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COMPARATIVE LCA STUDY OF BRAKE LINING MIXES WITH RECYCLED MATERIAL

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COMPARATIVE LCA STUDY OF BRAKE LINING MIXES WITH RECYCLED MATERIAL

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ABBREVIATIONS

AP	Acidification potential
CO_2	Carbon dioxide
EF	Environmental Footprint
EoL	End-of-Life
EP	Eutrophication potential
Kg	Kilogram
kWh	Kilowatt Hours
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Megajoule
NO_x	Nitrous oxide
OEM	Original Equipment Manufacturers
PCR	Product Category Rule
PEF	Product environmental footprint
PM	Particulate matter
POF	Photochemical ozone formation
RMS	Raw Material Services
SO_2	Sulfur dioxide
VOC	Volatile organic compounds

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1. EXECUTIVE SUMMARY

The RMS Raw Material Service GmbH & Co. Kg (RMS) is a producer of dry mixes for the friction industry. The dry mixes produced by RMS are used as friction materials in disc pad and drum lining applications for trucks, passenger cars and rail vehicles as well as in industrial applications. The processing of post-consumer and pre-consumer materials closes an important gap in the recycling of raw materials. The use of the recycled dry mix avoids the costly landfilling or thermal utilization (incineration) of the used materials, which until now has been the usual disposal route for used friction materials. Thus, the RMS process is part of the development to a circular economy which is needed to replace linear product life cycles.

RMS would like to discover the potential environmental benefits of its processes compared to the primary production route. As additional outcome of the study RMS would like to understand differences and sources of environmental impacts of its different mixes.
The findings are mainly relevant for RMS in terms of costumer relations and communication. The company intends to provide their customers with the benefits of the recycled friction materials based on comparative LCA environmental data of their product.

The study at hand compares three mixtures sold by RMS with a mixture containing 100% primary material. Data was provided by the producer to assess all processes with high data quality. The assessment covers two different end-of-life options for the primary mix using a cradle-to-grave approach. For the RMS processes a cradle-to-gate approach is chosen. This reflects the fact that the RMS recycling process avoids the deposition or incineration of the used friction material.

As an overall conclusion it can be stated that the provision of raw materials is the main driver for all impact categories assessed. The results clearly underline the positive effect of substituting raw materials as it is the case for the RMS mixes. Of course, higher shares of recycled material are beneficial in this case. Especially when recycled materials replace the critical inputs, that have the highest shares in terms of impacts, the effect is advantageous.
A second outcome is the relevance of the two end-of-life scenarios for the primary mix. It becomes obvious that the recycling of used brake linings reduces environmental impacts by avoiding deposition or incineration. This applies in particular to climate change in case of the incineration of the used friction materials.

2. GOAL OF THE STUDY

This chapter describes the goal of the assessment to set the basis for further decisions within the study. The goal is defined based on the reason for carrying out the study, its application and audience.

2.1 Reasons for carrying out the study

RMS is a producer of dry mixes for the friction material industry. The dry mixes produced by RMS are used as friction materials in disc pad and drum lining applications for trucks, passenger cars and rail vehicles as well as in industrial applications The friction material specifications, mixes and batches are prepared according to the customer's requirements.
The input materials to produce RMS dry mixes are, on the one hand, the (used) brake pads and linings removed in contract workshops, which are collected throughout Europe (post-consumer) and delivered to RMS. Another input stream is the supply of production rejects (pre-consumer), which are generated in the primary production of brake pads, linings and industrial friction applications, as well as grinding dusts, which are also collected in primary production and supplied to.
The processing of post-consumer and pre-consumer materials closes an important gap in the recycling of raw materials. The use of this dry mix avoids the costly landfilling or incineration of the materials used, which until now has been the usual disposal route for removed brake pads. Thus, the RMS process is part of the development to a circular economy which is needed to replace linear product life cycles.
RMS would like to discover the potential environmental benefits of its processes compared to the primary production route. As an additional outcome of the study RMS would like to understand differences and sources of environmental impacts of its different mixes.
The findings are mainly relevant for RMS in terms of costumer relations and communication. The company intends to provide their customers with the benefits of the recycled friction materials based on comparative LCA environmental data of their product vs. a mix consisting of 100% primary material.

Given this background, the following question can be derived for this study:

> How big is the difference in various environmental impacts in the production of the RMS products compared to a product consisting of 100% primary material?

2.2 Intended applications

Based on the needs of RMS the intended applications of the study are:

- The creation of meaningful, transparent, and technically/scientifically sound environmental profiles for the different brake pad mixtures.
- The environmental profiles must allow an assessment of the order of magnitude of the advantages/disadvantages of all products
- The results of the study must be suitable for external communication

2.3 Target audiences

The results of this study will be used for external communication with focus on relevant stakeholders of the sector and costumers of RMS:

- Existing and potential customers of the company RMS
- Original Equipment Manufacturers (OEMs), Brake Manufacturers (Tier 1) and Friction Manufacturers (Tier 2)
- Representatives of the industry (international)

The study is intended to be disclosed to the public.

2.4 Comparative assertions of the study

The study includes comparative assertions of different production routes of the friction materials also considering end of life routes of the primary product.

2.5 Commissioners of the study

The study is commissioned by Ramboll ESG & LCA Consulting. Ramboll is a leading engineering and management consulting company with more than 16,500 employees and offices in 35 countries. In Germany, Ramboll is represented by more than 800 employees at 14 locations. Ramboll has global expertise in life cycle assessment, energy optimization, circular economy, and low impact construction.

3. SCOPE OF THE STUDY

3.1 Product systems

Within this study two different routes of friction material mixes are compared:

1. The production of three different friction material mixes with different shares of recycled friction material. In this case no end-of-life scenarios are considered.
2. The production of a friction material mixes with 100% primary raw materials and its end of life, with belowground deposition or incineration.

The first route represents the RMS manufacturing process. The input materials to produce RMS dry mixes are, on the one hand, the (used) brake pads and linings removed in contract workshops, which are collected throughout Europe (post-consumer) and delivered to RMS. Another input stream is the supply of production rejects (pre-consumer), which are generated in the primary production of brake pads, linings, and industrial friction materials, as well as grinding dusts, which are also collected in primary production and supplied to RMS.
The mixtures are used for further processing to produce various types of friction products, such as brake pads and brake linings for disc brakes and drum brakes for again various applications (car, train, industrial etc.).
The mixture has the same function as mixtures without recycled material and can be further processed in the same way and for the same period. The composition of the compounds differs in the proportion of recycled material and other ingredients. The recycled material is produced by mechanical separation of friction material from the metal content of used drum and disc brake pad and linings, in addition, scrap from friction material production is used. Further processing steps include crushing, screening, sieving, compacting, optimizing, and filling of the material; it is then mixed with the primary (virgin) components and packaged.

The second product system represents the route without a recycling process. The virgin ingredients of the formulation are mixed, filled and packaged for onward transport. The production process is thus the same as with recycled material, apart from the upstream recycling process. After the use phase the friction materials are either deposited underground or incinerated.

The characteristics of the friction material mixes with recycling content are comparable. They are of the same quality as mix made of 100% primary compounds and meet the relevant standards and specifications. There is no difference in the possible service life compared with the primary compounds and no difference is to be expected in the service life regarding abrasion and the corresponding environmental impact.
The purchased components are equal in quality and origin to those of primary compounds but differ depending on the formulation. The selected products are specific formulations and correspond to commercially available compounds.

3.2 Function and functional unit

The function of the friction material mix is the continuously repeatable control/reduction of speed in different applications.

The functional unit is 1 kg of packed friction material mixture at gate of the production site. The reference flow is the same as the functional unit.

The comparison of 1 kg of friction material mix (primary and recycled) meets the objective of the study as the mixes are functionally identical and thus a statement can be made about the relative environmental effects of the different mixes.

3.3 System boundaries and cut-off criteria

The boundaries of a product system describe which flows, processes and life cycle stages are included in the assessment and which are omitted. For the product systems under consideration different scopes are chosen.
For the RMS product system, a cradle to gate approach is selected. The used friction materials are burden free from their primary production. For the primary route the assessment covers a cradle to grave scope with two end-of-life scenarios including transport to the deposition or incineration site. For both systems the further production steps and the use phase are omitted.
The choice of the two different scopes can be justified as follows:

a. The RMS system recycles used friction materials and thus extends the lifetime of the material. Considering an end-of-life phase would lead to a double counting.
b. The further production steps and the use phase are equivalent for both product systems to be compared and thus can be neglected.
c. The difference between the abrasion of a primary brake pad and a pad made of recycled material is hard to quantify. According to the studies of Gialanella S. et al (2019) and Filip P., Jogineedi R., Singireddy V.R. (2016) the brake pad made of recycled material has lower abrasion rate. However, it was decided not to include the use phase and abrasion occurring in this phase in this study due to lack of efficient evidence and not sufficient scientifical references. In case the brake pads from recycled material show a lower abrasion, rate this would mean they had a longer lifetime, which is a positive characteristic from an environmental point of view. Excluding the use phase bases on the assumption that primary and secondary material have equal lifetimes. As no robust characterization factor is available, assuming equality of both materials is chosen as conservative approach.

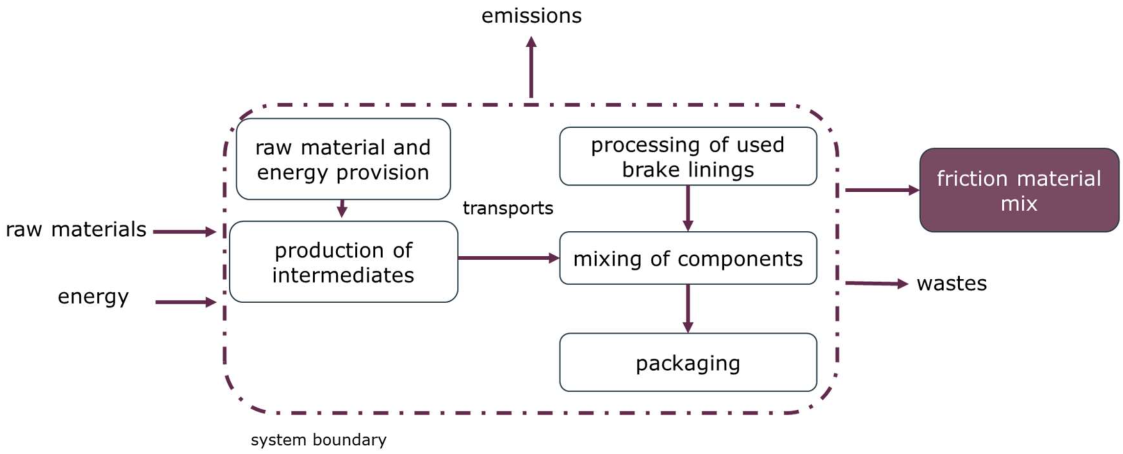

Figure 1: System boundary of RMS product system

The system boundaries of the RMS product system include the provision of raw materials needed for the friction material mix. Further the mechanical recycling process, the mixture of the different components, and the packaging of the mix. All transports of materials (raw materials and used brake pads and linings) to the RMS production site are also included. The system boundaries end at the packed lining mix ready for transport. Flows leaving the system are the friction material mix as only products, wastes and emissions. Capital goods and infrastructure are excluded because they are expected to be below 1% cut-off criteria. Human labor and employee commute are out of the system boundary.
All processes included or excluded from the system are summarized in table 1.

Table 1: system boundaries for RMS product system

Included	Excluded
Raw material and energy provision	Assembling of brakes (equivalence of processes)
Production of intermediates	Transports after gate (equivalence of processes)
Processing of used brake linings	Use of brake linings (equivalence of processes)
Mixing of components	Below ground disposal/incineration (material is already recycled)
Transports of utilization materials and used brake pads and linings	Capital goods (expected to be below 1% cut-off criteria)
Packaging	Infrastructure (expected to be below 1% cut-off criteria)
Energy use	Human labor and employee commutes (out of system boundary)

As explained above the system boundary for the primary mix product system is extended to include the end-of-life of the friction materials. In general friction materials are either disposed below ground or incinerated.

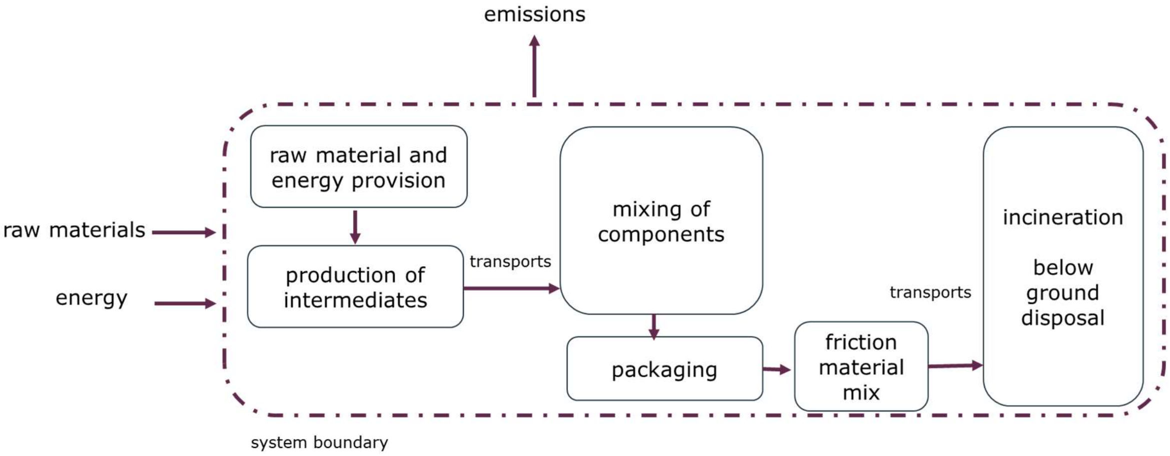

Figure 2: System boundary of primary brake lining mix product system

The logic of excluding or including system elements follow the one applied for the RMS product system, except the inclusion of end-of life. The elements are described in Table 2.

Table 2: System boundaries for primary mix product system

Included	Excluded
Raw material and energy provision	Assembling of brakes (equivalence of processes)
Production of intermediates	Transports after gate (equivalence of processes)
Mixing of components	Use of brake linings (equivalence of processes)
Transports of utilization materials	Recycling
Transports to disposal/incineration	Capital goods (expected to be below 1% cut-off criteria)
Packaging	Infrastructure (expected to be below 1% cut-off criteria)
Below ground disposal/incineration	Human labor and employee commutes (out of system boundary)
Energy use	

3.3.1 Time coverage

Data used refer to recently used mixtures. Formulations that are available on the market are usually left unchanged for about 20 years. Thus, the data applied can be regarded as valid for that timeframe. Data for energy production and use refer to the recent situation. No scenarios for 2030 or 2050 are calculated. Data for transportation processes refer to the recent emission standards.

3.3.2 Technology coverage

The preparation and mixing processes shown are state of technique in industrial application. Also selected processes for incineration and disposition reflect the recent technology at the time of the preparation of this study.

3.3.3 Geographical coverage

All processing steps of both product systems are in Germany, also the end-of-life processes of the primary mix system. Purchased components for the mixes are produced or processed in different countries: USA, UK, Germany, The Netherlands, China, South Africa, Brazil, Australia, Switzerland, India, Italy, Czech Republic, and France.

Data selected and their time, geographical and technology coverage are depicted in chapter 4.

3.4 Scenarios

Two different scenario groups are applied within this study. One varies the electricity mix and the end-of-life, the second one analyzes how the impacts of the OE mix changes if raw materials are substituted by recycled material to a certain share.

3.4.1 Electricity and end-of-life scenarios

The three different energy scenarios considered in this study are listed in the table 3. The baselines are set as follows:

- Primary product: German standard electricity grid mix, underearth landfill
- Recycled product: Three different mixes, hydropower

Deviating therefrom the following scenarios are applied:

- Primary product: incineration instead of underearth landfill
- Recycled product: German green grid mix and 100% solar power instead of hydropower. This assumption depicts the best case (all electricity demand can be covered by own solar power on the factory roof top).

The scenarios are summarized in the following table:

Table 3: Electricity and end-of-life scenarios

Baseline	Scenario	Description
Underearth landfill (primary product)	I. Thermal incineration End-of-Life	The EoL of the brake pads is deposing them in underearth landfill (mine-landfill). The brake pads can also be thermically treated (incineration of waste).
Energy from hydropower	II. Energy green electricity mix	The energy for recycling processes is produced from hydropower (green electricity certificate). To consider possible change of the energy source while buying the green electricity a regular green electricity mix is also examined (case Germany).
Energy from hydro power	III. Energy electricity from solar power	In the future the installation of solar cells on the roof of recycling plant is planned. This scenario is considered to evaluate possible burden shifting.

3.4.2 Raw material scenarios

To depict the potentials of impact reduction by substituting raw materials in the OE mix by recycled material, two scenarios are chosen:

- A reduction of raw materials by 25% (except resin), end of life only for primary material share (incl. transports)
- A reduction of raw materials by 50% (except resin), end of life only for primary material share (incl. transports)

For the substitution all raw materials except resin are equally replaced.

3.5 Allocation

No multi-output allocation is applied for the systems assessed. Both product systems have one single output.
For the end-of-life allocation a credit approach is chosen for the RMS system. The used brake pads and linings enter the system burden-free.

3.6 Selection of LCIA Methodology and Impact Categories

Impact categories describe the potential effect of a product or service on the environment. In the last decades different impact assessment methods have been developed. They represent a set of impact categories and associated characterization models. For the study on hand the Product Environmental Footprint (PEF) approach was chosen. The PEF is recommended by the European Commission and thus the most recent and relevant set of categories and models for the European scope. Characterization factors are scientifically robust and widely applied in the LCA community. It must be stated that this study does not represent a full PEF study, so not all impact categories are evaluated. For the time being, no applicable Product Category Rule (PCR) for this assessment is available.

The following EF impact categories have been selected:

Climate change total: climate change is chosen because of its relevance as pressing issue in public. Climate change is amongst others influenced using energy carriers and thus of relevance to all energy consuming processes and product systems. Unit of this impact category is kg CO_2 equivalents per functional unit. Climate change can be evaluated subdivided into biogenic and fossil emissions. As the product system on hand does not include relevant biobased sources separate calculation and presentation of their contribution to the results is considered not relevant.

Eutrophication, acidification, and photochemical ozone creation: these impact categories were chosen as they are connected to air, soil and water quality and address potential impacts caused by NO_x, SO_2, VOC, and others.

Particulate matter: it can be expected that particulate matter emissions occur within the upstream processes of input materials for the brake lining mixes and are thus considered to be relevant for this study.

Resource use: this impact category describes the depletion of fossil and abiotic resources and thus addresses the issue of resource scarcity.

Table 4 summarizes all chosen impact categories and characterization models according to Zampori and Pant (2019).

