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At the end of the road: is there life after rolling?

Life cycle assessment of the impacts of different end of life treatments of tyres

Master's Thesis in Industrial Ecology
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Abstract

End of life tyres (ELTs) are waste in the form of passenger car tyres that are no longer suitable to perform their original function. As such, this waste must be disposed of in compliance with European legislation, which forbids them to be landfilled and at the same time encourages them to be recovered or recycled with the End of Life Vehicle Directive. This study is performed for Volvo Car Corporation to map out the Swedish ELT treatment system and, by performing a life cycle assessment, quantify the impacts of the system. An additional goal was to analyze which of all the fates in the treatment of tyres is less impactful from an environmental perspective.

The objective of this report is to analyze the fates of ELTs and their impacts in Sweden. The increasing environmental concern which eventually turns into legislation puts pressure on companies to acquire knowledge for the environmental impacts of their products.

The method of this study is LCA and it is performed from gate to grave. It is a method to assess the environmental impacts related to a product or a service. The stages that were taken into account were the use of energy, resources, water and transportation. The results are presented in the form of different impact categories which gives a broader perspective in the environmental attribute. LCA can be used for detecting improvement possibilities and mapping all the different processes in a system not studied as a whole, and calculate their impacts, which is what is done in this study.

The system was mapped and the four main fates were found to be: incineration of ELTs as fuel in the clinker production, with 40.4% of the share per weight; incineration in coal furnaces for the production of metallurgical coke, with 32% of the share per weight; separation into rubber, steel and textile fractions, as 12% of the share per weight; and pyrolysis with 5% of the share per weight.

The impact assessment shows that the incineration of ELTs as fuel in both coal furnaces and clinker production contribute the most to the overall impact of the system. When a system expansion is done, however, the credits from avoiding the production and incineration of fossil fuels paints a different picture on the role of ELTs play in the system as a viable replacement of fossil fuels in energy intensive processes.

Pyrolysis was found to be the best treatment option for ELTs from an environmental standpoint, and a sensitivity analysis was performed to evaluate the change in the overall impacts of the system with an increase in the pyrolysis share. The sensitivity analysis confirmed that an increased percentage of pyrolysis in the system would lower its overall emissions.

Keywords: ELT, tyres, end of life, end of life tyres, ELV, end of life vehicles, LCA, life cycle assessment

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Efstathios Pasakopoulos
Pedro Anchustegui
Göteborg June 2019

Contents

Abbreviations:

LCA: Life cycle assessment.
LCI: Life cycle inventory.
EOL: End of life.
ELT: End of life tyre.
TDF: Tyre derived fuel.
EU: European Union
GWP: Global Warming Potential.
POCP: Photochemical Ozone Creation Potential.
AR: Asphalt rubber.
GHG: Greenhouse gases.
IVL: Swedish environmental institute
rCB: recovered Carbon Black
CR: Crumb rubber
EU: European Union
ELV: End-of-life vehicle
US: United States

1. Introduction

Tyres are complex products consisting of a variety of different materials. The percentage of each material included varies depending on the company producing it, as each company has its own proprietary mix of materials, and on the type of vehicle on which it is going to be used. Figure 1 shows the average composition of a tyre [1].

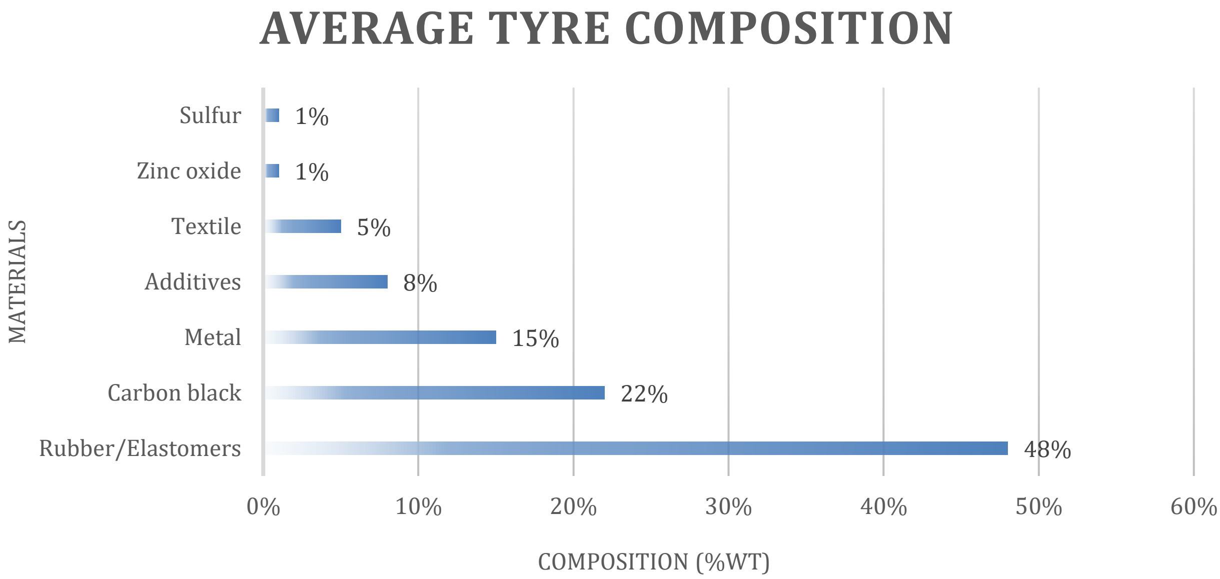

Figure 1: Average composition of a tyre based on [1]

Tyres exist in significant numbers worldwide, and this number is increasing as new-car purchases increase [2]. This increase is also reflected in the number of tyres to be disposed annually. This is demonstrated on Table 1 where the end-of-life tyres (ELTs) in the European Union (EU) are presented for each year from 2008 to 2013 [3].

Table 1: EU ELTs from 2008 to 2013

Year	ELTs (k tons)
2008	2650
2009	2621
2010	2699
2011	2645
2012	2765
2013	2883

Other reasons to treat ELTs exist. ELTs are non-degradable waste which is generated in significant amounts and might lead to a series of environmental and health hazards, if improperly disposed [4], [5]. The recyclability of some of its components, as well as the high average calorific value of an ELT (approximately 32.5 MJ/kg, similar to that of coal [6]) allows different possible End of Life (EOL) treatment for them. An efficient waste management strategy can considerably reduce the adverse environmental impacts of ELTs and at the same time provide outputs that could serve as resources for other activities.

There are two categories of used tyres: part-worn tyres, which can be reused as vehicular tyres, either as a second-hand purchase or after reprocessing (e.g. retreading); and end-of-life tyres (ELT), which are non-reusable as vehicular tyres. ELTs are waste that needs to be managed using material recycling and energy recovery since it is illegal to be sent to landfill since 2006, in Europe [7].

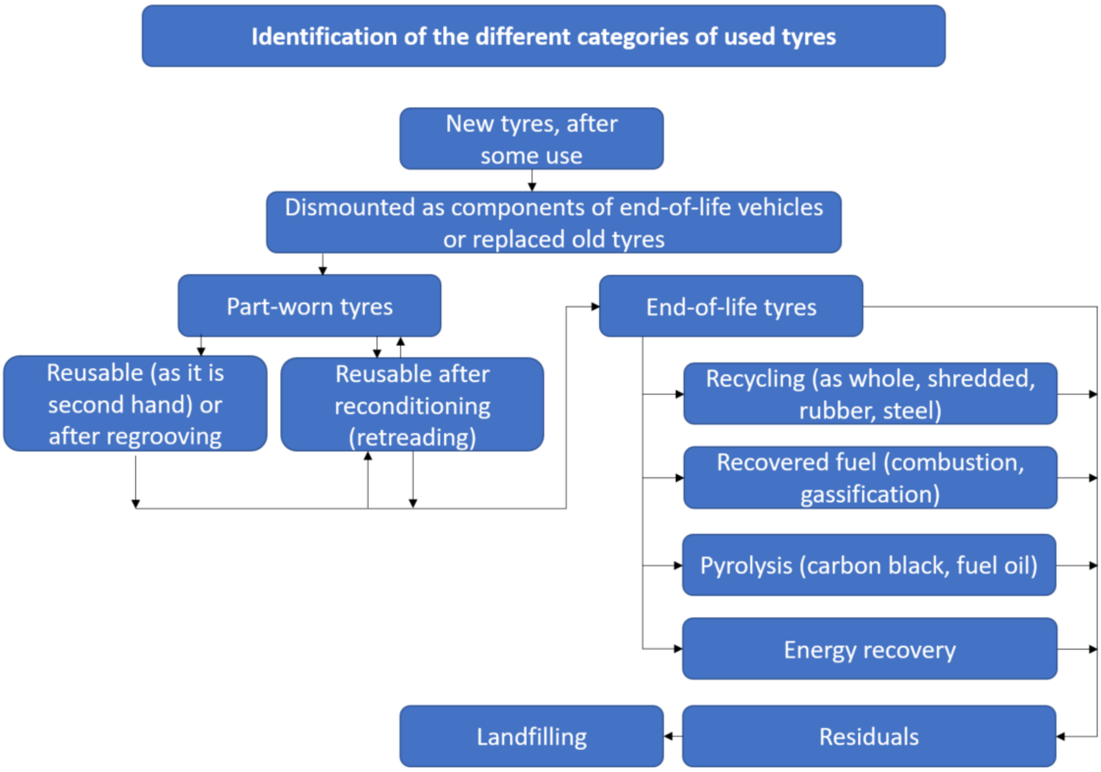

Figure 2: Potential fates of ELT as seen on ETRMA [8]

When examining the situation in Sweden, about 60% of ELTs are incinerated for energy recovery, 34% are recycled into different products, 5% are used for other uses in civil engineering like erosion barriers and landfill construction [9], and 1% is exported [10]. Svensk Däckåtervinning AB is charged with the collection of all used tyres in Sweden [11], which is done by Ragn-Sells Tyre Recycling on their behalf [12].

One existing methodology to assess the environmental impact of such different EOL fates is Life Cycle Assessment (LCA) allowing the evaluation of the environmental impacts of each different ELT fate. In an LCA, the emissions throughout the life of a product are classified and characterized into impact categories and indicators, in order to assess the environmental impact the product has. This study seeks to map the current EOLs of ELTs in Sweden and evaluate the environmental impacts of these.

Given that the European landscape is progressively stricter when it comes to environmental regulations, the current and future fates of a product like an ELT could be of high interest to those who, like Volvo Cars, must comply with extended producer's responsibility for the EOL of tyres.

This study is conducted for Volvo Car Corporation (from here on referred to as Volvo Cars), a car manufacturing company based in Gothenburg. The goal is to map and quantify the current EOLs of a tyre in Sweden, and to estimate the environmental impact that the entire system has in reference to a single

ELT. Moreover, the impacts of each fate will be discussed in order to provide Volvo Cars with an overview of the environmental attribute of EOL treatment options for ELTs in Sweden.

2. Literature Review

2.1. Shredding and separation of ELT

One fate of ELTs is the separation of the three main materials (rubber, steel, textiles) through granulation of ELT, mechanically or cryogenically[1] [13], to use the materials separately to be either recycled or incorporated into new products (e.g. asphalt modifiers or football turfs). There have been numerous studies and LCA, both from academia and from industry, exploring potential uses of the resulting products, particularly that of rubber or textiles (steel is already known to be recyclable to an extensive degree). Examples of such studies are [14], [15], [16].

Some ELT fates (such as pyrolysis or coal furnaces) requires the ELT to be pre-processed. This is often done by shredding the whole ELT into chips of smaller and more manageable size. Separation is one fate where the reduction in size is taken even further, pulverizing the rubber and resulting in a separation of the steel, textile and rubber share of the ELT. The main processes to separate the material are mechanically or cryogenically. These separation processes also affect the amount of electricity consumed, since grinding smaller granules of rubber requires more energy [6], [13]. These two studies show that there are no airborne emissions from the process, other than small amounts of dust.

2.2. Energy recovery

Waste to energy is a way of recovering ELTs. Tyre Derived Fuel (TDF) is used predominantly in co-incineration to reduce the demand of fossil fuels [6], although there can be other reported benefits in the use of TDF (e.g. cement and coal furnaces benefit from using TDF due to iron content [13], [17]).

2.2.1. Cement – Clinker production

The usage of waste as alternative fuel in cement production has been studied by several authors. Cement production is responsible for 5-7% of all anthropogenic greenhouse gas (GHG) emissions, [18]. This has driven research for solutions to improve cement’s environmental performance and decrease its fossil fuel consumption at a production level. One of such measures is the utilization of waste-derived fuels and waste as a raw material in the clinker production [19].

