Life cycle assessment of waste tyre treatments: Material recycling vs. co-incineration in cement kilns

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1. Executive summary

This life cycle assessment study investigates two European end-of-life treatment options for used tyres including processing of tyres for material recycling (main scenarios use rubber as infill material in third-generation artificial turf) and co-incineration of tyres in cement kilns. Thus, the study intends to estimate the environmental impacts of processing tyres for material recycling in comparison with incineration of tyres. The main focus in terms of material recycling is on the use of waste tyres as infill in modern artificial-turf football pitches but applications of cryogenic powder rubber are also considered.

The study was commissioned by Genan (tyre recycler), and carried out by FORCE Technology. It has been reviewed by a critical-review panel. The composition of the panel and the critical review statement can be found in Appendix 5.

This is a comparative LCA intended for public disclosure and the LCA is expected to be used as a decision-support tool. It contains all elements described as compulsory in the ISO standards for life cycle assessment (ISO 14040:2006 and ISO 14044:2006).

The overall scope of the LCA study is the comparison of the potential environmental impacts of the following two end-of-life treatment scenarios for whole tyres:

1) Processing of tyres for material recycling at Genan's recycling facilities. This option implies the following applications for the main recycled tyre components:

a. The recycled rubber is used in applications, where it replaces different materials, which would otherwise be used for the given applications. To represent this, the major use as an infill material in modern, third-generation artificial turf fields is modelled. The results of the main recycling scenarios in this report are therefore applicable for that use only. However, the report includes a discussion about the comparability with other rubber applications;

b. Steel is separated as a steel scrap fraction, which is re-melted for production of new steel;

c. A residual fraction, mainly consisting of synthetic fibers and rubber, is separated and used as secondary fuel in cement kilns.

2) Use of tyres as secondary fuel (co-incineration) in cement production. This process involves:

a. Energy recovery of the combustible component of tyres (rubber, fibers);
b. Utilization of the tyres steel component as a source of iron, substituting other sources of iron in the cement process.

Additional scenarios for cryogenic powder rubber

An additional two secondary scenarios are included for the application of tyre-derived rubber. These two scenarios are applicable for the fine rubber granulate powder from a cryogenic production line, where the rubber granulate is further processed in a cryogenic process. The produced rubber powder is very fine and relatively uniform. It is of a particularly high quality and therefore has more high value applications in comparison with the ambient rubber granulate, which is not further processed. Examples of common applications include the use in new tyres and other industrial products [Genan, 2019]. Little documented information is available about the use of the rubber material in these applications due to producer confidentiality concerns. Therefore, the two cryogenic rubber scenarios rely on the prerequisites described in the following:

1. The cryogenic rubber is used in applications where it replaces carbon black in a ratio of 1:1 by weight. It is assumed that there are no impacts related to the use stage and that final disposal is by incineration.
2. The cryogenic rubber is used in applications where it replaces synthetic rubber in a ratio of 1:1 by weight. It is assumed that there are no impacts related to the use stage and that final disposal is by incineration.

These two scenarios differ from the main material recycling scenario in two ways. First, the production includes an extra processing step (the cryogenic process) and secondly they differ w.r.t the rubber applications, which are as described above.

Functional unit and system boundary overview

The functional unit is defined as **the treatment of one tonne of tyres** in Europe. The overall system boundaries are shown separately for the material recycling and the co-incineration methods in Figures 1.a and 1.b below.

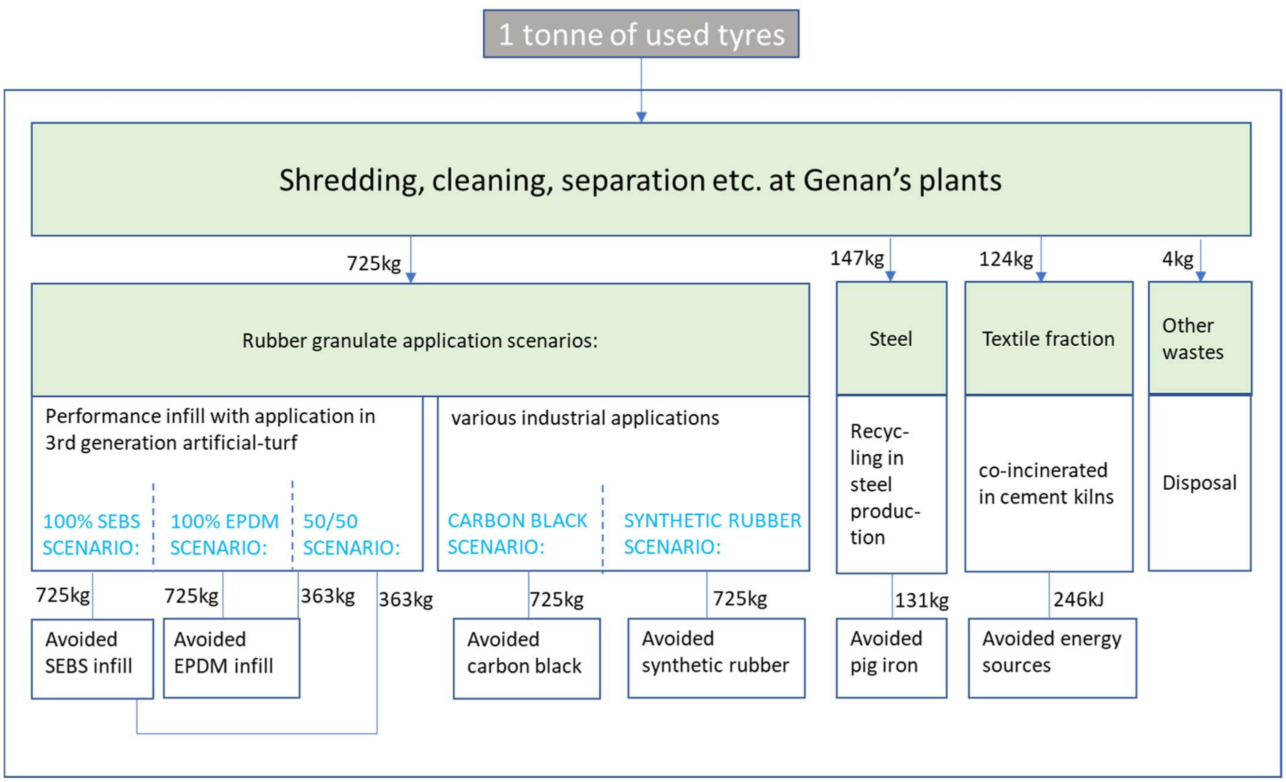

Figure 1.a System boundaries for material recycling methods. All infills are incinerated after dismantling of artificial turfs. (SEBS is styrene ethene butene styrene copolymer, EPDM is ethylene propylene diene monomer)

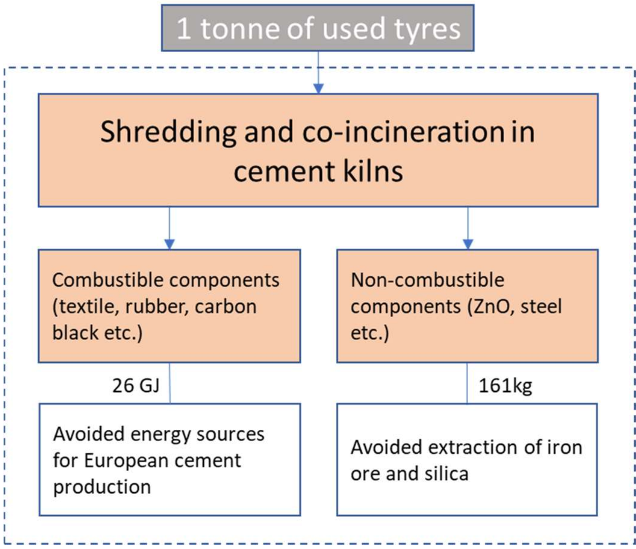

Figure 1.b System boundaries for co-incineration method

Main results – material recycling for infill vs. co-incineration

The potential environmental impacts identified in an LCA are assessed by calculating the results for a broad range of impact categories. The impact categories investigated in the project are those included in the results in table 1 below. The corresponding characterization and normalization factors applied are EF 2.0.

The total results for each of the modelled scenarios are represented in Table 1 below. Numbers in green indicate that the value is lower than the corresponding value for the co-incineration scenario.

Table 1. Total life cycle results of material recycling (rubber used for infill) vs. co-incineration (green figures in the material recycling scenario indicate that the impacts are lower than the corresponding impact category in the co-incineration scenario).

IMPACT CATEGORY	Co-incineration	Material recycling (SEBS infill)	Material recycling (EPDM infill)	Material recycling (50/50 infill)
Climate change fossil (kg CO2-eq.)	-197	**-838**	**-972**	**-905**
Acidification terrestrial and freshwater (Mole of H+ eq.)	-0.801	**-2.61**	**-3.08**	**-2.84**
Eutrophication freshwater (kg P eq.)	-0.0039	0.000867	**-0.0136**	**-0.00635**
Eutrophication marine (kg N eq.)	-0.237	**-0.552**	**-0.648**	**-0.6**
Eutrophication terrestrial (Mole of N eq.)	-2.69	**-6.08**	**-9.48**	**-7.78**
Ozone depletion [kg CFC-11 eq.]	-3.37E-06	2.84E-06	-2.07E-6	3.83E-07
Photochemical ozone formation (kg NMVOC eq.)	-0.656	**-1.79**	**-2.12**	**-1.95**
Ionising radiation (kBq U235 eq.)	-3.15	**-204**	**-228**	**-216**
Respiratory inorganics (Disease incidences)	-4.38E-06	**-2.18E-05**	**-2.60E-05**	**-2.39E-05**
Ecotoxicity freshwater (CTUe)	26.6	**-8.59E+01**	**-1.35E+02**	**-110**
Cancer - human health (CTUh)	-1.46E-06	**-5.74E-06**	**-6.04E-06**	**-5.89E-06**
Non-cancer human health effects (CTUh)	4.99E-05	0.000103	9.10E-05	9.70E-05
Land Use (Pt)	-5.90E+02	**-4.18E+03**	**-5.18E+03**	**-4.68E+03**
Ressource use, energy carriers (MJ)	-1.02E+04	**-3.12E+04**	**-3.39E+04**	**-3.25E+04**
Ressource use, mineral and metals (kg Sb eq.)	-0.0000299	**-1.45E-04**	**-0.0501**	**-0.0251**
Water scarcity (m^3 world equiv.)	-12.6	**-8.18E+01**	**-8.62E+01**	**-84**

When comparing the material recycling scenarios (rubber used as performance infill) with each other, then the table above shows that all environmental impact categories are better when 100% EPDM[1] performance infill is replaced in comparison with the scenario where 100% SEBS[2] performance infill is replaced. However, for most of the impact categories the results are in the same order of magnitude. The 50/50% SEBS/EPDM infill scenario is, naturally, an average of the two other scenarios.

[1] Ethylene propylene diene monomer
[2] Styrene ethene butene styrene copolymer

The table also shows that material recycling has a lower impact in 14 out of 16 impact categories compared with co-incineration when the replacement infill scenarios are 100% EPDM or 50/50 SEBS/EPDM. The two exceptions are ozone depletion and non-cancer human health effects. The impact category for non-cancer human health effect is associated with a large degree of uncertainty in the underlying LCA method as is also the case for all the human and ecotoxicity impact categories. The results are similar when the replacement infill scenario is 100% SEBS except for the impact category eutrophication, which in this case is lower when the tyre treatment route is co-incineration. That means, that when the scenario is 100% SEBS, then only 13 out of 16 impact categories are lower for material recycling in comparison with co-incineration.

The potential climate change impact category is 76-80% lower in the material recycling system compared with the co-incineration system. Expressed in another way, the potential climate change benefit from the material recycling (infill) is 4.3 - 4.9 times greater in comparison with the potential benefit from the co-incineration of used tyres. The most favorable climate change results are obtained in the 100% EPDM scenario and the 50/50% EPDM/SEBS scenario is again in the middle of the two other infill scenarios.

While the material infill recycling treatment is better than co-incineration for most impacts, the co-incineration system also has net-negative values in most categories, which means that both treatment systems lead to significant savings in potential environmental impacts.

Normalization of main results – material recycling for infill vs. co-incineration

With the aim to further scrutinize and discuss the magnitude of the overall findings the results are normalized. It is noted, however, that normalization is not an integral part of the results and is according to ISO 14040 only an additional optional value judgement based on the LCA results. One of the reasons for this is that normalization factors are relatively uncertain.

Figure 2 below shows the normalized impacts for the material recycling method using rubber as infill (100% infill scenarios) in comparison with the co-incineration treatment method for used tyres. Here it is noted, that the least robust environmental impact categories are left out with the aim that the interpretation focuses on those impacts, which can be assessed with a higher degree of certainty.

For most impact categories the normalized impacts for the co-incineration system are higher than the normalized impacts for the material recycling system (infill) and for most impact categories it is a notable difference. One exception is ozone depletion, where the impacts are so small that they do not show in the graph. For the 100% SEBS infill scenario another exception applies for eutrophication freshwater, where the contribution to this impact is so small that it does not show in the graph.

The normalized values for climate change are the largest (most negative) and the savings on climate change in the material recycling system corresponds to more than 0.1 global persons contribution to climate change during one year for all material recycling performance infill scenarios. In comparison the co-incineration system saves less than 0.03 person equivalents in the climate change category.

It should be noted that the scale in Figure 2 below shows net-negative values !

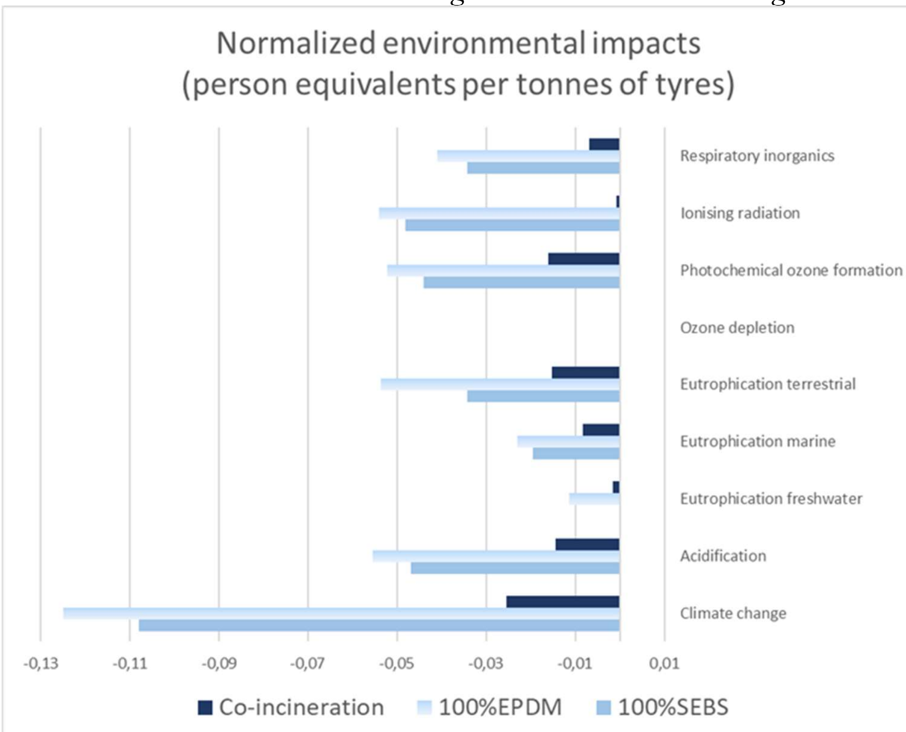

Figure 2. Normalized potential environmental impacts from different treatment options of one tonne of tyres – application of recycled rubber as infill

Results of cryogenic rubber scenarios:

For the tyre material recycling, where the recycled rubber in the form of cryogenic powder rubber replaces either carbon black or synthetic rubber, the results shows that material recycling has the lowest impact in 7-10 out of 16 impact categories in comparison with the co-incineration tyre treatment method. The potential climate change impact from the cryogenic scenarios is 7-10 times lower than when the tyres are treated with the co-incineration method.

Normalization of the results of the cryogenic rubber scenarios:

With the aim to further scrutinize and discuss the magnitude of the overall findings the results are normalized. It is noted, however, that normalization is not an integral part of the results and is according to ISO 14040 only an LCA step. One of the reasons for this is that normalization factors are relatively uncertain.

The normalized results of the cryogenic scenarios are shown in Figure 3 below. The impact category, which shows the greatest (net-negative) contribution to the person equivalents is climate change and, for the scenario where carbon black is replaced, also respiratory inorganics. For both cryogenic scenarios, the contribution to climate changes is 7-10 times lower in comparison with the co-incineration treatment method.

It should be noted that the scale in Figure 3 *below shows net-negative values !*

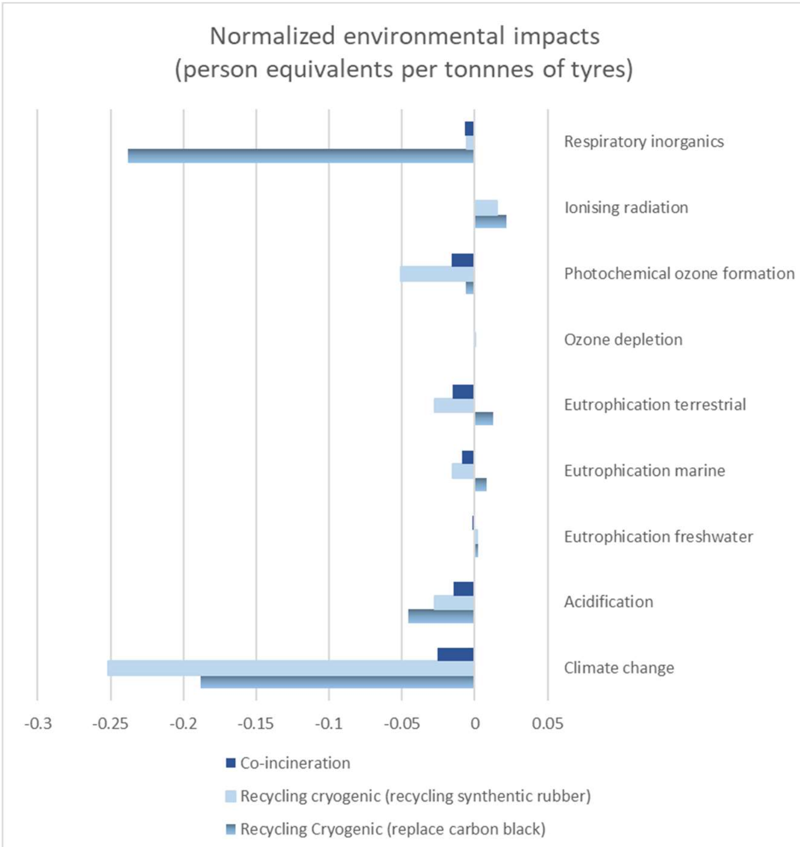

Figure 3. Normalized potential environmental impacts from different treatment options of one tonne of tyres – applications of recycled cryogenic rubber

Main assumptions

As in any LCA, the quantification of environmental impacts relies on a number of qualified assumptions, which must be transparently communicated in the LCA report. This is an inherent part of an LCA, and it is common that conclusions are highly dependent on some of those assumptions. In order to check the robustness of the conclusions, the most important assumptions are tested in a sensitivity analysis. In this LCA several assumptions were made in the favor of the co-incineration treatment method for used tyres. The reason for this is to ensure that material recycling is not unduly favored over co-incineration as the study commissioner Genan material-recycle tyres. These assumptions can thus be considered to be conservative. The main conservative assumptions made in this LCA (in favor of co-incineration) are:

- The assumption that recycled tyre rubber from Genan replaces virgin infills in a ratio of 1:1 on a weight basis: This assumption is considered to be conservative mainly because of the following aspects:
    - The refill quantity required for maintenance of the fields during the life time of the fields is in reality expected to be greater for virgin infills due to the higher content of rubber in End of Life Tyres (ELT) rubber infill
    - The life time of the fields may in reality be longer for ELT rubber in comparison with virgin infill, due to quality characteristics

- No recycling is assumed for any of the infill materials at the end-of-life of the artificial sports turfs. Based on the information gathered in this study, the authors consider it more likely that ELT infill will be recycled into valuable applications in comparison with virgin infills. This is particularly relevant when considering the environmental implications in the longer run as recycling may be expected to become more widespread.

- The share of waste fuels used for co-incineration influences the assumed replacement of fuels in the co-incineration treatment method. The replacement of waste fuels is a key assumption, which in this study is based on a European average. For this reason, a sensitivity assessment was carried out. This showed, that if the share of waste fuels were higher, then the potential environmental impacts from the co-incineration treatment method would generally also be higher. This is the case in Germany, where they have a large cement production sector. In this context it is highlighted, however, that some European countries also have a lower share of waste fuel inputs in comparison with the European average. For details about which fuels were assumed to be replaced see Table 14 the second column.

The sensitivity assessment includes calculations for a scenario, where landfilling of infill materials are assumed at the end-of-life. The ratio of primary iron sources for steel production and for co-incineration was also tested in the sensitivity analysis.

None of the sensitivity assessments carried out changes the overall conclusions in the LCA study and thus the sensitivity assessment demonstrates that the influence of the assumptions on the results is not decisive. The majority of the results are consistently in favor of the material recycling method, where the rubber is used as performance infill for artificial-turf football pitches, when compared with co-incineration of the used tyres. Two exceptions are ozone depletion and non-cancer human health effects which are lower for co-incineration. In the SEBS infill scenario the eutrophication freshwater is also lower for co-incineration.

2. Introduction

This report presents the results of a Life Cycle Assessment (LCA), which quantitatively compares the potential environmental impacts resulting from the two most commonly practiced end-of-life alternatives for the treatment of tyres in Europe [ETRMA, 2015]:

1) processing of tyres for recycling

2) co-incineration of tyres in cement kilns

The study is a comparative LCA and contains all elements described as compulsory in the ISO standards for life cycle assessment (ISO 14040:2006 and ISO 14044:2006). This report includes detailed explanations of all assumptions made as well as a thorough analysis of related uncertainties. The results and conclusions are focused on comparing the two end-of-life alternatives for tyres.

This study was commissioned by Genan, a large company that recycles used tyres. Similar studies were published in 2007 [Villanueva et al., 2008] and in 2009 [Schmidt et al, 2009], with the 2009 study being carried out in a collaboration between FORCE Technology, ifeu and Copenhagen Resource Institute. The results of both studies showed unequivocally that recycling is a better option than co-incineration from an environmental point of view, and the study is widely used in Genan's communication with different stakeholders on environmental aspects related to waste tyres.

Genan is continuously working on improving their environmental performance, which has resulted in a relatively lower energy consumption and higher material utilization ratios since the original studies. Also the prevailing applications of the granulated rubber have changed. This is reflected in the current study, which is mainly based on using the recycled rubber as infill material in artificial-turf football pitches.

This study was primarily carried out by FORCE Technology, although with a significant contribution from ifeu to the analysis of the co-incineration treatment method. To some extent the study draws on findings and information gathered in the original studies from 2007 and 2009. However, observed market and technology changes in end-of-life treatment alternatives in the last decade have been updated. Also, the current study takes into account developments within best practices for LCA methodology including the work done within the International Reference Life Cycle Data System (ILCD) and in the European Union.

3. Glossary

ECHA:	European Chemicals Agency
ELT:	End of Life Tyres
EOL:	End-of-life
EPDM:	Ethylene propylene diene monomer
ILCD:	International Life Cycle reference Data
LCA:	Life cycle assessment
OTR:	Over The Road
PAH:	Polycyclic aromatic hydrocarbons
PEF:	Product Environmental Footprint

PEFCR: Product Environmental Category Rules

SEBS: Styrene ethene butene styrene copolymer

SBR: Styrene butadiene rubber

TPE: Thermoplastic elastomer

VOC: Volatile Organic Compounds

4. Goal and scope definition

Every year, large amounts of waste tyres are generated and introduced to the waste management systems all over the world. In Europe this accounts for tyres in excess of 2.88[3] million tonnes of tyres per year and the two predominant end-of-life treatment options in Europe are co-incineration in cement kilns accounting for an estimated 45% and recycling, which accounts for an estimated 46% [ETRMA, 2015]. In co-incineration, the inherent energy is utilized replacing different types of fuels and material recycling takes place to some extent, while in recycling the materials contained in the tyres replace virgin materials in different applications. Given the large volume of tyres, it is important to identify which treatment option is the most favorable from an environmental point of view.

4.1. Goal

The goal of the study is to estimate the environmental impacts of processing tyres for material recycling in comparison with incineration of tyres. The primary scenarios look at applying the recycled rubber as infill material in artificial-turf football pitches, where it is assumed to replace the most common alternative infills used in artificial turf today. The additional scenarios also consider application of cryogenic fine-powder rubber as a substitute for synthetic rubber or carbon black.

4.1.1. Decision-making context

The results of this LCA study can be used as an input to the ongoing debate on waste policy in the EU. With the EU circular economy action plan from December 2015, material recycling and an optimal use of resources is high on the agenda in Europe. The action plan lays out a number of initiatives to support the transition to a more circular economy as for example the development of standards for secondary raw materials. Also at a regional level recent initiatives are relevant for and impact the tyre treatment industries. For example the Danish authorities introduced a requirement for the recycling percentage of tyre recyclers, which shall be fulfilled for tyre collectors to be eligible for receiving financial subsidies.

The Waste Framework Directive[4] states in Article 4 the waste hierarchy, which is a five-step prioritization of waste treatment options. The hierarchy has waste prevention as a first priority, followed by preparing for re-use, recycling, other recovery operations and finally disposal. Considering that this is a general prioritization hierarchy there will be examples of products and materials for which incineration with energy recovery could

[3] This number is based on 2013 statistics and the report [ETRMA, 2015] states that the number has since gone up.

[4] Council Directive 2008/98/EC of 19 November 2008 on waste

be a better solution than material recycling with regards to the environment. The EU recommends life cycle thinking as a basic approach to adhere to or deviate from the hierarchy.

4.1.2. Target groups

This LCA is intended for public disclosure, with the following primary stakeholders:

- Genan Holding A/S internally for awareness, product development and communication/marketing purposes.
- Policy makers involved in the formulation of waste and resource related policies at EU, national or regional levels in Europe.
- Tyre experts (tyre manufacturers as well as waste tyre management and recycling companies) and cement co-incineration experts.

Other stakeholders include experts and others working with recycling and circular economy infrastructure in general.

The report has a rather technical character, documenting the results and methodology. It is therefore primarily aimed at LCA experts. Communication of the LCA results to the other audiences should follow in a different and more digested form, which is suitable for non LCA experts. However, it should be noted that only this report has been critically reviewed and any further communication beyond this report is not covered by the critical review.

4.2. Scope

The overall scope of the LCA study is the comparison of the potential environmental impacts of the following two end-of-life treatment scenarios for whole tyres at a European scale:

1) Processing of tyres for material recycling at Genan's recycling facilities. This option implies the following applications for the main recycled tyre components:

a. The recycled rubber is used in applications, where it replaces different materials, which would otherwise be used for the given applications. To represent this, the major use as an infill material in modern, third-generation artificial turf fields is modelled in three scenarios. Two additional scenarios are also modelled, where the rubber is used in applications, where it replaces carbon black or synthetic rubber. The results in this report are therefore applicable for these uses only. However, the report includes a discussion about the comparability with other rubber applications and the choice regarding rubber application is further justified in chapter 4.2.4.;

b. Steel is separated as a steel scrap fraction, which is re-melted for production of new steel;

c. A residual fraction, mainly consisting of synthetic fibers and rubber, is separated and used as secondary fuel in cement kilns.

