \cdot 10^{-9}$	b.d.l.	$3,0 \cdot 10^{-12}$	$1,0 \cdot 10^{-12}$	$7,0 \cdot 10^{-12}$
dioxin [%]	0	0	0,27	5,44	94,17	0,00	0,03	0,01	0,07

b.d.l. = below detection limit²

Figure 3-5: Mass flow of dioxins for the MVR waste incineration process (technology dependent)

The formation of dioxins is rather dependent from the used technology then from the input into the process. This means the chosen incineration and treatment technology is liable for a

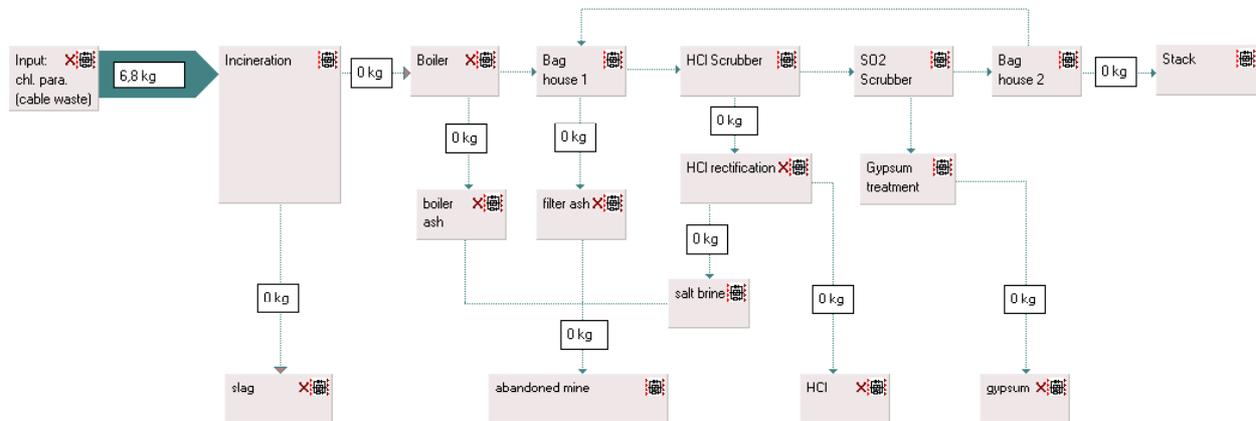
² MVR reported PCDD/F concentrations in HCl (2,3 pg/l HCl), which are much lower than for the other products. For symmetry reasons the values are considered "below detection limit".

Mass Flow and Environmental Results

possible creation and destruction of dioxins; rather than the PVC input (see chapter 3.1.1 for detailed description).

MVR - mass flow chlorinated paraffins

GaBi 4 Prozeßplan: Mass



	Input		Output						
	mixed cable waste	Auxiliary materials	Slag	Boiler ash	Filter ash	HCl	Salt brine	Gypsum	Flue gas
chl. paraffins [kg]	6,8	not expected	not exp.	not exp.	not exp.	not exp.	not exp.	not exp.	not exp.
chl. paraffins [%]	100	0	0	0	0	0	0	0	0

Figure 3-6: Mass flow of chlorinated paraffins for the MVR waste incineration process

The chlorinated paraffins are completely destroyed in the combustion chamber of the incineration plant, as the destruction starts at 200° C (see chapter 3.1.1).

Beside the displayed categories the technology of MVR also ensures a very low level of heavy metals emissions. The cadmium emission for example is lower 0,002% of the input. The predominant share of cadmium is expected again in the filter ash, some cadmium could be found in the slag and boiler ash as well. An assessment of antimony will result in comparable figures.

Halogenated compounds (e.g. with Br or F) will be cracked in the combustion. The halogens are found in the flue gas as acid (HBr or HF) which reacts partly with adsorbent or CaO. A minor part will be found in the filter ash. The major part is washed out in the sour scrubber and is found in the raw acid. The rectification is separating HCl from the other salts, which leave the process as mixed salt.

3.1.4 Energy balance of the waste incineration process

The major energy input of the waste incineration process is the energy content of the mixed cable waste. To safeguard the full steam supply for the industrial customers even during inspections, it is necessary to maintain an extra boiler. Due to this fact, a certain demand of natural gas is compulsive; furthermore some natural gas is needed for ignition. The efficiency of the steam production is 94%. The net share of energy supply for extern customers is 36,4% of the energy input. The main steam and electricity consumers within the process are:

Table 3-1: Main steam and electricity consumers in the incineration

Steam	Electricity
○ Reheating of flue gas	○ Fans
○ HCl rectification	○ Scrubbers
○ SNCR	○ Steam-condensate-pump
○ Periphery	○ Periphery

Figure 3-7 shows four bars of the energy balance. The left bar is the energy input of the mixed cable waste (calorific value). The bar next to it represents the extern process energy demand, which is needed in average to burn 1000 kg mixed cable waste (natural gas). The bar on the right hand side is showing the energy content of the steam and electricity sold to extern customers. The difference between input and output are the process energy losses.

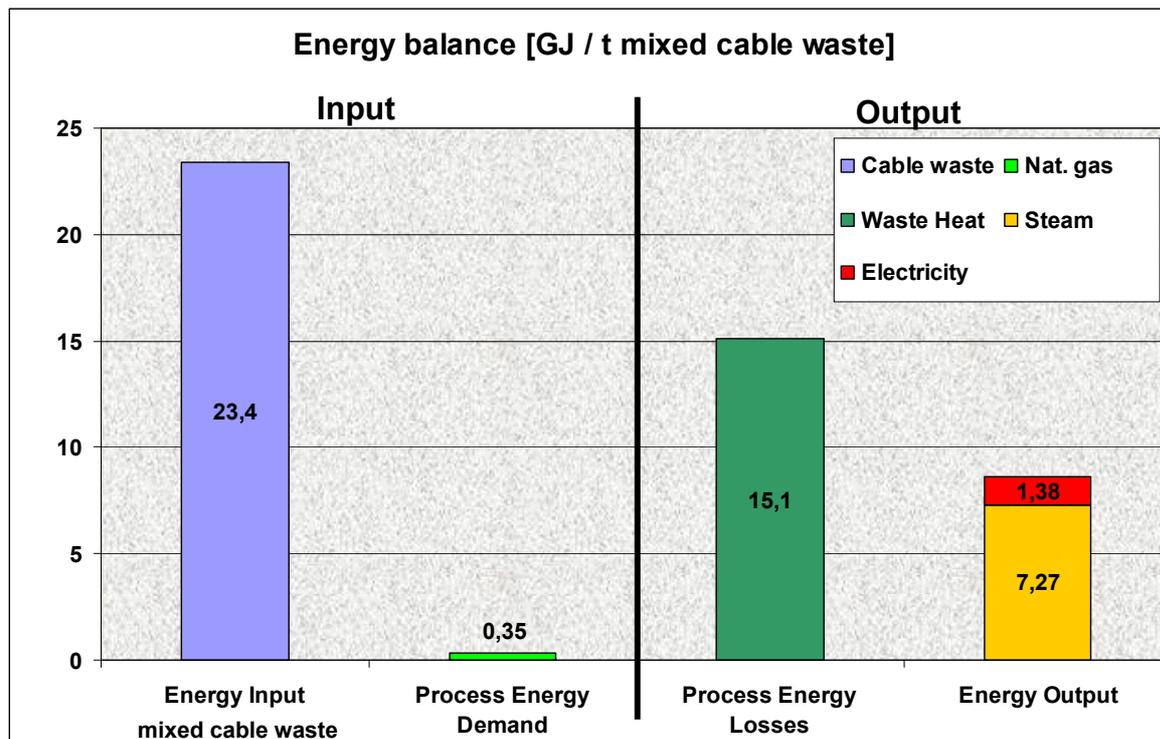


Figure 3-7: Energy balance of the MVR waste incineration process

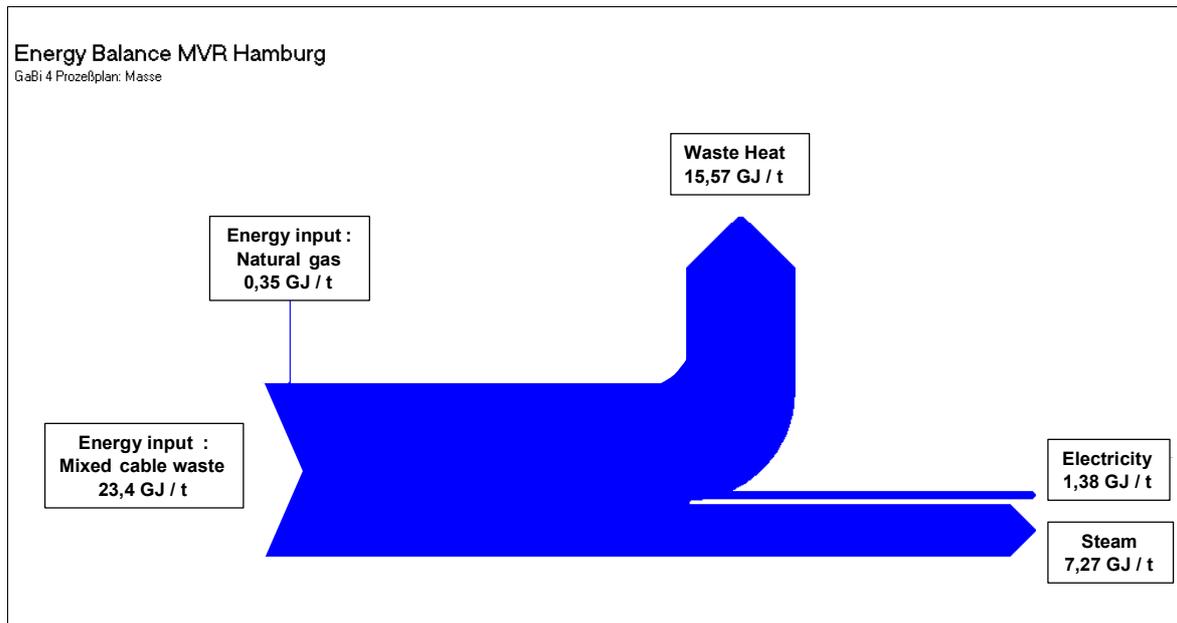


Figure 3-8: Sankey diagram of the energy balance of the MVR waste incineration process

Figure 3-8 shows the same fact as Figure 3-7 in a Sankey diagram. The constituents of the process energy losses are mainly own requirements of steam and electricity as well as generator losses. Those energy losses finally appear as waste heat.

3.1.5 Environmental profile of the MVR Hamburg waste incineration

The primary energy demand of MVR (cradle to gate including treatment of waste) is dominated by the treatment of the residues (ashes and mixed salt) in a abandoned mines (>63%). Mainly electricity is used to operate the mines. About 14% is caused by the natural gas use, 13% by the aluminium chloride.

The global warming potential is driven by the CO₂ emissions (96,4%), which is mainly the result oxidation of carbon in the combustion. Laughing gas (N₂O) and methane (CH₄) only play a smaller role.

The acidification potential is mainly caused by sulphur dioxide (62%) and nitrogen oxide (33%). Only 7% of the acidification potential is emitted at the MVR site, more than 50% of this is caused by the consumption of electricity used for the treatment of the ashes in the mines. The rest is caused by the supply of the auxiliaries like aluminium chloride (26%) or caustic soda (8%).

Table 3-2: Environmental Profile and Recovered Products for the recovery of 1 t mixed cable waste in the MVR waste incineration process

Recovery of 1 t mixed cable-waste:		
Environmental Profile		
Environmental Loads		
Primary Energy (non renewable)	2448	MJ
Global Warming Potential	2177	kg CO ₂ -Eq.
Acidification Potential	0,37	kg SO ₂ -Eq.
Hazardous waste	123	kg
Municipal waste	296	kg
Inert waste	445	kg
Waste water (only process itself)	0	m ³
Products (resulting in Environmental Benefits)		
HCl (31%)	298	kg
Copper in non ferrous metal fraction	7,5	kg
Electricity	377	kWh
Steam	1969	kWh

The hazardous waste is mainly filter ash (91%) from the flue gas treatment of the incineration process itself. To guaranty very low emission levels at the stack, as much as possible flue gas traces are filtered out. The incineration of PVC generates, due to the high calorific value respectively the conversion of the carbon matrix into gases (like CO₂), less filter ashes than the average municipal waste input in the MVR incineration. The filter residues are treated to prevent elution and dumped in approved underground facilities for hazardous waste (like described in chapter 3.1.3).

Boiler ash and residual mixed salts are categorised as municipal waste (accounting for over 99% of this category) and can be dumped in municipal waste landfills without further treatment.

The inert waste is mainly overburden from the energy chain and primarily caused by the electricity production for the operation of the underground facilities (dump site) for e.g. air ventilation, water pumping and transport.

3.2 Watech PVC Feedstock Recycling Process

3.2.1 System modelling of the Watech process

The following Figure 3-9 shows the overall system modelling of the Watech process. For a more detailed figure of the recovery process steps as such see chapter 2.4.2.

WATECH Mass Flow

GaBi 4 process plan: Masse

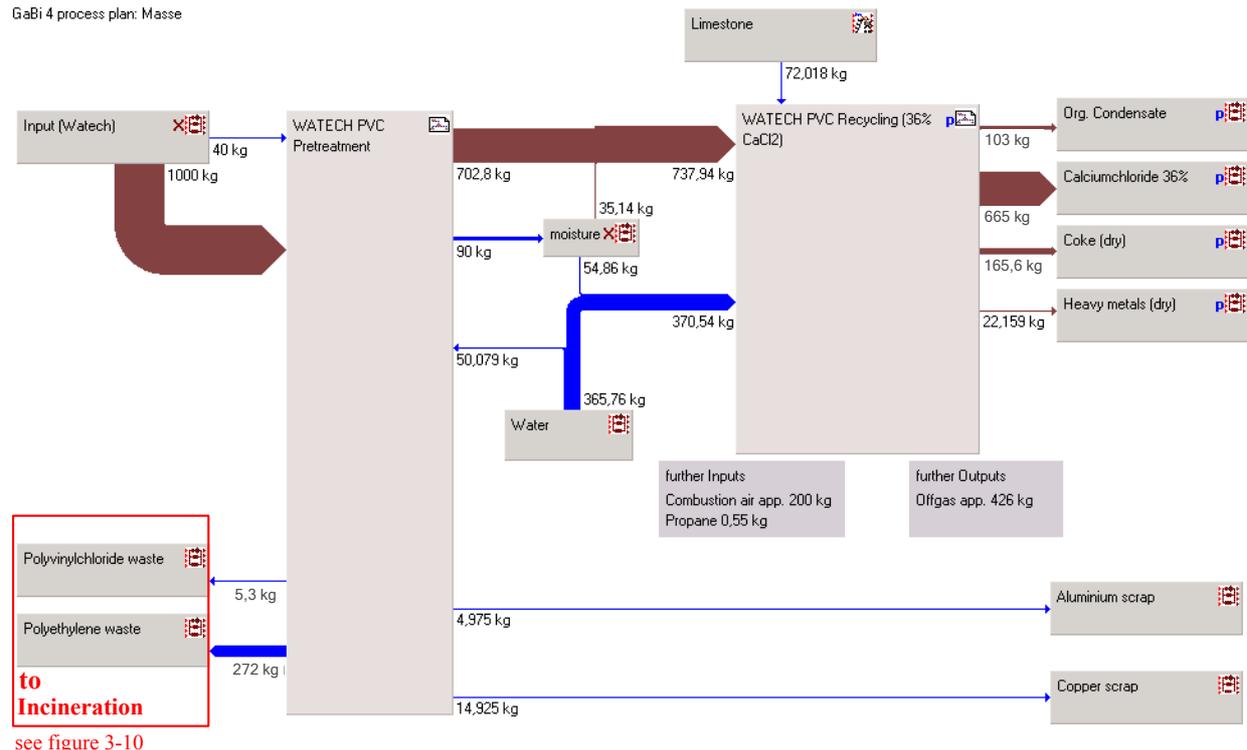


Figure 3-9: Mass flow Analysis model for 1t PVC cable waste with Watech Process

The pretreatment process mainly separates polyethylene (some trace PVC is following the PE stream) as well as metal scraps (Al and Cu). The containing rubber fraction follows the PVC into the Recovery Process (reactor). Two Calcium sources occur: The Ca of the filler bound in the PVC and the added limestone. No wastewater is generated, as the produced water is needed in the process again (loop) or leaves the system together with the product CaCl₂ in a 36% solution. The main mass flow route is:

PVC into reactor ▶ Coke (incl. CaCl₂) ▶ Recycle water + CaCl₂ 36% solution

The process is modelled from cradle to gate. That means all mass flows and environmental impacts from resource extraction to the products leaving the recovery processes are modelled. This includes the production of energy and auxiliaries as well. Hence - depending

Mass Flow and Environmental Results

on the process parameters - the environmental impact of the up-stream processes may exceed some of the environmental impact of the recovery process itself.

According to latest information the trace PVC mass flow, that follows the PE mass flow from pretreatment to separation, can be reduced with the existing pretreatment process to 0,14 kg/t. This reduces the amount of chlorine and lead to incineration and thus reduces the amount of produced HCl and causes wastes in the incineration plant slightly. The changes are of minor importance, as they don't change the overall results significantly.

The separated PE and trace PVC is incinerated. Figure 3-10 shows the Input – Output situation for incineration of the separated cable fraction from Watech (related to 1000 kg of separated cable fraction as input to the incineration).

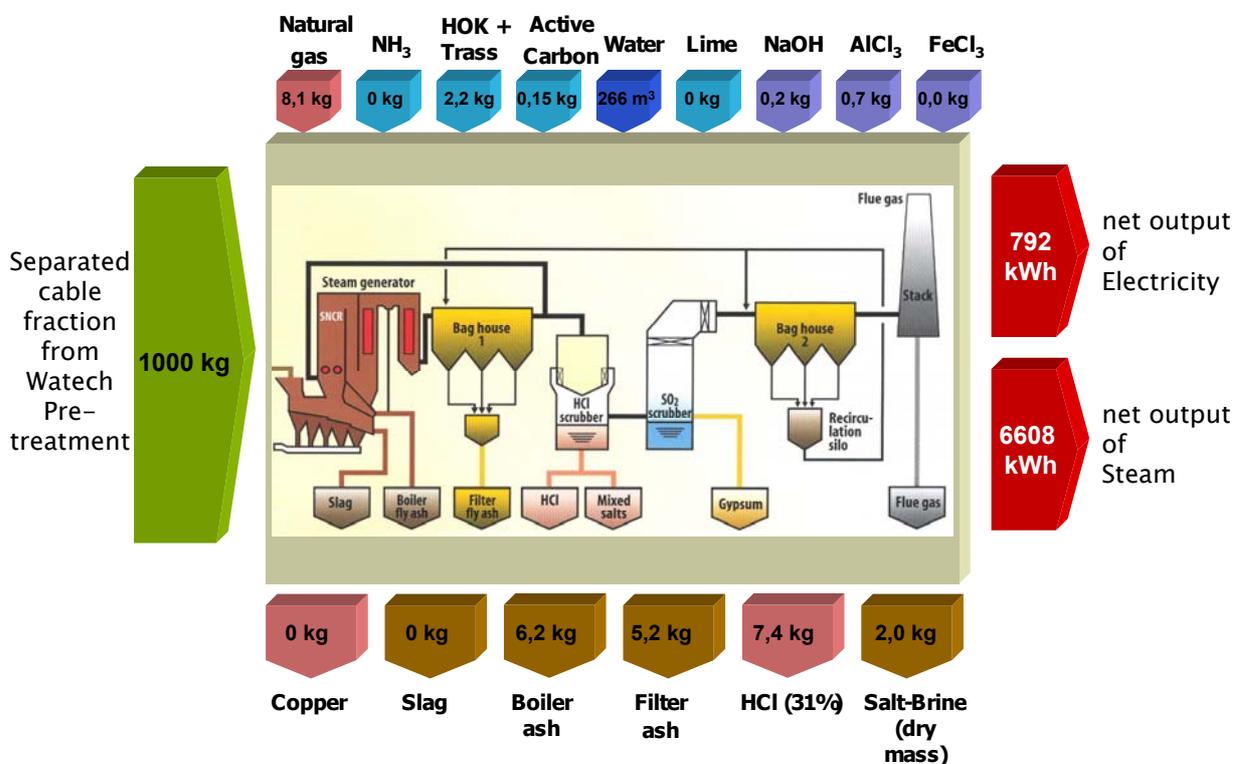


Figure 3-10: Mass flow Analysis model for incineration of 1000kg sep. cable fraction from Watech Process

The separated cable fraction is converted into the shown residues, substances and energy products according to the incineration model (see 2.4.1 and 3.1 for details).

3.2.2 Mass flow of chlorine, lead, dioxins and chlorinated paraffins

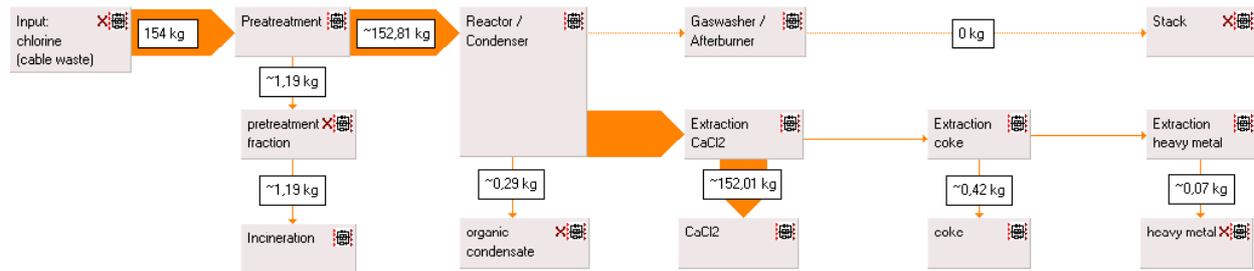
The following figures are showing the mass flows of the analysed substances through the process. Some chlorine is following the PVC traces from the pretreatment to the incineration. About 0,2% is found as chlorinated hydrocarbons in the organic condensate (this figure has

Mass Flow and Environmental Results

been lowered according to Watech to 0,01% during the timeframe of the study). More than 98% of the chlorine is converted into the CaCl_2 product. Traces of less than 0,4% is found in the coke and less than 0,1% in the metal product as metal-chlorides.

Watech - mass flow chlorine

GaBi 4 Prozeßplan: Mass



	Input mixed cable waste	Output pretreatment fraction	organic condensate	calcium- chloride	coke	heavy metal product	stack
chlorine [kg]	154	~1,19	~0,29	~152,01	~0,42	~0,07	<i>not measured</i>
chlorine [%]	100	0,77	0,19	98,71	0,28	0,05	0

Figure 3-11: Mass flow of chlorine for the Watech process

Considering the specific pretreatment information mentioned above (chapter 3.2.1) the chlorine percentage in the column “pretreatment residues” would decrease from 0,77 % to app. 0,05 %. The difference (0,72 %) would be distributed according to the specific share of the individual product. Hence most of the 0,72 % would end up in the salt product.

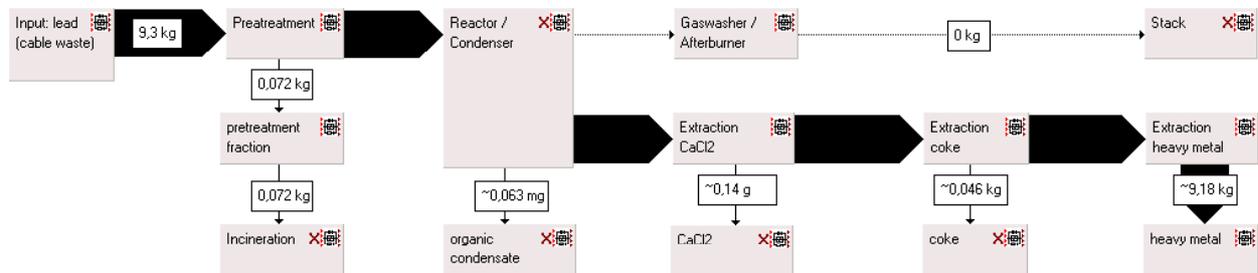
Some lead (of the PVC filler) is following the PVC traces from the pretreatment to the incineration. Traces are found in organic condensate, CaCl_2 and coke. The major amount is extracted into the metal product.

Considering the specific pretreatment information mentioned above the lead in the column “pretreatment residues” would decrease from 0,072 kg to 0,004 kg. The difference would be distributed according to the specific share of the individual product. Hence most of the lead would end up in the heavy metal product.

Mass Flow and Environmental Results

Watech - mass flow lead

GaBi 4 Prozeßplan: Mass



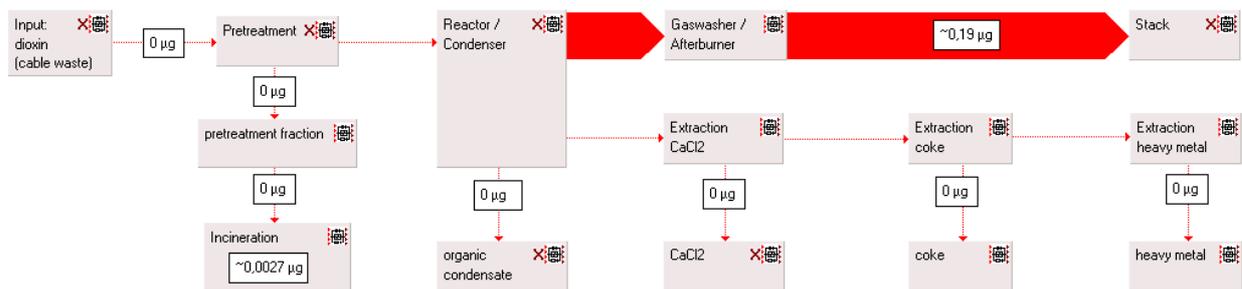
	Input	Output					
	mixed cable waste	pretreatment fraction	organic condensate	calcium-chloride	coke	heavy metal product	stack
lead [kg]	9,3	0,072	$6,3 \cdot 10^{-8}$	$1,4 \cdot 10^{-4}$	0,046	9,18	not expected
lead [%]	100	0,77	$6,8 \cdot 10^{-7}$	$1,5 \cdot 10^{-3}$	0,49	98,73	0

Figure 3-12: Mass flow of lead for the Watech process

The formation of dioxin can be understood like the De-Novo-Synthesis explained in chapter 3.1.2. In contrast to the waste incineration process, the pyrolysis process works under exclusion of oxygen. The hot pyrolysis gas is “quenched” in the condenser in oxygen rare atmosphere. Hence the formation of dioxin is effectively suppressed.

Watech - mass flow dioxin

GaBi 4 Prozeßplan: Mass



	Input	Output					
	mixed cable waste	pretreatment fraction	organic condensate	calcium-chloride	coke	heavy metal product	stack
dioxin [kg]	not expected	$2,7 \cdot 10^{-12}$	b.d.l.	not measured	b.d.l.	not measured	$1,9 \cdot 10^{-10}$
dioxin [%]	0	1,4	0	0	0	0	98,6

b.d.l. = below detection limit ³

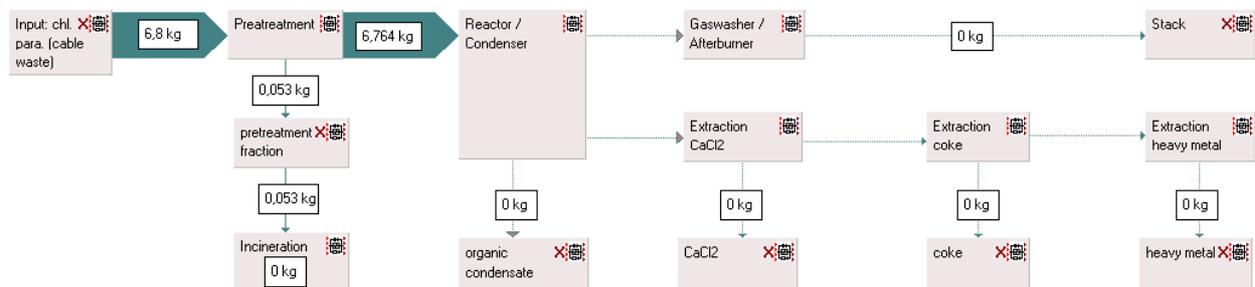
Figure 3-13: Mass flow of dioxins for the Watech process

³ SGS Control-Co.m.b.H in Wismar, Germany made the Watech dioxin measurements. The detection limits vary for the different dioxin compounds from 0,01 to 0,1 ppb.

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Watech - mass flow chlorinated paraffins

GaBi 4 Prozelplan: Mass



	Input mixed cable waste	Output pretreatment fraction	organic condensate	calcium- chloride	coke	heavy metal product	stack
chl. paraffins [kg]	6,8	0,053	not expected	not expected	not expected	not expected	not expected
chl. paraffins [%]	100	0,78	0	0	0	0	0

Figure 3-14: Mass flow of chlorinated paraffins for the Watech process

As mentioned before, the destruction of chlorinated paraffins starts at 200° C. The temperature in the Watech reactor is two times higher, therefore a complete destruction can be assumed.

Cadmium and bromine play a minor role in the case of cable waste, as those components were not detected in the cable waste or are very unlikely to appear. Nevertheless the behaviour of those mass flows is described, to clarify a situation of appearance.

Possible cadmium compounds (e.g. from stabilisers) would mainly follow the CaCl₂. Before the evaporation step, a further cadmium removal step (pH regulated precipitation) can be implemented, to separate the cadmium from the CaCl₂ solution. Thus a further cadmium product would be produced.

If bromine compounds are part of the cable waste fraction, it is likely that bromine follows mainly the CaCl₂ flow as well (as bromine is a halogen like chlorine). That means possible bromine (e.g. in flame retardants) would lead to impurities of the CaCl₂ solution. A separation or purification of CaCl₂ may be added after the evaporation, if needed.

3.2.3 Energy balance of the Watech process

Figure 3-15 shows four bars of the energy balance. The left bar is the energy input for the mixed cable waste. The next bar represents the extern process energy demand, which is needed in average to recover 1000 kg mixed cable waste. The bar on the far right hand side shows the energy content of the products. The bar next to it shows the output of energy content in the residues of the pretreatment (which go to incineration). The difference between input and output are the process energy losses.

The energy demand of the recovery process is saturated by electricity and by the combustion of internally produced organic condensate. The Watech process itself does not produce electricity or steam. The benefit from an energy viewpoint is the recovery of the energy content (calorific value) in the products. In the following, two different energy balances of the Watech process for processing 1000 kg mixed cable waste are illustrated. In the intermediate energy balance, the energy content of the intermediate products such as polyethylene is separately displayed. In contrast, the final energy balance represents the net energy benefit including steam and electricity after processing the intermediate products in an incineration plant. To visualise the energy flows of the process for both energy balances, Sankey diagrams are shown (see Figure 3-16 and Figure 3-18).

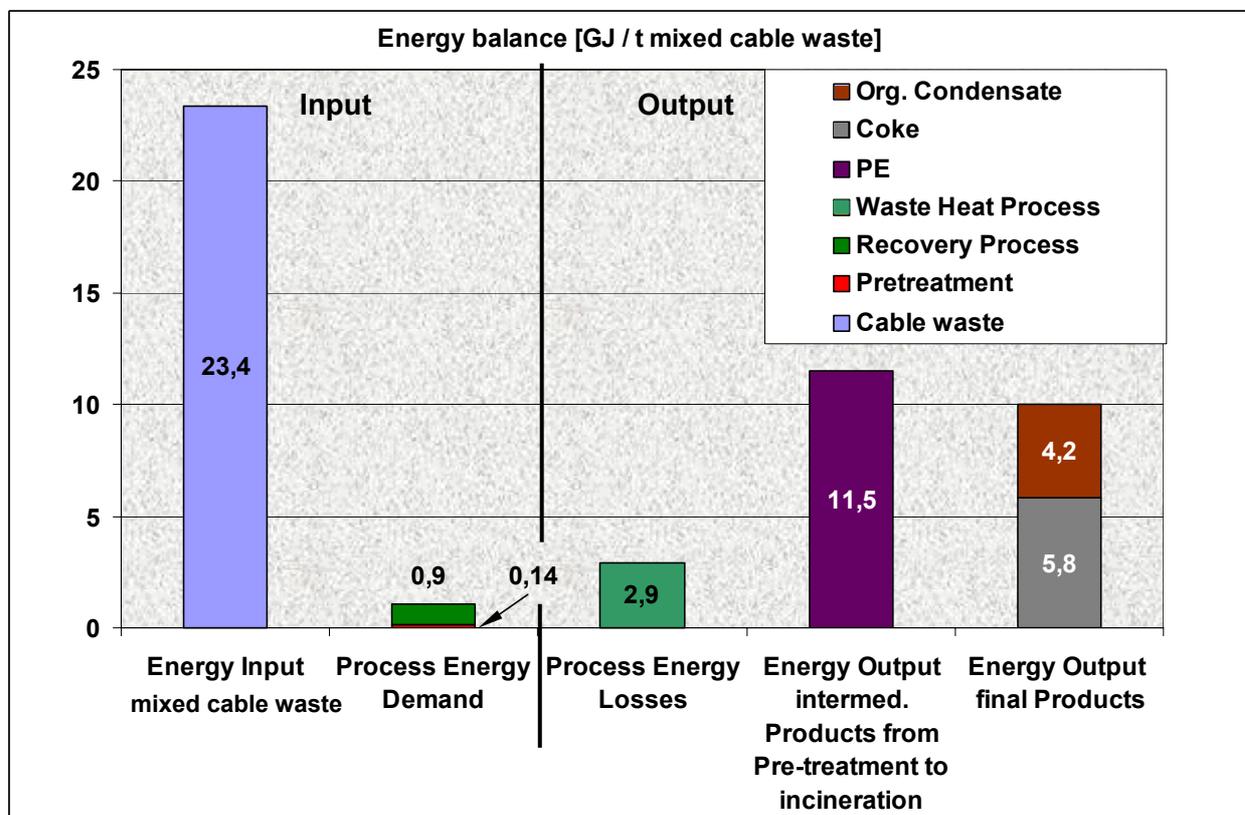


Figure 3-15: Intermediate energy balance of the Watech process

Mass Flow and Environmental Results

The 23,4 GJ are representing the energy input (calorific value of PVC cable waste) due to the input of the PVC cable waste in the process. The pretreatment has an energy demand of 0,14 GJ (some electricity for conveyers and flow-sink-separators). The process itself needs 0,9 GJ for e.g. the reactor, pumps, valves, filter press. The combustion of a share of the organic condensate to supply thermal energy for evaporation and extraction accounts for 1,8 GJ of the process energy losses of totally 2,9 GJ. Together with the PE 11,5 GJ are separated in the pretreatment. 10 GJ are converted into coke and organic condensate. Figure 3-16 shows the above mentioned visualised in a Sankey diagram.