Table 4: Impact categories and characterization models chosen

EF impact category	Impact category indicator	Unit	Characterization model
Climate change total	Radiative forcing as global warming potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, aquatic	EUTREND model	fresh water: kg P equivalent marine: kg N equivalent	Struijs et al., 2009 as implemented in ReCiPe
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Photochemical Ozone	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008
Particulate Matter	Impact on human health	Disease incidence	PM method recommended by UNEP (UNEP 2016)

Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Resource use, minerals, and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb equivalent, MJ (net calorific value)	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.

Impact categories excluded from the assessment are:
Ozone Depletion: active ozone depleting substances were legally phased out until 2030 and thus are considered as not relevant for this study.
Human toxicity and eco-toxicity: characterization models for toxicity impacts are still in development and recommended with caution by the European Commission.

3.7 Interpretation to be used

The interpretation follows the goal and scope of the study defined above. The following aspects are addressed:

- Depiction of relevant findings related to the relevance of processes and flows for the selected impact categories
- Check of completeness and consistency
- Check the relevance of processes excluded from the system and assumptions made
- Conclusions, limitations, and recommendations.

3.8 Data quality requirements

Representativeness

Timely: primary data collected refers to the year 2022. All background data sets used are the most recent available in the ecoinvent database.

Technology: no major changes or innovation is expected to change the overall technical approach of recycling, mixing and end-of life options.

Geographical coverage
For production and end of life of the friction material processes are modelled with regards to German conditions. For purchased goods country specific data sets were used.

Completeness: all relevant process steps are included in the study with respect to the goal and scope. Justification of excluded elements can be found in chapter 3.3.

Consistency: all primary data was collected at the same level of detail from the same data source. Background data was taken from ecoinvent database.

Reliability: data was collected with respect to the used technology in close exchange with the producer. Data received from the producer was checked for completeness and quality. Background data was taken from ecoinvent database.

Reproducibility: due to confidentiality no details on input materials and their masses of the single recipes can be disclosed in this study. This states limitation for the reproducibility of the results.

3.9 Format of the report

This report is created in accordance with ISO 14040 and 14044.

3.10 Software and database

The LCA model was created using the LCA software Umberto LCA+ provided by iPoint-systems GmbH (iPoint 2022). The database used is the ecoinvent LCA database version v3.8 (ecoinvent 2022).

3.11 Critical Review

As this study includes comparative assertions and is intended to be disclosed to public a panel review according to ISO 14044, section 6.3 has been conducted. The description of all members of the review panel can be found in chapter 7.1. A documentation of reviewer's comments and authors responses can be found in chapter 7.2 and 0.

4. LIFE CYCLE INVENTORY ANALYSIS

4.1 Data collection procedures

Since the LCA quality strongly depends on the quality of the data used, it was aimed to implement only the most representative data available. The data was collected in an iterative process between RMS and Ramboll. Thus, data collection template was specifically adjusted to needs of this study and distributed to RMS. The data collection sheet covers all inputs and outputs for each process and distances traveled to the gate, as well as cleaning processes and required auxiliary materials. The data quality index is also taken into consideration. The screenshots from the template are found in the Figure 3 and Figure 4.

	Einheit	Menge	MSDSs oder CAS #	Data Quality Index (DQI)	Kommentare
Zusammensetzung (BOM) - *bitte Angaben zu Materialtypen und Beschichtungen machen*					
Prozess 1					
Inputs	**Masse**	**0,0**		Wählen Sie eins...	Calculated = CAD Data
Material 1	*kg*	*0,0*		*Gemessen*	
Material 2	*kg*			*Gerechnet*	
Material 3	*kg*	*0,0*		*Gerechnet*	
Hilfsmaterialien				Wählen Sie eins...	
Schmierstoff	*kg*	*0,0*		*Abgeschätzt*	
Klebstoff	*kg*	*0,0*		*Gemessen*	
Material 5	*kg*	*0,0*		*Literatur*	
Outputs				Wählen Sie eins...	
Ungefährliche Abfälle (Recycling)	*kg*	*0,0*		*Gemessen*	
Ungefährliche Abfälle (Energieverwertung)	*kg*	*0,0*		*Gerechnet*	
Ungefährliche Abfälle (Deponie)	*kg*	*0,0*		*Abgeschätzt*	
Gefährliche Abfälle	*kg*	*0,0*		*Gemessen*	
Abwasser	*kg*	*0,0*		*Literatur*	

Figure 3: Data collection sheet for production processes

Transport von Liefaranten i			
Transportmittel 1 (von Lieferanten zur Anlage)	**Einwegstrecke**	**Einheit**	**Kommentare**
Wählen Sie eins...			
		km	
		km	
		km	
		km	
		km	
		km	
LKW		km	
LKW		km	
LKW		km	
LKW		km	
LKW		km	

Figure 4: Data collection sheet for transport processes

After kick-off meeting the template was sent to RMS. RMS has provided Ramboll with the data for three recycling processes (dust, disc brake pad recycling process and drum brake pad recycling process). The data used for recycling processes was calculated based on daily production rate of the RMS recycling plant (mass of various materials). The energy demand for brake pad recycling was measured from the grid. The electricity mixed used at the plant is green (99% hydropower Norway, 1% hydropower France and wind power Denmark) [Energieversorgung Leverkusen (2021), Umweltbundesamt, HKNR (2021)]. The use of propane for transports with forklift at the plant was also measured.

Moreover, the data for exemplar composition of primary mix for production of brake pads, as well as different mixes with 20%, 64% and 70% recycled material was also supplied. For the manufacturing of primary product and the product with recycled material the data was estimated on professional judgement and experience of RMS.

4.2 Qualitative and quantitative description of unit processes

In the following the processes covered by the assessment are described qualitatively and quantitatively. In case of the quantitative description masses are not provided for the raw materials input for the mixes. Also, three input materials are not named. This is due to confidentiality and to protect the intellectual property rights of the producer.

Several processes are covered and modelled as part of the study of recycled brake lining mixture production. In general, the material for recycling is recovered from used disc and drum brake pads and product rejects collected during the primary production of brake pads. The recovered material is then added to different product mixes, substituting primary material. These brake lining mixes are further developed to produce different types of brakes or various applications (cars, trucks, trains etc.). The different recycling and mixture production processes are explained in more detail along with the depiction of the model.

As depicted in Figure 5 the process charts and the corresponding inventory tables cover the recycling processes of three different input products, followed by a description of the mixing processes for three different mixes and finally a description of the production of the primary mix.

Recycling processes RMS	Mix production processes RMS	Primary mix production process
Figures 6 to 8	**Figures 9 to 11**	**Figure 12**
Recycling process of disc brake pads	Production of mix 20% recycled material for manufacturing of brake pads	Production of primary mix for manufacturing of brake pads
Recycling process of drum brake pads	Production of mix 64% recycled material for manufacturing of brake pads	
Recycling process of grinding dust from brake pads production	Production of mix 70% recycled material for manufacturing of brake pads	

Figure 5: Overview of figures of the qualitative description of the processes

As explained in Figure 6, the disc brake pads with the metal back plates, including add-on parts (damping plates, springs, wear indicators etc.) go through a pre-cleaning process. The residues such as cable, rubber, garbage etc. are removed and the cleaned material is transported via a forklift, which runs on propane, to the mill. Mechanical separation processes are used so separate metal such as springs, sheet, backplates and other junk. This scrap metal is sent for metal recycling and the screened recycled material is sent to the mill for fine grinding. The grinded particles are further screened, and the oversize particles are sent back to the mill to be ground again, ensuring that the waste is minimal. Finally, the recycled material is packaged and if necessary mixed with resin or dust later. Green electricity mix which consists of 99% electricity from hydro and 1% energy from wind is used for the different processes.

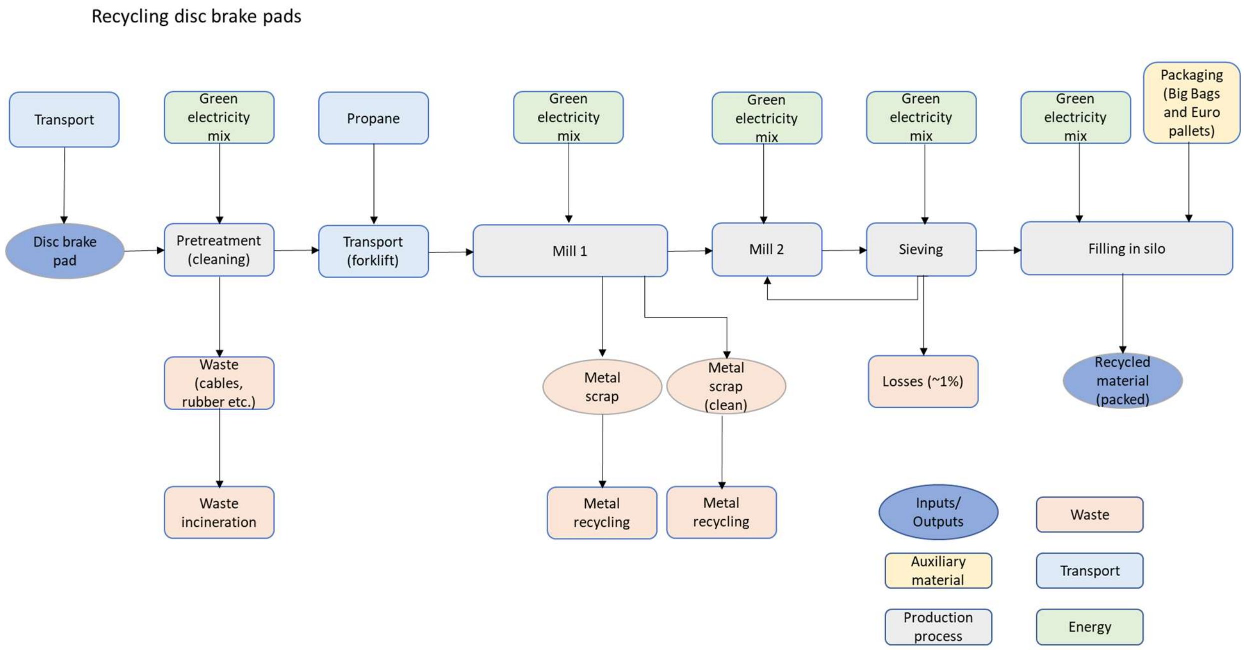

Figure 6: Recycling process of disc brake pads

Table 5: Inventory of recycling disc brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Pre-treament Inputs	Electricity	kWh	Green Energy Mix (self-modelled process)
	Disc braking pad	kg	(self-modeled flow)
	Steel scrap	kg	scrap steel (CH, market for scrap steel)
Outputs	Disc braking pad	kg	(self-modeled flow)
Transport Inputs	Propane	kg	propane (GLO, market for propane)
	Disc braking pad	kg	(self-modeled flow)
Outputs	Disc braking pad	kg	(self-modeled flow)
Mill 1 Inputs	Electricity	kWh	Green Energy Mix (self-modelled process)
	Disc braking pad	kg	(self-modeled flow)
Outputs	Milled braking pad	kg	(self-modeled flow)
Mill 2 Inputs	Electricity	kWh	Green Energy Mix (self-modelled process)
	Milled braking pad	kg	(self-modeled flow)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Outputs	Milled braking pad	kg	(self-modeled flow)
Filling in silo Inputs	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)
	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
Outputs	Milled braking pad	kg	(self-modeled flow)
	Packed milled braking pad	kg	(self-modeled flow)

Process	Amount	Unit	Eoinvent 3.8 Dataset
Transport via truck	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)

As explained in Figure 7, the drum brake linings also go through the pre-cleaning process at first. The residues are sent for incineration. The cleaned material is transported via a forklift to the mill for the shredding process. After that another screening process is carried out to identify oversize granulate that is crushed again and sent back to the recycled material mix, ensuring minimal losses. Finally, the recycled material is packed for shipping and is ready for the shipment. Similar green electricity-mix as explained in previous model is used.

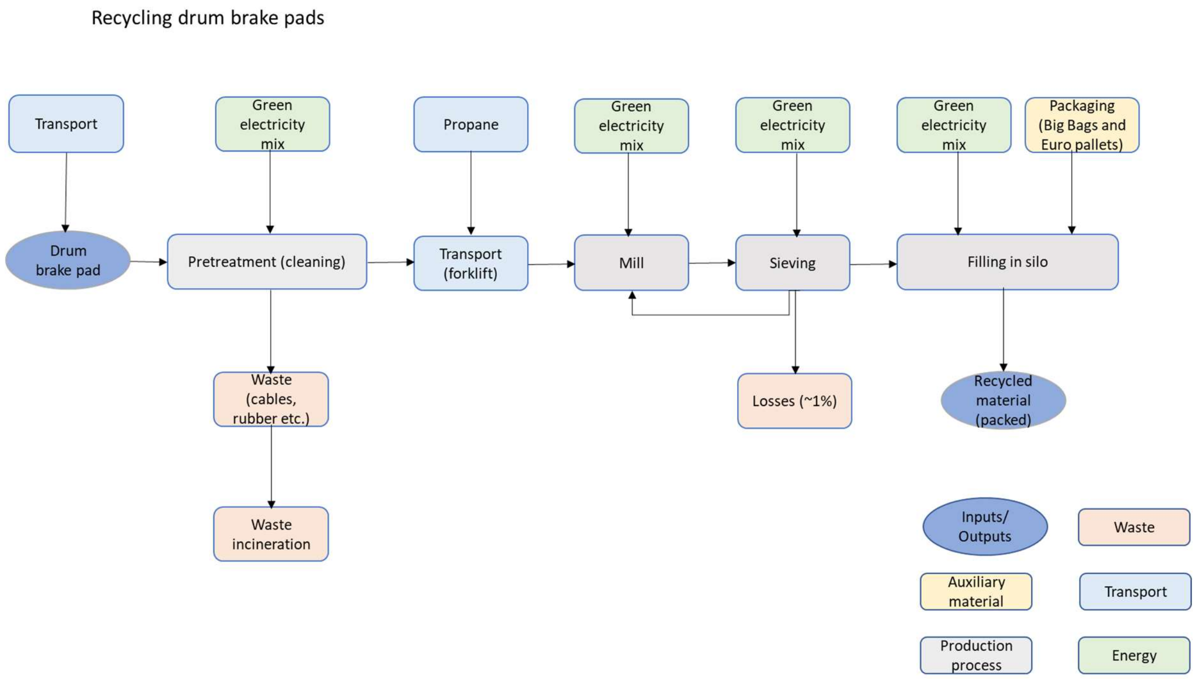

Figure 7: Recycling process of drum brake pads

Table 6: Inventory of recycling drum brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Pre-treament	Electricity	kWh	Green Energy Mix (self-modelled process)
Inputs	Drum braking pad	kg	(self-modeled flow)
Outputs	Drum braking pad	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Drum braking pad	kg	(self-modeled flow)
Outputs	Drum braking pad	kg	(self-modeled flow)
Mill 1	Electricity	kWh	Green Energy Mix (self-modelled process)
Inputs	Drum braking pad	kg	(self-modeled flow)
Outputs	Milled braking pad	kg	(self-modeled flow)
Mill 2	Electricity	kWh	Green Energy Mix (self-modelled process)
Inputs	Milled braking pad	kg	(self-modeled flow)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Outputs	Milled braking pad	kg	(self-modeled flow)
Filling in silo Inputs	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)
	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
	Milled braking pad	kg	(self-modeled flow)
Outputs	Packed milled braking pad	kg	(self-modeled flow)

Table 7: All transport processes of recycling drum brake linings

Process	Amount	Unit	Eoinvent 3.8 Dataset
Transport via truck	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)

As explained in Figure 8, the grinding dust also goes through the pre-cleaning process, which separates waste from the dust that occasionally occurs (such as plastic parts or ear plugs from workers). The residual waste such as wooden and plastic particles etc. is removed and incinerated. After the impurities are cleaned, the next step is the homogenization process in which the material is made uniform. Afterwards, there is the fine screening and mixing process, partially with necessary additives (Adhesive & resin). The resulting product is transported with a forklift or air pressure system. After a final compacting process, the packaging is done. Similar green electricity-mix as explained in the first model is used.

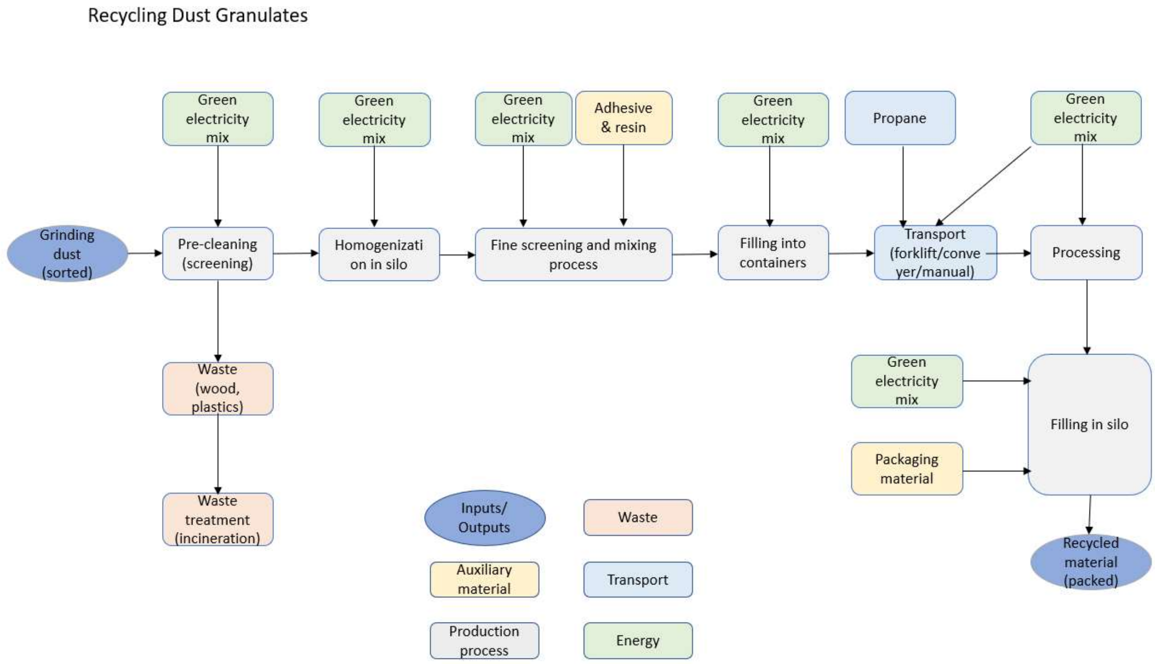

Figure 8: Recycling process of grinding dust from brake pads production

Table 8: Inventory of recycling of grinding dust

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Pre-treament	Electricity	kWh	Green Energy Mix (self-modelled process)
Inputs	Dust	kg	(self-modeled flow)
	Steel scrap	kg	scrap steel (Europe without Switzerland, market for scrap steel)
	Waste Plastic	kg	Waste plastic, mixture (DE, market for waste plastic, mixture)
Outputs	Dust	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Dust	kg	(self-modeled flow)
Outputs	Dust	kg	(self-modeled flow)
Mill 1	Dust	kg	(self-modeled flow)
Inputs	Adhesive	kg	adhesive production, for metal (DE)
Outputs	Output Mixing	kg	(self-modeled flow)
Filling in silo	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)
Inputs	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
	Output Mixing	kg	(self-modeled flow)
Outputs	Packed Final Product	kg	(self-modeled flow)

Table 9: All transport processes of recycling of grinding dust

Process	Amount	Unit	Eoinvent 3.8 Dataset
Transport via truck	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)

Figures 6, 7 and 8 showcase the production process of different brake pad and lining mixes from the recycled material from disc, drum or grinding dust. Different mixture compositions of the recycled material (20%, 64% and 70%) are combined with several ingredients such as minerals, steel, natural fibers, resin etc. to prepare the complete brake lining mix. The final brake lining mix goes through the cleaning and packaging process at the end.