2) Use of tyres as secondary fuel (co-incineration) in cement production. This process involves:

c. Energy recovery of the combustible component of tyres (rubber, fibers);

d. Utilization of the tyres steel component as a source of iron, substituting other sources of iron in the cement process.

4.2.1. Temporal and geographical scope

The technologies and the life cycle assumptions are those which apply today, although some of the most important assumptions, which are expected to change in the coming years, will be further analyzed in the sensitivity analysis. This is done because the goal of this LCA is to trigger a political debate that may result in new legislation, which is not necessarily implemented in the next few years. Furthermore, the ELT granulate used as infill material in artificial turf today may have a useful life of up to ten years before the final waste handling of the material.

The overall geographic scope is tyre treatment in Europe.

4.2.2. Functional unit

The functional unit is defined as **the treatment of one tonne of tyres** in Europe.

4.2.3. System boundaries and the life cycle of a tyre

The life cycle of a tyre is illustrated in Figure 4. A tyre consists of several materials, mainly synthetic rubber, natural rubber, carbon black, fibers, and steel. A more detailed and elementary substance composition table for used tyres is provided in the inventory.

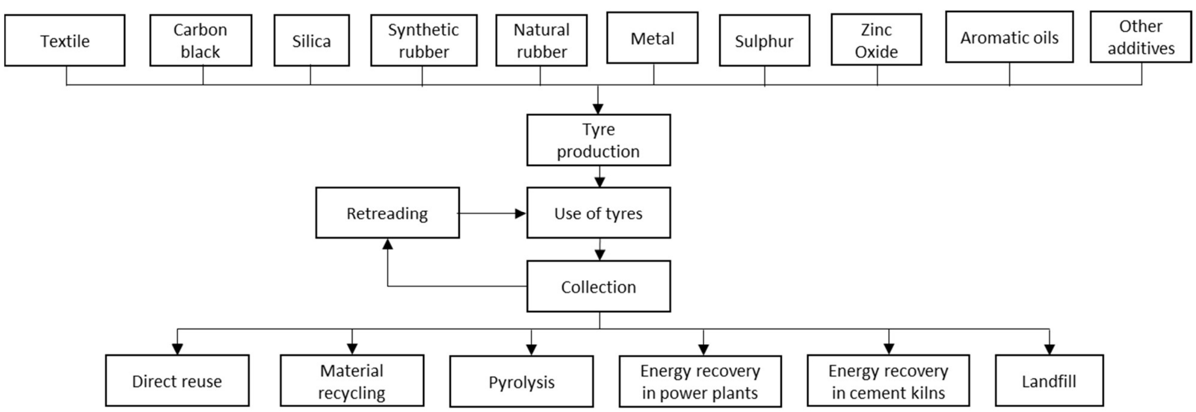

Figure 4. The life cycle of a tyre. Material recycling and energy recovery in cement kilns are the subject of this study.

Producing a tyre is a complex process, where several sub-processes of material assembly take place, followed by chemical binding through vulcanization. During use, the tyre has a significant potential environmental impact, since the fuel consumption of the vehicle is closely related to the rolling resistance of the tyres. Furthermore, the tyre is worn (losing 10-20% of its weight in its average lifetime) and as a result, tyre debris is emitted to the environment [BLIC, 2001].

After use, most tyres are collected and can be retreaded, re-used, recycled, incinerated with energy recovery, treated by pyrolysis or landfilled. In the EU, landfilling of tyres were banned in 2003 (whole tyres) and 2006 (shredded tyres) following the EU Landfill Directive. To some extent, illegal landfilling of used tyres is still likely to occur, but landfilling is not included in this life cycle assessment except in the sensitivity analysis.

The system boundaries in this LCA focuses on the end-of-life phase, as illustrated in Figure 5. For both included end-of-life options, the upstream processes of the life cycle are identical, and are therefore omitted from the system. The reason for comparing co-incineration with material recycling is that these are the two predominant treatment options in Europe [ETRMA, 2015].

When used tyres are material recycled the tyres are shredded, milled and the tyre materials are separated into fractions, that are as clean as possible, which subsequently can be used to replace other materials in new applications. The primary materials, which are avoided, are virgin infill materials and steel. For a detailed description of the material recycling processes at Genan, see the inventory.

When tyres are used as a fuel in a cement kiln, alternative fuels are substituted by the combustible components (rubber, carbon black and fibers). Used tyres can be shredded or fed directly into the rotary oven, without pre-treatment. The avoided processes depend on the mix of fuels used in the specific cement kiln analyzed.

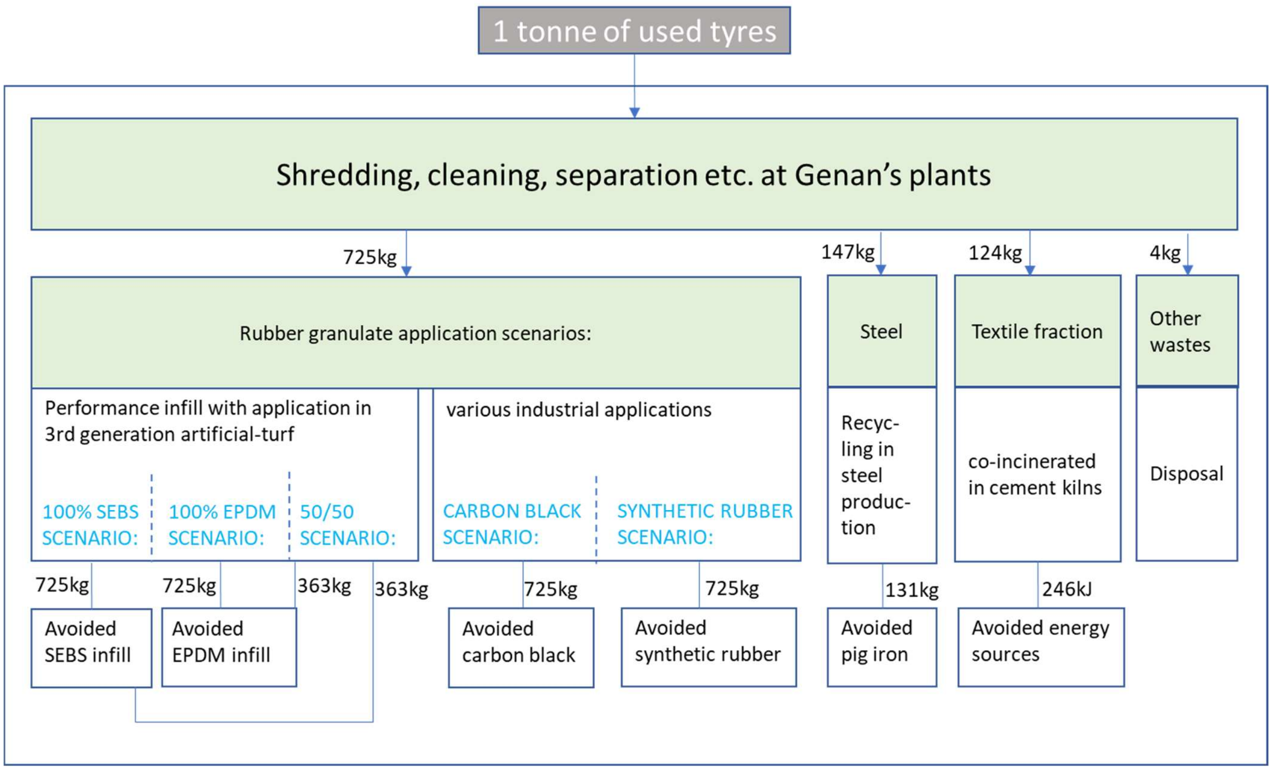

Figure 5.a System boundaries for the material recycling methods. All infills are incinerated after dismantling of artificial-turfs. (SEBS is styrene ethene butene styrene copolymer, EPDM is ethylene propylene diene monomer)

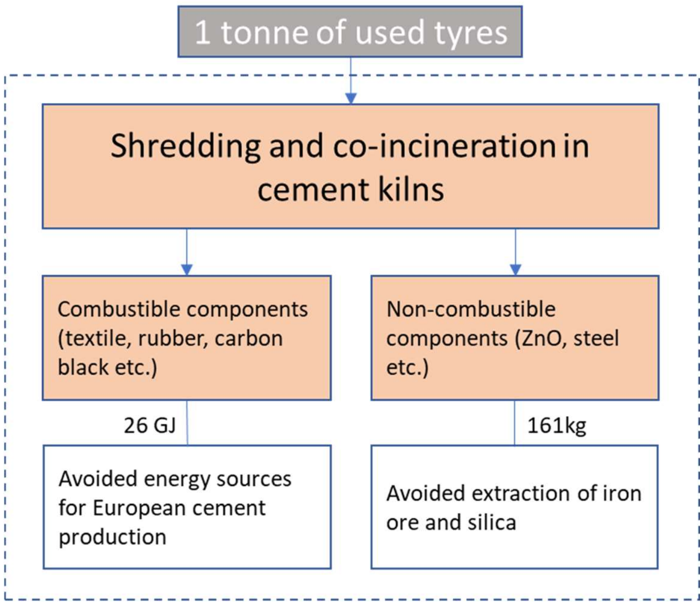

Figure 5.b System boundaries for the co-incineration treatment method

4.2.4. Applications of recycled rubber from tyres

Approximately 75% of the output from the recycling operation is rubber granulate and powder, which can be used for several purposes. According to Genan, a large amount of the rubber granulate in Europe is used in synthetic surfaces of sports grounds, such as synthetic turf in football fields. Examples of other applications are shown in Table 2 below.

Table 2. Examples of applications of tyre derived rubber (not including infill). The examples are not exhaustive.

Application area:	Product:	Examples of replaced materials:	Comments:
Sport and leisure	E-layer, which is the lower basis layer in the construction of artificial sports turfs and athletic running tracks	Polyethylene, polyurethane foam, synthetic rubber	The rubber granulate is mixed with a polyurethane binding agent (this also applies to e-layers made of virgin materials)
	Shock-absorbing rubber fall surfaces at playgrounds	Synthetic rubber (e.g. EPDM)	The layer is either molded in situ or it is build using pre-fabricated rubber mats.
Industrial production	Shoe soles	Waste rubber from shoe production, synthetic rubber	Cryogenic recycled tyre rubber
	Prefabricated mats for animal welfare and floors	Virgin elastomers	Molded rubber granule from ELT binded with polyurethane

	Solid wheels for e.g. waste bins and fitness equipment	Synthetic rubber (eg. EPDM/TPE)	Press molded rubber powder/granulate from ELT's
Asphalt and bitumen	Modification of bitumen before being added to asphalt	Virgin SBS	The ELT rubber is mixed with a 4,5% of a semi-crystalline polyoctenamer
Car industry	Tyres	Carbon black, Synthetic rubber	Cryogenic recycled tyre rubber

Sources: [Genan web, 2019] and [Genan, 2019]

The Genan rubber granulate comes in six different qualities based on the granule sizes. These are categorized as fine, fine/mix, medium, coarse, super coarse and ultra coarse. The most common qualities, which are used for infill, are fine, fine/mix and medium. Furthermore a fraction of ambient rubber powder from 0.2-0.8 mm is produced. The cryogenic rubber is a special very fine quality, which is in the form of a powder.

Research is being undertaken to develop new uses for recycled tyre materials as for example incorporating rubber in concrete to lighten the concrete and increase its performances (increased resistance to cracking and the capacity deformation of these materials) [ETRMA, 2015]. Such immature applications are, however, not considered in this study.

The main scenarios in this LCA study models the application of the rubber as infill in 3rd generation artificial turf. The reason for this is, that infill is currently one of the main applications [Genan, 2019]. In fact, it is the largest single application for recovered rubber from Genans tyre recycling facilities and Genan is the largest material recycling company for used tyres, [Genan, 2019]. The exact figures are confidential to Genan and are therefore not reported here, but FORCE Technology was allowed to see their sales and market research data.

According to Genan, the assumptions and details of the infill application is largely shared with a number of other applications, thereby expanding the applicability/relevance of the LCA results. The main assumptions in this regard are the quantity and quality of replaced virgin materials (EPDM, SEBS, fillers, additives) as well as the final disposal route of the materials. According to Genan, many other applications of the rubber granulate result in the same types of virgin materials being replaced in comparable amounts and where the material can eventually be expected to be incinerated with energy recovery as it is assumed in the infill scenario. Genan has explained that especially the industrial applications are expected to have comparable end of life routes, whereas the use in new tyres will go through the ELT cycle once more. These similarities were not investigated in any detail in this study, which only calculates LCA results for the specific recycling scenario where the recovered tyre derived rubber is used as a performance infill in FIFA certified football fields as well as the two additional cryogenic rubber applications, which are described at the end of this chapter. For this reason, the results cannot be directly applied to any other recycling scenarios where the rubber is used for other applications where the same assumptions do not apply.

The replacement of virgin infills with tyre derived ELT infill in artificial turf may, during the use stage, have a significance beyond the initial material replacement during establishment of the artificial turfs. For example, it can influence the need for replacement infill, the quality and lifetime of the artificial turf as well as the need for maintenance activities to uphold the quality of the artificial pitch. Details about the use stage assumptions are described in chapter 6.5.

When the artificial turf is at the end of its useful life and shall be disposed of, the treatment of ELT rubber granulate is included. The potential environmental impacts from the disposal of ELT rubber differ from the disposal of corresponding virgin infills. For this reason, the avoided end-of-life processes applicable for virgin infills are also included. The primary end-of-life scenario is based on incineration of both ELT and virgin infills. Assumptions and data for end-of-life are described in the inventory chapter.

An additional two secondary scenarios are included for the application of tyre derived rubber. These two scenarios are applicable for the **fine rubber granulate powder from a cryogenic production line**, where the rubber granulate is further processed in a cryogenic process. The produced rubber powder is very fine and relatively uniform. It is of a particularly high quality and therefore has more high value applications in comparison with the ambient rubber granulate, which is not further processed. The reason for including these two cryogenic scenarios is that Genan is interested in investigating these scenarios due to the extra production step and the added rubber value. Examples of common applications are shown in Table 2 and include the use in new tyres and other industrial products. Little documented information is available about the use of the rubber material in these applications due to producer confidentiality concerns. Therefore the two cryogenic rubber scenarios are based on assumptions, which may not accurately reflect specific uses. However, in applications where these assumptions do apply, the results will naturally also be valid. The two cryogenic scenarios are the following:

3. The cryogenic rubber is used in applications where it replaces carbon black in a ratio of 1:1 by weight. It is assumed that there are no impacts related to the use stage and that final disposal is by MSW incineration.
4. The cryogenic rubber is used in applications where it replaces synthetic rubber in a ratio of 1:1 by weight. It is assumed that there are no impacts related to the use stage and that final disposal is by MSW incineration.

5. Methodology

The study is of the cradle-to-grave type and is based on state-of-the-art LCA methods following the standards ISO 14040: "Environmental management - Life cycle assessment – Principles and framework" as well as ISO 14044: "Environmental management - Life cycle assessment - Requirements and guidelines".

An LCA study consists of four phases as presented in Figure 6. The main purposes of the goal and scope definition are to clarify the purpose of the study, what it can and cannot be used for, the product system studied and its boundaries. In the inventory analysis, data on the inputs and outputs of the processes included in the system are collected or calculated. On the basis of this inventory, the potential environmental impacts are assessed and finally the results are interpreted. Carrying out an LCA is by definition an iterative process as illustrated by the arrows in Figure 6.

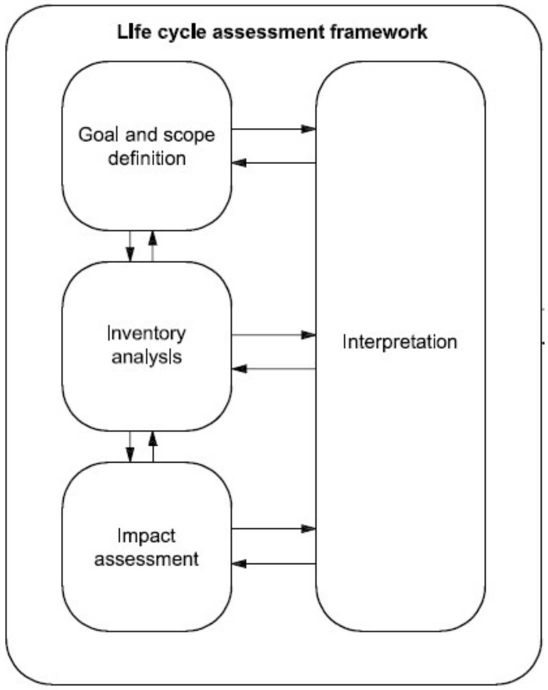

Figure 6. Phases of an LCA (ISO 14040, 2006)

Although the described international LCA standards did not change since 2006, the more detailed best practices for LCA methodology have developed significantly. In particular, an extensive work done within the European Union, where a number of guidance and methodological documents were published in recent years.

5.1.1. Methodological LCA work within the European Union (ILCD and PEF)

In the Communication on Integrated Product Policy[5], the European Commission committed to produce a handbook on best practice in Life Cycle Assessment (LCA). In 2010 this resulted in The International Reference Life Cycle Data System (ILCD) Handbook, which aimed at providing governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments.

Based on the work carried out within the ILCD program, the EU work on LCA has continued with the initiative named Product Environmental Footprint (PEF). The PEF project mainly focuses on product and organizational footprint studies with a micro-level decision support[6] aim and is thus not specifically focusing on the type of LCA studies, which aim to influence policy making. In PEF, more detailed guidance documents, the so-called Product Environmental Category Rules (PEFCR), have been developed for a number of product and organizational categories/business areas. In April 2018, the PEF project was launched at a large conference in Brussels. Since this conference, the PEF work is continuously under development and among other things more PEFCR's are being developed and work is ongoing to improve the applicable environmental impact categories.

[5] http://ec.europa.eu/environment/ipp/ippcommunication.htm

[6] Life cycle based decision support on micro-level, i.e. typically for questions related to specific products. "Micro-level decisions" are assumed to have limited and no structural consequences outside the decision-context.

Considering that no PEFCR exists for the treatment of used tyres, this LCA study cannot be completed as a PEF study. This LCA study does, however, take the methodological work carried out within the EU into consideration.

Furthermore, it is noted that the 2009 study [Schmidt et al., 2009] applied two overall methodological approaches in parallel. Namely, the attributional and the consequential approaches, whereas this study applies the ILCD guidance in this respect as described in this chapter.

In an attributional LCA, the current situation is the object of study, while the consequential approach assesses the consequences of a change. An attributional LCA would include average data on each unit process within the life cycle in order to identify the contribution of different elements in the results. For instance, in this study, tyres substitute the average mixture of fossil and waste fuels used in cement kilns. In principle, the model does not include unit processes other than those of the life cycle of the tyre.

The consequential LCA approach has a different perspective and focuses on examining all known consequences of a change, including unit processes that are significantly affected by the change, irrespective of whether they are within or outside the life cycle. Using the example above of fuels used in cement kilns, the consequential approach, instead of using the average fuel mixture, would investigate which is the exact fossil fuel or waste fraction that the cement kiln would burn if used tyres were no longer used as a fuel, because of new higher rubber recycling targets. In LCA terminology, this type of information is called marginal data, as opposed to the average data used in the attributional approach.

In this study any decisions fulfilling the criteria for consequential modeling in line with the prescriptions of the ILCD shall be modelled in accordance with the consequential LCA approach. The remaining LCA study will apply the attributional approach, also in line with the ILCD prescriptions. Given a situation where the criteria may be fulfilled, but it is not possible to document this, a consequential modeling may be included in the sensitivity analysis to establish the consequences of this choice for the conclusions. In particular, this may be applicable with regards to the fuels replacing used tyres for co-incineration in cement kilns.

For a more detailed description of the two overall LCA approaches, see chapter 2 in the LCA study [Schmidt et al, 2009].

Every year, large amounts of waste tyres are generated and introduced to the waste management systems globally. Shifting end-of-life treatment of used tyres in Europe from co-incineration in cement kilns to material recycling may have consequences for installed capacities in the background systems. An example of this could be if new facilities are needed to provide fuels for the production of cement, which would otherwise not be needed. Questions related to the economy of scale has significance for the modelling and will therefore be addressed in the LCA study.

The LCA modelling software is Gabi program version 8.7.0.18 and database version 8. 7.

5.1.2. Allocation

Allocation is the term used in LCA to distribute the environmental loads between different parts of a system. For example, when a cow produces both milk and meat the question is how to distribute net environmental impacts from the feed between these two valuable output products.

The ISO 14044 standard as well as the ILCD recommends using a method called system expansion to handle allocation questions. In comparative studies, system expansion means adding the processes, which one part of the system has and the other part does not have, thereby avoiding a distribution of the environmental loads. For example, in this study, the recycled rubber granulate for use in artificial turf is included in this system to avoid allocation of the energy consumption and emissions from the tyre recycling plant between the valuable outputs of the plant processes.

The two systems compared in this study represent one function (treatment of 1 tonne of waste tyres), but have several outputs, for instance the production of the mentioned rubber granulate or the energy produced in the cement kiln. In order to guarantee the equivalence of the routes, it is necessary to account for these outputs. We have expanded the system to include the avoided alternative production of these outputs. With respect to the infill for artificial turf, for example the production of synthetic rubber and thermoplastic elastomer is avoided, and the potential environmental impacts from these processes are subtracted. This is also the case for the fuels and iron sources used in cement kilns. These are the avoided processes presented in the bottom part of Figure 5.

6. Life cycle inventory analysis and description of main assumptions

6.1. Data collection and procedures for data treatment

Data collection is based on production statistics, supplier information, literature search, direct contact with experts, researchers and industry as well as on LCA databases.

6.1.1. Completeness and representativeness

Data used in this study are in overall terms considered complete (i.e. all relevant materials and activities are covered) and representative, relating to geographical, temporal and technological boundaries as outlined in the scope of the study. Basic data, in many cases directly from plant operators, have been found and used for all processes. In some cases, primary data were not available from the production sites, and we have used generic or average values instead. This is largely the case for virgin infill materials, where more or less rudimentary information can be found in the public domain, while precise information on composition and production processes is considered proprietary.

Whenever possible, average and generic values have been associated to ranges of variation, obtained through reference to different literature sources, or contact to experts in the specific processes. Extremes have been tested in the sensitivity analysis to validate the conclusions.

Detailed discussions on data quality and representativeness are included in the specific sub-sections of this inventory, and an overall data quality assessment is presented in chapter 7.

6.2. Secondary datasets applied

An overview of the main secondary datasets applied from the GaBi database in is shown in Table 3 below and the processes, which the datasets are used for are shown in the last column to the right. The data quality is discussed in chapter 7.

The majority of secondary datasets are from thinkstep although a few other sources are also used as can be seen in the Table.

Table 3. Overview of the main datasets.

DATASET:	DATA-BASE/ SOURCE:	GEOGRAP-HICAL REPRESENTATIVITY:	REFERENCE YEAR or VALID UNTIL YEAR:	GaBi QUALITY INDICATOR (where applicable)	USED FOR / COMMENT:
Electricity grid mix	TS	DE and DK	2016/2021	1.8	Electricity consumption at Genan
Electricity grid mix	TS	Europe	2016/2021	1.8	Multiple processes
Steel plate	Worldsteel	Europe	2014/2020	n/a	Steel for knives at Genan
market for iron ore, beneficiated, 65% Fe	ecoinvent	GLO	2018		Iron substituted by recycled steel
Inert matter (Unspecific construction waste) on landfill	TS		2018/2021	1.7	Genan sand and gravel waste
Styrene ethene butene styrene copolymer (SEBS, TPE-S)	TS	DE	2017/2020	1.7	SEBS infill
Limestone (CaCO3; washed)	TS	DE	2018/2021	1.8	Limestone in virgin infills
Styrene-butadiene rubber (S-SBR) mix	TS	DE	2018/2021	1.5	Synthetic rubber replaced by cryogenic powder / is among other things used for tyres according to dataset documentation
Plastic waste on landfill	TS	Europe	2018/2021	1.7	Disposal of rubber materials
Plastic packaging in municipal waste incineration plant	TS	Europe	2017/2020	1.8	SEBS incineration / CO_2 emission adjusted according to SEBS chemical formula and energy generation adjusted in

(modified by FT)					accordance with calorific value of SEBS.
Inert waste in waste incineration plant (modified by FT)	TS	Europe	2017/2020	n/a	Incineration of limestone in virgin infills / CO_2 emissions adjusted in acccordance with chemical formula.
Ethylene Propylene Diene Elastomer (EPDM)	TS	DE	2018/2021	1.7	EPDM virgin infill
EPDM seal in waste incineration plant	TS	Europe	2018/2021	1.7	Incineration of EPDM in virgin infill
Carbon black (furnace black; general purpose)	TS	DE	2018/2021	1.5	Carbon black replaced by cryogenic tyre derived rubber / this process is among other things used for tyres according to the dataset documentation
treatment of waste rubber, unspecified, municipal incineration	ecoinvent	Europe without Schwitzerland	2018	n/a	Incineration of rubber / for TDR the process was modified to the specific properties of the material
Nitrogen (liquid)	TS	DE	2018/2021	1.7	Cooling at cryogenic milling line / via cryogenic air separation
activated silica production	ecoinvent	Global	2018	n/a	Ultrasil usage at cryogenic milling line
Truck-trailer, Euro 4, 34 - 40t gross weight / 27t payload capacity	TS	Global	2018/2021	1.5	Multiple transportation processes
Diesel mix at refinery	TS	Europe	2016/2021	1.8	Multiple processes

Hard coal mix	TS	Europe	2016/2021	1.8	Hard coal replaced by tyres for co-incineration
Lignite mix	TS	Europe	2016/2021	1.8	Lignite replaced by tyres for co-incineration
Petroleum coke at refinery	TS	Europe	2016/2021	1.8	Pet coke replaced by tyres for co-incineration
Heavy fuel oil at refinery (1.0wt.% S)	TS	Europe	2016/2021	1.8	Heavy fuel oil replaced by tyres for co-incineration
Light fuel oil at refinery	TS	Europe	2016/2021	1.8	Light fuel oil replaced by tyres for co-incineration
Natural gas mix	TS	Europe	2016/2021	1.8	Natural gas replaced by tyres for co-incineration

6.3. Composition of used tyres

A tyre may contain more than one compound and more than one type of rubber. For example, on a car tyre there will be a sidewall rubber, a casing rubber and a top tread rubber, all adding different elements to the performance of the tyre. The detailed composition of a tyre is thus complex and rubber recovered from a tyre may contain an amalgam of different compounds, and yet this material presents homogeneous properties when adequately sampled [ETRMA, 2015].