Galvez-Martos & Schoenberger [19] detail, for a case study in Germany, how the usage of waste-derived fuels is done for an economic reason, and the change that this has had on cement plants operators becoming “waste managers”. The study also points out that in clinker production the use of TDF has remained relatively constant in that country for the years 1998 to 2011. The authors conclude that using waste-derived fuel in cement production leads to a decrease in fossil fuel consumption, despite marginally affecting GHG emissions of the process, and that if reducing those emissions is the goal, the more effective route is to reduce the proportion of clinker included in cement.

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[1] Mechanical separation involves the use of shredders that reduce the size of the ELT until the result is crumb (or pulverized) rubber, steel and textiles.
Cryogenic separation involves lowering the temperature of the rubber chips to facilitate the reduction in size.

Georgiopoulou & Lyberatos [20] review the potential replacement of the fuel needed for the production of clinker with, among others, TDF. The results also show marginal improvements on GWP when compared with 100% fossil fuel scenarios with coal, coke, etc. For other impact categories however, the results show considerably better performance when using TDF as fuel (e.g. acidification/eutrophication, ecotoxicity, land use, etc.).

Rahman et al. [21] provides a status of the use of different alternative fuels in cement, including TDF. The authors provide percentages of ELTs used by different producers of cement, and TDF is shown to be between 10 and 20% of the alternative fuels used. The paper reviews and compares different benefits and obstacles when using TDF as whole tyres, shredded, or crumb tyres. Interestingly, the authors point out that there is a 30% TDF substitution limit in cement kilns, since a higher share of TDF might affect the process of cement production adversely. Additionally, the authors point out that there are several conflicting results in existing literature when it comes to emissions (e.g. NOx, SO2, dioxins, furans, etc.) from using TDF in cement kilns.

2.2.2. Incineration in coal furnaces

According to the "Energy in Sweden 2017" report [22], coke and coal sources represent approximately only 4% of the total energy system production in Sweden. The majority of coal is utilized in industry, specifically for the production of metallurgical coke to be used as a reductant in iron production [22].

Pavlovich, Solovyova and Strakhov [17] detail advantages of using crushed waste tyres with steel cord2 as an alternative for coal. According to the authors, this is beneficial not only for economic reasons, but also because of different properties that this use brings to metallurgical coke. Adding ELTs improves the yield of the coking furnaces, the mechanical strength, and improves the yield of valuable byproducts such as tar and benzene. Furthermore, the output ash has a higher content of iron oxide, which is beneficial for its use in blast furnaces.

2.2.3. Textiles incineration

Textiles is one of the three main components of a tyre and is about 5% of its weight [1]. Their fate after being separated from an ELT typically is incineration for energy recovery [23], [24].

The main issue for recycling textiles from ELTs is contamination with rubber which prevent the production of an economically feasible product. Cleaning the textiles is not usually done, since currently there is not yet a market that justifies the required effort and resources. There is however a lack of available information on the characteristics of the textile fiber [23] and the common fate of these textile fibers is to be landfilled or be incinerated for energy recovery.

It has also been demonstrated the technical feasibility of reusing textile fibers as secondary raw materials in asphalt and plastic compounds [23]

[2] Radial tyres have a steel cord in their build, allowing for a longer life-span and a smoother ride, better suited for passenger use. Bias tyres do not have a steel cord in them and are better suited for construction and other utility applications since it reinforces both tread and build [52].

2.3. Material reuse and recycling

2.3.1. Pyrolysis

Pyrolyzing shredded ELT has been gaining interest recently, since it allows for recovery of many of the composing materials of the ELT, as well creating potential new materials of value for other processes [25].

Pyrolysis can be described as "a process which decomposes organic materials in an inert condition into liquid, gas and solid products" [25]. This is done by submitting the material to high temperatures in absence of oxygen.

The above mentioned solid product is called recovered carbon black (rCB), a substance which otherwise would be produced from crude oil and it is used extensively in tyres and rubber applications [26]. Pyrolysis is not yet applied in an industrial scale, although there are actors who are performing this process and trying to scale up. One of them is Scandinavian Enviro Systems [27], based in Gothenburg. Enviro was approached by the authors of this study and during an interview provided information about rCB not being able to replace virgin carbon black in a one to one basis in all of its uses due to degraded quality. Nevertheless, rCB can be a part of different, less mechanically demanding, products such as, for example, general rubber or rubber membrane [28]. According to Enviro, every kilo of rCB which replaces the production of carbon black from virgin materials, corresponds to 1.5-2kg of crude oil savings [29]. In addition, the gaseous and liquid oil-like by-products, have both a high calorific value which gives them economic value if being used as fuels. More specifically the gas product can supply the energy needed for the pyrolysis process itself while the oil-like product can be used, with some additional processing, as a replacement for diesel fuels or chemicals produced from fossil fuels like 1,3-butadiene, limonene, benzene, toluene and xylene [25]. However, the high sulfuric content of tyres could lead to these products causing major environmental problems once combusted, such as acidification due to SO2 emissions. According to Oh Choi & Kim [25] in a two-stage pyrolysis the sulfur content can be reduced by approximately 40%. However, this process is still in an experimental phase. Pyrolysis can be considered as an option for treating ELTs with a prospect of upscaling and potentially being a more environmentally friendly option compared to other treatment processes, as the main product generated today by this process is carbon black, it might help creating more 'circularity'[3] in the life cycle of a tyre [30].

2.3.2. Steel recycling

Steel is a particularly valuable material of car tyres because of its properties. Another characteristic of iron as a material is that since it can be indefinitely recycled into new forms and with new properties [31]. Recovered steel from an ELT is steel scrap and can be recycled. An advantage of steel scrap is that it requires less energy to be reprocessed into a "new" product, and therefore it is more economical and

[3] Circularity: It refers to circular economy which can be defined as decoupling the economic from the consumption of finite resources and designing waste out of the system [53]

results in lower emissions than virgin steel production [32]. According to Yellishetty [33] since 1950, worldwide scrap consumption by the steel industry has grown by 12% per year. The same study mentions that since 1987 the prices of iron ore increased at a rate of 24% per year, while scrap prices grew by 13% per year.

All these facts, in addition to an increasing trend in the use of steel [34], result in greater value being given to products from which steel can be recovered, like ELTs [33].

2.3.3. Other uses

Shredded tyres can be used in a wide range of products like civil engineering applications, rubber mats, shoe soles, dyes and inks [1]. The rubber share resulting from the separation process, known as crumb rubber (CR), can be also used for different applications, of which the biggest share has infill in football turfs and asphalt.

2.3.3.1. Infill in football turfs

After the process of separation, an important use of rubber is as infill material for football turfs. It is estimated that in European market 83 % of the existing artificial turf fields have rubber infill from recycled tyres (referred to in the article as styrene butadiene rubber (SBR)) [35]. According to an LCA study performed by Ragn-Sells [15] the environmental impact due to the use of such replacement materials might be considerably greater. In the last 20 years the market of artificial turf fields has increased in Scandinavia so the demand for rubber as infill has consequently also followed this trend [35]. Since the estimated lifetime of football turfs is 15 years [36] the amount of rubber granulates that will require treatment in the future is likely to grow as a growing number of football turfs will reach its end of life, and the treatment could become an issue. According to Magnusson [37] about one hundred artificial turf fields are built in Sweden every year.

The impact of the use phase of rubber infill has not been extensively studied, and thus no information to describe how they impact, for example, water bodies was found. The major dispersion pathways that is followed by rubber infill are through rain water runoff, drains system, snow moving and players who will carry it in their shoes or clothes [35]. In addition to that, the same report indicates that granulates degrade and wear over time, forming a layer of dust at the bottom of the turf. Since this is within the size range of microplastics their environmental impact needs to be studied further. These infill losses result in a need of refilling the infill with, on average, 5.5tons per year for a regular football pitch as stated in a report by Rambøll [38]. One of the main treatments of worn granulates, nowadays, is incineration for energy recovery [39]. To the best of our knowledge, the only Scandinavian company that recycles football turfs and their rubber infill is Re-Match [40] which collects and recycles turf waste. A study conducted by IVL has estimated the loss of granulates between 1640 and 3510 tons per year in Scandinavia from 1336 football turfs [37].

2.3.3.2. Mixing CR with bitumen in asphalt

Asphalt is generally produced by mixing bitumen and aggregates (stone, sand or gravel [41]). Modified asphalt concrete is produced by mixing crumb rubber (a possible outcome of ELT treatment) with bitumen. The combination of this modified asphalt concrete with the aggregates results in what is known as Asphalt Rubber (AR) [15].

In an LCA performed by Ragn-Sells, Johansson [15] explains the advantages of using AR pavements, such as increased life of the road, reduced noise, and less crack propagation. The study investigates three different types of AR surfaces, by a scenario analysis approach. The authors find that, the manufacturing of AR shows a worse environmental performance compared to that of conventional asphalt. However, the ability to reduce the thickness of the asphalt layers when using AR could lead to lower overall environmental impacts. The potential reduction of the life span of AR due to the use of studded tyres in Sweden is also mentioned.

Farina et al. [42] performs an LCA on road paving technologies containing different recycled materials, such as AR. The study found that the AR resulted in lower energy usage and global warming potential (GWP) in both the production and maintenance phase.

2.4. Insights from the literature review

There is a number of different pathways for reusing or recycling tyres, leading to diverse environmental impacts, energetic requirements and/or final products. This results in ELTs being handled in different ways in different countries. LCAs on ELTs are commonly done to fulfill one of two functions: either to compare different EOL fates(e.g. [6], [13]), or to assess the impacts of using ELTs into a specific process or product(e.g. [17], [20]). The focus on specific processes and individual comparisons has not yet translated to a study that evaluates the system as a whole. This is relevant because the Swedish ELT treatment system is a combination of different treatment processes and fates that connect to many other processes, and thus the actual impact of the disposal of an ELT, or a kilo of it, has so far not been assessed, and it likely differs from the impact that could come from treating an ELT in one single process.

3. Methodology:

3.1. Life Cycle Assessment

The ISO standard 14040 (1997) states that “LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system
- Evaluating the potential environmental impacts associated with those inputs and outputs
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study”

Figure 3 shows the LCA methodology as described by Baumann and Tillman [43].

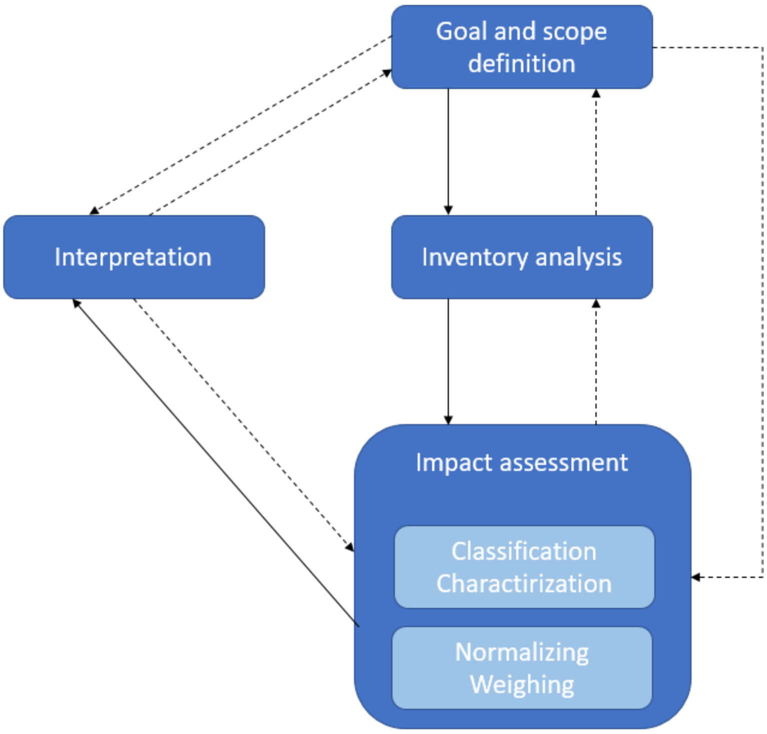

Figure 3: LCA methodology based on "A Hitch Hiker's Guide to LCA" by Baumann & Tillman

3.2. Goal of the study

Given the variety of end-of-life treatments of tyres mentioned in the previous section, research on the topic becomes very relevant in order to broaden the knowledge Volvo Cars has about the EOL fates and impacts of ELTs. Because of this, it was determined to investigate the following questions:

- What are the possible fates that Volvo Cars’ ELTs undergo and what are the potential environmental implications arising from such fates?
- Under an environmental perspective, what are the preferable fate for Volvo Cars’ ELTs?