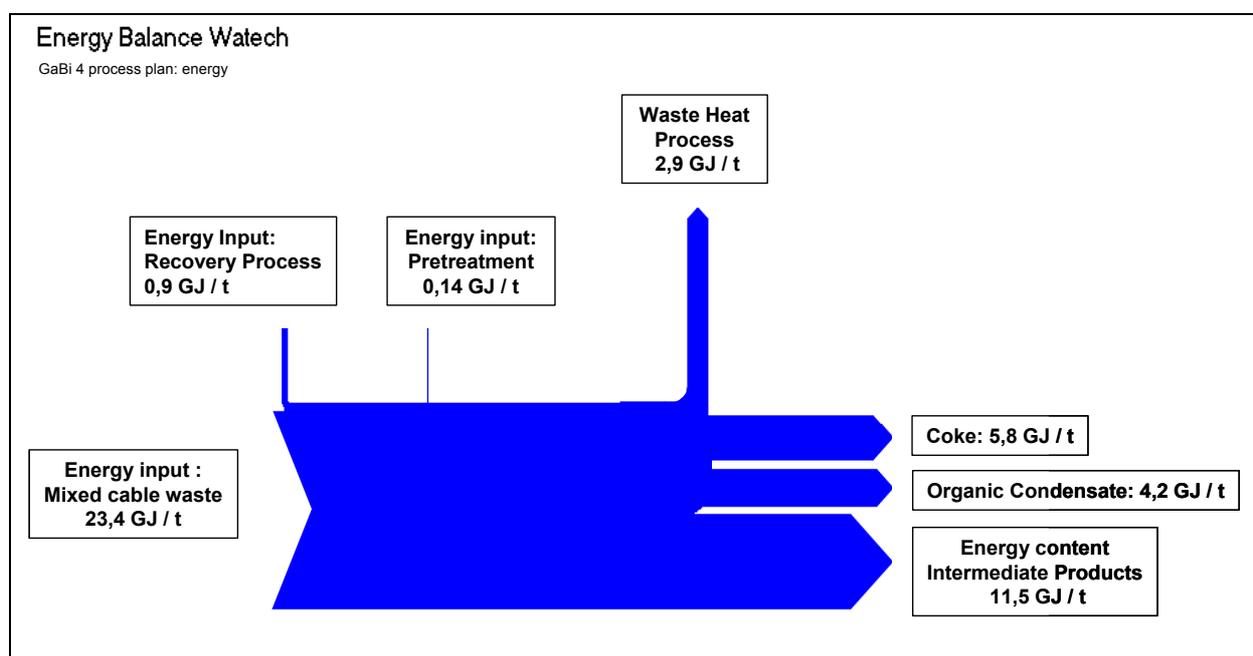


Figure 3-16: Sankey diagram of the intermediate energy balance of the Watech process

The intermediate products are further treated in the incineration. Hence a overall energy balance can be set up after integrating the incineration model.

The 11,5 GJ of PE (input of intermediate products into the incinerator) are converted to 0,8 GJ electricity, 7,1 GJ steam accompanied by 3,6 GJ losses.

Mass Flow and Environmental Results

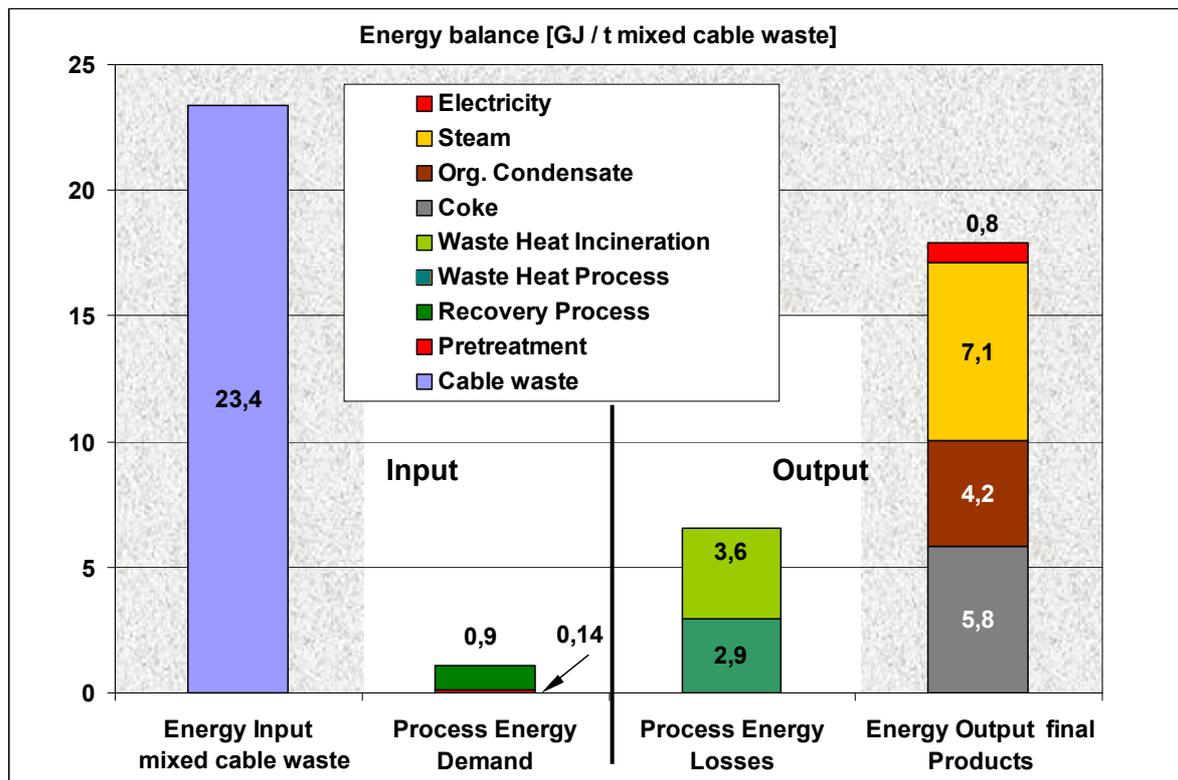


Figure 3-17: Energy balance for processing 1 t PVC cable waste with the Watech process

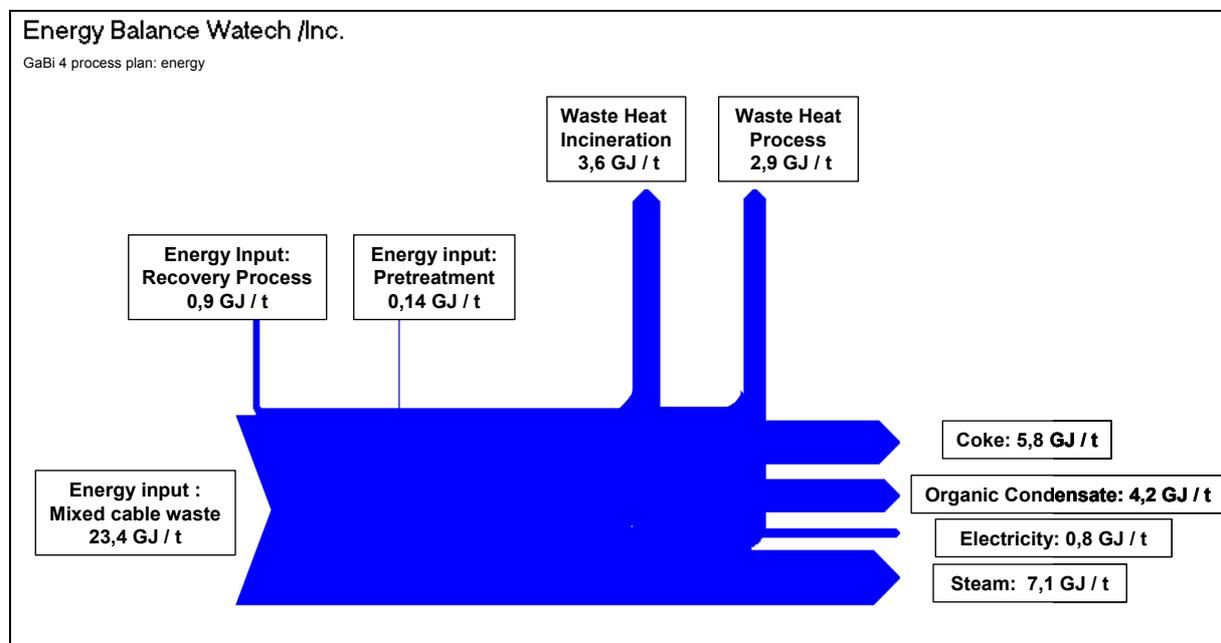


Figure 3-18: Sankey diagram of the energy flows within the Watech process

Coke and organic condensate provide app. 42% of the recovery related to the 23,4 GJ input, as can be seen in Figure 3-18. The separated PE fraction (converted to steam and electrical power in the incineration) accounts for a high recovery share of more than 30%.

3.2.4 Environmental profile of the Watech process

Primary Energy Demand of the Watech process

The primary energy demand is modelled from cradle to gate. That means further processing of the pretreatment fraction is not considered in this chapter. The energy demand is dominated by electricity. The combustion of a share of the internal produced organic condensate for the generation of thermal energy can satisfy app. 85% of the necessary energy demand of the process.

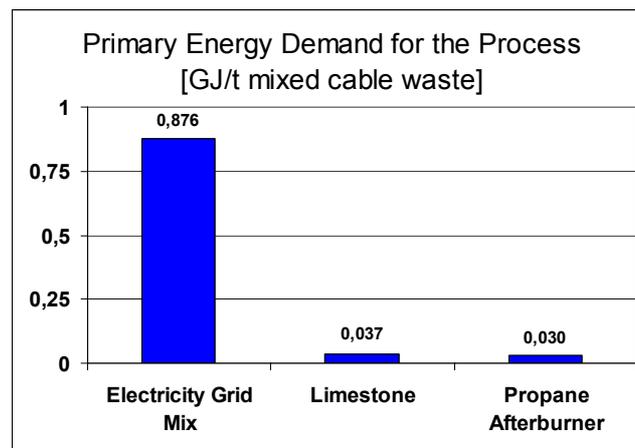


Figure 3-19: Primary Energy demand of Watech Process

The electricity is needed for process control, pumps, valves, filter presses, blowers and mills. The limestone (for extraction purposes) and some propane to fire the afterburner account for app. 7% of the energy demand.

Global Warming and Acidification Potential of the Watech process

The Global Warming Potential (GWP) and the Acidification Potential (AP) are modelled similar to the primary energy balance. The afterburner (app. 177 kg CO₂-Eq./ t_{mixed cacle waste} in stack) and the combustion of organic condensate (app. 132 kg CO₂-Eq./ t_{mixed cacle waste}) as well as the use and production of electricity (app. 72 kg CO₂-Eq./ t_{mixed cacle waste}) are the main contributors to the GWP.

The main contributors to the AP are the production of electricity (0,096 kg SO₂-Eq./ t_{mixed cacle waste} to air and 6,9E-09 SO₂-Eq./ t_{mixed cacle waste} to water), the combustion of organic condensate (app. 0,0074 SO₂-Eq./ t_{mixed cacle waste} to air), the production of propane (0,0024 SO₂-Eq./ t_{mixed cacle waste} to air and 2,42E-07 SO₂-Eq./ t_{mixed cacle waste} to water). The impacts of the pretreatment are mainly due to electricity consumption.

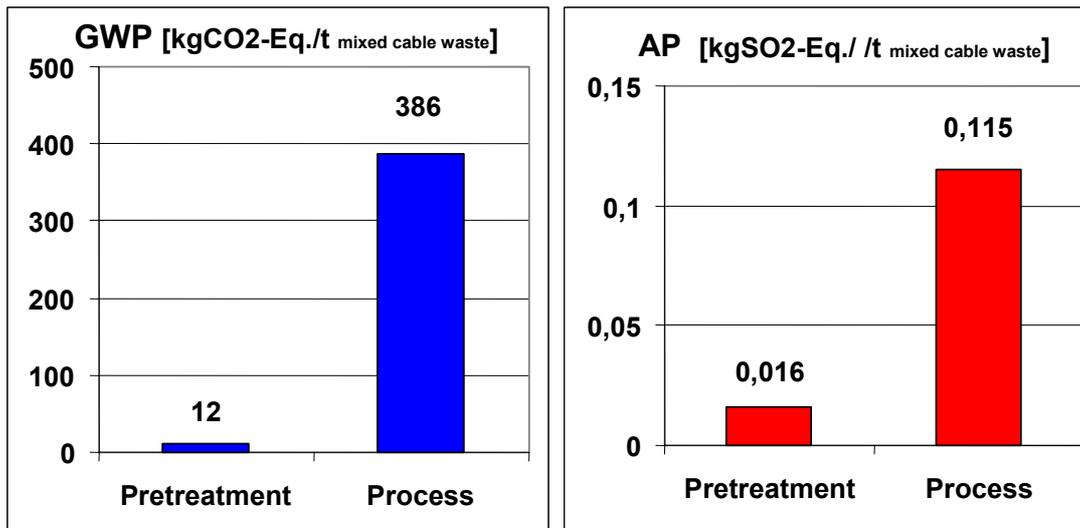


Figure 3-20: Global Warming Potential and Acidification Potential of the Watech Process

Overview:
Environmental Profile of Watech process and Incineration of pretreatment residues

Table 3-3: Environmental Profile and Recovered Products for the recovery of 1 t mixed cable waste in the Watech Process and Incineration Plant

Recovery of 1 t mixed cable-waste:		
Environmental Profile		
Environmental Loads		
Primary Energy (non renewable)	1142	MJ
Greenhouse Warming Potential	1272	kg CO ₂ -Eq.
Acidification Potential	0,138	kg SO ₂ -Eq.
Hazardous waste	2,9	kg
Municipal waste	3,2	kg
Inert waste	92	kg
Waste water (only process itself)	0	m ³
Products (resulting in Environmental Benefits)		
Organic Condensate	104	kg
Coke	166	kg
CaCl ₂	239	kg
Copper	14,9	kg
Aluminium	5,0	kg
HCl (31%)	2,3	kg
Electricity	220	kWh
Steam	1969	kWh

The primary energy relates to app. 83% to the Watech process and app. 17% to incineration. The major share of the Global Warming Potential is due to the incineration (app. 65% due to combustion and electricity and steam production). The Acidification mainly comes from the Watech process itself (95%), as the incineration has a very effective flue gas cleaning system. 1,35 kg of the hazardous waste is related to the Watech process, mainly due to electricity production. For the municipal waste 0,94 kg are related to the Watech process as such (mainly electricity production and dirt from pretreatment separation). The inert waste is related electricity production again (app. 73 kg from Watech process).

3.2.5 Parameter Variation (Scenarios)

Basic task of the parameter variation is to analyse important parameters (process parameters or input related parameters). Important means here, that a variation of the parameters influences the environmental performance of the system significantly. In the study, process parameters or input related parameters are varied within reasonable intervals, to figure out the importance and impacts on the complete system.

Impacts under study are the impact on the primary energy demand, GWP, AP and the waste masses.

a) Parameter 1: Share of process energy provided by the combustion of organic condensate

If no internally produced organic condensate (or fuel) could be used, the end-energy demand for heating of the process may have to be covered by electricity or natural gas. The electricity grid mix used in Denmark has an efficiency (in terms of primary energy) of app. 40% from cradle-to-usage. Fossil fuel has an efficiency of around 90%.

Non renewable Primary Energy demand for the Watech Process

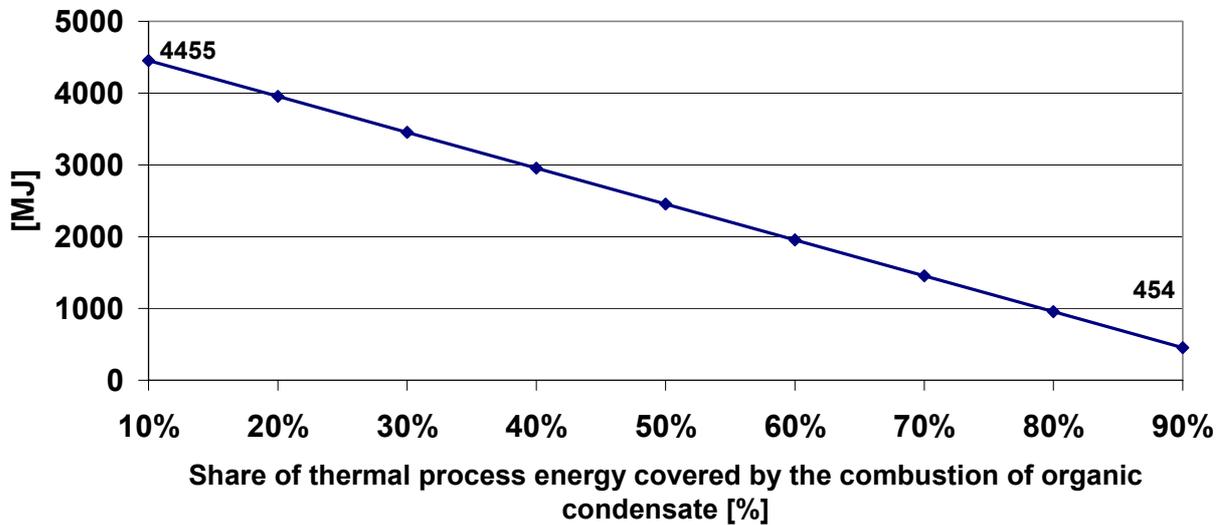


Figure 3-21: Parameter organic condensate and impact on primary energy demand (Watech)

The results of the primary energy demand are shown in Figure 3-21. The share of the thermal process energy is varied from 90% electricity and 10% organic condensate (left) to 10% electricity and 90% organic condensate (right). The pilot plant used 0% organic condensate (100% electricity). For the situation of the 15000 t/a plant a use of 80% organic condensate seems to be the preferable.

Greenhouse Warming Potential for the Watech Process

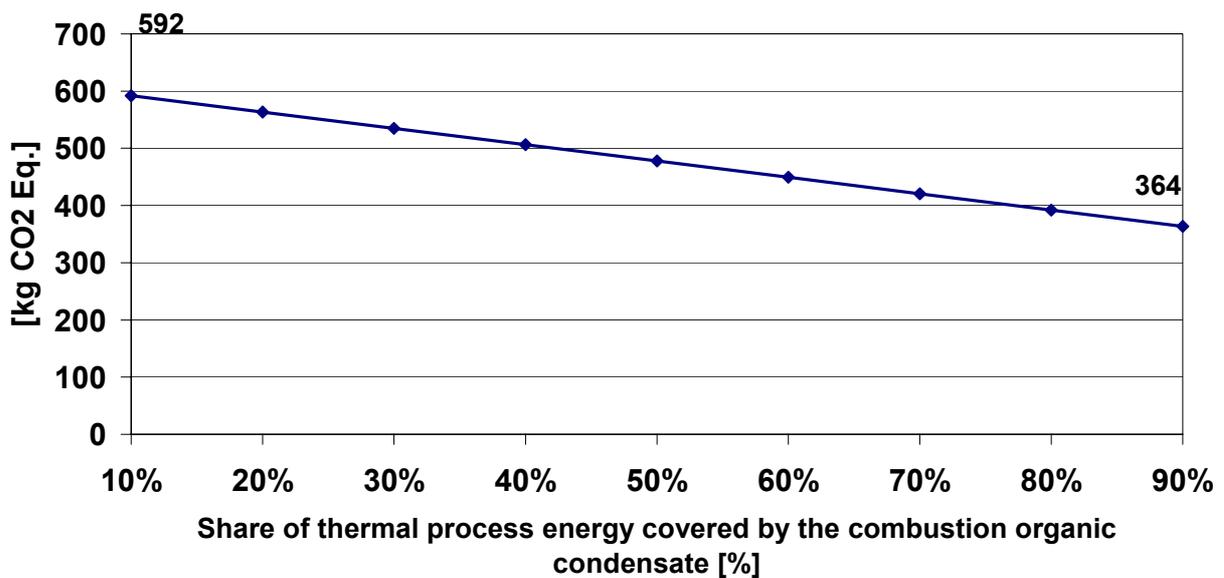


Figure 3-22: Parameter organic condensate and impact on GWP (Watech)

The results show the same tendency, but less intensive for the Global Warming Potential than for primary energy demand.

Acidification Potential for the Watech process

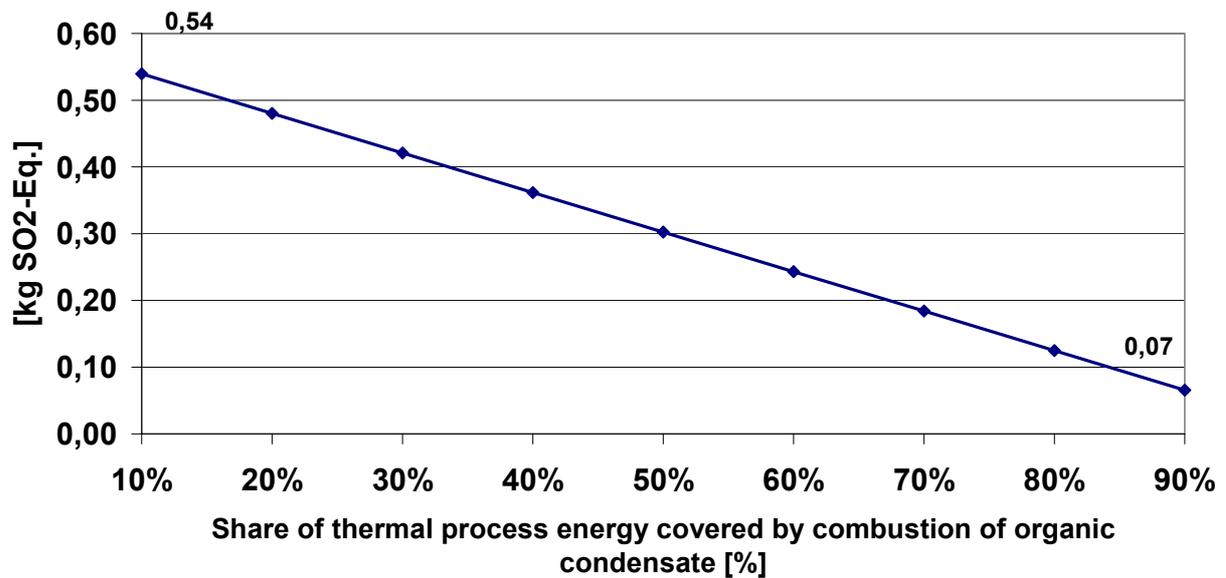


Figure 3-23: Parameter organic condensate and impact on AP (Watech)

Waste masses of the Watech process

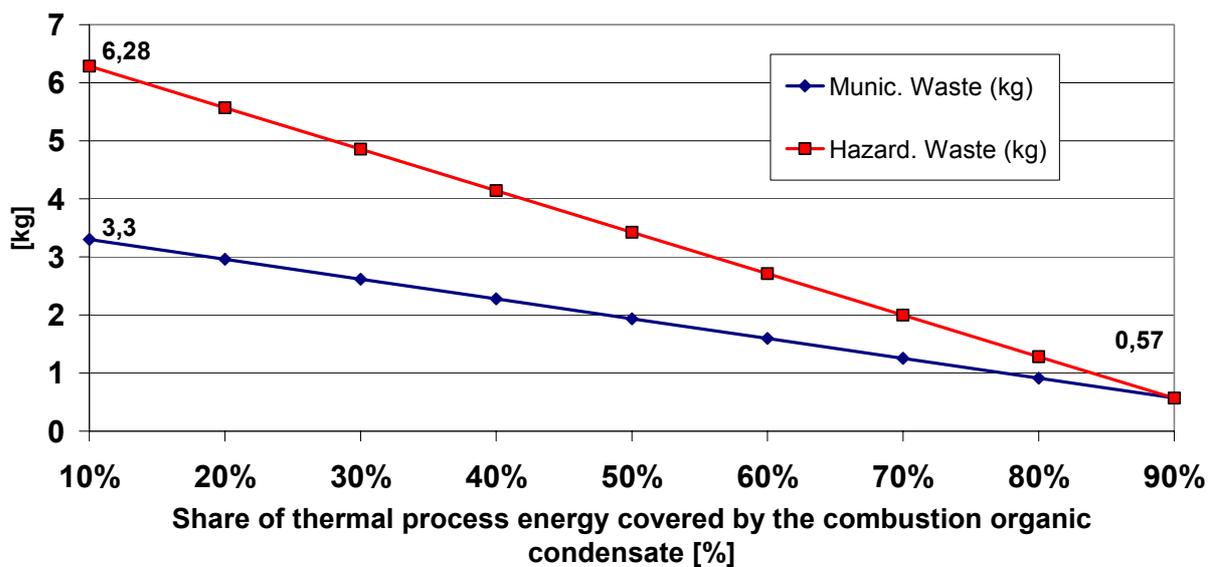


Figure 3-24: Parameter organic condensate and impact on wastes (Watech)

As well the results for acidification and waste masses show the same tendency.

Interpreting the results of the parameter variation leads to the following bullet points:

- All impacts show a linear dependency
- The parameter has especially high influence on the impacts primary energy demand, acidification and hazardous waste

Considering a share of “combustion of organic condensate” of 80% following benefits are achieved:

- The respective primary energy consumption can be reduced by app. 90% (strong dependency on the primary energetic efficiency of electricity consumption. No extra primary energy demand for the supply of organic condensate as fuel)
- The Global Warming Potential can be reduced by app. 40% (Global-Warming emissions, do not decrease in the same manner, as additional internal GWP emissions arise, due to the combustion of the organic condensate)
- The Acidification Potential can be reduced by app. 85% (Acidification Potential follows primary energy. Combustion of organic condensate (no sulphur content) only adds to NO_x emissions. So the main acidifying emissions of the system are related to the electricity production.
- The mass of hazardous waste is reduced by app. 90% (The main hazardous waste producing processes of the system are related to the electricity production as well).
- The mass of municipal waste is reduced by app. 85% (the main hazardous waste producing processes of the system are related to the electricity production as well).

Hence to consider a maximum of process energy provided by burning organic condensate is preferable from the viewpoint of the analysed impacts.

b) Parameter 2: CaCl₂ concentration as a parameter of product output

A second interesting parameter to vary is the output concentration of the CaCl₂ solution. The less the concentration is the less energy is needed for evaporation. But a certain amount of thermal energy is needed in the process for the extraction processes. The focus is to find out, at which concentration the ratio between lowering evaporation energy demand and providing necessary heat for the process is the most efficient for the impacts under study.

Non renewable Primary Energy demand for the Watech process

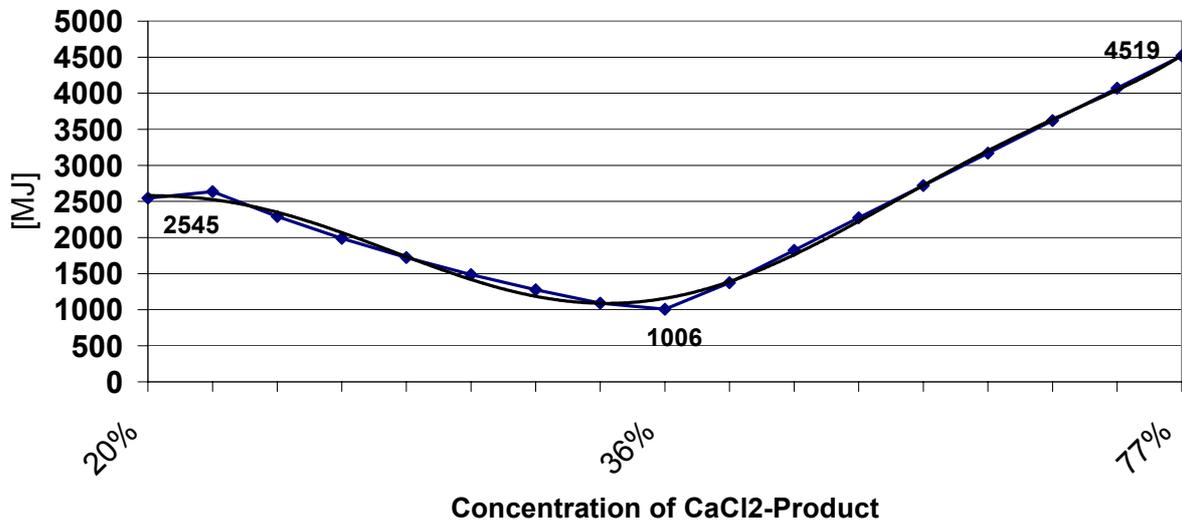


Figure 3-25: Parameter CaCl₂ concentration and impact on Primary Energy (Watech)

The Figure 3-25 shows the results of the primary energy demand, if the concentration of the outgoing solution is varied from 20% (raw concentration directly after the extraction of CaCl₂ and no further evaporation is needed) to 36% (actual concentration) to 77% (industrial grade concentration). A concentration around 36% seems to be most preferable, from a viewpoint of the primary energy demand.

Greenhouse Warming Potential for the Watech process

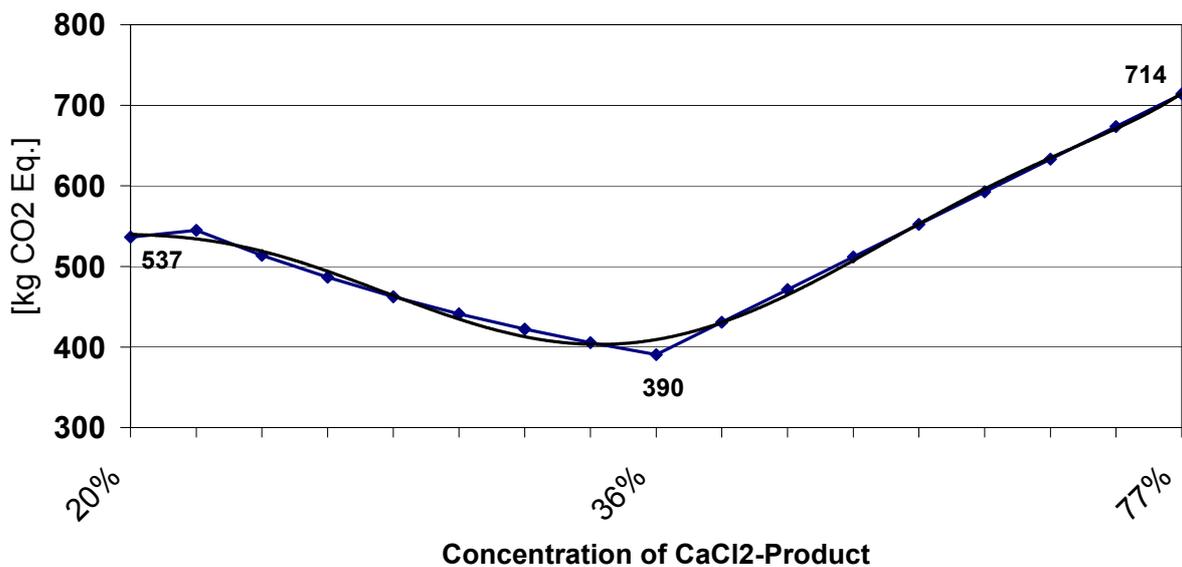


Figure 3-26: Parameter CaCl₂ concentration and impact on GWP (Watech)

The result shows the same tendency, but less intensive for the Global warming potential than for primary energy demand.