Most of the available data on the composition of tyres refer to new tyres. During the use of tyres, the tread rubber is worn, on average 10-20% by weight during the lifetime of a tyre [BLIC, 2001]. Since the tread rubber makes up about 33% of the rubber weight in a new radial passenger car tyre, the composition data of new tyres are slightly different from those of used tyres [WRAP, 2006]. Table 4 and Table 5 show the composition data for mixed used tyres used in the LCA. The primary source of data is [Schmidt et al., 2009]. It is acknowledged that this is a relatively old reference, but it was not possible to find more recent information and in the time scope selected for this study, no significant changes in the composition of tyres are expected, just as no evidence was found to support a significant change since 2009. Other, more recent reports about ELT also use old references to describe the composition of tyres [ETRMA, 2015].

Table 4. Composition of mixed used tyres – elementary composition [Schmidt et al., 2009]

	UNITS (FM: fresh matter)	VALUE
Calorific value	MJ/kg FM	26
Water	% FM	3.5
Ash content	% FM	1
Scrap content	% FM	18
Carbon, total	g/kg FM	707
Carbon, fossil	g/kg FM	516
Carbon, biogenic	g/kg FM	191
Sulphur	g/kg FM	15
Chlorine	g/kg FM	0.75
Fluorine	g/kg FM	n.a.
Antimony	g/kg FM	0.0007
Arsenic	g/kg FM	0.02
Cadmium	g/kg FM	0,008
Chromium	g/kg FM	0.097
Cobalt	g/kg FM	0.25
Copper	g/kg FM	0.45
Lead	g/kg FM	0.41
Manganese	g/kg FM	0.75
Mercury	g/kg FM	0.00017
Nickel	g/kg FM	0.077
Thallium	g/kg FM	0.00025
Tin	g/kg FM	0.01
Vanadium	g/kg FM	0.005
Zinc	g/kg FM	15

Table 5. Composition of mixed used tyres – material composition by weight [Schmidt et al., 2009]

	Composition of new tyres 1) (%)	Estimated composition of used tyres (%)
Synthetic rubber	24.5	20.6
Natural rubber	17.6	11.8
Carbon black	23.0	18.7
Silica	5.1	6.5
Sulphur	1.3	1.1
Zinc oxide	1.6	0.9
Aromatic oils	7.0	7.3
Steel wires	11.6	18.0
Textile fabrics	4.7	14.0 2)
Other	3.8	1.0

1) average value of silica based and carbon black based new tyres
2) contains 75% recycled rubber granulate by weight

Data in Table 4 are used in the inventory to calculate the emissions from co-incineration, using transfer coefficients. The concept of transfer coefficients is described in chapter 6.8.1. In the recycling route, the composition of used tyres is used.

6.4. Material recycling at Genan

The main processes in the material recycling route are shredding, cleaning with water and granulation, where the cryogenic powder is additionally subjected to a milling process at very low temperatures. The production flow is illustrated in Figure 7. The main outputs of the recycling processes are rubber granulate in various sizes, a steel scrap fraction and a residual fraction consisting of textile and rubber. The total European capacity equals 275.000 tonnes of tyres per year.

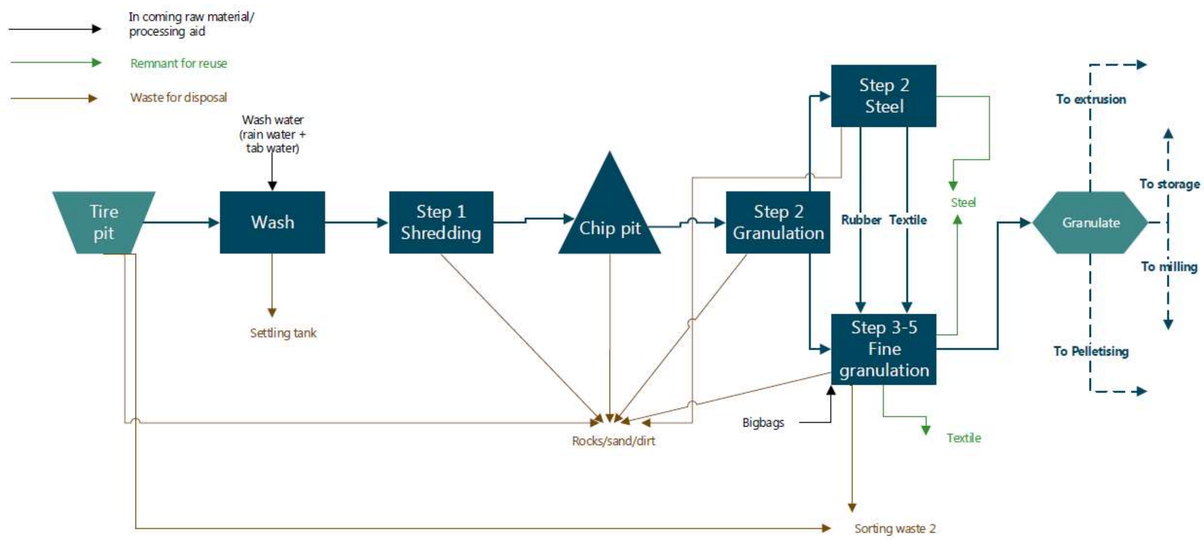

Figure 7. Genan material recycling flow diagram

All data in this chapter 6.3 was provided by Genan during the data collection and was collected for the full year 2017. The sources of information is bills and weight registrations.

Genan has 4 European facilities for tyre recycling including 3 facilities in Germany and one in Viborg. The applied technologies and main unit processes are largely identical. According to Genan's own analysis of the energy consumption at each of the production sites, the difference in energy consumption of the processes is small and the most significant difference is related to the starts/stop of the plant, the variation in input (OTR[7]/Truck & Bus/Passenger car tyres) and to some extent the output product. The higher share of fines produced means more granulation, equalling more energy required. In this respect the Viborg plant is in the high end representing a conservative energy consumption (in favour of the co-incineration method for treatment of tyres).

At the Viborg plant, there is an additional production line for cryogenic treatment of a small part of the recovered rubber from tyres. The inventory for the cryogenic treatment is provided under a separate headline below.

[7] Over the road

Energy and water utilities:
Electricity is used for various operations at the plants including shredding, knife sharpening, washing, lighting etc. The total electricity consumption is 276 kWh per tonne of treated tyres. The source of electricity is assumed to be 25% from the Danish grid and 75% from the German grid representing all four Genan production plants.

Water is primarily used for cleaning purposes and the water is cleaned and re-circulated at the plant. Some water is evaporated and there is no wastewater from the plant. The water consumption from municipal supply is 45 liter per tonne of treated tyres. In addition, rainwater collected from the plants 2.429 m^2 roof is used.

Natural gas is used for heating purposes including comfort heat and the total consumption is 1.98 m^3 per tonne of treated tyres.

One liter of diesel fuel per tonne is used for internal transport purposes such as outdoor forklifts, tractor and reach stacker.

The output air from the granulation processes is filtered and the only air emissions are small amounts of dust totaling approximately 0.035 kg per tonne of treated tyres.

Materials:
The main recovered materials from the tyres are the rubber granulate, steel and a textile fraction. The rubber granulate is further separated into the seven different standard qualities: fine, fine/mix, medium, course, super course, ultra course and powder. The different qualities are recycled in different applications replacing other materials, see chapter 4.2.4 for examples. For performance infill applications, primarily the fine and the fine/mix qualities are used. A weighted average of the densities of these qualities is 405 kg/m3. This density has gone down from 550 kg/m3 since 2007 due to optimized sieve curves and decreased amounts of dust in the Genan production.

Recycled steel from the tyres is used as input to steel works, where it replaces other sources of steel as described in chapter 6.6. The knives used for shredding the tyres and the rubber are produced and sharpened on site, which requires an input of 0.4 kg new steel per tonnes of treated tyres. Discarded steel is returned to the steel works for remelting similar to the steel recovered from the tyres.

Throughout the treatment processes at the plant some impurities, primarily consisting of sand and gravel, are removed and collected by a local waste management company for nearby landfilling.

Packaging materials for the recycled rubber is excluded from the study based on the assumption that similar packaging is used for supplying the virgin infill materials, which are replaced by the recycled rubber.

A summary of the life cycle inventory for the material recycling process at Genan is provided in Table 6 below.

Table 6. Summary of LCI for the material recycling process (excluding the cryogenic milling line)

Utility, materials, waste	UNIT	VALUE	SOURCE
Electricity from the grid	kWh/tonne	276	Electricity bill
Water – municipal supply	L/tonne	45	Water bill
Natural gas for heat	M3/tonne	1.98	Gas bill
Diesel for on site vehicles	L/tonne	1	Bill
Steel for steel blades	Kg/tonne	0.4	Weightings

Dust emissions	Kg/tonne	0.035	Measurements
Sand and gravel for landfilling	Kg/tonne	4	Weightings
Steel for recycling	Kg/tonne	147	Weightings
Textile residual fraction	Kg/tonne	124	Weightings
Rubber granulate for recycling	Kg/tonne	725	Weightings

The applied secondary dataset for the on site diesel consumption is not an exact technological match, but it is considered a reasonable proxy as this is a low consumption quantity.

Cryogenic powder production line:
One rubber fraction is converted into rubber powder at a cryogenic milling line at Genan's production facility in Viborg. The cryogenic process uses liquid nitrogen to freeze the granulate, which subsequently is milled into smaller granulate <0,425mm sizes, separated and sieved into the final qualities as illustrated in Figure 8. In addition to the use of utilities and material consumption described in the above chapters, the per ton of tyres consumption for the cryogenic production line is 1296 kWh electricity, 80 m^3 natural gas (heating), 2333 kg liquid nitrogen and 5 kg flow agent. A datasheet is available for the flow agent. The liquid nitrogen is supplied from AirLiquide in a special transport vehicle with cooling to 150 degrees. The distance is 95km from Hedensted.

Figure 8. Cryogenic rubber powder production processes

A summary of the LCI for the cryogenic milling line is provided in Table 7.

Table 7. Summary of LCI for the cryogenic milling line

Utility, materials, waste	UNIT	VALUE	SOURCE
Electricity from the grid	kWh/tonne	1296	Bill
Natural gas for heat	M3/tonne	80	Bill

Liquid nitrogen	Kg/tonne	2333	Bill
Flow agent	Kg/tonne	5	Bill

6.5. Application of recovered rubber and avoided virgin materials

The recovered rubber is used as performance infill material in artificial sports turfs, and this application has increased significantly over the past 10-20 years. Artificial sports turfs are an alternative to natural grass, which allows sport at the fields all year around. Many qualities of artificial turfs exist worldwide, although the basic components are relatively similar [FIFA, 2017]. FIFA has, through a quality program for football turf, developed standards for the so called 3rd generation (3G) turfs, which is the type of turf, which the rubber infill is used for in this LCA model.

The structure of a 3G artificial turf is shown in Figure 9 below. A secondary backing of a liquid polyurethane or latex binds the pile to the backing, while a stabilizing infill of sand is used to keep the fibers vertical during use. On top of the stabilizing infill is a performance infill, which provides chock absorbance and a similar feeling to natural grass. Some turfs apply a shock pad as the deepest layer, in which case, the amount of performance infill can be reduced. Generally, artificial turfs, which do not apply a shock pad, usually have an SBR performance infill because of the higher cost of virgin infills. Therefore, the replacement of virgin infills is mostly relevant for turfs using a shock pad.

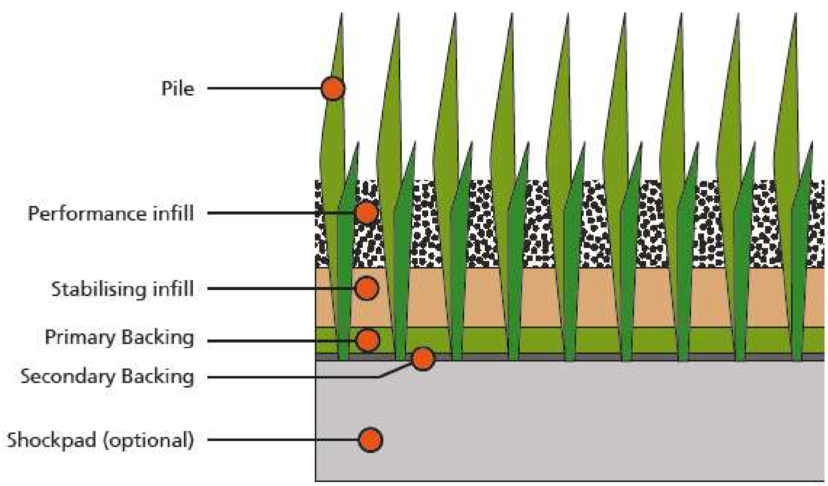

Figure 9. Typical components of a 3G typical artificial football turf [FIFA, 2017]

According to FIFA, the dominating performance infill used is SBR from end-of-life tyres (ELT), which is applied in around 80% of the FIFA certified turfs [FIFA, 2017]. For non-FIFA certified turf this share is even higher due to the low cost of ELT rubber. The environmental implications of using ELT rubber as infill depends on which other infill materials are replaced by the ELT rubber in the artificial–turf football pitches. At the same time, the number of artificial-turf pitches continues to grow significantly and is expected to grow by around 12.7% annually from 2017 to 2023 measured in economic market value[8]. For this reason, more infill material will also be needed. If the demand is not met by ELT rubber then other materials are

[8] https://www.alliedmarketresearch.com/artificial-turf-market

needed in replacement of ELT rubber. Virgin alternatives include infills based on the synthetic rubber compounds EPDM (ethylene propylene diene monomer) and TPE (thermoplastic elastomer) as well as a small amount of organic infills such as for example cork or coconut fibers. The synthetic rubber compounds are the most common alternatives and in FIFA certified artificial-turf pitches they each have an about equal market share [FIFA, 2017], see Figure 10.

It is estimated that FIFA certified pitches only make up a smaller fraction of the total market for artificial turf (estimated 10-15%). Therefore, the European average may differ from the average for FIFA certified football fields especially when looking 5-10 years ahead. As described above, the number of pitches is expected to grow, but it is difficult to predict with any accuracy what would be used as infill, if ELT is not used.

Considering the uncertainties in identifying the exact mix of alternative infill materials, which would replace ELT rubber in Europe, this study investigates the environmental impacts for each of the most common alternative infill materials separately (and one mixed scenario). The following infill scenarios are included:

EPDM scenario:
In the EPDM scenario ELT replaces 100% EPDM based virgin infill.

TPE scenario:
In the TPE scenario ELT replaces 100% TPE based virgin infill.

50/50 scenario:
In the 50/50 scenario ELT replaces 50% EPDM and 50% TPE virgin infill (this ratio between EPDM and TPE corresponds to the current average ratio, for the use of these two materials, in FIFA certified artificial-turf pitches in accordance with Figure 10 below).

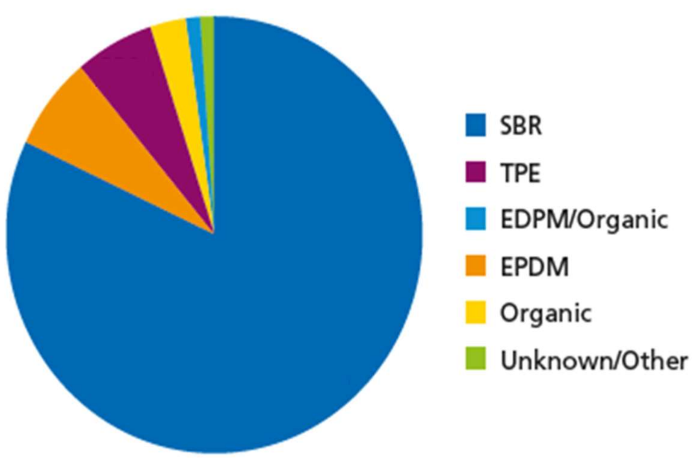

Figure 10. Performance infill market shares [FIFA, 2017] (the original figure from the FIFA report was modified by removing percentage numbers, because the numbers contained an error).

6.5.1. Organic infills

It is possible that ELT rubber for infills could in some cases also be replaced by organic infills such as for example cork. In FIFA certified pitches, organic infills are used in around 3% [FIFA, 2017], but this corresponds to 20% of the ELT alternatives for FIFA certified football pitches. However, organic infills include a number of different types, with each having a small market share. Artificial-turf pitches, which are not FIFA certified, are expected to use even less organic infills because of the low price of ELT rubber infill. Organic infills have not been used for as many years as the other common infill materials. Therefore, there is less experienes made and a lack of information available about the use with regards to the lifetime of these infills, the functional characteristics, the quantity needed etc. In fact, there are indications that the cork infill disappears more quickly from the fields leading to an increased need for top-up in comparison with the synthetic alternatives [Myhrvold, 2020], [Greenfields, 2020]. For this reason, FORCE Technology believes that there are too many uncertainties to make a plausible scenario where organic infill replaces the ELT infill. If, for example, that the lifetime is different or if more infill is needed due to more top up (kg per kg ELT infill) then this could have a significant impact on the comparison. It is, however, recognized that the benefits of replacing organic infills could be significantly different from the benefits related to replacing plastic based infills. In fact, the FIFA study indicates that the use of cork for infill has a lower contribution to climate change impact in comparison with SBR rubber.

The installation of artificial grass fields including performance infills requires special machinery. However, the installation processes depend primarily on the artificial grass element and not the infill material. Spreading the infill in a homogeneous layer requires special machinery, but the same machinery can be used in establishing artificial turf with different types of infill. Likewise, machinery for turf maintenance is also specialized, but not in relation to the type of infill [FIFA, 2015]. For this reason, maintenance is outside the scope of the study.

6.5.2. Virgin infill composition

The virgin rubber products, substituted by tyre derived ELT rubber for performance infill, are based on either EPDM or TPE with an equal share of each as described in chapter 6.5. Both infill types contain approximately 20% rubber materials, while the remaining 80% are fillers and additives [ETRMA, 2015], [Schmidt et al., 2009], [Terra, 2006]. A material safety datasheet for a SEBS infill material from the same supplier shows a content of calcium carbonate of approximately 60% [Terra, 2015]. There is little information available on the exact composition and on the production of the infill qualities in the market. Both production processes and specific recipes are considered as proprietary knowledge. However, according to Genan and interviews with a leading producer of EPDM infill, there has been little development of the infill materials since the LCA study [Schmidt et al., 2009] and the products available today are the same as those, which dominated the market in 2009 [Genan, 2019]. A supplier of infill material states that the following types of fillers and additives are found in both EPDM and SEBS based infill [Terra, 2006]:

- UV-stabilizer
- Anti-oxidant
- Chalk
- Pigments

EPDM rubber is carbon chains build up of the monomers ethylene and propylene as well as a dien component, typically norbonene, as a side chain. The advantage of this polymer structure is a good weather resistance and a polymer, which does not need addition of anti-ozonants. EPDM can be either peroxide or sulphur vulcanized. In both cases zinc oxide can be added, although the highest quantities are used by sulphur vulcanization. By sulphur vulcanization, common accelerators based on nitrogen and sulphur are used. By peroxide vulcanization, organic peroxides, typically dicumyulperoxide, are used and these cleave acetophenon during the vulcanization. Other methods can cleave tert-buthyl alcohol. Softeners used for EPDM are predominantly naphtenic oils with a relatively low aromatic content. Triallyl cyanurate is used for peroxide vulcanized EPDM rubber as a cross-linking regulator [Nilson et al., 2008].

TPE is short for thermoplastic elastomers. SEBS is a typical thermoplastic elastomer based on Styrene-ethene-butylene-styrene block co-polymer. TPE is different from rubber as it is not vulcanized and therefore also no vulcanization additives are used. Instead the net structure is formed by the styrene segments forming crystalline domains. Because the chain structure is saturated, SEBS is also characterized by good weather resistance [Nilson et al., 2008].

The ratio between the two main components of SEBS, styrene and ethylene-butylene, can vary in different SEBS materials commercially available in products in Europe. In this study a polystyrene content of 30% is assumed based on the typical values in suited products from a large producer [Kraton link http://www.boundarybayenterprises.com/files/Kraton_G.pdf] and on the German LCA dataset applied "Styrene ethene butene styrene copolymer (SEBS, TPE-S)", which states that this type of SEBS is used for sports equipment among other things.

As regards the content of fillers and additives, it is possible that there are differences between the composition of specific products and for this reason the assumed composition includes the most important raw materials in representative amounts as shown in Table 8:

Table 8. Production and main components of virgin infill types

INGREDIENT:	QUANTITY:	SOURCES:
SEBS INFILL:		
SEBS	20%	[Schmidt et al., 2009]
$CaCO_3$	65%	[Terra, 2015], [Schmidt et al., 2009]
Paraffinic oil	15%	[Schmidt et al., 2009]
Electricity	2,6 MJ/kg	[Schmidt et al., 2009]
EPDM INFILL:		
EPDM	20%	[ETRMA, 2015], [Schmidt et al., 2009], [Terra, 2006]
$CaCO_3$	60%	[Schmidt et al., 2009]
Lubricant oil	13,6%	[Schmidt et al., 2009]
Organic chemicals	4,5%	[Schmidt et al., 2009]
Zinc	1,9%	[Schmidt et al., 2009]
Electricity	2,6 MJ/kg	[Schmidt et al., 2009]

6.5.3. Substitution ratio between tyre derived rubber and infill materials

As mentioned in chapter 6.4, the density of the Genan rubber has gone down over the past ten years and this allows a reduced quantity to be used per m^2 artificial turf. When an artificial turf is established, the quantity of performance infill applied is assumed to be equal for different types of performance infill on a weight basis. This key assumption is based on [FIFA, 2017] as well as an extensive Danish study of 256 artificial turfs [DTI, 2018][9].

For a typical artificial turf pitch of 106 x 71 meters the quantity of performance infill applied is 120 tonnes and additional infill is applied over the lifetime of the pitch in order to sustain the thickness of the infill layer and consequently maintain the chock absorbance and the playing qualities of the pitch. The need for refill is a consequence of several factors in the lifetime of an artificial turf pitch. A primary cause is the gradual compaction of the infill layer, which reduces the good performance of the pitch. Other causes are loss of infill, which is accumulated in soil and reinforced areas, transfer onto shoes and clothes, loss by snow removal and loss with water. A recent study on international literature describing the mass balance of SBR[10] rubber infill estimates the annual loss of infill to be in the range of 1.8% - 3.6%. Assuming a lifetime of 10 years this corresponds to a total refill quantity of 18 – 36%, [DTI, 2018].

To the extent that the needed refill quantity differs between the different types of performance infills, this has a large influence on the substitution ratio. If, for example, a refill quantity of 40% would be needed for the virgin infill and only 20% is needed for the tyre derived infill, then the replacement ratio would be 1:1.17 instead of 1:1. There is, however, only little information available to document a difference between the infills on this issue. ELT granulate has been used for decades for third generation artificial fields and it is judged to retain its quality very well [Aliapur, 2010]. The qualitative aspects of ELT granulate, which can substantiate this, is the high rubber content and the initial use of the rubber, which is in tyres. Tyres are designed to be subject to high friction and weight, when driving on the road, and they must withstand the wear and tear of time and outdoor whether conditions including thermal and UV-induced degradation.

For TPE and EPDM infills no reliable information is available to estimate the actual lifetime and need for refill of these materials, but there is no indication that TPE and EPDM should have a longer technical lifetime in comparison with ELT granulate. On the contrary, a life cycle study on the end of life of used tyres carried out by Pricewaterhouse Coopers [Aliapur, 2010] showed that 1 kg of SBR rubber (ELT) replaces 2.5 kg of EPDM based virgin infill. It was, however, not possible to verify the validity of this assumption. Another study by LABOSPORT, carried out for Genan in 2018, compares the durability of different types of performance infills including both recycled tyre rubber granules, virgin EPDM and virgin TPE infills, [LABOSPORT, 2018]. This study includes a test program designed to reproduce a wear, equivalent to a real outdoor exposure of 5 to 8 years, under typical European conditions (climate, hours per week of use, maintenance, types of sports, shoes, etc.). The test program combines the three main ageing aspects affecting the durability of infill: UV radiation, high temperature and mechanical wear of shoe studs. The results of the LABOSPORT study showed the best durability for the rubber granules from recycled tyres (non-coated) as this sample was the only one, which did not show any visual nor any mechanical change, after being subject to the simulated weather tests. The included TPE and EPDM samples showed varying results across the individual samples and tests.

In the establishment of some artificial turf fields, which do not need to fulfill special quality requirements, there may be a desire to lower the price of the field by reducing the content of rubber in virgin infills resulting in the amount of fillers and other components going up. This is known to have a negative influence on the quality of the field and in result also the lifetime [Terra, 2006], [Schmidt et al., 2009], [Genan, 2019]. However, in this study only 3G fields, which fulfill the FIFA quality requirements are considered.

There can be several reasons for removing a field, which are not related to the choice of infill. For example the field may be removed if the turf itself no longer satisfies the needs or if the field is converted to natural

[9] The excel sheet, which the report is based on
[10] Styrene-butadiene rubber

grass fields or to another purpose altogether [Genan, 2019]. Furthermore, there are not sufficient studies or statistical material available to show a general difference between lifetime and refill quantities for the different types of infill. Therefore the assumption is, that ELT granulate replaces TPE and EPDM infills in the ratio 1:1 on a weight basis. This is considered a conservative assumption from a Genan point of view (meaning that it is in favor of the co-incineration treatment method).

According to a recent literature review of the mass balance of rubber granulate disappearing from artificial turfs, between 2-12% of infill material is lost to the natural surroundings during the use stage [DTI, 2018]. Based on this, it is assumed that an average of 7% is lost without being related to any environmental impacts or benefits. It should be noted, however, that lost infill may contribute to micro plastics in the natural surroundings, see appendix 2 for more details.

6.5.4. Leaking of hazardous substances from infills during the use stage

During the use of infills in artificial turf fields there may be an effect on the surrounding environment as well as health issues for players and workers at the fields. These effects are related to the risk of leaking of substances with unwanted health or environmental properties. It is difficult to quantify these aspects and to properly capture these in the LCA results. Instead a comparison of the risks related to the different types of infills was analyzed and discussed in the separate appendix 2. The appendix is based on the most recent literature on the topic and the main conclusions are the following:

- The general risk to human health is considered to be insignificant based on the current level of knowledge.
- The most concerning substance in ELT rubber is PAH's. However, the PAH content in Genan rubber granule is continuously tested and the test results are published in their MSDS on the Genan website. The PAH content complies with EHCA's suggested restriction proposal on PAH's in infill material in synthetic turf pitches [ECHA, 2019b]. Furthermore, all new tyres marketed in the EU must live up to a new PAH restriction for tyres and therefore the content of PAH in tyres can be expected to gradually diminish in the future. For more details se appendix 2.
- The most concerning substance for EPDM infills is zinc, which may leak to freshwater environments. However, it was not possible to conclude on the extent of this potential problem.
- It is not possible to make a clear distinction between the infill types ELT, EPDM and TPE with respect to health and ecotoxic properties and a choice between infill materials should not be based on these properties with the existing level of knowledge.

6.5.5. End of life of performance infills

Potential end of life options for artificial turfs are:

- Re-use and recycling
- Landfill
- Incineration

Recycling:

Although some manufacturers inform that reuse and recycling is possible, this not currently a widespread practice. The biggest issues for recycling (and re-use) are the contamination by the sand infill and a lack of viable end markets, which have suitable applications for the recycled material [FIFA, 2017].

