CHALMERS
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Does a catalytic converter cause more loss of lives than it saves?

A human health life cycle assessment study

Master thesis within the Master's Programme Industrial Ecology

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Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
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MASTER'S THESIS

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Cover:

Collage of two photos. The one above shows mining in the Bingham Canyon Mine of Rio Tinto's subsidiary, Kennecott Utah Copper. The photo is from http://en.wikipedia.org/wiki/Mining#/media/File:Bingham_Canyon_April_2005.jpg. The photo below shows passenger car in Sweden, and was taken by the author of this report.

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Abstract

Purpose This study was conducted to investigate the production impacts and use phase benefits of a catalytic converter using the disability adjusted life year (DALY) indicator over its life cycle, starting from resource extraction to end of life management. The assessment was conducted for a generic three way ceramic honeycomb catalytic converter. The aims of the case study were to identify social hotspots of the catalytic converter's life cycle and to evaluate whether the catalytic converter is saving more lives than are lost during production.
Methods The case study was based on the human health focus approach and on the social life cycle assessment (SLCA) method described in the Guidelines for SLCA. All relevant stakeholders are included. Material and energy inputs, as well as outputs for unit processes of the catalytic converter production system, are determined from relevant patents and studies, and from the Ecoinvent V. 2.2 life cycle inventory database. To assess the human health benefits and production impacts, the ReCiPe impact assessment method was used. To assess the occupational health impacts, occupational DALY characterization factors (CFs) reported by Scanlon, et al., (2015) were used. Calculations were performed using the openLCA V. 1.4.1 software (GreenDelta, Berlin, Germany).
Results and discussion In general, a catalytic converter causes more loss of lives (11 days) then it saves (4.5 days) under the egalitarian value perspectives for the baseline production scenario of 160,000 km functional life. Contrary to that, the catalytic converter saves lives (5.5 days and approx. 6 days for the hierarchist and individualist perspectives, respectively) than it causes loss (about 1 day and 0.6 days for the hierarchist and individualist perspectives, respectively) for the baseline production scenario for 160,000 km functional life under hierarchist and individualist perspectives. The geographical hotspot analysis reveals that, while the catalytic converter saves lives in Sweden where it is used, it causes more loss of lives elsewhere in the world, particularly in South Africa and Russia. In total, the loss of lives is around 11 days for the base line production system at low recycling rate and egalitarian perspective; at high recycling rate the loss of lives reduced to about 7 days. Overall, the DALY varies between 0.62 days and 11.3 days, mainly due to differences in value perspective.
Conclusions The study showed that increased use of recycled platinum group metals, extended functional life of the catalytic converter, and value perspective can alter the health balance of the product system. This human health-focused SLCA case study identified methodological issues that need further attention, for example development of occupational DALY characterization factors (CFs) for the countries involved in the production of three way ceramic honeycomb catalytic converter, and emission DALY CFs for platinum group elements (PGEs) emitted during the use phase of catalytic converter.

Keywords: Social life cycle assessment (SLCA), hotspot assessment, catalytic converter, DALY, occupational hazards.

Abbreviations and Notations

CAGR-Compound Annual Growth Rate.
DALY- Disability Adjusted Life Years.
Emission DALY- Lives lost measured in DALY unit due to the environmental emission from the production system.
HCs-Hydrocarbon.
LCA-Environmental Life Cycle Assessment.
LCC-Life Cycle Costing.
LCIA-Life cycle impact assessment.
LCI-Life Cycle Inventory.
LCSA -Life Cycle Sustainability Assessment.
NO_x-Oxides of nitrogen.
Occupational DALY- Lives lost measured in DALY unit due to occupational hazard in the work place as well as from resource consumption within the production system.
PGEs- Platinum group elements.
PGMs-Platinum group metals.
SETAC-Society of Environmental Toxicology and Chemistry.
SLCA-Social Life Cycle Assessment.
UNEP- United Nations Environment Programme.