Acidification Potential for the Watech process

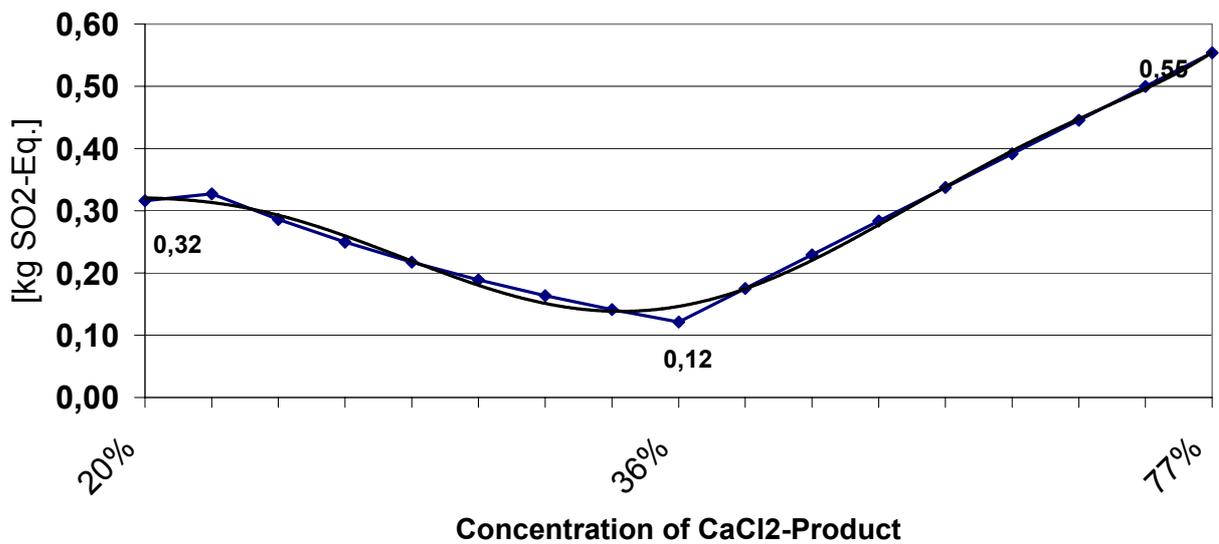


Figure 3-27: Parameter CaCl₂ concentration and impact on AP (Watech)

Waste masses of the Watech process

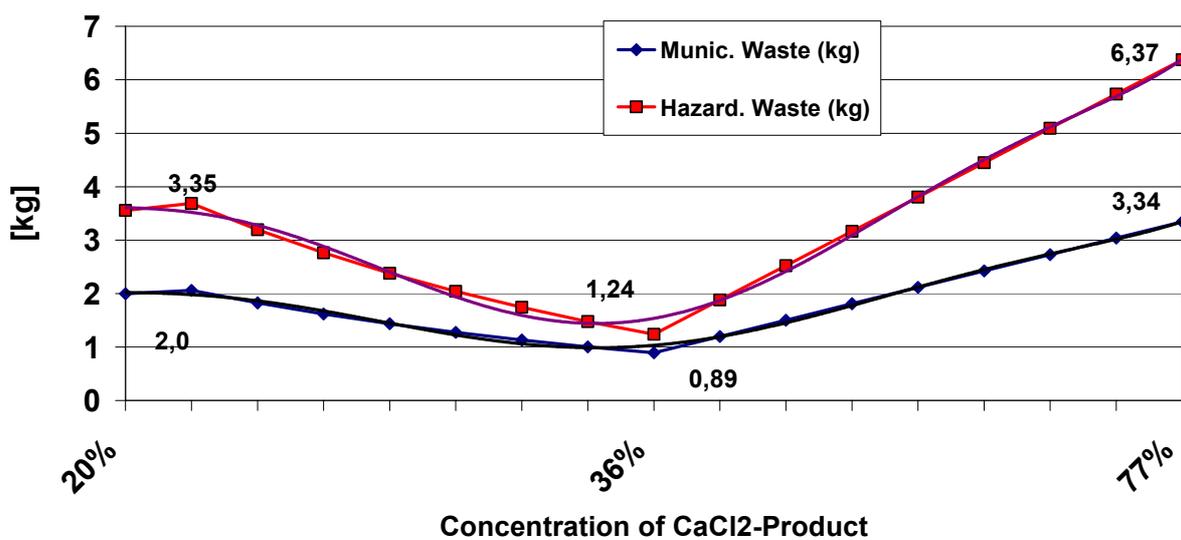


Figure 3-28: Parameter CaCl₂ concentration and impact on waste masses (Watech)

Again the results for acidification and waste masses show the same tendency.

Interpreting the results of the parameter variation leads to the following bullet points:

- All impacts show a non-linear dependency, with an optimum at a CaCl_2 concentration around 36%
- The parameter has as well especially high influence on the impacts primary energy demand, acidification and hazardous waste

If the concentration of the CaCl_2 solution would be changed from 36% to 20% or 77% the following disadvantages would be arise:

- An increase of the primary energy demand of app. 150% in case of 20% CaCl_2 and increase of app. 350% in case of 77% CaCl_2 (In case of 20% no evaporation energy is needed, but a certain thermal energy is needed to run the process. The needed thermal energy has to be provided by primary energy supply, as no off-heat can be used. In case of 77% more evaporation energy is needed, but the amount of produced off-heat does mote than compensate the demand in the process. Waste heat streams to the environment occur)
- As the impacts are dominated by the kind of energy used in the process, the facts for primary energy are valid for all the impacts under study.
- Additionally it is to state, that in the case of a 20%-concentration, more water will leave the system as part of the product. Hence additional water feed (app. 2,5 times more) is needed to saturate the demand. In case of 77% concentration almost no additional water input is need, as only 23% of the output product consists of water and the remaining evaporated and condensed water can be looped back into the process.

Hence a concentration of 36% CaCl_2 (as is now), is the most effective related to the environmental impacts under study.

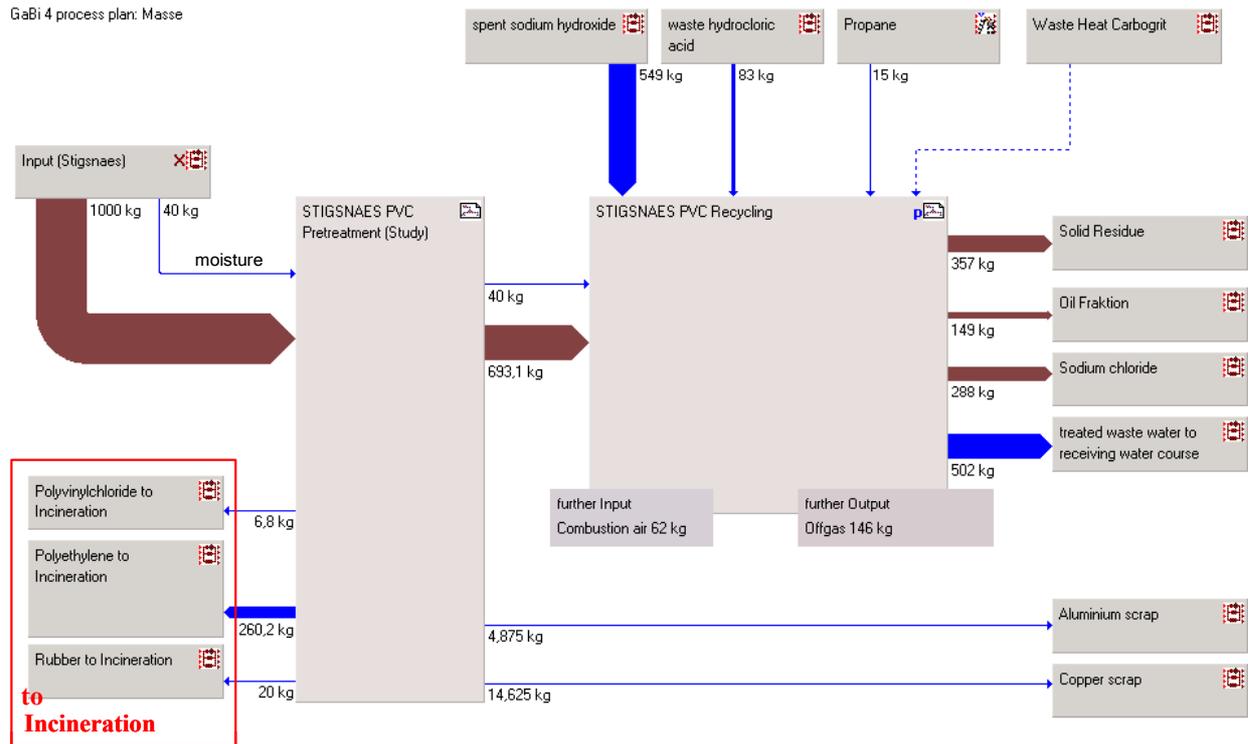
3.3 Stignæs PVC Feedstock Recycling Process

3.3.1 System modelling of the Stignæs process

The following Figure 3-29 shows the overall system modelling of the Stignæs process. For a more detailed figure of the recovery process steps as such see chapter 2.4.3.

STIGSNAES Mass Flow

GaBi 4 process plan: Masse



see figure 3-30

Figure 3-29: Mass flow Analysis model for 1t PVC cable waste with Stignæs Process

The pretreatment process mainly separates polyethylene and rubber (some trace PVC is following the PE stream) as well as metal scraps. The caustic source for hydrolysis is spent caustic soda. The HCl solution is needed for the organic-inorganic separation of the hydrolysis product. No additional water feed is needed. Some organics have to be purged and diluted with (condensed, distilled) water generated within the process.

The generated water is needed in process again (loop). The main mass flow route is:

PVC into reactor + NaOH ▶ Hydrolysis product ▶ Separation ▶
 Recycled water + Solid residue + Sodium chloride + waste water

The process is modelled from cradle to gate. That means all mass flows and environmental impacts from resource extraction to the products leaving the recovery processes are modelled. This includes the production of energy and auxiliaries as well. Hence - depending

Mass Flow and Environmental Results

on the process parameters - the environmental impact of the up-stream processes may exceed some of the environmental impact of the recovery process itself.

The separated PE and trace PVC is incinerated. Figure 3-30 shows the Input – Output situation for incineration of the separated cable fraction from Stignsnaes (related to 1000 kg of separated cable fraction as input to the incineration).

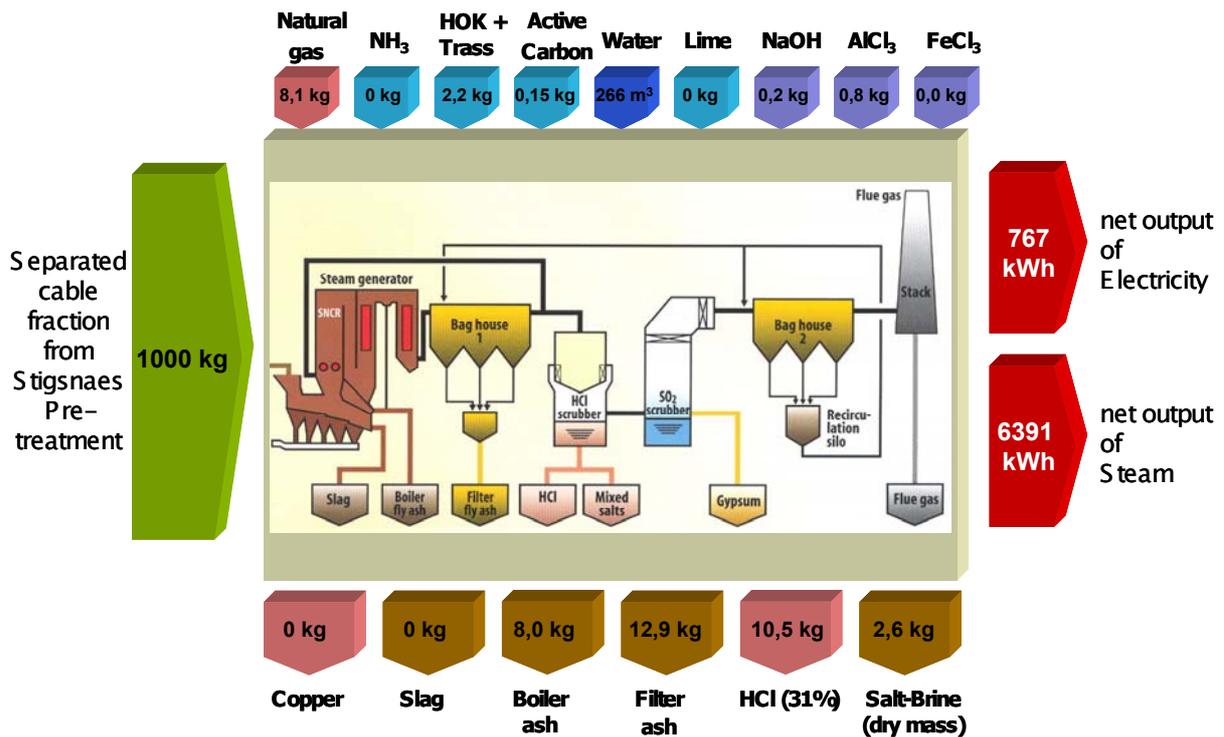


Figure 3-30: Mass flow Analysis model for incineration of 1000kg sep. cable fraction from Stignsnaes Process

The separated cable fraction is converted into the shown residues, substances and energy products according to the incineration model (see 2.4.1 and 3.1 for details)

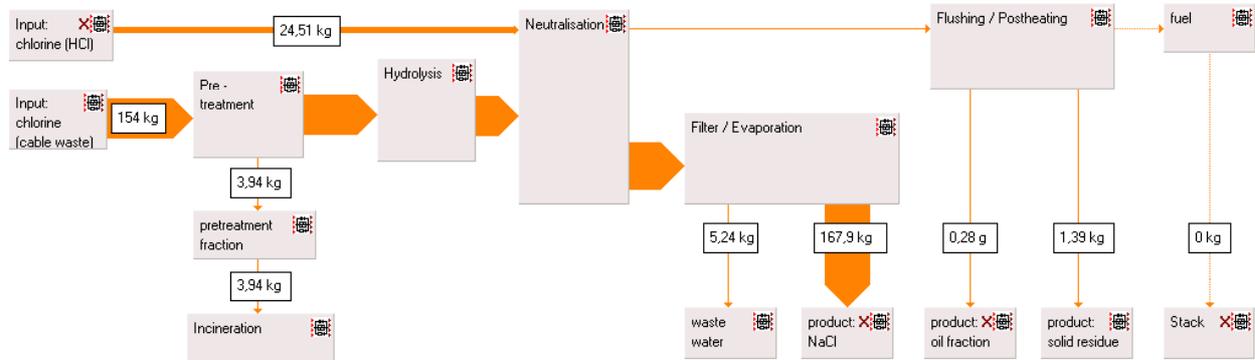
3.3.2 Mass flow of chlorine, lead, dioxins and chlorinated paraffins

The following figures are showing the mass flows of the analysed substances through the process.

Mass Flow and Environmental Results

Stigsnaes - mass flow chlorine

GaBi 4 Prozeßplan: Mass



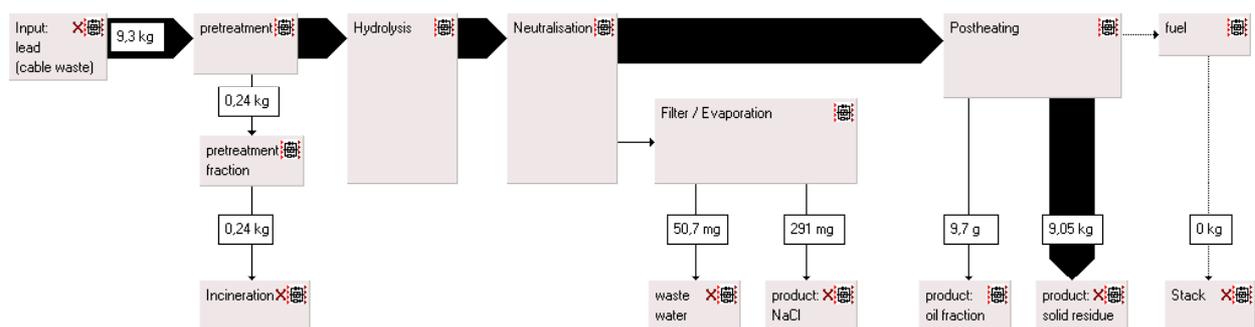
	Input		Output					
	mixed cable waste	auxiliary materials	pretreatment fraction	wastewater	NaCl	oil product	solid residue	fluegas
chlorine [kg]	154	24,51	3,94	5,24	167,94	$2,84 \cdot 10^{-4}$	1,39	not measured
chlorine [%]	86,27	13,73	2,21	2,94	94,08	0,00016	0,78	0

Figure 3-31: Mass flow of chlorine for Stigsnaes

The majority (over 94 %) of the chlorine input is rediscovered in the sodium chloride product (but the additional Cl input from HCl is later on not considered as recovered). About 2 % is following the PVC traces from separation to incineration and 3 % is leaving the system via the wastewater purge.

Stigsnaes - mass flow lead

GaBi 4 Prozeßplan: Mass



	Input		Output					
	mixed cable waste	auxiliary materials	pretreatment fraction	wastewater	NaCl	oil product	solid residue	fluegas
lead [kg]	9,3	not expected	0,24	$5,07 \cdot 10^{-5}$	$2,91 \cdot 10^{-4}$	0,0097	9,05	not measured
lead [%]	100	0	2,56	$5,45 \cdot 10^{-4}$	0,003	0,10	97,31	0

Figure 3-32: Mass flow of lead for Stigsnaes

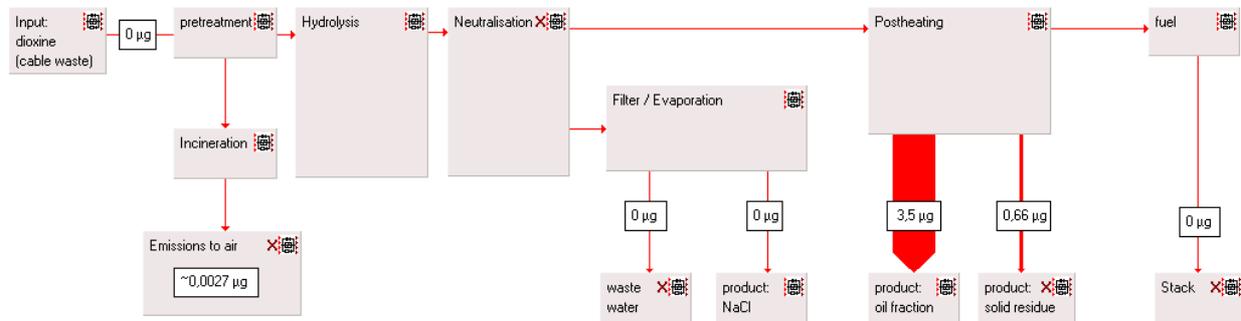
The main sink of lead is the solid residue product and app. 2,5 % are following the PVC traces from pretreatment to incineration. Newest developments reduced the lead flow into the

Mass Flow and Environmental Results

salt to $3 \cdot 10^{-5}$ kg or 0,0003%. This corresponds with a lead concentration less than 0,1ppm.

Stignæs - mass flow dioxin

GaBi 4 process plan: Mass



	Input		Output					
	mixed cable waste	auxiliary materials	pretreatment fraction	wastewater	NaCl	oil product	solid residue	fluegas
dioxin [kg]	not expected	not expected	$2,7 \cdot 10^{-12}$	b.d.l.	b.d.l.	$3,5 \cdot 10^{-9}$	$6,6 \cdot 10^{-10}$	exp. b.d.l.
dioxin [%]	0	0	0,06	0	0	84,08	15,86	0

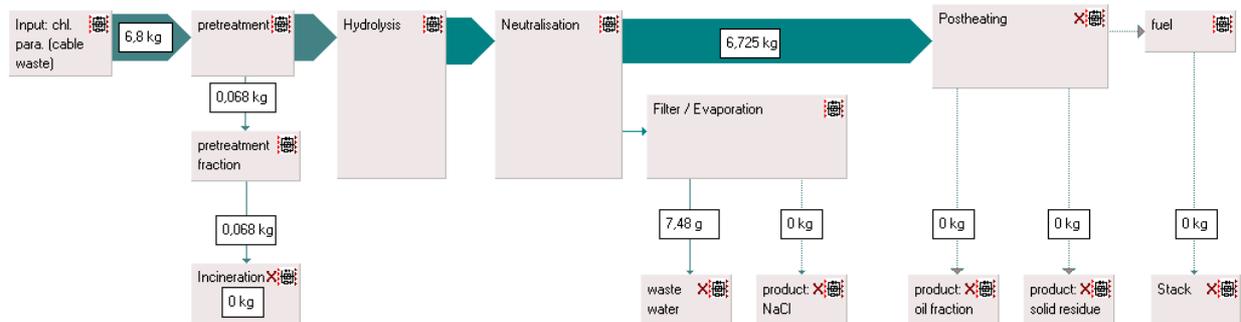
b.d.l. = below detection limit⁴; exp. b.d.l = expected to be below detection limit⁵

Figure 3-33: Mass flow of dioxins for Stignæs

Beside the presence of chlorine, the thermal conditions in the post-heating enable the formation of small amounts of dioxin/furan (see chapter 3.1.2 for details).

Stignæs - mass flow chlorinated paraffins

GaBi 4 Prozessplan: Mass



	Input		Output					
	mixed cable waste	auxiliary materials	pretreatment fraction	wastewater	NaCl	oil product	solid residue	fluegas
chl. paraffins [kg]	6,8	not expected	0,068	0,007	not exp.	not exp.	not exp.	not exp.
chl. paraffins [%]	100	0	1,00	0,11	0	0	0	0

Figure 3-34: Mass flow of chlorinated paraffins for Stignæs

⁴ Stignæs has used the Gesellschaft für Arbeitsplatz- und Umweltanalytik mbH in Münster, Germany for dioxin measurements. The detection limits vary for the different dioxin compounds from 0,003 to 0,2 ppb.

⁵ Stignæs have decided to adjust the processing route to minimize dioxin/furan formation. These adjustments will eliminate dioxin/furan from the flue gas.

Likewise, the temperature in the post-heating (3 stages between 300-600°C) is high enough for the destruction of chlorinated paraffins, as the destruction of chlorinated paraffins starts at 200°C.

Cadmium and bromine play a minor role in the case of cable waste, as those components were not detected in the cable waste or are very unlikely to appear. Nevertheless the behaviour of those mass flows is described, to clarify a situation of appearance.

Possible cadmium compounds (e.g. from stabilisers) would mainly follow the lead flow and end up in the solid residue.

It is expected that bromine would follow the chlorine. Essentially the bromine would end up in the salt and a small fraction in the wastewater stream.

3.3.3 Energy balance of the Stignæs process

Figure 3-35 shows four bars of the energy balance. The left bar is the energy input for the mixed cable waste. The next bar represents the external process energy demand, which is needed to recover 1000 kg mixed cable waste. The bar on the right hand side shows the energy content of the products, the bar next to it shows the output of energy content in the residues of the pretreatment (which go to incineration). The difference between input and output are the process energy losses.

The energy demand of the recovery process is saturated by electricity and by the combustion of internally produced fuel gas from the post-heating step. The Stignæs process itself does not produce electricity or steam. The benefit from an energetic viewpoint is the recovery of the energy content in the solid residue for the Carbogrit plant and the organic products. In the following, two different energy balances of the Stignæs process for processing 1000 kg mixed cable waste are illustrated. In the intermediate energy balance, the energy content (calorific value) of the intermediate products such as polyethylene is separately displayed. In contrast, the final energy balance represents the net energy benefit including steam and electricity after processing the intermediate products in an incineration plant. To visualise the energy flows of the process for both energy balances, Sankey diagrams are enclosed.

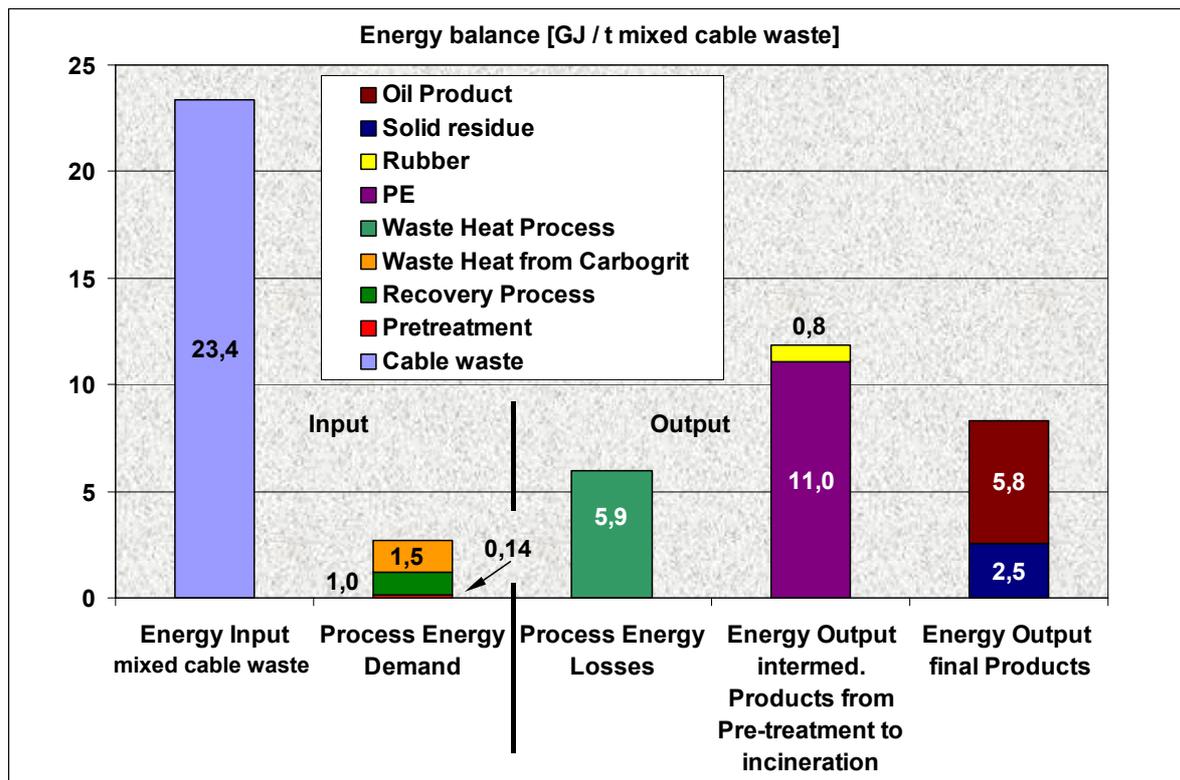


Figure 3-35: Intermediate energy balance of the Stignsæs process

The 23,4 GJ are representing the energy input (calorific value) due to the PVC cable waste input in the process. The pretreatment is accounting for 0,14 GJ of the energy demand. The process itself needs 2,5 GJ for e.g. the reactor, pumps, valves, filter press, evaporation. 1,5 GJ of the 2,5 GJ can be supplied by waste heat from the nearby Carbogrit process. Obviously this is an advantageous situation. The combustion of internally produced fuel gas accounts for app. 1,6 GJ to supply thermal energy for post-heating (is included in the 5,9 GJ losses). 11,8 GJ are separated with the PE and the rubber in the pretreatment. 8,3 GJ are converted into solid residue and oil product.

Figure 3-36 shows the above mentioned visualised in a Sankey diagram.

Mass Flow and Environmental Results

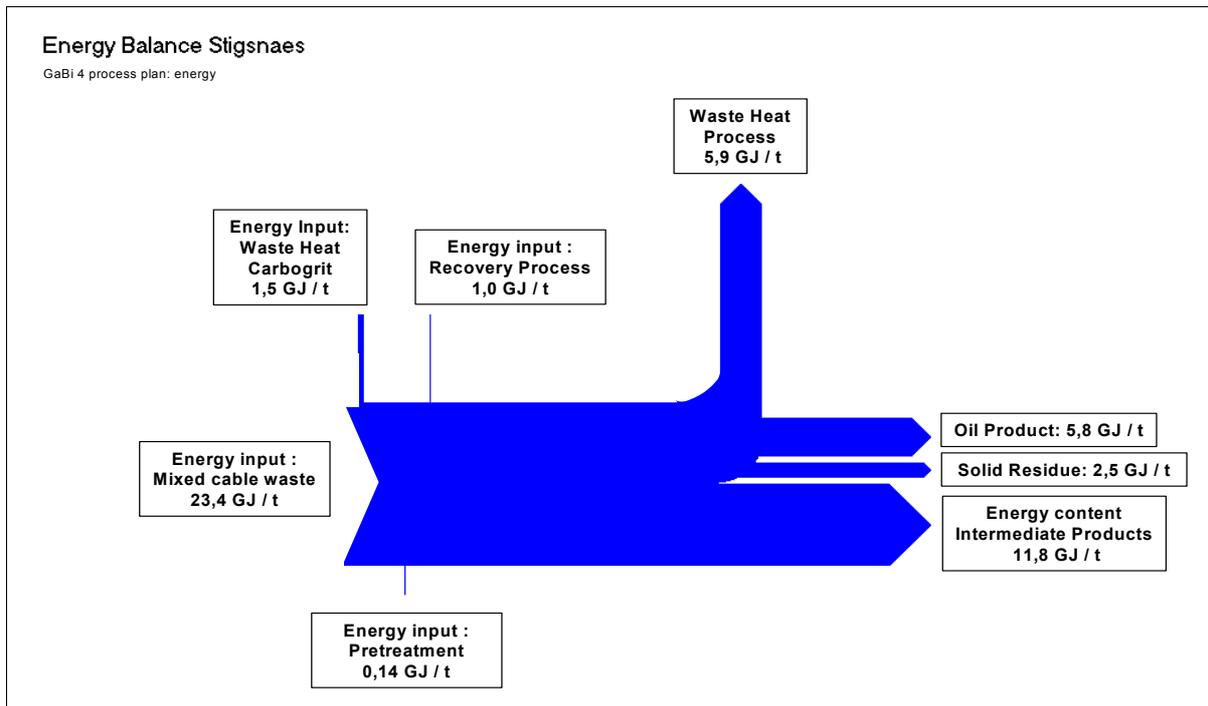


Figure 3-36 Sankey diagram of the intermediate energy balance of the Stigsnaes process

The intermediate products are further treated in the incineration. Hence a overall energy balance can be set up after integrating the incineration model.

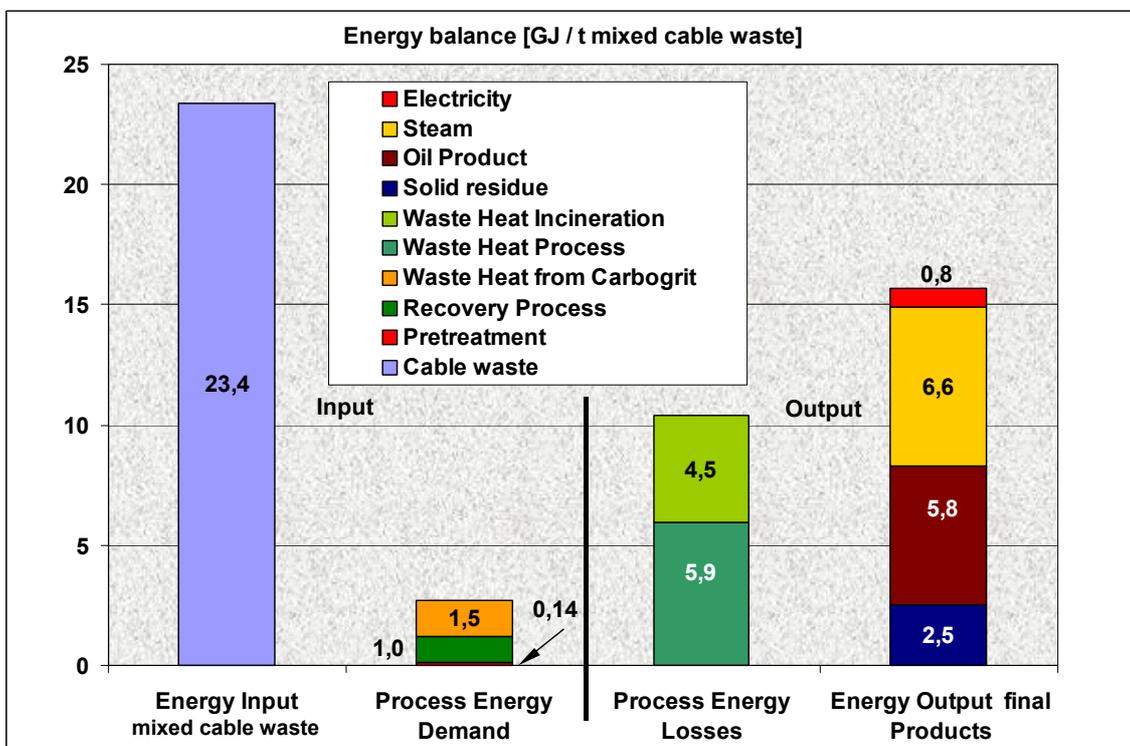


Figure 3-37: Final energy balance of the Stigsnaes process

The 11,8 GJ of PE input to the incinerator are converted to 0,8 GJ electricity, 6,6 GJ steam accompanied by 4,5 GJ waste heat losses.