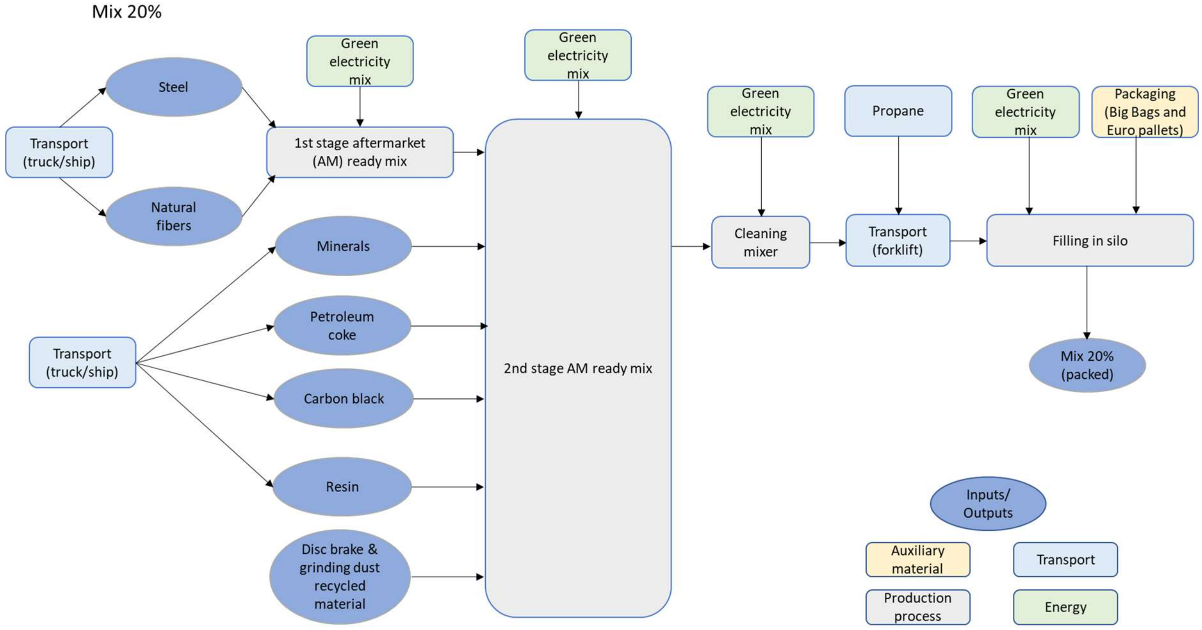

Figure 9: Production of mix 20% recycled material for manufacturing of brake pads

Table 10: Inventory of mix 20% recycled material for manufacturing of brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
BOM Disc Braking Pad – 20% Mix	Electricity	kWh	Green Energy Mix (self-modelled process)
	Aluminium oxide	kg	Aluminium oxide, metallurgical (CN, aluminium oxide production)
Inputs	Epoxy resin	kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Graphite	kg	Graphite (RoW, graphite production)
	Petroleum coke	kg	Petroleum coke (RoW, petroleum coke production, petroleum refinery operation)
	Sulfur	kg	Sulfur (RoW, sulfur production, petroleum refinery operation)
	Steel	kg	Wire drawing, steel (RoW)
	Synthetic rubber	kg	Synthetic rubber (RoW, synthetic rubber production)
	Silica sand	kg	Silica sand (DE, silica sand production)
	Barite	kg	Barite, (RER, barite production)
	Dust	kg	(self-modeled flow)
	Disc braking pad	kg	(self-modeled flow)
Outputs	Ready Mix 2	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Ready Mix 2	kg	(self-modeled flow)
Outputs	Ready Mix 2	kg	(self-modeled flow)
Filling in silo	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Inputs	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
	Ready Mix 2	kg	(self-modeled flow)
Outputs	Final Product 20%	kg	(self-modeled flow)

Table 11: All transport processes of mix 20% recycled material for manufacturing of brake pads

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
Aluminium oxide	Aluminium oxide		kg	Aluminium oxide, metallurgical (CN, aluminium oxide production)
	Transport	800	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Epoxy resin	Epoxy resin		kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Transport	80	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Graphite	Graphite		kg	Graphite (RoW, graphite production)
	Transport	700	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Petroleum coke	Petroleum coke		kg	Petroleum coke (RoW, petroleum coke production, petroleum refinery operation)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
	Transport	700	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight,

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
				lorry 16-32 metric ton, EURO6)
Steel	Steel		kg	Wire drawing, steel (RoW)
	Transport	13500	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
	Transport	400	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Sulfur	Sulfur		kg	Sulfur (RoW, sulfur production, petroleum refinery operation)
	Transport	400	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
	Transport	22000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Silicium dioxide	Silica sand		kg	Silica sand production (DE)
	Transport	50	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Synthetic rubber	Synthetic rubber		kg	Synthetic rubber (RoW, synthetic rubber production)
	Transport	400	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Barite	Barite		kg	Barite, (RER, barite production)
	Transport	470	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Outputs	Ready Mix 2		kg	

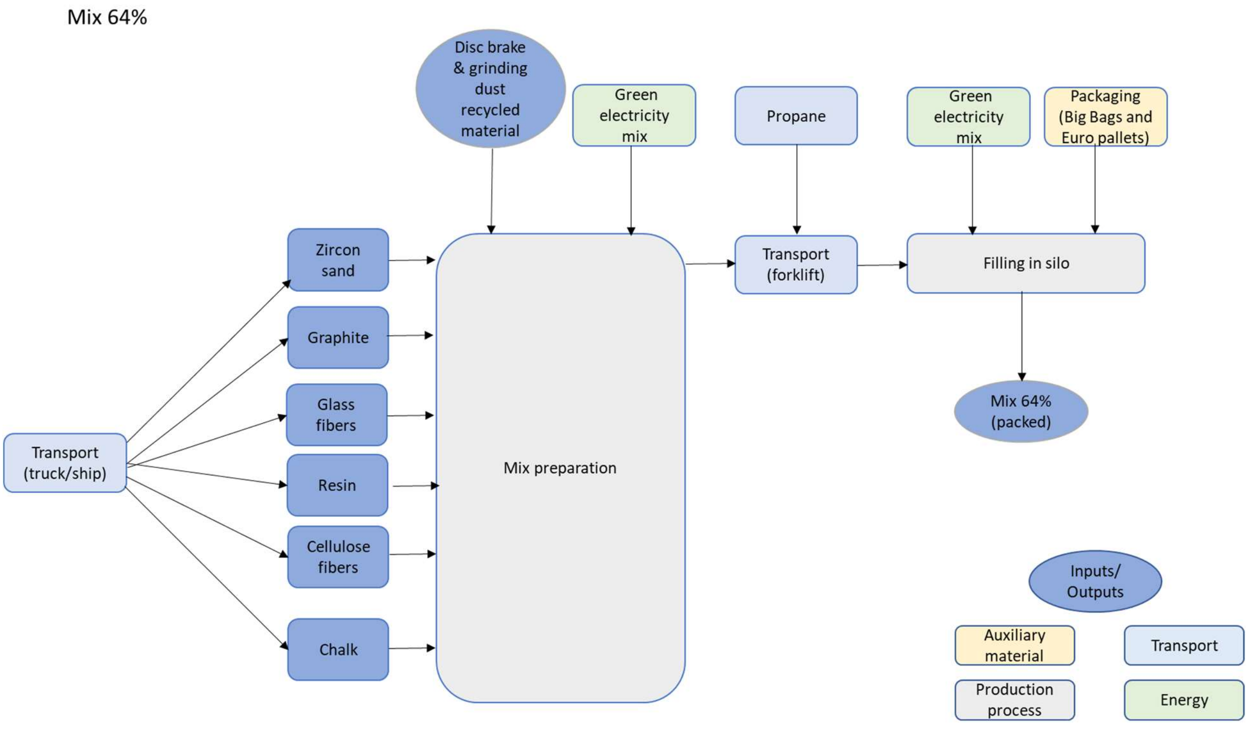

Figure 10: Production of mix 64% recycled material for manufacturing of brake pads

Table 12: Inventory of mix 64% recycled material for manufacturing of brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
BOM Drum Braking Pad – 64% Mix Inputs	Electricity	kWh	Green Energy Mix (self-modelled process)
	Chalk	kg	Calcium carbonate, precipitated (RER, calcium carbonate production, precipitated)
	Epoxy resin	kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Graphite	kg	Graphite (RoW, graphite production)
	Cellulose fibre	kg	Cellulose fibre, (RoW, cellulose fibre production)
	Zircon sand	kg	Zircon, 50% zirconium (RoW, heavy mineral sand quarry operation)
	Glass fibre	kg	Glass fibre (RoW, glass fibre production)
	Dust	kg	(self-modeled flow)
	Drum braking pad	kg	(self-modeled flow)
Outputs	Ready Mix	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Ready Mix	kg	(self-modeled flow)
Outputs	Ready Mix	kg	(self-modeled flow)
Filling in silo	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Inputs	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Ready Mix 2	kg	(self-modeled flow)
Outputs	Final Product 64%	kg	(self-modeled flow)

Table 13: All transport processes of mix 64% recycled material for manufacturing of brake pads

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
Chalk	Calcium carbonate		kg	Calcium carbonate, precipitated (RER, calcium carbonate production, precipitated)
	Transport	330	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Epoxy resin	Epoxy resin		kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Transport	80	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Graphite	Graphite		kg	Graphite (RoW, graphite production)
	Transport	650	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Cellulose fibre	Cellulose fibre		kg	Cellulose fibre, (RoW, cellulose fibre production)
	Transport	420	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Zircon	Zircon		kg	Zircon, 50% zirconium (RoW, heavy mineral sand quarry operation)
	Transport	2000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
	Transport	350	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER,

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
				market for transport, freight, lorry 16-32 metric ton, EURO6)
Drum Braking Pad	Drum Braking Pad		kg	(self-modeled flow)
	Transport	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Dust	Dust		kg	(self-modeled flow)
	Transport	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Glass fibre	Glass fibre		kg	Glass fibre (RoW, glass fibre production)
	Transport	400	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Outputs	Ready Mix		kg	

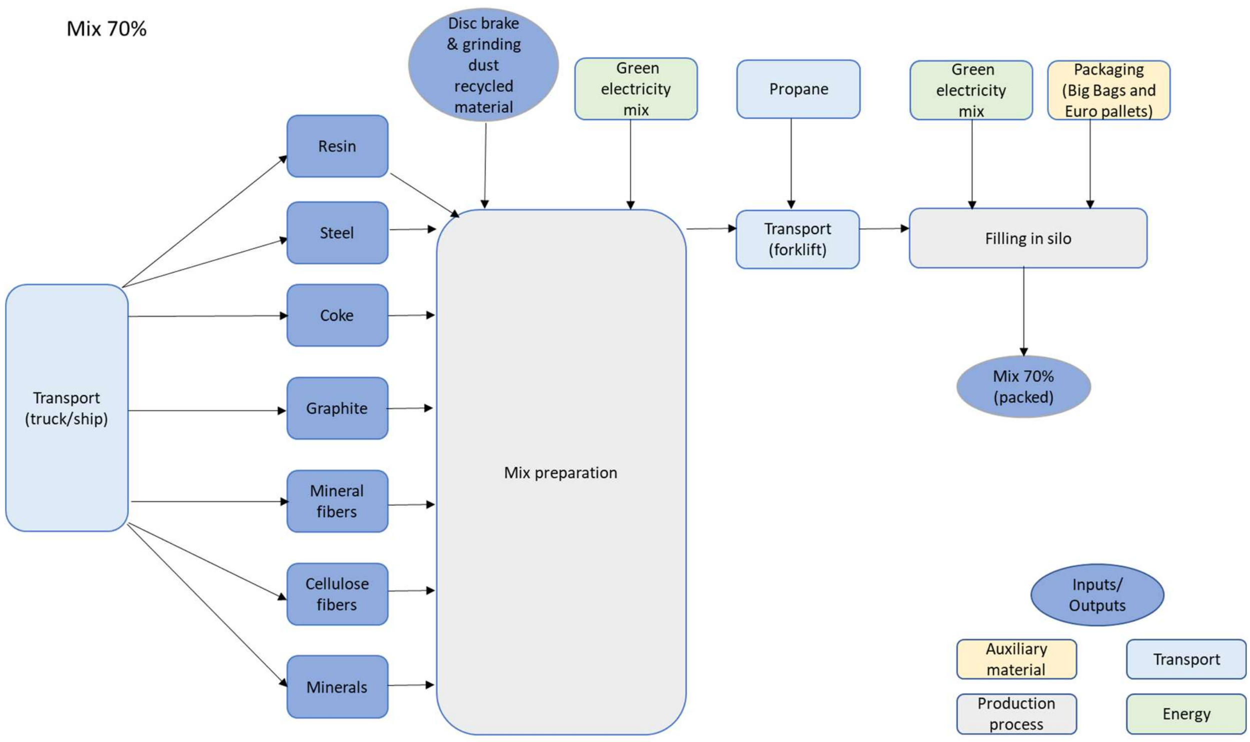

Figure 11: Production of mix 70% recycled material for manufacturing of brake pads

Table 14: Inventory of mix 70% recycled material for manufacturing of brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
BOM Disc Braking Pad – 20% Mix Inputs	Electricity	kWh	Green Energy Mix (self-modelled process)
	Cellulose fibre	kg	Cellulose fibre, (RoW, cellulose fibre production)
	Epoxy resin	kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Graphite	kg	Graphite (RoW, graphite production)
	Petroleum coke	kg	Petroleum coke (RoW, petroleum coke production, petroleum refinery operation)
	Stone wool	kg	Stone wool (CH, stone wool production)
	Steel	kg	Wire drawing, steel (RoW)
	Synthetic rubber	kg	(RoW, synthetic rubber production)
	Silica sand	kg	Silica sand (DE, silica sand production)
	Barite	kg	Barite, (RER, barite production)
	Dust	kg	(self-modeled flow)
	Disc braking pad	kg	(self-modeled flow)
Outputs	Ready-mix	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Ready-mix	kg	(self-modeled flow)
Outputs	Ready-mix	kg	(self-modeled flow)

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
Filling in silo Inputs	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)
	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
	Ready Mix 2	kg	(self-modeled flow)
Outputs	Final Product 70%	kg	(self-modeled flow)

Table 15: All transport processes of mix 70% recycled material for manufacturing of brake pads

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
Cellulose fibre	Cellulose fibre		kg	Cellulose fibre, (RoW, cellulose fibre production)
	Transport	420	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Epoxy resin	Epoxy resin		kg	Epoxy resin, liquid (RER, epoxy resin production, liquid)
	Transport	80	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Graphite	Graphite		kg	Graphite (RoW, graphite production)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Petroleum coke	Petroleum coke		kg	Petroleum coke (RoW, petroleum coke production, petroleum refinery operation)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Steel	Wire drawing, steel		kg	Wire drawing, steel (RoW)
	Transport	13500	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
	Transport	400	Km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Stone wool	Stone wool		kg	Stone wool (CH, stone wool production)
	Transport	100	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Silicium dioxide	Silica sand		kg	Silica sand production (DE)
	Transport	800	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Barite	Barite		kg	Barite, (RER, barite production)
	Transport	470	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Disc Braking Pad	Disc Braking Pad		kg	(self-modeled flow)
	Transport	200	Km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Dust	Dust		kg	(self-modeled flow)
	Transport	200	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Outputs	Ready-mix		kg	(self-modeled flow)

The alternative route for producing brake pad and lining mixes is without the recycled material. As explained in figure 12, various elements such as polymers, chemical compounds, minerals, metals, etc. are used to prepare this 100% original mix. The exact details of the materials used in the mix cannot be disclosed due to NDA. After preparation, the mix goes through a cleaning and packaging process.