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CHAPTER 1

Introduction

1.1 Background

Sustainability assessment of a product or technology should be based on impact assessment encompassing three established dimensions—the social, the environmental, and the economic—from a life cycle perspective in order to avoid problem-shifting in the product system [Ciroth et al., 2011; Finnveden et al., 2009; Kloepffer, 2008]. In view of this urgency for sustainability assessment of human production and consumption, there is an increase in research on environmental life cycle assessment (LCA) since around 1990. Such scholarly research works resulted into methodological harmonization, practical case studies and subsequent standard development, leading to increased maturity and methodological robustness of LCA [Cooper and Fava, 2006; Finnveden et al., 2009; Guinée et al., 2011; Reap et al., 2008; Rebitzer et al., 2004]. LCA conventionally includes environmental impacts, human health impacts and impacts on natural resources. LCA has a 'planet concern' rather than covering all the three dimensions people, planet and economic prosperity included in the sustainability concept [Benoit and Mazijn, 2009]. Therefore recommendations based on LCA only do not explicitly address the social and economic concerns in the product life cycle [Dreyer et al., 2006]. To overcome this inadequacy in decision making for sustainability, two methods complementary to LCA have been developed. One is life cycle costing (LCC), which considers economic implications (costs and benefits) in a life cycle perspective of a product; LCC was developed from the 1930s and has more recently been adapted to be used in parallel with LCA. Another method is social life cycle assessment (SLCA), which focuses on the social impacts related to product life cycles [Benoit and Mazijn, 2009].

SLCA is a "social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; re-use; maintenance; recycling; and final disposal. SLCA complements environmental LCA with social and socio-economic aspects. It can either be applied on its own or in combination with environmental LCA" [Benoit and Mazijn, 2009]. In spite of increasing interest in developing and using SLCA, SLCA is still in its infant stage in comparison with LCA [Jørgensen, 2013]. A limited number of SLCA case studies have so far been conducted, for example a comparison of cut roses from different countries [Franze and Ciroth, 2011]; identifying social hotspots of laptop computers [Ekener-Petersen and Finnveden, 2013]; attribute assessment of greenhouse tomatoes [Andrews et al., 2009]; and comparative life cycle assessment and social life cycle assessment of a used PET bottle [Foolmaun and Ramjeeawon, 2013]; with an aim to evaluate the applicability of the Guidelines for Social Life Cycle Assessment of Products developed by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) working group [Benoit and Mazijn, 2009]. Based on the social life cycle approach, another case study has also been

conducted, focusing on human health assessment to evaluate the lifesaving potential of an airbag system. This study also used the disability adjusted life year (DALY) indicator to evaluate lives saved during the use phase of an airbag system and compare the results with lives lost during the production [Baumann et al., 2013].

1.2 Purpose and rationale of the study

The case studies mentioned in the previous section highlight concerns regarding the applicability of the UNEP/SETAC approach of SLCA to products with a more complex life cycle [Franze and Ciroth, 2011]. Yet based on the UNEP/SETAC approach of SLCA, recently one study is conducted on laptop having a complex life cycle [Ekener-Petersen and Finnveden, 2013]. The guideline is not based on research experience and outcome from actual case studies [Baumann et al., 2013]. The social topics such as working hours, child labor, freedom of expression, etc., used in UNEP/SETAC framework [Benoit and Mazijn, 2009], are not unambiguous. Indicator values chosen are more or less ideological and have marked variation from country to country [Baumann et al., 2013]. So there is a need to develop uniform indicators, particularly under the health category, to assess the social impacts for complex product systems involving a number of countries in the production chain. So far, the studies listed above having some sort of SLCA orientation have had two general approaches. One is the SLCA guideline approach and the other one is a human health focus approach. This study has a human health focus approach. In view of the aforementioned context, this study is conducted to investigate the human health impact of a catalytic converter using the DALY indicator over its life cycle. The use phase beneficial effect to society is calculated as saved lives from emission reduction of toxic or otherwise harmful substance like carbon monoxide (CO), unburned hydrocarbons (particularly benzene, formaldehyde, acetaldehyde, and 1, 3-butadiene), nitrogen oxides (NO_X), and sulfur dioxide (SO_2) from exhaust gas. The production system's negative social impact is calculated from two sources. One is occupational hazard for workers using occupational DALY characterization factor (CF) [Scanlon et al., 2015], and the other one is emissions emitted throughout the production system of three catalytic converter using the ReCiPe impact assessment method [Goedkoop et al., 2013].