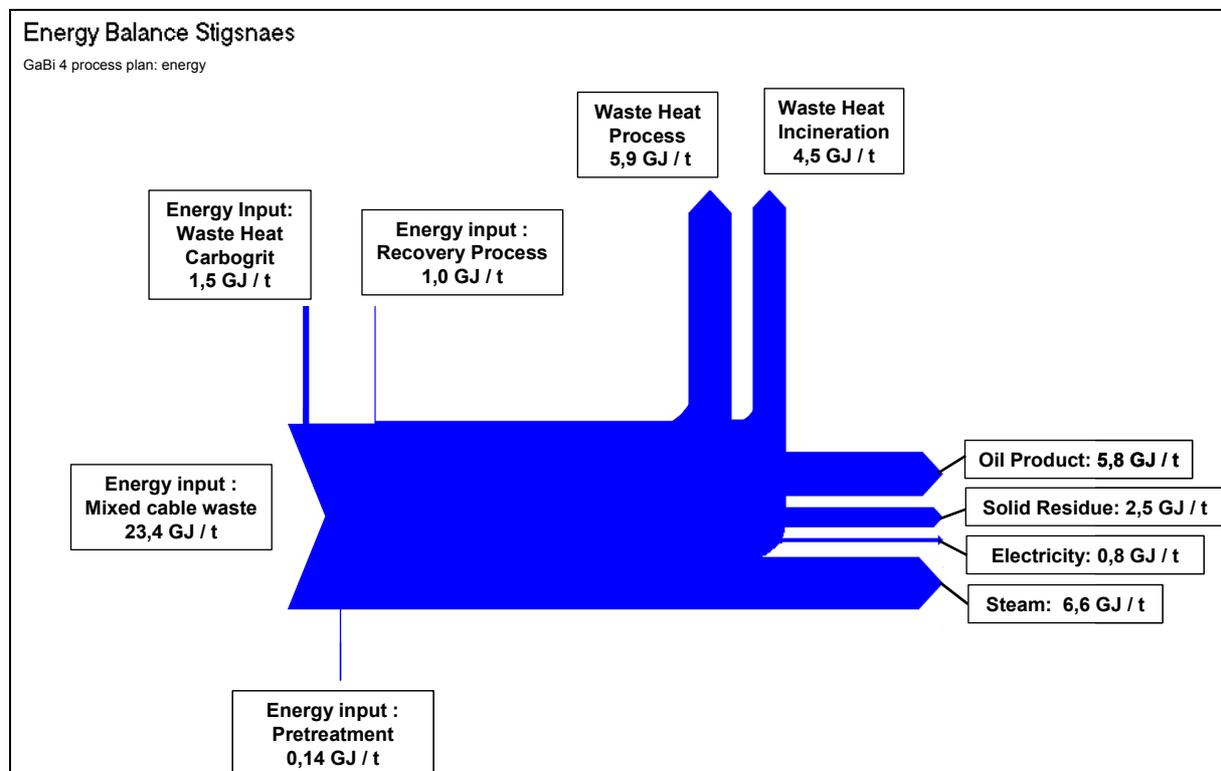


Figure 3-38: Sankey diagram of the final energy balance of the Stigsnaes process

The oil product and the solid residue provide app. 35% of the recovery related to the 23,4 GJ input. The separated PE and rubber fraction (converted to steam and electrical power in the incineration) are accounting for a high recovery share of over 30%.

3.3.4 Environmental profile of the Stigsnaes process

Primary Energy Demand

The primary energy demand is modelled from cradle to gate, that means the further processing of the pretreatment fraction is not considered in this chapter. The energy demand is dominated by the production and use of the propane in the post-heating process. The combusting of the internal produced fuel gas for the generation of thermal energy can cover app. 70% of the needed energy demand in the post-heating unit. The rest will be provided by propane firing. The caustic soda and hydrochloric acid do not contribute to primary energy consumption. Spent caustic soda is coming from metal cutting industry and oil industry. Hence no environmental burden including no primary energy demand is related to the

production of NaOH. The caustic soda would be waste, if the process would not use it. The use of virgin caustic soda would raise the energy balance by 7,22 GJ.

Further waste hydrochloric acid is used (without burden as otherwise waste). Virgin HCl would raise the energy balance by 0,07 GJ.

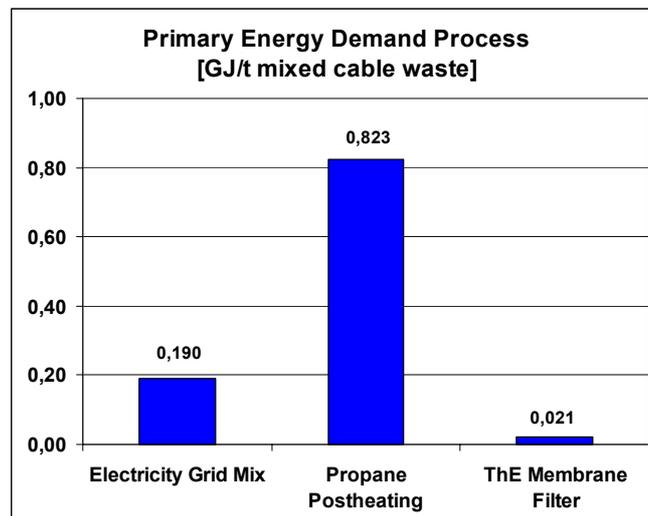


Figure 3-39: Primary Energy demand of Stignsnes Process

Global Warming and Acidification Potential

The Global Warming Potential (GWP) and the Acidification Potential (AP) are modelled similar to the primary energy balance. Fuel gas and propane firing (app. 192 CO₂-Eq./ t_{mixed cable waste} in stack) and electricity demand (app. 15 CO₂-Eq./ t_{mixed cable waste}) are the main contributors to the GWP. The main contributors to the AP are the combustion of fuel gas and propane (app. 0,105 kg/t AP to air), the production of propane (0,066 SO₂-Eq./ t_{mixed cable waste} to air and 6,56E-06 SO₂-Eq./ t_{mixed cable waste} to water) and the production of electricity (0,021 SO₂-Eq./ t_{mixed cable waste} to air and 3,5E-07 SO₂-Eq./ t_{mixed cable waste} to water).

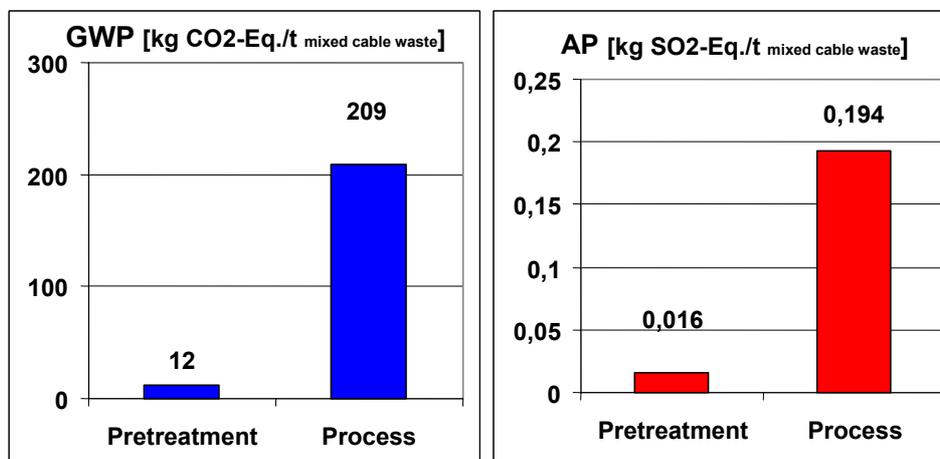


Figure 3-40: Global Warming Potential and Acidification Potential of the Stignsnes Process

Overview:
Environmental Profile of Stignæs process and Incineration of pretreatment residues

Table 3-4: Environmental Profile and Recovered Products for the recovery of 1 t mixed cable waste in the Stignæs Process and Incineration Plant

Recovery of 1 t mixed cable-waste:		
Environmental Profile		
Environmental Loads		
Primary Energy (non renewable)	1309	MJ
Greenhouse Warming Potential	1111	kg CO ₂ -Eq.
Acidification Potential	0,223	kg SO ₂ -Eq.
Hazardous waste	4,2	kg
Municipal waste	5,0	kg
Inert waste	30	kg
Waste water (only process itself)	0,507	m ³
Products (resulting in Environmental Benefits)		
Oil product	149	kg
NaCl (solid)	288	kg
Copper	14,6	kg
Aluminium	4,9	kg
HCl (31%)	3,0	kg
Electricity	220	kWh
Steam	1834	kWh
Solid residues to Carbogrit (containing lead), which is an intermediate product	357	kg

The primary energy relates to app. 79% to the Stignæs process and app. 21 % to incineration. The major share of the Global Warming Potential is due to the incineration (app. 80 % due to combustion and electricity and steam production). The Acidification mainly comes from the Stignæs process itself (94 %), as the incineration has a very effective flue gas cleaning system. 0,86 kg of the hazardous waste is related to the Stignæs process, mainly due to electricity and propane production. For the municipal waste 0,41 kg are related to the Stignæs process (mainly electricity production and dirt from pretreatment separation). The inert waste is related to electricity production again (app. 24 kg from Stignæs process). The wastewater treatment accounts for 4,65 kg sludge (not shown in table).

3.3.5 Parameter Variation (Scenarios)

Basic task of the parameter variation is to analyse parameters (process parameters or input related parameters), which influences the environmental performance of the system. In the study, process parameters or input related parameters are varied within reasonable intervals, to figure out the importance and impacts on the complete system.

Impacts under study due to the variation of the share of process energy provided by the combustion of fuel gas product are the impact on the primary energy demand to run the process, GWP, AP and the waste amounts.

In this figures the impacts of two parameters are visualised according their influence on the environmental performance in one diagram.

Parameter 1+2: Share of spent Sodium Hydroxide and waste Thermal Energy

At the beginning of the project it was planned to run the Stignæs processes with waste heat of the Carbogrit plant as thermal energy input in the process. Further it was planned to use spent NaOH from metal processing. The parameter variation shows the sensitivity and the significance related to the system.

Figure 3-41 shows the results of the primary energy demand. In this parameter variation the share of spent NaOH or waste thermal energy of the Carbogrit plant used in the process is raised from 50% to exclusively use (100%), which represents already the actual development status of the process. During the project the process could already be operated with 100% waste heat and spent NaOH. As NaOH (and it's primary production route) has significant influence on the primary energy demand, the choice of using spent NaOH was accurate and adequate.

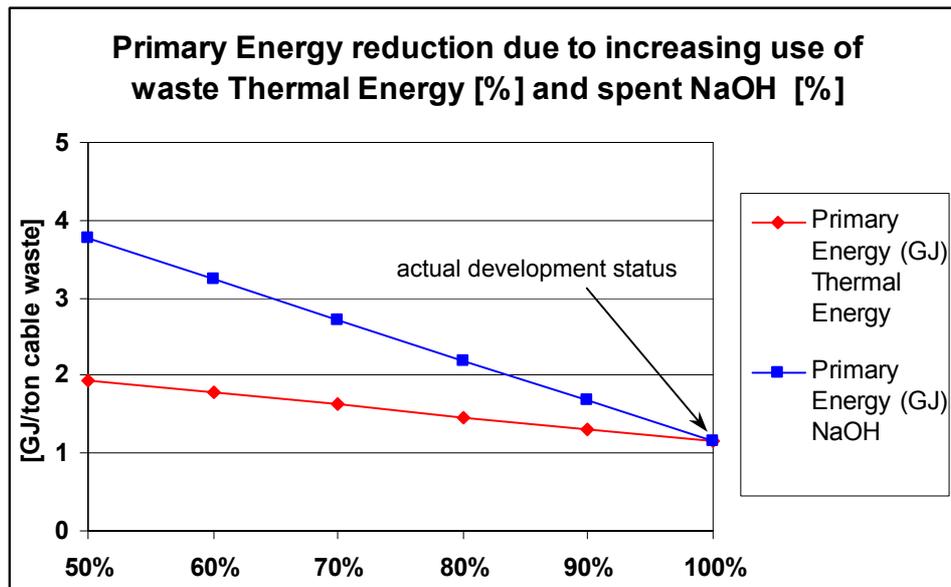


Figure 3-41: Parameters “NaOH” and “thermal energy” with impact on primary energy (Stignæs)

The primary NaOH production is an energy intensive process. Therefore the decrease of primary energy consumption is significant, if spent NaOH is used. The decrease due to primary thermal energy production is obvious, as gas, oil or coal as energy carrier can be saved.

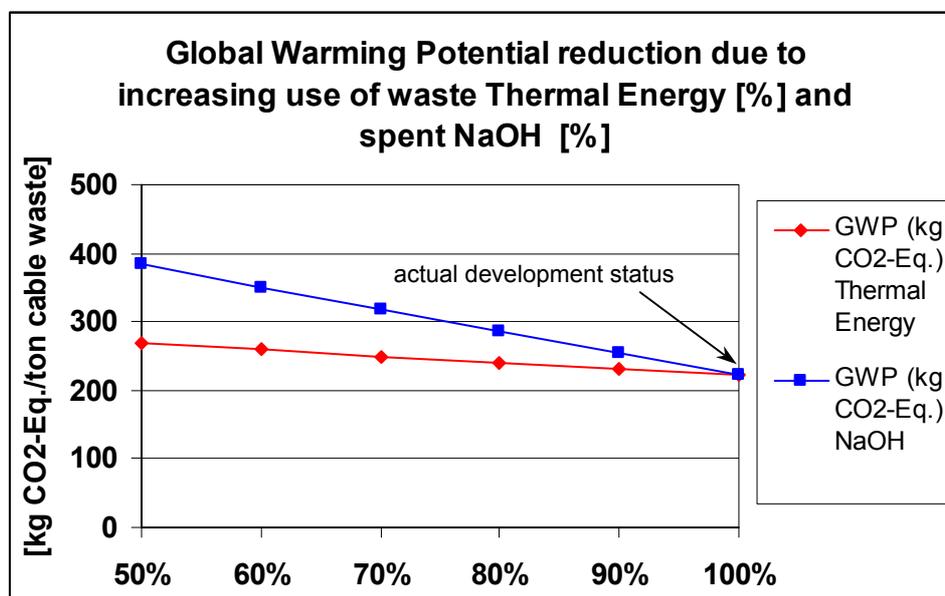


Figure 3-42: Parameters “NaOH” and “thermal energy” with impact on GWP (Stignæs)

The results on GWP show the same tendency. Due to exclusively use of spent NaOH the Global Warming Potential is significantly decreased. The use of waste heat accounts for additional but less decrease of Global Warming Potential in comparison to spent NaOH.

Mass Flow and Environmental Results

Due to the fact that the GWP is not only driven by energy supply process, the influence on the overall system is slightly lower than on primary energy demand.

The results for Acidification show the same tendency as well.

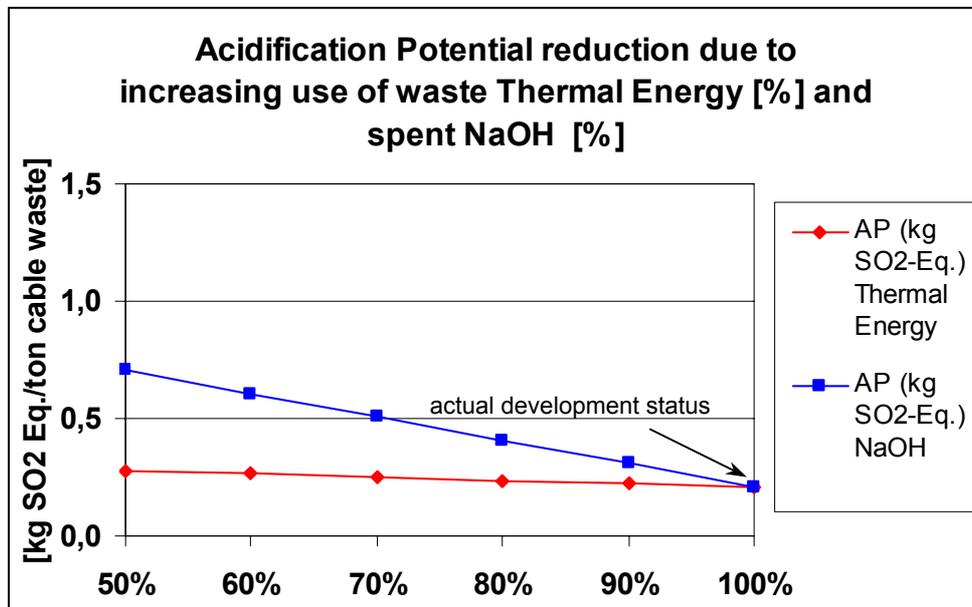


Figure 3-43: Parameters “NaOH” and “thermal energy” with impact on AP (Stignæs)

The effect on AP is comparable to primary energy demand (see above).

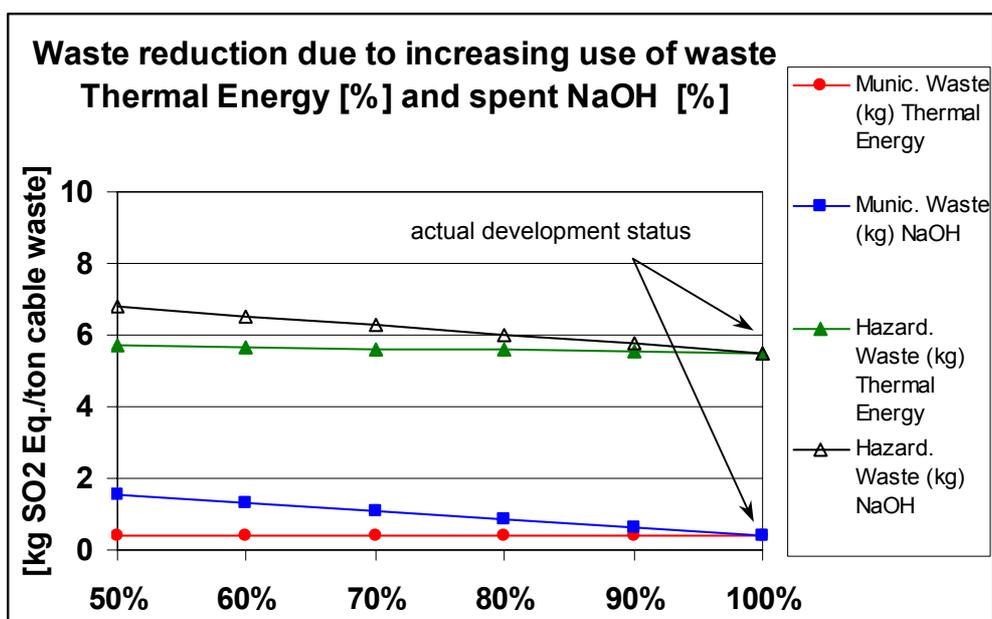


Figure 3-44: Parameters “NaOH” and “thermal energy” with impact on waste masses (Stignæs)

The results for municipal waste masses show that the source of thermal energy does not significantly influence the system, but municipal waste amounts can be reduced by using spent NaOH, as the primary NaOH production is a waste intensive. The decrease due to primary thermal energy production is negligible, because in the thermal energy chains from natural gas very small sources of municipal waste appear anyway.

The results for hazardous waste amounts show that the use of waste thermal energy does influence the system just slightly as well (like in the case of municipal waste), but the amount of hazardous waste is decreased significantly with the use of spent NaOH.

The parameter variation shows that increasing the use of spent NaOH and waste thermal energy significantly reduces impacts on primary energy use, GWP, AP and waste. The parameter NaOH has a particular relevancy. Therefore the use of spent NaOH is very effective regarding the reduction of the impacts on primary energy demand, acidification and municipal waste amounts.

3.4 Vinyloop PVC Mechanical Recycling Process

3.4.1 System modelling of the Vinyloop process

On the basis of data for the treatment of a known composition of PVC waste, the modelling of the Vinyloop process had been done. The temperature inside the process is low, the procedures in the process are rather of a physical nature. Hence, and due to the fact that only the mass allocation and not the general composition vary, the transfer coefficients for the single elements and compounds remain constant. The modelling handles the different compounds of a mixed cable waste separately. That means that there are transfer coefficients available for the following compounds of the input: Polyethylene (PE), rubber, PVC resin, plasticiser, filler, stabilisers, pigments, chlorinated paraffins, copper and aluminium.

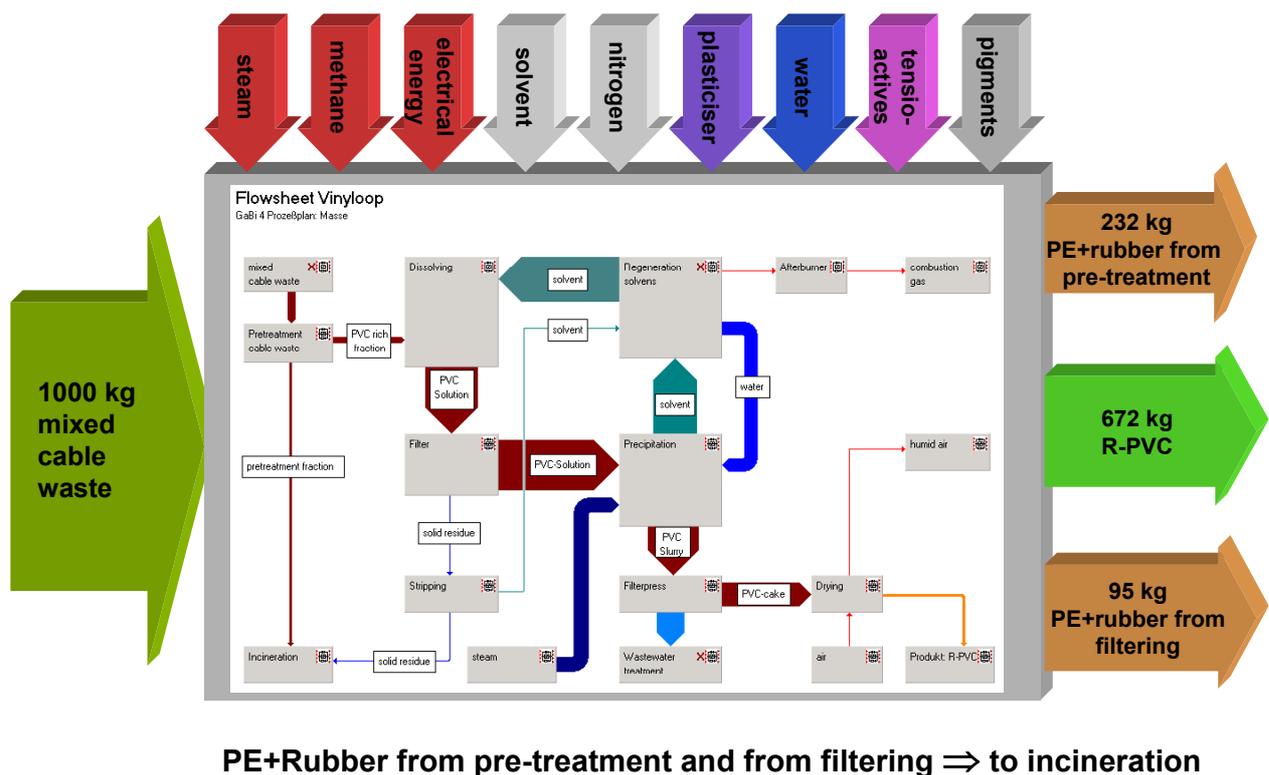


Figure 3-45: Mass flows of the Vinyloop PVC Recycling

In addition, some further assured assumptions had been implemented:

PVC polymer and PVC additives: A small share (<1%) of the input (untreated) PVC fraction is separated in the pretreatment stage.

Mass Flow and Environmental Results

The PVC polymer is resistant to degradation within the Vinyloop process. It is considered that no polymer chain is cracked. So, more than 98% of the PVC polymer and consequently additives such as filler, stabilisers and plasticiser are leaving the process as reclaimed PVC compound.

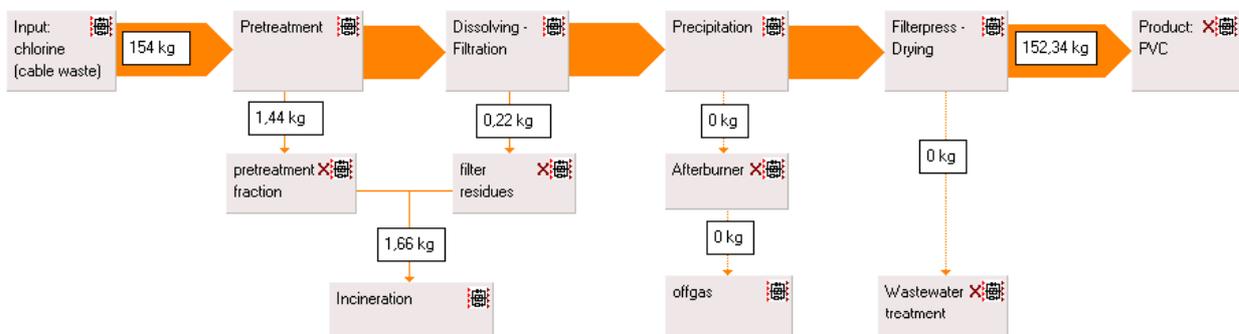
Rubber and Polyethylene Independent from the composition of the inserted PVC waste fraction, a constant share of the plastics such as rubber and polyethylene is separated in the pretreatment stage. The rest of them, about 25 %, are end up in the solid filter residue.

3.4.2 Mass flow of chlorine, lead, dioxins and chlorinated paraffins

The entire amount of chlorine that enters the process is fixed in the PVC matrix and the chlorinated paraffins. As mentioned above, no polymer destruction occurs. Hence, almost all of the input chlorine can be found in the output product PVC compound.

Vinyloop - mass flow chlorine

GaBi 4 Prozeßplan: Mass



	Input mixed cable waste	Output				PVC product
	pretreatment fraction	filter residues	offgas	wastewater		
chlorine [kg]	154	1,44	0,22	not expected	not measured	152,34
chlorine [%]	100	0,94	0,14	0	0	98,92

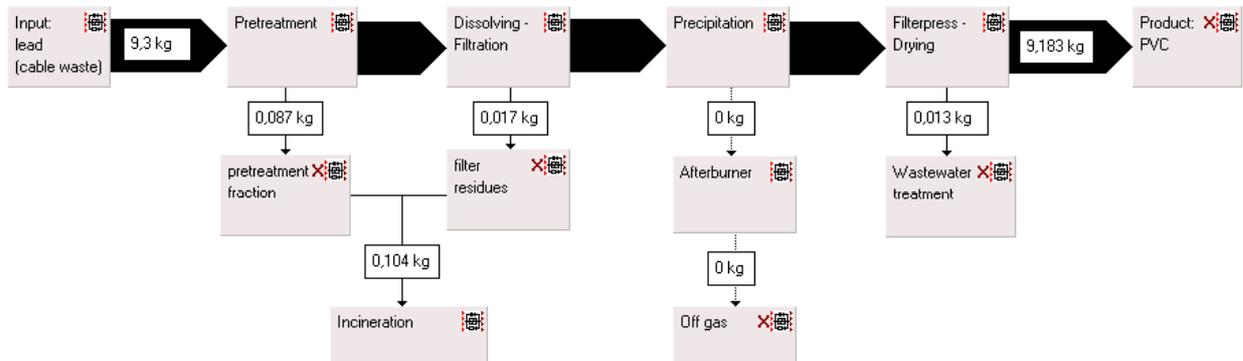
Figure 3-46: Mass flow of chlorine for Vinyloop

Most of the lead also remains in the PVC compound. Only a very small part leaves the process with the wastewater. A downstream wastewater treatment plant purifies the process water.

Mass Flow and Environmental Results

Vinyloop - mass flow lead

GaBi 4 Prozeßplan: Mass



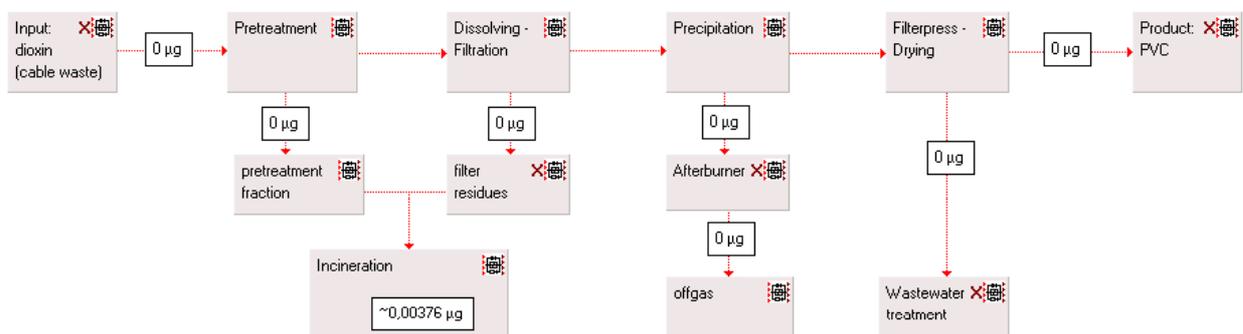
	Input	Output				
	mixed cable waste	pretreatment fraction	filter residues	offgas	wastewater	pvc product
lead [kg]	9,3	0,087	0,017	not expected	0,013	9,183
lead [%]	100	0,94	0,18	0	0,14	98,74

Figure 3-47: Mass flow of lead for Vinyloop

Looking for other heavy metals like cadmium or antimony compounds it can be assumed that they will be treated in the same way as lead compounds, that means that they will mainly stay in the recycled PVC product as well.

Vinyloop - mass flow dioxin

GaBi 4 Prozeßplan: Mass



	Input	Output				
	mixed cable waste	pretreatment fraction	filter residues	offgas	wastewater	PVC product
dioxin [kg]	not expected	$3,76 \cdot 10^{-12}$	not expected	not expected	not expected	not expected
dioxin [%]	0	100%	0	0	0	0

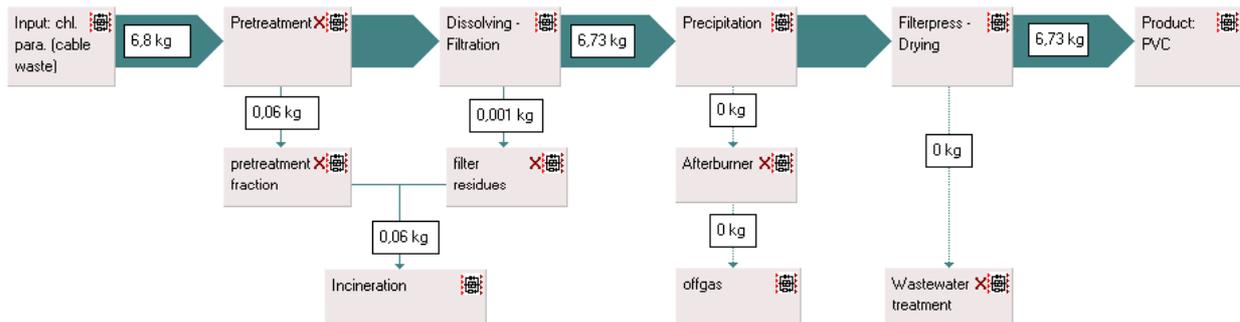
Figure 3-48: Mass flow of dioxins for Vinyloop

Mass Flow and Environmental Results

Dioxin formation is not possible. The critical temperature in almost all of the process stages is too low. Only in the afterburner the temperature would be high enough for dioxin formation, but there is no copper and chlorine available, therefore no dioxin measurement was required.

Vinyloop - mass flow chlorinated paraffins

GaBi 4 Prozeßplan: Mass



	Input	Output				
	mixed cable waste	pretreatment fraction	filter residues	offgas	wastewater	PVC product
chl. paraffins [kg]	6,8	0,064	0,001	not expected	not measured	6,735
chl. paraffins [%]	100	0,94	0,02	0	0	99,04

Figure 3-49: Mass flow of chlorinated paraffins for Vinyloop

Chlorinated paraffins are not destroyed in the Vinyloop process. The temperature is too low (<200°C), hence the major part remains in the PVC compound.

3.4.3 Energy Balance of the Vinyloop process

Similar to the Watech and the Stignæs process, two energy balances had been illustrated: The first one without, the second one with burning the pretreatment residue fraction.

It is obvious, that the Vinyloop process needs a higher amount of external energy input than the other recovery options, which are using partly the energy content of the cable waste itself to run the process. On the output side one can see that most of the energy is still available in the PVC compound and in the intermediate products which will be further treated in the incineration.

Vinyloop mainly uses process steam to heat up the process and to precipitate the PVC compound afterwards. The process steam comes from the ENICHEM site next to the Vinyloop site in Ferrara/Italy. ENICHEM also operates the wastewater treatment facility, where the wastewater of the Vinyloop process is treated as well. The production of the steam and the treatment of the wastewater are considered within the system boundaries.