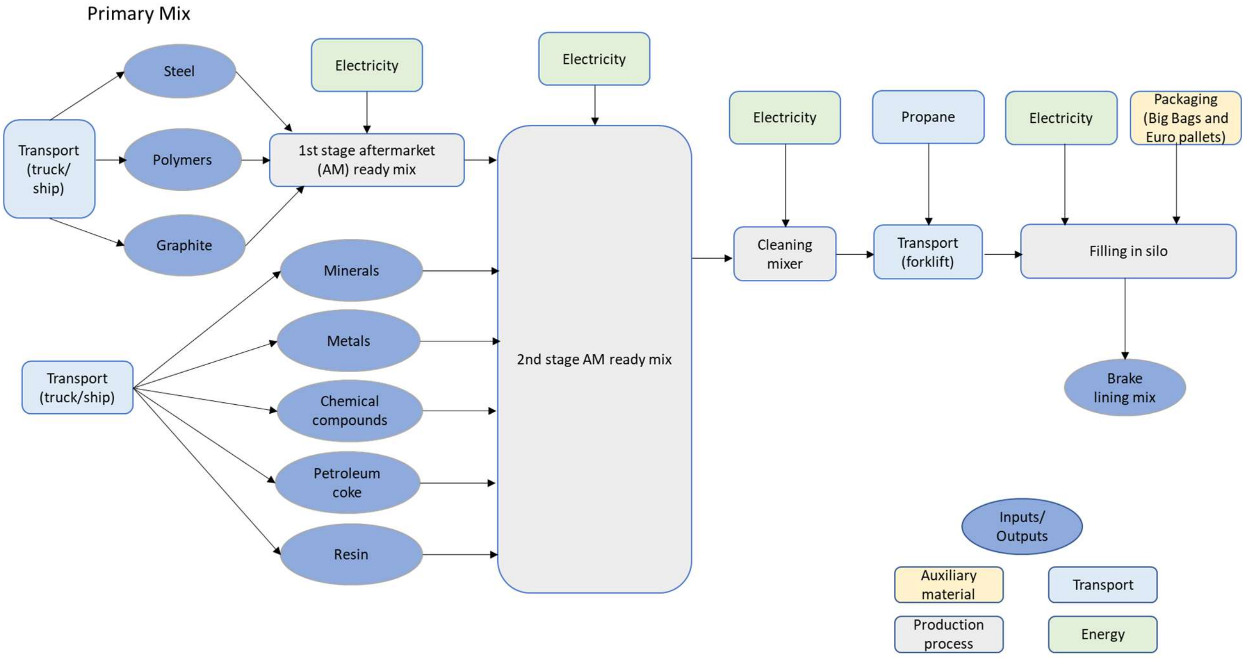

Figure 12: Production of primary mix for manufacturing of brake pads

Table 16: Inventory of primary mix for manufacturing of brake pads

Process	Material/flow	Unit	Eoinvent 3.8 Dataset
BOM Disc Braking Pad – 20% Mix Inputs	Polyacrylamide	kg	polyacrylamide production (GLO)
	Aluminium oxide	kg	treatment of aluminium scrap, new, at refiner (RER)
	Epoxy resin	kg	epoxy resin production, liquid (RER)
	Synthetic Graphite	kg	synthetic graphite production, battery grade (CN)
	Petroleum coke	kg	petroleum coke production, petroleum refinery operation (RoW)
	Portafer	kg	portafer production (RER)
	Steel	kg	Wire drawing, steel (RoW)
	Material 1	kg	(self-modeled flow)
	Silica sand	kg	silica sand production (DE)
	Barite	kg	barite production (RER)
	Material 3	kg	(self-modeled flow)
	Aluminium alloy, AlLi	kg	aluminium alloy production, AlLi (RoW)
	Fluorspar	kg	fluorspar production, 97% purity (GLO)
	Silicon carbide	kg	silicon carbide production (RoW)
	Material 2	kg	
	Glass fibre	kg	glass fibre reinforced plastic production, polyamide, injection moulded (RER)
Outputs	Ready Mix 1&2	kg	(self-modeled flow)
Transport	Propane	kg	propane (GLO, market for propane)
Inputs	Ready Mix 1&2	kg	(self-modeled flow)
Outputs	Ready Mix 1&2	kg	(self-modeled flow)

Filling in silo Inputs	Euro Pallets	kg	wood pellet, measured as dry mass (RER, market for wood pellet, measured as dry mass)
	Wooden frames	kg	wood chips, dry, measured as dry mass (RER, market for wood chips, dry, measured as dry mass)
	Plastic stripes	kg	packaging film, low density polyethylene (GLO, market for packaging film, low density polyethylene)
	Big Bag	kg	polypropylene, granulate (GLO, market for polypropylene, granulate)
	Ready Mix 1&2	kg	(self-modeled flow)
Outputs	Final Product 100% Primary	kg	(self-modeled flow)
End of Life	Waste	Kg	treatment of hazardous waste, hazardous waste incineration (Europe without Switzerland)

Table 17: All transport processes of primary mix for manufacturing of brake pads

Process	Material/flow	Amount	Unit	Ecoinvent 3.8
Inputs				
Calcined coke	Calcined petroleum coke		kg	Petroleum coke (RoW, Petroleum coke production, petroleum refinery operation)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Material 1			kg	(self-modeled flow)
	Transport	20000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Resin	Epoxy resin		kg	Epoxy resin production, liquid (RER)
	Transport	500	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Material 2			kg	(self-modeled flow)
	Transport	15000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Aluminum alloy	Aluminium		kg	Aluminium alloy production, AlLi (RoW)
	Transport	22000	km	Transport, freight, sea, container ship (GLO

				Transport, freight, sea, container ship)
Calcinated alumina	Alumina		kg	Treatment of aluminium scrap, new, at refinery (RER)
	Transport	450	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Silicium dioxide	Silica sand		kg	Silica sand production (DE)
	Transport	1000	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Material 3			kg	(self-modeled flow)
	Transport	1000	km	transport, freight, lorry 16-32 metric ton, EURO6 (RER, market for transport, freight, lorry 16-32 metric ton, EURO6)
Silicon carbide (Archeson process)	Silicon carbide		kg	Silicon carbide production (RoW)
	Transport	10000	km	Transport, freight, sea, container ship (GLO Transport, freight, sea, container ship)
Outputs	Primary mix		kg	

The green electricity mix is composed of waterpower from Norway (99%), waterpower from France and wind power from Denmark (together 1%). The table below shows the electricity mix composition in kWh.

Table 18: Green electricity mix

Process	Amount 20%	Amount 64%	Amount 70%	Unit	Ecoinvent 3.8 Dataset
Hydro power	0,9	0,9	0,9	kWh	electricity, high voltage (NO, electricity production, hydro, pumped storage)
Wind power	0,013	0,013	0,013	kWh	electricity, high voltage (DK, electricity production, wind, 1-3MW turbine, onshore)
Hydro power	0,087	0,087	0,087	kWh	electricity, high voltage (FR, electricity production, hydro, pumped storage)
Output	1	1	1	kWh	

Table 19: Germany photovoltaic electricity

Process	Amount	Unit	Ecoinvent 3.8 Dataset
Solar Power	1	kWh	electricity production, photovoltaic, 570kWp open ground installation, multi-Si (DE)
Output	1	kWh	

The "Germany Green Electricity Mix" is composed as follows (based on BDEW):

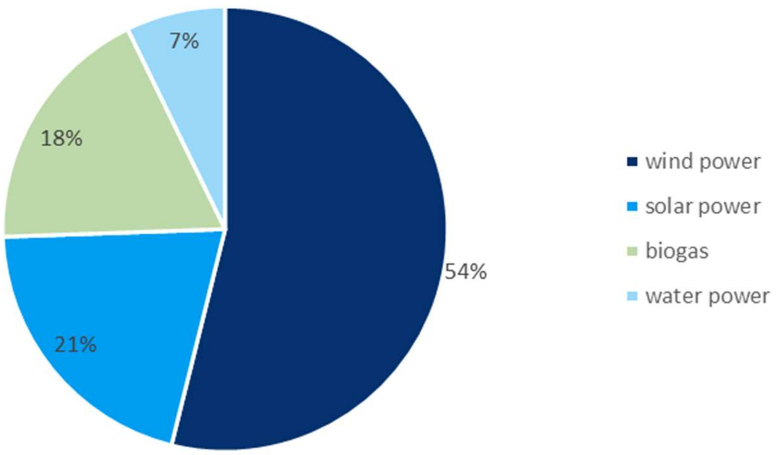

Figure 13: Composition of German green electricity mix

The electricity consumption in kWh is depicted in the table below:

Table 20: Germany Green Electricity Mix

Process	Amount	Unit	Ecoinvent 3.8 Dataset
Hydro power	0,072	kWh	electricity production, hydro, pumped storage (DE)
Solar power	0,218	kWh	electricity production, photovoltaic, 570kWp open ground installation, multi-Si (DE)
Biogas	0,18	kWh	heat and power co-generation, biogas, gas engine (DE)
Wind Power	0,53	kWh	electricity production, wind, 1-3MW turbine, onshore (DE)
Output	1	kWh	

5. LIFE CYCLE IMPACT ASSESSMENT

5.1 Results of the study

In this section the results of the impact assessment are presented. First the overall results in absolute figures are depicted. They represent the results for each impact category selected according to chapter 3.6 per functional unit.
To allow a more detailed view on the impacts and their source, a detailed depiction is provided in chapter 5.1.2.

5.1.1 Overall results

The following table shows the overall results for the different mixes assessed:

Table 21 Overall results per impact category and functional unit

Impact Category	RMS Mix 20% (RMS Electricity)	RMS Mix 64% (RMS Electricity)	RMS Mix 70% (RMS Electricity)	RMS OE 100% primary + waste incineration	RMS OE 100% primary + Underground Deposit
Climate Change (kg CO2-eq.)	8,13E-01	6,50E-01	4,88E-01	5,49E+00	3,42E+00
Eutrophication, freshwater (kg P-eq.)	2,08E-04	1,33E-04	1,13E-04	5,16E-03	4,88E-03
Eutrophication, marine (kg N-eq.)	1,40E-03	7,97E-04	6,31E-04	1,05E-02	1,00E-02
Eutrophication, terrestrial (mol N-eq.)	1,39E-02	7,91E-03	6,38E-03	1,24E-01	1,20E-01
Acidification (mol H+-eq.)	6,95E-03	4,08E-03	3,29E-03	1,02E-01	9,95E-02
Photochemical ozone formation (kg NMVOC-eq.)	5,11E-03	3,02E-03	2,49E-03	3,50E-02	3,41E-02

Resource use, fossils (MJ)	1,82E+01	1,22E+01	1,07E+01	6,39E+01	5,70E+01
Resource use, minerals & metals (kg Sb-eq.)	1,07E-03	1,03E-03	6,29E-04	1,01E+01	1,01E+01
Particulate matter (disease incident)	3,52E-04	2,52E-04	1,80E-04	3,87E-03	3,80E-03

The Table 21 shows the overall results of the conducted LCA study done via the evaluation method of Environmental Footprint 2.0., which is developed by the European Union Joint Research Centre. The RMS mixtures from recycled friction material (disc brake, drum brake and granulated dust) are compared with the friction material mix prepared from the primary materials without the recycled material. The methodology provides the environmental performance across 9 different impact categories as mentioned in the Table 21. This information allows the understanding of the environmental impact of producing recycled brake lining mixes through different routes. The information can be used by OEM's, brake, and friction manufacturers to make an informed decision when selecting sustainable raw materials for production.

The environmental impact categories for the OE 100% Primary + waste incineration have the highest impact among all the compared mixtures, especially when it comes to climate change. This mixture includes incineration in the end-of -life stage that drives the environmental impact across all the different impact categories, the climate change category is impacted the most due to incineration. The end-of-life route of the OE 100% Primary + underground deposit is landfilling dumping, which has a lower environmental impact across all impact categories compared to incineration as end-of-life route.

The OE 100% mix uses more raw materials compared to the disc brake and drum brake recycled material mixes from RMS. Instead of recycling brake pads to manufacture recycled material, this mixture is made from combing several minerals, chemical compounds, natural fibers as well as steel. The environmental impact of the raw materials across all the impact categories used in the OE process have a higher impact than the raw materials used for the different brake lining recycled material mixtures. The mining and processing of these materials contribute to the higher environmental impact for the mix. One metal in the material with the highest environmental impact pushes the overall environmental impact of the OE mix 100% much higher than the other mixes. Epoxy resin is another material with higher impact and is used in different quantities in all the mixtures produced by RMS.

Therefore, OE 100% Primary + waste incineration has the highest environmental impact across all the categories, followed by the OE 100% Primary + underground deposit. The RMS recycled material mixtures have comparatively 70-80% less impact across different impact categories. A more detailed explanation of the results is mentioned in the section below.

5.1.2 Detailed results

The detailed results are shown in the figures below (Figure: 14 to Figure 22). The X-axis shows the different product systems assessed: primary product with underground deposit, primary product with incineration and the different mixes: 20%, 64% and 70% recycled material mix. The Y-axis shows the values and the unit of the environmental impact category. Transport, electricity, raw materials, packaging, and End-of-Life (considered only for the primary product; two first columns on the left) were used to group the data. There is no specific separation of the different input materials to the recycling process in the discussion of results. This is due to the minor deviations of the impacts arising from the different materials compared to the overall results.

All extraction techniques and resource processing are covered by the group "raw materials." The raw material depletion is significantly less for three RMS mixtures (20%, 64%, and 70%) because they do not require as many primary material inputs as a core product does.
The transfer to gate and the transit to EoL treatment were both included in the transport processes. This indicates that due to EoL transportation to underground landfill, which was assumed for 1000 km in Germany, the emissions due to transportation from primary product underground deposit are higher than for primary product incineration which was assumed to be only 200km.
While the production of friction materials is dispersed around the nation, underground deposit primarily occurs at mines in East Germany that are no longer in operation. The furthest distance conceivable was thought to be the worst case (1000 km).
Electricity used for manufacturing does not contribute to the emissions share as much as other groups as the manufacturing processes are not that energy intensive.
Packaging (Euro pallets, timber frames, and big bags) was assumed to be reused. Multiple use cycles have reduced the environmental burden of the packaging. The assumption was met that big bags would complete 5 and pallets 10 use cycles before entering EoL treatment. For this reason, the packaging-related emissions have a comparatively low share of the overall emissions.

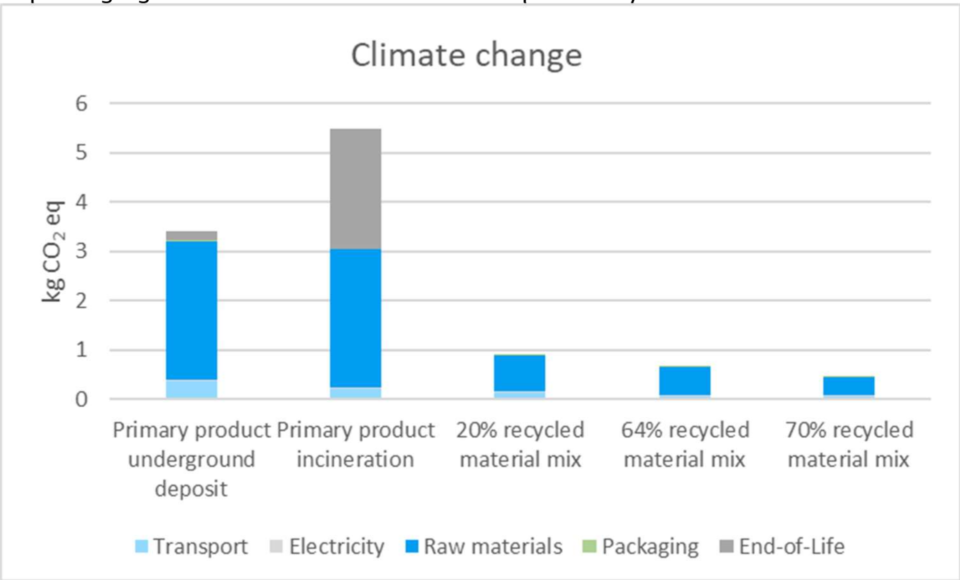

Figure: 14 Detailed results for the environmental impact category Climate change

Friction material products consisting of 100% primary products (incineration and underground deposit) are the main contributors to the category Climate change. The emissions from burning the waste are higher than they would be in the event of an underground primary product deposit. The mining of raw materials and their processing account for a significant portion of the emissions for the first two columns. Additionally, a sizeable portion of the CO_2 emissions are caused by the transport procedures (larger in case of primary product underground deposit due to longer EoL transportation). Electricity and packaging do not considerably increase the CO_2 emissions contribution.

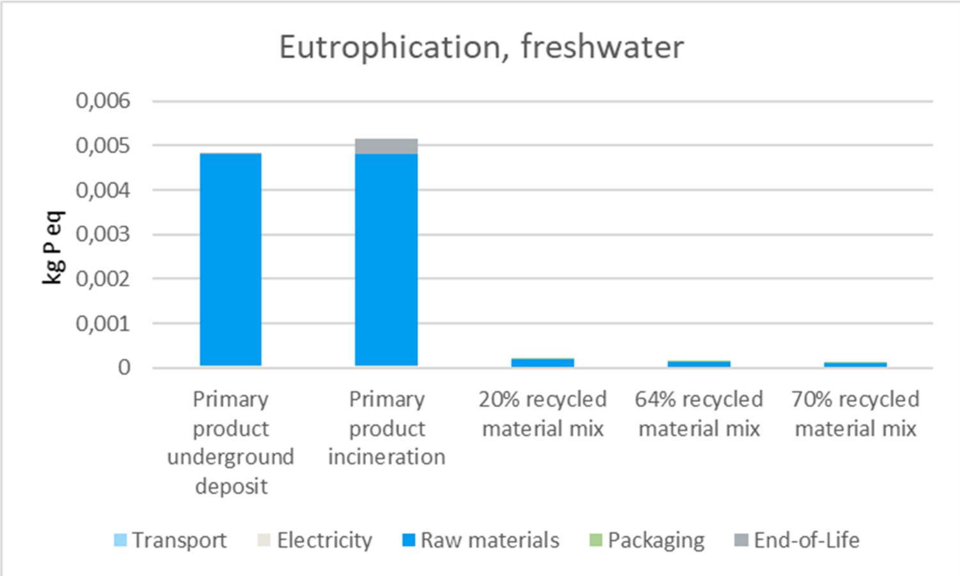

Figure 15: Detailed results for the environmental impact category Eutrophication, freshwater

Mining and processing of raw materials has the largest impact on the category Eutrophication, freshwater. Incineration of hazardous waste generates phosphates and nitrate compounds as well. On contrary to other impact categories, the transport processes do not contribute significantly to the emissions share.

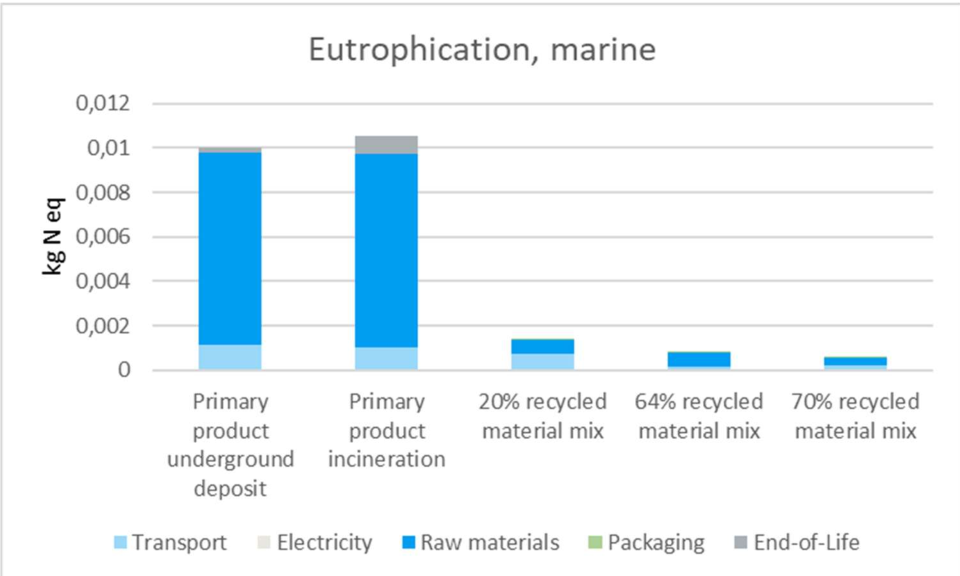

Figure 16: Detailed results for the environmental impact category Eutrophication, marine

For description see Figure 15.