1.3 Software, tools and data

Unit process input and output data mostly taken from the Ecoinvent 2.2 life cycle inventory (LCI) database. All the production system modeling (baseline production system and other scenarios) and calculations were performed using openLCA v. 1.4.1 software (GreenDelta, Berlin, Germany). The ReCiPe impact assessment method was used for the calculation of production impact related to environmental emissions throughout the product system. For the calculation of lives lost due to occupational hazard throughout the production system, occupational DALY CFs reported by Scanlon

et al., (2015) was used. The MS Excel program was used as visualization tool. Data quality is presented in a table in Appendix A.5.

1.4 Scope and limitation

Strict air pollution control standard in different countries around the world initiated widespread introduction of catalytic converters to control air pollution from vehicles. It was first introduced in the United States automobile market in 1975. Since the introduction of the catalytic converter, toxic air pollutant emissions have been reduced considerably. Catalytic converters convert toxic emissions of hydrocarbons, carbon monoxide, nitrogen oxides to less toxic pollutants [Cooper and Beecham, 2013; Twigg, 2011].

From a life cycle perspective, it is mandatory not only to assess emission reductions of a catalytic converter merely in the use phase, but also to take into account the impacts starting from extracting raw materials, producing and disposal of a catalytic converter as part of its life cycle from local and global perspective. Amatayakul and Ramnäs, (2001) reported that from a life cycle perspective, the catalytic converter is "converting" rather than reducing environmental impacts. Based on a conducted LCA, the authors wrote that it is reducing exhaust gas emissions from use phase in Sweden, while increasing environmental burdens in other places during its production. But so far, no study has been conducted to assess net human health impacts of catalytic converter, and to identify social impact hotspots in terms of human health impact. The production system of catalytic converter is composed of a number of global multinational manufacturers as discussed in chapter 4 of this report.

This study evaluates the social impact in terms of human health, encompassing the stakeholders workers, the local community and society, consumers and community affected during the use phase of catalytic converter and production phase along the value chain of a catalytic converter. Dreyer et al., (2006) wrote that in SLCA, the product life cycle is comprised by a number of companies operating industrial processes and the conduct of each company towards its stakeholders is analyzed and aggregated in the inventory. The authors also write that the product manufacturer has the highest influence on first tier suppliers, and the influence then subsequently decreases upwards in the life cycle, and similarly for distributor to recycler downwards in the life cycle. Considering this fact, the product system of this study started from the platinum group metals (PGMs) mining to recycling phase from a life cycle perspective.

The case study is about a generic three way ceramic honeycomb catalytic converter and not about any specific model or company-produced catalytic converter. The results should thus not be associated with any specific company producing three way ceramic honeycomb catalytic converters. Since this study is about a generic three way ceramic honeycomb catalytic converter, material input for the catalytic converter production is mostly taken from relevant patents, theses and published

research work as mentioned in the inventory chapter. For PGMs, the data is taken from Ecoinvent 2.2 LCI unit process database. This unit process data is already allocated based on economic value of the PGMs, so in this study it was not possible to analyze the variation in result if that process is based on physical allocation. This study also does not included the oxygen sensor or the Lambda probe manufacturing impacts.

This SLCA case study is conducted with an aim to assess the social impacts in terms of lives lost and lives saves by catalytic converter using the DALY indicator. A similar study is also conducted by Baumann et al., (2013) on the lifesaving potential of an airbag system. This SLCA case study can play a vital role for identifying social hotspots of the generic catalytic converter production system, and can provide information on whether a catalytic converter is saving more lives than it causes lives loss during production. The study will also test the applicability of the DALY indicator within the UNEP/SETAC framework of SLCA for a complex product system involving a large number of countries in the manufacturing process.