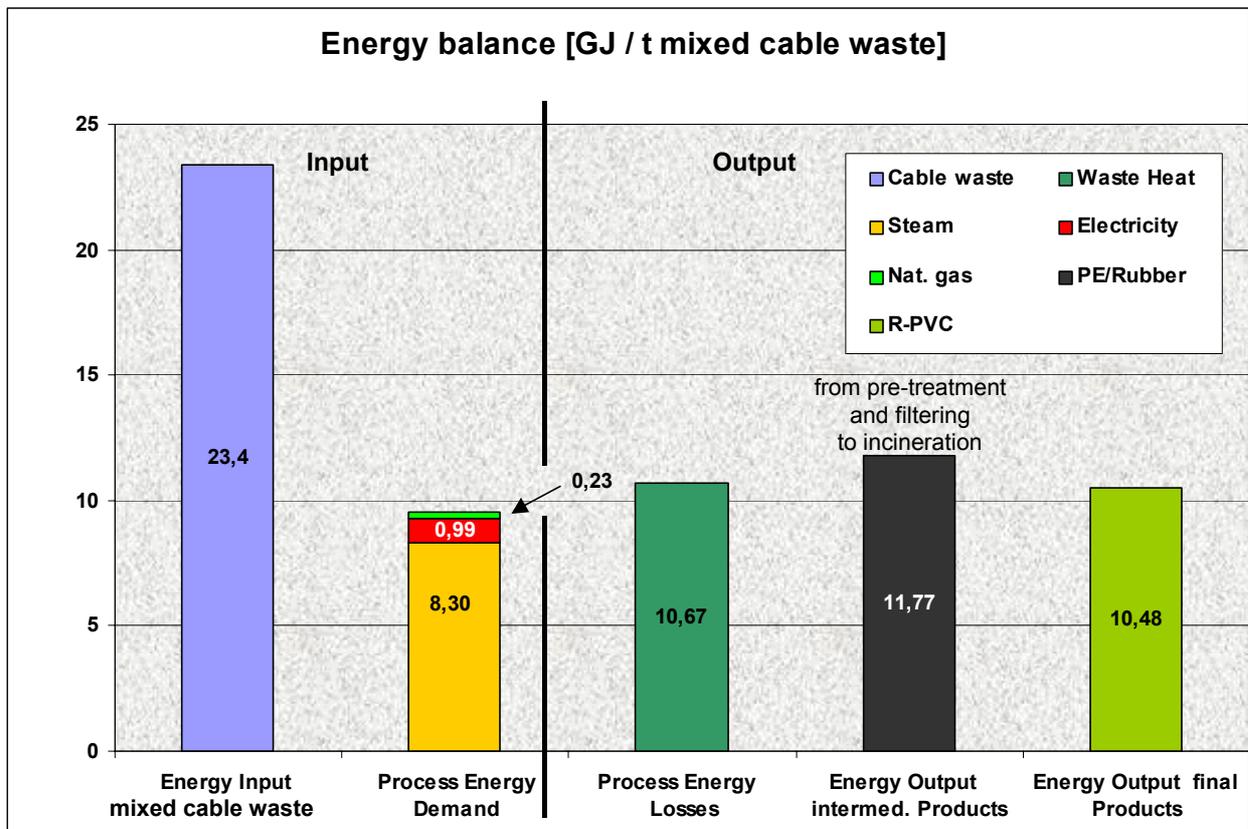


Figure 3-50: Intermediate energy balance of the Vinyloop process

Figure 3-50 shows five bars of the energy balance. The left bar is the energy input of the mixed cable waste (calorific value). The bar next to it represents the extern process energy demand of electricity, steam and natural gas, which is needed in run the process with an input of 1000 kg mixed cable waste. The bar “Process Energy Losses” represents the amount of off-heat. The bar “Energy Output intermediate products” reflects the amount of polyethylene and rubber, separated in pretreatment and filtering, which is incinerated. The “Energy Output final products” are the calorific value of the recovered PVC compound.

Mass Flow and Environmental Results

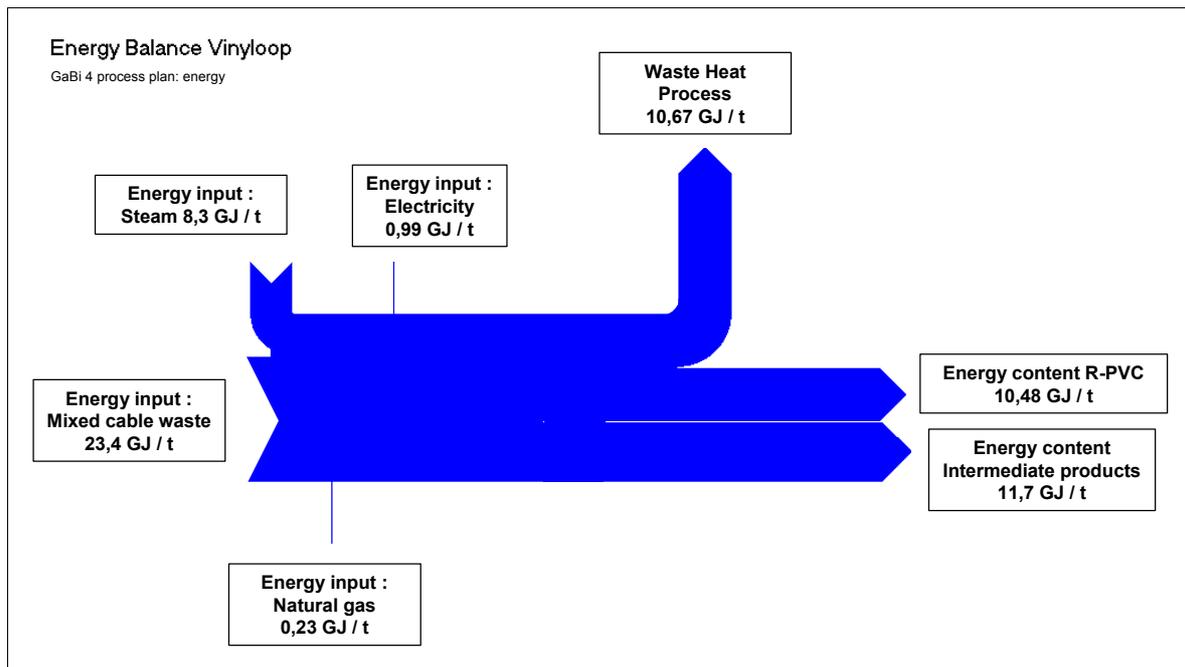


Figure 3-51: Sankey diagram of the intermediate energy balance of the Vinyloop process

Figure 3-51 visualises the facts in a Sankey diagram. The intermediate products are further treated in the incineration plant and a final energy balance can be calculated.

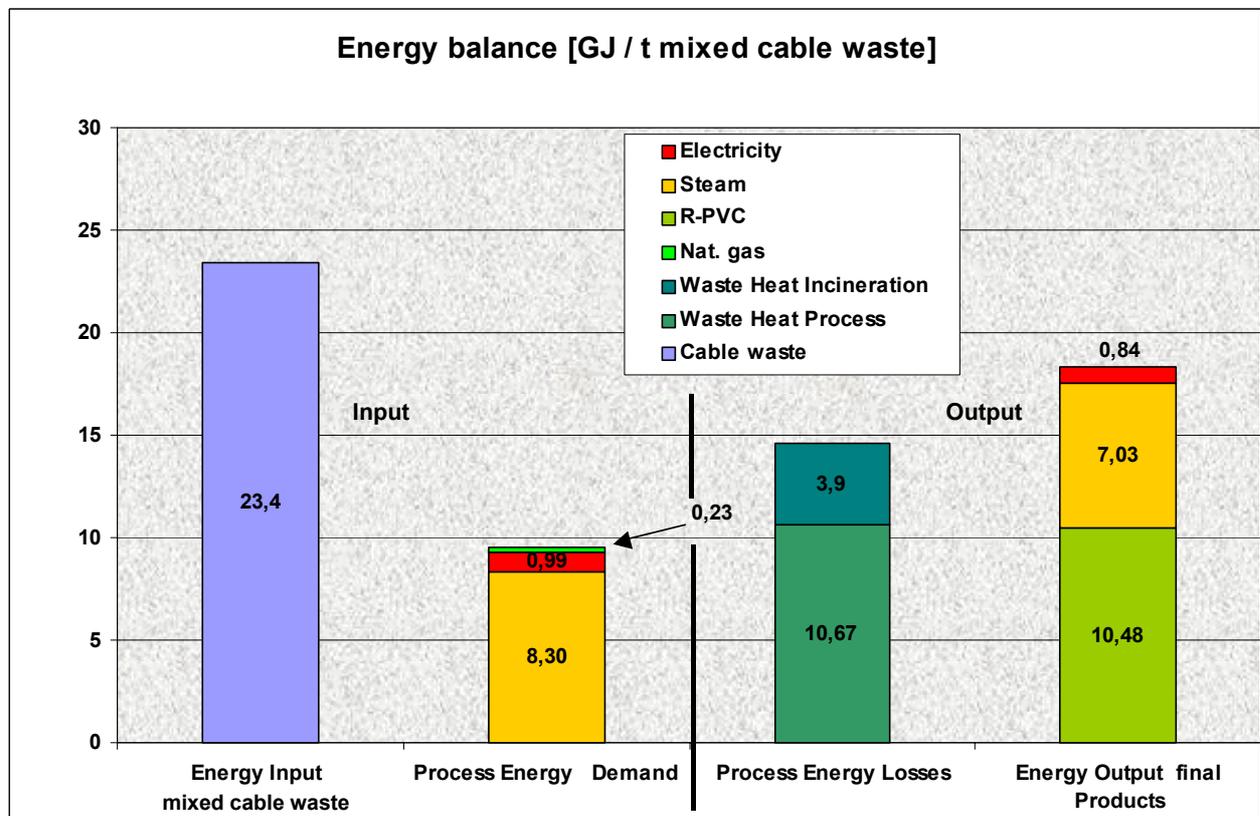


Figure 3-52: Final energy balance of the Vinyloop process

Mass Flow and Environmental Results

In Figure 3-52 and Figure 3-53 the 11,77 GJ of the “Energy Output intermediate products” are distributed to “Process Energy Losses” and “Energy Output final products”, because the intermediate products (polyethylene and rubber) are converted into the products steam and electricity in the MVR incineration plant, showing process energy losses (see chapter 3.1.4).

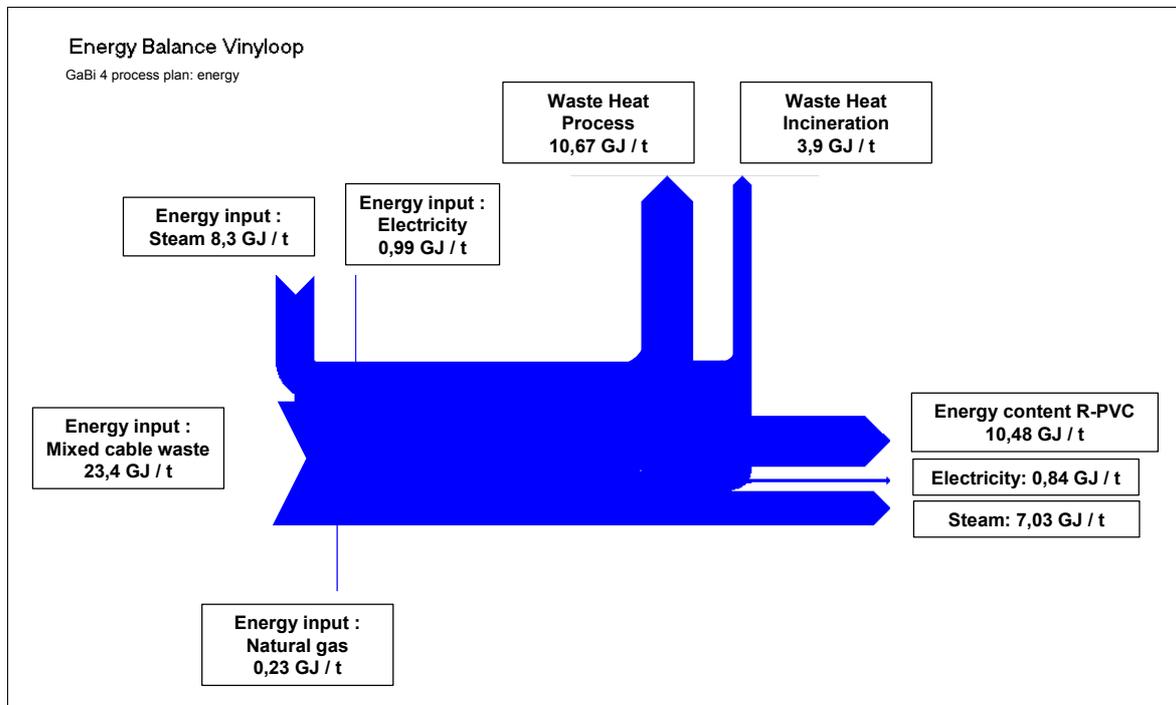


Figure 3-53: Sankey diagram of the intermediate energy balance of the Vinyloop process

3.4.4 Environmental profile of the Vinyloop process

The environmental results for the Vinyloop process are mainly driven by steam and electricity because there is a low demand of auxiliary materials. The primary energy demand and global warming potential (GWP) are dominated by the steam production. The result for the acidification potential shows a higher influence of the electricity production. The reason for that are SO₂ and NO_x emissions from the average Italian electricity production.

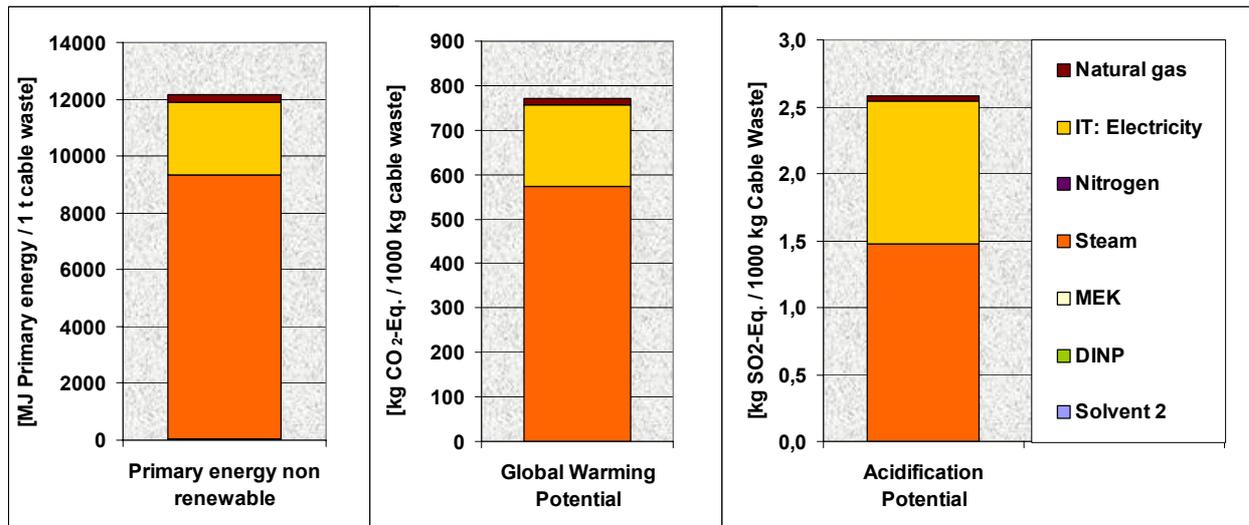


Figure 3-54: Primary energy (non renewable), global warming potential and acidification potential to process 1 t mixed cable waste in the Vinyloop process

Due to the steam demand of the process there are 9,1 m³ wastewater coming from the Vinyloop process per t mixed cable waste input. The wastewater is treated in the ENICHEM wastewater treatment plant.

Looking at the environmental profile of the Vinyloop process plus the incineration of the pretreatment fraction and the filter residues it is obvious that the Vinyloop process dominates the result of primary energy, global warming potential and acidification potential.

Hazardous waste mainly comes from the incineration of the pretreatment fraction and the filter residues (59%). The background processes of the steam and electricity production are responsible for the remaining part.

Municipal waste mainly comes from the incineration of the pretreatment fraction and the filter residues (almost 100%).

The inert waste is mainly overburden from mining the energy carriers for the steam and electricity production.

Overview:
Environmental Profile of Vinyloop process and Incineration of pretreatment residues

Table 3-5: Environmental Profile and Recovered Products for the recovery of 1 t mixed cable waste in the MVR incineration

Recovery of 1 t mixed cable-waste:		
Environmental Profile		
Environmental Loads		
Primary Energy (non renewable)	12350	MJ
Global Warming Potential	1729	kg CO ₂ -Eq.
Acidification Potential	2,599	kg SO ₂ -Eq.
Hazardous waste	11,7	kg
Municipal waste	7,2	kg
Inert waste	118	kg
Waste water (only process itself)	9,1	m ³
Products (resulting in Environmental Benefits)		
PVC compound	672	kg
Copper in non ferrous metal fraction	7,4	kg
HCl (31%)	3,4	kg
Electricity	234	kWh
Steam	1954	kWh

3.4.5 Scenario analysis

The Vinyloop process is calculated with Italian boundary conditions. To check if the results will be transferable to other European countries the main drivers for the environmental results (steam and electricity) are assessed in the scenario analysis.

Electricity

To represent European conditions in the scenario UCPTTE electricity production has been chosen as a reference. Figure 3-55 shows a comparison of the primary energy demand for the production of 1 kWh electricity produced in Italy and 1 kWh electricity from the UCPTTE mix.

Using the UCPTTE mix the primary energy demand of the Vinyloop process will grow while the global warming potential will decrease because of lower demand of fossil fuels.

Calculating the systems Vinyloop with electricity from the UCPTTE mix need 3,5% more primary energy in comparison to the Italian electricity mix.

The global warming potential is 6,4% lower because of the high share of nuclear power.

The acidification potential grows 6,4%. The reason for that is the higher share of electricity from hard coal and lignite.

Steam

The second parameter with high influence on the environmental results of the Vinyloop process is the steam consumption.

Solvay quotes a possible reduction of the steam consumption by 20% for the second generation of the Vinyloop process [LEITNER et al. 2002].

Calculating the system with this reduced steam consumption the influence of the steam production becomes obvious.

20% less steam consumption results a reduction of 15,3% of the primary energy and 14,8% of the global warming potential. The acidification potential would be 11,4% lower as well.

There is no significant difference in steam production from the same energy carrier (e.g. natural gas) in Europe. Only the supply of the energy carriers differs between the countries, the technology of steam production is more or less the same.

Co-generating steam and electricity would be another improvement potential from an environmental point of view. The efficiency is much higher than separate production.

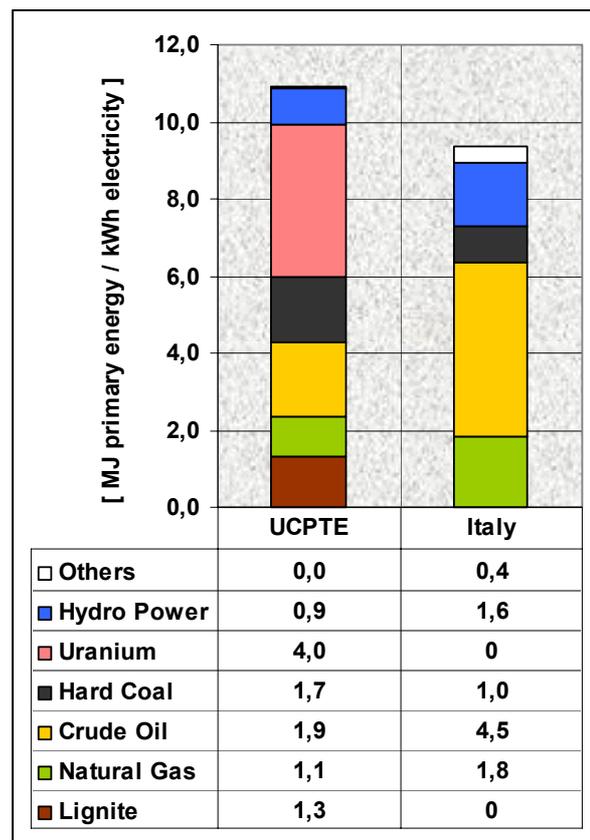


Figure 3-55 Primary energy of Italian and UCPTTE electricity production

4 Reference Scenario Landfill

4.1 Introduction

Although a rather minor waste stream, PVC cables contribute a certain share of the substance inventory in land filled waste. Depending on the composition of the PVC cable, the contribution to certain environmentally relevant substance groups may give a first indication of a possible impact of PVC cables on landfill emissions [MERSIOWSKY 2002a].

PVC cable compounds consist of the PVC polymer resin itself as well as a number of additives. The principal additives are plasticisers. For cables, Di-isononyl phthalate (DINP) or di-isodecylphthalate (DIDP) is commonly applied. Furthermore, stabilisers play an important role, with lead being the most relevant heavy metal applied in PVC stabilisers, and predominantly in cables. Further additives include fillers (e. g. chalk) as well as pigments and certain other discretionary substances. Based upon the standardised composition of a PVC cable, as selected by the project steering committee, the following target compounds and their flows in the landfill system will have to be addressed:

- PVC polymer
- Plasticiser: DINP
- Stabiliser: tribasic lead sulphate
- Filler: chalk, CaCO_3
- Other organic constituents: chlorinated paraffins, polyethylene, rubber
- Other inorganic constituents: copper (Cu) and aluminium (Al).

From this range of target compounds and indicator elements, the potential contributions of phthalates and lead are most relevant.

4.2 Behavior of Target Compounds under Landfill Conditions

4.2.1 PVC polymer

The question arose whether the PVC polymer under landfill conditions is subject to thermal or biological degradation. Polymeric materials are generally not assumed to degrade during the surveyable time period [BJÖRKLUND 1998]. Neither biological nor abiotic mechanisms for a depolymerisation process under the investigated environmental conditions are known. Indeed experimental evidence shows that the molecular weight distribution of the PVC polymer remains unchanged in landfill simulation experiments. This is considered indicative that no polymer chain scission took place [MERSIOWSKY *et al.* 2001]. These findings agree with other studies on PVC products retrieved from soil after decades [HJERTBERG/GEVERT 1995; OTAKE 1995; PLATE 1997]. In cases where alterations of mechanical properties or other effects were observed, these were either due to chemical decomposition or a degradation of additives. For instance, brittleness or discoloration may occur, particularly at

elevated temperatures, due to a loss of certain additives (particularly plasticisers, pigments, lubricants etc.). Alternatively, in case of aerobic pretreatment or deposition at the landfill surface, discoloration may also be due to photochemical or oxidative reactions [HJERTBERG 1995].

The PVC polymer was found to be resistant to degradation in landfills. In particular, there is no formation of vinyl chloride attributable to PVC. This assertion is made in contrast to the common assumption of a minor degradation of polymer matrices under landfill conditions, set out for instance by [BEZ *et al.* 1998]. For the purposes of a pragmatic assessment of the behaviour during the surveyable time period, the PVC polymer must be considered inert. Neither landfill gas (methane, carbon dioxide) nor vinyl chloride emissions can be allocated to it.

4.2.2 Plasticisers

The plasticiser DINP constitutes about 18 %, or 180 kg/t of the investigated PVC cable waste. The theoretical biogas yield from ideal anaerobic conversion of DINP with the molecular formula $C_{26}H_{42}O_4$ is 1,394 m³ per tonne of DINP. The methane contents will be 66 %, and the carbon dioxide contents 34 %. The experimental findings suggest that if there is any loss of plasticiser from the cable at all, it will be limited by glass transition before the entire quantity is lost. Further, only a certain portion of the plasticiser will be subject to biodegradation, either primary (into the corresponding monoester MINP and/or phthalic acid), or ultimate (into biogas). DINP as a lipophilic compound with high affinity for solids will also undergo adsorption. In absence of a verified distribution 50 % of the DINP are assumed to remain in the PVC cable compound at glass transition and 25 % are completely degraded into landfill gas. The rest is either adsorbed or partially degraded. In addition, only 50 % of this amount is assumed to escape as diffuse emissions while the rest is captured.

With regard to the formation of landfill gas, this means that one tonne of PVC cable waste gives rise of 31 m³/t. Due to the uncertainty of the assessment above, a variation of the degradation efficiency between 0 % and 100 % and of the diffuse emission between 5 % and 75 % is recommended (0–188 m³/t).

Obviously, while the specific yield of landfill gas from one tonne of PVC cable waste is in the same order of magnitude as for one tonne of municipal waste (although expected to be somewhat lower). The very low share of PVC cable waste in average land filled waste renders the contribution to landfill gas generation completely negligible: weighted by its expected average share of 0,15 %, the impact of PVC cable waste on landfill gas volumes is indistinguishable. If the share of PVC cable waste in land filled waste is varied up to 50 or even 100 % – a mono-landfill with only PVC cable waste yet assumed to show the behaviour of a regular MSW landfill – the expected amounts of landfill gas tend to decrease.

As for concentrations of phthalic compounds in landfill leachate, no measurements of DINP or MINP are available. Based upon findings reported by [MERSIOWSKY 2002b] on other phthalates in European landfill leachate, it appears reasonable to take the concentration range observed for DEHP – the most abundant, but least water-soluble phthalate – as a guideline: a ballpark estimate of 50 µg/L (range 0–500 µg/L) is adopted. With the diffuse leachate emissions associated with one tonne of MSW (300 L/t, range: 40–1500 L/t), the substance flow of phthalic compounds from DINP in PVC cable waste would be 15 mg/t (range: 0–750 mg/t). It is important to bear the reservation in mind that this crude estimate relies upon the following assumptions:

DINP originates exclusively from PVC cable waste, there is no background in MSW; the average concentration range of DEHP in landfill leachate is applicable to DINP as well; furthermore, the concentration range of DINP/MINP is determined by solubility/sorption equilibria and landfill development rather than the substance inventory (i.e. no scale-down for relative amounts is required). Provided that these hypotheses are not too far off reality, the given concentration range could be applied irrespective of actual amounts of PVC cable waste, since the very low-level of leachate emissions of DINP would not be a function of its total inventory in the landfill.

4.2.3 Stabiliser

Apart from losses of plasticisers, very little is known about the behaviour of additives in land filled PVC waste. Knowledge about soil-buried PVC products is somewhat better and may give an indication. A study by [PLATE 1997] on the loss of additives from soil-buried PVC confirms that no contamination of the soil is evident, even after irrigation with landfill leachate. The relevance of PVC stabilisers regarding the amounts of heavy metals in landfills is generally assessed to be inconsiderable, and a significant contamination of the leachate is not expected [POHLE 1997].

Reports on pipes and cables unearthed after 25 years of soil-burial indicate that there was neither any indication of migration of heavy metals within the PVC plastic matrix, nor did the surrounding soil exhibit any contamination which would conclusively originate from the PVC product [HJERTBERG/GEVERT 1995]. In the landfill simulation assays, the PVC cable exhibited the most notable release of stabilisers. Taking the analytical difficulties into consideration, the deficit of lead from the PVC compound was tentatively estimated at around 10 % [MERSIOWSKY 2002a]. The presence of heavy metals lead and zinc in the leachate was obviously correlated with the early development of the landfill simulation assays. The concentration levels during the acidogenic phase were considerably elevated because of the acidity and high organic pollution. The release of lead from the investigated PVC cable and pipe is probably attributable to superficial leaching. This means, a very small quantity of the stabiliser is reasonably available to leaching at the exposed surface of the

PVC product. However, the greater part of the lead contents is fixed in the matrix of the PVC compound and will under regular circumstances not migrate to the surface. Consequently, once the available lead is washed off from the surface and thus removed, a further leaching is not expected. This is corroborated by experiences with potable water pipes.

The heavy metal lead (Pb) constitutes about 1 % of the investigated PVC cable compound: 1,4 % lead sulphate stabiliser with a lead content of 68 %, or approximately 9500 mg/kg (ppm). The availability of lead from the PVC resin matrix is very low, assumed to be 10 % at most. This assumption could be the subject of a sensitivity analysis. The emission profiles of PVC cable compound and MSW would be rather congruent (leaching during the acidogenic phase, then declining elution). Therefore a contribution of PVC cable waste to the overall emission pattern of landfills can be computed. The content of lead in MSW is in the range of 650 mg/kg (ppm) [MERSIOWSKY 2002a/b]. PVC cable waste has a higher specific content of lead (about 15 times more). According to empirical findings, landfill leachate contains 100 µg/L (range: 10–1000 µg/L) of lead. With the diffuse leachate emissions associated with one tonne of MSW (300 L/t, range: 40–1500 L/t), thus the scenarios can be considered. It is obvious that the impact of PVC cable waste on levels of lead in the leachate becomes distinguishable only in the case of mono-landfills. Another possibility is if at least considerable amounts are disposed in one landfill cell. The substance flow of lead into MSW landfills conveyed by PVC cables, based upon average formulations, was calculated to be approximately 2,600 tonnes of lead per year (Western Europe). With MSW containing background levels of lead of around 650 mg/kg (ppm) dry solids, while PVC cables contain lead in the range of 1–3 % (i.e. around 30 times more than average MSW), this corresponds to a relative contribution to the lead inventory in sanitary landfills of approximately 4 % [MERSIOWSKY 2001; MERSIOWSKY 2002a]. This is noticeably more than the relation of the material flows of PVC cables in comparison to MSW, but still a rather minor contribution.

4.2.4 Filler

The filler chalk (CaCO_3) has not to be considered further since calcium carbonate is ubiquitous and abundant in landfills and soil. Any possible contribution by the PVC cable waste is certainly irrelevant.

4.2.5 Other organic constituents

- Chlorinated paraffins

With respect to the chlorinated paraffins, it appears reasonable to assume a de-hydro chlorination since this is the most probable biochemical transformation. While their leachability is unknown, any losses will be limited by the glass transition of the polymer resin similar to the loss of plasticiser. Biodegradation of any released chlorinated paraffins would

thus render chloride, which is an already abundant constituent of landfill leachate. The paraffin residues, which in turn could result in a slight increase of landfill gas production. With reference to the low contents of chlorinated paraffins in the PVC cable waste, it seems permissible to neglect these contributions.

However, any leached chlorinated paraffins and their chlorinated degradation products would contribute to AOX. The content of chlorinated paraffins in the investigated PVC cable waste is given as 0,7 %, existing out of 50 % chlorine. Assuming that 10 % could be available for leaching, there is a potential of leachable AOX compounds amounting to 350 mg/kg (ppm). Since little is known about the corresponding contents of AOX compounds in MSW and their respective leachability, this potential is estimated to be about equal. According to empirical findings, the concentrations of AOX in landfill leachate are in the range of 2000 µg/L (300–3000 µg/L). This concentration would thus be applicable to the emission flow from PVC cable waste as well, which then depends only on the leachate volume.

- PE and rubber

Polyethylene (PE) and rubber are expected to behave similar compared to most other technical polymers that those are resistant to biodegradation. In the light of scientific evidence [OTAKE 1995], it does not seem defensible to assume any degradation within the surveyable period of time. Even if a conservative approach had been adopted, supposing a minor degradation, this would still render macromolecular particles and possibly traces of carbon dioxide. Therefore it appears more realistic to assume inert residues and no significant contribution to landfill gas.

4.2.6 Other inorganic constituents

Copper and aluminium

Finally, copper (Cu) and aluminium (Al) are not constituents of the polymer resin but rather of the metallic conductor of the PVC cable. Hence a fixation as was the case with lead stabiliser cannot be assumed. Their behaviour in the shredded cable waste will probably resemble scrap metal. Due to the very low contents of aluminium in the PVC cable waste, no substantial contribution is expected. The content of copper in MSW is in the range of 900 mg/kg (ppm) [MERSIOWSKY 2002a/b]. The PVC cable waste has a specific content of about 17 times more (15,000/900). For copper in an average landfill, a transfer coefficient of 45 % is assumed for the relocation from the waste into leachate (predominantly by leaching and dissolution of scrap metal) during the surveyable time period. Average leachate concentrations of copper in MSW landfill are expected to be similar to lead, 100 µg/L. With these estimates, an approach in analogy to lead becomes possible. As with lead, the impact of the presence of PVC cable waste on the levels of copper in leachate becomes noticeable

only in the case of mono-landfills or if at least considerable amounts are disposed of in one landfill cell.

4.3 Environmental Results

Table 4-1: Landfill emissions - Input: 1kg mixed cable waste, time period = 100 a

Output	Responsible PVC constituent	Output amount [kg]
CH ₄ (emissions to air)	Plasticisers (DINP)	0,0146
CO ₂ (emissions to air)	Plasticisers (DINP)	0,0815
Cu (emissions to water)	Copper	2,25*10 ⁻⁷
Pb (emissions to water)	Stabiliser	4,41*10 ⁻⁸
DINP (emissions to water)	Plasticisers (DINP)	1,5*10 ⁻⁸
AOX (emissions to water)	Chlorinated paraffins	6*10 ⁻⁷
TOC (emissions to water)		3,75*10 ⁻⁵
Cl (emissions)	PVC polymer, chlorinated paraffins	0
Dioxin (emissions)	PVC polymer, chlorinated paraffins	0

5 Characterisation of the Products

One of the most important aspects of the study is the benefit of the received reclaimable products of the different processes. In the following, the environmental and economic value of these products will be described. Whether a product can substitute a raw material of the regarded substance - respectively a complete conventional production chain - or not is apparently significant from the environmental point of view. Nevertheless, especially from the economic perspective, the value or characteristic of the reclaimable product compared to conventional production does play an important role. Further important information is the approximate proportion of the amount of the alternative production to conventional production. The assessment of the products had been done concerning:

- Amount of the production (potential effects of substitution)
- Use of the product (possible end-product from the alternative product)
- Conventional primary production (for comparison reasons)
- Use of primary products (possible end-product from the primary product)
- Relevant by-production (from existing production chains)
- Characterisation of value (parameters that may restrict the value of the product)
- Possible integration process in existing production chains (flexibility of use in various processes)
- Value or characterisation aspects in comparison to conventional production or substitution (possible aspects of switching to alternative products as feedstock for established processes)

The value and particularly the demand of some products are regionally and temporally fluctuating or different. This is especially in terms of physical demand and cost figures (demand and cost often interrelated).

In some cases, the general assessment of the reclaimable products is quite problematic, especially for the last topic. As an example gypsum from an incineration plant is chosen. One can see that the substantial quality and the content of hazardous substances compared to conventional produced gypsum, is in the majority of the cases equal. Sometimes the quality is even better, but the effective demand for the so called REA-gypsum is quite low. Hence a substitution of primary produced gypsum would be possible, but in reality the gypsum is disposed into abandoned mines.

This chapter does not intend to judge the “quality” of the recovered products. The tables intend to draw a realistic picture of the specific topics in the case of the processes under study. Local and regional supply and demand side as well as locally arranged possibilities of

Characterisation of the Products

integrated production (use of waste energy and waste substances of other processes) influence the value (e.g. the price) of the products significantly. Influences on current markets are not considered.