3.3. Scope

3.3.1. Initial Flow Chart

In Figure 4, an initial flowchart of the analyzed system is presented. Here the study includes all fates of an ELT grouped as either material recycling/reusing or as energy recovery and the inputs (energy and material resources) and outputs (emissions to air, water and soil) of the system. It is a "gate-to-grave" study which means that the use phase, the production and the extraction of materials will not be considered.

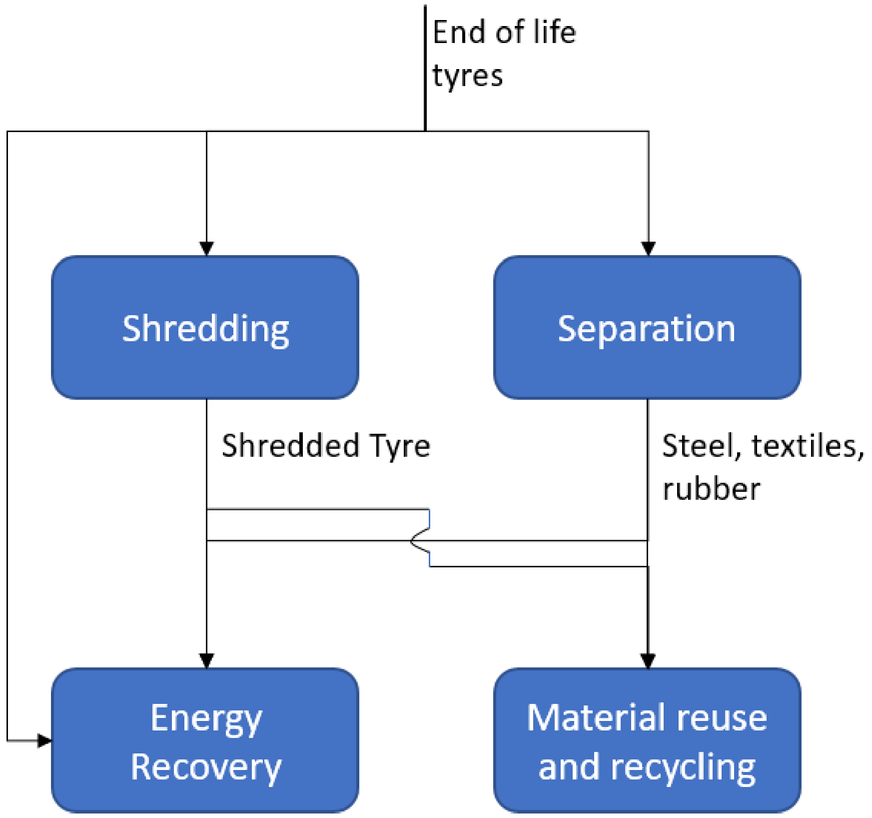

Figure 4: Initial flow chart

3.3.2. Functional Unit

One characteristic of an LCA is that all flows and results have to be related to the functional unit of the system that is being analyzed. As such, an appropriate functional unit allows addressing all the different aspects relevant to the analysis, while being representative of the system.

In this study, the chosen functional unit is "one ELT entering treatment" since the function of the system is to analyze the various ways of treating an ELT. As a reference flow one kilogram of ELT entering treatment was chosen.

3.3.3. Life cycle impact assessment (LCIA) methodology and impact categories

Tyres have a high content of carbon so, when incinerated, carbon dioxide emissions are expected. Another important element of a tyre is sulfur (see Section 1) which can be a result from energy recovery in the form of sulfur oxides. NOx emissions are produced during combustion processes, and therefore can be expected to be present as a result of all combustion related activities. Activities in the background as well, like electricity are expected to affect the results.

Because of these expected emissions, in this study, the assessed mid-point impact categories included in this study are the following:

- Global Warming
- Freshwater and Terrestrial Acidification
- Eutrophication
- Photochemical Ozone Creation

The impact categories were also chosen according to their relevance to the scope of this project. Global warming is a relevant and global issue. Acidification is relevant to Sweden as it is a sensitive area where acid rain has caused problems in the past both in terrestrial and water ecosystems. Eutrophication of natural ecosystems has affected many areas of northern Europe such as the Baltic Sea. Finally, photochemical ozone creation is an important impact assessment category as far as human health is concerned. As such, it was decided to be included in the report.

The characterization factors for the impact categories were obtained from the Environmental Footprint database v3,0 of the European Platform on Life Cycle Assessment [44].

3.3.4. Type of LCA

There are currently two accepted types of LCA methodologies, each serving a different purpose that must be aligned with the goal and scope of the project, since they affect the type of data and decisions required to model the entire system, and therefore affect the resulting impacts. These two different types are attributional and consequential LCA.

Consequential LCA (CLCA or change-oriented LCA) is a type of assessment concerned with comparing the environmental consequences of alternate courses of action, modelling the effects of change [43].

Attributional LCA (ALCA) is also known as accounting LCA, and aims to compare different options, or to assist in future decisions by showing the impact that the functional unit has on average. As such, this is the type of assessment that will be performed since the purpose of the study is to determine the impacts of the current system and compare the different EOL pathways.

3.3.5. Allocation

In this study, allocation will be dealt with using two different approaches. In the baseline assessment, a “strictly attributional” allocation will be done, meaning that the analysis will be performed considering no credits or additional burdens outside of the system as per the attributional LCA methodology. This is because it is considered that the ELT is waste that is disposed at, for example, cement production and coal furnaces, so the impact resulting from their disposal should be attributed to the ELT. If the ELT is processed into a feedstock for a new process, only the impact of processing the ELT will be considered, and once the new feedstock is produced, it leaves the system boundaries.

As an alternative to allocation, a method known as system expansion is to be used, where the system under study is credited for the outgoing flows that can be used as feedstock in other activities, replacing the use of virgin materials or energy resources. These credits come from the following replacements being made:

- The replacement of petroleum coke burning by TDF in clinker production and the avoidance of petroleum coke production
- The replacement of hard coal burning by TDF in coal furnaces and the avoidance of hard coal production in Europe (without Rusia or Turkey)
- Recovered carbon black replacing virgin carbon black and thus avoiding its production
- Scrap resulting from the process turned into low alloy steel replacing low alloy hot rolled steel produced globally

3.3.6. System Boundaries

3.3.6.1. Technical system boundaries

No information regarding the resource extraction, production or use-phase of the tyres will be considered, since a "gate-to-grave" assessment will be performed from a strictly attributional point of view, reviewing only the impacts from the moment the ELT leaves the use-phase until it reaches its final fate. This is because only the EOL fates and impacts are assessed in this study.

3.3.6.2. Geographical boundaries

This study focuses on ELT processing in Sweden Since Volvo Cars has the largest share of vehicles sold cars in Sweden [45], the company is a relevant source of ELTs in the country.

3.4. Data gathering and data quality

For this study, average data coming mainly from scientific reports and articles, and grey literature is used. Additional information was gathered first hand from interviews and conversations with companies involved in the system. The information used for all the calculations of pyrolysis were used exclusively from an interview with Enviro and the share of each fate was based on a flowchart from Ragn-Sells and some further discussions with them.

Finally, the environmental profile related to inflows (lubricating oil or electricity for example)4 and the production of virgin materials were extracted from ecoinvent 3.5 [46].

[4] The complete list of these flows, as well as the datasets from ecoinvent, can be found in the Annex 2

3.5. Assumptions and Limitations

3.5.1. Transport

Transportation was simplified so calculation of the travelled distances was feasible. ELTs are generated all over Sweden, and no information was found regarding amounts of tyres recovered and transported to the many different places where they would be further processed. The transport method determined was then road transport by trucks. Distances and the mass-distance value of each route can be found in Annex 2. The simplifications done were the following:

- A single point of collection and shipping from Stena was considered in Halmstad, since there were many Stena recycling facilities close to it, and it is located in the middle of the southern part of Sweden, central to the population density of the country
- A single point of processing and shipping was considered for Ragn-Sells in Vänersborg. This was based on the location of their granulate factory [15].
- Of the three cement production plants from Cementa, the one in Slite was chosen. This is the biggest plant Cementa operates in Sweden [47]
- A single point for the coal furnaces was assumed in Oxelösund. As mentioned previously coal furnaces are mainly used in the production of metallurgical coke, which is commonly done in integrated steel plants. Oxelösund, at the biggest integrated steel plant operated by SSAB [48]. As mentioned previously coal furnaces are mainly used in the production of metallurgical coke, which is commonly done in integrated steel plants
- The facility of Enviro Systems is located in Åsensbruk [27], so all transports to and from are to be assumed to come from there.

3.5.2. Simplification of clinker production

The production of clinker requires different fuels and raw materials. These fuels (TDF, biomass, and fossil fuels) are burnt simultaneously and, as a result, it is difficult to measure which emissions come from each fuel. This problem was dealt with by collecting data about the emissions of burning TDF exclusively. It is not an accurate representation of what happens in the kiln, because several chemical reactions might take place simultaneously, which might lead to emissions directly related to the interaction of the combustion of TDF with other chemical species, but assuming that TDF is burnt separately is assumed to be an approximation of reality.

3.5.3. Simplification of coal furnaces

The use of ELT in the coal furnaces for the production of metallurgical coke improves, as mentioned in Section 2.2.2, the yield of byproducts and the organic content of the coke. This likely results in a percentage of the ELT mass used in this fate going to both the coke and to the byproducts. However, the split between the emissions to air, coke and byproducts share was not found by the authors. Because of this it is assumed that, as in clinker production, ELTs in this process are used only as TDF.

3.5.4. Infill in football turfs limitations

Despite the negative impacts that could result from infill leakage, there are no regulation today which binds either the producer or the purchaser for their treatment.

3.5.5. Assumptions regarding mass balance of the flowchart

Some assumptions were made in order to reconcile the mass balance numbers that were used in the flowchart. The mass balance data were based on data published by Ragn-Sells [10] and on information provided by them via email. However, there were some data gaps in the information which were dealt with by assumptions. These were the following:

- Fates mentioned in Section 2.3.3 were not included in the calculation of the emissions. This was because they represent either only a small percentage of ELTs fate in Sweden, or because the CR is utilized in many different fates with different processes and amounts and has an overall low share of emissions. In the latter case, the corresponding fates should be studied further.
- No explicit distinction on the amount of crumb rubber undergoing different fates were available
  - There are several small uses of crumb rubber (e.g. shoe soles, various plastic products, etc.) that are not considered in the split, but instead it is divided into the two main categories, i.e. football turfs and asphalt rubber
  - The split between these two categories is not known, but AR is currently in test-phase in Sweden, so the use of it is likely not widespread [15]. This, combined with the considerable amount of crumb rubber that an artificial turf requires yearly [35], and the fact that only one small company that recycles it was found, lead us to assign the majority of crumb rubber to artificial turfs. Due to the cut-off being made after crumb rubber is produced, this does not alter our results and thus is simply meant to be informative
  - Blasting mats are produced from whole tyres by the mining industry. However, the share of tyres used this way is unknown, and in provided information by Ragn-Sells, it is mentioned that the fate of the majority of whole tyres is cement production. Because of this, a 10% share of whole tyres is assumed for blasting mats. Since this represents 1% of total tyres, this fate is omitted.

4. Life Cycle Inventory

4.1. System Flowchart

Figure 5 shows the process flowchart as the result of the data gathering process. In Table 2 below, the share of the weight that is processed by each fate is shown. This share was obtained through conversations with Ragn-Sells, as well as through the assumptions mentioned in section 3.5.3.