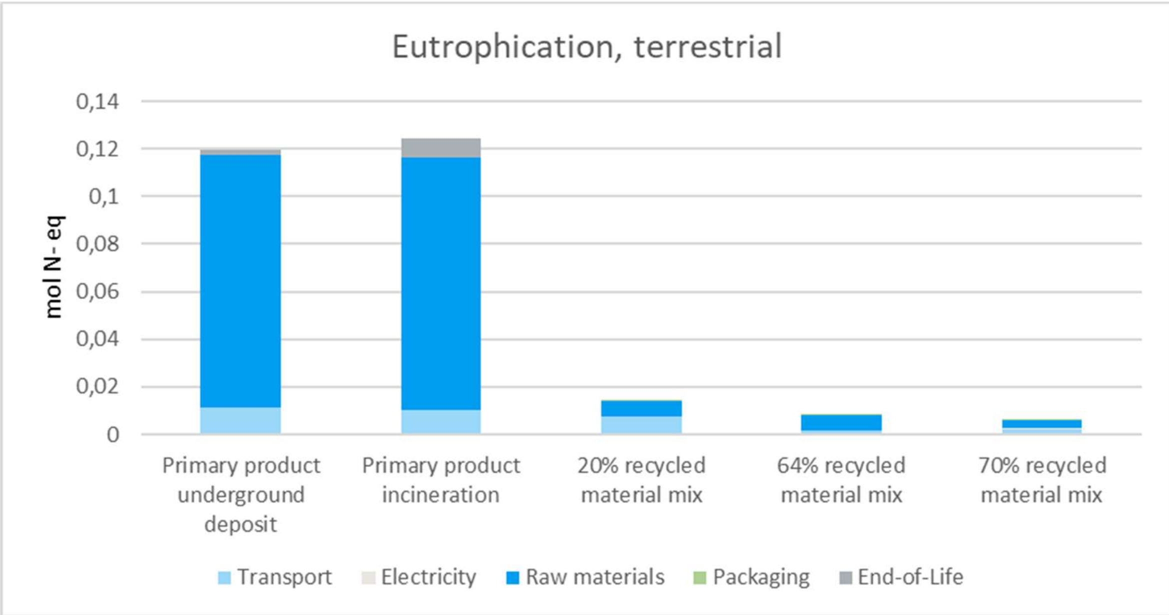

Figure 17: Detailed results for the environmental impact category Eutrophication, terrestrial

The extraction and processing of raw materials is the main cause of emissions for the category Eutrophication (marine and terrestrial). Transport generates the second largest share of emissions and EoL the third. Electricity and packaging, as previously mentioned, do not provide an increase in emissions compared to other groups.

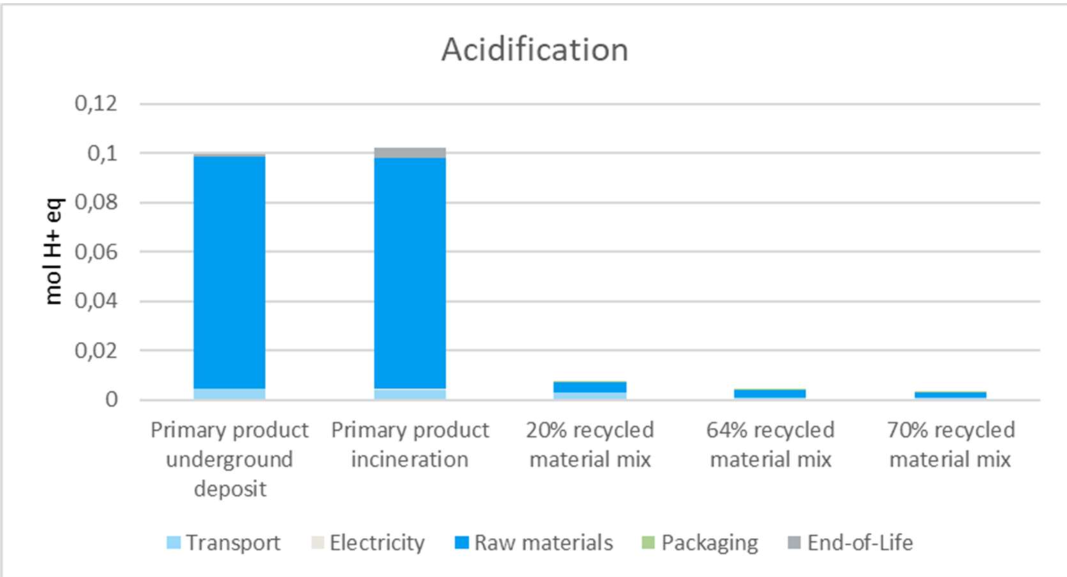

Figure 18: Detailed results for the environmental impact category Acidification

For Acidification, the biggest share of emissions, after raw materials depletion, originates firstly in transport processes, then in EoL treatment. However, for Primary product incineration the EoL emissions are as high as the emissions from transportation.

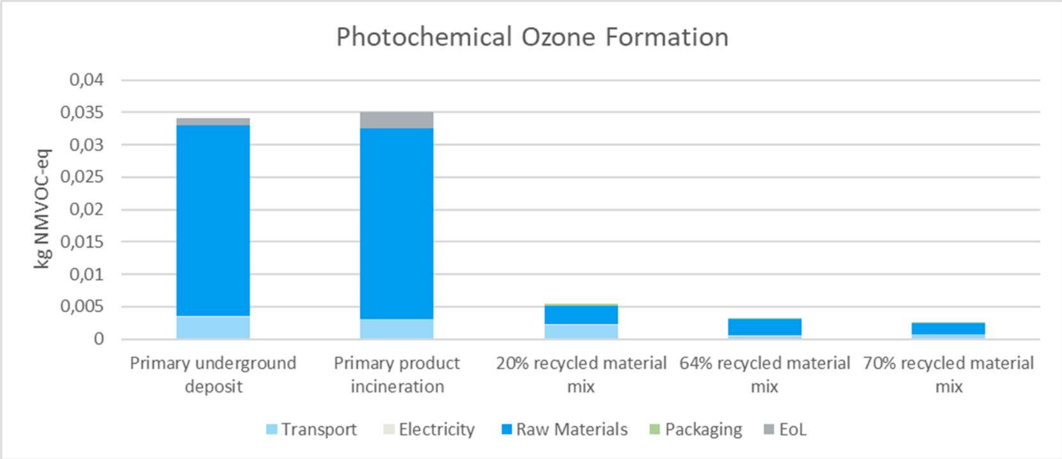

Figure 19: Detailed results for the environmental impact category Photochemical ozone formation

Photochemical ozone formation emissions are mostly assigned to mining and processing of materials. Due to high nitrate oxides emissions coming from transport processes, the transportation is also a significant contributor to this impact category. Incineration of hazardous waste has a large impact on POF as well.

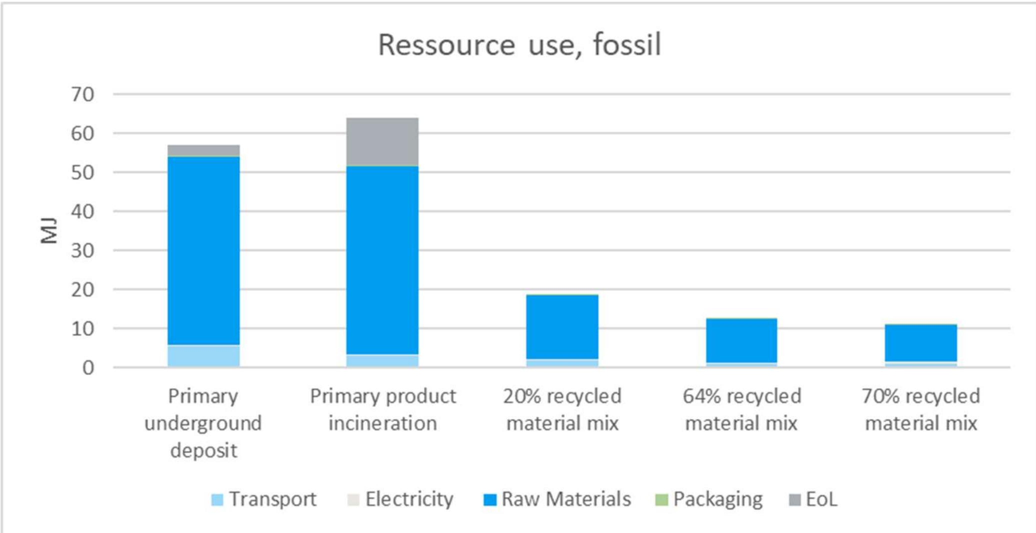

Figure 20: Detailed results for the environmental impact category Resource use, fossil

EoL has a significant impact for resource use fossil, especially in case of primary product incineration where the energy is used to burn the waste. Lastly, the transport processes use fossil fuels and have accordingly larger share of emissions.

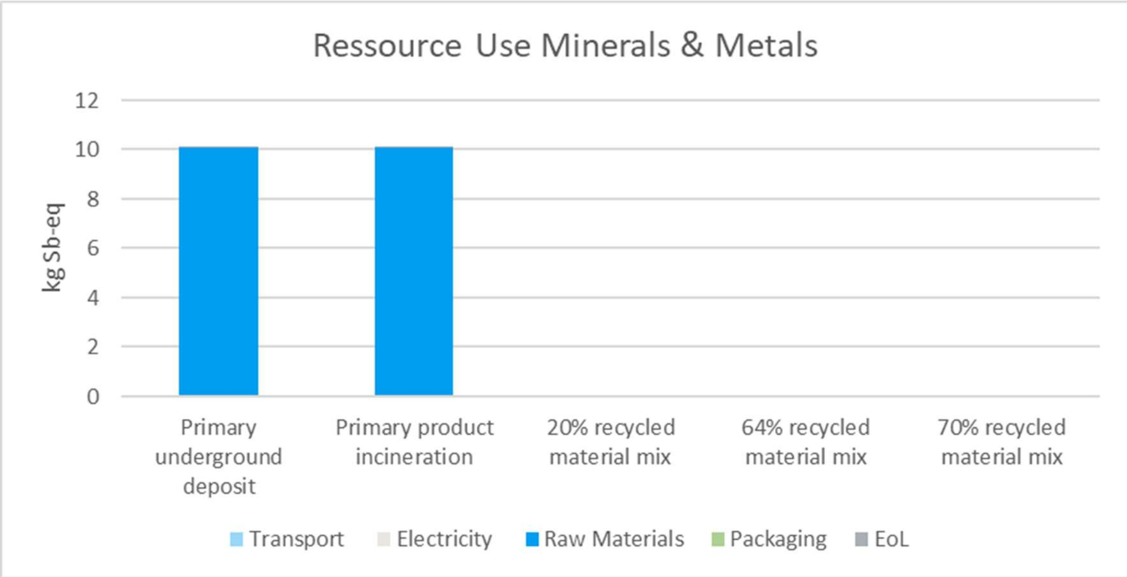

Figure 21: Detailed results for the environmental impact category Resource use, minerals & metals

For Resource use mineral & metals the largest contribution are resource mining and processing which was already anticipated in the beginning. The brake pads contain a high number of metals, binders and other minerals that not only cause emissions during their extraction but if not recycled lead to resource depletion.

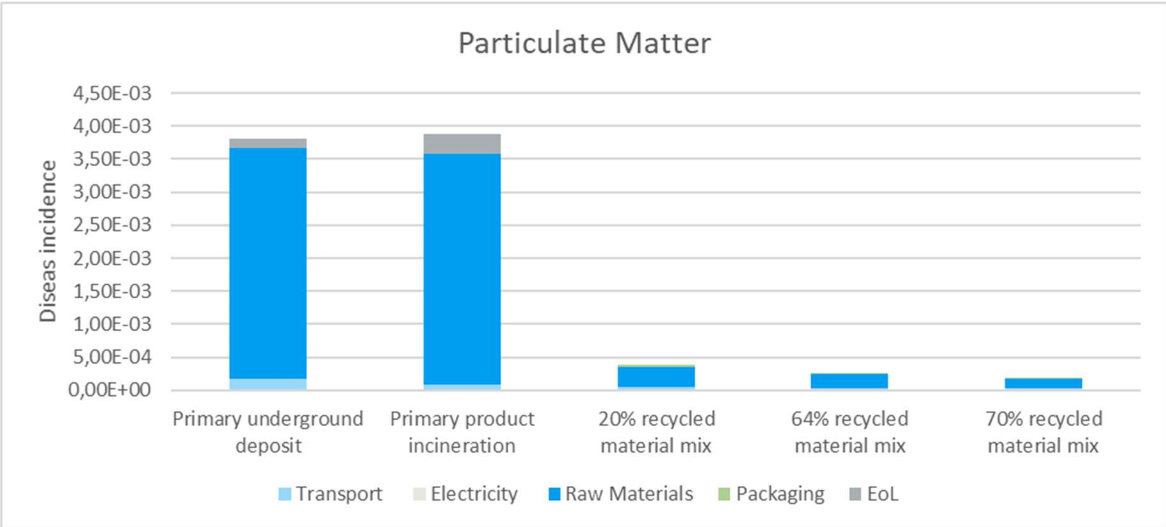

Figure 22: Detailed results for the environmental impact category Particulate matter

The highest impact on Particulate matter is caused by resource depletion and processing. Also, the incineration contributes to formation of particulate matter. Finally, the transport processes generate through abrasion the big share of particulate matter emissions.

It becomes obvious that raw material provision is the main driver of all impact categories assessed. This is especially the case for the primary mix which contains metals that contribute to a major share to the impacts. Due to confidentiality reasons these raw materials cannot be named.

5.2 Normalization, grouping and weighting

Within this study no normalization, grouping or weighting has been applied to allow a comparative assertion.

5.3 Scenario analyses

5.3.1 Electricity scenarios

In this section, different scenarios will be compared. In each scenario, there are two variables which are the product type and the electricity source. The baseline is recycling of disc brake pad, drum brake pad and dust by Green Electricity Mix.

Even tough electricity consumption shows a minor share of impacts compared to other contributors it is relevant to assess the differences of grid mixes. At the time of assessment RMS receives almost 100% waterpower from Norway, which is very beneficial from an environmental point of view. However, it is not guaranteed that this mix will stay the same as RMS is only assured to receive 100% green energy independently from the composition of energy carriers. Moreover, RMS is planning to install solar panels to substitute electricity from the grid. Thus, the scenarios shown in the following addresses this variability.

Recycling of disc brake pads and drum brake pads is relatively easier than recycling of dust. The only process, which takes place to recycle disc brake pad and drum brake pad is pre-sorting and the heavy crushing process. The only resource used in this operation is electricity. Which means, electricity is the only climate change impact produced by this process. Because of that, changing the source of electricity affects the total climate change impact of recycling disc and drum brake pads dramatically. On the other hand, recycling dust is done by homogenization, and mixing processes. Homogenization process produces steel scrap and plastic as waste. Additionally, in mixing process, adhesive for metal is used alongside with electricity. Due to that, a change in electricity source has relatively lower impact on the total climate change impact of recycling dust process.

Furthermore, our baseline models for all recycling processes uses Green Electricity Mix. Using Germany Green Electricity Mix instead of Green Electricity Mix would have a 75%, 200%, and 1% greater impact on climate change on disc brake pad recycling, drum brake pad recycling, and dust recycling, respectively. Additionally, using 100% Solar Electricity (Germany) instead of Green Electricity Mix would have a 44%, 100%, and 1% greater impact on climate change on disc brake pad recycling, drum brake pad recycling, and dust recycling, respectively.
It must be noted that RMS is currently evaluating the option to set up solar panels on site to a big extend. The scenario depicted here for solar energy is valid for the case that RMS purchases solar energy but also for own solar panels on the factory roof.

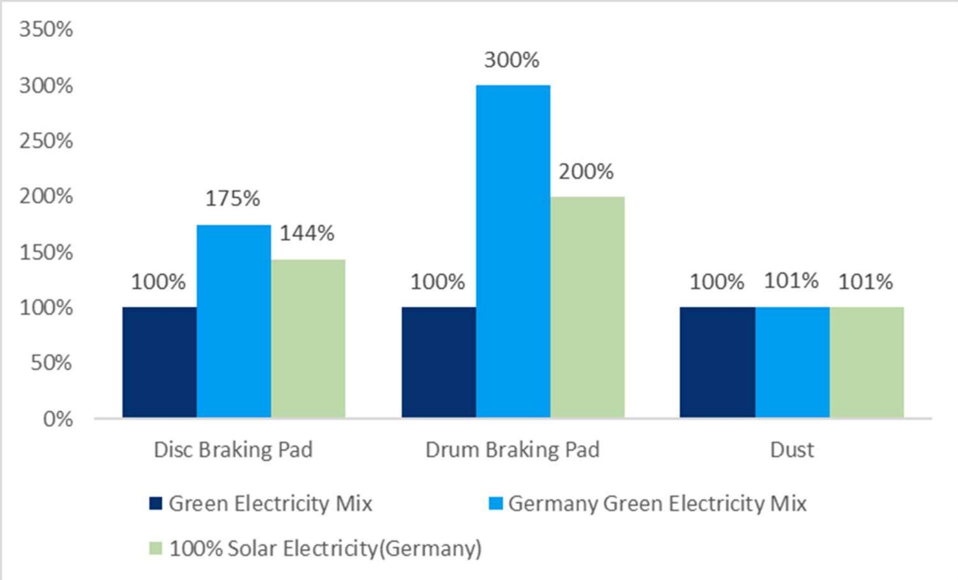

Figure 23: Energy scenario, climate change

Table 22 shows the results for climate change for the different scenarios. It becomes obvious that there are minimal changes of impacts compared to the baseline. This can be explained by the overall low impact of electricity consumption to climate change which for the case of the three baseline mixes is between ~ 4-7%. Nevertheless, the average German green energy mix increases the results the most. The results for all impact categories of the scenarios are provided in the Annex.

Table 22: Overall results for climate change for electricity scenario

Overall kg CO_2 eq.	20% recycled material mix	64% recycled material mix	70% recycled material mix
Green Energy Mix (baseline)	0,8126	0,6502	0,4877
Solar Electricity	0,8129	0,6549	0,4933
Germany Green Energy	0,8158	0,6587	0,4977

Consequently, it can be stated that solar panels can be favourable depending on the actual mix RMS receives. Still this decision is not only an environmental question but also an economic one. Moreover, independency from the grid can be seen as an advantage.

5.3.2 Raw material scenarios

As described in chapter 3.4.2 different assumptions for substituting raw materials of the OE mix are calculated. This scenario is used to provide a clearer picture of the potential recycled material has when substituting primary material of the OE mix, without comparing different mixes (and consequently different raw materials) as it has been done in the basic assessment discussed above. For the remaining share of primary materials end of life routes are considered.
The scenario results of all chosen impact categories are summarized below:

Table 23: Results for raw material scenarios

Impact Category	25% Substitution	50% Substitution	100% Primary Mix
Climate Change (kg CO2-eq.)	2,62E+00	1,81E+00	3,43E+00
Eutrophication, freshwater (kg P-eq.)	2,49E-03	2,49E-03	4,82E-03
Eutrophication, marine (kg N-eq.)	7,57E-03	5,13E-03	1,00E-02
Eutrophication, terrestrial (mol N-eq.)	9,00E-02	6,04E-02	1,20E-01
Acidification (mol H+-eq.)	7,35E-02	4,91E-02	9,95E-02
Photochemical ozone formation (kg NMVOC-eq.)	2,57E-02	1,73E-02	3,41E-02
Resource use, fossils (MJ)	4,36E+01	3,02E+01	5,70E+01
Resource use, minerals & metals (kg Sb-eq.)	7,58E+00	5,05E+00	1,01E+01
Particulate matter (disease incident)	2,88E-03	1,95E-03	3,81E-03

In the following the results for climate change are depicted and discussed. In general, the overall picture repeats itself over the different impact categories. The results for all categories are depicted in the annex.