1.5 Structure of the thesis report

The current chapter 1 gives an overview of the study issue, rationale and scope of the study. History of the catalytic converter adoption for automobile emission control, working mechanism of the catalytic converter, human health impacts of automobile exhaust emissions and regulation affecting the use of catalytic converters worldwide are discussed in chapter 2. The method of this SLCA case study is discussed in chapter 3. Goal, scope and system boundaries are discussed in chapter 4. Inventory analysis of this SLCA case study is discussed in chapter 5. Chapter 6 and 7 present the results and discussion, and conclusion, respectively.

CHAPTER 2

Automobile Emissions and adoption of Catalytic converter

2.1 Automobile catalytic converter: A brief history

A catalytic converter in vehicle is a device to reduce emissions by catalyzing redox reactions. Those emissions are hydrocarbons (HCs), carbon monoxide (CO) and nitrogen oxides (NO_x), from burning of petrol or diesel in an automobile internal combustion engine [Cooper & Beecham, 2013; Taylor, 1984; USEPA, 1994]. With the advent of industrial and urban growth, and increasing automobile mobility from rising economic activity in some large cities, such as Los Angeles in the United States and Tokyo in Japan, automotive air pollution became a topic of vital concern starting from the 1950s and during the late 1960s [Alkemade & Schumann, 2006; Twigg, 2011]. The rising number of cars lead to increasing range of personal mobility and became a major source of pollutants [Twigg, 2007]. Pollutants emitted from automobiles, such as hydrocarbons (HCs) and nitrogen oxide (NO), were identified as precursors for the formation of photochemical smog through photochemical reactions in the lower atmosphere and later on other secondary pollutants in the lower atmosphere. Peroxyacetylnitrate (PAN), an extremely powerful eye irritant, is an example of secondary pollutants in the lower atmosphere from HCs and NO [Twigg, 2011]. To reduce the automobile air pollution, the catalytic converter concept was originally developed by the French mechanical engineer Eugene Houdry in the United States during the 1950s, but its widespread implementation did not commence until the prohibition of the anti-knocking agent tetra-ethyl lead, which has environmental impacts but is also poisoning catalytic converters. Later, John J. Mooney and Carl D. Keith at the Engelhard Corporation (owned by BASF) further developed the catalytic converter, and the first commercial production of catalytic converters started in 1973 [Zhang, n.d.].

The industrial-scale use of catalytic converters to lower the emissions of carbon monoxide (CO) and hydrocarbons (HC) from automobile exhaust started in the United States America (USA) with the introduction of the 1975 models in the fall of 1974 [Taylor, 1984]. Because of effective automobile pollution control by catalytic converter in the USA, a few years later in Japan and thereafter in Europe during 1986, the industrial-scale adoption of automotive catalysts started [Shelef & McCabe, 2000]. Since then, catalytic converters served as key components of automobile exhaust systems and are probably a vital factor for the rising number of global vehicles fleet to 920 million in 2010 [Kaspar et al., 2003].

2.2 HCs, CO and NO_x formation mechanism from automobile

The majority of automobile engines use the technology of combustion of fuels derived from crude oil at a refinery to run the automobile (internal combustion engine vehicles ICEV). Petrol and diesel are mixtures of hydrocarbons (HCs), which consist of carbon and hydrogen atoms. The perfect combustion of hydrocarbons (HCs) in a perfect engine ideally leads to the formation of only water (H_2O) and carbon dioxide (CO_2) due to combustion with oxygen from air and nitrogen from air acts as non-reactive species as represented in equation 2.1. However, since the automobile engines do not act as an ideal engine in

reality, imperfect combustion and high temperatures in the combustion chamber lead to the formation of significant amounts of pollutants as represented in equation 2.2 [Heck et al., 2009; Kaspar et al., 2003; USEPA, 1994].