A search for companies recycling artificial turfs did not identify many companies who support a claim that they can recycle the turf materials. In Denmark, the company Re-Match claim to be able to recycle 99% of the sand, rubber, backing and plastic materials in artificial turfs, although little information is available to identify what the recycled infill materials are used for nor which materials and quantities are replaced. Case examples, however, show that some of the materials in the artificial turf are used to produce new products such as for example furniture, [Re-Match, 2018].

The Re-Match process is patented for recycling synthetic turf. The process downsizes, cleans and separates worn-out turf from e.g. football pitches into the original raw materials; sand, rubber, backing and plastic fiber. The first factory in Denmark has been operational since 2016 and processes 40.000 tonnes per year, while the company currently has ambitious global expansion plans [Re-Match, 2018].

In October 2017, Kiwa ISA Sport B.V. completed laboratory tests for Re-Match, which concluded that recycled SBR infill rubber is suitable for use as new infill, based on the material characteristics [Kiwa, 2017].

It was not possible to verify whether or not Re-Match also receive and recycle artificial turf using virgin material infills. However, information from Re-Match claim a "99% clean sand and rubber, grass fiber and backing" whereas no claims have been identified as regards the recycling of limestone or other filler materials, which make up the majority of virgin infill materials [Re-Match, 2018].

Based on the above information and reflections, we consider it more likely that ELT rubber is recycled into valuable new applications in comparison with how likely it is that virgin infill materials are recycled into valuable new applications. However, the available information is two scarce to allow inclusion of a justified recycling scenario in this study and, besides, infil recycling is not currently considered a widespread practice. No attempt was made to collect primary market data for the recycling of infills.

Incineration and landfilling:

Many of the countries, which install the most football turf in Western Europe, rely strongly on incineration as their primary waste treatment form for unrecycled waste. This is a result, typically, of the deployment of landfill taxes and bans, often jointly, but sometimes with one or the other used as the primary driving mechanism [FIFA, 2017]. Despite these mechanisms some artificial turfs are, to a smaller extent, still likely to end up in landfills at the end of their useful life. The trend in European waste disposal is towards less landfilling and with an expected lifetime of 7-10 years for artificial turfs the quantity of infills being installed today, which will be landfilled, is expected to be even lower than it is the case today.

In this study it is assumed that the infill will be incinerated, but a landfilling scenario is included in the sensitivity analysis to show the importance of this assumption.

According to [Schmidt A. et al, 2009] the infills was in 2009 assumed to be co-incinerated in cement kilns. However, today this is not deemed a likely disposal route due to the relatively low bulk quantities. Cement kilns do, to some extent, accept rubber crumbs as a source of energy in the kilns, but only if it is supplied continuously in large and relatively clean quantities exceeding around 15,000 tonnes per year. The cement kilns are not likely to accept small quantities of different origin with different impurities etc., which makes this material unfit for cement kilns [Portland, 2019]. Incineration is thus assumed to take place in regular municipal incineration plants with energy recovery.

In practice the incineration of various components in the infill materials is modelled using separate processes for each of the components. $CaCO_3$, constituting a significant part of the virgin infill materials, is in the incineration process appearing as CaO_3, which is converted to CO_2 and CaO. CaO is used in some European incineration plants for removing sulphur or preventing waste from sticking to the sides during the process. This process applies a technology described as UHT injection. CaO is a very reactive substance and it is assumed to react with sulphur in the boiler room, where the waste is inserted [Faxe, 2019].

6.5.6. End-of-life of cryogen powder and substituted materials

The two secondary scenarios for the application of recycled rubber material, which applies the cryogen rubber powder in applications where it replaces either carbon black or synthetic rubber, assumes the end-of-life route is by incineration. This assumption applies to the cryogenic powder as well as to the avoided carbon black and the avoided synthetic rubber. This assumption will not be true in all applications of cryogenic powder and no general investigation was conducted to map the end-of-life for the various applications. For this reason, it is highlighted that the results for these two scenarios are only valid for applications where this end-of-life can be justified.

6.6. Avoided new iron in steel production

The steel scrap fraction and the steel from the knife line is of a high purity and substitutes other input materials in the production of steel coils, slabs or other profiles [Genan, 2019]. The purity is continuously measured for the Viborg production plant [Genan steel, 2019]. The iron content in the tyre steel scrap is approximately 92% [Genan, 2019]. The iron substituted in the steel production is based on the current average sources of iron for steel production, which are 63% pig iron (from iron ores) and 37% from scrap steel [Worldsteel, 2019]. No major changes to this assumption is expected in the longer term, but future predictions about the steel scrap input are difficult as they depend on the development in international steel markets. The tyre recycling treatment system is only credited for substituted virgin iron.

The principal iron ores for iron making are hematite and magnetite. According to the [RMIS, 2018] Iron Profile, source countries for EU28 imports of iron ores and concentrates, in average between 2013 and 2017, are mainly Brazil (43.5%) and Canada (16.6%). Deposits in Brazil are banded iron formation deposits with average ore grade above 60%. The calculated substitution equivalency is based on an assumed iron content in the ore of 65% in accordance with the applied ecoinvent dataset "market for iron ore, beneficated, 65% Fe". The overseas transport was assumed with 10,000 km by ship, 200 km by lorry and about 900 km by train.

The total amount of steel scrap resulting from material recycling is 147 kg per ton. This substitutes 131 kg pig iron.

6.7. Textile fraction

The textile fraction is essentially the residue of the tyres, which is left, when all that can be material recycled has been removed. The textile fraction is send to co-incineration in cement kilns, where it replaces other sources of energy. It consists of 57.5% rubber, 0.5% steel and 42% textiles [Genan, 2019]. Textiles are used as a reinforcement material in the tyres. The textile is assumed to consist of nylon, polyester and rayon in the ratio 1:2:1 [Schmidt et all, 2009]. The elementary composition is shown in Table 9.

Table 9. Characterization and composition of textile fraction

	UNITS (FM: fresh matter)	VALUE	SOURCE
Net calorific value	MJ/kg FM	30.5	Genan, 2019
Ash content	% FM	6	Genan, 2019
Scrap content	% FM	0.5	Genan, 2019
Carbon, total	g/kg FM	700	Schmidt et al., 2009
Carbon, fossil	g/kg FM	530	Schmidt et al., 2009
Carbon, biogenic	g/kg FM	170	Schmidt et al., 2009
Sulphur	g/kg FM	13	Schmidt et al., 2009
Chlorine	g/kg FM	0.65	Schmidt et al., 2009
Fluorine	g/kg FM	0	Schmidt et al., 2009
Hydrogen	g/kg FM	77	Schmidt et al., 2009
Nitrogen	g/kg FM	17.3	Schmidt et al., 2009
Oxygen	g/kg FM	163	Schmidt et al., 2009
Antimony	g/kg FM	0.0006	Schmidt et al., 2009
Arsenic	g/kg FM	0.02	Schmidt et al., 2009
Cadmium	g/kg FM	0.007	Schmidt et al., 2009
Chromium	g/kg FM	0.08	Schmidt et al., 2009
Cobalt	g/kg FM	0.2	Schmidt et al., 2009
Copper	g/kg FM	0.4	Schmidt et al., 2009
Lead	g/kg FM	0.35	Schmidt et al., 2009
Manganese	g/kg FM	0.65	Schmidt et al., 2009
Mercury	g/kg FM	0.00015	Schmidt et al., 2009
Nickel	g/kg FM	0.07	Schmidt et al., 2009
Thallium	g/kg FM	0.0002	Schmidt et al., 2009
Tin	g/kg FM	0.01	Schmidt et al., 2009
Vanadium	g/kg FM	0.004	Schmidt et al., 2009
Zinc	g/kg FM	13	Schmidt et al., 2009

The co-incineration of the textile fraction substitutes other fuels and the contained steel substitutes iron ore. The energy content is used as a substitution factor. For the substituted materials as well as the input and process related emissions, the same considerations are valid as described for the co-incineration of mixed used tyres in chapter 6.8.

6.8. Co-incineration in a cement kiln

The technology of clinker production is characterized by the type of raw material preparation. A distinction is made between dry process, semi-dry/semi-wet process and wet process [ifeu, 2018]. In Germany and most of Europe, more than 90% of production is based on dry processes, thanks to the availability of dry raw materials. Wet processes are more energy consuming and thus more expensive [BREF, 2013]. In order to reduce energy consumption, Best Available Technique (BAT) is to use a dry process kiln with multistage preheating and precalcination [EU, 2013].

Cement clinker, the main constituent of cement, is made from a raw material mix mainly consisting of calcium oxide (CaO), silicon dioxide (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). The iron oxide required for melt formation is either contained in the clay minerals in the form of ferrous hydroxide or it is added in the form of iron ore. [VDZ, 2018].

The raw materials are milled, mixed and usually preheated before being introduced in the rotary kiln where the combustion process takes place, using fossil fuels or a mixture of fossil fuels and waste (e.g. waste tyres). At the input side of the cement kiln, a temperature of 850°C is reached in the calcining zone (or secondary firing). At the end of the kiln, in the sinter zone (or primary firing), a temperature of 1,450°C is reached. The flue gas reaches a temperature of 2,000°C. During the combustion process the raw materials form new compounds known as clinker phases. The near-molten material is rapidly cooled to a temperature of 100 - 200°C. Clinker is then ground with gypsum and other materials to produce the grey powder known as cement. There is no output of slag or waste from the cement production process as all outputs from the kiln are included in the cement. No wastewater is generated. [Schmidt et al. 2009], [VDZ, 2018], [CEMBUREAU, 2016].

The co-incineration process including air emissions from incineration is based on an ifeu model [ifeu, 2018] as described in this chapter. The ifeu model calculates the emissions from co-incineration based on the elementary composition of the materials being incinerated (tyres, textiles, replaced fuels) using the information about emissions as specified in this chapter. The ifeu model was entered into the GaBi software, where the contribution to environmental impacts are calculated in the LCA.

6.8.1. Co-incineration of waste tyres

Co-incineration of waste in general is increasing in the EU. The EU cement industry already uses about 40% fuels derived from waste and biomass, and the European Commission included co-processing of waste in cement kilns in their recent Communication on Waste-to-Energy, [Ecofys, 2017].

The modelling of co-incineration of waste tyres in a cement kiln focuses on those aspects that are influenced by using tyres instead of other fuels or other waste materials. These aspects are:

- collection and pretreatment of refuse derived fuel (RDF)
- emissions from co-incineration
- avoided emissions by substitution of fossil fuels and raw materials

Data used for the process steps are described in the following. The source of information is [ifeu, 2018] unless otherwise specified.

Transportation and pretreatment of used tyres

Transport is modelled with a medium lorry of 17.5 tons maximum payload and a transportation distance of 150 km [ifeu, 2018].

30% of the used tyres are shredded in advance. The estimated electricity demand for shredding of used tyres is 100 kWh/t [ifeu, 2018]. The use of steel for knives to cut the tyres is assumed not to be important since the analysis of the use of knives for granulating tyres in the recycling route (see chapter 6.4) shows that it has a relatively low impact. Compared to the use of knives for the granulation process, the shredding of tyres into 50 x 50 mm pieces before feeding into the cement kiln is a much less demanding process with regards to the use of knives.

Emissions from the co-incineration process

Emissions from the incineration process are distinguished between input related emissions and process related emissions. Input related emissions depend on the waste composition and are calculated with material specific transfer coefficients. The input quantity of a substance/material into the co-incineration process is multiplied with the transfer coefficient to calculate the output emission of that substance.

Process related emissions are particulate matter, nitrous oxides, carbon monoxide and organic pollutants. The latter only play a minor role in the cement production process as organic compounds are largely destroyed due to the high sinter and/or flue gas temperature. In addition, with temperatures of 1,450°C in the sinter zone and 2.000°C in the flue gas, N-content related NO_x emissions are irrelevant compared to thermally induced NO_x emissions derived from nitrogen in air. Thus, NO_x formation mainly depends on the gas produced and final NO_x emissions depend on the gas cleaning technology installed (altogether process-related emissions).

Halogen compounds such as HCl and HF as well as SO_2 are mainly absorbed by chemical reaction with the alkaline components. Heavy metals are also mainly integrated into the cement clinker. The part of the heavy metal compounds, that is emitted into the air after cleaning in an electric or fabric filter, is calculated by transfer coefficients.

In Germany air emissions from the cement production process are reported yearly by "Verein Deutscher Zementwerke e.V. (VDZ)", the German association of cement plants. This includes transfer coefficients for heavy metals for rotary kilns with cyclone preheater. Kilns with cyclone preheaters represent about 94% of the total capacity in Germany. The values reported in the recent VDZ report [VDZ, 2018] for the year 2017 correspond to the transfer coefficients used in [Villanueva et al., 2008] and [Schmidt et al., 2009]. However, for mercury the emissions from German cement plants decreased in principle compared to the time horizon of the studies [Villanueva et al., 2008] and [Schmidt et al., 2009]. The transfer coefficient of 0.4 represents a rather conservative assessment. Some cement plants in Germany even achieve a transfer factor of 0.2 [ifeu, 2015]. For Germany VDZ confirmed a transfer coefficient of 0.3. Mercury emissions are measured continuously in German cement kilns since some years, and thus a valid data basis on mercury emissions exists, which supports the assumption of a transfer coefficient of 0.3 [ifeu, 2015].

Similar information for other heavy metals is not available, and transfer coefficients for zinc, sulphur, chlorine and fluorine are not reported in [VDZ, 2018]. Therefore, the transfer coefficients reported in [Villanueva et al., 2008] and [Schmidt et al., 2009] are applied. Although they represent the status quo of the time horizon of 2005 these are considered plausible based on the good correlation of most of the other factors as described above. The transfer coefficients are presented in Table 10.

Table 10. German transfer coefficients to air emissions in the cement production process.

Component	Transfer coefficient (kg/kg)	Source
Sulphur (sulphur dioxide)	0.005	[Villanueva et al., 2008], [Schmidt et al., 2009]
Chlorine (hydrogen chlorine)	0.001	[Villanueva et al., 2008], [Schmidt et al., 2009]
Fluorine (hydrogen fluorine)	0.0001	[Villanueva et al., 2008], [Schmidt et al., 2009]
Antimony	0.0003	[VDZ, 2018]
Arsenic	0.00023	[VDZ, 2018]
Cadmium	0.0017	[VDZ, 2018]
Chromium	0.00012	[VDZ, 2018]
Cobalt	0.00019	[VDZ, 2018]
Copper	0.000093	[VDZ, 2018]
Lead	0.0005	[VDZ, 2018]
Manganese	0.00018	[VDZ, 2018]
Mercury	0.3	[ifeu, 2015]
Nickel	0.0003	[VDZ, 2018]
Thallium	0.013	[VDZ, 2018]
Vanadium	0.00052	[VDZ, 2018]
Tin	0.00074	[VDZ, 2018]
Zinc	0.0003	[Villanueva et al., 2008], [Schmidt et al., 2009]

Further reported air emissions in the VDZ environmental data series are carbon dioxide, dust, nitrogen oxides (NO_x), ammonia (NH_3), sulphur dioxide (SO_2), total organic carbon (TOC), dioxins and furans (PCDD/F), polychlorinated biphenyls, polycyclic aromatic hydrocarbons (PAH), benzene, toluene, ethylbenzene, xylene, gaseous inorganic chlorine and fluorine compounds. These emission data are presented in graphs for yearly average concentrations in clean gas measured at up to 40 cement kilns. The concentration values represent up to 94% of the total capacity in Germany. Table 11 displays the range of yearly concentrations in clean gas of cement kilns derived from the graphed values in [VDZ, 2018] as well as a roughly estimated average.

Table 11 also presents daily emission limit values for co-incineration in cement plants according to the German Ordinance 17. BImSchV (2013). The values in brackets for total dust, NO_x and NH_3 as well as the values for heavy metals (except mercury) and PCDD/F account for co-incineration in cement kilns in case more than 40% of the thermal firing capacity is derived from using hazardous waste. In Germany, typically non-hazardous waste is used for co-incineration.

Compared to the German emission limit values, the measured concentrations are mostly lower. Exceptions are SO_2 and TOC where the regulatory authority can approve exceptions.

Table 11. Roughly estimated average or range of yearly concentrations (in mg/Nm³) from [VDZ, 2018] and daily emission limit values for co-incineration in cement plants of the German Ordinance 17.BImSchV (2013)

Air pollutant	Roughly estimated average or range of yearly concentrations in clean gas of cement kilns for 2017 displayed in [VDZ, 2018]	German Ordinance for co-incineration in cement kilns (17. BImSchV 2013), valid for operating plants as of 01.01.2019
Dust, total	range 0-9; average about 2.5	10 1) (5) 2)
NOx	range 150-500; average about 300	200 1) (150) 2)
Organic compounds as TOC	range 0-150; average about 25	10 3)
CO	range 0-3800; average about 800	4)
Hg	range 0-0.026; mostly < 0.015	0.03 3)
NH3 (in case of SCR/SNCR)	range 0-80; average about 25	30 1) (10) 2)
HCl	range 0-16; mostly < 5	10
HF	range 0-0.5; mostly < 0.25	1
SOx expressed as SO2	range 0-380; more than half < 50	50 3)
Cd + Tl	Cd mostly < 0.01; Tl < 0.005	0.05 2)
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	(low values, partly < detection limit)	0.5 2)
PCDD/F	range 0-0.00000007; mostly < 0.00000001	0.0000001 2)

1) Intensified limit values compared to the German Ordinance 17. BImSchV 2003 (total dust 20 mg/m³, NO_x 500 mg/m³, NH_3 no limit)

2) Limit values for co-incineration in cement plants in case more than 40% of the thermal firing capacity is provided by hazardous waste

3) The regulatory authority can approve for exceptions if appropriate due to the composition of the mineral raw materials, but mercury emissions must not exceed 0.05 mg/Nm³

4) To be determined by regulatory authority

Emissions on EU level are available from the adapted Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide [BREF, 2013]. Based on this, the European Commission established BAT conclusions in its commission implementing decision [EU, 2013]. The BAT-associated emission levels (AEL) of the decision are presented in Table 12.

Table 12. BAT-associated emission levels of the EU Commission implementing decision (EU 2013)

Air pollutant	BAT-associated emission levels	comment
Dust	daily average < 10-20 mg/Nm^3	from flue gases of kiln firing processes
NOx	daily average < 200-450 1) mg/Nm^3 daily average < 400-800 2) mg/Nm^3	for preheater kilns for Lepol and long rotary kilns
Organic compounds as TOC	-	BAT is to avoid feeding raw materials with a high content of volatile compounds
CO	-	description to reduce CO trips
NH3 slip	daily average < 30-50 3) mg/Nm^3	when SNCR is applied
HCl	daily average < 10 mg/Nm^3	also for average over the sampling period (at least half an hour)
HF	daily average < 1 mg/Nm^3	also for average over the sampling period (at least half an hour)
SOx expressed as SO2	daily average < 50-400 mg/Nm^3	range takes into account the sulphur content in the raw materials
Hg	< 0.05 4) mg/Nm^3	average over the sampling period (at least half an hour)
Cd + Tl	< 0.05 mg/Nm^3	
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	< 0.5 mg/Nm^3	
PCDD/F	< 0.05-0.1 ng/Nm^3	average over the sampling period (6-8 hours)

1) The upper level of the BAT-AEL range is 500 mg/Nm^3, if the initial NO_x level after primary techniques is > 1000 mg/Nm^3

2) Depending on initial levels and NH_3 slip

3) NH_3 slip depends on the initial NO_x level and the NO_x abatement efficiency. For Lepol and long rotary kilns, the level may be even higher

4) Values higher than 0.03 mg/Nm^3 have to be further investigated. Values close to 0.05 mg/Nm^3 require consideration of additional techniques (e.g. lowering of the flue-gas temperature, activated carbon)

In general, the BAT-AELs are less strict or equal to the emission limit values of the German Ordinance 17. [BimSchV, 2013] and emissions from German cement plants on average are either below these values or at the lower range. The comparison depicts that German cement kilns on average represent a rather high state-of-the art according to the cleaning technology in cement kilns. In this LCA study, the average German transfer coefficients and emission factors are applied, since these are considered to be more suitable than the EU BAT values. Using the German values is in favor of the co-incineration process as higher transfer coefficients and higher emission factors would result in higher impacts from the co-incineration. Using the data for Germany is thus considered a worst case assumption in the comparison with material recycling. Additionally, Germany is the largest cement producer in the EU28 [CEMBUREAU, 2018].

The emission factors for fossil methane, dinitrogen oxides, BaP and PCDD/F are based on [Villanueva et al., 2008] and Schmidt et al. (2009) either because no current information is available or because the emission factors seem valid compared to the graphed values in [VDZ, 2018].

The NOx and NH3 values are based on the German limit values, although the estimated averages are higher. This is based on the expectation that the operating plants in Germany will implement improvements in order to comply with the limit values. Deviating from the average concentrations of [VDZ, 2018] the stricter limit value for NOx is assumed to be complied with, but also the less strict NH_3 limit value, considering that some of the plants with SNCR technology[11] will increase the ammonia solution input to minimize the NOx emissions. In total, this assumption is also in favor of the co-incineration treatment method compared with material recycling of tyres.

Table 13. Estimated concentrations (in mg/Nm³)

Air pollutant	Emission factor	Source
Particulate matter (PM10)	2.6	[VDZ, 2018]
Dust (>PM10)	0.4	[VDZ, 2018]
Dust, total	3	[VDZ, 2018]
NO_x	200	17. BlmSchV
NH_3	30	17. BImSchV
CO	800	[VDZ, 2018]
CH_4, fossil	0.5	(Villanueva et al. 2008, Schmidt et al. 2009
N_2O	1	(Villanueva et al. 2008, Schmidt et al. 2009
PAH (excl. BaP)	0.115	[VDZ, 2018]
BaP	0.00001	(Villanueva et al. 2008, Schmidt et al. 2009
PCDD/F	0.00000001	[VDZ, 2018] and (Villanueva et al. 2008, Schmidt et al. 2009

6.8.2. Avoided processes

Co-incineration of tyres in a cement kiln substitutes fuels and the non-combustible parts of the tyres (inert materials, steel) replace primary materials that would otherwise be needed for the clinker production. The steel parts substitute a part of the iron ore that is otherwise introduced in the process. The inert fraction is not relevant for used tyres, as they have a lower ash content than the substituted solid fossil fuels (1%) and most of the other alternative waste fuels (up to 13-15%) [Schmidt et al. 2009].

The source of information is [ifeu, 2018] unless otherwise specified.

Substituted materials - Steel in tyres

[11] In 2017, in Germany 37 cement plants were equipped with SNCR and 4 with SCR.

The modelling of substituted new steel is described in Chapter 6.6.

It has to be considered that the scrap content of the co-incinerated used tyres substitutes not only iron ore, but also residues from the iron and steel industry used by the cement industry. This portion, being wastes, does not imply any benefit of iron ore substitution. Only the portion of primary iron used in the cement production process is credited. In 2017, this portion was 61.6% [VDZ, 2018]. The same proportion is assumed to apply in a 10 year horizon based on the historic development since 2000 and the assumption that steel residues will still be generated in the future [ifeu, 2018].

The substituted waste fuels also contain iron scrap (mainly from the 5.6% by mass of used tyres, and in addition by the 23.6% by mass of other industrial/commercial waste). This iron input, which is replaced by tyres, is subtracted from the credited amount of primary iron [ifeu, 2018].

Substituted fuels (fossil and other wastes)

Precise statistical data on fossil fuels used in cement kilns on the EU level is not available. Instead, as a proxy, data for the Germany cement industry is used since Germany is the largest cement producer in the EU28, [CEMBUREAU, 2018]. In Germany the main fossil fuels used are lignite and coal, see Table 14, whereas the fossil fuels used in the EU in average are mainly coal and pet coke. In [CEMBUREAU, 2013] a fuel mix of 60% alternative fuels, 30% coal and 10% pet coke is used to calculate future developments, which implies a relation for coal and pet coke of 75:25 for the EU average.

German cement kilns use one of the highest shares of waste as fuels in the EU (65% in 2017). According to CEMBUREAU (2018) currently only 43% of the fuel need in the EU is supplied by alternative fuels taken from different waste streams. The share of waste fuels in the European countries, which also have large cement production, is lower or much lower than it is in Germany (13% in Italy, 37% in France, 52% Poland, 23% in Spain, [ifeu, 2018].

The substitution/replacement of fossil fuels implies greater environmental benefits than does the replacement of other waste materials in the cement production. For this reason, using the German average fuel mix is not favorable for the co-incineration scenario in comparison with the material recycling scenario. Therefore, in this study the share of waste fuels is 43% in accordance with [CEMBUREAU, 2018], whereas the types of waste fuels and the share of different fossil fuels is based on the fuel inputs to German cement kilns as shown in Table 14. The column "Conservative approximation for Europe" in Table 14 lists the fuels, which are substituted in the co-incineration tyre treatment route in this study.

In the sensitivity analysis, two calculations are completed to assess an alternative expected future scenario as well as an extreme case and thereby test the sturdiness of the LCA conclusions.

The average fuel input composition to cement plants in Germany is shown in Table 14.

Table 14. Fuel input in German cement kilns 2017 and conservative estimate of fuel input in Europe (percent by energy content)

FUEL INPUT TO CEMENT KILNS	Germany 2017 [VDZ, 2018]	Conservative approximation for Europe
Hard coal	8.5%	13.8%
Lignite pulverized	21.1%	34.4%
Pet coke	3.6%	5.9%

Heavy fuel oil	0.5%	0.8%
Light fuel oil	0.7%	1.1%
Natural and other gases	0.5%	0.8%
Other fossil fuels	0.1%	0.16%*
Total fossil fuels	**35.0%**	**57%**
Used tyres	5.8%	3.8%
Waste oil	2.1%	1.4%
Pulp, paper, cardboard	0.4%	0.3%
Plastics	16.1%	10.7%
Packaging waste	0%	0%
Textiles	0%	0%
Other industrial/commercial waste	23.6%	15.6%
Animal fat/meal	2.8%	1.9%
RDF from MSW	8.2%	5.4%
Others (distillation residues, oil sludge)	0.8%	0.5%
Waste wood	0.01%	0.01%
Solvents	3.4%	2.2%
Hydrosilicate ("Bleicherde")	0%	0%
Sewage sludge	1.8%	1.2%
Total waste fuels	**65.0%**	**43%**

* Other fossil fuels is modelled as 50/50 hard coal and pet coke

The composition of the mixed waste fuel input in 2017 is presented in Table 15. The compositions of the single waste types correspond to those used in [Schmidt A. et al, 2009], except for the calorific values, which are reported in [VDZ, 2018] and, which have been the basis for calculating the energy share of co-incinerated waste materials.