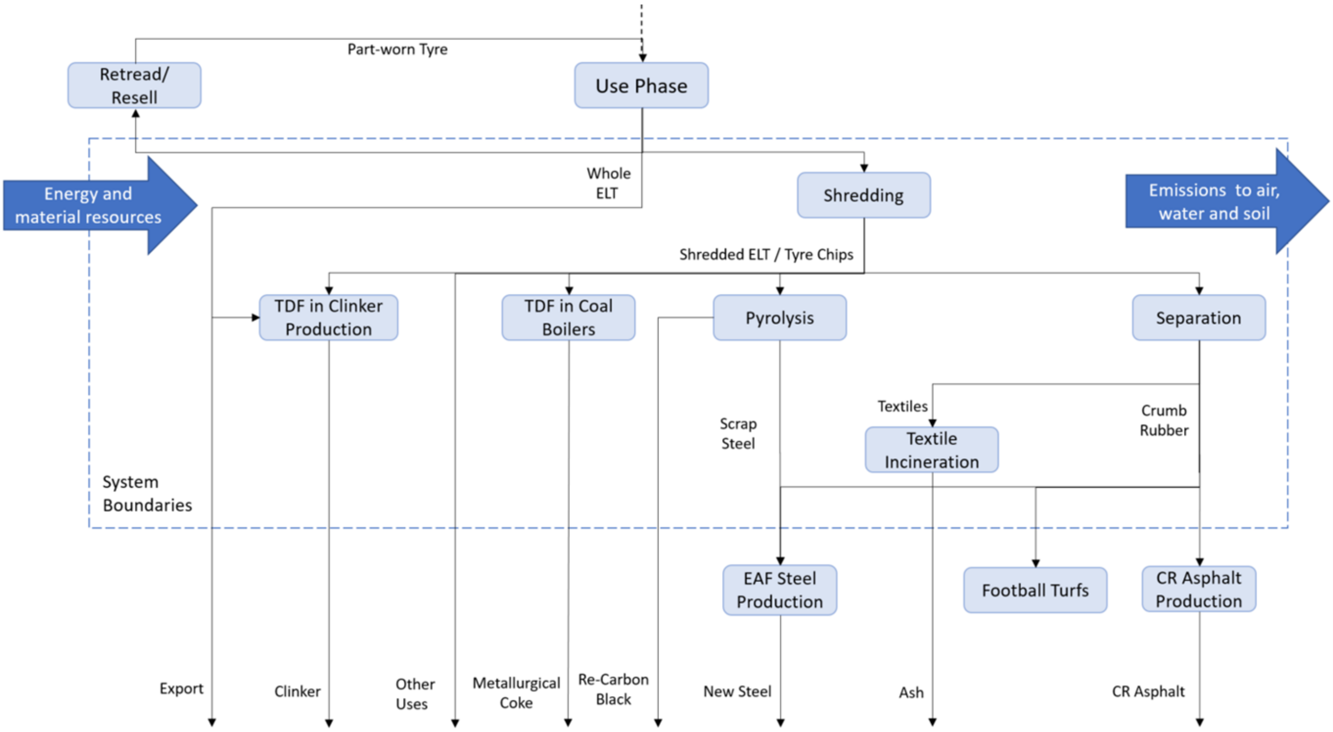

Figure 5: System flowchart

Table 2: Share of ELTs flow to each fate by weight percentage

Share of ELTs flow to each fate by weight percentage					
Whole	**11%**	**Shredded**	**77%**	**Separation**	**12%**
Export	1%	Pyrolysis	5%	Crumb Rubber	8%
Retreading	0,5%	Cement	32%	Textile Incineration	2%
Cement Whole	8,4%	Coal Furnace	32%	Secondary Steel	2%
Blasting Mats	1.1%	Other Uses	5%		
		Secondary Steel	3%		

Table 2 shows that the share of ELT that is currently directed towards energy recovery is currently 74.4% (32% to cement as shredded ELT, 32% to coal furnaces, 8.4% to cement as whole ELT and 2% as textile incineration). Material recovery and recycling then takes 23% of the weight (8% as CR, 5% as pyrolysis, 5% other uses, 3% as secondary steel from shredding and 2% secondary steel from separation). The remaining 2.6% consists of 1.1% of ELT to blasting mats (see section 3.5.3). Finally, 1% leaves the system as an export to other countries and 0.5% is refurbished or retreaded and re-used.

4.2. Results of the Life Cycle Inventory

Tables Table 3, Table 4 and Table 5 below shows the emissions, inputs and products of all the different fates included in the calculations. The exception to that is pyrolysis, due to confidentiality reasons.

Table 3: Material and energy inputs

Material and energy inputs per kg of ELT				
System flows	**Shredding**	**Separation**	**TDF in cement production**	**TDF in coal furnace**
Electricity (kWh)	0.04	0.04		
TDF (kWh)			3.61	2.87
TDF (kg)			0.41	0.32
Water	0.12	0.02		
Whole ELT	0.77	0.12	0.08	
Shredded ELT			0.32	0.32
Lubricating Oil	8.47×10^{-6}	1.32×10^{-6}		
Steel	1.77×10^{-4}	5.29×10^{-5}		

Table 4: Elementary flows; emissions to air

Direct emissions to air (kg reference substance/kg of ELT)				
Elementary flow	**Shredding**	**Separation**	**TDF in cement production**	**TDF in coal furnace**
CO_2 total (bio+fossil)	-	-	1.26	1.01
CO2 biogenic	-	-	-	-
CO	-	-	-	-
SO_2	-	-	0.01	0.01
NO_x	-	-	4.78	3.82
Particulates (PM10)	-	2.2945×10^{-8}	-	-
O_2	-	-	0.24	0.19
HCl	-	-	0.01	0.01
P_2O_5	-	-	0.07	0.05

Table 5: Main and coproducts

Products				
Technical system flows	**Shredding**	**Separation**	**TDF in cement production**	**TDF in coal furnace**
Shredded Tyre	0.74			
Crumb Rubber		0.11		
Textiles		0.01		
Scrap Steel	0.03	0.03		

4.2.1. Hydrogen chloride and cement production

Hydrogen chloride emissions occur as a result of the incineration of TDF, as can be seen in Table 4. However, these emissions are not the same as the emissions that the entire clinker production process has, but instead only the emissions of the TDF incineration. As can be seen in detail in Annex 3: Calculations for HCl allocation in clinker production, an energy allocation was done to estimate the emissions of HCl from the clinker production process that can be attributable to the incineration of TDF within said process.

4.2.2. Coal furnaces results

It was assumed that the use of TDF in furnaces has no byproducts was made (see Section 3.5.3).. No information regarding the shares of products resulting from the use of ELTs on coal furnaces for coking was found, and thus no allocation is done. Because of this, the emissions presented for coal boilers here (and in the scenario analyses) are likely higher than they would be.

5. Life Cycle Impact Assessment

5.1. Characterization

Table 6 shows the impacts of the entire system for each category for one kg of ELT entering treatment. in terms of their mid-point indicators.

Table 6: System's impact categories

Impact Categories	Values	Units
Global Warming	2.28	kg CO_2-equivalents
Freshwater & Terrestrial Acidification	5.84	Mol H+-equivalents
Terrestrial Eutrophication	11.75	Mol N-equivalents
Photochemical Ozone Creation	8.61	kg NMVOC-equivalents

When assessing the system as a whole, the strictly attributional perspective shows that there is an actual environmental impact from the processing of ELTs.

Below, Figure 6 presents the results for each impact category for each fate of the system. In each fate all activities (shredding, transportation, electricity, water use etc.) required by that fate are included. The major contributors to the environmental impact of the system in all the mentioned impact categories are cement and coal furnaces. The share of impact from cement production and coal furnaces is similar in all categories because both fates process ELTs as TDF and thus have the same emissions. Cement production contributes more to the impact than coal furnaces because of the higher amount of ELT destined to it. As fates, pyrolysis and separation have smaller impacts, being an almost dismissible share of the results shown in Figure 6. This is likely due to a combination of having a smaller share of ELT being processed by them (in terms of mass), as well as being fates where the materials of the ELT are recycled or reused, rather than incinerated for energy recovery.

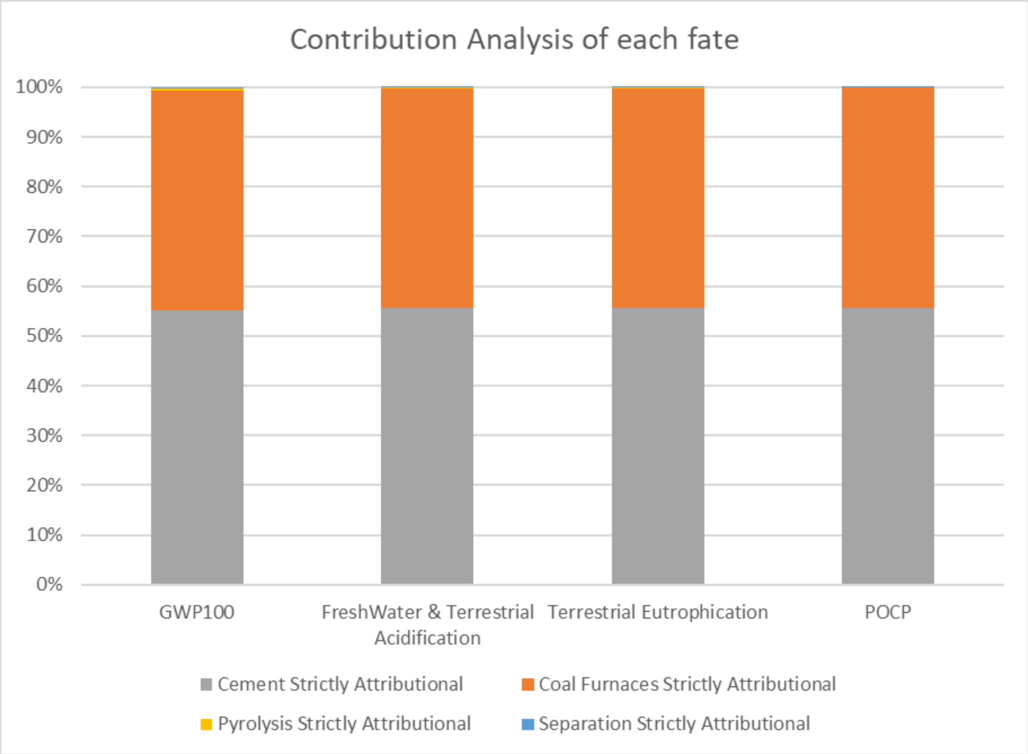

Figure 6: Contribution of each fate to the overall environmental impacts of the system

Since almost a major share of ELTs are utilized as fuel, and therefore consumed, the emissions in all impact categories are large when compared to more circular options such as pyrolysis or separation. When the system is seen not in terms of fates, but of the processes that form those fates, the results are similar. Incineration of TDF in both coal furnaces and clinker production dominate the impacts in each category, being 99.1% in GWP, 98.2% in freshwater and acidification, 97.9% for terrestrial eutrophication and 99.9% for POCP. The impacts from the remaining activities (such as pyrolysis, separation, shredding and background processes) were small. These results show that the impact from energy recovery fates is higher than the share of ELT processed by them, and thus meaning that the material recovery and recycling fates could be less impactful.

When not accounting for the incineration of TDF, the most impactful activities in terms of GWP are pyrolysis, incineration of textiles, and electricity for separation. However, on the other impact categories, transport represents the dominating share of impact.

5.2. Normalization

In order to provide a reference point for the results of the system, the impacts were normalized following the Environmental Footprint 3.0 global normalization factors per capita (complete list in Annex 2). Figure 7shows the results for the chosen impact categories in percentage relative to the global normalization factors per capita.

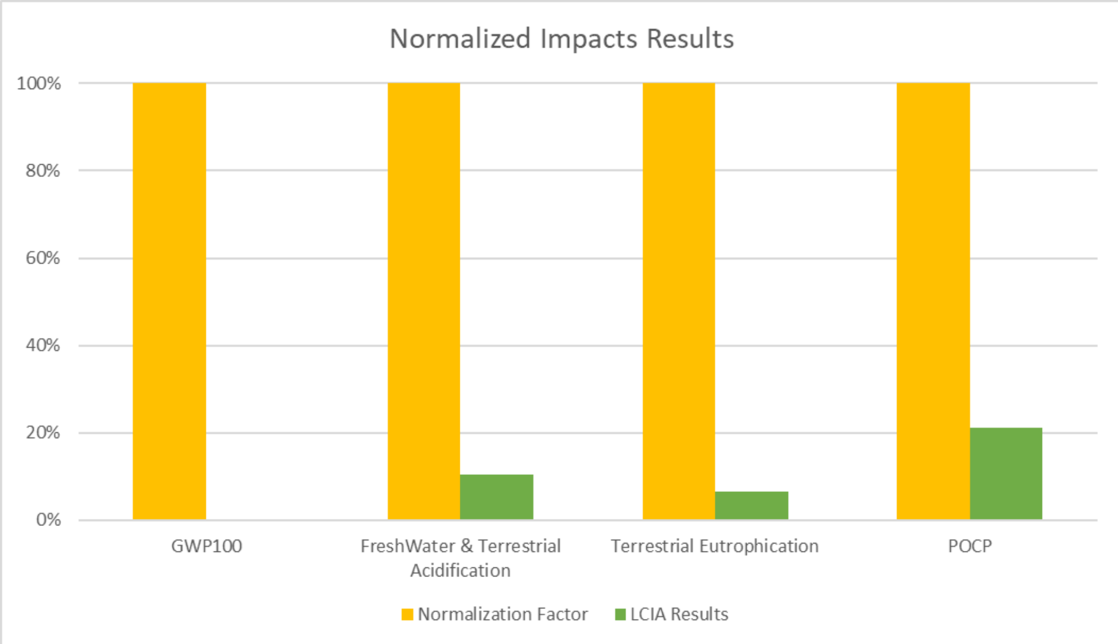

Figure 7: Impacts of the entire system relative to the global per capita normalization factors of EF3.0

When compared to the average total impacts per person worldwide, the impact from one kilogram of ELT processed is of over 20% when it comes to POCP. Acidification and eutrophication have a lower impact, of approximately 10% and 6% respectively. Finally, the GWP impact is small, being equivalent to less than 0.03% of the kg of CO2-equivalents emitted per capita world-wide.