$HCs + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2$ (equation 2.1)

$HCs + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2 + \text{un-burned HCs} + NO_x$ (equation 2.2)

Since complete oxidation of petrol and diesel in the engine to CO_2 and H_2O is not effectual; exhaust gas contains significant amounts of unburned hydrocarbons and some partially combusted products like aldehydes, ketones, and carboxylic acids. These unburned hydrocarbons count as hydrocarbons (HCs) in terms of exhaust emissions, for which the concentration level varies from 500 to 1,000 vppm [Heck et al., 2009]. High temperature in the combustion chamber due to diffusion burning of the petrol droplets influence N_2 and O_2 to react to form nitrogen oxides (NO_x) through a series of exothermic and endothermic reactions, which lead to a combination of NO and NO_2 (equation 2.3-2.4), and concentration levels vary in the range of 100 to 3,000 vppm. The incomplete combustion of HCs also results in carbon monoxide (equation 2.5), with concentrations varying from 1 to 2 volume percentage. NO_x, HCs and CO are the three primary pollutants in the exhaust gases from cars [Heck et al., 2009b;Twigg, 2007; Twigg 2011].

$N_2 + O_2 \rightarrow 2NO - 6\,182.4$ KJ/mole (equation 2.3)
$2NO + O_2 \rightarrow 2NO_2 + 113.8$ KJ/mole (equation 2.4)
$4H_mC_n + (2_{n+m})\,O_2 \rightarrow 2_mH_2O + 4nCO$ (equation 2.5)

The quantity of pollutants and their levels is critically influenced by a number of factors, such as (1) the type of engine (e.g. two- or four-stroke, spark- or compression (diesel)-ignited), (2) driving conditions (e.g. urban or extra-urban), (3) vehicle speed, (4) acceleration/deceleration and (5) engine operating conditions (e.g. air–fuel ratio, combustion temperature, ignition timing, turbulence in the combustion chamber, combustion form). Among these factors, the most critical one is air-to-fuel (A/F) mass ratio, denoted lambda (λ), in the combustion cylinder [Heck et al., 2009a; Kašpar et al., 2003; Reşitoğlu et al., 2015]. The A/F mass ratio is defined as the actual air-to-fuel ratio divided by the air-to-fuel ratio at the stoichiometric point (equation 2.6). $\lambda = 1$ represents, the specific amount of air required to completely oxidize all fuel, which is 14.6 for petrol. $\lambda < 1$ represent the A/F rich or insufficient air condition, and $\lambda > 1$ represent A/F lean or excess air condition [Heck et al., 2009a].

$\lambda = (A/F)_{actual} / (A/F)_{stoichiometric}$ (equation 2.6)

In case of insufficient air or A/F rich condition, the CO and HCs emissions are highest and NO_x emissions are low, because complete combustion of HCs is not possible due to deficiency of oxygen. NO_x emissions are reduced because of reduction in the adiabatic flame temperature. On the other hand, A/F lean condition leads to reduced CO and HCs emission because of complete combustion, but more NO_x is produced (Figure 2.1). A typical range of three major pollutants emitted from different engine are presented in Table 2.1.