Table 15. Composition of mix of waste fuel input to cement kilns in Germany 2017

Parameter	Units	Waste input mix 2017
Calorific value	MJ/kg FM	17.57
Water	% FM	13.6
Ash content	% FM	12.8
Scrap content	% FM	1.8
Carbon, total	g/kg FM	426
Carbon, fossil	g/kg FM	254
Carbon, biogenic	g/kg FM	173
Sulphur	g/kg FM	2.7
Chlorine	g/kg FM	5.0
Fluorine	g/kg FM	0.1
Antimony	g/kg FM	0.006
Arsenic	g/kg FM	0.003
Cadmium	g/kg FM	0.007
Chromium	g/kg FM	0.1
Cobalt	g/kg FM	0.02
Copper	g/kg FM	0.4

Lead	g/kg FM	0.16
Manganese	g/kg FM	0.15
Mercury	g/kg FM	0.0003
Nickel	g/kg FM	0.04
Thallium	g/kg FM	0.0002
Tin	g/kg FM	0.02
Vanadium	g/kg FM	0.007
Zinc	g/kg FM	1.0

Sources: calculated based on data for calorific values from [VDZ, 2018], and other components as used in Schmidt et al. (2009)

The composition of the replaced fossil fuels (hard coal, lignite, pet coke, heavy and light fuel oil and natural gas) is provided in Appendix 1. These are the fossil fuels, which are not needed for the co-incineration process, if tyres are used instead.

6.8.3. Summary of LCI for co-incineration of tyres

The LCI data for the co-incineration treatment route is not repeated here, but Table 16 shows an overview of this LCI and were to find the data:

Table 16. Overview of LCI for co-incineration and where to find the data and data sources.

LCI data	Location reference:
Transport distance, transport means and pre-treatment of tyres	Chapter 6.8.1
Composition of tyres	Table 5
% replaced fuels (by energy content)	Table 14 (column "Conservative estimate Europe")
% of primary iron used in the cement production process.	Chapter 6.8.2
Composition of replaced fossil fuels	Appendix 1
Composition of replaced waste fuels	Table 15
Transfer factors	Table 10
Emission factors	Table 13

Based on the above LCI data, GaBi uses the Ifeu model to calculate the potential environmental impacts.

6.9. Transportation

Transportation of goods occurs throughout the system studied. Initially the tyres are collected and transported to the recycling plant or to the cement kiln. We have assumed that the distances to these two types of facilities are equal.

The steelworks supplying steel to and receiving steel scrap from Genan is located in Kapfenberg, Austria [Genan, 2019]. Transport of recovered steel to the steelworks is omitted, since the replaced steel is assumed to be transported an equal distance. The textile fraction is send to Aalborg Portland in Aalborg, Denmark [Genan, 2019].

Table 17. Transportation inventory

TRANSPORT NEED:	DISTANCE:
Used tyres: From tyre collection to cement kiln / to Genan recycling plant	150 km
Steel for used knives (distance from steel supplier)	1439 km
Rubber granulate from Genan to artificial turf fields	300 km
Virgin infill material from producer to artificial turf fields	300 km
Main raw materials from suppliers to virgin infill production	500 km
Cryogenic rubber granulate from Genan to application	100 km
Virgin materials substituted by cryogenic rubber to application	100 km
Textile fraction from Genan to co-incineration	80 km
Steel fraction from Genan to steelworks and virgin iron ore to steelworks.	1439 km
Inert fraction from Genan to disposal	20 km
Avoided fuels to cement kiln	500 km

It was assumed that the products are transported by a typical Euro 4 type truck with a 27 ton payload capacity with a combination of motorway (70%), highway (23%) and urban roads (7%).

6.10. Economy of scale

Although the functional unit in this LCA study is one tonne, the systems analyzed are of a larger scale. In 2013, the EU used tyre ELT arisings were estimated at 2.6 million tonnes, of which an estimated 1.2 million tonnes were treated by material recovery and 1.4 million tonnes were treated by energy recovery [ETRMA, 2015]. For this reason, the consequences of decisions affecting the analyzed systems are of a larger scale.

Any theoretical shift of large volumes of used tyres being treated via co-incineration instead of material recycling could lead to a reduced need for fossil and waste fuels, which would be replaced by the used tyres. As regards fossil fuels, it is not likely that such a shift would impact the production or distribution facilities as the consumption for co-incineration is a small part of the general use of fossil fuels. As regards a reduced need for waste fuels, the shift may lead to more waste volumes being recycled or incinerated in regular incineration plants. However, the shift is not likely to influence the facilities for regular incineration and it is not possible to foresee any details of such a consequence.

On the other hand a theoretical shift of large volumes of used tyres treated via material recycling instead of co-incineration could lead to more virgin materials (primarily EPDM, TPE and limestone) being replaced, although it is also not the expectation that this would introduce a significantly reduced need for new facilities or changes in physical structures.

Based on the above discussed no consequences as regards the background capacity of any systems is modelled in this study.

7. Data quality assessment

In line with ISO 14044, data precision, completeness, representativeness, consistency and reproducibility are desired properties, which we have aspired to achieve as closely as possible. Several sources of information and data was used in the study and detailed discussions on data quality and representativeness for literature data are included in the specific sub-sections of the inventory, where they are presented. Therefore, the following assessment is focused on the overall data quality and the secondary datasets applied from the GaBi database.

Data for the Genan material recycling facilities

Primary data from Genan were all collected during 2018 and primo 2019. Manufacturing data including energy, water, ancillary material consumption, transport, material outputs as well as generation of waste materials is for the calendar year 2017.

Data for the application of recovered tyre derived rubber as infill in artificial football fields

The data regarding the use stage and lifetime of performance infills is subject to large uncertainties. For that reason, the conservative assumption that the replacement ratio of tyre derived rubber vs. virgin infills is 1:1 was made. The justification for this assumptions is provided in the inventory chapter 6.5.3.

The composition of virgin infill materials is also relatively uncertain. The best available information was applied, but precise information on composition and production processes is considered proprietary. The assumption that the virgin infills only contain 20% elastomer is considered a conservative choice as described in more detail in the sensitivity analysis in chapter 9.

The data for end-of-life route of performance infills being incinerated is considered a realistic scenario as described in chapter 6.5.5, but this aspect is also addressed in the sensitivity analysis.

Data for the co-incineration process

The co-incineration process including air emissions from incineration (or avoided incineration) of various materials is based on an ifeu model as described in [ifeu, 2018]. There is some uncertainty related to the data for air emissions from the co-incineration process as average European emission data is not available for most of the emissions. Therefore, primarily German emission and transfer factors were applied as these are reported annually by the cement kilns and these can be considered conservative approximations when comparing with the European BAT emission levels. In the same way, precise statistical data on fossil fuels used in cement kilns on the EU level is not available. Instead, as a proxy, data for the German cement industry is used since Germany is the largest cement producer in the EU28, [CEMBUREAU, 2018]. An exception to this is the share of waste fuels, which was reported for EU by CEMBUREAU, 2018.

A more detailed description was provided in chapter 6.8.

Secondary GaBi datasets

An overview of the main secondary datasets applied from the GaBi database in was shown in Table 3. The overview includes a quality analysis based on the following information about the datasets:

- The database / source
- The geographical coverage
- Year of representability / temporal validity
- GaBi quality indicator or other quality assessment
- Which life cycle processes they are used for in this study
- Comments regarding the technological representativity of the dataset

Most of the generic datasets applied in the study are consistent in the sense that predominantly datasets from thinkstep are used. Other data sources include one dataset from Worldsteel and three from ecoinvent.

The geographical coverage for most processes should be Europe as the study covers treatment of tyres in Europe. For the Genan facilities the geographical coverage shall be Germany and Denmark. Most applied secondary datasets in GaBi cover the applicable geographic area and where this was not available the best alternative match was selected.

The span of the data quality for thinkstep datasets is 1,5 – 1,8 based on the GaBi data quality indicator. This means they are all at least of good overall quality and can be considered adequate. The applied non-thinkstep datasets are all from acknowledged sources and verified in compliance with ISO14040 and 14044 according to the background documentation.

It was attempted to use data, which are as current as possible, and all the applied datasets are valid as regards the temporal data quality. Ecoinvent datasets are with reference year 2018, the Worldsteel dataset is with reference year 2014 whereas thinkstep data reference years are between 2016 and 2018.

The secondary datasets applied are selected to reflect the physical reality for the declared processes and in general it is assessed, that the applied secondary datasets are have good representativity as regards the technologies applied. Some of the incineration processes represent the incineration of similar, but different, materials than the materials, which are incinerated in the products systems. These secondary datasets were adjusted by FORCE Technology in accordance with the material properties of the specific materials incinerated. This concerns the generation of CO_2 emissions, electricity and heat.

Overall the data quality of the applied datasets is considered very good.

8. Life cycle impact assessment (LCIA)

This chapter presents the results of the modelling of potential environmental impacts of the two systems compared: co-incineration in cement kiln and material recycling. The material recycling is subdivided into five scenarios depending on the application of the recycled tyre rubber. The three main scenarios represent the use of the rubber as performance infill in artificial turfs, whereas two secondary recycling scenarios represent the use of cryogenic tyre derived rubber in applications where it replaces either carbon black or synthetic rubber.

First the total results are presented in a Table 19. For the infill and co-incineration scenarios, this is followed by a more detailed graphic presentation separately for each of the environmental impact categories with the exception of the most uncertain impact category, which are land use, eco-toxicity, the human health and the resource impact categories. The graphs shows the contributions from life cycle activities. The graphs are based on the 50/50% SEBS/EPDM infill scenario because the results of the two separate scenarios with

100% SEBS and with 100% EPDM infill replacement are very similar in the sense that the relative results throughout the life cycle in these scenarios are similar for most indicators. However, the disaggregated results for both 100% scenarios can be found in appendix 3 and the differences are discussed in the interpretation in Chapter 8.3.

All results are expressed *per functional unit* and the normalized results are presented in the next chapter.

8.1. Impact categories from the Life Cycle Inventory

All the applied environmental and resource impact categories are shown in Table 18, which also provides a short description of the impact categories. The corresponding characterization and normalization factors applied are EF 2.0. Biogenic carbon is excluded.

Table 18. Environmental impact categories

IMPACT CATEGORY	UNIT	EXPLANATION / EXAMPLES OF CONSEQUENCES
Climate change (fossil)	kg CO2-eq.	Climate change is the change in global temperature caused by the greenhouse effect that the release of "greenhouse gases" by human activity creates.
Acidification terrestrial and freshwater	Mole of H+ eq.	Some gases can result in acid rain, which can cause ecosystem impairment of varying degree, depending upon the nature of the landscape and ecosystems.
Eutrophication freshwater	kg P eq.	The accumulation of nutrients can cause damages to the freshwater, marine and terrestrial environments.
Eutrophication marine	kg N eq.	
Eutrophication terrestrial	Mole of N eq.	
Ozone depletion	kg CFC-11 eq.	Ozone-depleting gases cause damage to stratospheric ozone or the "ozone layer", which can result in an increase of ultraviolet UV-B radiation and skin illnesses.
Photochemical ozone formation – human health	kg NMVOC eq.	Photochemical ozone can cause smog. It is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight.
Ionising radiation - human health	kBq U235 eq.	Ionising radiation is a type of radiation composed of particles with enough energy to liberate an electron from an atom or molecule. Effects include health decline, cancer, illness etc.
Respiratory inorganics	Disease incidences	Small and varying sized particles can e.g. cause respiratory problems and health decline

Ecotoxicity freshwater	CTUe	The emission of some substances can have toxic impacts on the freshwater ecosystem
Cancer - human health	CTUh	Cancer
Non-cancer human health effects	CTUh	Effects on human health, which are not related to cancer
Land Use	Pt	The use of land can impact species loss, soil loss, amount of organic dry matter content, etc.
Ressource use, energy carriers	MJ	Resource depletion – energy
Ressource use, mineral and metals	kg Sb eq.	Resource depletion – minerals and metals
Water scarcity	m^3 world equiv.	Impact on water scarcity

8.2. Results

The total results for each of the modelled scenarios are represented in Table 19 and 20 below. Numbers in green indicate that the value is lower than the corresponding value for the co-incineration scenario.

Table 19. Total life cycle results for performance infill scenarios (green figures in the material recycling scenarios indicate that the impacts are lower than corresponding impact category in the co-incineration scenario).

IMPACT CATEGORY	Co-incineration	Material recycling (SEBS infill)	Material recycling (EPDM infill)	Material recycling (50/50 infill)
Climate change fossil (kg CO2-eq.)	-197	**-838**	**-972**	**-905**
Acidification terrestrial and freshwater (Mole of H+ eq.)	-0.801	**-2.61**	**-3.08**	**-2.84**
Eutrophication freshwater (kg P eq.)	-0.0039	0.000867	**-0.0136**	**-0.00635**
Eutrophication marine (kg N eq.)	-0.237	**-0.552**	**-0.648**	**-0.6**
Eutrophication terrestrial (Mole of N eq.)	-2.69	**-6.08**	**-9.48**	**-7.78**
Ozone depletion [kg CFC-11 eq.]	-3.37E-06	2.84E-06	-2.07E-6	3.83E-07
Photochemical ozone formation (kg NMVOC eq.)	-0.656	**-1.79**	**-2.12**	**-1.95**
Ionising radiation (kBq U235 eq.)	-3.15	**-204**	**-228**	**-216**
Respiratory inorganics (Disease incidences)	-4.38E-06	**-2.18E-05**	**-2.60E-05**	**-2.39E-05**
Ecotoxicity freshwater (CTUe)	26.6	**-8.59E+01**	**-1.35E+02**	**-110**
Cancer - human health (CTUh)	-1.46E-06	**-5.74E-06**	**-6.04E-06**	**-5.89E-06**
Non-cancer human health effects (CTUh)	4.99E-05	0.000103	9.10E-05	9.70E-05
Land Use (Pt)	-5.90E+02	**-4.18E+03**	**-5.18E+03**	**-4.68E+03**
Ressource use, energy carriers (MJ)	-1.02E+04	**-3.12E+04**	**-3.39E+04**	**-3.25E+04**
Ressource use, mineral and metals (kg Sb eq.)	-0.0000299	**-1.45E-04**	**-0.0501**	**-0.0251**
Water scarcity (m^3 world equiv.)	-12.6	**-8.18E+01**	**-8.62E+01**	**-84**

Table 20. Total life cycle results for cryogenic scenarios (green figures in the material recycling scenarios indicate that the impacts are lower than corresponding impact category in the co-incineration scenario).

IMPACT CATEGORY	Co-incineration	Material recycling (cryo – carbon black)	Material recycling (cryo – synthetic rubber)
Climate change fossil (kg CO2-eq.)	-197	**-1.46E+03**	**-1.95E+03**
Acidification terrestrial and freshwater (Mole of H+ eq.)	-0.801	**-2.53**	**-1.52**
Eutrophication freshwater (kg P eq.)	-0.0039	0.00592	0.00442
Eutrophication marine (kg N eq.)	-0.237	0.229	**-0.425**
Eutrophication terrestrial (Mole of N eq.)	-2.69	2.27	**-4.87**
Ozone depletion [kg CFC-11 eq.]	-3.37E-06	9.08E-06	9.08E-06
Photochemical ozone formation (kg NMVOC eq.)	-0.656	-0.253	**-2.05**
Ionising radiation (kBq U235 eq.)	-3.15	90.7	65.3
Respiratory inorganics (Disease incidences)	-4.38E-06	**-0.000151**	-3.26E-06
Ecotoxicity freshwater (CTUe)	26.6	**-407**	**-277**
Cancer - human health (CTUh)	-1.46E-06	**-2.39E-05**	**-1.89E-05**
Non-cancer human health effects (CTUh)	4.99E-05	**2.16E-05**	**-0.000641**
Land Use (Pt)	-5.90E+02	1.10E+04	8.29E+03
Ressource use, energy carriers (MJ)	-1.02E+04	**-3.21E+04**	**-4.85E+04**
Ressource use, mineral and metals (kg Sb eq.)	-0.0000299	0.000514	0.000439
Water scarcity (m^3 world equiv.)	-12.6	14.3	**-16.4**

The two recycling scenarios with 100% SEBS and with 100% EPDM infill replacement are very similar and the relative results throughout the life cycle in these scenarios are similar for most indicators. For this reason and for the sake of simplicity, the disaggregated results in the following are only shown graphically for the 50/50 SEBS/EPDM infill scenario. However, the disaggretated results for both 100% scenarios can be found in appendix 3 and the interpretation in Chapter 8.3 will discuss the differences.

All graphs in the following are structured in the same way as the below graph for climate change. The unit is written vertically to the left of the graph. The material recycling (rubber recycled for performance infill) results are shown in the left part of the figure, whereas the co-incineration results are presented to the right. The blue uni colored bars shows the aggregated results, i.e. the net balance of positive and negative values from the multi-colored bars. The multi-colored bars show the contributions from each of the life cycle activities as indicated in the legend.

The life cycle activities shown are: Transport, material recycling (at Genan), EOL infill (end-of-life of virgin infills), EOL (end-of-life of the tyre derived rubber), co-incineration, benefit steel recycling, benefit ore co-incineration, benefit infill (replacement of virgin infills), benefit fuel co-incineration (replacement of other fuels in cement kilns). Negative contributions to the potential environmental impacts are the results of avoided negative environmental impacts. For example potential environmental impacts are avoided by replacing fossil fuels in cement kilns or by replacing virgin infills with recycled tyre derived infill.

When assessing whether the change from co-incineration in cement kilns to material recycling will result in reduced or increased potential impacts on the environment, it is the difference between the blue bars that provides the answer.

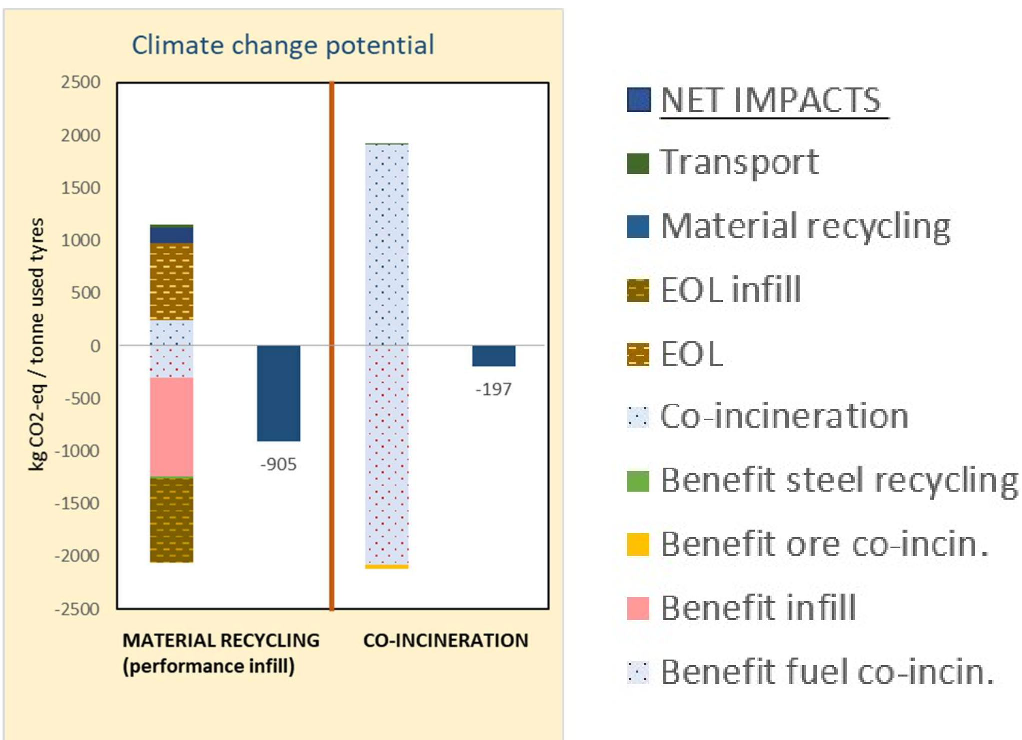

Figure 11. Climate change results (50/50 SEBS/EPDM scenario)

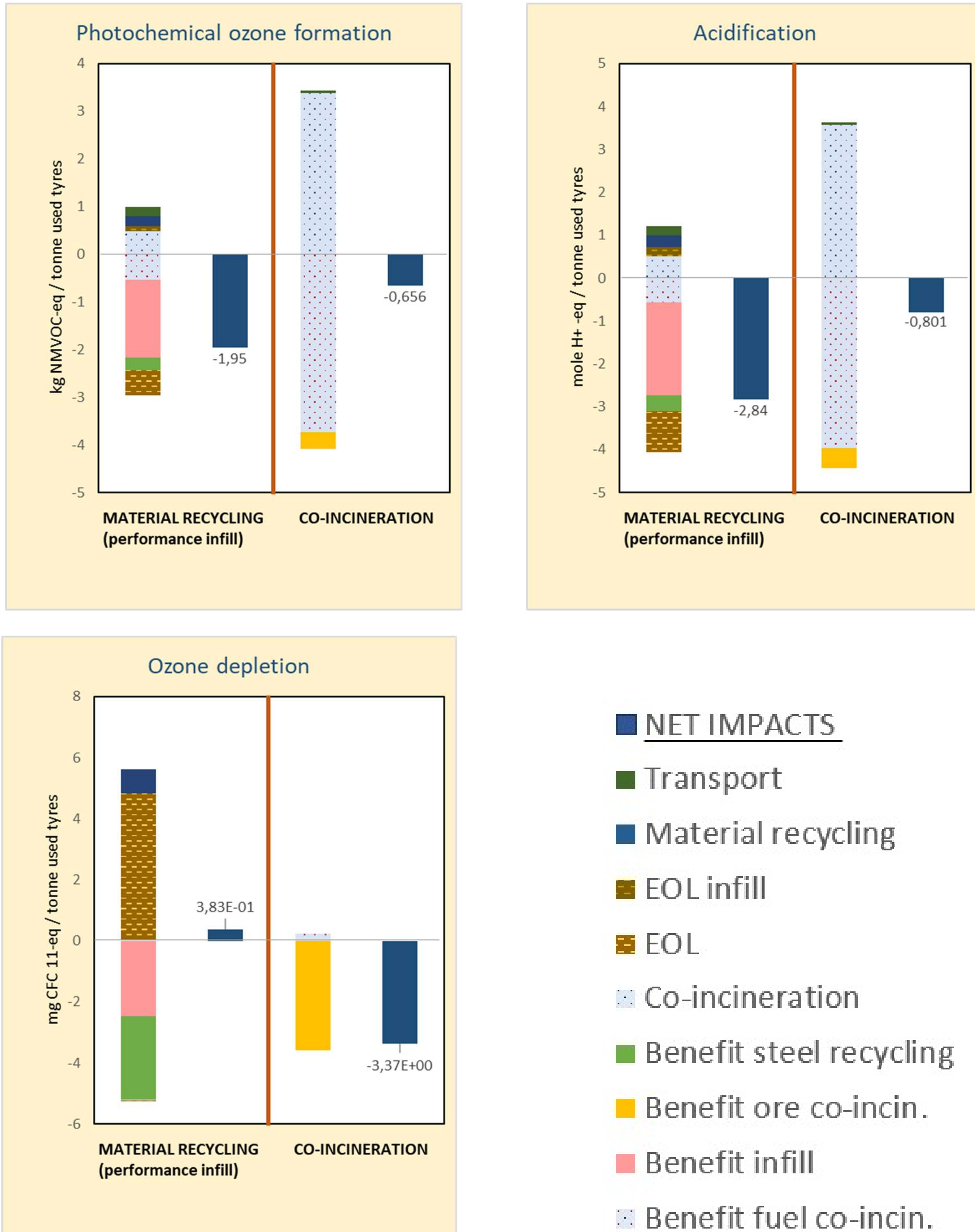

Figure 12. Photochemical ozone formation, acidification and ozone depletion potentials (50/50 SEBS/EPDM scenario)

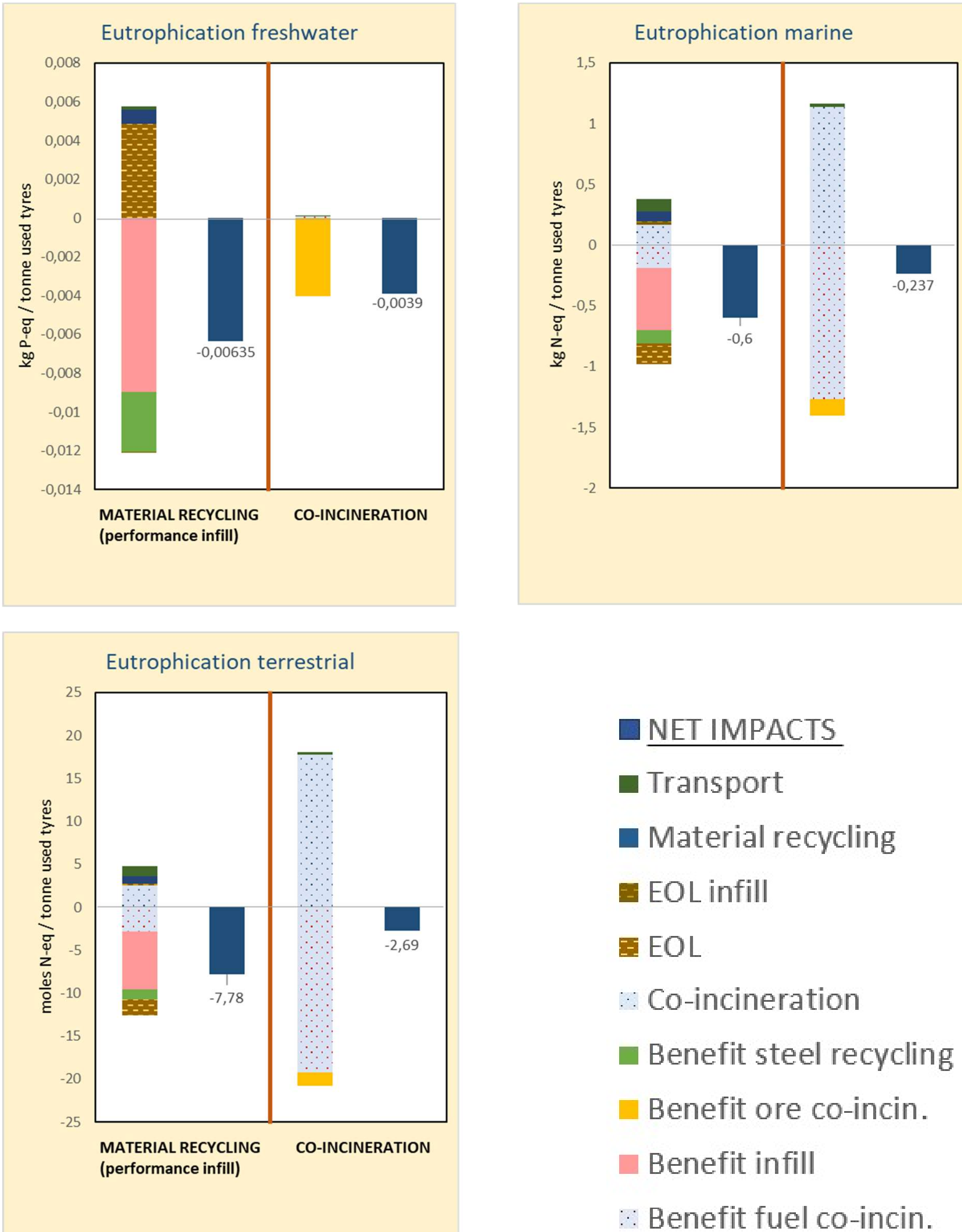

Figure 13. Eutrophication results (50/50 SEBS/EPDM scenario)