5.3. System Expansion Results

Results in this section are intended to show the system from a different perspective and evaluate the impact of each activity considering the emissions "avoided" when using ELTs instead of primary resources. This includes both the use of the virgin resources, as well as the avoidance in production of those resources.

Figure 8 shows the impacts of the entire system on the different impact categories (as seen in Table 6 in Section 5.1) and the credits resulting from the system expansion allocation. The values for each impact category are in a different unit (GWP100 is in kilograms of CO2-equivalents, freshwater and terrestrial acidification is in moles of H+-equivalents, terrestrial eutrophication in moles of N-equivalents and POCP is expressed in kilograms of non-methane volatile organic carbon-equivalents).

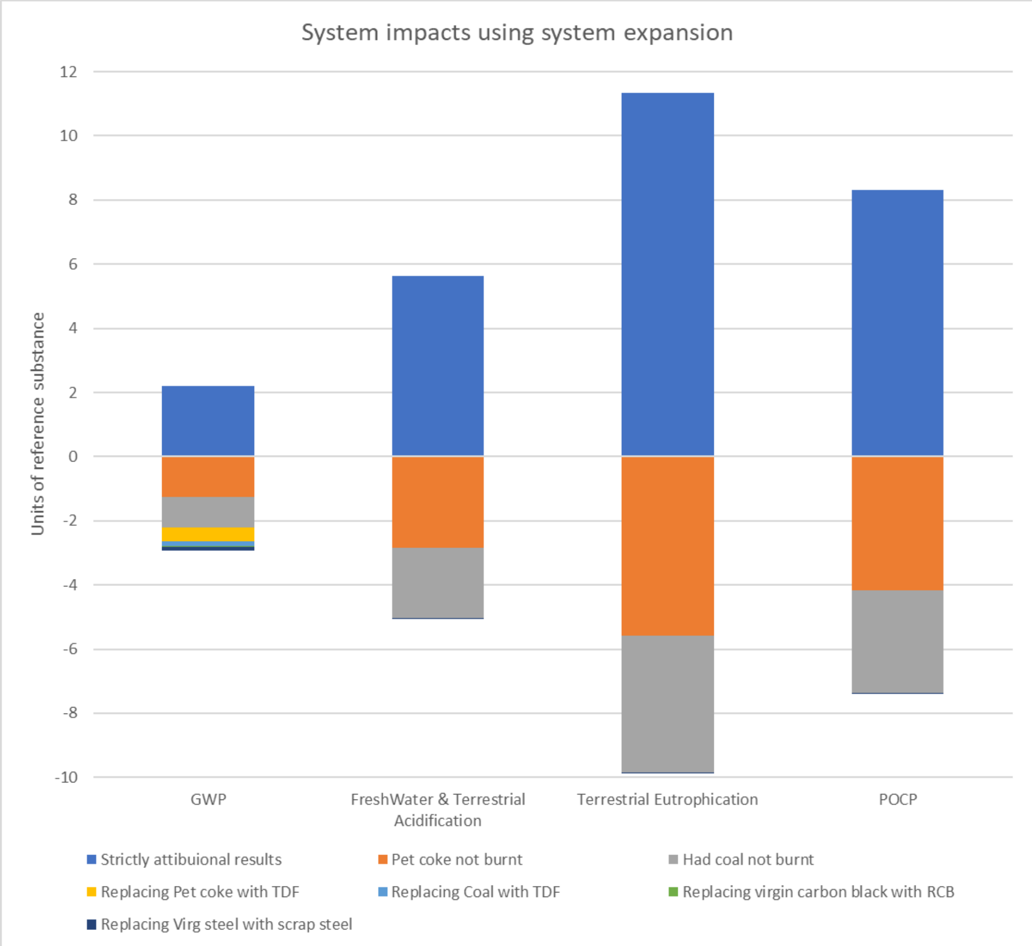

Figure 8: System's environmental impacts using system expansion. Units for each impact category are kilograms of CO2-equivalents, moles of H+-equivalents, moles of N-equivalents and kilograms of non-methane volatile organic carbon-equivalents respectively. Strictly attributional impacts are mentioned in Section 4.2

Results in Figure 8 show that, on all impact categories considered in this study, crediting for both avoided emissions from combustion and from replacing new products with products derived from the analyzed processes leads to smaller system impacts.

Further analysis into the impacts from each process was also done, comparing the cut-off and system expansion results. All impacts from the background system (i.e. those supporting the assessed system, such as electricity generation, lubricant oil production, and such others) as well as transport were allocated to each fate. The results of this analysis can be seen for cement and coal furnaces in Figure 9 and for pyrolysis and separation in Figure 10.

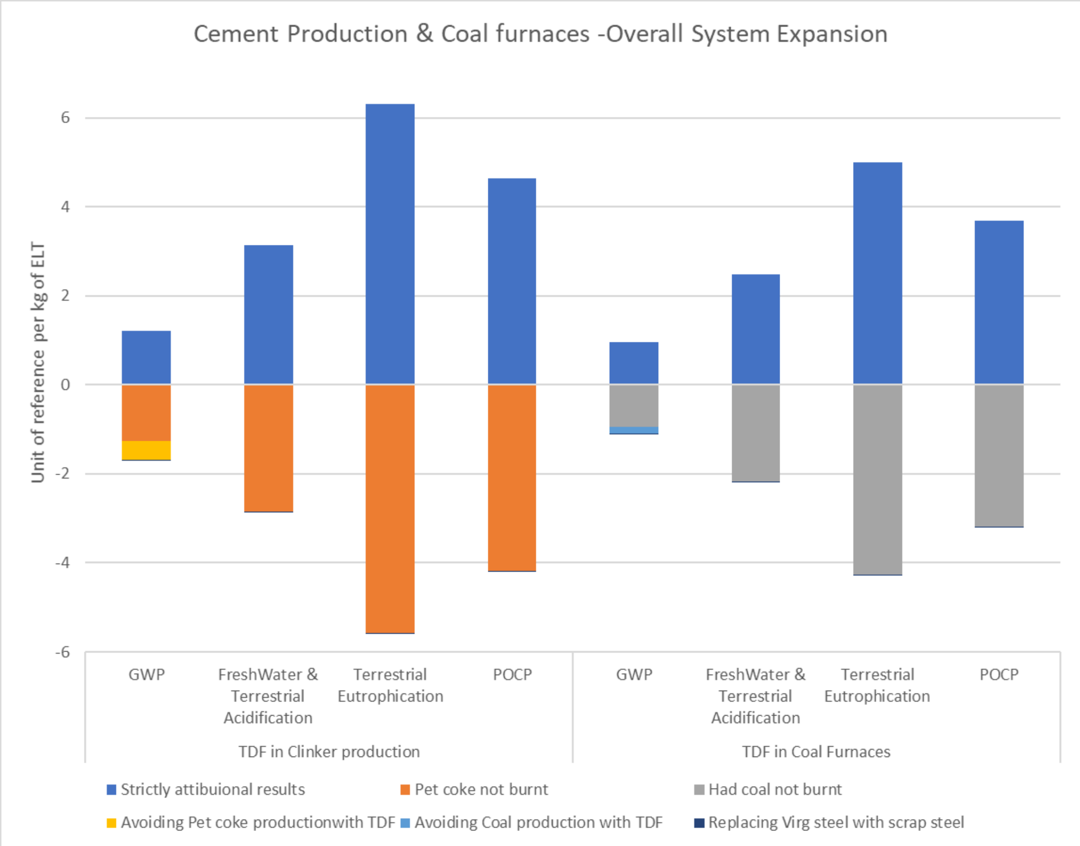

Figure 9: TDF in Cement production and coal furnace results from a system expansion allocation approach

Results in Figure 9 show that, when using a system expansion perspective, impacts are greatly reduced both in cement production and in coal furnaces on all impact categories, with GWP becoming negative on both fates. It is noticeable that all impacts are of similar magnitude on both fates, except GWP being lower for cement. Cement can be credited for the emissions coming from petroleum coke that are avoided from both consumption and its production. The GWP value becomes the lowest of all fates, and acidification, eutrophication and POCP are improved by an order of magnitude. Some uncertainty comes to these results since we are considering the emissions to be only from the incineration of TDF, and not considering the emissions at the end of the clinker production process. As far as incineration in coal furnaces is concerned the results are similar to cement. As mentioned in Section 4.2.2, the uncertainty that comes from the assumption that all emissions from TDF are burdened to the emissions to air, and that there are no byproducts, probably results in the impacts being higher than they would be.
GWP has the largest improvement from this system expansion, but it is not as noticeable as that seen in the cement production fate. This might be explained by considering that an ELT in a coal furnace replaces coal, and in cement it is replacing petroleum coke.

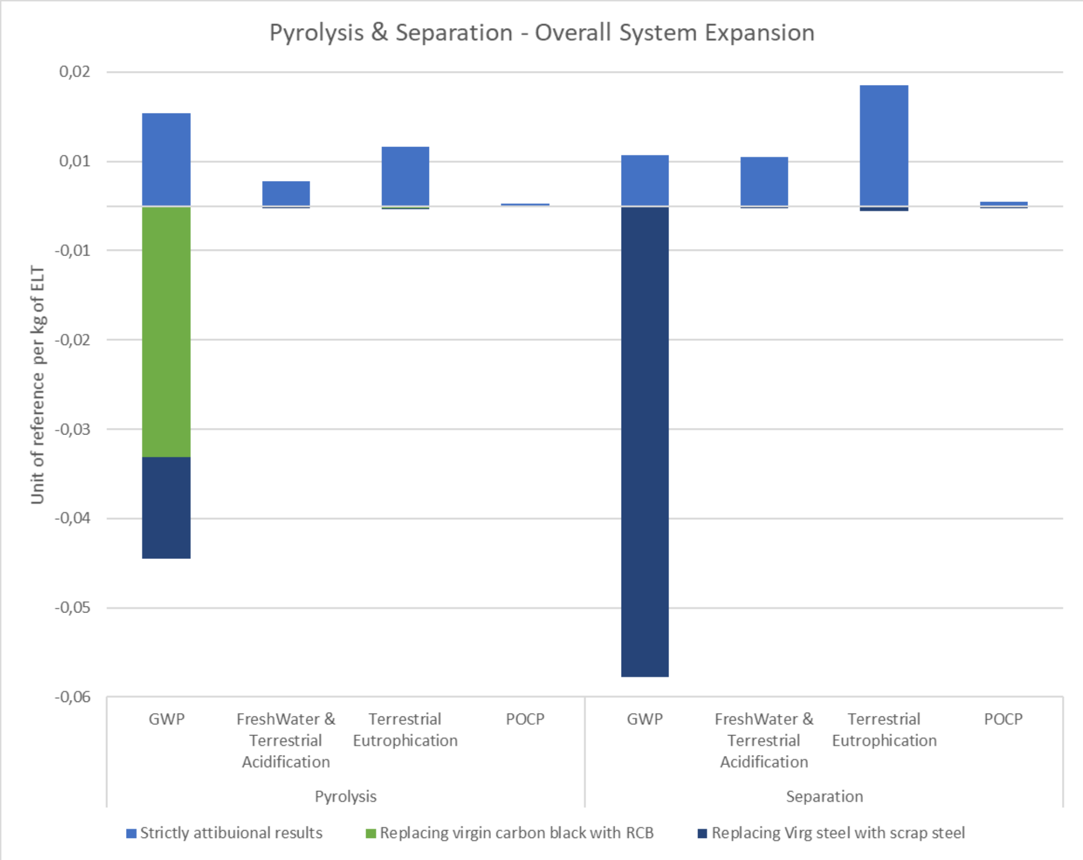

Figure 10: Pyrolysis and separation results from a system expansion allocation approach

Results for separation are shown in Figure 10, and the values for three of the four impact categories remain similar from both a system expansion and a strictly attributional perspective. The exception here is GWP, which changes from being a positive impact to a negative one. This is due to the credit from the scrap steel recycling.

Figure 10 also shows the results of pyrolysis. Results when analyzing the system from a system expansion perspective show a reduction on all impact categories, with GWP becoming negative and POCP being the second lowest impact category. This reduction is due to the credits of recycled steel and the recovered carbon black replacing the need for producing virgin carbon black. As mentioned, the pyrolysis oil is also a product that is currently being researched for the possibility of using it as a feedstock in refineries (and take advantage of its biogenic carbon content) and further refine it into a partial biofuel. These uses are still experimental and not widespread, but if they were to become widespread practices, the results of the process would likely improve further.