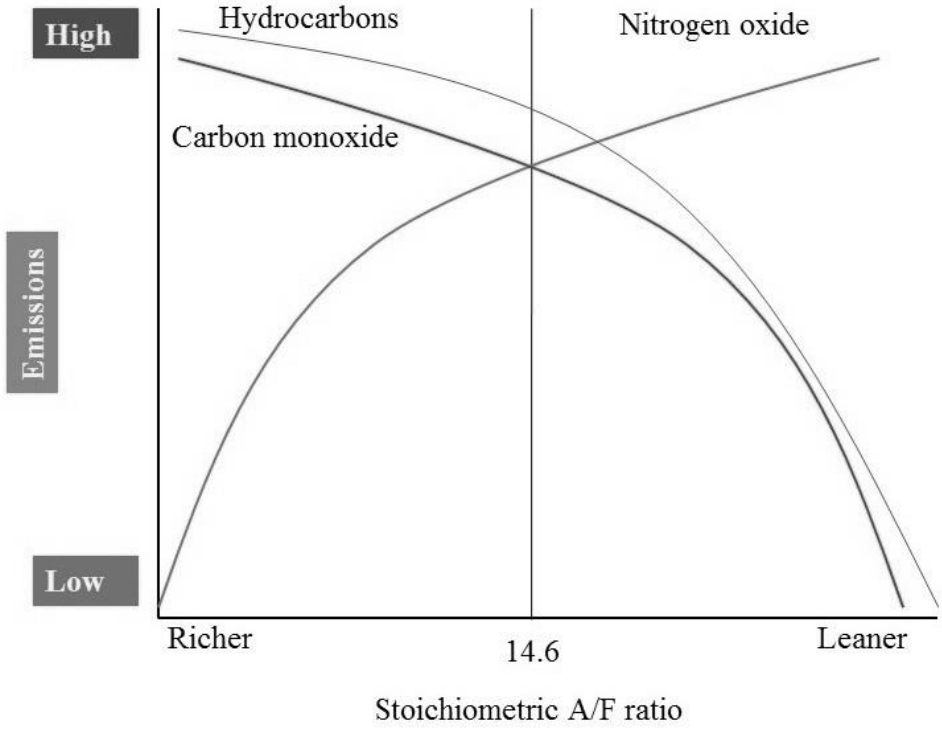


Figure 2.1: Petrol based automobile engine emissions as a function of the air-to-fuel (A/F) ratio [Source: developed from Heck et al., 2009a].

Table 2.1: Typical CO, HCs and NO_x emission levels from different types of engine and corresponding (A/F) ratio [Source: Kašpar et al., 2003]

Emissions and A/F ratio	**Diesel engine**	**Four-stroke spark ignited-engine**	**Four-stroke lean-burn spark ignited-engine**	**Two-stroke spark ignited-engine**
CO	300–1200 ppm	0.1–6%	≈1300 ppm	1–3%
HCs	50–330 ppm C	500–5000 ppm C	≈1300 ppm C	20,000–30,000 ppmC
NOx	350–1000 ppm	100–4000 ppm	≈1200 ppm	100–200 ppm
A/F ratio	≈1.8	≈1	≈1.16	≈1

2.3 Human health impact from exhaust emissions

Studies estimate that exhaust emissions from road vehicles cause around 180,000 deaths worldwide. A large number (91,000) of deaths are from ischemic heart disease, while 34,000 deaths is from respiratory infections (Table 2.2). In terms of DALY, the total worldwide burden is approximately 4.1 million in 2010 (Table 2.2). As mentioned earlier, HCs, CO and NO_x are the three primary pollutants emitted from automobile exhaust. However, once emitted, these three primary pollutants react with each other by mixing with atmospheric water vapors in the presence of sunlight to form secondary pollutants like ozone, PAN, and other complex organic substances collectively known as photochemical smog [Bhandarkar, 2013]. Some specific health effect of the three primary automobile exhaust emission along with secondary pollutants derived from them are highlighted here.

Table 2.2: Health burden due to emissions from motorized road transport [Source: Bhalla et al., 2014].

Diseases	**Deaths (in thousands)**	**DALY (in millions)**
Ischemic heart disease	91	1.9
Stroke	57	1.1
Chronic obstructive pulmonary disease (COPD)	17	0.35
Lower respiratory infections	5.7	0.50
Lung cancer	11	0.23
Totals	180	4.1

2.3.1 Hydrocarbons

Hydrocarbons (HCs) emitted from automobile exhaust in different forms are directly or indirectly harmful. They can react with NO_x in presence of sunlight to form ground-level ozone, a key constituent in summer smog formation. Ozone is highly irritant to the eyes, can damage the lungs by reacting with lung tissue, can decrease the lungs' working ability and cause respiratory problems. It can inflame and cause harmful changes in the breathing passage. Ozone can also cause coughing and chest pains, and even healthy adult people are found to be sensitive to ozone exposure [Ecology, n.d.; Resitoglu et al., 2015; USEPA, 1994]. HCs, especially aromatic compounds such as benzene (C_6H_6), can cause harmful effects on the human immune system. HCs can also directly irritate the lung and other tissues, can contribute to birth defects, and even cause cancer [HEI, 2010; Reşitoğlu et al., 2015].

2.3.2 Carbon monoxide

Carbon monoxide (CO) is a poisonous gas, and if inhaled it reacts with hemoglobin and consequently damages the oxygen carrying capacity of the bloodstream to brain, heart, other tissues and other organs. It is particularly dangerous and can directly cause death to persons with heart disease at high levels.