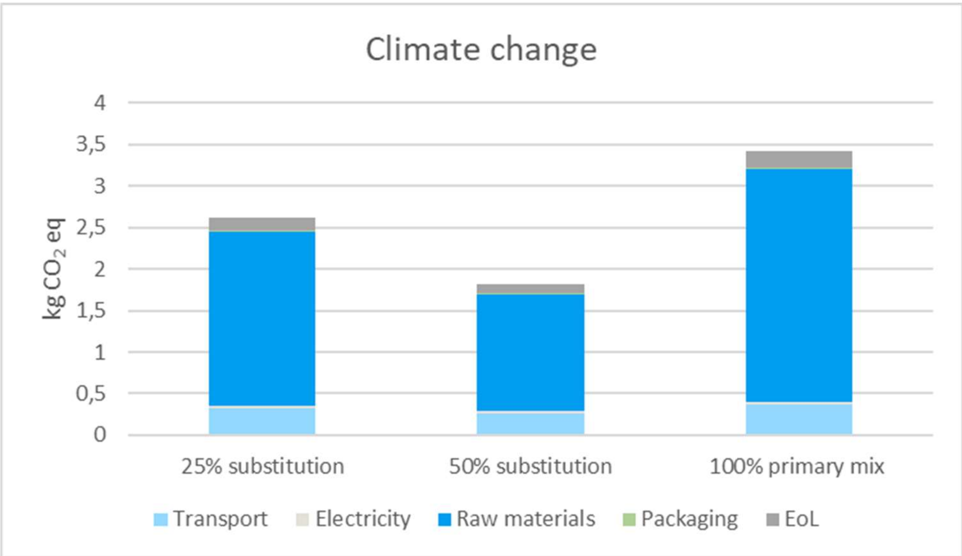

Figure 24: Results for climate change impacts for raw material scenarios

It is obvious, that the more primary raw material can be replaced the less impact is caused. Especially as the raw materials are the main contributors to all impact categories, a reduction is always beneficial. Note that replacing raw materials also reduces impacts caused by their transports. Also, there is a reduction of emissions due to end of life related to the share of primary raw materials substituted. Electricity consumption needed for the recycling processes and packaging are minor in this picture.

5.4 Uncertainty analyses

In this study no model parameters were applied. The variations of the systems are depicted within the scenarios analysis. Moreover, the relevance of different end-of-life settings have been depicted. As the relevance of the raw material inputs for all impact categories was found to be most relevant, the assessment of different variations of mixes including different shares of recycled material and different types of raw materials also shows their sensitivity.

6. LIFE CYCLE INTERPRETATION

6.1 Relevant findings

The key finding from the results of this study is that environmental performance across all impact categories improves with increasing recycled content. Table 21 shows that regardless which impact category is considered, the environmental performance increases with increasing recycled content.

In section 5.3 it was described that the primary mix product systems are evaluated including the end-of-life treatment. This differs from the evaluation of the RMS product systems, where the end of life is not considered. However, it is becoming obvious from the more detailed description of the results in section 5.1.2 that the general statement – *the environmental performance across all impact categories improves with increasing recycled content* – remains valid when the environmental impact of the end-of-life treatment is subtracted from the results of the product systems. The figures in section 5.1.2 are showing the environmental impacts of the product systems analyzed about the main processes (transport, electricity, raw materials, packaging, and end of life).

The illustrations of the detailed results are showing clearly that the provision of raw materials has the greatest impact on the results across all impact categories. The transport of materials is not assigned to this category. Accordingly, the substitution of the primary raw materials obviously has a major impact on the result. This is also shown by the comparison between the primary and secondary product systems. In the case of the latter, the impact is reduced by the provision of the raw materials.

The contribution of the transport processes (shown in the figures of section 5.1.2) to the selected environmental categories is generally low in relation to the supply of raw materials, but nevertheless clearly visible. By looking at the detailed results, a correlation between recycling share and transport emissions in the different impact categories can be identified – the higher the recycled material content, the lower the transport emissions. This can be attributed to the fact that all recycling processes take place in Germany. This reduces the transport distances for all recycled material since both recycling and their use in the final product take place in Germany. As the use of recycled material increases, the mass of primary materials used and thus their transport distances are reduced.

The electricity and packaging processes of the analyzed product systems have the lowest contribution in all impact categories.

6.2 Assumptions and limitations

The current study has certain assumptions and limitations that are necessary to be understood during the application of the results from the study. These assumptions and limitations arise due to the current state of science, availability of data and the methodological approaches used to conduct the study. The following considerations need to be made by when applying the results of the study

- **Dataset Availability (proxies):** There are a several raw materials inputs used by RMS in manufacturing the brake lining mixes via both the recycled material and primary material routes. The dataset for some of these raw materials are not available in the current databases used for the LCA calculation. The manufacturing processes of these raw materials are studied to identify suitable proxies with similar properties and manufacturing processes. It is ensured that for the most important raw materials that have a higher quantity, accurate datasets are chosen however for certain raw materials, suitable proxies are chosen. Using the proxies limits the accuracy of the LCA calculations but provides the best estimate of the environmental impact of such raw materials. Nevertheless, proxies had to be chosen for material inputs of all mixes, so this limitation applies to all and thus is less relevant.
- **Dataset Availability (geographical representation):** The mixtures manufactured by RMS require a lot of different raw material input. A lot of these raw materials come from different corners of the world. Finding an accurate dataset for all the raw material input which is an exact geographical and technically match is a big challenge. As some of these raw materials come from countries which lack adequate data collection infrastructure, the global average geographical representative data sets of are used for such raw materials to conduct the LCA study. These global average datasets might not represent the accurate information regarding the production processes and energy requirements in the geographical locations from where these raw materials come from. However, they provide close estimations that allow the calculating the best estimate environmental impact.
- **Methodology limitations:** The LCIA methodology and the results produced via it proves the relative and potential, not measured, environmental impacts. These are relative to the functional unit and can't be used to predict specific instance of the adverse impacts and risks associated with the downstream and upstream processes. These models generally attempt to showcase the most probable case. Also, the categories evaluated with the Environmental Footprint 2.0 methodology do not cover all the environmental impacts associated with the product. However, the information provided via the study does provide useful information to manufacturers, end users, authorities etc. in benchmarking and decision-making regarding sustainability or environmental performance evaluation.

6.3 Data quality assessment

6.3.1 Precision and completeness

The available data received by the customer of the study is of high quality especially regarding the processes that are realized at the production site of RMS. Due to the mutually signed NDA there was the possibility for the customer to submit primary data based on the exact recipes. The energy consumption of the recycling processes carried out at RMS could also be accurately determined. Regarding the recycled brake pad variants, the data can be seen as nearly complete.

From the production steps that are not realized at RMS and the primary production of the brake pad variants, the available data loses some of its quality. The exact composition of the added primary materials required for the 20%, 64% and 70% variants as well as the primary production variants are based on customer estimates and his brake industry knowledge.

6.3.2 Consistency and reproducibility

For reasons of confidentiality no detailed information can be given regarding the used materials and their mass, reproducibility is limited for parties not involved in this study. On the other hand, reproducibility is possible at any time for the parties involved.

Since all data were collected in the same way and are based on measurements and formulations for the recycled brake pad variants, a high degree of consistency can be assumed. This applies to the data of the recycling processes carried out at RMS. In contrast, the data collected for primary production and final mixing of the recycled variants with the added primary materials are less consistent and unlikely to be reproducible if a similar study would be conducted again.

6.3.3 Representativeness

On the one hand, the data are geographically limited, since RMS produces in Germany, and it was also assumed that the primary comparison products were produced in Germany when the data were collected. In addition, the geographic link to Germany means that all background data sets also have this regional (German) reference.
Furthermore, this study is a snapshot in time. This applies in particular to the specific electricity mix used by RMS. Only RMS receives this electricity mix in this form, and it is only certified for one year at a time. It is therefore possible that the electricity mix used by RMS will be different in subsequent years.
Finally, it must be mentioned that the data collected explicitly refers to the technology used by RMS. Possible other recycling technologies for brake pads are not covered by the data collected and therefore not by this study.

6.3.4 Model consistency and completeness

The models depict all relevant processes steps for each product system in sufficiently completeness in accordance with the defined goal and scope.
The models are consistent in terms of modelling approach and background data used (only recent ecoinvent datasets). System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

6.4 Conclusions, Limitations and Recommendations

In the following chapter conclusions will be drawn from the findings described in chapter 6.1. Further all limitations of the study will be described, and recommendations given on how the study could be improved.

6.4.1 Conclusions

As overall conclusion it can be stated that the provision of raw materials is the main driver for all impact categories assessed. This effect depends on the composition of the mixes. Nevertheless, the results clearly underline the positive effect of substituting raw materials as it is the case for the RMS mixes. Of course, higher shares of recycled material are beneficial in this case. Especially when recycled materials replace the critical inputs, that have the highest shares in terms of impacts, the effect is advantageous.
A second outcome is the relevance of the two end-of-life scenarios for the primary mix. It becomes obvious that the recycling of used brake linings reduces environmental impacts by avoiding deposition or incineration. This applies to climate change in case of the incineration of the used linings.
Moreover, the energy scenarios provide a more complete picture than only assessing the “status quo” situation of RMS, which is an almost 100% hydro power supply, a very advantageous energy source. In case other energy sources are used this result will change and might result in higher impacts for climate change.
In general, it must be noted, that the assessment on hand bases on the assumption that there is a kind of closed loop of the recycling processes which would mean that RMS receives their products in return and thus, an end-of-life was omitted. This can be seen as the ideal case that shows the potentials of a product of circular economy.

6.4.2 Limitations

The study results represent the mixes and state of technique described. It must therefore not be deduced that the positive effect of substituting primary raw materials is always in the same range as shown. It must be clearly stated that the results mainly depend on the type of input materials for the mixes and which ones are replaced.
Another limitation is the beneficial energy mix used for RMS processes, as it might not reflect the future situation. Also, it is not clear yet to what extend energy supply can be covered by on-site solar power plants. However, as the impact share of energy consumption is comparatively low, it can be assumed that this limitation is minor.

6.4.3 Recommendations

To overcome the limitations described above, it can be recommended to extend the study by additional mixes to get a clearer picture of the relevance of the different raw materials. This information could be used to for product development to find substitutes for the most critical inputs. It is clear that this assessment can only give hints for optimization potentials from an environmental point of view. However, there might be tradeoffs between environmentally beneficial raw materials and their technical performance, which must be prioritized.

7. CRITICAL REVIEW

7.1 Name and affiliation of reviewers

PhD (Dr. sc. ETH) Roland Hischier, iPoint-Systems (Lead of review panel)

Univ.-Prof. Dr.-Ing. Ralph Mayer, TU Chemnitz

Lars Hettenhausen, Continental

7.2 Critical review report

iPoint

Comparative LCA Study of Brake Lining Mixes with Recycled Materials

Final Review Report

Version 1.0 / 04.08.2022

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1 Organisation of the Critical Review

The herein described critical review process, commissioned by Ramboll (Germany), being the consultant company executing the study " *Comparative LCA Study of Brake Lining Mixes with Recycled Materials* ", took place in the period from July to August 2022. The study is a classical LCA study according to the ISO EN DIN 14040 series [1a+b], for which a critical review process in accordance with the ISO series [1a] has been made by a team of three reviewers. This on hand critical review report is based on the final report [2], version from August 3, 2022. It will be integrated in the very final version of the mentioned report.

1.1 Critical Reviewers

The panel for the critical review of this study included the following persons:

Dr. Roland Hischier (Chairman)
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72760 Reutlingen - Germany

Prof. Dr. Ralph Mayer
TU Chemnitz – Professur Fahrzeugsystemdesign
Reichenhainer Straße 70
09126 Chemnitz

Dipl. Ing. Lars Hettenhausen
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Guerickestr. 7
60488 Frankfurt

1.2 Course of Action

The entire critical review process can be considered an accompagning survey, as the review started with a discussion between the authors and the chairman about choices related to goal and scope of the study. After that, the reviewers received a first (draft) final report Mid of July 2022, which was reviewed by each of the members of the panel individually. The chairman collected the comments from all members and summarized them in order to give a written feedback to the authors (i.e. Ramboll) and the commissioner of the study (i.e. RMS Raw Material Services). During an (online) meeting on July 20, 2022, between the reviewers, Ramboll and RMS, these comments were discussed and the next steps were agreed upon. On July 27, 2022, a second version of this final report has been sent to the reviewers, which was again reviewed by each of the members of the panel individually. The chairman collected the comments from all members and summarized them in order to give a written feedback. Based on this feedback, the authors established a further version of the report that has been sent to the chairman on August 3, 2022. This version of the report is the basis for the following final critical report.

2 Comments about the report

According to chapter 7.2 of the ISO standard 14040 [1a], a critical review facilitates understanding and enhances the credibility of an LCA study. In the framework of the here described review process, the following criteria have been examined:

- the acceptability of the **methodology and the assumptions** used, their consistency with the goal and scope of the project;
- the **acceptability of the data** used in the study and their consistency with the goal;
- the **transparency and the consistency** of the study **report** ;
- the **compatibility of the conclusions with the goal**, method, data and assumptions used.

2.1 Methodology

Goal and scope of the study are clearly stipulated. Separate chapters address the goal and scope definition of the study in a very structured and comprehensive manner. It can be seen from these chapters that the objective of the study is the evaluation of the potential environmental benefits of the processes of RMS and the resulting products compared to the primary production route for similar products. The study is a cradle to gate LCA study – taking into account all activities from the extraction of the required resources to the finished product, sold to the clients; based on the assumption that the different materials show in the subsequent (but excluded) use phase a similar abrasion behaviour (which is, based on some cited studies a conservative approach, as those studies showed a lower abrasion rate for recycled materials) – established in a transparent and clear way for internal and external communication.

The **functional unit** – 1 kg of friction material at the gate of the production site – is a reasonable choice and makes sense in the context of the study here (and its goals). Its practical implementation is documented in a clear and transparent manner across the entire study report.

The chosen **system boundaries** – covering all the processes from the extraction of the required resources to the final product (i.e. the brake lining mixes) – make sense in relation to the objectives of the study and the fact that the abrasion is similar for all mixes. In case of the recycled materials, no end-of-life treatment is taken into account, which is reasonable – the recycling process is prolongating the use of these materials and an inclusion of the end-of-life treatment would lead to a double counting.

On the level of the covered **impact assessment factors**, the study relates to a total of 8 different midpoint impact categories, according to the Environmental Footprint (EF) assessment method from the European Commission (established in the frame of the Product Environmental Footprint (PEF) activities). These factors are covering all types of elementary flows (i.e. releases to air and water as well as resource consumption) and the choice of the categories is described in a logical and transparent manner in the report. Hence, the study is in accordance with the requirements of the ISO 14040 standard, stipulating in section 5.4.1 at the end that "(…) transparency is critical to the impact assessment to ensure that assumptions are clearly described and reported."

All in all, it can be concluded that method and assumptions used in the framework of this study are sufficiently logic and scientific in accordance with the goal and the scope of the study, but also in accordance with the underlying ISO 14040 standard.

2.2 Data

The requirements and the actual data collection process are described in an open and comprehensive manner in chapter 4 of the project report, split into the different life cycle stages taken into account in this study. All in all, the applied information seems to be in accordance with the goal and scope of the study here. In the background, a single data source is used for this study – the database ecoinvent (version v3.8, as stipulated in the middle of page 15, in chapter 3.10, of the final report). Due to confidentiality reasons, some of the ingredients of the various mixes (especially the primary mixes) are not shown in this report – and thus, it was not possible for the reviewers to verify if adequate data have been used for those materials. In all other cases, the connection between the materials and the used background data is shown in chapter 4 in a transparent manner. For all the latter material it can be concluded that the used data are adequate and in accordance with the goal and scope of this study here.

2.3 Report

The report (for the review, the version of the final report dated August 3, 2022, has been used) is structured in a clear and logic way, most of time rather easily understandable and properly designed.

2.4 Results, Discussion and Conclusion

The chapters covering results, discussion and conclusion summarize in a comprehensive and adequate manner the results of this project – and thus the content of the report.

The authors start in chapter 5.1 with a comparison of the three mixes from RMS and the two different options for the primary production (using different end-of-life options). Each of the included impact category is shown with a diagram (i.e. Figures 14 to 22), followed by a short discussion of the shown results. From these figures it could be seen that all the impact categories show a rather similar pattern – showing much lower impacts for the three RMS mixes than for the two primary material options. In all situations, the production of the raw materials is by far the most dominating element.

Within chapter 5.3 – covering the scenarios (or sensitivities) related to the used electricity mix and the provision of the raw materials for the primary products – the authors show (again) in a very transparent manner the low influence on the overall results by a change of the (current) green electricity mix towards other, green options, as well as the influence of a partial replacement of the primary materials by respective secondary materials for the original mixes. From the latter it could be seen (by comparing Figure 24 and 14) that even a 50% amount of secondary materials in these original mixes still results in a considerable higher impact than the RMS mixes. Only element missing her is the influence of the grid mix from Germany on the results – however, taking into account the shown low relevance of the electricity on the results, it could be reasonable assumed that also with such a fossil-dominated mix, the overall results of the study (i.e. RMS mixes show clearly lower impacts than the primary mixes) wouldn't change.

Last but not least, the last section (Life Cycle Interpretation) starts with a comprehensive summary of the achieved results, followed by a section that contains a comprehensive overview (as bullet list) of all those points that have to be seen as limitations for this study. And last but not least, in a final "Conclusion, limitations and recommendations" chapter, key aspects of the results are summarized on a single page, showing like this in a very easy and clear manner the main points that result from this study.

3 Summary and Conclusion

The complete study has been established in a transparent and logic way. For the examined functional unit – i.e. 1 kg of friction material at the gate of the production site – the authors of this study make clear statements concerning the advantages/disadvantages of the three different mixes from RMS in comparison to a comparable mix based on primary materials. For the review panel, the present study is in accordance with the international standards for LCA (ISO 14'040 and 14'044) and the panel is therefore in favour of and supports the publication of this attributional LCA study comparing different types of brake lining materials used in the automotive industry.

4 References

[1a] International Standard (ISO): Environmental management - Life cycle assessment - Principles and framework. Standard ISO 14040:2006 (2006).

[1b] International Standard (ISO): Environmental management - Life cycle assessment – Requirements and Guidelines. Standard ISO 14044:2006 (2006).

[2] Ramboll (2022): Comparative LCA Study of Brake Lining Mixes with Recycled Materials. Final report. A study established on behalf of RMS Raw Material Services.