5.4. Scenario Analysis: Single fate scenario

Further analysis of the different fates was done assuming that the entirety of the ELT would be processed in one fate, in order for the study to be able to determine which fate would be preferable for the ELTs of Volvo Cars.

Results were the separated into 2 different figures to ensure clarity and readability. In Figure 11, the results for cement and coal furnaces are shown, while the results for pyrolysis and separation are shown in Figure 12

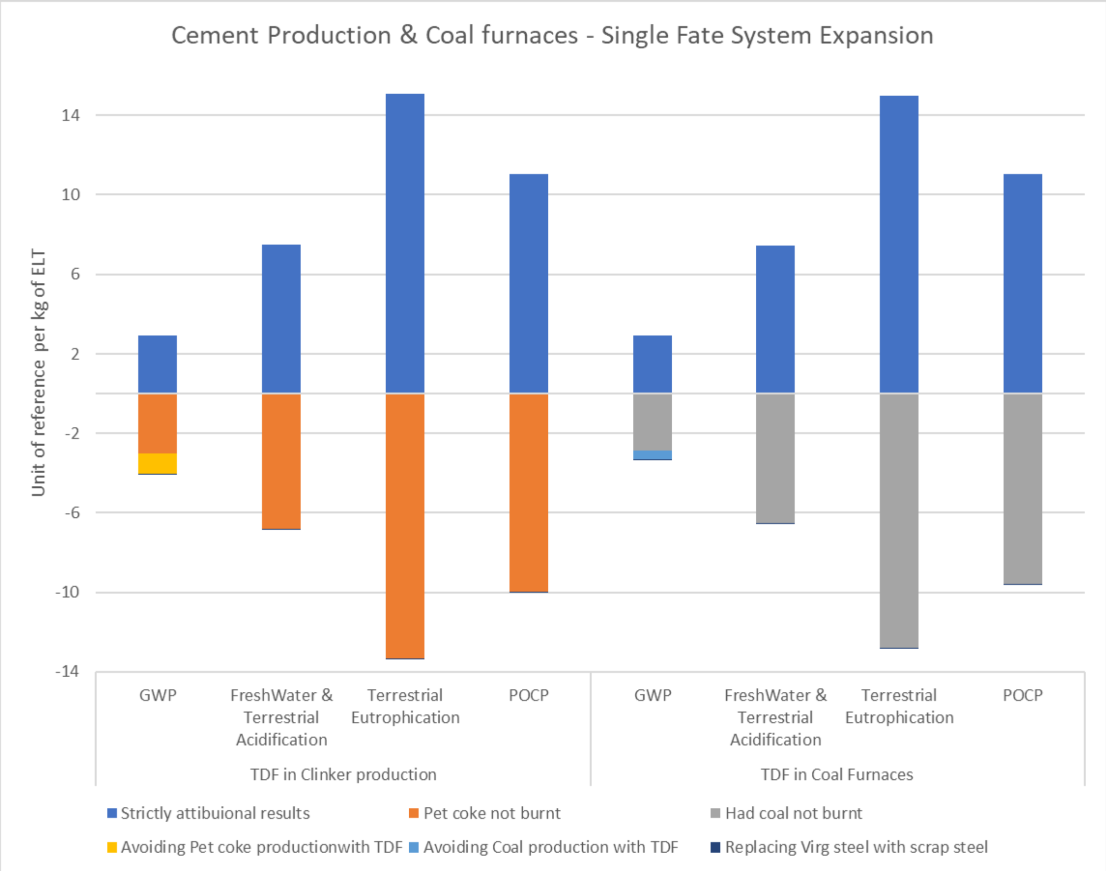

Figure 11: TDF in cement production and coal furnace results from a system expansion allocation approach in a scenario where all ELTs in the system is treated by a single fate

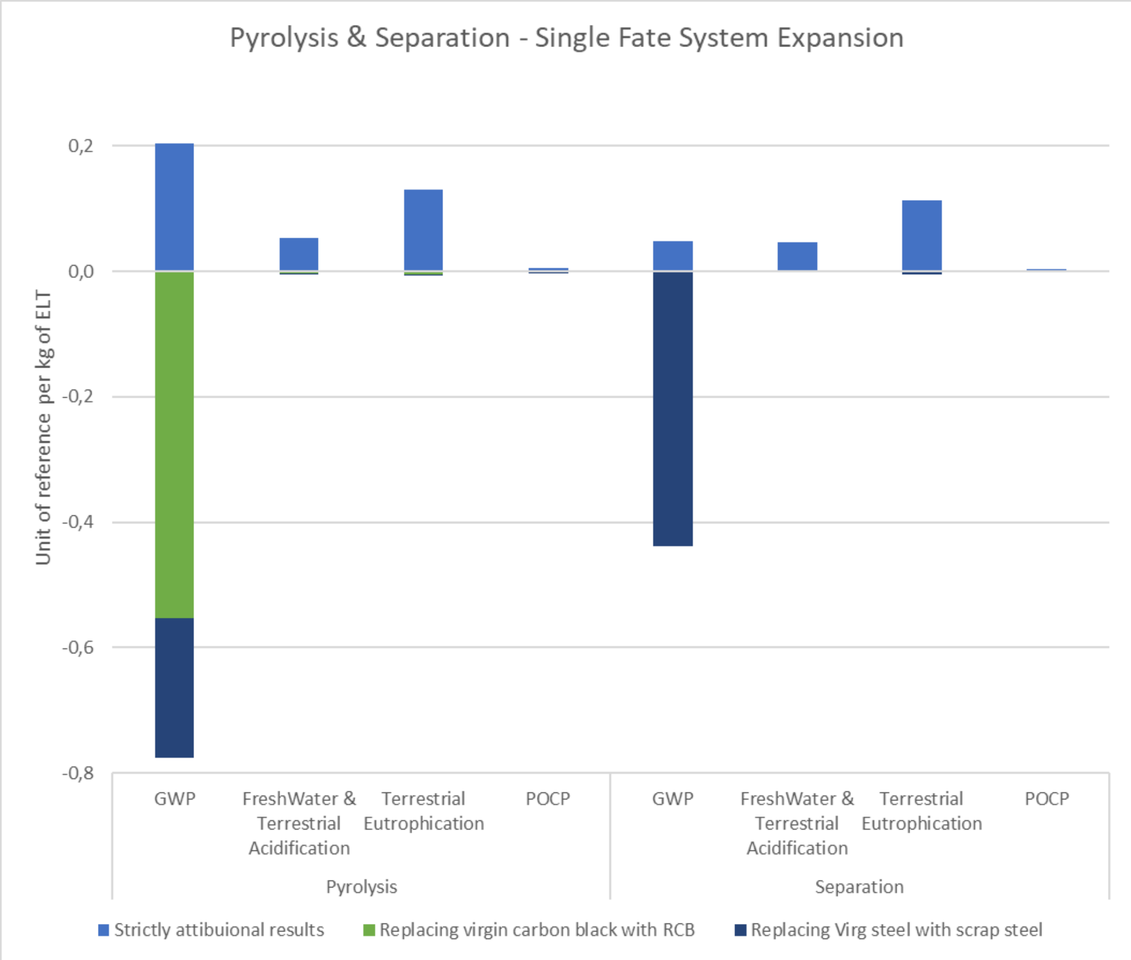

Figure 12: Pyrolysis and separation results from a system expansion allocation approach in a scenario where all ELTs in the system is treated by a single fate

Separation is the fate with the lowest emissions when using a strictly attributional allocation, with the main impacts coming from the electricity required by the process, and the incineration of textiles (recycling of these is not yet done at an industrial scale but if this was done, and thus not incinerated, the impacts from separation would reduce considerably). CR obtained from separation is mostly used in two processes that, nowadays, use no other replacement. Those are asphalt rubber and infill in football turfs. Asphalt rubber produced with the addition of CR gives it some characteristics like absorption of vibrations which are given solely by CR. Although, this kind of asphalt currently has very limited use in Sweden and since it is not well-studied its impacts are mostly unknown.

Infill in football turfs is made almost exclusively by CR, thus assessing replacements wouldn't be realistic for today's situation. Infill has leakages which cause pollution because of the microplastics (worn CR) and this is not properly studied yet. Also, there is no regulation for a specific treatment of the infill, so it is mostly treated as waste (this could change in the future, as the number of football turfs entering their EOL increases, and consequently the need to treat the end-of-life granulates).

Further studies on the infill leakage could reveal the true extent of the pollution and possible treatments, in order to reduce its impact especially since the use of artificial football turfs is increasing. Additionally, possible replacements with less environmental impact could be researched (e.g. the development of football turfs without infill).

Pyrolysis is a fate that shows good performance when assessing its environmental impacts. From a strictly attributional perspective, it falls short only of separation, and in the categories of acidification, eutrophication and POCP the impact ranges between 16% and 31% more than the respective separation impacts. In the case of GWP this number is a few times higher than the strictly attributional results of separation. However, the outputs of pyrolysis are better known and the total impacts of the pyrolysis can be quantified more easily, and the inclusion of benefits coming from commercial uses of pyrolytic oil could close this gap further. The system could likely be further improved by changing the current share of ELT fates. When assessing this, it was determined that separation was not to be increased from its current share because, as mentioned above, there is not enough information regarding the impacts of some of the main uses of crumb rubber and the current lack of recyclability where textiles are concerned. It is because of this that the recommendation is to increase the share of pyrolysis since its environmental performance is among the best of the analyzed fates, and the process brings circularity to a number of different materials, instead of simple energy recovery. The potential of this increase was analyzed in the next section.

5.4.1. Sensitivity analysis

A sensitivity analysis was performed to further understand how the total share of an ELT treated by pyrolysis affects the total results of the system. Pyrolysis was selected as the fate to test since, from previous results, it is one of the best performing fates, and had a low overall share in the system (separation shows better results as a single fate but, for reasons better explained in section Figure 13: Change in overall system impact by changing share of ELT pyrolyzed, it was not chosen as the variable to shift in this analysis). Figure 13 shows that as the share of pyrolysis increases in the system, all environmental impacts improve in an almost linear manner.

This analysis was done by changing the share of pyrolysis while adjusting all other fates to maintain the relative proportion they had to each other.

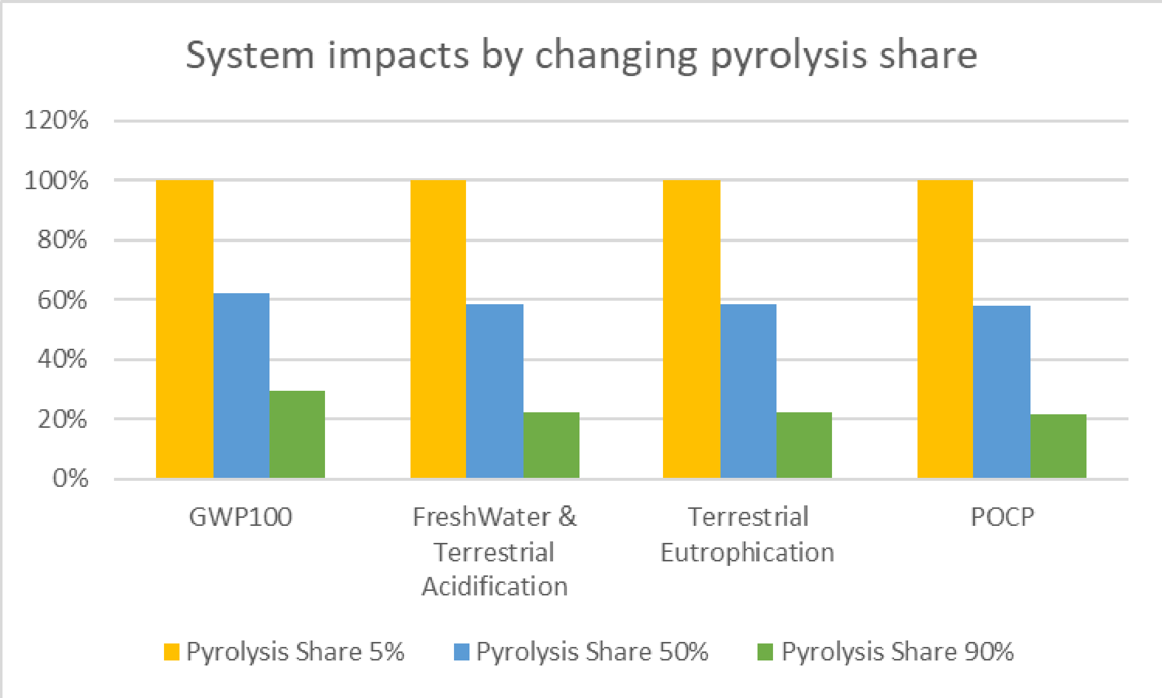

Figure 13: Change in overall system impact by changing share of ELT pyrolyzed

As can be seen from the sensitivity analysis, increasing the share of pyrolysis in the system improves the overall results in a linear fashion, with no significant penalty for increasing the share. This does not mean, however, that the share of pyrolysis could be increased to that level anytime soon. Production capacity for pyrolyzing tyres is not capable of managing the increase in volume, and thus any evaluation of whether or not to increase this production should be done in a consequential LCA. Also relevant is that products and services that have grown dependent to a certain amount of ELTs in their feedstock (such as cement production or football turfs) could likely have issues adapting to this change. Because of these reasons, the sensitivity analysis here is only used to examine the theoretical benefits of increasing ELT processing by pyrolysis.