Exposure to CO can even cause headaches, fatigue, visual impairment, reduced reflexes in healthy people and can affect the central nervous system. Newborn children are also highly affected by CO exposure [HEI, 2010; Resitoglu et al., 2015; USEPA, 1994].

2.3.3 Nitrogen oxides

Nitrogen Oxides (NO_x) refer to NO and NO_2. They are noxious pollutants and cause ground level ozone formation, smog and acid rain formation. Both can travel long distances and exposure to them can severely affect the respiratory system [Ecology, n.d.; HybridCars.com, n.d.; USEPA, 1994]. They can react with ammonia, moisture, and other airborne compounds to form minute particles. These particles can penetrate acutely into the sensitive parts of lungs and consequently cause respiratory diseases such as emphysema and bronchitis, which can aggravate existing heart diseases as well as increased infant mortality, cardiovascular diseases and premature death [Colvile et al., 2001; US EPA, 2014]. NO_2 is five times more toxic than NO and it can irritate the lungs and can cause human lung disease. NO_2 can also facilitate respiratory infection such as influenza [Resitoglu et al., 2015].

2.4 Regulations worldwide influencing the use of catalytic converter

Emission standards for CO, HCs and NO_x, set by different regulatory agencies around the world since 1970, have been the critical factors for the progressive use of catalytic converters in automobiles, and consequently driving down CO, HCs and NO_x emissions from automobiles [Twigg, 2011]. A number of countries have enacted emission regulations to control CO, HCs and NO_x, and the main response has been to install catalytic converters in automobiles. A brief review of these regulations follows here.

2.4.1 USA

In terms of emission regulation by using catalytic converter, Californian regulations set by the California Air Resources Board (CARB) are the pioneers, because already in 1977 this agency enforced lower emission levels than the rest of the USA [Twigg, 2006, 2007, 2011]. In USA, passenger cars and light duty vehicles fall under the Tier 1 (Table 2.3). Until now, the automobile exhaust emission standard in the US is changing toward stricter standard. The use of catalytic converter in automobile for driving down the emission of CO, NO_x and HCs in response to emission standard set by different countries seems to be effective for reducing toxic emissions. Reductions of NO_x, CO and HCs emissions from American cars over the period 1970–1990 due to the use of catalytic converters are reported by Twigg (2007). During the 1970s, the emission of NO_x, CO and HCs was around 4.5, 70 and 9 million tons, respectively, while during 1990s these emissions dropped notably and continue to decrease [Twigg, 2007].

2.4.2 Europe

In 1970, the first European exhaust emission standard for passenger cars was introduced, but regulation for the use of catalytic converter started from 1993 with the Euro 1 standard to control CO [Lindqvist, 2012; Twigg, 2011]. In Europe, automobile exhaust emissions are controlled using two basic frameworks. One is the "Euro standards" for NO_x, HCs, CO, particulate matter (PM), and particle numbers (PN); and the other one is the regulation of CO_2 emissions. The standards for light-duty vehicles (passenger cars and light commercial vehicles) are referred to as "Euro" and followed by a number, 1,2, 3 etc. (Table 2.4) [Lindqvist, 2012].

2.4.3 Japan

Similarly, during the 1970s, Japan also first established automobile emissions standards for light-duty vehicles. The Ministry of the Environment is the regulatory agency for setting emission standards under authority of Japan's Air Pollution Control Law. From 2000 and onwards, the exhaust emission standards have been tightened three times. The emission standards were developed as "New Short Term Standards" during the years 2000-2002, then the "New Long Term Standards" during 2005-2007, and finally "Post New Long Term Standards" in 2009-2010. The latest one is similar to the Euro 6 standards (Table 2.5) [DieselNet, 2007; Olivares, 2013].