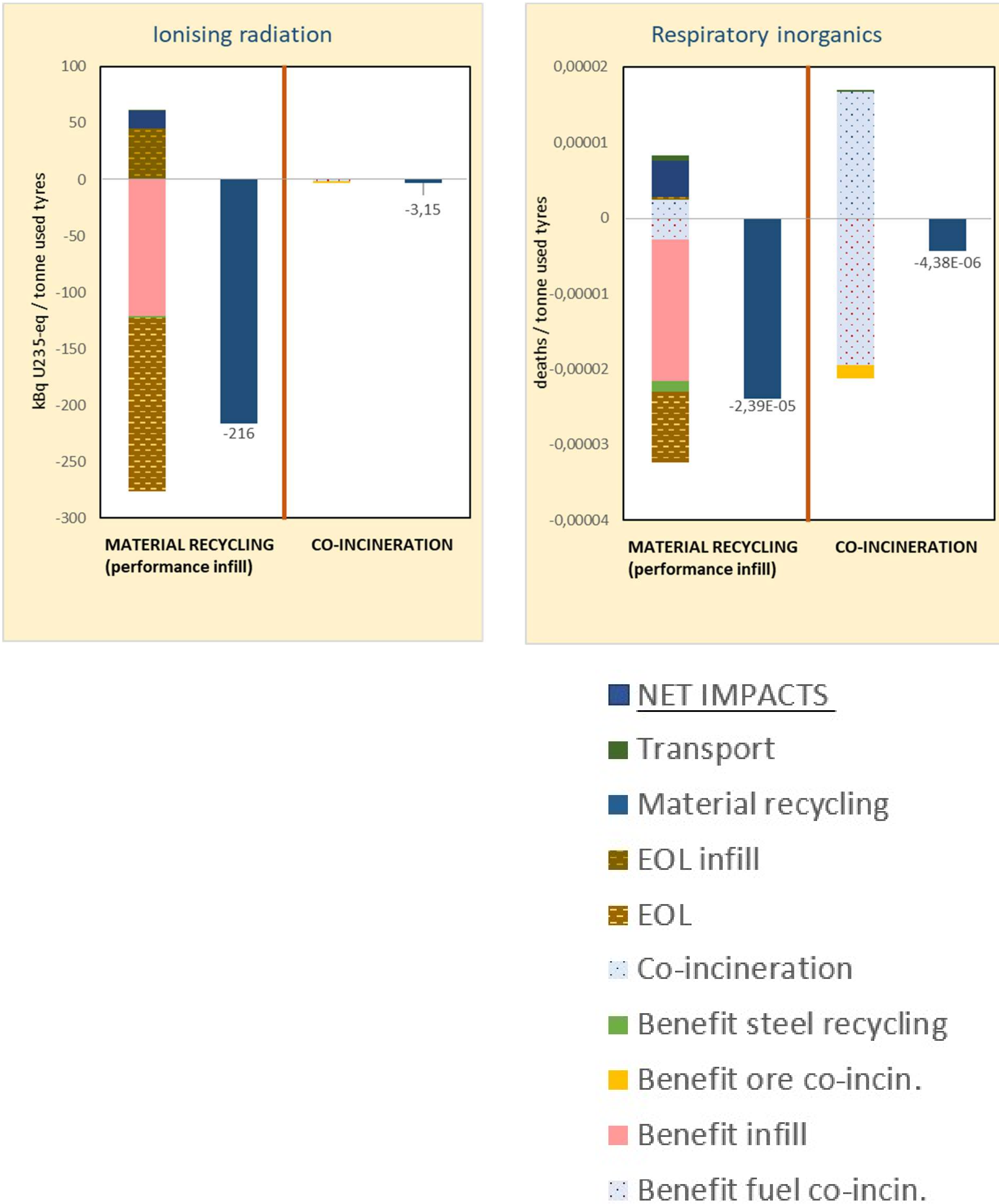

Figure 14. Results for ionising radiation and respiratory inorganics (50/50 SEBS/EPDM scenario)

The following two figures show the life cycle results for the two cryogenic scenarios, where the recovered rubber replaces either carbon black or synthetic rubber. The results include all the potential environmental impacts in one graph except for the most uncertain ones which have been left out. The results have been indexed with the Production stage being set at index 100. This means that all other stages are shown relative to the production stage (which includes raw materials, recycling activities at Genan and treatment of output materials from Genan except the rubber). The reason for indexing the results is so that all impact categories can be shown in the same graph where the importance of each life cycle stage is shown relative to one another. EOL stands for end of life and BF replaced carbon black stands for the benefits of replacing carbon black. BF replaced synthetic rubber stands for the benefits of replacing synthetic rubber.

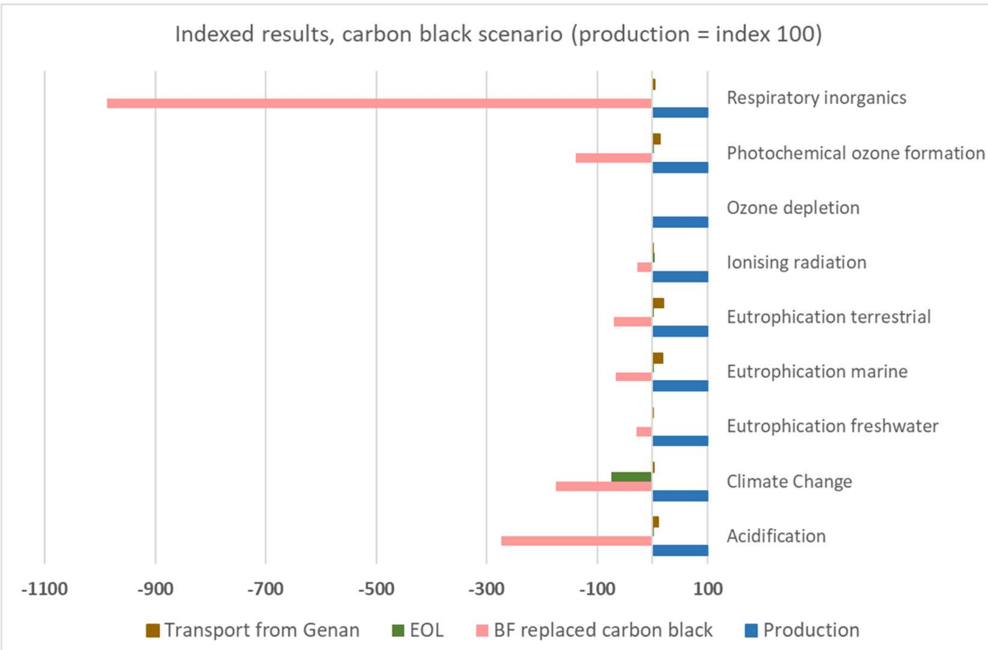

Figure 15. Indexed results for the carbon black scenario

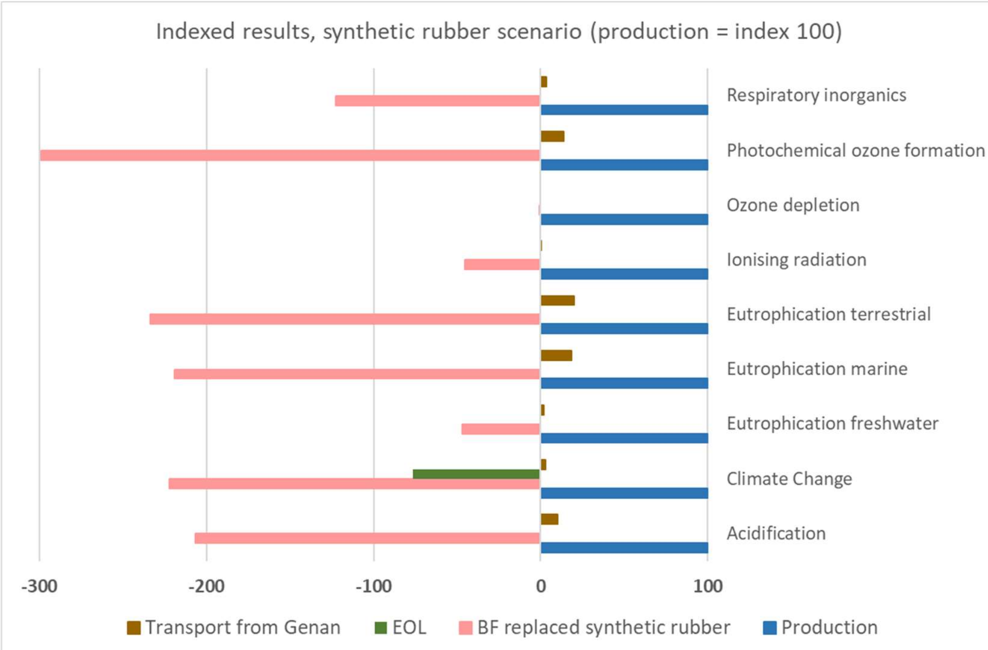

Figure 16. Indexed results for the synthetic rubber scenario

The full and not indexed results for the two cryogenic scenarios are provided in Appendix 4.

8.3. Life cycle interpretation

When comparing the material recycling scenarios (rubber used as performance infill) with each other, then Table 19 shows that all environmental impact categories are better when 100% EPDM performance infill is replaced in comparison with the scenario where 100% SEBS performance infill is replaced. However, for most of the impact categories the results are in the same order of magnitude. The 50/50% SEBS/EPDM infill scenario is, naturally, an average of the two other scenarios.

Table 19 also shows that material recycling (rubber used as performance infill) has a lower impact in 14 out of 16 impact categories compared with co-incineration when the replacement infill scenarios are 100% EPDM or 50/50 SEBS/EPDM. The two exceptions are ozone depletion and non-cancer human health effects. The impact category for non-cancer human health effect is associated with a large degree of uncertainty in the underlying LCA method as is also the case for all the human and ecotoxicity impact categories. The results are similar when the replacement infill scenario is 100% SEBS except for the impact category eutrophication freshwater, which in this case is lower when the tyre treatment route is co-incineration. That means, that when the scenario is 100% SEBS, then only 13 out of 16 impact categories are lower for material recycling in comparison with co-incineration.

The potential climate change impact category is 76 - 80% lower in the material recycling system compared with the co-incineration system. Expressed in another way, the potential climate change benefit from the material recycling (infill) is 4.3 - 4.9 times greater in comparison with the potential benefit from the co-incineration of used tyres. The most favorable climate change results are obtained in the 100% EPDM scenario and the 50/50 EPDM/SEBS scenario is again in the middle of the two other infill scenarios.

Detailed results for the co-incineration treatment route:

The detailed life cycle results, depicted in Figure 11 to Figure 14 show, for the co-incineration treatment route, that most of the analyzed potential environmental impacts come from the co-incineration process itself and the net-negative/avoided impacts come mainly from the replacement of co-incinerated fuels. Exceptions are the ozone depletion potential and the freshwater eutrophication, both of which are dominated by a replacement of iron ore, due to recycling of recovered iron from the incinerated tyres. The co-incineration system has little potential impact on ionising radiation.

The reason why most of the net-positive analyzed potential environmental impacts come from the co-incineration process itself is the air emissions. For example, the incineration of rubber in the tyres lead to CO_2 emissions, which contributes to potential climate changes. Other examples are nitrogen oxides and dusts emissions, which contribute to the respiratory inorganics impact.

As mentioned above, the net-negative contributions mainly come from the replacement of co-incinerated fuels. This is because, when tyres are co-incinerated in cement kilns, then the energy in the tyres is utilized in the co-incineration process and in turn the need for other energy sources is reduced. As described in chapter 6.8.2, the co-incineration system is therefore credited for the production of the replaced fuels as well as for the air emissions from co-incinerating these fuels. However, the results for ozone depletion potential and freshwater eutrophication potential show that there is not much benefit related to the replaced fuels, since co-incinerating the fuels do not cause many emissions of substances, which contribute to ozone depletion or freshwater eutrophication. Instead, the replaced iron ore lead to benefits within these two impact categories. The reason why iron ore is replaced is because the tyres contain iron, which is recovered from the co-incineration process and is subsequently recycled.

Detailed results for the material recycling infill treatment route:

The detailed results generally show a very similar picture with regards to the relative importance of each of the activities throughout the life cycle of this tyre treatment route regardless of which infill scenario is applied. Exceptions are for the environmental impact categories ozone depletion and eutrophication freshwater. For both of these impact categories the benefits related to avoided production of virgin infill is notably greater if 100% EPDM infill is avoided as opposed to if 100% SEBS infill is avoided.

The detailed results for the material recycling treatment route (all infill scenarios) show different dominating contributions for the various environmental impact categories. However, in general the replacement of virgin infills contributes with net savings on potential environmental impacts and the material recycling at the Genan facilities have a low contribution to the results. For most of the environmental impact categories the Genan facilities contribution is less than 6% of the total numerical impacts (all infill scenarios). The impact category, where the Genan facilities have the greatest relative contribution, is for land use, where the contribution is 18% when the infill scenario is 100% SEBS.

The net savings on potential environmental impacts, due to replacement of virgin infills, implies avoiding the production of virgin infills as well as avoiding the end-of-life incineration of those same virgin infills. The general picture is that the greatest benefits are related to the avoided production of virgin infills – with two exceptions. One exception is for the results for ionising radiation, which show that the greatest negative contribution comes from the avoided incineration of infill at the end of life (all infill scenarios). The other exception is only applicable for the 100% EPDM infill scenario and it is for the environmental impact ecotoxicity freshwater, where the benefits related to avoided incineration of virgin infill implies the greatest benefits. This is because production of the virgin infills requires extraction of raw materials, production of infills and transportation. When virgin infills are incinerated at the end of life this leads to emissions from the incineration process, but it also generates energy in the form of electricity and heat. Therefore the avoided end of life of virgin infills lead to negative as well as positive potential environmental impacts.

The benefit related to recycling iron ore from the tyres primarily contribute to the potential environmental impacts ozone depletion and eutrophication freshwater. These findings are in line with the results for the co-incineration treatment route, which also showed benefits from iron recovery within these two impact categories.

In general the co-incineration of the textile fraction does not contribute much to the results, but those indicators, where the contribution from this fraction is even visible in the figures 11-14 (climate change, photochemical ozone formation, acidification, eutrophication marine, eutrophication terrestrial and respiratory inorganics) show that the net negative and the net positive contributions are almost equal although the net negative values are slightly greater, which implies a small benefit from co-incinerating the textile fraction, which is recovered from the tyres.

Results of cryogenic rubber scenarios:

For the tyre material recycling resulting in cryogenic rubber replacing carbon black, Table 20 shows that material recycling has a lower impact in 7 out of 16 impact categories in comparison with the co-incineration tyre treatment method. The potential climate change impact from the cryogenic-carbon black scenario is more than 7 times lower than it is when the tyres are treated with the co-incineration method.

For the tyre material recycling resulting in cryogenic rubber replacing synthetic rubber, Table 19 shows that material recycling has a lower impact in 10 out of 16 impact categories in comparison with the co-incineration tyre treatment method. The potential climate change impact from the cryogenic-synthetic rubber scenario is more than 9 times lower than it is when the tyres are treated with the co-incineration method.

An analysis of the environmental contributions across the life cycle shows that the cryogenic milling line contributes with 940 kg CO2 eq to the climate change impact category. This is significantly more than the other material recycling processes, which contribute with 140 kg CO2 eq, and is mainly due to the relatively large electricity consumption for this process, but also the use of liquid nitrogen for cooling. The reason why the end result is still more favorable in the climate change impact category is, that the benefits related to the avoided/replaced virgin materials (carbon black and synthetic rubber) are even greater than the benefits related to the replaced virgin infill materials. The reason for this is that the virgin infill materials contain a large amount of fillers (chalk), which have a lower carbon footprint in production compared with carbon black and synthetic rubber.

Figure 15 and Figure 16 shows that the most significant contributions to the net positive environmental impacts generally stem from the production at Genan (including raw materials and treatment of other output materials than rubber). The figures also shows that the most significant contributions to the net negative environmental impacts generally stem from the avoided production of either carbon black or synthetic rubber. Transportation from Genan and end of life are generally less significant except for climate change where the end of life benefit due to avoided incineration of either carbon black or synthetic rubber is relatively significant an contributes with approximately 20%.

In these two cryogenic rubber scenarios Genan refines the recovered tyre rubber by cryogenic processing with the aim to increase the value of the rubber and be able to replace more high value virgin materials (in this study carbon black or synthetic rubber). Regarding the environmental problem climate change the results show that this is a good idea. When looking more broadly across environmental impacts there is no final conclusion to say which material recycling scenario is the better one.

Considering that not all potential environmental impacts are in favor of neither the co-incineration method nor the material recycling methods, which results in the recycling of cryogenic rubber powder, the overall results are analyzed further by normalization in Chapter 8.4.

8.4. Normalization

For the reader not familiar with LCA terminology, and indeed also for the LCA experts, the units used to express impact assessment, such as CO_2-equivalents, SO_2-equivalents or PM-10-equivalents, can be difficult to grasp: it is difficult to get an impression of the order of magnitude of the potential impact of a difference between recycling and co-incineration of, say, 100 kg of CO_2-equivalents. Is such a difference big or small, compared to other human activities? The LCA methodology can also express impacts in a more intuitive way, by comparing them to the average impacts of a global citizen. This procedure is called normalization.

The normalized impacts are calculated by relating the impact potential of each category by a normalization reference, representing the total impact by one global citizen in a given year. It is noted, however, that normalization is according to ISO 14040 only an additional optional value judgement based on the LCA results. One of the reasons for this is that normalization factors are relatively uncertain. The normalization results must be interpreted with this in mind.

The normalized results are expressed as person equivalents (PE) or milli person equivalents (mPE) per functional unit and the normalization factors applied are EF 2.0.

It shall be noted that the scale in Figure 17 below shows negative values !

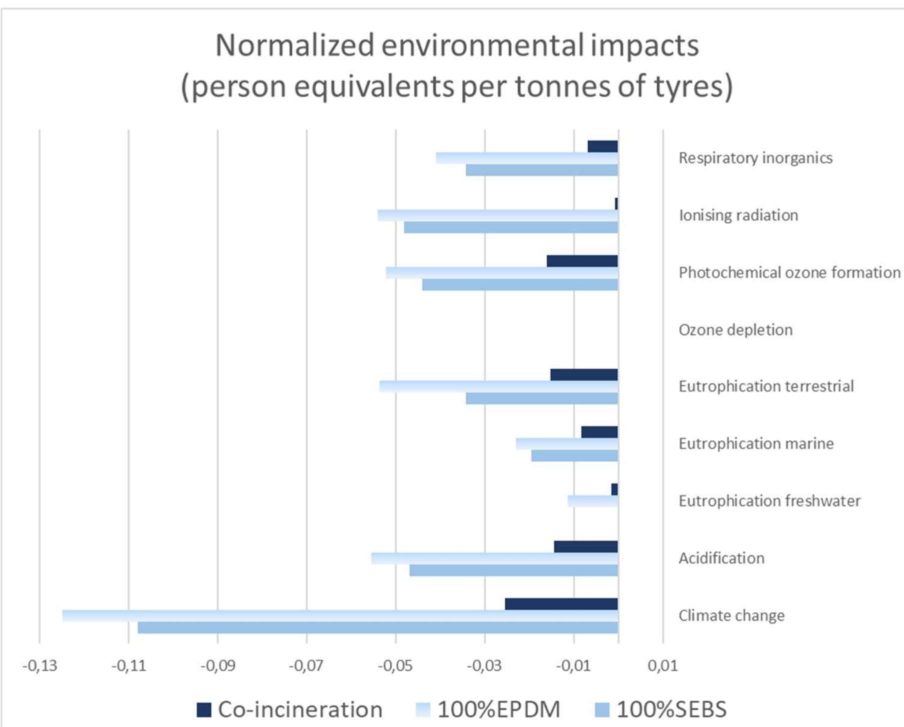

Figure 17. Normalized potential environmental impacts from different treatment options of one tonne of tyres – application of recycled rubber as infill

Figure 17 shows the normalized impacts for the material recycling method using rubber as infill in comparison with the co-incineration treatment method for used tyres. Only the scenarios where 100% SEBS or 100% EPDM performance infills are avoided are depicted in the figure, because the 50/50 scenario is an average of the two 100% scenarios.

For all impact categories the normalized impacts for the co-incineration system are higher than the normalized impacts for the material recycling system (infill) and for most impact categories it is a notable difference. One exception is ozone depletion, where the impacts are so small that they do not show in the graph. For the 100% SEBS infill scenario another exception applies for eutrophication freshwater, where the 100% SEBS scenario contribution to this impact is so small that it does not show in the graph.

The normalized values for climate change are the largest (most negative) and the savings on climate change in the material recycling system corresponds to more than 0.1 global persons contribution to climate change during one year for all material recycling performance infill scenarios. In comparison the co-incineration system saves less than 0.03 person equivalents in the climate change category.

Normalization of cryogenic rubber scenario results:

It shall be noted that the scale in Figure 18 *below shows negative values !*

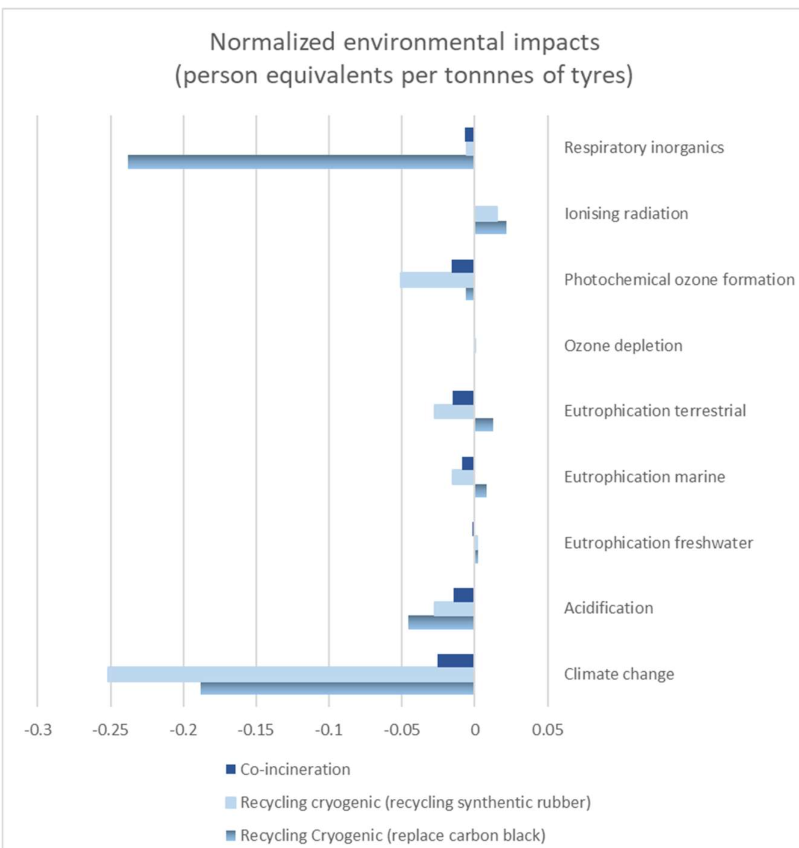

Figure 18. Normalized potential environmental impacts from different treatment options of one tonne of tyres – applications of recycled cryogenic rubber

Figure 18 shows the normalized environmental impacts for the two cryogenic scenarios of material recycling against the co-incineration method for used tyres. The impact category, which shows the greatest (negative) contribution to the person equivalents is climate change, although for the recycling scenario where carbon black is replaced the savings on respiratory inorganics is even higher and much higher than both of the other scenarios. For both cryogenic scenarios, the contribution to climate changes is in the range of 7-10 times lower in comparison with the co-incineration treatment method.

9. Sensitivity analysis

In the sensitivity analysis, the robustness of the results is discussed, and the importance of the main assumptions and uncertainties are tested. Additionally, the applicability of the results when considering expected future developments in the analyzed systems is addressed.

The sensitivity analysis contains the results of further investigations on the variables that have been found to be of most influence to the conclusions of the comparison of the treatment methods. These variables are:

- Energy sources used for cement production (fossil fuels and waste)
- The ratio of primary iron ore sources for steel production and for cement co-incineration
- End-of-life of recycled and virgin infills (incineration vs. landfill)

Other assumptions are also considered to be significant to the results, but are not expected to change the conclusion, because a further investigation of the results are expected to be in favor of (or neutral for) the material recycling system. The material recycling system already show the lowest potential contribution to most of the environmental impacts. These assumptions are therefore qualitatively addressed and they are:

- Lifetime and refill of performance infills during the use stage
- The assumption that the CO_2 emitted during incineration of natural rubber is CO_2 neutral
- The relative quantity of rubber in virgin infills is assumed to be 20%. If this were assumed to be higher, then more rubber would be replaced instead of filler materials and this would benefit the material recycling system.

The following uncertainties are not further addressed, because they are considered to be of low importance for the results:

- Differences between Genan production sites including the differences in electricity grid mix in Germany vs. Denmark. In general the recycling processes at the Genan facilities do not contribute much to the potential environmental impacts as described in the interpretation of results in chapter 8.3.

To the extent that the cryogenic recycled rubber scenarios would replace the virgin materials carbon black or synthetic rubber in different ratios than assumed, the results for these recycling scenarios can be scaled up or down accordingly.

9.1. Energy sources for cement production

The results for the co-incineration treatment route showed that the benefits related to replaced fuels in the cement kilns are very important for all the results with the exceptions of ozone depletion, eutrophication freshwater and ionising radiation. In this respect, the quantity of replaced waste fuels is a key assumption because the replacement of fossil fuels implies greater environmental benefits than does the replacement of other waste materials in the cement production. No benefits related to production of replaced waste fuels is included. When fossil fuels are replaced then the production of these fuels are credited the co-incineration system. Additionally, the quantity of replaced waste fuels represents the greatest uncertainty with regards replaced fuels. As mentioned in chapter 39, co-incineration of waste is increasing in the EU and the European Commission included co-processing of waste in cement kilns in their recent Communication on Waste-to-Energy. For this reason, a sensitivity analysis was carried out assuming 65% waste fuels in cement kilns corresponding to the current German inputs of co-incineration waste fuels. The results are compared with the worst of the modelled recycling scenarios, which is the SEBS infill replacement scenario. This is done, because if the material recycling SEBS infill scenario turns out to still be better than the co-incineration sensitivity scenarios, then this conclusion will also hold for the other material infill recycling scenarios. The results are shown in Table 21 below.

Additionally, a sensitivity scenario is included, where it is assumed that only fossil fuels in the form of 50% hard coal and 50% lignite are replaced in the co-incineration in cement kilns. This scenario does not represent a current average, it also does not represent a current specific case, nor does it represent a future average. The reason for including this fossil scenario is to test the results with regards to extreme cases and to show the results assuming a consequential/marginal[12] energy supply to European cement kilns.

[12] The energy source, which is increased or degreased, if the demand changes a bit in the short term

Table 21. Sensitivity results: Energy sources for co-incineration in cement kilns (green figures in the last column indicate that the impact from the worst material recycling scenario (SEBS) is lower than each of the co-incineration scenarios).