The following tables discuss the products from the specific PVC-recovery processes according to the bullet points mentioned above. The pretreatment fraction for incineration is not considered to be a final product, as it is further processed and converted in to steam and electricity in the incineration plant.

Table 5-1: Characterisation and assessment of the produced Steam

Product name	Steam
Associated process	MVR Hamburg
Amount of production	391680 MWh (2001)
Use of product (possibility)	Flexible (for nearby customers)
Conventional primary production	Power plants, combustion of fossil fuels
Use of the primary products	Everywhere possible where steam is demanded, but distance limited
Existing By-Production	So far not known for a customer relevant amount of steam
Possible integration process in existing production chains	<ul style="list-style-type: none"> - Industrial processes where steam is needed - (Community heating)
Characteristic property	Exergy, calorific value
Value or characterisation aspects in comparison to alternative primary production	No difference

Table 5-2: Characterisation and assessment of the produced Electricity

Product name	Electricity
Associated process	MVR Hamburg
Amount of production	35496 MWh (2001)
Use of product (possibility)	Flexible
Conventional primary production	See grid mix (share of coal, nuclear power, biomass, renewable energies)
Use of the primary products	Everywhere possible where electricity is demanded
Existing By-Production	No
Possible integration process in existing production chains	Everywhere possible where electricity is demanded
Characteristic property	Exergy/Energy content
Value or characterisation aspects in comparison to alternative primary production	No difference

Table 5-3: Characterisation and assessment of the produced Gypsum

Product name	Gypsum
Associated process	MVR Hamburg
Amount of production	1193,4 t (2001)
Use of product (possibility)	Production of gypsum plaster board, mortar
Conventional primary production	Plaster burning of natural gypsum
Use of the primary products	Flexible use in the building sector
Existing By-Production	Flue gas desulphurisation in coal power plants
Possible integration process in existing production chains	See "Use of product"
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	Chemical consistency comparable to natural gypsum, seldom differences concerning colour and smell.

Table 5-4: Characterisation and assessment of the produced Hydrochloric Acid

Product name	Hydrochloric Acid (31%)
Associated process	MVR Hamburg
Amount of production	3825 t (2001)
Use of product (possibility)	<ul style="list-style-type: none"> - Production of PVC - Extraction of various metal ore - Conditioning of water
Conventional primary production	Synthesis of chlorine and hydrogen
Use of the primary products	<ul style="list-style-type: none"> - Conditioning of water - Extraction of various metal ore and various chemical processes
Existing By-Production	Chlorination process of organic compounds
Possible integration process in existing production chains	See "Use of product"
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	Value of the produced acid (according to EN 939) is comparable to primary produced HCl.

Table 5-5: Characterisation and assessment of the produced Copper from non ferrous metal fraction

Product name	Copper in non ferrous metal fraction
Associated process	MVR Hamburg
Amount of production	466 t non ferrous metals (2001), copper + lead content 12 - 15%
Use of product (possibility)	Flexible
Conventional primary production	Mining of copper ore and further electrolysis
Use of the primary products	Flexible
Existing By-Production	So far not known for relevant amounts
Possible integration process in existing production chains	Flexible in the range of recycled copper applications
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	No relevant difference

Table 5-6: Characterisation and assessment of the produced Calcium Chloride

Product name	CaCl ₂ (36%, industrial grade)
Associated process	Watech
Amount of production	app. 10000 t/a (at processing of 15000 t _{PVC} /a)
Use of product (possibility)	Road salt (hydrophilic character)
Conventional primary production	Synthesis of HCl and CaCO ₃
Use of the primary products	Thaw salt, drying agent (crystalline condition)
Existing By-Production	Production of soda-ash
Possible integration process in existing production chains	No integration so far known (end product)
Characteristic property	Purity, (CaCl ₂ content)
Value or characterisation aspects in comparison to alternative primary production	No differences known

Table 5-7: Characterisation and assessment of the produced Coke

Product name	Coke
Associated process	Watech
Amount of production	app. 2500 t/a (at processing of 15000 t _{PVC} /a)
Use of product (possibility)	Fuel for energy production
Conventional primary production	Hard coal processing
Use of the primary products	Fuel for energy production and feedstock for chemicals
Existing By-Production	None
Possible integration process in existing production chains	As fuel directly into the power or energy production process chain
Characteristic property	Energy content
Value or characterisation aspects in comparison to alternative primary production	Depending on the PVC input inorganics may accumulate in coke (influencing the heating value), no difference in the physical condition of the coke in comparison to pulverised hard coal expected

Table 5-8: Characterisation and assessment of the produced Organic Condensate

Product name	Organic condensate
Associated process	Watech
Amount of production	app. 1500 t/a (at processing of 15000 t _{PVC/a})
Use of product (possibility)	Fuel for energy production
Conventional primary production	Crude oil processing
Use of the primary products	Fuels
Existing By-Production	No relevant by-production in this sense
Possible integration process in existing production chains	As fuel directly into the power or energy production process chain
Characteristic property	Energy content
Value or characterisation aspects in comparison to alternative primary production	Product consists of a variable mixture of different hydrocarbons, no homogeneous composition, up to 15% 2-ethyl-1-hexanol

Table 5-9: Characterisation and assessment of the produced Heavy Metal Product

Product name	Heavy metal product
Associated process	Watech
Amount of production	App. 330 t/a (at processing of 15000 t _{PVC/a})
Use of product (possibility)	Possible feedstock to non-ferrous metal refinery, application possibilities so far questionable, but still under examination
Conventional primary production	Primary non-ferrous metal production
Use of the primary products	Various non-ferrous metal applications
Existing By-Production	None
Possible integration process in existing production chains	So far questionable, still under examination
Characteristic property	Metal content, Purity
Value or characterisation aspects in comparison to alternative primary production	Mixture of different non-ferrous metals and further inorganic fractions, contents of single non-ferrous metals max. 40-60%. For useful application it is believed that a separation of metals is needed.

Table 5-10: Characterisation and assessment of the produced Sodium Chloride

Product name	NaCl (vacuum salt)
Associated process	Stignæs
Amount of production	17000 t/a (at 60000 t _{PVC} /a)
Use of product (possibility)	Chemical Industry: Production of HCl, Soda-ash, chlorine, NaOH
Conventional primary production	Vacuum salt production
Use of the primary products	See use of products
Existing By-Production	(Waste) product of the conditioning process of seawater (industrial grade only)
Possible integration process in existing production chains	See use of products, flexible interaction points in process routes (Na and Cl content)
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	Alternative products can be produced with a high purity, hence no differences expected.

Table 5-11: Characterisation and assessment of the produced Oil Fraction

Product name	Oil fraction
Associated process	Stignæs
Amount of production	App. 9000 t/a (at processing of 60000 t _{PVC} /a)
Use of product (possibility)	Feedstock in Refinery
Conventional primary production	Crude oil processing
Use of the primary products	Fuels and chemical intermediates
Existing By-Production	No relevant by-production in this sense
Possible integration process in existing production chains	Feed into reformer or cracker sections of refinery
Characteristic property	Energy content or Hydrocarbon content
Value or characterisation aspects in comparison to alternative primary production	Product consists of a variable mixture of different hydrocarbons and some water, no homogeneous composition

Table 5-12: Characterisation and assessment of the produced Solid Residue

Product name	Solid residues
Associated process	Stignæs
Amount of production	21000 t/a (at 60000 t _{PVC} /a)
Use of product (possibility)	Intermediate for sandblasting product
Conventional primary production	Gravel pit and coke
Use of the primary products	Construction and road building processes
Existing By-Production	Sludge use from waste water treatment
Possible integration process in existing production chains	Use as intermediate sandblasting product in the nearby Carbogrit plant
Characteristic property	C-Content (energy content) to heat the Carbogrit process and the mineral content as part of the granulated substance of the sandblasting product
Value or characterisation aspects in comparison to alternative primary production	In this particular application no difference known

Table 5-13: Characterisation and assessment of the produced R-PVC compound

Product name	R-PVC compound
Associated process	Vinyloop
Amount of production	< 10000 t/a
Use of product (possibility)	PVC processing
Conventional primary production	Primary PVC compound production
Use of the primary products	Flexible, in PVC processing
Existing By-Production	None
Possible integration process in existing production chains	Manufacturing of products on the basis of PVC compound (see: "Use of product")
Characteristic property	High grade substitute of primary PVC compound
Value or characterisation aspects in comparison to alternative primary production	The marketability is dependent on the applied additives and national attitudes. The colour might constrict further applications.

Table 5-14: Characterisation and assessment of the produced Copper

Product name	Copper
Associated process	Watech / Stignæs
Amount of production	14,925 kg/t / 14,625 kg
Use of product (possibility)	Flexible
Conventional primary production	Mining of copper ore and further electrolysis
Use of the primary products	Flexible
Existing By-Production	So far not known for relevant amounts
Possible integration process in existing production chains	Flexible in the range of recycled copper applications
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	No relevant difference

Table 5-15: Characterisation and assessment of the produced Aluminium

Product name	Aluminium
Associated process	Watech / Stignæs
Amount of production	4,975 kg/t / 4,87 kg
Use of product (possibility)	Aluminium casting ⇒ Various applications, e.g. Cylinder head
Conventional primary production	Mining of Bauxite and further electrolysis
Use of the primary products	Various aluminium applications
Existing By-Production	So far not known for relevant amounts
Possible integration process in existing production chains	Flexible in the range of recycled aluminium applications
Characteristic property	Purity
Value or characterisation aspects in comparison to alternative primary production	No relevant difference

The following Table 5-16 aims to give an overview of the expanded processes. The first column shows the products of the analysed processes, whereas the second column shows the common primary processes, which are used to expand the system according to the method of system expansion.

Table 5-16: Products and used (common) primary processes for system expansion.

Products of recycling processes under study	Used primary production processes	Comment
Steam	Steam from natural gas	94% efficiency, Germany
Electricity	Electricity Grid Mix	1998, Germany
Gypsum	CaSO ₄ *1/2 H ₂ O Mix	~50% natural resources, ~50% from FGD, Germany
Hydrochloric acid (31%)	Hydrochloric acid (31%)	As major by-product of chemical industry, Germany.
Copper	Bilster copper	>98% Copper content, Germany
Calciumchloride (36%)	Calciumchloride (36%)	By-product of chemical industry processes like the epichlorohydrine synthesis, Germany
Coke	Hard coal Mix	in MJ, Germany
Organic condensate	Fuel oil	Refinery product in MJ, Germany
Copper of metal fraction	Cu concentrate	in Copper content, Germany
NaCl (vacuum salt)	NaCl	Purified rock salt, Germany
Oil fraction	Naphtha	Refinery product in MJ, Germany
Solid residue	Mix of Hard coal and limestone	Hard coal for calorific value, limestone for mineral part, Germany
PVC compound	PVC cable compound	Virgin PVC cable compound, composition see Figure 2-1, Germany

6 Environmental Comparison of the Recovery Options

This chapter compares the three impacts Primary Energy Consumption, Global Warming Potential and Acidification Potential of the four technologies with the reference situation landfilling.

Three different views are presented, to enable different perspectives of the analysis and conclusions. To be in accordance with ISO 14040 ff. it is to state, that this comparison is just for internal use. If it is intended to disclose the comparison to public, it is to show that other environmental impacts like Eutrophication Potential, Ozone Depletion Potential, Toxic Potentials, Photochemical Oxidant Formation do not significantly influence the overall tendency and conclusions.

Primary Energy Demand: Comparison with system expansion

The Primary Energy Demand compares the different technologies and resulting products from the view point of burdens.

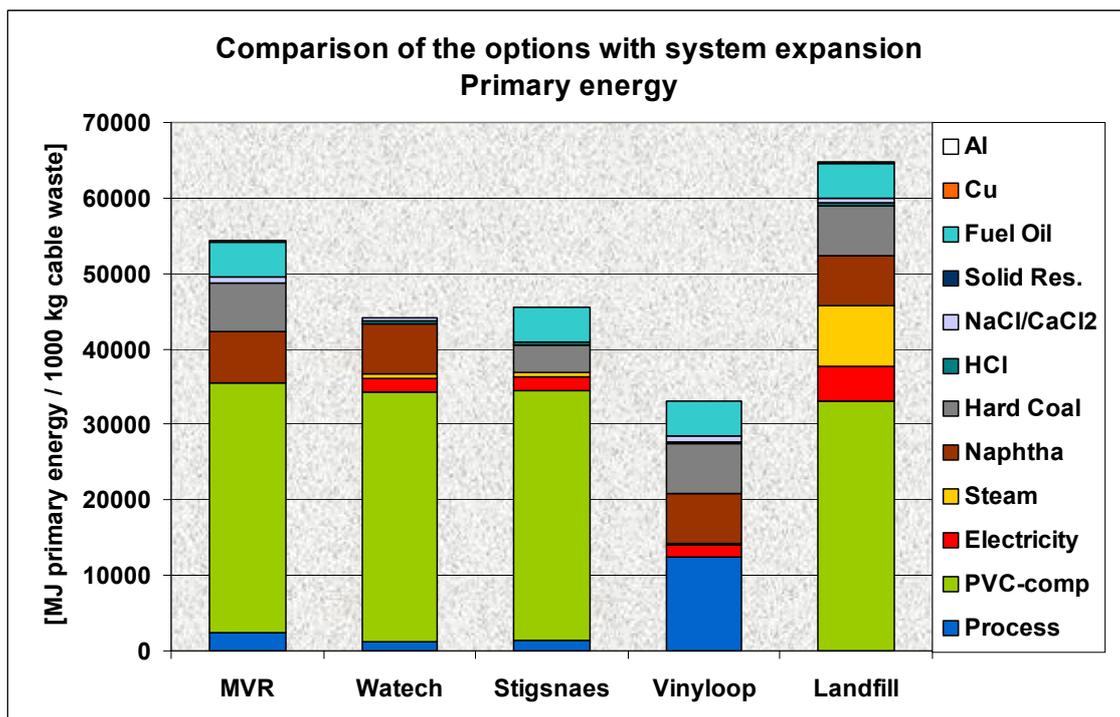


Figure 6-1: Primary Energy demand of the recovery options with system extension

Hence in Figure 6-1 only burdens are displayed, generated by the system expansion to make the technologies at the different products comparable. The higher a bar is, the more burden (due to comparative system expansion method) the technology has to account for. The blue share of the bars characterizes the burden due to the operation of the individual process

itself. A matter of system expansion (see chapter 2.3 for details) is to make processes comparable, which produce different products (as it is here).

The explanation is shown with an example: The MVR carries the burden of the energy needed to operate the process (blue) and the burden of all products, produced by the other processes of Stignæs (naphtha, solid residue and NaCl), Watech (hard coal, fuel oil and CaCl₂) and Vinyloop (PVC compound) rather than to get credits for the own products. The other processes (Stignæs, Watech, Vinyloop and landfill) carry the burdens for all the produced products incl. MVR (steam, electricity) respectively. Landfill does not produce any product; hence only gaining burden of the other recovery processes occur and landfill has the highest burden. Figure 6-1 therefore provides information, which recovered products are most relevant for the impact under study (here primary energy).

Remark: The Figure 6-1 expresses the same results as the following Figure 6-2, only from a different viewpoint of interpretation.

Net Consumption of Primary Energy: Comparison to landfill with system expansion

The Net Consumption of Primary Energy compares the difference of the primary energy needed to operate the process to the primary energy value of the recovered products. In this view the individual processes do not carry the benefits of the other processes as burden. In the following Figure 6-2 the benefit of the individual processes and its individual products is directly substituted from burden caused by each process. Hence negative values can arise, if more benefit than burden occurs.

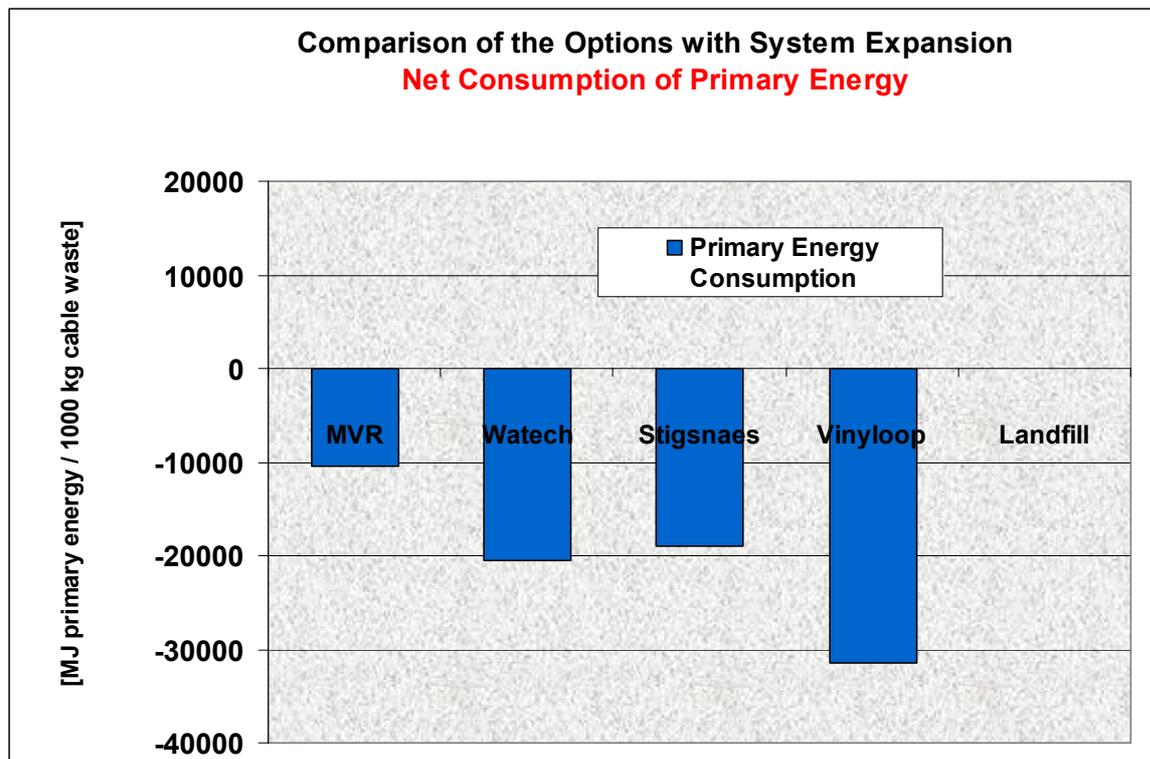


Figure 6-2: Net Consumption of Primary Energy of the recovery options with system extension

Environmental Comparison of the Recovery Options

Figure 6-2 shows that all recovery options recover more primary energy by supplying different products, than needed to operate the processes (bars drop to negative). The reference landfilling shows no recovery of primary energy; just small burdens to operate the landfill. The values displayed are interpreted on an example. If the result of a recovery process shows negative values (e.g. MVR app. -11000 MJ/t cable waste), the process recovers 11000 MJ/t more primary energy (in the form of products) than the process needs to be operated. Hence all analysed recovery options reach the goal of energy recovery compared to landfill.

The mathematical value of Figure 6-2 can be generated with the values of Figure 6-1 by substituting the sum of burden of all products recovered by all processes (see the bar for landfill), from the bar of the individual technology.

Figure 6-2 therefore provides information about the net situation of each technology, relating burden to run the process and value of produced recovery products from view point of the impact under study (here primary energy).

Primary Energy Demand: Life Cycle view with system expansion

The goal of the last view is to relate the recovery burden and benefits to the life cycle.

The white bar represents the amount of energy needed to produce 1000 kg of virgin cable mix.

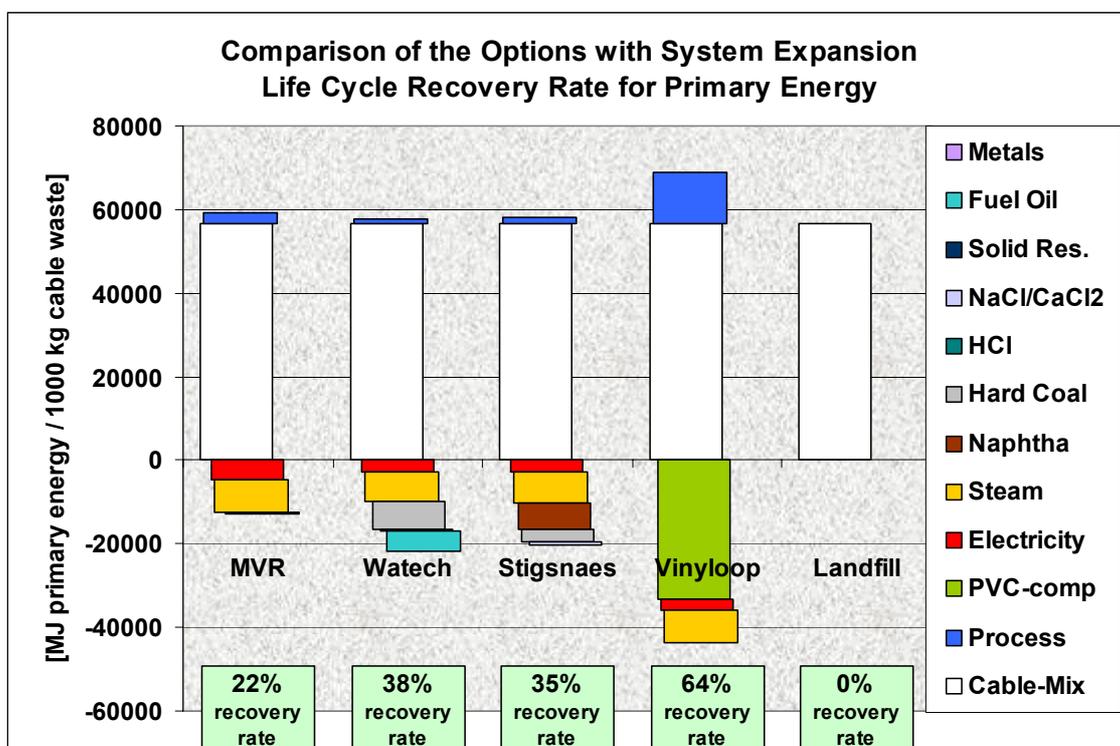


Figure 6-3: Primary Energy of the recovery options with system extension (Life Cycle view)

Environmental Comparison of the Recovery Options

It can be seen that e.g. in case of the MVR the burden to operate the process (blue) and the benefit for recovering products (steam: yellow, electricity: red, HCl: dark green, poorly seen) in comparison to the production of 1000 kg virgin cable mix is rather low.

Hence the ratio of the sum of the negative values to the positive value of each bar results in the recovery rate displayed in the diagram. The recovery rate is related to the energy demand of the initial production of 1000 kg virgin cable mix.

The mathematical value of Figure 6-2 can be generated with the values of Figure 6-3 as well. The difference between the positive blue share and the sum of the negative yellow, red and dark green shares would lead to the result of Figure 6-2 again (app. -11000 MJ/t).

Global Warming Potential: Comparison with system expansion

As explained for primary energy, the following figures display the results for the Global Warming Potential accordingly.

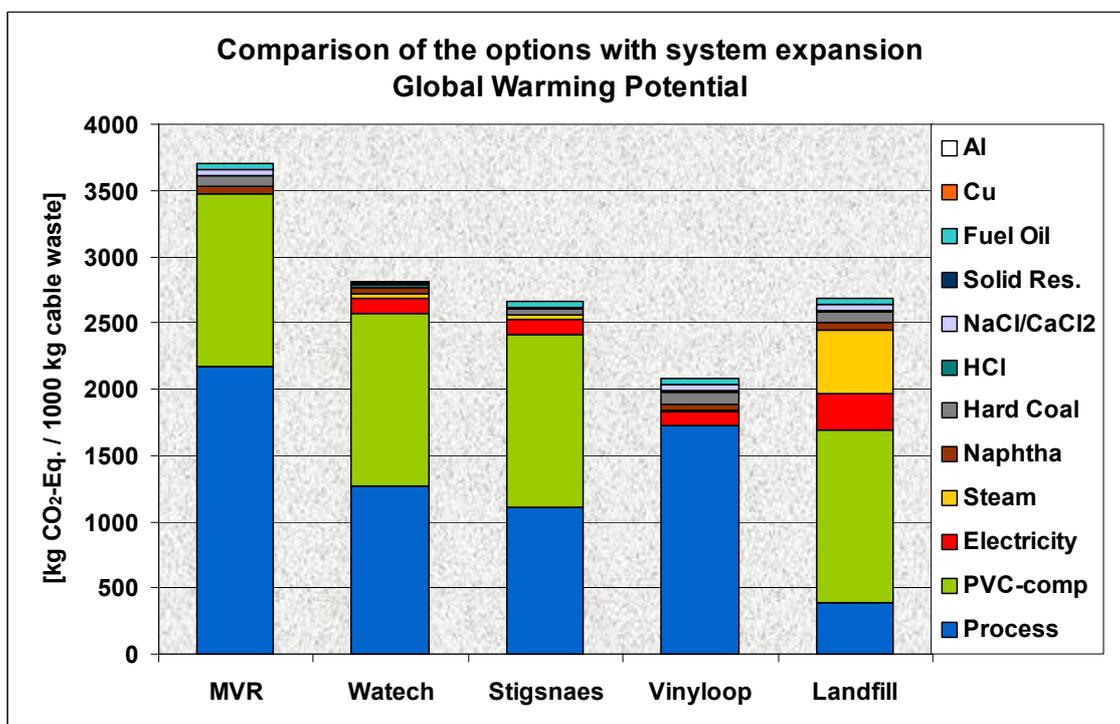


Figure 6-4: Global Warming Potential of the recovery options with system extension

Due to the relatively high GWP emissions in the operation of the incineration plant, the MVR incineration plant performs worse in terms of global warming. The Vinyloop has comparable high GWP emissions in the operation, but recovers a product (PVC-compound), that has a high GWP saving potential. That is because the recovery of the PVC-compound (and hence the potential prevention of a it's GWP intensive virgin production of PVC) leads to high GWP savings. The landfill has relatively low GWP emissions in operation, but has to carry all the product burdens of the other processes, as landfill does not recover products.

Net Global Warming Potential: Comparison to landfill with system expansion

As explained before Figure 6-5 shows the Net Global Warming Potential results.

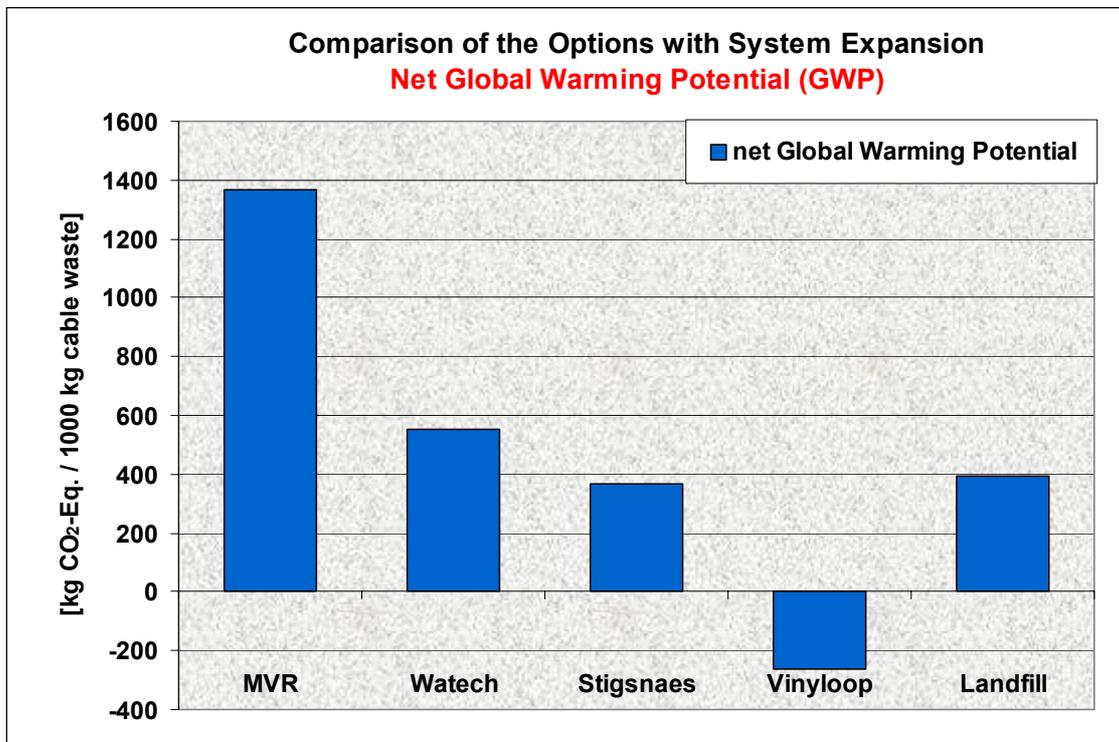


Figure 6-5: Net Global Warming Potential of the recovery options with system extension

The MVR produces by far most GWP. That is obvious, as the PVC is incinerated and thus in operation high GWP emissions arise. On the other hand side the amount and kind of products (electricity and steam) does account only for relatively low GWP savings (the efficiency of the MVR is optimised to incinerate waste with low environmental burden, rather than to produce electricity and steam in a effective way). Only the Vinyloop process prevents more GWP emission, than generated by the process.

Global Warming Potential: Life Cycle view with system expansion

The relation of the recovery burden and benefits to the life cycle is shown in Figure 6-6.

The white bar represents the amount of GWP emissions released to produce 1000 kg of virgin cable mix.

Hence even related to the GWP emissions released to produce 1000 kg of virgin cable mix, the MVR operating emissions are quite high and the GWP prevention benefits of the product are comparably low. It can be seen, that the prevented GWP emissions of the Vinyloop process are in the order of magnitude of the GWP emissions released to produce 1000 kg of virgin cable mix; but also the GWP emissions to run the process.

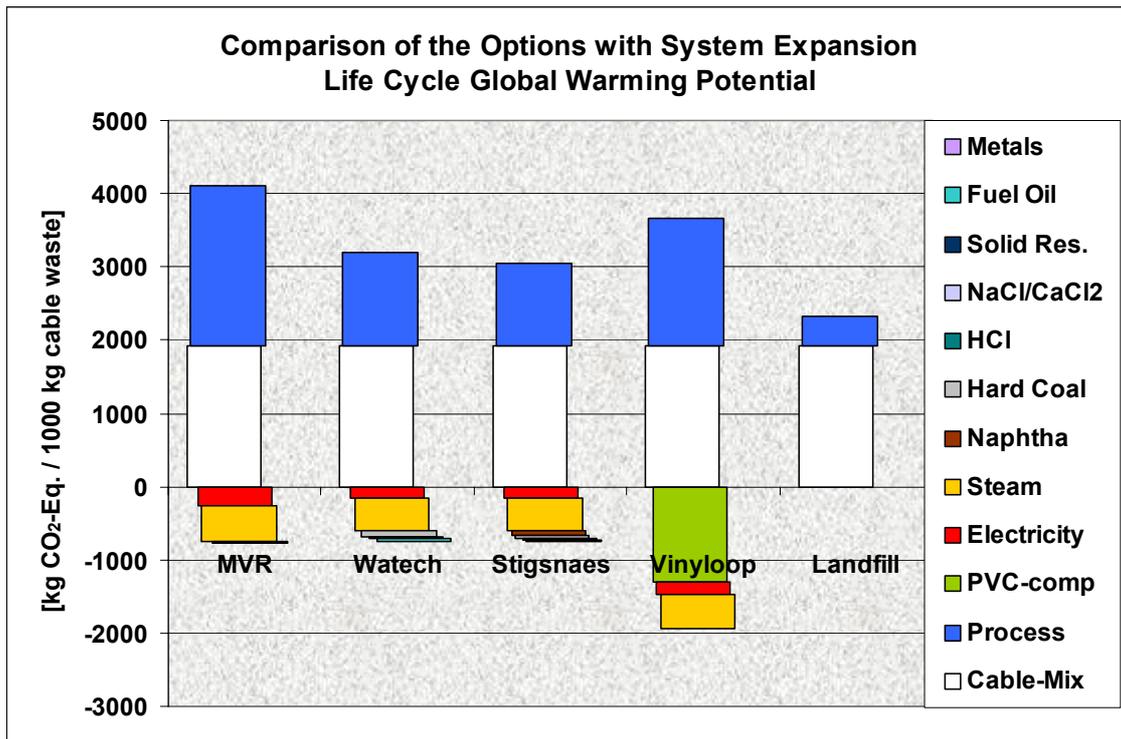


Figure 6-6: GWP of the recovery options with system extension (Life Cycle view)

Acidification Potential: Comparison with system expansion

Respectively the following figures display the results for the Acidification Potential. Landfill again is compared to the technologies under study the worst option.