Hamburg, August 4, 2022;

on behalf of the review panel,

Dr. Roland Hischier, Chairman of the review panel

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7.3 Responses to recommendations

	Reviewer	Art des Fehlers*	Seite/Zeile(n)	Kommentar des Reviewers	Empfehlung des Reviewers	Antwort der Autoren
1	Hir	E,M,H	p.9 / 237-238	Die Begründung für das «Weglassen» des End-of-Life ist in meinen Augen zu wenig präszise … es ist nicht die Tatsache, dass Material wiederverwendet wird – sondern dass diesem Material eine Lebensdauerverlängerung ermöglicht wird und eine Berücksichtigung des End-of-Life zu einer Doppelzählung des letzteren führen würde.	Bitte Bullet-point klarer formulieren …	Erklärung eingefügt
2	Mayer		241	Abrieb ist durchaus zu quantifizieren: entweder in klassischer Form durch Absolvieren vergleichbarer Prüfprogramme am Schwungmassenbremsenprüfstand (Gewichtsvergleich) oder durch aufwendigere Messungen und Klassifizierung des Abriebs in PM10 und PM2,5	• Durch Messung belegen	s. Kommentar 3
3	Hir	E,M,H	p.9 / 241ff	Eine «lower abrasion rate» für das Recyclingmaterial heisst, dass diese Beläge tendenziell länger halten würden – somit ist der gewählt Ansatz (i.e. das Weglassen der Use phase ist gleichbedeutend mit «same abration rate» …) als konservativer Ansatz für das Produkt von RMS anzusehen.	Bitte diesen «konservativen» Ansatz expliziter machen im Text hier …	Erklärung eingefügt
4	Mayer		242	Ist die Vergleichbarkeit der zitierten Studien gegegeben? Der geringere Abrieb von Recyclingbelägen ist nu rein Kriterium neben nicht erwähnten wie Reibwert, Reibwertstabilität unter Temperatureinfluß etc.		s. Kommentar 3
5	Hir	E	Figures & Tables	Für die Figuren und Tabellen werden unterschiedliche Logiken betreffend Nummerierung (Figure 1, Figure 2, …. Table 3-1, Table 3-2, …) eingesetzt – bitte vereinheitlichen.	Nummerierungs-Logik vereinheitlichen	angepasst
6	LH	Methodik		So far my understanding with EF 2.0 you can perform PEF (Product Environmental Footprint) if PEFCR (Product Environmental Footprint Category Rules are existing), I assume PEFCR is not existing.	Please make a statement	Korrekt, es gibt derzeit noch keine passende PEFCR, Hinweis eingefügt
7	Hir	E,M	Fig.2	Im Fall des Primärproduktes ist kein Prozess «processing of used break lining» nötig!	Bitte Figur entsprechend korrigieren …	angepasst
8	Hir	E,M	Table 3-2	Die Liste der Prozesse hier ist – analog wie das Bild von Fig.2 auf Ihre Korrektheit hin zu prüfen. In meinen Augen sind folgende Zeilen zuviel hier : «Recycling» … und es fehlt demgegenüber eine Zeile mit «Disposal» !	Bitte korrigieren …	korrigiert
9	LH	Methodik	10 / Tab 3-2	What is behind "Recycling" during primary mix production system? Usually there is no recycling process step during primary mix production. In rare cases direct recycling of grinding dust is observable in the Brake Pad Industry.	After clarification I would recommend to eliminate this step for primary production	korrigiert, s. Kommentar 8

10	Hir	E	p.11 / 286	Verweis auf Kapitel mit den Daten ist nicht korrekt	Korrekten Verweis einfügen bitte …	korrigiert
11	Hir	E,M,H	p.11 / 287ff	Ich verstehe diese «3 Szenarien» hier nicht wirklich – was stellen diese genau dar? Es ist weiter oben die Rede von drei verschiedenen Zusammensetzungen welche für den RMS-Prozess betrachtet werden … hier geht es aber um etwas anderes, oder?	Bitte klarer formulieren …	Erklärung eingefügt
12	Mayer		289	Zu "Table 5.4 Scenario description" Scenario III "III. Energy electricity from solar power": ist der Energieaufwand für das Belagrecycling überhaupt durch Solarenergie auf der Produktionsanlage zu decken? Wenn ja, für welche Betriebsszenarien; 24/7?	Angabe des Energieaufwands / kg recycletem Belagmaterial	Annahme als best case, erwähnt in der Szenario Beschreibung
13	Hir	E	p.16 / 407-417	Text ist – wie bereits als Kommentar aufgeführt – nicht klar für den Leser; in der Einleitung ist die Rede von «post consumer» und «pre consumer» inputs in den Recyclingprozess … hier ist die Rede von «first route» und «second route» -- macht es nicht klar für Leser	Text revidieren & begrifflich an die Einleitung anpassen, so dass der Leser Link machen kann …	Beschreibung angepasst
14	Hir	E,M	p.16ff / Kap. 4.2	Das Kapitel mit seinen verschiedenen Figuren ist nicht ganz einfach verständlich für den Moment – wie hängen die Figuren 5-7 und die Figuren 8-10 genau zusammen? Es könnte von Vorteil sein, am Anfang des Kapitels 4.2 eine zusätzliche Figur als eine Art «Übersicht» einzufügen, Figur aus welcher dann auch hervorgeht, was die Figuren 5-10 davon abdecken …	Zusätzliche Figur zur Gesamtübersicht einfügen …	eingefügt
15	LH	Methodik	16 / Figure 5 18 / Figure 6	Granulation process is not included in the process flowchart, is that process step only applied for the grinding dust recycling?	Please confirm	Ja Granulierung findet nur in der Staubaufbereitung statt
16	LH	Methodik	17 / Tab 4-1	Disc Braking Pad (self-modeled flow), what kind of process was used for reference? What is considered here as industry standard?	I would like to review the "Disc and Drum Braking Pad" modeled flow	Hier handelt es sich um einen Hilfsfluss um die Produkte aus dem Recyclingprozess mit der Weiterverarbeitung zu verbinden
17	LH	Methodik	17 / Tab 4-1	Steel Scrap is considered as "Output"?		Steel scrap ist ein Output da es sich um Abfall mit Marktwert handelt
18	LH	Methodik	20 / Figure 7	What is behind Pre-Cleaning process?	Please make a statement	Erklärung eingefügt
19	Mayer		429	Figure 5 Recycling process of disc brake pads: gut verständliches Diagramm zum Prozeßablauf, leider mit schlechter Lesbarkeit durch Schriftgröße	Prozeßablaufplan von oben nach unten darstellen anstelle von links nach rechts	Schriftgröße angepasst, farbliche Markierungen eingefügt für bessere Lesbarkeit
20	Mayer		433	Table 4-1: Inventory of recycling disc brake pads: Verschleiß und Standzeiten der Mühlen sind nicht aufgeführt	Sollte der Verschleiß der Werkzeuge vernachlässigbar sein, sollte darauf hingewiesen werden. Anderweitig wäre es in die Bilanz mit aufzuführen;	Maschinen und Infrastruktur sind außerhalb der Systemgrenzen, s. Kapitel 3.3

					Ähnliches gilt für den Stapler: hier ist nur "tank to wheel" betrachtet, was ähnlich unsachlich wäre wie die politische Bevorzugung von E-Fahrzeugen	
21	Mayer		442	Figure 6 Recycling process of drum brake pads: siehe Anmerkungen zu 429	- " -	angepasst
22	Mayer		459	Figure 7 Recycling process of grinding dust from brake pads production: Lesbarkeit / Schriftgröße	Gilt für die folgenden Diagramme gleichermaßen	angepasst
23	Hir	E,M	p.34ff / Table 4-11 to 4-13	Diese Tabellen sind schwierig zu lesen, da in jeder Tabelle eine andere Energiemenge (in kWh) als Basis benutzt wird.	Tabellen umrechnen, so dass die Aufteilung sich jeweils auf ein Total von 1 kWh (out) bezieht …	Prozentuale Zusammensetzung des Mixes dargestellt
24	Hir	E,M,H	p.35 / Table 4-14	Tabelle so macht wenig Sinn da nur zwei von 4 Szenarien gezeigt werden – ich würde hier zumindest einmal für alle vier Szenarien die Resultate zeigen … oder allenfalls Darstellung (mit dem Hinweis auf die Vertraulichkeit …) komplett weg-lassen.	Weiteren zwei Szenarien einfügen … oder ganze Tabelle streichen	Tabelle entfernt
25	Hir	E	p.36 / 533	Verweis auf Tabelle 7.1 erscheint falsch …	Verweis prüfen und ggf. korrigieren	korrigiert
26	LH	Methodik	36 / Tab 5-1	For the first 3 category the table says "RMS Electricity", which Electricity Mix is considered for the "OE" Categories?	Please make a statement	DE Mix, Verweis in Szenariobeschreibung eingefügt
27	LH	Editorial	37/ 559	"lesser" → less		korrigiert
28	Hir	E	p.37 / 571-574	Text nochmals revidieren … ist nur verständlich dann dem Kommentar …	Text revidieren & verständlicher machen	angepasst
29	Hir	E	p.37 / 583-584	Letzter Satz hier auf Seite 37 ist nicht verständlich … im Vergleich zu was sind die Anteile der Verpackung zurückgegangen ?	Text revidieren …	angepasst
30	Hir	E	p.38ff / Figures 12-20	Die Farben der Bereiche «Transport», «Electricity» und «Packaging» erscheinen alle gleich (schwarz od. dunkelblau) … bitte Farben so wählen, dass diese drei Bereiche ebenfalls klar unterschieden werden können.	Farbwahl anpassen für die Bereiche «Transport», «Electricity» und «Packaging»	angepasst
31	Hir	E	p.38 / 591-593	Satz erscheint als Repetition von erstem Satz des Absatzes …	Text revidieren / Wiederholungen entfernen	Angepasst. Der erste Satz bezieht sich auf das Gesamtprodukt, der angemerkte Satz auf den Anteil der Rohmaterialien am Impact
32	Hir	E	p.39 / 611-612	Satz macht keinen Sinn (da weitere Impact-Kategorien auf den folgenden Seiten jeweils wieder diskutiert werden und nicht den gleichen Sachverhalt wie diese beiden Kategorien hier zeigen …)	Satz korrigieren resp. entfernen	gelöscht
33	Hir	E	p.41 / 629-630	Auch dieser Satz erscheint mir fragwürdig …	Satz korrigieren resp. entfernen	gelöscht
34	Mayer		640	Figure 20 Detailed results for the environmental impact category Particulate matter: Skalierung sollte mit einheitlicher Nachkommaanzahl versehen sein (nur Kosmetik)		Angepasst an Wissenschaft-Zahlenformat

35	Hir	M,H	p.42 / 649-651	Das eine schliesst in meinen Augen das andere nicht aus – es kann durchaus Sinn machen, als zusätzliche Angabe auch noch Resultate (zumindest) von einer Normalisierung hier einzufügen … denn damit würde man eine erste Aussage zur Relevanz der verschiedenen Impact-Kategorien bekommen.	Schauen, ob nicht zumindest der Schritt «Normalisierung» noch hinzugefügt werden kann …	Wie abgestimmt wurde keine Normalisierung durchgefügt
36	Hir	E,H	p.42/43 / 668ff plus Figure 21	OK – hier wird der enorme/grosse Einfluss des Strommixes auf den Kernprozess gezeigt … aber was heisst dies nur für die hier betrachtete «funktionale Einheit» ?	Bitte Kapitel ergänzen was diese Veränderungen des Strommixes für die funktionale Einheit bedeuten …	Auswertung nach FU eingefügt
37	LH	Editorial	43/675	"evaluation" -> evaluating		korrigiert
38	Hir	M,H	p.43 / 677-678	Ich bin absolut NICHT einverstanden, dass die Belastung von PV nur wenn diese Anlage auf dem eigenen Dach steht, auf 0 fällt … denn die (in Fig.21) gezeigte Belastung von PV stammt in erster Linie von der Infrastruktur – und diese ist auch nötig wenn die PV-Anlage auf der eigenen Fabrik installiert wird.	Bitte Satz so entfernen – ist aus Sicht ISO 14'040/14'044 nicht richtig !	entfernt
39	Hir	E,M	p.43 / Kap. 5.4	Es ist doch nicht nur, was hier aufgeführt ist, sondern auch noch die Tatsache, dass drei verschiedene Mixe von RMS in der Studie der Produktion aus Primärmaterial gegenübergestellt werden, welche ausmacht, dass man die Variabilität schon weitgehend abgedeckt hat.	Bericht ergänzen …	ergänzt
40	Hir	E	p.43 / 689	Verweis auf Tabelle 7.1 erscheint falsch …	Verweis prüfen und ggf. korrigieren	korrigiert
41	Hir	E	p.43f / 693ff	Verweise auf Kapitel, Tabellen und Figuren in diesen Absätzen hier stimmen nicht …	Bitte alle Verweise kritisch prüfen und korrigieren	korrigiert
42	Hir	E,M,H	p.44 / 720-721	Dieser Satz ist etwas im Widerspruch zur Tatsache, dass bei der Sensitivität einzig die Elektrizität angeschaut wird …	Ganze Sachverhalt(e) so erläutern hier – sowie in früheren Teilen des Berichtes – das klar wird, wieso die Sensitivität des Strommixes Sinn macht und diese Aussage hier nicht im Widerspruch dazu steht …	Erklärung zur Relevanz der Szenarios in Kapitel 5.3.1 eingefügt
43	Hir	M,H	p.44 / 729ff	Wie steht es mit diesen «Proxies» … kommen diese nur in einem Teil der Mischungen zum Einsatz (dann ist es wohl eine Limite der Studie) – oder kommen diese in allen Mischungen zum Einsatz (denn dann hat es einen deutlich geringeren Einfluss auf die Studie – da es die Aussagekraft der Studie damit nicht beeinträchtigt … da der «gleiche» Fehler in alle Mischungen einfliesst).	Aspekt mehr im Detail ausführen hier und klarer machen, ob ein Aspekt für alle Mischungen oder nur für einen Teil der Mischungen …	Proxies sind in jedem Mix enthalten → Formulierung eingefügt
44	Hir	M,H,	p.44 / 738ff	Gleicher Sachverhalt wie im obigen Punkt …	dito	Proxies sind in jedem Mix enthalten → Formulierung eingefügt
45	Hir	M	p.45 / 775-777	Verstehe diese Aussage nicht … wieso sollen diese Teile nicht «reproducible» sein ? Was heisst dies für die Resultate – dass diese eine Art «Zufallsresultat» darstellen ?	Punkt ist besser zu erläutern/klären …	Genauer erläutert

46	Hir	E,M,H	p.45 / 779	Aber dies war doch auch nicht das Ziel der Studie – wieso soll dies dann eine Einschränkung/Limite sein? Alle weiteren Zeilen dieses Abschnittes 6.3.3 zeigen dann ja eigentlich genau was die Studie macht – sie vergleicht die Prozesse von RMS mit der Primärproduktion …	Würde diesen ersten Satz weglassen …	entfernt
47	Hir	E,H	p.46 / 812-816	Wie weiter oben vermerkt, so ist der Einfluss der unterschiedl. Energieszenarien nicht klar ersichtlich – da nicht auf die funkt. Einheit bezogen gezeigt. Zudem ist die Aussage, dass PV auf dem eigenen Dach = 0 kg CO2e aus einer LCA-Sicht schlicht und einfach falsch …	Absatz überarbeiten & Anpassungen weiter oben mitberücksichtigen	Überarbeitet; dennoch wurden die Energieszenarien isoliert ausgewiesen, weil deren Auswirkungen auf Grund des geringen Anteils in der Gesamtdarstellung nicht sichtbar gewesen wären (Erklärung eingefügt)
48	Hir	E,M,H	p.46 / 827ff	Hier sollte unbedingt auch der technische Aspekt Erwähnung finden … denn Mischungen müssen in erster Linie aus der Sicht der Anwendung Sinn machen, bevor man schaut, ob (und wenn ja, welche) Rohstoffe ersetzt werden könnten …	Text anpassen	ergänzt
49	Mayer		858	Link funktioniert nicht		Gelöscht, da nicht mehr zitiert
50	Mayer		861	Link funktioniert nicht		Link auf höherer Ebene eingefügt
51	LH	Methodik	EOL scenarios	No discussion on (maybe it's a not relevant idea but worth discussing): if e.g. 20 % recycling material is used, why not include 80 % EOL incineration vs energy recycling @ incineration why is re-used process wasted similar to be treated as EOL recovered brake pad material (also what is the share used in the study) direct comparison on cradle to cradle for option recycling and 100% virgin	Point for discussion	Szenarien für das Ersetzen von Rohstoffen im OE Mix wie besprochen eingefügt. Ein Vermerk über die Annahme des best case wurde eingefügt in den Conclusions
52	LH	Methodik	Result discussion	Drum brakes and disk brakes in the inventory analysis, but result discussion does not separate or comment why it is not separated	Could be refined or explained	Unterschiedliche Verarbeitungsprozesse, aber im Gesamtergebnis keine relevanten Unterschiede -> Erklärung eingefügt in 5.2.1
53	LH	Editorial	wording	Usually the components are called "Disc Brake Pads" and "Drum Brake Linings"	Can be adapted	Begriffe wurden bereits vor dem Umlauf vom Hersteller angepasst

#	Reviewer	Art des Fehlers*	Seite/Zeile(n)	Kommentar des Reviewers	Empfehlung des Reviewers	Antwort der Autoren
54	Hir	E,M	p.9-11 / Figures 1-2 und Tables 1-2	In den Figuren und Tabellen werden teilweise leicht unterschiedliche Begriffe verwendet, so dass die klare Abgrenzung betreffend was ist enthalten und was ist nicht enthalten, nicht klar sichtbar ist.	Bitte sicherstellen, dass gleiche Begriffe Verwendung finden …	korrigiert