6. Conclusions & Further research

ELTs are a waste stream which could be a feedstock for different products and, therefore, has value. The different fates of ELTs have different environmental impacts, so the emissions of the system have the potential to be reduced if the shares of ELTs processed by each fate change. Of course, this has many parameters to be considered; pyrolysis has a low capacity and an expansion of it would need the construction of more facilities and, therefore, a certain carbon footprint from the construction. Cement is a complicated process which produces a considerable amount of emissions. It is a well-suited process for waste disposal, and because of this, the mix of energy feedstocks varies between countries. There are many studies regarding the use of alternative energy feedstocks in the cement process. However, the optimization of the combination of feedstocks specific to a country or region is something that can be further studied.

Another fate of ELTs is coal furnaces. The information found regarding LCAs and the use of ELTs in coal furnaces was limited. Because of this, our calculations were based on the assumption that ELTs are burnt as TDF.

Pyrolysis, although not widely used is a process with low emissions. Increasing the share of pyrolysis treatment would lower the emissions of the whole system. Pyrolysis appears to be a promising fate for ELTs as it produces secondary products which can replace other virgin products, thus preventing fossil fuel extraction and additional processing. This is notable when system expansion is used in order to credit the system. Pyrolysis as a fate improves the circularity of the system because of its outputs (e.g. carbon black, steel). The pyrolytic oil has been and is being studied to evaluate its potential as a refinery feedstock and as a component of alternative fuels. Further developments in these efforts might improve the results of pyrolysis when considering an expansion of our system.

Separation has also very low environmental impact, but some of its products, namely football turf infill and asphalt could be further researched. Infill in football turfs is the main use of crumb rubber. The level of pollution derived from CR in football turfs is still unknown and, given that the use of CR in football turfs is constantly growing, researching a more environmentally friendly replacement might be interesting. In spite of separation’s good environmental performance, further research on the resulting products, especially those that include CR, should be done before increasing the share it has in the system.

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Annex 1: Life Cycle Impact Assessment full results

Life cycle impact assessment from a strictly attributional perspective

Impact Category	**Total Impact**	**Unit**
GWP100	2.20E+00	kg CO2-Eq
FreshWater & Terrestrial Acidification	5.64E+00	mol H+ -Eq
Freshwater Ecotoxicity	1.72E+01	CTU
Freshwater Eutrophication	9.96E-02	kg P-Eq
Marine Eutrophication	3.23E+00	kg N-Eq
Terrestrial Eutrophication	1.14E+01	mol N-Eq
Carcinogenic Effects	7.98E-06	CTUh
ionising radiation	3.53E-02	kg U235-Eq
non-carcinogenic effects	1.31E-03	CTUh
ozone depletion	2.91E-09	kg CFC-11-Eq
POCP	8.32E+00	kg NMVOC-Eq
respiratory effects inorganics	1.67E-07	decease incidence
Dissipated Water	2.09E-02	m3 water-Eq
Fossils	5.13E-01	MJ
Land use	4.04E-01	Points
minerals and metals	5.55E-03	kg Sb-Eq

Life cycle impact assessment from a systems expansion perspective

Impact Category	**Total Impact**	**Unit**
GWP100	-7.17E-01	kg CO2-Eq
FreshWater & Terrestrial Acidification	6.15E-01	mol H+ -Eq
Freshwater Ecotoxicity	-6.46E+00	CTU
Freshwater Eutrophication	9.90E-02	kg P-Eq
Marine Eutrophication	3.65E-01	kg N-Eq
Terrestrial Eutrophication	1.49E+00	mol N-Eq
Carcinogenic Effects	7.98E-06	CTUh
ionising radiation	7.59E-03	kg U235-Eq
non-carcinogenic effects	1.31E-03	CTUh
ozone depletion	-8.19E-08	kg CFC-11-Eq
POCP	9.41E-01	kg NMVOC-Eq
respiratory effects inorganics	-4.42E-07	decease incidence
Dissipated Water	-3.58E-02	m3 water-Eq
Fossils	-1.84E+01	MJ
Land use	-2.39E+00	Points
minerals and metals	5.55E-03	kg Sb-Eq

Life cycle impact assessment of comparison of each fate in the current Swedish system

	Cement		**Coal Furnaces**		**Pyrolysis**		**Separation**	
	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.
GWP100	1.2E+00	-4.9E-01	9.7E-01	-1.5E-01	1.0E-02	-1.9E-02	5.7E-03	-4.7E-02
Freshwater & terrestrial acidification	3.1E+00	2.9E-01	2.5E+00	3.1E-01	2.7E-03	2.5E-03	5.5E-03	5.2E-03
Freshwater ecotoxicity	9.6E+00	-1.3E+01	7.6E+00	6.2E+00	5.9E-04	-9.5E-03	2.1E-03	8.6E-03
Freshwater eutrophication	6.3E+00	7.3E-01	5.0E+00	7.3E-01	6.7E-03	6.4E-03	1.4E-02	1.3E-02
Marine eutrophication	4.1E-06	4.1E-06	2.8E-06	2.8E-06	2.2E-07	2.2E-07	4.4E-07	4.4E-07
Terrestrial eutrophication	6.8E-03	-7.5E-03	6.7E-03	-2.5E-03	5.2E-03	6.5E-05	1.6E-02	1.6E-02
Carcinogenic effects	6.8E-04	6.8E-04	4.7E-04	4.7E-04	3.5E-05	3.5E-05	7.2E-05	7.2E-05
Ionising radiation	7.8E-10	-5.1E-08	6.6E-10	-1.1E-08	3.6E-10	-1.8E-08	1.0E-09	-1.5E-09
Non-carcinogenic effects	4.6E+00	4.6E-01	3.7E+00	4.8E-01	2.4E-04	1.5E-04	4.3E-04	1.7E-04
Ozone depletion	9.2E-08	-2.5E-07	7.3E-08	-1.8E-07	4.9E-10	-3.9E-09	9.7E-10	-2.9E-09
POCP	3.9E-03	-6.2E-03	3.9E-03	-1.8E-02	3.1E-03	5.7E-04	9.4E-03	-8.4E-03
Respiratory effects inorganics	9.8E-02	-3.2E+00	9.8E-02	-1.4E+01	7.5E-02	-1.1E+00	2.3E-01	-4.1E-01
Dissipated water	7.7E-02	-3.1E-01	7.7E-02	-2.0E+00	6.0E-02	-9.8E-03	1.8E-01	-2.0E-02
Fossils	2.9E-03	2.9E-03	2.0E-03	2.0E-03	1.5E-04	1.5E-04	3.0E-04	3.0E-04
Land use	1.2E+00	-4.9E-01	9.7E-01	-1.5E-01	1.0E-02	-1.9E-02	5.7E-03	-4.7E-02
minerals and metals	3.1E+00	2.9E-01	2.5E+00	3.1E-01	2.7E-03	2.5E-03	5.5E-03	5.2E-03

Life cycle impact assessment of the single fate scenario

	Cement		Coal Furnaces		Pyrolysis		Separation	
	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.	Strictly Attrib.	System Exp.
GWP100	2.91E+00	-1.18E+00	2.90E+00	-4.39E-01	2.04E-01	-5.73E-01	4.74E-02	-3.92E-01
FreshWater & terrestrial acidification	7.49E+00	6.94E-01	7.46E+00	9.32E-01	5.36E-02	4.89E-02	4.57E-02	4.35E-02
Freshwater ecotoxicity	2.28E+01	-3.02E+01	2.27E+01	1.86E+01	1.15E-02	-1.62E-01	1.79E-02	7.15E-02
Freshwater eutrophication	1.23E-01	1.22E-01	1.06E-01	1.05E-01	5.28E-02	5.26E-02	4.56E-02	4.51E-02
Marine eutrophication	4.30E+00	4.23E-01	4.28E+00	5.63E-01	5.08E-04	-1.22E-04	2.93E-04	-1.55E-04
Terrestrial eutrophication	1.51E+01	1.75E+00	1.50E+01	2.19E+00	1.31E-01	1.24E-01	1.13E-01	1.08E-01
Carcinogenic effects	9.82E-06	9.82E-06	8.49E-06	8.49E-06	4.23E-06	4.24E-06	3.65E-06	3.67E-06
Ionising radiation	1.85E-02	-1.53E-02	2.02E-02	-7.63E-03	1.02E-01	4.37E-03	1.29E-01	1.36E-01
Non-carcinogenic effects	1.62E-03	1.62E-03	1.40E-03	1.40E-03	6.97E-04	6.97E-04	6.01E-04	6.01E-04
Ozone depletion	2.00E-09	-1.21E-07	1.98E-09	-3.38E-08	6.98E-09	-3.63E-07	8.53E-09	-1.24E-08
POCP	1.11E+01	1.09E+00	1.10E+01	1.45E+00	4.67E-03	1.95E-03	3.55E-03	1.38E-03
Respiratory effects inorganics	2.21E-07	-6.02E-07	2.18E-07	-5.49E-07	9.60E-09	-9.15E-08	8.08E-09	-2.45E-08
Dissipated water	1.07E-02	-1.57E-02	1.17E-02	-5.33E-02	6.00E-02	-5.94E-02	7.84E-02	-7.00E-02
Fossils	2.68E-01	-7.78E+00	2.92E-01	-4.05E+01	1.47E+00	-2.34E+01	1.90E+00	-3.41E+00
Land use	2.12E-01	-7.28E-01	2.31E-01	-6.05E+00	1.17E+00	-9.79E-01	1.49E+00	-1.67E-01
Minerals and metals	6.83E-03	6.83E-03	5.91E-03	5.91E-03	2.94E-03	2.94E-03	2.54E-03	2.53E-03

Annex 2: Inventory Data

Tyre Derived Fuel, Petroleum Coke, and Coal emission factors from Combustion [20]

Net Calorific Value	TDF	Coal	Petroleum Coke
MJ/kg dry fue	32000	30000	33000
Emissions	**TDF**	**Coal**	**Petroleum Coke**
CO_2	3.00E+00	2.76E+00	3.23E+00
H_2O	9.42E-01	5.97E-01	5.01E-01
O_2	5.79E-01	4.70E-01	5.37E-01
NO_x	1.14E+01	9.28E+00	1.06E+01
SO_2	2.61E-02	9.05E-02	1.08E-01
HCl	2.04E-02	3.20E-03	4.88E-02
P_2O_5	1.62E-01	0.00E+00	0.00E+00

Shredding and Separation Data [13]

Authors divide the Shredding and Separation into three different processes, while we divide them into two. However, the first step (shred tyres for us, or Ground tyres for the authors) is the same for both, and the result of the third process is what we consider crumb rubber (Pulverized and fine pulverized tyres for the authors). Because of this, the second a third step are consolidated in our calculations into a single process. Here is the data as presented by the authors in their article.

Inputs	Outputs	Amount	Unit
End of Life Tyre to Shredded tyres			
ELT		1000	kg
Electricity		170	MJ
Water		150	kg
Steel		0.230	kg
Oil		0,011	kg
	Ground tyres	966	kg
	Iron Scrap	34	kg
Ground Tyres to Crushed Tyres			
Ground Tyres		1000	kg
Electricity		573	MJ
Steel		0.01	kg
	Crushed tyres	750	kg
	Iron Scrap	250	kg
Crushed Tyres to Pulverized & fine Pulverized tyres			
Crushed Tyres		1000	kg
Electricity		513	MJ
Steel		0.278	kg
	Fine Pulverized tyres	630	kg
	Pulverized tyres	310	kg
	Textile Fibers	60	kg
	Particulate Matter	263.92	mg

Pyrolysis information

The source of most information regarding pyrolysis was Enviro Systems. Information confidential to their process and operation was used, and it was required by them to keep it from appearing explicitly in the report. However, the following information was used to calculate the mass of the pyrolysis gas used as fuel, to then obtain the emissions:

Transport information

Distances were obtained using Google maps to plot the over the road route from each point. When available, exact addresses were used, otherwise the waypoint was decided to be at the center of the location. Doing this could lead to imprecision on the final distance, but the difference is likely dismissible, given the relatively small impact transport has on the total environmental impacts in each category.