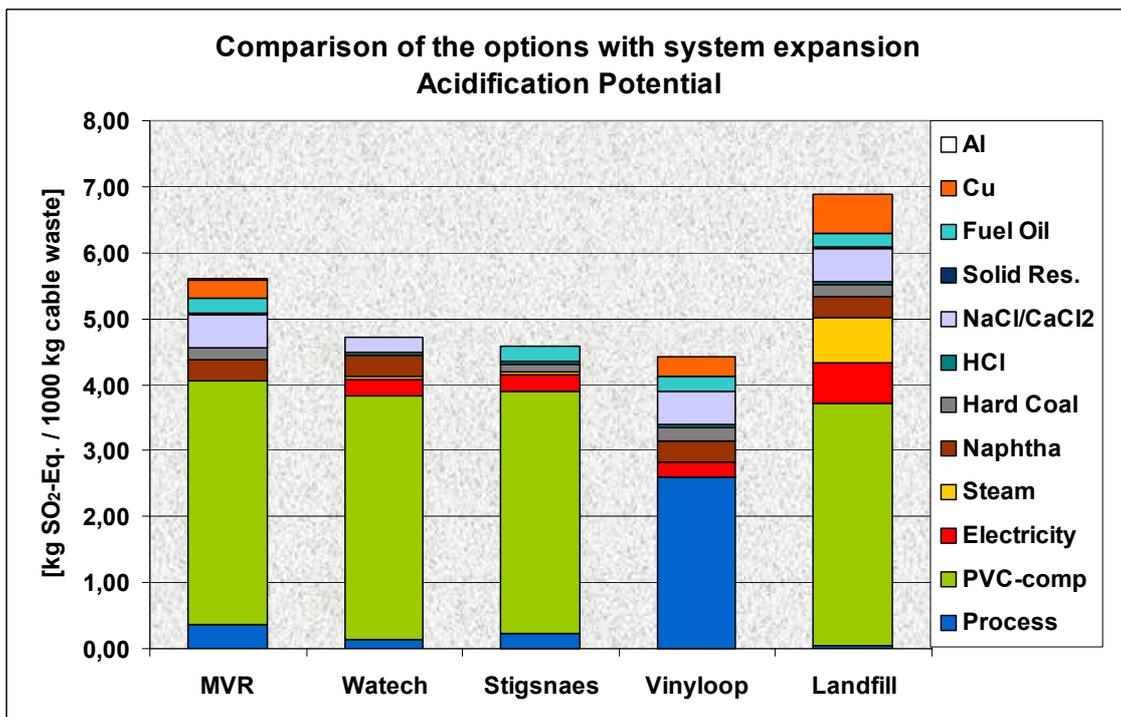


Figure 6-7: Acidification Potential of the recovery options with system extension

Net Acidification Potential: Comparison to landfill with system expansion

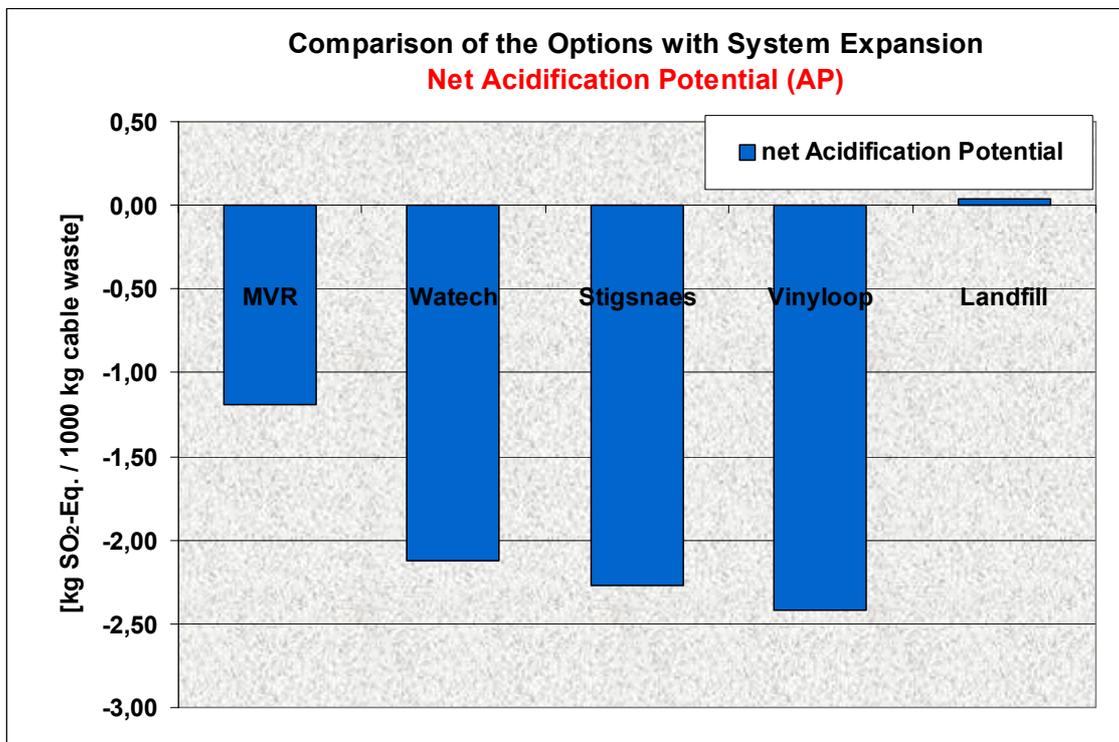


Figure 6-8: Net Acidification Potential of the recovery options with system extension

All recovery processes show a Net Acidification benefit. Landfill does not recover any products, therefore just has burdens due to the operation of the landfill.

Acidification Potential: Life Cycle view with system expansion

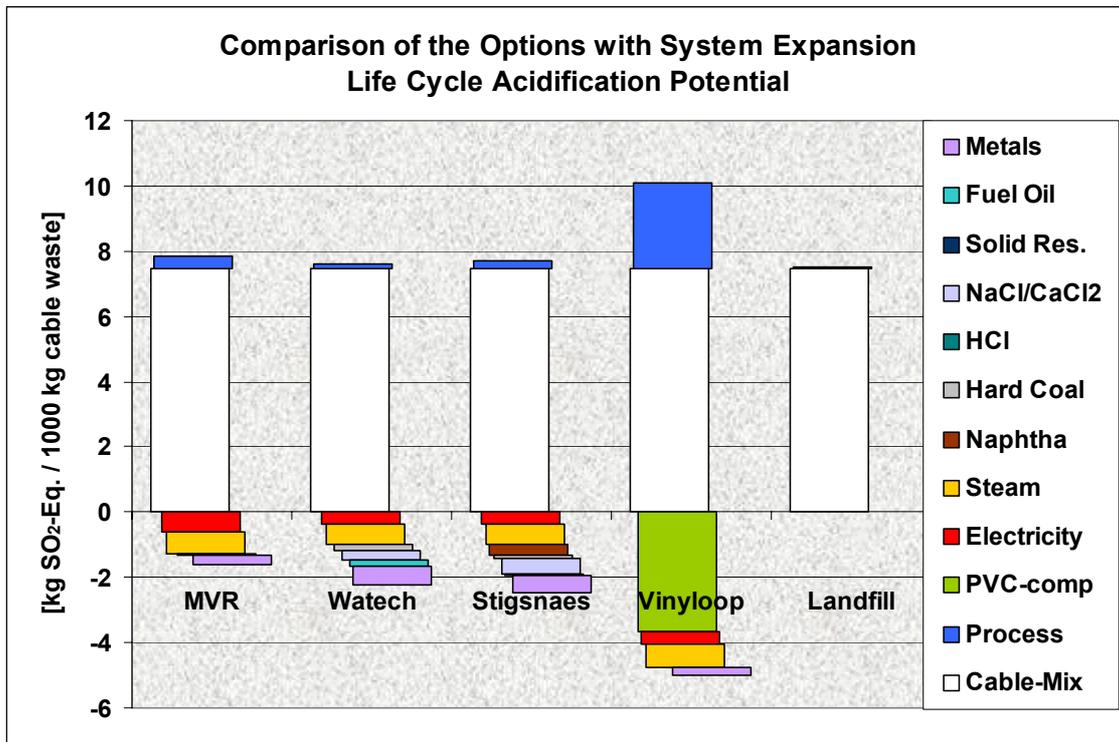


Figure 6-9: Acidification Potential of the recovery options with system extension (Life Cycle view)

It can be seen that the Acidification Potential of operation of the processes is relatively low at least for MVR, Watech, Stigsnaes and landfill. But the recovery processes and most of them Vinyloop can offset benefits due to the prevention of Acidification Emission for the recovered products.

The results of this chapter show clearly one main fact. If taking into account system expansion and arguing from an environmental point of view the quality of the products play a far more dominant role, than the processes itself. Hence a quality increase of the products is a more sensible point of a better environmental profile, than process optimisation.

Municipal and Hazardous Waste

Depending on the technology, the amount and characteristics of generated waste differs. This depends mostly on the waste generated in the individual core processes.

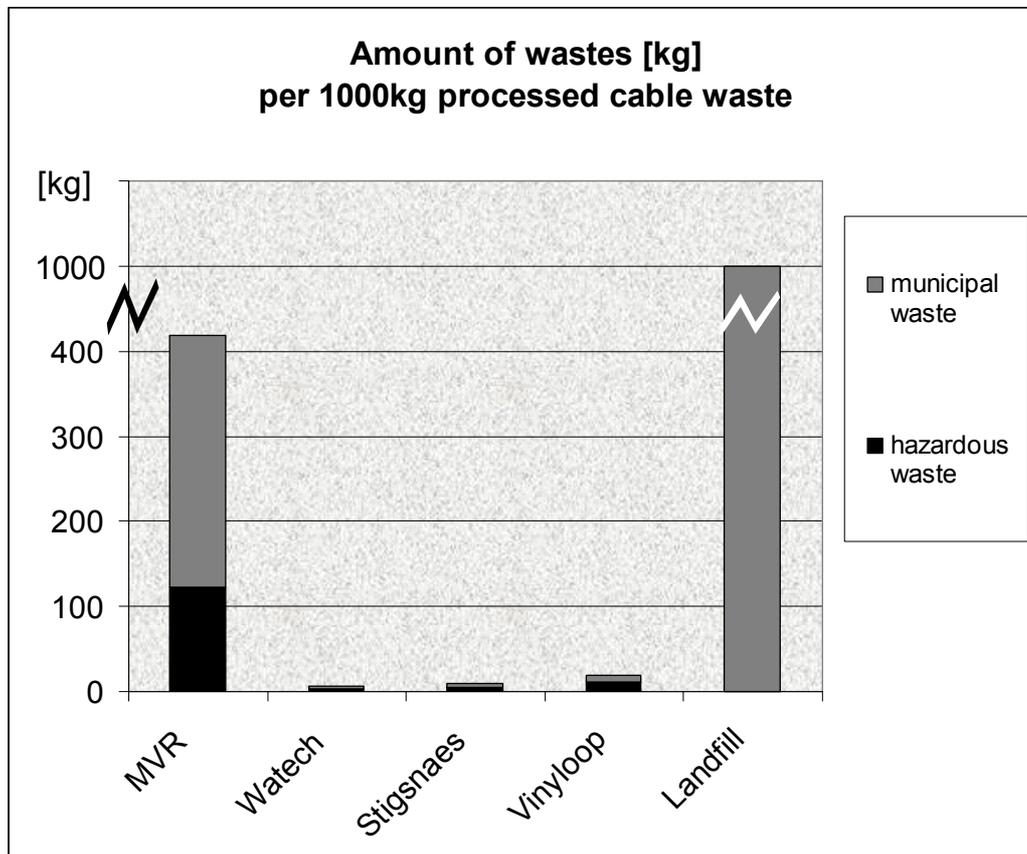


Figure 6-10: Wastes of different using different technologies

In landfill obviously 1000kg municipal waste are generated. The MVR incineration reduces the amount of waste to 419 kg in sum. The recovery options perform a lot better. Watech generates with 6,1 kg the smallest amount.

For a more detailed description of the origin of the wastes of the individual technologies see chapters 3.1.5, 3.2.4, 3.3.4 and 3.4.4.

Fate of selected substances

Depending on the technology, the fate of specific substances differs. Depending on the national attitudes the (environmental) importance of different substances is rated differently.

Lead

Especially in the Nordic countries the fate of the lead, which is contained in the PVC stabiliser, is of interest.

To compare the fate of the lead in an overall comparison six categories of “endpoints” of the lead are defined:

- Lead as emission to environment (e.g. as a stack emission due to incineration of PVC; lead is not recovered; direct impact to environment)
- Lead as part of municipal waste or hazardous waste (e.g. as residue in filter ash; lead is not recovered; no direct environmental impact; if dumped properly like in MVR Hamburg; lead going to landfill as PVC stabiliser, environmental impact due to emission see chapter 4.3).
- Lead as trace in resulting products (e.g. lead as traces in salt or organic products; lead is not recovered; environmental or quality impact relates to further use of products)
- Lead to Carbogrit plant (lead is contained in solid residue. Lead in this fraction does not fulfil a particular function and will be separated in a further production step – here Carbogrit plant, which is excluded from the study – and then recovered or disposed)
- Lead as component of product (lead used again as stabiliser in recovered PVC compound, lead is recovered, heat stability function provided by lead, new life cycle)
- Lead concentrated in a product (e.g. lead as heavy metal product, lead can be recovered, environmental or quality impact relates to further processing and use of product)

In this chapter an overview is provided with the help of a comparison. For detailed descriptions of the individual lead mass flows of different technologies see chapter 3.1.3, 3.2.2, 3.3.2 and 3.4.2.

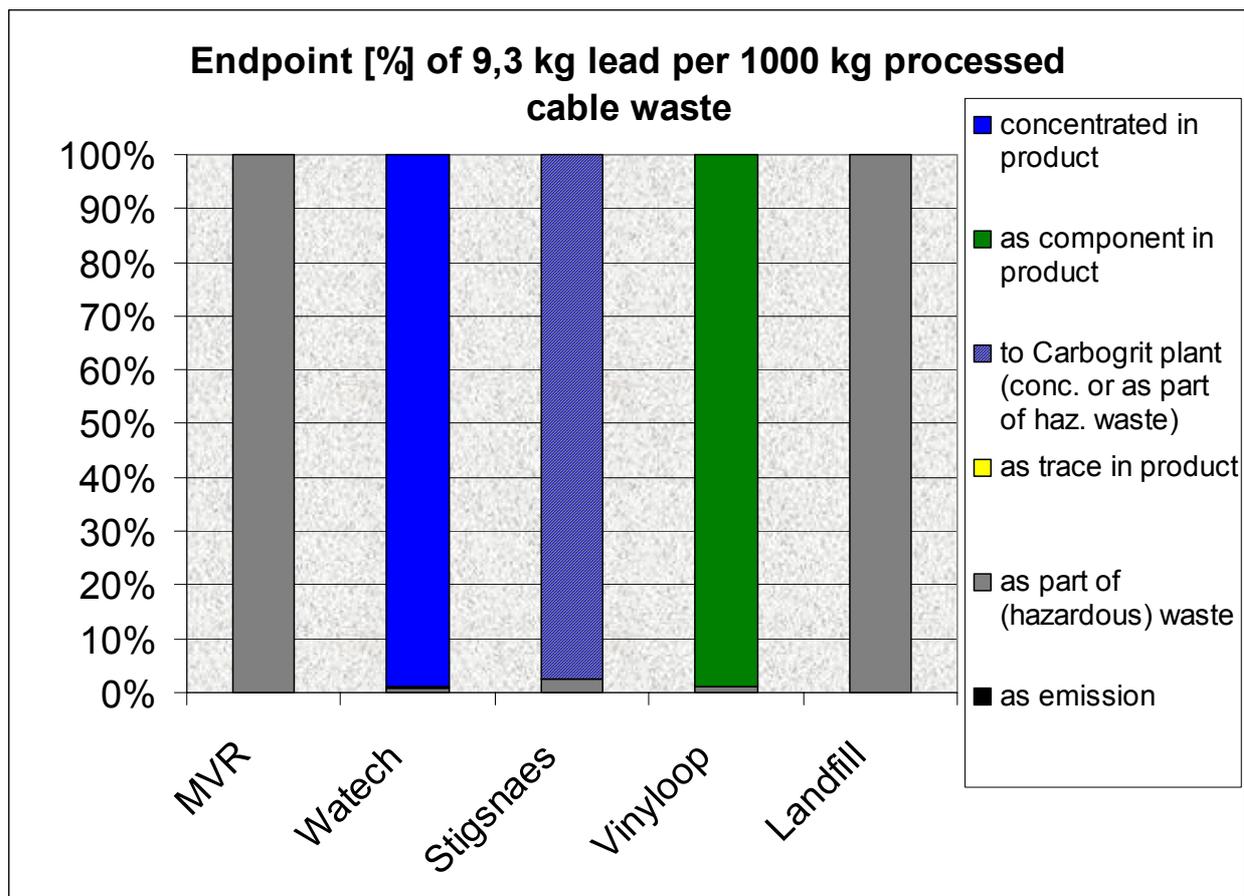


Figure 6-11: Fate of lead using different technologies

As all of the technologies have to deal with the equal input of lead (9,3 kg from PVC-compound) and no additional lead enters the systems, a relative chart was chosen to ease the interpretation.

In the **MVR incineration** plant almost 99,98% of the lead ends up in the filter residues, ashes as well as in the salt brine and goes into the underground hazardous waste site without a direct impact to the environment. A small part (app. 0,02%) is found as traces in HCl, slag and gypsum. The smallest share (app. 0,001%) is emission of the stack. No lead is recovered.

In the **Watech process** more than 98,7% of the lead can be recovered, as it is concentrated in a metal product together with different other metals. Only app. 0,7% are found in the hazardous waste site, due to the fact that a small share of PVC is separated in the pretreatment together with the polyethylene and sent to the incineration and most of this 0,7% end up after incineration in the hazardous waste site (see above). Only a small share of the 0,7% is found in the MVR products and emissions. Less than 0,5% are found as traces in products (mainly in coke). Very little emissions occur due to the incineration of the pretreated

fraction from Watech in the MVR (less than $8 \cdot 10^{-6}\%$). No lead was detected as emissions from the stack.

In the **Stignsnæs process** most of the lead ends up in the solid residue, which is used in the Carbogrit plant (app. 97,3%). The final “endpoint” of the lead in the solid residue (to Carbogrit) can only be defined, if the Carbogrit plant is analysed (outside the scope of this study). In the Carbogrit plant the applied technology defines the further fate of the evaporated lead (transfer into a concentrated product for recovery, into an emission, into traces of other products or as part of hazardous waste). Approx. 2,6% of the lead ends up as part of the hazardous waste in the filter ash due to incineration of the pretreatment fraction in MVR. App. 0,1% are found as traces in products (mainly in the oil product). Around 0,00057% of the lead are leaving the system as emission (mainly to wastewater treatment, where a part of the lead is found in the sludge, which is transferred to the Carbogrit plant for further processing). The remaining lead is finally emitted to water.

In the case of the **Vinyloop process** most of the lead (app. 98,7%) are found as a component (stabiliser) in the recovered PVC-compound again. About 1,1% are going to hazardous waste, mainly due to the incineration of the pretreatment fraction. With the waste water about 0,14% lead are emitted to waste water treatment, where a part of the lead is going into the sludge and ends as hazardous waste and the rest is finally emitted to water. A very small share (app. 0,0002%) is found as traces in the products due to the incineration of the pretreatment fraction.

In **Landfilling** it is considered that $4,41 \cdot 10^{-5}$ kg lead per 1000kg of landfilled mixed cable waste are emissions (see chapter 4.3). This accounts for app. 0,0005% of the lead. The rest (>99,999%) is considered as firmly bound to the PVC matrix and therefore part of waste.

Dioxin

To discuss the fate of dioxins in an overall comparison, three categories of “endpoints” are defined, although they all are technology dependent:

- Dioxin as emission to environment (e.g. as a flue gas emission due to an incineration; direct impact to environment)
- Dioxin as part of hazardous waste (e.g. as residue in filter ash; no direct environmental impact; if dumped properly like in MVR Hamburg).
- Dioxin as trace in resulting products (e.g. as traces organic products; environmental or quality impact relates to further use of products)

For detailed descriptions of the individual dioxin mass flows of different technologies see chapters 3.1.3, 3.2.2, 3.3.2 and 3.4.2.

In the **MVR municipal solid waste incineration** the formed dioxins end up in filter ash (> 94%), boiler ash (app. 5,5%) and salt brine (app. 0,03%) and are dumped in the hazardous waste site with no direct impact on environment. The balance is found as emissions in the flue gas and as traces in the HCl.

In the **Watech process** the very small amount of formed dioxins is found in the stack emissions, which accounts already for more than 98% of all dioxin formation. The balance is found in hazardous waste and as traces in the MVR products, due to incineration of the pretreatment fraction.

In the **Stignæs process** traces of dioxins/furans end up in the oil product and in the solid residue. The stack emissions are expected to be below detection limit. The balance is found in hazardous waste and as traces in the MVR products, due to incineration of the pretreatment fraction as well.

In the case of the **Vinyloop process** all of the dioxin formed is related to the incineration of the pretreatment fraction in the MVR, as no other dioxin was detected respectively measured.

In **Landfilling** no formation of dioxins is considered emissions (see chapter 4.3).

Chlorinated Paraffins

The mixed cable waste contains 6,8 kg for chlorinated paraffins (see chapter 2.2.2).

In the **MVR incineration process** all chlorinated paraffins enter the combustion chamber and are totally destroyed. No chlorinated paraffins can be detected in products, residues or as emission.

The **Watech feedstock recycling process** shows also a complete destruction of the chlorinated paraffins in the pyrolysis. No chlorinated paraffins can be detected in products or as emission. A small share of chlorinated paraffins ~ 0,05 kg is transferred with the pretreatment fraction to the incineration and destroyed there (see above).

In the **Stignæs feedstock recycling process** almost 99% of the chlorinated paraffins are destroyed in the post-heating section. A small share of chlorinated paraffins ~1% is transferred with the pretreatment fraction to the incineration and destroyed there (see above). About 7,5 g leave the system as emission in wastewater and will be treated further in waste water treatment plant. No chlorinated paraffins can be detected in products or as emission to air.

In the **Vinyloop mechanical recycling process** almost 99% of the chlorinated paraffins are transferred through the system into the PVC compound. A small share of ~1% is transferred

with the pretreatment fraction and filter residues to the incineration and destructed there (see above). No chlorinated paraffins can be detected in the product or as emission.

Antimony and Cadmium

Antimony and Cadmium were not assessed, because the selected representative composition of the mixed cable waste did not show any of these substances.

Polychlorinated biphenyls (PCB)

The recovery processes themselves do not produce any PCB. It might be possible, that concentrations up to 50ppm occur in the cable waste. If PCB traces occur this input is most likely from other sources (e.g. from transformer oil which was in contact with the cables). Because of the very low concentration levels and the fact, that the origin is not the PVC cable, PCBs were not considered more in detail within this study.

7 Economic Comparison of the Recovery Options

The economic comparison of the different recovery options is based on the price the supplier has to pay to the operator of the recycling facility for the cable waste. This “gate fee” is used as a baseline to compare the economic dimension.

If an external operator does the pretreatment off-site, these costs are to be added to obtain “comparable gate fees”:

The boundary conditions and assumptions for the calculation of the gate fee are as follows:

- Depreciation time of the plant: 10 years
- Rate of return is 8 %
- The calculation of the gate fee has to include the following costs and are based on the respective national conditions:
 - o costs for pretreatment of the PVC cable waste
 - o costs for utilities and effluents
 - o labour and other direct costs
 - o waste treatment (mostly incineration) and transport
 - o revenues of the products

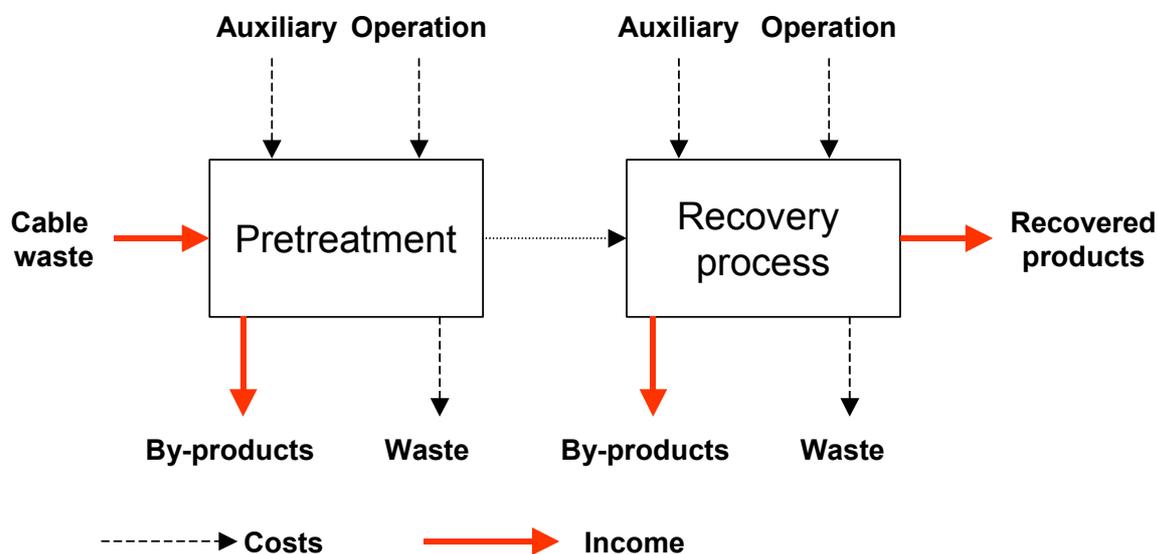


Figure 7-1: Relevant cost flows for calculation of the gate fee

For the base scenario the calculations are done without considering possible grants. These gate fees represent either the actual gate fee or a calculated gate fee without grants.

For landfill the gate fees - the main interest of landfill operators - are varying heavily (35 €/t - 200 €/t in Germany, 20 €/t - 200 €/t in Europe). For the study 50 €/t was taken as an average gate fee for landfill.

Economic Comparison of the Recovery Options

Table 7-1: Capacities and gate fees for mixed cable waste without grants for the recovery options and landfill

Plant	Capacity per year	Cost for recovery of one ton mixed cable waste		Characteristics
MVR Hamburg	up to 15 kt	100 €/t	average gate fee, specified by MVR Hamburg	no pretreatment necessary
Watech	5 kt (year 1+2) 10 kt (year 3+4) 15 kt (year 5-10)	183 €/t	gate fees calculated by Watech	pretreatment included
	15 kt (year 1-10)	159 €/t		
Stignæs	40 kt expandable to 50 kt	166 €/t	gate fee calculated by Stignæs	pretreatment included
Vinyloop	10 kt after pretreatment	~ 50 €/t	gate fee calculated by Solvay	pretreatment included
Landfill	infinite	~ 50 €/t	average gate fee determined by PE Europe (telephone survey + literature)	no pretreatment necessary

8 Eco-Efficiency of the Recovery Options

Preamble

The investigated recovery technologies have all their country or region specific boundary conditions. This includes specific regulatory demands and situations. Therefore the findings and comparisons of the chosen technologies within this study (compare goal and scope in chapter 0) cannot be automatically extrapolated to the situation of any other country outside the actual location of the plants.

In chapter 6 and 7 the environmental and economic comparisons were done separately. In this chapter this two dimensions put into relation to each other. In order to illustrate the relation between the environmental effects and the costs of the investigated recovery options, economic and environmental aspects are presented in an Eco-efficiency diagram. To be able to do a comprehensive and sound interpretation the results for the individual criteria are to be presented: Primary energy, GWP and AP are presented in a system expansion view. Further more a life-cycle view is shown as well as three process-specific charts. The Eco-Efficiency Approach goes back to the World Business Council for Sustainable Development [WBCSD 1993], but is further adapted according to the goal of this study. The results are points in an x,y-coordinate system. On the horizontal axis, the economic, and on the vertical axis the environmental assessment of the technology is displayed (high values = higher impact or costs, low values = lower impact or costs). The values are normalised with reference to the base case of landfilling (designated as 1 on each axis). That means any economic and environmental performance of each technology is set into relation to the performance of the reference landfill.

Environmental Dimension = Environ. Dimension of technology / Environ. Dimension of landfill

Economic Dimension = Econ. Dimension of technology / Econ. Dimension of landfill

Hence landfill always performs with 1,0 on each axis and the other technologies with the respective ratio to landfill. If the ratios are lower than 1,0 the technology performs better. The most preferable technology is therefore found in the upper right corner of the diagram.

1. System Expansion View

Primary Energy (non renewable)

All recovery options perform better than landfilling from an environmental perspective. However, with the exception of the Vinyloop process, all recovery options are more expensive than landfilling. The Vinyloop process shows the lowest primary energy impact in combination with a gate fee that is comparable with the reference option of landfilling.

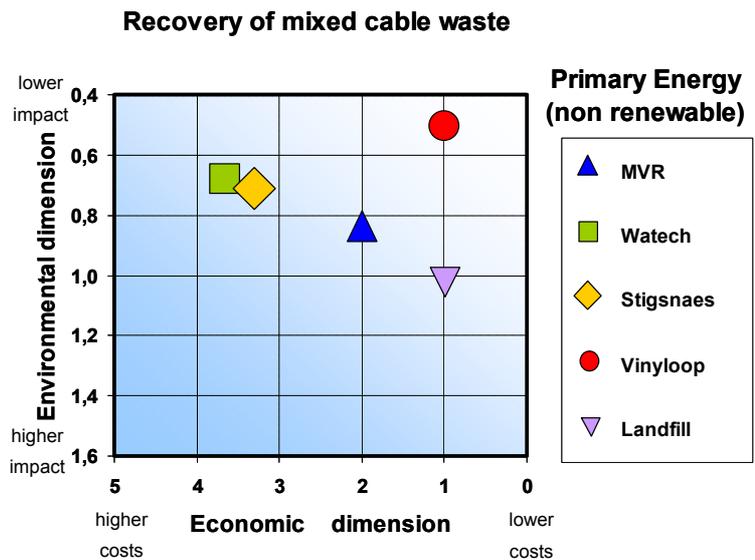


Figure 8-1: Primary Energy (non renewable) with system expansion view

Global Warming Potential

Concerning the GWP, the Vinyloop process shows an environmental advantage while the economic dimension is comparable with landfilling. The Stigsnaes and Watech processes show a comparable GWP to landfilling but higher gate fees. The MVR incineration process increases both the costs and the GWP load in relation to landfilling, since carbon from the cable waste is converted into greenhouse-relevant exhaust gases.

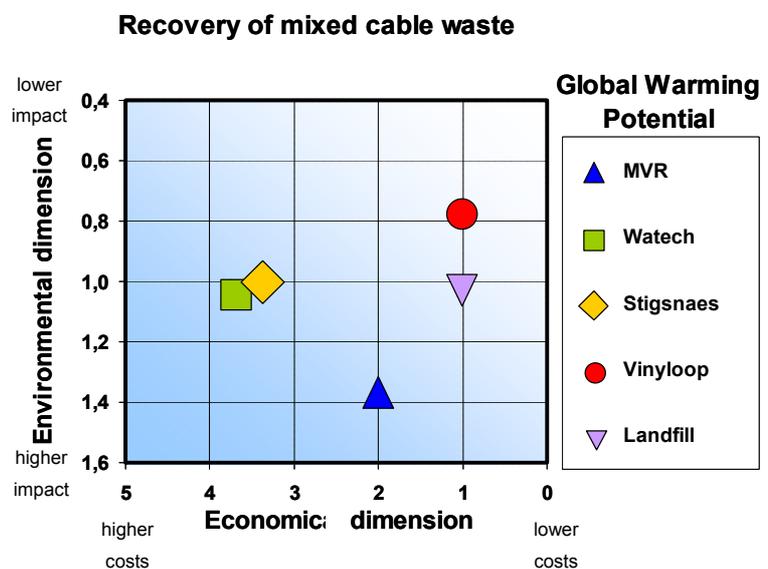


Figure 8-2: Global Warming Potential with system expansion view

Acidification Potential

Considering AP the landfill performs worst again, as no products are recovered. In this case the incineration performs better, as extensive flue gas cleaning systems are installed to prevent acidifying emissions (NO_x catalyst, sulphur removal,...). From an acidifying point of view the recovery options Vinyloop, Watech and Stignæs perform best at almost the same level. Watech and Stignæs are emitting less in the process than Vinyloop, but Vinyloop gains more due to the recovered PVC compound.

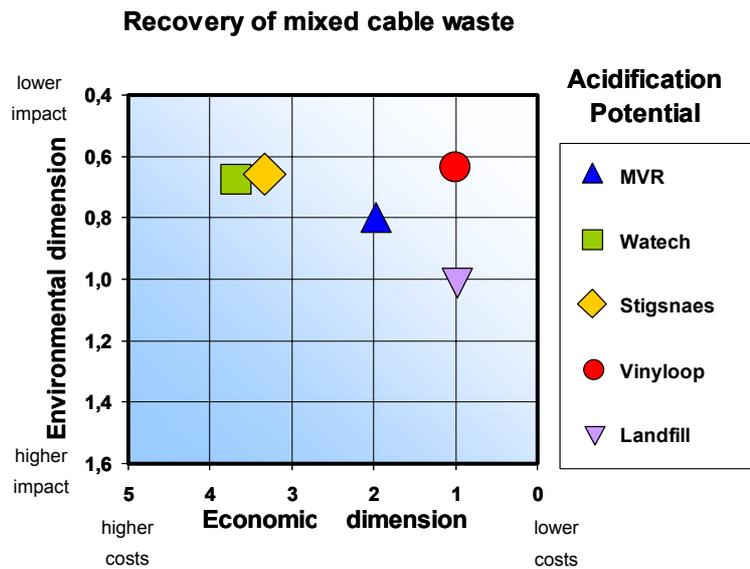


Figure 8-3: Acidification Potential with system expansion view

2. Life Cycle View

Net recovery of primary energy

The dimension of the y-axis is switched to the interval 0 to 100 %. If the net recovery of primary energy is 0%, nothing of the primary energy used to produce the cables is recovered (see landfill). 100% recovery is the (theoretically) upper limit. This would mean, that all of the needed energy in the life cycle is recovered without any losses.