IMPACT CATEGORY	Co-incineration (baseline)	Co-incineration (German fuel input to kilns)	Co-incineration (fossil / marginal)	Material recycling (SEBS infill)
Climate change fossil (kg CO2-eq.)	-197	69.2	-767	**-838**
Acidification terrestrial and freshwater (Mole of H+ eq.)	-0.801	-0.57	-1.36	**-2.61**
Eutrophication freshwater (kg P eq.)	-0.0039	-0.0037	39.7	0.000867
Eutrophication marine (kg N eq.)	-0.237	-0.179	-0.00423	**-0.552**
Eutrophication terrestrial (Mole of N eq.)	-2.69	-2.05	-0.426	**-6.08**
Ozone depletion [kg CFC-11 eq.]	-3.37E-06	-3.26E-06	-3.60E-06	2.84E-06
Photochemical ozone formation (kg NMVOC eq.)	-0.656	-0.494	-1.14	**-1.79**
Ionising radiation (kBq U235 eq.)	-3.15	-2.57	-3.81	**-204**
Respiratory inorganics (Disease incidences)	-4.38E-06	-2.86E-06	-9.00E-06	**-2.18E-05**
Ecotoxicity freshwater (CTUe)	26.6	34.2	39.7	**-85.9**
Cancer - human health (CTUh)	-1.46E-06	-1.22E-06	-5.37E-07	**-5.74E-06**
Non-cancer human health effects (CTUh)	4.99E-05	2.81E-05	9.08E-05	0.000103
Land Use (Pt)	-5.90E+02	-425	-1.01E+03	**-4.18E+03**
Ressource use, energy carriers (MJ)	-1.02E+04	-6.39E+03	-1.90E+04	**-3.12E+04**
Ressource use, mineral and metals (kg Sb eq.)	-0.0000299	-2.59E-05	-3.06E-05	**-1.45E-04**
Water scarcity (m^3 world equiv.)	-12.6	-9.33	-18.3	**-8.18E+01**

The sensitivity analysis for a fossil energy supply (50/50% hard coal/lignite) shows that 13 out of 16 impact categories are still lower in the material recycling system. However, many of the impact categories have gone down in comparison with the baseline co-incineration scenario. For example, the climate change impact category is only 15% lower in the fossil scenario than it is in the material recycling scenario. Here, it is noted, however, that the fossil scenario is considered an extreme case not representative of real life conditions.

The sensitivity analysis of the energy sources for cement production also show, that if the share of waste fuels increase, then 15 out of 16 impact categories would be higher than they are in the baseline co-incineration scenario. The one exception is the potential impact on non-cancer human heath effect, which is around 36% higher in the baseline scenario.

In general the results of this sensitivity analysis show that the results are sensitive to the energy sources for cement production. We consider a development towards a higher share of waste fuel inputs more likely than a decrease and this would shift the results further to the advantage of the material recycling system.

9.2. Steel recycling

The detailed results for the environmental indicators Europhication freshwater (Figure 13) and Ozone depletion (Figure 12) differ significantly from the the remaining indicators in the sense that the contributions from steel recycling is noticeably greater. Because steel recycling entails a replacement of virgin iron this is a benefit, meaning that the contributions to the environmental indicators are negative. As described in the inventory, chapters 6.6 and 6.8.2, only primary iron is replaced. This means that any replaced secondary iron sources are not credited in the tyre treatment systems.

Recycled steel from material recycling at Genan replaces iron sources in the production of new steel products and here it was assumed that the share of primary iron sources to average steel production is 63%. This figure from Worldsteel is for the global steel production. This figure was used because Worldsteel is considered a relevant source and steel is a commondity, which is extensively traded on the global market[13]. However, if the steel production were considered separately for the European production then the average share of secondary iron sources may be different. According to Eurofer[14] about 50%[15] of the EU steel production is derived from recycled steel scrap. A sensitivity assessment was therefore carried out assuming that the recycled steel only replaces 50% primary iron from iron ore. This sensitivity assessment was applied to the 50/50 SEBS/EPDM infill recycling scenario as a representative for each of the infill replacement scenarios as these do not differ with regards to steel recycling in production.

As regards the iron sources for co-incineration in cement kilns it was assumed that this was 62%. Based on the historical development, the availability of secondary iron sources varies over time [VDZ, 2018], and therefore the share of secondary iron for cement production could also change in the future. However, no other sources were identified in this study to predict a realistic range for the primary iron share. For this reason, a sensitivity analysis was carried out testing the extreme situation where 100% of the iron sources for co-incineration is from primary iron sources. With this assumption 100% of the recovered iron in the tyres is replacing primary iron from iron ores.

Both of the above assumptions in the sensitivity analysis are in favour of the co-incineration treatment route.

Since the steel recycling is primarily influencing the results for the environmental indicators Europhication freshwater and Ozone depletion, the results of the sensitivity calculations are only analysed for these two indicators. However, FORCE Technology has checked the calculations for the remaining indicators and the new assumptions in the sensitivity assessments do not change the ranking of the tyre treatment method for any of these other indicators.

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[13] https://www.trade.gov/steel/countries/pdfs/imports-eu.pdf

[14] The European Steel Association

[15] http://www.eurofer.org/Sustainable%20Steel/Steel%20Recycling.fhtml

Table 22. Sensitivity assessment – iron ore replacement ratios changed

IMPACT CATEGORY	Material recycling (50/50 infill)	Material recycling (50/50 infill - sensitivity)	Co-incineration (baseline)	Co-incineration (sensitivity)
Eutrophication freshwater (kg P eq.)	-0.00635	-0.00572	-0.0039	-0.00621
Ozone depletion [kg CFC-11 eq.]	-3.83E-7	9.44E-007	-3.37E-06	-5.44E-006

The results show that the changed assumptions regarding primary iron ore replacement (50% in steel production and 100% in cement production) has increased the eutrophication freshwater and Ozone depletion indicators for the material recycling (performance infill) treatment route and decreased the same indicators for the co-incineration treatment route. The eutrophication freshwater indicator is now 8% higher for tyre recycling (performance infill) compared with co-incineration of the tyres. With the original assumptions regarding steel recycling the difference was 63% in favor of the material recycling (performance infill) treatment route.

With the original iron ore assumptions the ozone depletion indicator was 89% lower for the co-incineration treatment route compared with material recycling (performance infill). With the assumptions applied in the sensitivity scenario as described above it is 117% lower. What is also worth mentioning is, that with the new iron ore assumptions the ozone depletion indicator for the material recycling (performance infill) treatment route is nolonger negative, which means that the credit for recycling is not enough to outweigh the other life cycle contributions to this indicator.

The sensitivity assessment carried out for assumptions regarding iron ore replacement for steel recycling has shown that the indicators Eutrophication freshwater and ozone depletion are relatively sensitive to these assumptions. If these assumptions are significantly changed in favor of co-incineration then the potential eutrophication freshwater potential may be slightly lower for the co-incineration treatment route compared with material recycling (peformance infill). However, it is not deemed likely that cement kilns will not use any secondary sources of iron at all. If only the assumed ratio of secondary iron ore sources for primary steel was changed to 50%, whereas the iron ore sources for co-incineration remain as in the base scenarios, then the Eutrophication freshwater indicator will still be the lowest for the material recycling route.

9.3. End-of-life of infills

Many of the countries, which install the most football turf in Western Europe, either have a ban on landfilling used tyres and/or they have landfill taxes to divert waste from landfills. At the same time, there are still countries in Europe where landfill can be a realistic treatment method for used tyres. Therefore, we have included a sensitivity analysis, which assumes the performance infill material is landfilled at the end of its useful life and the results are shown in Table 23 below. For the sake of simplicity the 50/50 infill replacement scenario was used for this sensitivity calculation.

Table 23. Sensitivity analysis. Landfilling infills at end-of-life (green values are lower than the corresponding values for the co-incineration treatment route). The sensitivity assessment is based on the 50/50 SEBS/EPDM infill scenario.

IMPACT CATEGORY	Material recycling (50/50 infill)	Material recycling (50/50 infill - landfill)	Co-incineration
Climate change fossil (kg CO2-eq.)	-905	**-841**	-197
Acidification terrestrial and freshwater (Mole of H+ eq.)	-2.84	**-2.09**	-0.801
Eutrophication freshwater (kg P eq.)	-0.00635	**-0.0111**	-0.0039
Eutrophication marine (kg N eq.)	-0.6	**-0.454**	-0.237
Eutrophication terrestrial (Mole of N eq.)	-7.78	**-6.17**	-2.69
Ozone depletion [kg CFC-11 eq.]	3.83E-07	**-4.40E-06**	-3.37E-06
Photochemical ozone formation (kg NMVOC eq.)	-1.95	**-1.52**	-0.656
Ionising radiation (kBq U235 eq.)	-216	**-107**	-3.15
Respiratory inorganics (Disease incidences)	-2.39E-05	**-1.50E-05**	-4.38E-06
Ecotoxicity freshwater (CTUe)	-110	**-191**	26.6
Cancer – human health (CTUh)	-5.89E-06	**-6.32E-06**	-1.46E-06
Non-cancer human health effects (CTUh)	9.70E-05	**-8.98E-06**	4.99E-05
Land Use (Pt)	-4.68E+03	**-2.09E+03**	-5.90E+02
Ressource use, energy carriers (MJ)	-3.25E+04	**-2.44E+04**	-1.02E+04
Ressource use, mineral and metals (kg Sb eq.)	-0.0251	**-0.0251**	-0.0000299
Water scarcity (m^3 world equiv.)	-84	**-93.6**	-12.6

The sensitivity analysis shows that if the performance infill material is landfilled instead of being incinerated, then 16 out of 16 potential impacts are lower in the material recycling system compared with the co-incineration system. In this scenario the results show that the material recycling system is unambiguously environmentally favorable in comparison with the co-incineration system for used tyres.

9.4. Lifetime and maintenance during the use stage

As it was described in Chapter 6.5, differences in the durability of the compared types of performance infill materials can impact the lifetime of the artificial sports fields and the need for replacement infill during the use stage. An increased need for replacement infill will influence the assumption about the replacement ratio and the assumption that the use of machinery for maintenance activities alike for all infills. Likewise, differences in the lifetime of the infills also influence the assumption about the replacement ratio of virgin infills.

As indicated in the Chapter 6.5, the assumptions regarding lifetime and durability of performance infills are regarded as conservative in the sense, that they favor the co-incineration treatment method for used tyres (because the durability of recycled tyre rubber performance infills is at least as good and in some cases maybe better than the durability of the replaced virgin infill materials). However, due to a lack of quantifiable information about the these differences, the above mentioned assumptions were not quantitatively tested in the sensitivity analysis.

9.5. CO_2 emissions from incineration of natural rubber

Natural rubber, used in the recycled tyres, is assumed to be CO_2 neutral when incinerated. This assumption is only valid if the natural rubber originates from sustainable forestry where deforestation does not occur. However, the impact of this assumption on the comparative results is considered to be limited, because this rubber is incinerated in both tyre treatment systems.

10. Conclusion

In this LCA study the main recycling scenarios are based on the tyre derived rubber being used as performance infill in artificial-turf football pitches. In a situation where the demand for infill materials cannot be met by ELT rubber, it is difficult to foresee with any accuracy, which other materials would be used for the artificial turf instead of ELT. For this reason, the following scenarios are included:

EPDM scenario:
In the EPDM scenario ELT replaces 100% EPDM based virgin infill.

TPE scenario:
In the TPE scenario ELT replaces 100% TPE based virgin infill.

50/50 scenario:
In the 50/50 scenario ELT replaces 50% EPDM and 50% TPE based virgin infill (this ratio between EPDM and TPE corresponds approximately to the current average ratio for the use of these two materials in FIFA certified artificial-turf pitches).

Here, it is highlighed that while EPDM and TPE are the most common alternative infill materials, these are not the only materials, which can be used as performance infill in artificial-turf pitches. Therefore, the results of the infill recycling scenario could look different under different circumstances, such as for example if organic infills are replaced instead of plastic based virgin infills. A FIFA study indicates a favorable climate change profile of cork infill when compared with SBR infill. However, due to the novelty of this infill material, there is a lack of solid data available to model a cork scenario with regards to the lifetime of the infill, the quantity needed and other aspects, which are decisive for the results. For this reason, no replacement scenario was included for organic infills.

For most impacts, the results of the LCA study are consistently in favor of the material recycling method, where the rubber is used as performance infill for artificial football fields when compared with co-incineration of the used tyres (all infill scenarios). Two exceptions are the ozone depletion potential and the impact category for non-cancer human health effects (all infill scenarios). The latter is associated with a large degree of uncertainty in the underlying LCA method as it is also the case for all the human and ecotoxicity impact categories. If the normalization of the results is considered, then the ozone depletion potential can be regarded as not material for either of the used tyre treatment methods. However, normalization is not an integral part of the results and therefore this is not a firm conclusion. For the SEBS infill scenario eutrophication freshwater is also an exception as the co-incineration treatment route has the lower contribution to eutrophication freshwater when compared with the SEBS infill scenario for tyre recycling. All other impact categories are lowest for material recycling (all scenarios), although there are variations with respect to their relative differences.

While the material infill recycling treatment is generally better, the co-incineration system also has net-negative values in most categories, which means that both treatment systems lead to significant savings in potential environmental impacts.

The potential climate change benefit from the material infill recycling is 4.3 (SEBS scenario) - 4.9 (EPDM scenario) times greater in comparison with the potential benefit from co-incinerating the used tyres instead.

In the sensitivity analysis the most critical assumptions were analyzed and tested and this contributed to further strengthen the conclusion that material recycling (infill) used tyres is preferable to co-incinerating the tyres from an environmental point of view. However, the sensitivity assessment also showed that the indicator for eutrophication freshwater could change in the favor of tyre co-incineration in the extreme case where it is assumed that no secondary sources of iron is used in the European cement production.

Assumptions regarding the replacement of virgin infills and lifetime of the infills in the use stage are quite uncertain, but they are also regarded as conservative in the sense that the assumptions are most likely to favor the co-incineration treatment method for used tyres.

The LCA study includes two additional scenarios modelling the recycling of tyres, where recycled rubber is further processed at a cryogenic milling line and used to replace either carbon black or synthetic rubber. The results show that some environmental impact categories are favorable for the material recycling, whereas others are favorable for the co-incineration scenario. In general the cryogenic processing mill increases the impacts from the material recycling significantly, but the added value of the recovered rubber leads to more environmental savings compared with the main recycling scenario, where the recovered rubber is used as performance infill.

The normalized results in the figure below show exactly which environmental impact categories, that are more favorable in each of the cryogenic recycling scenarios compared with the co-incineration treatment route. The normalized results also shows that the impact category climate change is relatively very important. Furthermore, it shows that the carbon black scenario has a significant relative benefit within the respiratory inorganics impact category, which is an indicator related to human health. However, normalization factors are uncertain and the normalized results should be interpreted accordingly. For both cryogenic scenarios, the contribution to climate changes is within the range 7-10 times lower in comparison with the co-incineration treatment method.

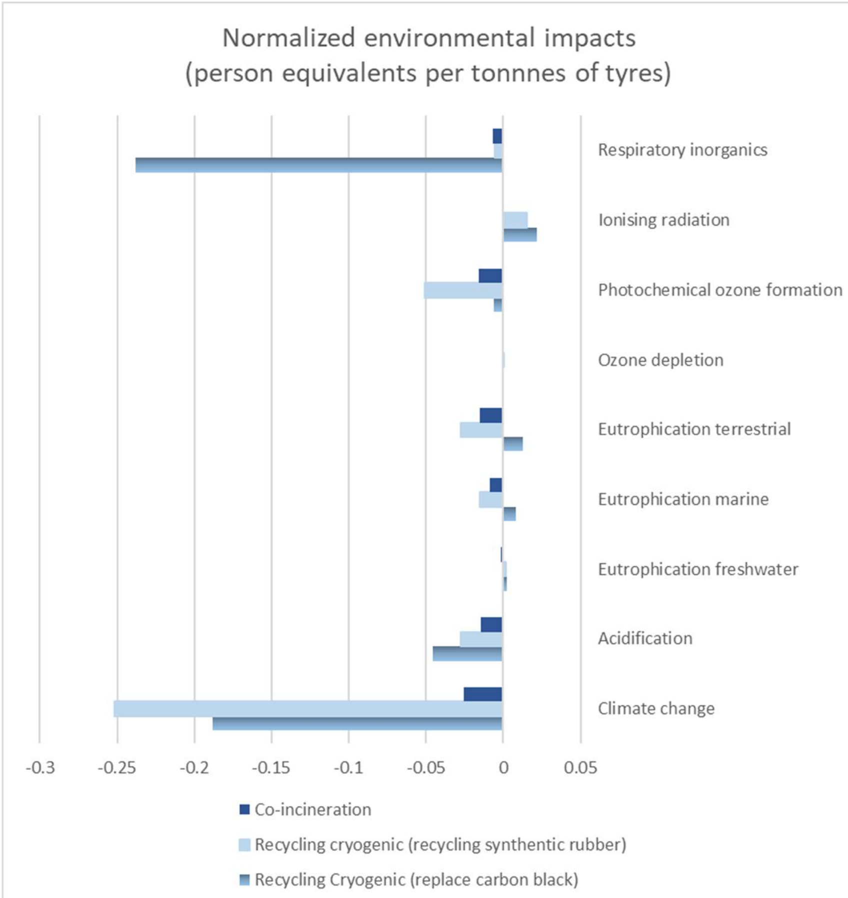

Figure 19. Normalized potential environmental impacts from different treatment options of one tonne of tyres – applications of recycled cryogenic rubber

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Appendix 1: Composition of fossil fuels

	Unit	Hard coal	Lignite	Pet coke	Heavy fuel oil	Light fuel oil	Natural gas
Calorific value	MJ/kg FM	29.49	21.47	31.02	40.61	42.73	37.78
Water	% FM	2.86	11.93				
Ash content	% FM	15.52	15.13				
Scrap content	% FM	0	0	0	0	0	0
Carbon, total	g/kg FM	748	544	812	864	862	577
Carbon, fossil	g/kg FM	748	544	812	864	862	577
Carbon, biogenic	g/kg FM	0	0	0	0	0	0
Sulphur	g/kg FM	5.3	21.1	20	10	1.5	0.02
Chlorine	g/kg FM	0.06	0.16	0.09	0.1	0.01	0.01
Fluorine	g/kg FM	0.29	0.06	0.009	0.009	0.0004	0.001
Antimony	g/kg FM						
Arsenic	g/kg FM	0.004	0.00025	0.0008	0.0007	0.0003	0
Cadmium	g/kg FM	0.00015	0.00025	0.002	0.001	0.0005	0
Chromium	g/kg FM	0.045	0.005	0.001	0.001	0.0005	0
Cobalt	g/kg FM				0.002	0.001	
Copper	g/kg FM				0.003	0.001	
Lead	g/kg FM	0.014	0.002	0.0035	0.004	0.001	0
Manganese	g/kg FM				0.0005	0.0005	
Mercury	g/kg FM	0.00009	0.00006	0.000006	0.00001	0.00002	0.0005
Nickel	g/kg FM	0.022	0.005	0.04	0.024	0.0025	
Thallium	g/kg FM	0.00085	0.0003	0.0005	0.0003	0.0005	
Tin	g/kg FM						
Vanadium	g/kg FM				0.1	0.01	
Zinc	g/kg FM	0.035	0.05	0.0025	0.0025	0.00003	0

Source: [Schmidt et al., 2009]

Appendix 2: Emissions of potentially problematic substances from artificial turf infill materials

This appendix compares the potential environmental (and health) impacts due to the leaking of unwanted substances from infills for artificial turf (recycled and virgin). The assessed turf infill materials are:

- Recycled rubber granules from tyres (based on NR, SBR)
- Virgin infill material based on TPE-S (thermoplastic elastomers, including SEBS, SBS and SEPS)
- Virgin infill material based on EPDM (ethylene-propylene-diene-M-class rubber)

The estimated composition of used tyre rubber and the different alternatives are described in the table below, which is based on Table 5 and Table 8 in this report.

Recycled tyre rubber (NR/SBR)*	**Virgin SEBS**	**Virgin EPDM**
25 % Synthetic rubber 14 % Natural rubber 23 % Carbon black 8 % Silica 1 % Sulphur 1 % Zinc oxide 9 % Aromatic oils 17 % textile fabrics (containing 58% recycled rubber granulates) 1 % Other materials	20 % SEBS 65 % $CaCO_3$ 15 % paraffinic oil	16 % polyethylene 4 % polypropylene 60 % $CaCO_3$ 1.9 % Zinc 21.3 % Oils (paraffinic) and other chemicals

* 'steel wires' from Table 3 has been removed and new percentages up to 100 % has been calculated.

Qualitative environmental and health aspects of infill materials

In the LCA study [Schmidt et al., 2009], it is described that the environmental issues in relation to infill materials are leaching and de-gassing of substances with unwanted properties regarding health and the environment. The report concluded that the general risk to human health is insignificant, but it was also concluded that real-life and long-term measurements of substances in run-off and leachate from existing fields was missing. A research was carried out for more recent investigations and the findings are summarised below.

One of the most recent European reports on the issue is the ECHA Report "An evaluation of the possible health risks of recycled rubber granules used as infill in synthetic turf sports fields" - Annex XV, [ECHA, 2017a]. This ECHA report was published in February 2017 and summarises different studies on this area from 2004 to 2016. Even though the report focuses mainly on health aspects, also environmental aspects such as leaching is summarised in the annexes to the report [ECHA, 2017b].

In 2017 and 2018, the National Institute for Public Health and the Environment in the Netherlands (RIVM) published two reports, one evaluating the health risks of playing sports on synthetic turf pitches with rubber granulate and the other evaluating the environmental effects of synthetic turf pitches. Since these reports are newer than the [ECHA, 2017] evaluation they were not considered in the [ECHA, 2017] evaluation.

Health aspects of infill materials

A risk assessment was carried out in the ECHA report [ECHA, 2017a] to evaluate the health risks of using recycled tyre rubber as infill. The risk assessment is based on exposure by skin contact, inhalation, and ingestion. Also, the risk assessment is based on exposure of the most sensitive users (children) as well as the most exposed humans (goalkeepers and workers installing and maintaining the fields). The overall conclusion in the ECHA report is that there is a very low level of concern due to exposure to substances found in recycled rubber used as infill material.

ECHA lists the substances below as the substances of highest concern. This information is based on literature and results form a number of recent studies.

- PAHs (polycyclic aromatic hydrocarbons)
- Metals
- Phthalates
- VOCs (volatile organic hydrocarbons) and SVOCs (semi-volatile organic hydrocarbons)

ECHA describes in more details, that their conclusion is consistent with the results of several other studies including among others the investigations from RIVM (Netherlands) in 2016 as well as investigations carried out by the State of Washington in the US. However, there are still some knowledge gaps as regards the substances present and their concentrations in the recycled rubber granules typically used as infill material in sport fields. The ECHA reports notice that the US EPA is expected to publish a detailed report "Recycled Tyre Crumb Used on Playing Fields" soon (expected to be published in early 2019). The US EPA study on this area is an extensive study and ECHA expects to review their evaluation after this report becomes available.

The reports [RIVM, 2017] and [RIVM, 2018b] conclude, in line with the report [ECHA, 2017], that that the health risk of playing sports on synthetic turf pitches with an infill of rubber granulate is virtually negligible. This conclusion was based on chemical analysis of content of substances of concern, as well as migration analyses of rubber granulate from 100 sports pitches representative for the Netherlands.

Limited information about the health risks of the alternative infill materials SEBS and EPDM was found. However, the general conclusion of all the identified reports is that the health risk is insignificant – and this applies for all infill materials, i.e. SEBS, EPDM and recycled rubber granulates.

PAH

The group of substances of highest concern in both [ECHA, 2017a], [RIVM, 2017] and [RIVM, 2018b] was found to be PAH's, but in the RIVM reports the maximum levels of the 8 restricted PAH's of 20 mg/kg presented no appreciable health risk, when measuring the actual exposure (migration). Therefore, ECHA and RIVM concludes that it is considered safe for people to play sports on such pitches. However, [ECHA 2017b] points out, that considerably larger amounts of PAH's may be found in non-EU tyre granules, and for this reason ECHA suggests a restriction proposal for the content of PAH in infill material for artificial turfs (see below).

In the studies that ECHA has evaluated the concentrations of PAHs in recycled rubber granules have normally been well below the limit values set in the REACH restriction relevant for such mixtures. The following restrictions of PAH's are relevant for tyres and rubber articles:

- REACH Annex XVII no. 50.1: Extenter oils for the production of tyres may not be used if the concentration of specific PAH's exceeds 10 mg/kg as a sum of all 8 restricted PAH's. The limit value for one specific PAH (BaP) is 1 mg/kg.
- REACH Annex XVII no. 50.5: Rubber articles that come into contact with the skin may not be placed on the market if the concentration of any of the 8 restricted PAH's exceeds 1 mg/kg.
- A new restriction proposal on artificial turf: Granules or mulches shall not be placed on the market for use as infill material in synthetic turf pitches or in loose form on playgrounds and in sport applications if these materials contain more than 17 mg/kg of the sum of 8 restricted PAH's [ECHA, 2019b]. This restriction proposal will restrict the PAH concentration in both granules made of recycled rubber as well as granules made of other materials (recycled or virgin, synthetic or natural). [ECHA, 2019b].

According to an expert statement in [ECHA, 2017b], PAH's will practically not be present in the paraffinic oils used in both the alternatives SEBS and EPDM. The limited information available for SEBS and EPDM also illustrates that the content of PAH's in these materials are lower than in recycled tyre materials [ECHA, 2017b]. Migration or emission of PAH's is therefore not considered to be a health risk for the alternatives based on SEBS and EPDM.

The Genan rubber granule complies with the suggested restriction proposal on PAH's in infill material in synthetic turf pitches [ECHA, 2019b]. Genan regularly perform chemical analysis of their granule samples and have at no point measured concentrations of any of the 8 restricted PAH's in concentrations above 5 ppm and the total concentration of the 8 restricted PAH's is below 15 ppm[16]. Furthermore, Genan states that the concentration of PAH's in tyres is continuously diminishing over time, as all new tyres marketed in the EU must live up to the PAH restriction for tyres (extenter oils for production of tyres).

Emission of VOC's from infill materials/artificial turfs

A Norwegian investigation reported in [ECHA, 2017b] concludes that the concentrations of volatile organic compounds from EPDM infill material were lower compared to the recycled rubber granules (based on SBR).

The Norwegian investigation reported in [ECHA, 2017b] also concludes that the total content of the VOC's benzene, toluene and xylene was lower in TPE (SEBS) based infill material compared to recycled tyre (SBR based) infill material. Similar another Norwegian investigation reported in [ECHA, 2017b] concludes that the total volatile organic compounds (TVOC) measured in different indoor artificial turf pitches were lower in the hall which used TPE (SEBS) infill material compared to the hall using recycled rubber infill material (based on SBR).

The Dutch study [RIVM, 2017] study did not detect VOC in their study or only in very low concentrations. Measurements were carried out mainly for recycled tyres (SBR) and a few EPDM samples.

In outdoor environments VOCs emitted from rubber granules are not a concern as regards the potential to cause irritation to the respiratory track, eyes and skin.

Other substances:

Some of the main points, not related to PAH, to be noticed in the ECHA risk assessment are:

[16] TDS for medium granulate: https://www.genan.dk/wp-content/uploads/2019/03/2019-TDS_GENAN-MEDIUM-GRANULATE_DK.pdf; TDS for fine/mix granulate: https://www.genan.dk/wp-content/uploads/2019/03/2019-TDS_GENAN-FINE-MIX-GRANULATE_DK.pdf

Given the available, although limited, migration data for metals, the concern to players and workers is negligible, as the values of metals in leachate are below the limits allowed to migrate from toys in the current toys legislation.