55	Hir	E,M	p. 10-11 / Table 2	→ Korrektur ist nicht umgesetzt; «Disposal» wird weiterhin bei den nicht berücksichtigten Prozessen gezeigt, ist aber ein Teil des Systems (und somit «included») hier !	Bitte (nochmals / weiter) korrigieren …	angepasst
56	Hir	E	p.12 / Zeile 326-327	Hier sollte es wohl heissen «powered by own solar power on the factory roof top» und nicht «powered by on solar power» - ansonsten nicht genügend verständlich …	Bitte korrigieren (on → own) resp. ergänzen …	korrigiert
57	Hir	E,M,H	p.12 / Kapitel 3.4.2 p.45-46 / Kapitel 5.3.2	UNKLAR was hier gemeint ist und was dies an Sensitivität in die Studie bringt – die RMS Mixe sind ja auch bereits eine Mischung aus rezyklierten Materialien sowie primären Materialien … wieso sind diese beiden zusätzlichen %-Werte nötig ? Ist dies Reaktion auf die Diskussion betreffend «Einschluss EoL» für die Anteile Primärmaterial bei RMS-Mixen? Mein Verständnis von jener Diskussion ist, dass die Sensitivität für die Primäranteile EoL einschliessen soll …	Grundannahmen des Szenario nochmals überdenken – und Textblöcke entsprechend anpassen …	Szenarien angepasst
58	Hir	E	p.17 / Zeilen 458-464	Bitte Text nochmals kritisch lesen … es werden jetzt zwar die gleichen Begriffe wie im Rest des Berichtes verwendet – aber für den Begriff «Pre-consumer» wird aus dem Satz nicht klar, was er hier zu suchen hat …	Bitte Text nochmals kritisch ansehen und korrigieren …	Begriff gelöscht da redundant.
59	Hir	E	p. 17 / Figur 5	Die Figur 5 macht Sinn (siehe alten Kommentar 14) – allerdings sind die Verweise aufgrund dieser zusätzlichen Figur falsch … es sollte statt 5-7 6-8 heissen, etc.	Bitte Verweise korrigieren (jeweils um 1 Wert nach oben)	korrigiert
60	Hir	E	p. 35-36 / Table 18-20	Weiterhin (siehe alten Kommentar 23) unklar … ganze Information liesse sich in eine einzige Tabelle packen – mit Mixen jeweils in % von 1 kWh Strom dargestellt.	Zu korrigieren	umgesetzt
61	Hir	E	p. 38 / Zeile 605	Verweis auf die Figuren stimmt nicht – es sind die Figuren 14-22 und nicht mehr 12-20 …	Zu korrigieren	korrigiert
62	Hir	E	p.39 / Figur 14	Farbe für «Electricity» sowie «End-of-Life» ist gleich – bitte letztere auf das dunklere Grau ändern wie in den übrigen Figuren hier im Resultate-Kapitel	Zu korrigieren	korrigiert
63	Hir	E	p.44 / Zeilen 725-726	Aussage betreffend Solarenergie gilt nicht nur bei eingekaufter Solarenergie – gilt auch für eigene Anlage auf dem Dach …	Zu korrigieren	korrigiert
64	Hir	E,M,H	p.45 / Figur 24	Verstehe Figur 24 nicht … ich ersehe aus diesen absoluten Zahlen hier nicht, wie gross der Einfluss des Strommixes auf das Gesamtresultat ist …	Zu revidieren / klarer machen	Neue Berechnung eingefügt
65	Hir	E	p.46/47 Zeilen 778ff	Verweise auf Kapitel 7.1.2 etc. sind nicht korrekt	Zu korrigieren	korrigiert
66	Hir	E	p.49 / Zeilen 899-900	NEIN – eine eigene PV-Anlage auf dem Dach reduziert die CO2-Belastung des Stromes nicht auf Null … denn die PV-Anlage muss hergestellt werden (und darin steckt GWP)	Zu korrigieren	korrigiert

8. REFERENCES

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9. ANNEX

9.1 Electricity Scenario results

Table 24: Electricity scenario results

Impact Category	RMS Mix 20% (Green Electricity)	RMS Mix 64% (Green Electricity)	RMS Mix 70% (Green Electricity)	RMS Mix 20% (Germany Green Electricity)	RMS Mix 64% (Germany Green Electricity)	RMS Mix 70% (Germany Green Electricity)	RMS Mix 20% (Germany Solar Electricity)	RMS Mix 64% (Germany Solar Electricity)	RMS Mix 70% (Germany Solar Electricity)
Climate Change (kg CO2-eq.)	8,13 E-01	6,50E-01	4,88E-01	8,16 E-01	6,59 E-01	4,98 E-01	8,13 E-01	6,55 E-01	4,93 E-01
Eutrophication, freshwater (kg P-eq.)	2,08 E-04	1,33E-04	1,13E-04	2,13 E-04	1,39 E-04	1,20 E-04	2,10 E-04	1,35 E-04	1,16 E-04
Eutrophication, marine (kg N-eq.)	1,40 E-03	7,97E-04	6,31E-04	1,40 E-03	8,02 E-04	6,37 E-04	1,41 E-03	8,05 E-04	6,40 E-04
Eutrophication, terrestrial (mol N-eq.)	1,39 E-02	7,91E-03	6,38E-03	1,40 E-02	8,02 E-03	6,50 E-03	1,39 E-02	7,97 E-03	6,45 E-03
Acidification (mol H+-eq.)	6,95 E-03	4,08E-03	3,29E-03	6,98 E-03	4,13 E-03	3,35 E-03	6,98 E-03	4,13 E-03	3,34 E-03
Photochemical ozone formation (kg NMVOC-eq.)	5,11 E-03	3,02E-03	2,49E-03	5,11 E-03	3,04 E-03	2,51 E-03	5,12 E-03	3,05 E-03	2,52 E-03
Resource use, fossils (MJ)	1,82 E+01	1,22E+01	1,07E+01	1,81 E+01	1,21 E+01	1,06 E+01	1,81 E+01	1,21 E+01	1,06 E+01
Resource use, minerals & metals (kg sb-eq.)	1,07 E-03	1,03E-03	6,29E-04	1,08 E-03	1,05 E-03	6,49 E-04	1,11 E-03	1,09 E-03	6,96 E-04
Particulate matter (disease incident)	3,52 E-04	2,52E-04	1,80E-04	3,52 E-04	2,55 E-04	1,83 E-04	3,53 E-04	2,56 E-04	1,84 E-04

9.2 Raw material scenario results

In this chapter the results for all impact categories under consideration (except climate change) are presented for the raw material scenarios (see chapter 5.3.2)

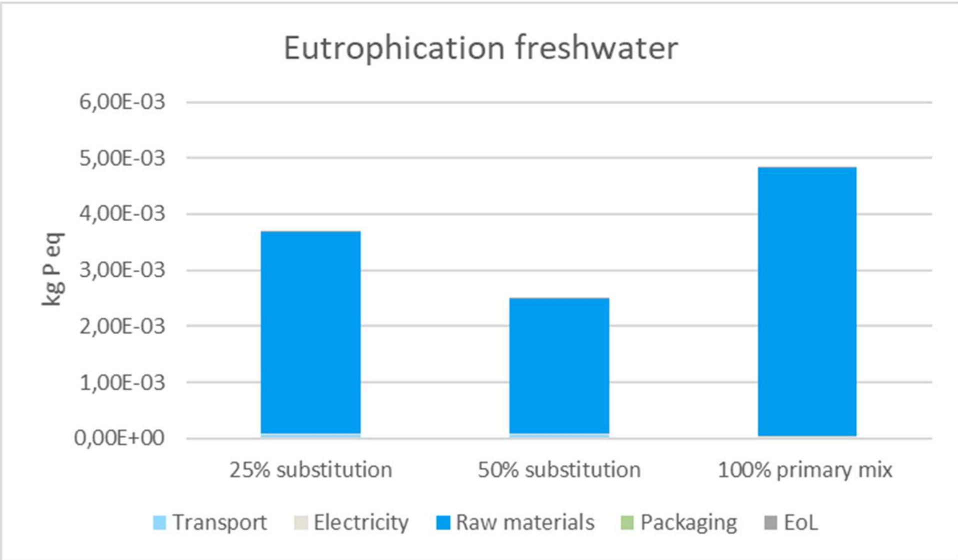

Figure 25: Scenario results (raw material substitution) for EP freshwater

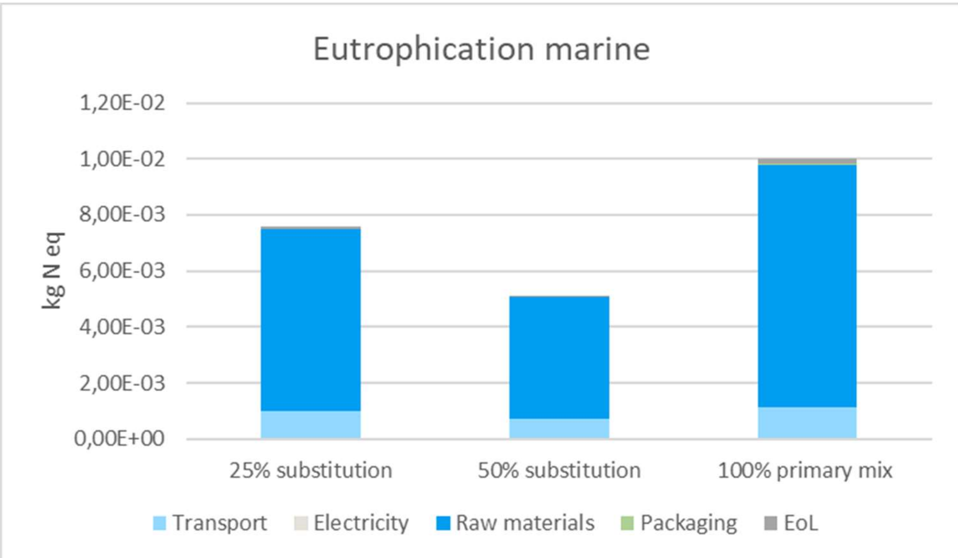

Figure 26: Scenario results (raw material substitution) for EP marine

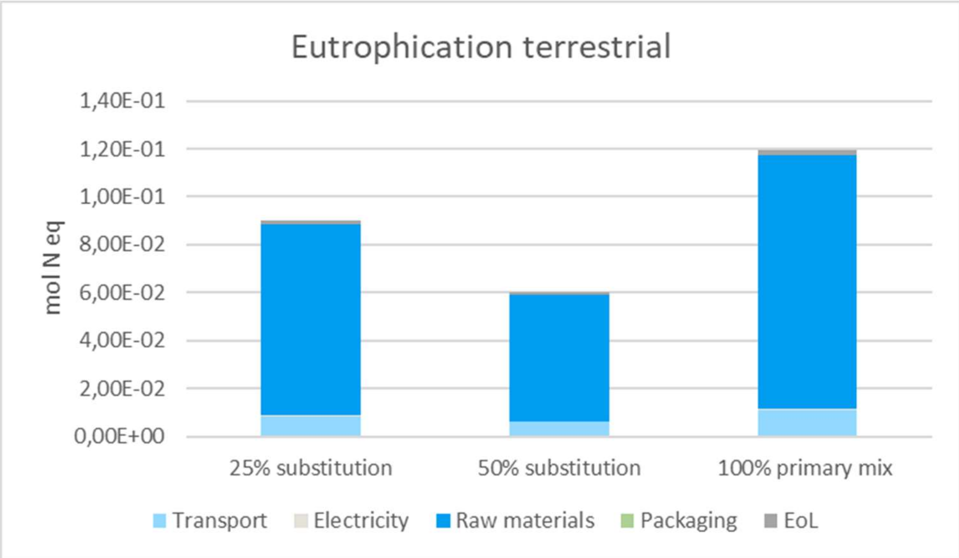

Figure 27: Scenario results (raw material substitution) for EP terrestrial

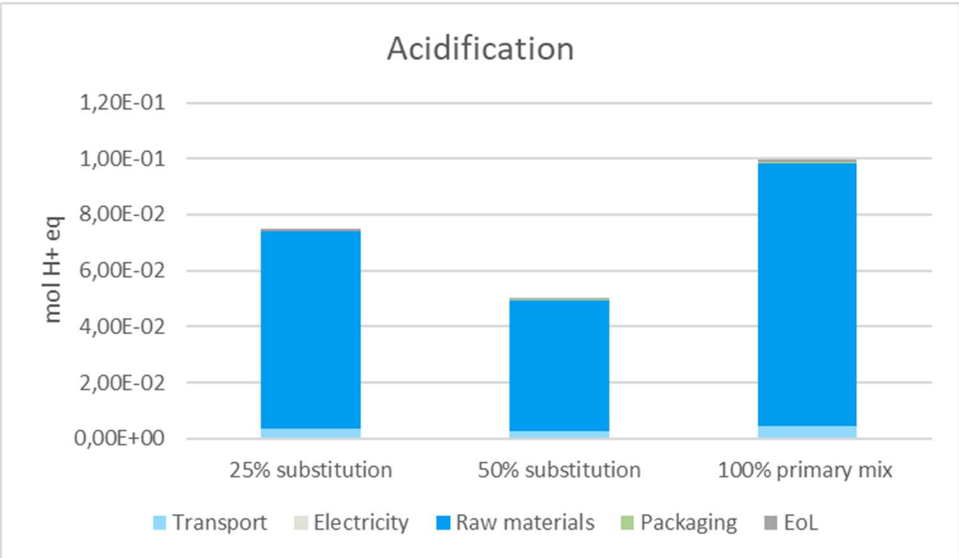

Figure 28: Scenario results (raw material substitution) for AP

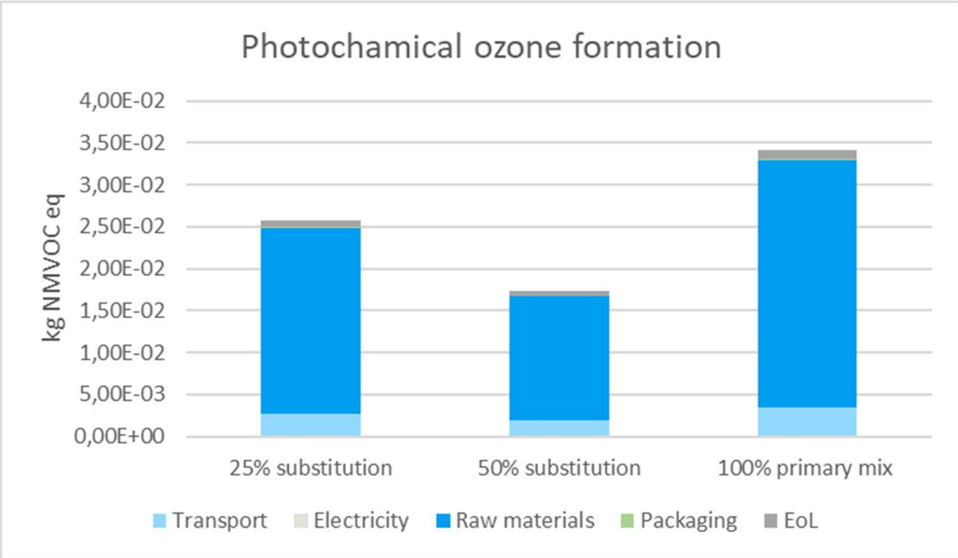

Figure 29: Scenario results (raw material substitution) for POCP

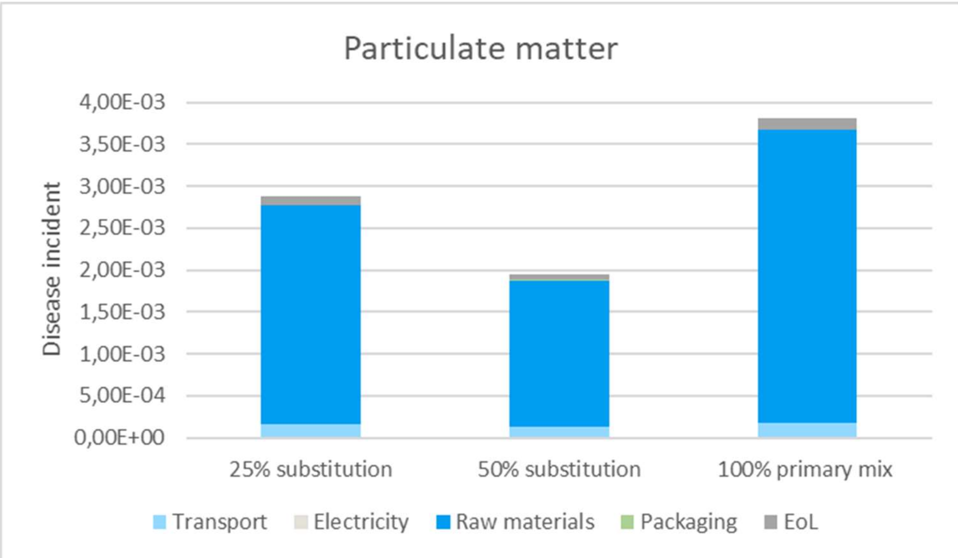

Figure 30: Scenario results (raw material substitution) for PM

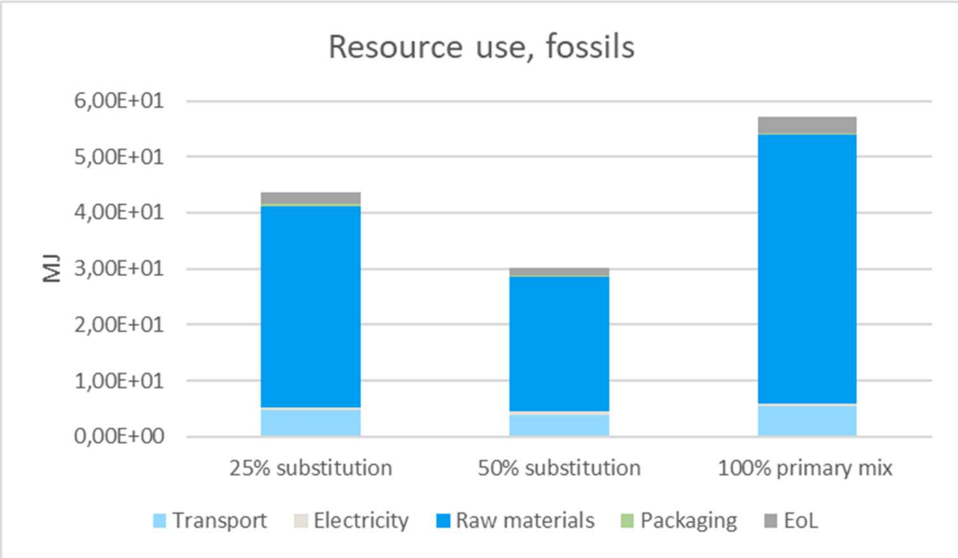

Figure 31: Scenario results (raw material substitution) for Resource use, fossil

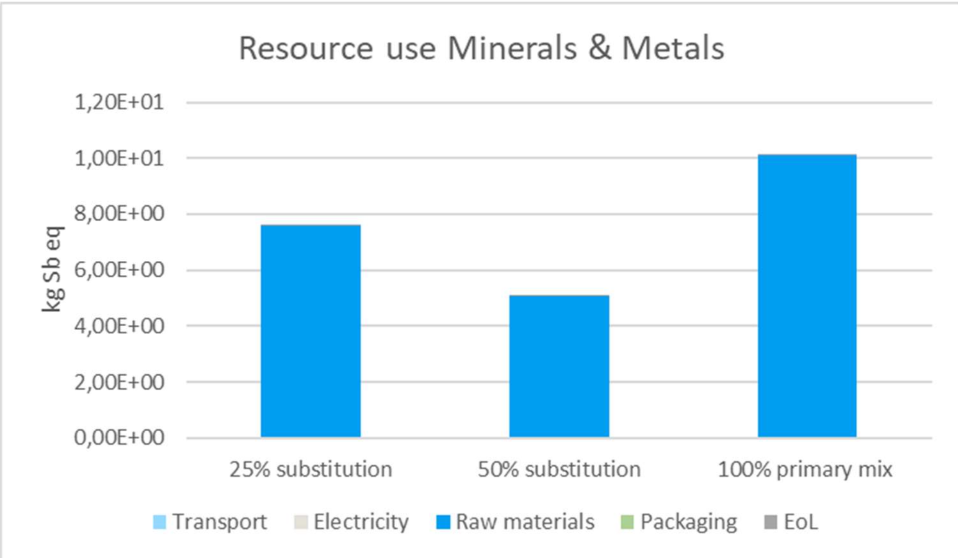

Figure 32: Scenario results (raw material substitution) for Resource use, minerals, and metals