Transportation step	Route - Location to location	Distance in km
Stena to Ragn-Sells	Halmstad - Vänersborg	274
Ragn-Sells to Cementa	Vänerborg - Slite	487
Ragn-Sells to Enviro	Vänerborg - Lindholmen (gbg)	55
Ragn-Sells to SSAB	Vänerborg - Oxelösund	386

The mass-distance value for each route was calculated with the distribution of the ELT, resulting in the following values:

Route	Mass-distance in kg*km
Stena to Ragn-Sells	1918
Ragn-Sells to Cementa	1385.19
Ragn-Sells to Enviro	18.92
Ragn-Sells to SSAB	870.95
Total	4193.07

ecoinvent 3.5 LCIA datasets used for the assessment

Flow	Dataset Used
Transport	Market for transport, freight, lorry 16-32 metric ton, EURO5, RER
Energy	market for electricity, medium voltage, SE
Water	market for tap water, Europe without Switzerland
Steel	market for steel, low-alloyed, hot rolled, GLO
Lubricant Oil	market for lubricating oil, RER
Textile Incineration	market for waste textile, soiled, CH
Carbon Black	market for carbon black, GLO
Petroleum Coke	market for petroleum coke, GLO
Coal	market for hard coal, Europe, without Russia and Turkey
Scrap Steel	steel production, electric, low-alloyed, RER

Methods used for calculation of the mid-point indicators in the Environmental Footprint 3.0 methodology:

Mid-point impact category	Mid-point indicator
Acidification	Accumulated Exceedance (AE)
Climate change	Radiative forcing as Global Warming Potential (GWP100)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)
EF-particulate Matter	Impact on human health
Eutrophication marine	Fraction of nutrients reaching marine end compartment (N)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)
Eutrophication, terrestrial	Accumulated Exceedance (AE)
Human toxicity, cancer	Comparative Toxic Unit for human (CTUh)
Human toxicity, non-cancer	Comparative Toxic Unit for human (CTUh)
Ionising radiation, human health	Human exposure efficiency relative to U235
Land use	Soil quality index
Ozone depletion	Ozone Depletion Potential (ODP)

Photochemical ozone formation - human health	Tropospheric ozone concentration increase
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserve)
Water use	User deprivation potential (deprivation-weighted water consumption)

Impact Category	Transport (per ton*km)	Energy (per kWh)	Water (per 1 kg)	Steel (per 1 kg)	Units
CC Total	166.22E-03	0.045406	0.000359	1.9971	kg CO2-Eq
FreshWater & Terrestrial Acidification	680.49E-06	0.00023623	2.52E-06	0.010648	mol H+ -Eq
Freshwater Ecotoxicity	407.67E-03	0.03742	0.00053	7.3519	CTU
Freshwater Eutrophication	13.32E-06	2.13E-05	2.77E-07	0.001785	kg P-Eq
Marine Eutrophication	199.07E-06	6.06E-05	4.09E-07	0.002169	kg N-Eq
Terrestrial Eutrophication	2.19E-03	0.00075056	5.59E-06	0.023927	mol N-Eq
Carcinogenic Effects	1.23E-09	1.43E-09	3.86E-11	6.20E-07	CTUh
ionising radiation	12.31E-03	0.42408	1.28E-04	0.10849	kg U235-Eq
non-carcinogenic effects	24.55E-09	1.38E-08	1.64E-10	1.36E-06	CTUh
ozone depletion	38.14E-09	2.44E-08	3.07E-11	1.22E-07	kg CFC-11-Eq
POCP	665.28E-06	1.20E-04	1.22E-06	9.44E-03	kg NMVOC-Eq
respiratory effects inorganics	11.64E-09	2.78E-09	2.01E-11	1.76E-07	decease incidence
Dissipated Water	9.26E-03	2.43E-01	2.58E-04	8.32E-01	m3 water-Eq
Fossils	2.55E+00	6.01E+00	7.13E-03	2,.76E+01	MJ
Land use	2.49E+00	4.83E+00	3.05E-03	1.05E+01	Points
minerals and metals	493.42E-09	0.045406	1.04E-09	2.22E-05	kg Sb-Eq

Impact Category	Lubricant Oil (per 1 kg)	Textile Incineration (per 1 kg)	Carbon Black (per 1 kg)	Petroleum Coke	Units
CC Total	1.3029	0.75089	1,8816	1,0682	kg CO2-Eq
FreshWater & Terrestrial Acidification	0.009956	2.74E-03	0,012173	0,001143	mol H+ -Eq
Freshwater Ecotoxicity	0.84599	0.073272	0,68138	0,12619	CTU
Freshwater Eutrophication	4.78E-04	1.18E-05	0,000166	1,21E-05	kg P-Eq
Marine Eutrophication	1.33E-03	2.01E-03	0,001367	0,000178	kg N-Eq
Terrestrial Eutrophication	0.015883	1.36E-02	0,015023	0,001949	mol N-Eq
Carcinogenic Effects	1.59E-08	2.25E-09	1,07E-08	9,45E-10	CTUh
ionising radiation	3.63E-02	3.42E-03	0,34423	0,036769	kg U235-Eq
non-carcinogenic effects	1.57E-07	7.93E-09	8,53E-08	1,02E-08	CTUh
ozone depletion	8.11E-07	1.64E-08	1,22E-06	1,28E-07	kg CFC-11-Eq
POCP	2.65E-02	3.23E-03	5,48E-03	6,95E-04	kg NMVOC-Eq
respiratory effects inorganics	6.35E-08	9.73E-09	2,87E-07	7,14E-09	decease incidence
Dissipated Water	4.11E-01	9.08E-02	1,49E-01	1,02E-02	m3 water-Eq
Fossils	6.56E+01	1.27E+00	7,54E+01	7,93E+00	MJ
Land use	8.61E+00	2.78E-01	4,45E+00	8,01E-01	Points
minerals and metals	1.12E-05	1.22E-07	4,77E-06	1,09E-07	kg Sb-Eq

Impact Category	Coal (per 1 kg)	Scrap Steel (per 1 kg)	Units
CC Total	0,42866	0,40282	kg CO2-Eq
FreshWater & Terrestrial Acidification	0,003672	0,002793	mol H+ -Eq
Freshwater Ecotoxicity	0,34462	7,5463	CTU
Freshwater Eutrophication	0,001322	0,000311	kg P-Eq
Marine Eutrophication	0,001194	0,00054	kg N-Eq
Terrestrial Eutrophication	0,011452	0,007193	mol N-Eq
Carcinogenic Effects	5,49E-09	6,73E-07	CTUh
ionising radiation	0,027784	0,13205	kg U235-Eq
non-carcinogenic effects	1,77E-07	2,41E-06	CTUh
ozone depletion	3,22E-08	4,55E-08	kg CFC-11-Eq
POCP	2,79E-03	1,56E-03	kg NMVOC-Eq
respiratory effects inorganics	1,56E-08	5,74E-08	decease incidence
Dissipated Water	4,53E-02	2,93E-01	m3 water-Eq
Fossils	38,946	8,35E+00	MJ
Land use	5,90E+00	4,51E+00	Points
minerals and metals	1,90E-07	1,24E-06	kg Sb-Eq

Annex 3: Calculations for HCl allocation in clinker production

In [49], the distinction between primary and secondary fuel is made. The amount of primary fuel used, with the exception of natural gas, was given in kilograms of fuel per kilogram of clinker produced. The rest of the fuels were given in megajoules (MJ). The list as found on the report is found in Table 7

Table 7: Share of fuels utilized in clinker production [49]

Fuel	Amount	Unit	Fuel	Amount	Unit
Natural gas	$6.81X10^{-3}$	MJ	TDF	$1.36x10^{-1}$	MJ
Light fuel oil	$3.74X10^{-4}$	kg	Distillation residue	$2.25X10^{-2}$	MJ
Heavy fuel oil	$2.55X10^{-2}$	kg	Plastics	$9.92X10^{-2}$	MJ
Hard coal	$3.54X10^{-2}$	kg	Rubber meal	$2.55X10^{-3}$	MJ
Petroleum coke	$3.91X10^{-3}$	kg	Crap coke	$8.32X10^{-3}$	MJ
Dried sludge	$7.51X10^{-2}$	MJ	Meat and bone meal	$4.66X10^{-2}$	MJ
Used oil	$5.84X10^{-1}$	MJ	Animal fat	$3.42X10^{-2}$	MJ
Solvents	$1.64X10^{-1}$	MJ	Substitute solid combustibles	$5.04X10^{-2}$	MJ

To obtain the total energy needed for one kg of clinker, the energy provided by the primary fuels had to be calculated. The low heating values used for this calculation can be seen in Table 8

Table 8: Low heating value (LHV) of primary fuels used in clinker production

Low heating value (MJ/kg)			
Fuel	Value	Fuel	Value
Light fuel oil [50]	40.6	Coal [20]	29
Heavy fuel oil [50]	39	Petroleum coke [20]	33

The equation for the calculation of the energy supplied by a fuel is shown as Equation 1. After all energy values were in MJ, the total energy was calculated according to Equation 2 and resulted in 3.43 MJ per kg of clinker.

$$Mass_{fuel} * LHV_{mass} = Energy_{fuel} \quad (1)$$

$$\sum Energy = Energy_{fuel1} + Energy_{fuel2} + \cdots \quad (2)$$

The share of the energy coming from TDF is, according to the calculation in Equation 3, 3.96%. The total HCl emissions to air for 1 kg of clinker is 6.31x10-6 kg, of which 2.5x10-7 kg come from TDF.

$$HCl_{TDF_{cement}} = HCL_{clinker} * Share_{TDF} = 6.31x10^{-6} \frac{kg_{HCl}}{kg\ clinker} * 3.96\% = 2.5x10^{-7} \frac{kg_{HCl}}{1\ kg_{clinker}} \quad (3)$$

This number is, however, the amount of HCl emitted that is allocated to TDF when producing 1 kg of clinker. To obtain the amount of HCl that is emitted by 1 kg of TDF, the amount of clinker that must be produced to consume 1 kg of TDF is first calculated. Equation 4 (derived from Equation 1) shows the calculation of how much TDF, in kg, is used when producing 1 kg of clinker (the LHV of TDF is 32 MJ per kilogram of TDF [20]), and Equation 5 shows how the total amount of clinker produced when 1 kg of TDF is used.

$$Mass_{TDF} = \frac{Energy_{TDF}}{LHV_{TDF}} = \frac{0.136\frac{MJ}{kg_{clinker}}}{33\frac{MJ}{kg_{TDF}}} = 4.25x10^{-3}\ \frac{kg_{TDF}}{kg_{clinker}} \quad (4)$$

$$\frac{kg_{clinker}}{kg_{TDF}} = \frac{1}{\frac{kg_{TDF}}{kg_{clinker}}} = \frac{1}{4.25x10^{-3}} = 235.29\frac{kg_{clinker}}{kg_{TDF}} \quad (5)$$

With the results from Equations 3 and 5, Equation 6 results in the total emissions to air of HCl due to the use of 1 kg of TDF in the clinker production.

$$HCL_{1kg_{TDF}} = HCL_{TDF_{cement}} * \frac{kg_{clinker}}{kg_{TDF}} = 2{,}5x10^{-7} * 235.29 = 5.89x10^{-5}\ \frac{kg_{HCl}}{kg_{TDF_{cement}}} \quad (6)$$

Equation 7 shows the calculation of the emissions coming from the incineration of 0.42 kg of TDF in cement (as seen in Table 3).

$$HCL_{ELT_{cement}} = HCL_{kg_{TDF}} * Mass_{ELT_{cement}} = 5.89x10^{-5}\ \frac{kg_{HCL}}{kg_{TDF_{cement}}} * 0.42\frac{kg_{TDF_{cement}}}{kg_{ELT}} = 2.47x10^{-5}\ \frac{kg_{HCl}}{kg_{ELT}} \quad (7)$$

Using the characterization factor used in the beginning of the section Equation 8 shows the calculation of freshwater ecotoxicity impact with the result of the allocation done for the HCl.

$$Freshwater\ Ecotoxicity_{HCl_{TDF}} = HCL_{ELT_{Cement}} * CF_{HCl_{Freshwater\ Ecotox}} = 2.47x10^{-5}\frac{kg_{HCl}}{kg_{ELT}} * 1153.5\frac{CTU}{kg_{HCl}} = 2.85x10^{-2}\frac{CTU}{kg_{ELT}} \quad (8)$$