The combined effects of all the substances in rubber granules are not known and very difficult to assess. However, this uncertainty is not considered to affect the main conclusions of the ECHA evaluation.

Environmental aspects for infill materials

In recent years, most reports have focused on the health risks of playing sports on synthetic turfs. For this reason, the available information about the above mentioned environmental aspects of infill materials is limited. The investigated environmental aspects, which could potentially be of concern during the use stage, are:

- leaching of unwanted chemical substances from the artificial turfs/infill materials when it is raining,
- loss of infill materials to the aquatic environment leading to the spreading of microplastics

Leaching of unwanted substances

According to an expert statement in [ECHA, 2017b], both the alternative infill materials SEBS and EPDM are less resistant materials against wearing compared to SBR/NR from recycled tyres (the order being: SBR/NR > EPDM > SEBS). The physical resistance against wearing could be a relevant parameter with respect to leaching of unwanted substances or emission of VOC's, but this aspect was not investigated in detail.

The report [RIVM, 2017] focuses on the health risk of playing sports on synthetic turf pitches with rubber granulate. The assessment was based on information and measurements from 6 x 100 granulate samples from synthetic turf pitches – 6 samples was taken at each turf pitch, in all 100 different turf pitches in the Netherlands. [RIVM, 2017] states that 90 % of the synthetic turf pitches in the Netherlands are made from recycled tyres (ELT) and the rest is based on either EPDM, TPE, cork, coated virgin SBR rubber, different mixtures of SBR rubber or various synthetic and natural materials. They have carried out different leaching and migration test in this study, but all 600 test results are published together, so it is not possible to see the differences between leaching and emission of unwanted substances from the different alternative infill materials. The sparse information describing the differences in the [RIVM, 2017] and the [ECHA, 2017b] reports are described below.

A summary of measurements performed on leaching of unwanted substances from recycled rubber granules is prepared in [ECHA, 2017b]. This summary of different Norwegian, Italian and Danish studies illustrated that the substances leaching from recycled rubber granules can be grouped into the types of chemical substances described below. The same groups of substances are described in the [RIVM, 2017] report except for styrene and ethylbenzene, which are only listed in the [RIVM, 2017] report.

- PAH's
- VOC's (focus on benzene, toluene, xylenes, styrene and ethylbenzene)
- Phthalates
- Benzothiazols
- Other substances, such as
    - Nonylphenols
    - 4-t-octylphenol

  - Bisphenol A
  - PCB's
- Metals

The environmental concern is low for most of the groups of substances found to leak. VOC's from infills do not reach concentration levels, which present an environmental problem in the outdoor environments, where infills are used. As described in the health description above, PAH's are not present in Genan ELT rubber materials in concentrations, which can be considered problematic. The Genan tyre derived rubber is regularly tested and fulfil the requirements with regard to migration of metals of the European toy legislation, which aims at ensuring that the migration of metals is at a level, where children can put the toys in their mouth without suffering any harm to their health. Additional test results and compliance with standards can be found in the technical datasheets available at Genans website.

The leaking substances of the highest concern with regards to the outdoor environment is considered to be metals.

Leaching of metals

The concentrations of metals in TPE infill is in the same order of magnitude as for recycled tyres (ELT) in general – however, for some metals (Al, Ba, Be, Cu and Mo) the concentrations were higher in TPE. EPDM contains the highest concentrations of zinc and chromium, but in general lower concentrations of other metals [ECHA, 2017a], [ECHA, 2017b]. The Genan tyre derived rubber is regularly tested for the content of metals, which is at a low level with typical values below 20 mg/kg.

The leaching tests carried out in [RIVM, 2017] illustrate that in less than 0,5% of the samples, heavy metals like lead and mercury are leaching from the infill material in small concentrations. The metals cupper and cobalt were found to be leaching into water for 66% of all samples, but in concentrations well below 1 mg/kg infill material. Cadmium were not detected to be leached to water in any of the samples.

In contrast, zinc was found to leach to water in all (100%) of the samples and in the highest concentrations. The median of the measured leaching of zinc to water for all samples was 21 mg/kg infill material with a maximum of 129 mg zinc/kg infill material. It is assumed that the highest measurements are found for EPDM that contains about the double zinc concentration compared to recycled tyre (ELT) infill material, but it is not possible to conclude based on the report.

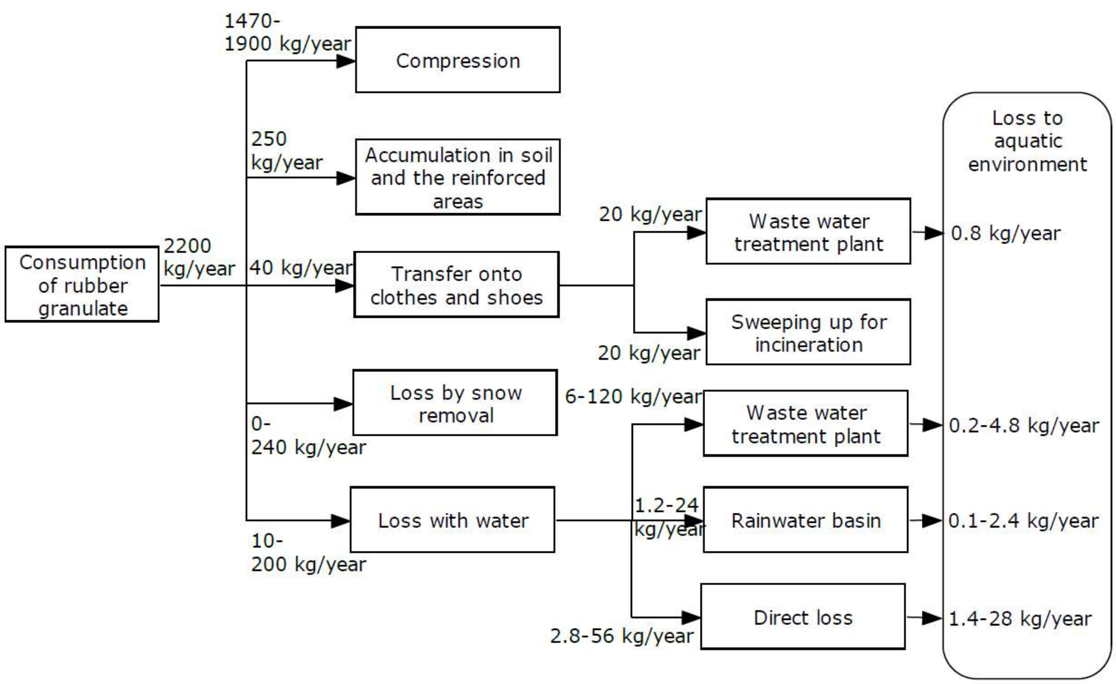
[RIVM, 2017] compares the leaching of zinc to water with the existing limit values in regulation for building materials used in or on the soil (soil quality regulation). The limit value for zinc is here 4.5 mg/kg, which is considerably lower than the measurements of leaching of zinc carried out for the samples in this study. However, as the [RIVM, 2017] report focuses on the health effects, the environmental effects of leaching of these higher zinc concentrations were not evaluated. [PlanMiljø, 2017] states that the leaching of zinc is seen as perhaps the most relevant environmental parameter, as some scientists claim that emission of zinc to the soil over time can exceed the environmental limit values.

Microplastic – loss to aquatic environment

A less quantifiable environmental burden is the issue of microplastics (defined as plastic particles smaller than 5 mm in all directions). [FIFA, 2017] states that it is currently difficult to quantify the problem, but recognises that these small microplastic particles can and do get ingested by various marine animals and can progress up the food chain potentially causing various chemical and physical effects. Plastic infill material (including recycled rubber tyres (ELT), and the alternative materials SEBS and EPDM) has been identified as a possible source for microplastic marine pollution [FIFA, 2017]. The infill material can get washed away during rain (and in worst-case scenarios washed into surface waters) or stick to clothing and boots before being put in a washing machine. Furthermore, in colder countries, the infill material can be removed during the removal of snow.

A Danish report [DTI, 2018] states that about 60 to 120 tonnes or rubber granulates are used for a typical football field (11-player-size). According to the report, a recent study suggests an average amount of 2.2 tonnes annually per field (based on contact to Danish suppliers). Based on the figures the [DTI, 2018] report estimated that the loss to the aquatic environment is about 2.5 kg to 36 kg annually (see the figure below).

Figure: Mass balance for rubber granulates according to [DTI, 2018]. Numbers are based on the best estimate based on measurements and assessments, but the uncertainty is relatively high.



A newly published Swedish research project[17] points to very low levels of microplastic from artificial sports turfs and concludes that this is not a significant environmental problem. The project was carried out by Bergaviks IP in cooperation with the Swedish Football Federation, Kalmar municipality, Ecoloop, Ragn Sells, Swedish Tyre recycling AB and Luleå University.

It should be noted that no investigation is available addressing the differences in loss of infill materials to the aquatic environment from artificial turfs with different infill materials. However, there is no reason to believe that there will be large differences in loss to the aquatic environment, whether recycled rubber material (SBR), SEBS or EPDM is used as infill material. [PlanMiljø, 2017] describes that the granules of the alternative materials TPE and EPDM have the same risk of ending up as micro plastic in nature as SBR rubber. The only major difference is that the actual content of plastic/rubber material in the recycled tyre material based on SBR (about 39%) is higher compared to the alternative materials based on SEBS (20%) and EPDM (20%).

[17] https://www.cirkulation.se/artiklar-och-notiser/mikroplast-fraan-konstgraes-litet-miljoeproblem/

It is noted, that the relative contribution to the potential environmental problems with microplastics is most likely notably higher due to rubber lost to the environment during the use of the tyres when these are driven in comparison with recycled rubber used as infills.

Summary of health and environmental effects of infills

The most recent studies on the issue of health and environmental impacts from infills suggest that there is little cause for concern for either of the infill materials included in this study, although it is also concluded that more research may be needed.

The substance of highest concern appear to be PAH from recycled tyre rubber. However, the level of the 8 restricted PAH's are in Genan recycled tyre rubber below 15 ppm[18] (which is also below the ECHA restriction proposal of 17 mg/kg for PAH in infill material) and is therefore of no concern to neither health nor the environment. With regards to the environment, the content of zinc in EPDM infills is by one source identified as a potential problem, although the issue is not investigated in sufficient detail to conclude to which extent this can impact the environment. All the evaluated types of infills share a potential risk of contributing to micro plastics in the environment, although there is no detailed investigations and reliable evidence to conclude if this is a problem nor to which extent it may be a problem.

[18] TDS for medium granulate: https://www.genan.dk/wp-content/uploads/2019/03/2019-TDS_GENAN-MEDIUM-GRANULATE_DK.pdf; TDS for fine/mix granulate: https://www.genan.dk/wp-content/uploads/2019/03/2019-TDS_GENAN-FINE-MIX-GRANULATE_DK.pdf

Appendix 3. Disaggregated results for infill and co-incineration scenarios

Disaggregated results for material recycling treatment route (performance infill – 100% SEBS):

IMPACT CATEGORY	Trans-port	Mate-rial re-cycling (at Genan)	BF steel recycling	BF fuel co-incineration (textile fraction)	Co-incineration (textile fraction)	BF infill	EOL	BF EOL (infill)
Climate change fossil (kg CO2-eq.)	36.1	141	-27.5	-303	244	-907	734	-755
Acidification terrestrial and freshwater (Mole of H+ eq.)	0.214	0.274	-0.363	-0.575	0.511	-1,98	-0.967	0,283
Eutrophication freshwater (kg P eq.)	0.000175	0.000741	-0.00308	1.23E-05	-1.38E-05	-0,0018	0.00483	-7.60E-06
Eutrophication marine (kg N eq.)	0.103	0.0831	-0.103	-0.185	0.165	-0,484	-0.176	0,0437
Eutrophication terrestrial (Mole of N eq.)	1.14	0.873	-1.2	-2.79	2.58	-5,23	-1.81	3,48E-01
Ozone depletion [kg CFC-11 eq.]	4.46E-15	7.87E-07	-2.75E-06	3.33E-08	-1.24E-08	-6,87E-11	4.79E-06	-2,03E-11
Photochemical ozone formation (kg NMVOC eq.)	0.199	0.218	-0.267	-0.543	0.489	-1,49E+00	-0.525	1,34E-01
Ionising radiation (kBq U235 eq.)	0.096	16.2	-1.49	-0.178	-0.00671	-117	-154	52,8
Respiratory inorganics (Disease incidences)	7.57E-07	4.84E-06	-1.37E-06	-2.83E-06	2.37E-06	-1,70E-05	-9.32E-06	7,78E-07
Ecotoxicity freshwater (CTUe)	5.35	5.88	-19.7	-3.92	8.29	-1,40E+02	160	-1,01E+02
Cancer – human health (CTUh)	2.19E-07	1.25E-07	-2.96E-07	-2.21E-07	4.19E-08	-6,05E-06	4.58E-07	-1,70E-08
Non-cancer human health effects (CTUh)	1.81E-06	3.70E-06	-2.02E-06	-9.20E-06	1.25E-05	-9,67E-06	0.000109	-3,44E-06

Land Use (Pt)	425	2.01E+03	-244	-55.1	-1.1	-3,90E+03	-3.53E+03	1,12E+03
Ressource use, energy carriers (MJ)	483	1.85E+03	-388	-1.43E+03	-1.74	-2,42E+04	-1.14E+04	3,86E+03
Ressource use, mineral and metals (kg Sb eq.)	2.52E-06	5.53E-05	-1.83E-05	-9.48E-07	-8.24E-08	-0,00015	-6.16E-05	3,08E-05
Water scarcity (m³ world equiv.)	0.782	6.42	-3.86	-1.13	-0.0173	-96,8	103	-8,98E+01

Disaggregated results for material recycling treatment route (performance infill – 100% EPDM):

IMPACT CATEGORY	Trans-port	Mate-rial re-cycling (at Genan)	BF steel recycling	BF fuel co-incineration (textile fraction)	Co-incineration (textile fraction)	BF infill	EOL	BF EOL (infill)
Climate change fossil (kg CO2-eq.)	36.1	141	-27.5	-303	244	-957	734	-839
Acidification terrestrial and freshwater (Mole of H+ eq.)	0.214	0.274	-0.363	-0.575	0.511	-2,33	-0.967	0,156
Eutrophication freshwater (kg P eq.)	0.000175	0.000741	-0.00308	1.23E-05	-1.38E-05	-0,0162	0.00483	-7,04E-05
Eutrophication marine (kg N eq.)	0.103	0.0831	-0.103	-0.185	0.165	-0,554	-0.176	0,0165
Eutrophication terrestrial (Mole of N eq.)	1.14	0.873	-1.2	-2.79	2.58	-8,33	-1.81	0,0439
Ozone depletion [kg CFC-11 eq.]	4.46E-15	7.87E-07	-2.75E-06	3.33E-08	-1.24E-08	-4,91E-06	4.79E-06	-1,58E-11
Photochemical ozone formation (kg NMVOC eq.)	0.199	0.218	-0.267	-0.543	0.489	-1,75	-0.525	0,0562
Ionising radiation (kBq U235 eq.)	0.096	16.2	-1.49	-0.178	-0.00671	-126	-154	36,9
Respiratory inorganics (Disease incidences)	7.57E-07	4.84E-06	-1.37E-06	-2.83E-06	2.37E-06	-2,05E-05	-9.32E-06	-5,64E-08
Ecotoxicity freshwater (CTUe)	5.35	5.88	-19.7	-3.92	8.29	-0,0162	160	-57.7
Cancer – human health (CTUh)	2.19E-07	1.25E-07	-2.96E-07	-2.21E-07	4.19E-08	-6,33E-06	4.58E-07	-3,41E-08

Non-cancer human health effects (CTUh)	1.81E-06	3.70E-06	-2.02E-06	-9.20E-06	1.25E-05	-2,18E-05	0.000109	-2,50E-06
Land Use (Pt)	425	2.01E+03	-244	-55.1	-1.1	-4,55E+03	-3.53E+03	765
Ressource use, energy carriers (MJ)	483	1.85E+03	-388	-1.43E+03	-1.74	-2,57E+04	-1.14E+04	2,70E+03
Ressource use, mineral and metals (kg Sb eq.)	2.52E-06	5.53E-05	-1.83E-05	-9.48E-07	-8.24E-08	-0,0501	-6.16E-05	2,13E-05
Water scarcity (m³ world equiv.)	0.782	6.42	-3.86	-1.13	-0.0173	-94,9	103	-96,1

Disaggregated results for material recycling treatment route (performance infill – 50/50 SEBS/EPDM):

IMPACT CATEGORY	Trans-port	Mate-rial re-cycling (at Genan)	BF steel recycling	BF fuel co-incineration (textile fraction)	Co-incineration (textile fraction)	BF infill	EOL	BF EOL (infill)
Climate change fossil (kg CO2-eq.)	36.1	141	-27.5	-303	244	-932	734	-797
Acidification terrestrial and freshwater (Mole of H+ eq.)	0.214	0.274	-0.363	-0.575	0.511	-2,16	-0.967	0.22
Eutrophication freshwater (kg P eq.)	0.000175	0.000741	-0.00308	1.23E-05	-1.38E-05	-0,00898	0.00483	-3.90E-05
Eutrophication marine (kg N eq.)	0.103	0.0831	-0.103	-0.185	0.165	-0,519	-0.176	0.0301
Eutrophication terrestrial (Mole of N eq.)	1.14	0.873	-1.2	-2.79	2.58	-6,78	-1.81	0.196
Ozone depletion [kg CFC-11 eq.]	4.46E-15	7.87E-07	-2.75E-06	3.33E-08	-1.24E-08	-2,46E-06	4.79E-06	-1.81E-11
Photochemical ozone formation (kg NMVOC eq.)	0.199	0.218	-0.267	-0.543	0.489	-1,62	-0.525	0.0953
Ionising radiation (kBq U235 eq.)	0.096	16.2	-1.49	-0.178	-0.00671	-121	-154	44.9
Respiratory inorganics (Disease incidences)	7.57E-07	4.84E-06	-1.37E-06	-2.83E-06	2.37E-06	-1,88E-05	-9.32E-06	3.61E-07
Ecotoxicity freshwater (CTUe)	5.35	5.88	-19.7	-3.92	8.29	-186	160	-79.3
Cancer – human health (CTUh)	2.19E-07	1.25E-07	-2.96E-07	-2.21E-07	4.19E-08	-6,19E-06	4.58E-07	-2.56E-08

Non-cancer human health effects (CTUh)	1.81E-06	3.70E-06	-2.02E-06	-9.20E-06	1.25E-05	-1,57E-05	0.000109	-2.97E-06
Land Use (Pt)	425	2.01E+03	-244	-55.1	-1.1	-4,22E+03	-3.53E+03	943
Ressource use, energy carriers (MJ)	483	1.85E+03	-388	-1.43E+03	-1.74	-2,49E+04	-1.14E+04	3.28E+03
Ressource use, mineral and metals (kg Sb eq.)	2.52E-06	5.53E-05	-1.83E-05	-9.48E-07	-8.24E-08	-0,0251	-6.16E-05	2.61E-05
Water scarcity (m^3 world equiv.)	0.782	6.42	-3.86	-1.13	-0.0173	-95,8	103	-92.9

Disaggregated results for co-incineration treatment route:

IMPACT CATEGORY	**Transport**	**Co-incineration**	**BF fuel co-incineration**	**BF ore co-incineration**
Climate change fossil (kg CO2-eq.)	9.180235	1.91E+03	-2.08E+03	-35.9
Acidification terrestrial and freshwater (Mole of H+ eq.)	0.054524	3.58	-3.96	-0.475
Eutrophication freshwater (kg P eq.)	4.45E-05	0.00	8.45E-05	-0.00403
Eutrophication marine (kg N eq.)	0.026306	1.14	-1.27	-0.134
Eutrophication terrestrial (Mole of N eq.)	0.290564	17.8	-19.2	-1.56
Ozone depletion [kg CFC-11 eq.]	1.14E-15	0.00	2.29E-07	-3.60E-06
Photochemical ozone formation (kg NMVOC eq.)	0.050576	3.38	-3.74	-0.349
Ionising radiation (kBq U235 eq.)	0.024429	0.00	-1.23	-1.95
Respiratory inorganics (Disease incidences)	1.93E-07	1.67E-05	-1.95E-05	-1.79E-06
Ecotoxicity freshwater (CTUe)	1.363172	78	-27	-25.8
Cancer – human health (CTUh)	5.58E-08	3.97E-07	-1.52E-06	-3.87E-07
Non-cancer human health effects (CTUh)	4.62E-07	0.000115	-6.34E-05	-2.64E-06
Land Use (Pt)	108.2814	0.00	-379	-319
Ressource use, energy carriers (MJ)	122.9414	0.00	-9.85E+03	-507

Ressource use, mineral and metals (kg Sb eq.)	6.42E-07	0.00	-6.53E-06	-2.40E-05
Water scarcity (m³ world equiv.)	0.199027	0.00	-7.76	-5.04

Appendix 4. Disaggregated results for cryogenic scenarios

Table showing the life cycle results for the cryogenic carbon black scenario. BF stands for benefit.

IMPACT CATEGORY	Production	Transport from Genan	BF replaced carbon black	EOL
Climate change fossil (kg CO2-eq.)	994.5	27.2	-1740	-745
Acidification terrestrial and freshwater (Mole of H+ eq.)	1.567	0.162	-4.29	0.0321
Eutrophication freshwater (kg P eq.)	0.0081595	27.2	-0.00236	2.20E-05
Eutrophication marine (kg N eq.)	0.4221	0.000132	-0.279	0.00744
Eutrophication terrestrial (Mole of N eq.)	4.323	0.078	-2.99	0.0799
Ozone depletion [kg CFC-11 eq.]	9.0579E-06	3.37E-15	-8.42E-12	1.71E-13
Photochemical ozone formation (kg NMVOC eq.)	1.107	0.15	-1.53	0.0213
Ionising radiation (kBq U235 eq.)	119.52529	0.0724	-32.7	3.84
Respiratory inorganics (Disease incidences)	0.00001721	5.72E-07	-0.00017	2.72E-07
Ecotoxicity freshwater (CTUe)	101.55	0.000132	-513	2.20E-05
Cancer – human health (CTUh)	7.10E-07	1.65E-07	-2.48E-05	8.48E-09
Non-cancer human health effects (CTUh)	3.42E-05	1.37E-06	-1.41E-05	2.14E-07
Land Use (Pt)	1.42E+04	321	-3.67E+03	91.1
Ressource use, energy carriers (MJ)	1.41E+04	364	-4.69E+04	300
Ressource use, mineral and metals (kg Sb eq.)	7.04E-04	1.90E-06	-0.000194	2.64E-06
Water scarcity (m³ world equiv.)	35.9127	0.59	-23.7	1.55

Table showing the life cycle results for the cryogenic carbon black scenario. BF stands for benefit.

IMPACT CATEGORY	Production	Transport from Genan	BF replaced synthetic rubber	EOL
Climate change fossil (kg CO2-eq.)	994.5	27.2	-2210	-763

Acidification terrestrial and freshwater (Mole of H+ eq.)	1.567	0.162	-3.24	-0.00086
Eutrophication freshwater (kg P eq.)	0.0081595	0.000132	-0.00384	-9E-07
Eutrophication marine (kg N eq.)	0.4221	0.078	-0.926	-0.00013
Eutrophication terrestrial (Mole of N eq.)	4.323	0.861	-10.1	-0.00133
Ozone depletion [kg CFC-11 eq.]	9.0579E-06	3.37E-15	-7.97E-12	-7.1E-15
Photochemical ozone formation (kg NMVOC eq.)	1.107	0.15	-3.31	-0.00034
Ionising radiation (kBq U235 eq.)	119.52529	0.0724	-54.1	-0.159
Respiratory inorganics (Disease incidences)	0.00001721	5.72E-07	-2.11E-05	-6.81E-09
Ecotoxicity freshwater (CTUe)	101.55	4.04	-0.00384	-0.0144
Cancer – human health (CTUh)	7.10E-07	1.65E-07	-2.21E+03	-2.39E-10
Non-cancer human health effects (CTUh)	3.42E-05	1.37E-06	-6.76E-04	-8.66E-09
Land Use (Pt)	1.42E+04	321	-6.26E+03	-3.75
Ressource use, energy carriers (MJ)	1.41E+04	364	-6.30E+04	-1.84
Ressource use, mineral and metals (kg Sb eq.)	7.04E-04	1.9E-06	-0.000267	-8.17E-08
Water scarcity (m^3 world equiv.)	35.9127	0.59	-52.8	-0.0645

Appendix 5. Verification statement

Critical review statement for the study

"Life cycle assessment of waste tyre treatments: Material recycling vs. co-incineration in cement kilns"

Commissioner of the LCA study:	Genan Holding A/S
Author of the LCA study:	FORCE Technology, Denmark
Critical reviewe panel:	Professor Adisa Azapagic, Ethos Research, UK
	Simon Hann, Eunomia Research & Consulting, UK
	Dr Wolfram Trinius, Ingenieurbüro Trinius GmbH, Germany
Date:	May 2020

Background

The international standards ISO 14040 and ISO 14044 define the methodological approach to environmental life cycle assessment. The standards also contain requirements for the reporting of publicly disclosed LCA studies.

An external critical review of an independent LCA expert or panel of experts serves to ensure that the reported study is conducted and documented in line with the requirements of the ISO standards.

Therefore, the above study was subject of a critical review, which was carried out by a panel of the aforementioned panel of experts. All members of the critical review panel are independent of the commissioner and the author of the LCA study.

Following the ISO 14040/44 requirements, the critical review was carried out to ensure that:

- the methods used to carry out the LCA study are consistent with the ISO standards;
- the methods used are scientifically and technically valid given the goal of the study;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation of the results and the conclusions of the study reflect the goal and the findings of the study; and
- the study report is transparent and consistent.

The panel reviewed and discussed with the author four successive versions of the report (the original and three revised versions). All the comments made by the panel were addressed by the author.

Critical review statement

The LCA study followed the requirements of the ISO 14040/44 standards. It was documented transparently allowing sufficient understanding of the approach, modelling and calculation of the LCA impacts. The analysis of the potential environmental impacts followed the currently established selection of impact categories.

In conclusion, the study was conducted in conformity with the ISO 14040/44 standards and can be considered technically and methodologically correct.

Disclaimer

The results of the study are driven by a range of scenarios and assumptions. Therefore, the results are only valid for these scenarios and assumptions and are not transferable outside the context of the study.

Communication to external stakeholders

The following should be mentioned when communicating the results of the study to external stakeholders:

- Some of the assumptions as well as the scenario definitions affect the results, interpretation and conclusions of the study. Therefore, it is of utmost importance that these and their influence on the results and conclusions are described transparently to avoid any potential misinterpretation of the study.
- It should also be mentioned that the critical review statement is available upon request.

Professor Adisa Azapagic Ethos Research	Simon Hann Eunomia Research & Consulting	Dr Wolfram Trinius Ingenieurbüro Trinius GmbH