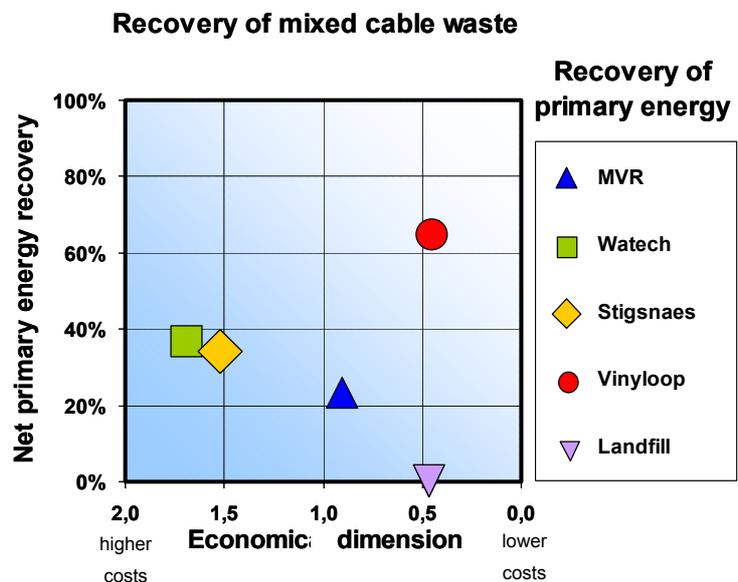


Figure 8-4: Net primary energy recovery over the complete life cycle ⁶

⁶ 1,0 on the economic scale represents in this case the average of all processes

The incineration is rather designed for (environmentally sound) waste disposal, than for effective energy production or recovery. The strength of the incineration is more the independency from homogenous inputs and pretreatment. Watech and Stigsnaes recover twice as much primary energy. Vinyloop recovers most of the primary energy (64%), as the recovered PVC-compound has comparable characteristics than the virgin product and the recovery process needs just 36% of the primary energy needed to produce the virgin product (compare Figure 6-3 on 106).

3. Process View

Waste reduction

The dimension of the y-axis is the reduction of waste related to 1000 kg of generated waste at landfilling. Waste in this sense is the sum of municipal and hazardous waste. This is only valid for a mass-indicator assessment, like in this case. Hence landfilling shows 0% reduction (100% disposal). The incineration plant reduces the amount of waste by 60%, due to combustion and conversion mainly into energy.

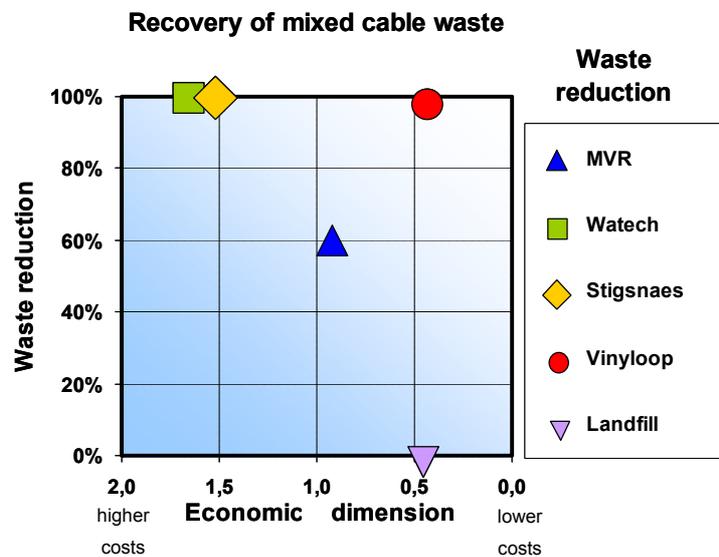


Figure 8-5: Waste reduction of processes⁷

Ashes and residues account for about 400 kg of waste. The three recovery options perform almost equally good. Between 98% and 99,4% of waste reduction is reached, as only between app. 6 and 19 kg of waste are generated. Most of the material is converted into products again and the processes generate relatively small amount of additional waste. The pretreated and in MVR incinerated fractions (intermediate products PE and rubber) of the recovery processes, account for very little amount of waste. This is due to the small waste generation potential of the polyethylene in the incineration.

⁷ 1,0 on the economic scale represents in this case the average of all processes

Energy and material recovery

In this last sub-chapter the energy and material recovery will be discussed and displayed.

Important note:

Remark 1: Recovered energy like steam and electricity does only account for energy recovery. Recovered material can account for material **and** energy, if the material is characterised by a calorific value. This view of the results does track the material and energy content of the cable waste through the processes. According to chapter 0 the input is for all options defined as 1000 kg mixed cable waste with 23,4 GJ energy content.

Remark 2: It is not correct to combine the values of the energy and material recovery rates, respectively, because double counting would occur (e.g. oil counts for mass and energy). Therefore, the charts can only be interpreted independently from each other.

Remark 3: In this particular energy and material view the fate of energy and material of the entering mixed cable waste is of interest. Therefore additional energy and material inputs to operate the processes - which vary between the different technologies - are not considered here (for a net recovery rate of primary energy including the process energy demands see figure 8-4).

The **energy recovery** is a measure, which amount of the initial energy content of the cable waste is available in products after the treatment. Two parameters are used:

- Amount of energy of the mixed cable waste ($Hu_{\text{mixed cable waste}}$)
- Amount of energy that is still technically available in the recovered products after the processing of the 1000 kg respectively 23,4 GJ cable waste ($Hu_{\text{recovery products}}$)

Definition of energy recovery:

The Energy content of any recovered product of the technology related to the energy content of the input (mixed cable waste). For this calculation the lower heating value has been used.

$$\text{energy recovery rate [\%]} = \frac{\sum Hu_{\text{recovery products}} [\text{MJ}]}{Hu_{\text{mixed cable waste}} [\text{MJ}]} \times 100 [\%]$$

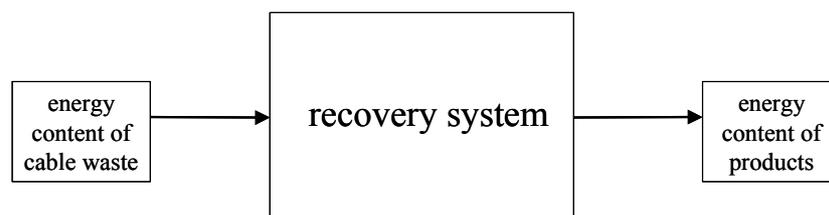


Figure 8-6: Energy recovery

The **material recovery** is a measure, which amount of the initial mass content of the cable waste is available in products after the treatment. All material counts in mass (kg) only, hence this is no measure of its quality. Two parameters are used:

- Amount of mass of the mixed cable waste (1000 kg_{mixed cable waste})
- Amount of elementary mass, that is still technically available in the recovered products after the processing of the 1000 kg cable waste and its **origin being mixed cable waste (dry mass_{recov. prod.})**

Water or water content is not considered as a material. Therefore the dry mass is considered as a recovered material. In the case of the mass recovery, some auxiliaries used (e.g. AlCl₃ in MVR, NaOH in Stigsnæs, CaCO₃ in Watech) are partly converted into products. To get results in pure relation to the input of cable waste, the share of products, which are formed due to the input of auxiliaries does not account to the recovery rate.

Definition of material recovery:

The share of mass, which is found in any recovered product of the option related to the input cable waste. The assessment is done on the elementary level.

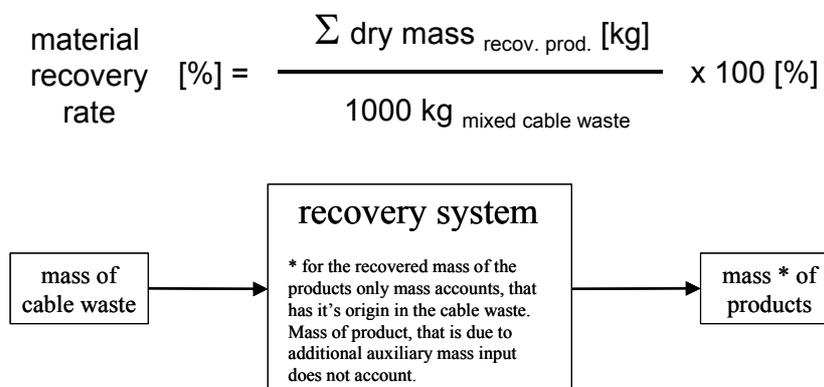


Figure 8-7: Material recovery

The following table shows which categories “energy” and/or “material” are assigned to the recovered products.

Table 8-1: Material and Energy accounting of the different products.

	material	energy		material	energy
Electricity		X	PVC-compound	X	X
Steam		X	HCl	X	
Naphtha	X	X	NaCl	X	
Hard Coal	X	X	CaCl ₂	X	
Solid Res.	X	X	Cu	X	
Fuel Oil	X	X	Al	X	

The benefit of recovering electricity and steam is only defined by the energy content (as the recovered amount is described in MJ). The benefit of recovering naphtha, hard coal, solid residue, fuel oil and PVC-compound can be defined by mass or by the energy content (recovered amount can be described in kg or MJ). The benefit of recovering HCl, NaCl, CaCl₂, Cu and Al are only defined by mass (the recovered amount can best be described in kg). **Tip:** For an easier comprehension of the results: Refer to chapter 3.

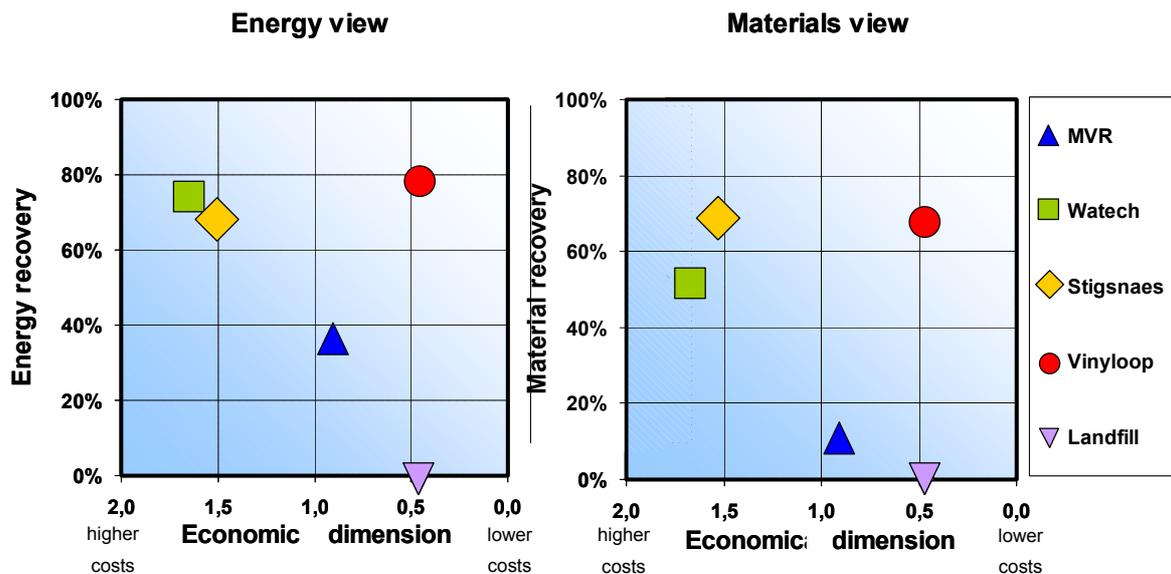


Figure 8-8: Energy and material recovery per treatment option⁸

The landfill neither recovers energy nor material (in both cases 0%).

In case of **energy recovery** all recovery options perform far better than landfill.

- **Vinyloop** recovers large amounts of PVC-product with a calorific value. The process recovers **10547 MJ** related to the recovered PVC, **842 MJ** due to electricity production and **7033 MJ** due to steam production of incinerated pretreatment fraction in MVR. In sum this are **18422 MJ**. Hence the recovery rate related to the energy input of 23400 MJ is app. **79%**.
- **Watech** shows an effective transformation into fuels (coke **5829 MJ**, organic condensate **4244 MJ**). Additionally **791 MJ** for electricity generation and **6597 MJ** for steam generation due to the incineration of the pretreatment fraction in MVR are produced. Therefore in sum **17460 MJ** are recovered out of 23400 MJ, which account for a recovery rate of **75%**.

⁸ 1,0 on the economic scale represents in this cases the average of all processes

- **Stignsnæs** recovers **2524 MJ** with the energy content of the solid residue and **5751 MJ** with the oil product. Additionally **792 MJ** for electricity generation and **6603 MJ** for steam generation due to the incineration of the pretreatment fraction in MVR are produced. This accounts for **15670 MJ** or a recovery rate of **67%**.
- **MVR** has an energy recovery rate of **36%** due to the lower energy production efficiency from such an incineration plant. From 23400 MJ cable waste input **1357 MJ** electricity and **7088 MJ** steam – in sum **8445 MJ** – are recovered.

The recovery options of Vinyloop, Watech and Stignsnæs all perform well in terms of recovering (or conserving) the energy content of the cable waste. But one has to keep in mind that the Vinyloop process has a higher process energy demand than Stignsnæs and Watech (which are about the same, see 3.2.3, 3.3.3 and 3.4.3). The incineration plant shows less energy recovery due to energy intensive emission reduction measures (reduced efficiency).

In case of **material recovery** Vinyloop, and Stignsnæs perform better than Watech and far better than incineration and landfill.

- **Stignsnæs** shows large amounts of recovered solid residue and NaCl salt (the additional sodium content from the sodium hydroxide input is not considered as recovered). 1000 kg of input cable waste account for **348 kg** of solid residue (the total mass of solid residue is 357 kg, but 9,18 kg of lead-content are not considered as recovered), further **149 kg** oil product is recovered as well as **150 kg** of Chlorine within the NaCl (the total mass of NaCl is 288 kg, but only the Cl content minus 24,5 kg additional Cl input from HCl can be accounted as recovered). Additionally **1 kg** Cl (HCl recovery in MVR) and **20 kg** metals (pretreatment) sum to the total of **668 kg** recovered material (recovery rate of **67%**) of the mixed cable waste input.
- **Vinyloop** shows a large amount of recovered PVC – product (**672 kg**). Additionally **1 kg** Cl from the HCl recovery in the MVR and **7 kg** copper are recovered. This accounts for **680 kg** or **68%** recovery rate of the mixed cable waste input.
- **Watech** recovers with app. 665 kg of CaCl₂ large amounts of water, which is not considered a material in this sense. This accounts for 239 kg dry mass CaCl₂, which consist of 153 kg Chlorine and 86 kg Calcium. All of the recovered chlorine has it's origin in the mixed cable waste (no auxiliary Cl enters the process). In case of Ca app. 74,4% are provided by the mixed cable waste. The rest is introduced with CaCO₃ at various stages of the process. Therefore 74,4% of the Ca in CaCl₂ is considered as recovered, which results in **217 kg** recovered CaCl₂. Further **166 kg** coke and **104 kg** organic condensate are recovered as well as **20 kg** metals in pretreatment. **1 kg** HCl are recovered in MVR incineration of the pretreatment

fraction. This accounts for **508 kg** or **51%** recovery rate of the mixed cable waste input.

- **MVR** recovers almost all input as energy. Only a small mass of HCl and copper is recovered. 299 kg of HCl aq. 31% are produced. Subtracting the water content 92,5 kg HCl are left (with Cl content of 90 kg). 19 kg AlCl_3 are used as auxiliary (Cl content 15,1 kg). 55% of the Cl are considered to follow the HCl flow the rest is going to salt brine. Hence $90 \text{ kg} - 8,3 \text{ kg} = \mathbf{82,7 \text{ kg}}$ of recovered Cl is leaving the MVR. Additionally **8 kg** Cu can be recovered, so the recovery rate is around **10%** of the mixed cable waste input.

9 Findings and Conclusions

Conclusions within this chapter are drawn with the background of:

- The type of cable waste input (see also goal and scope of the study in chapter 0)
- The individual technologies (see chapter 2.4)
- The mass flow and environmental results of the technologies (see chapter 3 and 4)
- The quality of the resulting recovery products (see chapter 5)
- The comparison of environmental, economic and eco-efficient performance (see chapter 6, 7, 8)

The **overall performance** of the recovery options depends on:

- The extent of the **environmental impacts** of the recovery processes
- The **recovery rates** of the recovery processes
- The **characteristics** of the recovered products
- The **costs**

The **recovery rates** of the recycling processes are high, taking into consideration, that mixed cable waste is a complex compound of many different substances and materials.

The **environmental assessment** was conducted according to the applicable standards ISO 14040 ff.

The different recovered products show very different **characteristics**, which are influenced by two major aspects.

- The location of the recovered product in the value creation chain (from resource, to intermediates to materials), because this determines the amount of process steps that can be saved due to the use of the recovered products. The characteristics (or “quality”) improves from resource-like recovery products (e.g. a gas similar to methane or natural gas) to fuel-like recovery products (e.g. an organic fluid similar to liquid hydrocarbons), to intermediate-like recovery products (e.g. more complex and pure chemicals) to material-like recovery products (e.g. recovered materials)
- The complexity of the recovered product. A recovered product may potentially substitute an energy resource (e.g. hard coal), an intermediate (e.g. naphtha, HCl or NaCl) or a final product (e.g. PVC compound). Generally the effort of production increases from resource to intermediates to final products, as the amount of process

steps increases as well. Therefore the environmental benefit from a recovered product is increasing, the more process steps may be substituted.

Hence the main differences in the valuation of the processes arise according to the individual possibility to integrate the product into the value creation chain again and the comparison of the characteristics of recovered products with the respective virgin products (see chapter 5).

The operators calculated the **costs** themselves, according to the individual investment situation (see chapter 6). But the costs vary according to the actual local situation (Denmark, Italy, Germany).

In general, the following conclusions can be drawn:

1. When considering recovery options for an integrated waste management concept, an Eco-efficiency approach provides valuable insights in the environmental and the economic aspects of the investigated processes.
2. Compared with the reference option landfilling, all of the investigated recovery options have a positive effect on the demand of primary energy, due to the recovery of either energy or materials. The Vinyloop mechanical recycling process shows the best performance in this respect, followed by the Watech and Stignsnes feedstock recycling processes, on a similar level, and with the MVR incineration process at 3rd place.
3. In addition to this criterion, the results for the other impact categories – global warming potential (GWP) and acidification potential (AP) – as well as the management of substance flows (lead and dioxin) also need to be considered. For example, the Watech and Stignsnes processes are the only ones allowing separating and recovering lead.
4. The management of the polymer as a resource plays a decisive role for the environmental assessment. In landfills, the carbon content of the waste product is “stored”, although a long-term fixation is uncertain. Furthermore, landfilling incurs long-term risks and liabilities, which cannot be represented in the Eco-efficiency diagram. At least in Europe, landfilling of plastic waste does not represent a long-term disposal option from a legal point of view. Incineration processes such as MVR use the embodied energy of the polymer, while recycling processes such as Vinyloop, Watech, and Stignsnes recover the material itself or its feedstock.
5. When taking the economic dimension (gate fees) into consideration, the Vinyloop process is shown to be competitive with landfilling, while all other recovery options entail higher costs – MVR, Stignsnes and Watech in order of increasing gate-fees – mainly because of their low revenues for the recovered products.

If **well-defined cable waste** in relatively **constant quality** is the basic input, the **Vinyloop mechanical recycling process** overall performs best in cost and environmental aspects (see chapter 8).

If the input consists of more mixed fractions or **varying input of PVC cable waste**, the **Watech**, **Stignæs** and **MVR** incineration processes are technically well capable to recover these wastes in an efficient way. Hence these processes show more flexibility – in terms of input composition - as the **Vinyloop** process.

Watech and Stignæs feedstock recycling processes show overall a similar environmental performance. Both processes can handle variations in the input composition. In energetic recovery Watech performs better than Stignæs, as Watech recovers products with a higher calorific value related to less mass. In material recovery Stignæs performs better than Watech, as Stignæs recovers products with a lower calorific value related to more mass.

The Watech process separates respectively recovers the cable waste into quite homogenous fractions. The Stignæs process consolidates the mineral and organic parts in the wanted product and separates the rest.

To operate the Stignæs process with an environmental performance as described, the integration with the existing Carbogrit plant and a wastewater treatment plant is required. The environmental performance of the Carbogrit plant plays an important role, but its environmental impact is not included in this study on purpose due to symmetry reasons of the system boundaries (see chapter 2.2 and 2.3).

The **MVR municipal solid waste incineration process** recovers mainly energy products and HCl (see chapter 2.4.1). The MVR-incineration can handle input related variation in the cable waste composition quite easily.

The boundaries of the variation of the cable waste composition are wider than at Watech and Stignæs (due to the mixed incineration with municipal waste), but the amount and quality of the recovered products is lower if cable waste is treated.

The MVR-incineration has a very good performance in recovering the pretreatment residues of Watech, Stignæs and Vinyloop. Hence the combination of the Watech, Stignæs and Vinyloop – process with the MVR-incineration is most desirable.

For the energetic recovery of undefined wastes (including wastes containing substances like halogens), that can hardly be sorted or pretreated, the MVR incineration is a capable, and also most tolerant process (concerning the undefined waste). The emission is well below the regulation levels in Germany due to a extensive flue gas treatment system. The hazardous substances are “securely” bound into the ashes and dusts. On the other hand – because of the latter mentioned facts – the efficiency of the “recovery” process is lower, as the treatment systems raise the internal energy demand. The costs are between Vinyloop/Landfill and Stignæs/Watech.

Landfill cannot compete in any of the environmental related issues (see chapter 4) except for global warming. Due to the fact that in landfilling carbon is still bound and stored in the cable waste, the global warming potential related to a timeframe of 100 years is not set free. But as a matter of fact on the other hand side the bound and stored carbon is not recovered into (different) usable products, as in all other processes. The low landfill costs seem to be attractive, but one has to take into account, that the costs vary highly from region to region and are highly fluctuant. Secondly it is to state, that the costs for landfilling are likely to increase in the future, whereas the costs of the recovery options may have further reduction potentials (e.g. because of future higher volumes and increasing efficiency of processes).

10 Limitations

The results of the environmental and economic system analysis from this study are only valid for mixed cable waste with the described composition and for the specific conditions of the investigated recovery plants.

Differences in national environmental policies may also effect the conclusions from this study.

The task for the decision-makers remains to arrive at an evaluation of the Eco-efficiency profile of each recovery option under consideration.

The final evaluation will have to be based upon the system boundaries, conditions and specific demands of the technology, but will also need to take local and regional aspects into consideration.

11 Critical Review

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Laboratoire fédéral d'essai des matériaux et de recherche
Laboratorio federale di prova dei materiali e di ricerca
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Critical Review

PVC Recovery Options

Environmental and Economic System Analysis

presented by

VINYL 2010 and PE Europe GmbH
Brussels and Leinfelden-Echterdingen

conducted by the

Swiss Federal Laboratories for Materials Testing and Research (EMPA)
Dübendorf

Dr. Frank Werner, Lead reviewer

Dr. Klaus Richter, Head Wood Laboratory

May 2003

11.1 Goal of the external critical review

PE Europe GmbH conducted an environmental life cycle assessment on different PVC recycling options and its landfilling, and compared these options taking their costs into account. This study was commissioned by VINYL 2010.

In February 2003, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) as a neutral and independent organization was asked to conduct an external critical review based on the final draft of the study. The critical review was elaborated by Dr. F. Werner, member of the working group Environment and Sustainability in Civil Engineering, and Dr. K. Richter, head of the EMPA Wood Laboratory.

The critical review process should ensure that:

- the methods used to carry out the LCA are consistent with the series of standards ISO 14'040ff,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study,
- the study report is transparent and consistent.

During the peer review procedure, modifications of the report text were made based on a preliminary version of this critical review text.

Since the series of standards ISO 14'040ff does not specify requirements on the goals or uses of the LCA results, a critical review can neither verify nor validate the goals that are chosen for an LCA, or the uses to which LCA results are put.

11.2 Scope of the critical review

The report "PVC Recovery Options; Concept for Environmental and Economic System Analysis" assesses and compares the environmental relevance of four recycling options for PVC cable waste with landfilling as a reference scenario.

In a further step, the environmental consequences are set into relation to the costs of each end-of-life option, and statements on the eco-efficiency are made. This last step goes beyond the framework set up by the ISO 14'040ff-standards, which are relevant for environmental life cycle assessment (LCA), and is thus not covered by this critical review. Nonetheless, the respective chapters are checked for their transparency and scientific soundness.

Besides the main text, the study contains an executive summary as well as a list of abbreviations and nomenclature used and consists of 144 pages incl. the review text and the list of the cited literature.

The four core elements of an LCA goal and scope definition, inventory analysis, impact assessment, and interpretation are clearly distinguished. The structure of the study follows the structure of the relevant standard ISO 14'040 and allows for an easy cross-comparison between the study and the ISO standards.

11.3 Goal and scope definition

11.3.1 Intended application, goal and audience

The intended application and the reasons to carry out the study are clearly stated. The intended forum—experts and decision makers within the PVC industry—are defined.

11.3.2 Scope of the study

The scope of the study describes the different circumstances and boundary conditions, which are important to correctly interpret the results.

11.3.2.1 Function and functional unit

As the functional unit, the processing and recovery of 1 t of mixed cable waste input after dismantling is defined. Among the reference cable waste, PVC cable waste adds up to 68%.

The technologies considered are waste incineration with energy recovery, the Watech process, the Stigsnæs process and the Vinyloop process. As a reference scenario, landfilling is evaluated.

Thus, the initial functional unit and the respective reference flows are clearly defined.

11.3.2.2 System boundaries

System boundaries include process specific pre-treatment of the mixed cable waste (excluding collection) and any relevant background processes, e.g. the production of auxiliary materials energy carriers. Infrastructure is excluded for a) being considered not relevant, and b) comparable for the different recycling options (not necessarily for landfilling).

The technologies in the study cover state-of-the-art technologies for the year 2001/2002 in an European average situation.

Initial system boundaries are chosen consistently for the comparison of the four recycling options and for the reference option. To make the different end-of-life options comparable, system expansion is used (see Chap. 3.2.4).

The elementary flows and impact categories considered in the system descriptions and in the inventory analysis—primary energy consumption, non renewable materials on inventory level, Global

Warming Potential (GWP), Acidification Potential (AP), selected characteristic emissions (dioxins, lead, chlorinated paraffins, cadmium, antimony and polycyclic biphenyls (PCBs)), hazardous waste, municipal and inert waste—cover the environmental aspects associated with the treatment of PVC waste.

11.3.2.3 Data quality requirements

To ensure reliable results data quality requirements with regard to required precision level, completeness, representativeness, consistency and reproducibility are stated.

These requirements are consistent with the goal and scope of the study.

11.3.2.4 Allocation

The recycling options under study provide different co-products besides the “disposal” of the mixed cable waste. Landfilling does not produce any co-products. To make the end-of-life options comparable, the methodological approach “system expansion” is applied: Mono-functional production processes are added to each of the initial systems under study in a way that finally all systems have the same outputs.

System expansion is stated in the standard ISO 14'041, Annex B.2, dot b) as a way to avoid allocation. System expansion is thus in conformity with the series of standards ISO 14'40ff.

Nonetheless, attribution and allocation problems related to multi-output and recycling processes cannot unambiguously be solved in LCA. Thus, system expansion is only one of several methodological approaches suitable to make multi-output and/or recycling systems comparable (see Werner, 2002a).

Further methodological approaches include:

- Strict co-product allocation proposed by Lindeijer & Huppes (2001). These authors propose to consider the recycling process as long as waste treatment process until the negative market price of the material in process—the cable waste—crosses the zero-point and becomes positive; all the processing with positive market price of the material is considered secondary material extraction that is attributed to the following product systems using these materials as inputs.
- Economic allocation, attributing the environmental impacts related to the PVC recovery to the different co-products (including the service “waste disposal”) based on the relative share of revenues of the different co-products (see, e.g., Huppes, 1992; Huppes, 1994).
- Value-corrected substitution, subtracting mono-functional processes of the “unintended” co-products, weighted by their relative market value compared to primary production material

(see, e.g., Werner, 2002a; Werner, 2002b; Werner & Richter, 2000a; Werner & Richter, 2000b).

The application of these methods would possibly lead to a more differentiated insight into the process structures and their related environmental burdens.

11.3.2.5 Critical review consideration

The conduct of an external critical review is clearly stated.

11.3.3 Summary of the review of the goal and scope definition

It can be stated that system boundaries, the defined functional units, data quality requirements and the main allocation procedures applied are transparently described and in line with the goal of the study; they comply with the current state-of-the-art of life cycle assessment according to the series of standards ISO 14'040ff. However, the use of further allocation procedures could reveal additional insights into the structure of the environmental impacts associated with the technologies under study.

11.4 Inventory analysis

11.4.1 General description of life cycle inventory

The study contains an in-depth characterisation of the technologies under study. Mass and energy balances as figures and/or tables are provided; numerical checks have not shown any data discrepancies in neither the energy nor the material balances. Relevant inputs, co-products and emissions for each technology are intensely described and evaluated.

In the report, an extensive data inventory is not provided for the reason of data confidentiality. Nonetheless, the data presented in the report allows one to follow the most important inventory parameters.

A parameter variation is made for the most relevant parameters of two recycling technologies as a sensitivity analysis with regard to the impact categories used in the impact assessment.

11.4.2 Data collection and calculation procedures

The study uses site-specific data for the recycling plants under study and average data for the upstream and downstream processes. References to scientific literature are quoted in an adequate way if necessary.

The software GABI—a state-of-the-art LCA calculation software—with its integrated database for background processes is used to calculate the life cycle inventories of the different end-of-life options under study. This means among others, that the calculation of energy flows takes into account the different fuels and electricity sources used, the efficiency of conversions and distribution of energy flows as well as the inputs and outputs associated with the generation and use of these energy flows.

The main allocation procedure used in the study—system expansion—is clearly described (see also Chap. 3.2.4). Nonetheless, the allocation procedures used to calculate mono-functional processes used for the system expansion are not documented in the study report; the respective documentation is available within the documentation of the GABI software.

11.4.3 Summary of the review of the inventory analysis

The procedures for the inventory analysis followed in the study are in conformity with the standards ISO 14'040ff. Taking the restrictions of data confidentiality into account, the data inventory, the data sources and the calculation procedures are complete, transparent (except the allocation procedures for the added processes during system expansion), and adequate for the goal of the study. A parameter variation is made for two recycling technologies as a sensitivity analysis with regard to the impact categories used in the impact assessment.

11.5 Environmental impact assessment

11.5.1 Assessment methodology

A quantitative environmental impact assessment is conducted for the following impact categories:

- primary energy consumption,
- Global Warming Potential (GWP),
- Acidification Potential (AP),
- hazardous waste, municipal and inert waste.

The environmental relevance of emissions associated with the recycling, incineration, or landfilling of PVC such as dioxins, lead, chlorinated paraffins, cadmium, antimony, and polycyclic biphenyls (PCBs) are discussed in a qualitative way.

These impact categories are commonly applied in LCA and reflect current state-of-the-art assessment methodologies; except the waste categories, they are highly dependent on energy issues. In combination with the qualitative evaluation of specific emissions, which are principally related to toxicity issues, the relevant environmental aspects associated with the treatment of PVC waste are covered by the study.

The selection of environmental categories is in line with the goal and scope of the study.

The calculation procedures for the different impact categories are not described; respective references are made in the study text.

11.5.2 Evaluation and presentation of the results

The environmental comparison units the respective results of the environmental impact assessment of the different end-of-life options in a variety of figures. An in-depth discussion of the comparison of the different impact categories and further specific emissions allows for an in-depth understanding and comparison of the environmental relevance of the different technologies under study.

Unfortunately, the results of the parameter variation made for two recycling options are not integrated into the figures and discussion of the results of the impact assessment.

11.5.3 Summary of the review of the environmental impact assessment

The methodology applied for the impact assessment is state-of-the-art, although not specifically explained in the study report. The evaluation and presentation of the results of the environmental impact assessment are transparent, complete and reasonably founded.

The methodology applied and the presentation of the results are in conformity with the series of standards ISO 14'040ff.

11.6 Interpretation

The interpretation step in the study goes beyond common interpretation of LCA results. The environmental impacts of each of the end-of-life options are set into relation to their respective gate fees. By doing this, the eco-efficiency of each end-of-life option with regard to different environmental impacts can be demonstrated.

Eco-efficiency is also calculated for the two indexes energy recovery and material recovery.

The results of this comparison are illustrated by several figures and extensively discussed.

The conclusions drawn from the study—from the environmental impact assessment as well as from the calculations of the different eco-efficiency indexes—are transparent; they are well founded by the study results and discussed in relation to the goal and scope of the study.

Limitations of the study results are clearly stated.

The interpretation step of the study report fulfils the requirements of the series of standards ISO 14'040ff; with the inclusion of eco-efficiency considerations it goes beyond the scope of common interpretation in LCA. Anyhow, also this step is transparently reported and interpreted.

11.7 Summary

The results of the external critical review can be summarised as follows:

- the methods used to carry out the LCA are consistent with the series of standards ISO 14'040ff,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study,
- structure and content of the study report complies with the requirements stipulated in ISO 14'040, chap. 6; the study report is transparent and consistent

We can herewith confirm after an in-depth critical review conducted according to EN ISO 14'040, chapter 7 that the compilation and valuation of environmental aspects of several end-of-life options for PVC cable waste in the report

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presented by PE Europe GmbH and dated 10th of April 2003 is in conformity with the actual series of standards EN ISO 14'040ff on environmental life cycle assessment (LCA). This part of the study is in line with the required structure of an LCA and fulfils the requirements on data quality, transparency, consistency, completeness and methodological soundness in dependency of the goal of the study.

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