2.4.4 Other countries

Similarly, other countries have also adopted emission standards to reduce the three key automobile emissions promoting the installation of catalytic converters in automobiles. For example, Canada has adopted emission standards for vehicles, which are quite similar to those of the United States. Automobile emission standards of Australia are also consistent with the European Union standard. China has already adopted Euro 2 standards particularly for both light- and heavy-duty vehicles and also have planned to adopt consecutively Euro 3, Euro 4, and Euro 5 standards in future. In 2006, South Korea adopted Euro 4 standards for diesel cars and for petrol cars Ultra-Low Emission Vehicle (ULEV) standards. The Euro 2 standards was adopted in India in 2005, and Euro 3 in 2010. In some major cities of India such as Mumbai, New Delhi, Bangalore, Chennai, and Hyderabad, Euro 4 standard was adopted in 2010 [HEI, 2010].

Table 2.3: California (CARB) emission standard (CO, HCs and NOx) in US [Source: Twigg, 2006; 2007, 2011]

Year	Category	Emissions (g/mile)		
		HCs	CO	NOx
1993		0.25[a]	3.40	0.40
1994	Tier 1	0.25[b]	3.40	0.40
2003	Tier 1	0.25[c]	3.40	0.40
2004	$TLEV_1$[d]	0.125	3.40	0.40
	TEV_2 [e, f]	0.075	3.40	0.05
2005	LEV_1 [d]	0.075	3.40	0.40
	$ULEV_2$ [e, f]	0.040	1.70	0.05
2006	$ULEV_1$ [d]	0.040	1.70	0.20
	$SULEV_2$ [e, f]	0.010	1.0	0.02
2007	ZEV_1	0	0	0
	ZEV_2	0	0	0

LEV = low emission vehicles, whereas T is transitional, U is ultra, and S is super; ZEV = zero emission vehicles.

[a] NMHC: non-methane hydrocarbons, i.e., all hydrocarbons excluding methane.

[b] NMOG: non-methane organic gases, i.e., all hydrocarbons and reactive oxygenated hydrocarbon species such as aldehydes, but excluding methane. Formaldehyde limits (not shown) are legislated separately.

[c] FAN MOG: fleet average NMOG reduced progressively from 1994 to 2003.

[d] type emissions categories phasing out 2004–2007.

[e] type emissions limits phasing in 2004 onwards.

[f] have same emission limits for passenger cars and trucks <8500 lb gross weight.

Table 2.4: Emission standard (CO, HCs and NO_x) for passenger cars in EU [Source: DieselNet, 2015]

Year	Category	Emissions (g/km)							
		CO		HCs		HCs + NO_x		NO_x	
		Diesel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
1992	Euro 1	2.72	2.72	--		0.97	0.97	--	--
1996	Euro 2	1.0	2.2	--		0.7	0.5	--	--
2000	Euro 3	0.64	2.30	--	0.20	0.56	--	0.50	0.15
2005	Euro 4	0.50	1.0	--	0.10	0.30	--	0.25	0.08
2009	Euro 5	0.50	1.0	--	0.10	0.23	--	0.18	0.06
2014	Euro 6	0.50	1.0	--	0.10	0.17	--	0.08	0.06

Table 2.5: Emission standard (CO, HCs and NO_x) for diesel passenger cars in Japan [Source: DieselNet, 2015]

Year	Emissions (g/km)						
	CO		HCs		NO_x		
	A Mean (Max)	B Mean (Max)	A Mean (Max)	B Mean (Max)	A Mean (Max)	B Mean (Max)	
1986	2.1 (2.7)	2.1 (2.7)	0.40 (0.62)	0.40 (0.62)	0.70 (0.98)	0.90 (1.26)	A-Vehicle weight <1250 kg B-Vehicle weight >1250 kg
1990	2.1 (2.7)	--	0.40 (0.62)	--	0.50 (0.72)	--	
1992	--	2.1 (2.7)	--	0.40 (0.62)	--	0.60 (0.84)	
1994	2.1 (2.7)	2.1 (2.7)	0.40 (0.62)	0.40 (0.62)	0.50 (0.72)	0.60 (0.84)	
1997	2.1 (2.7)	--	0.40 (0.62)	--	0.40 (0.55)	--	
1998	--	2.1 (2.7)	--	0.40 (0.62)	--	0.40 (0.55)	
2002	0.63	0.63	0.12	0.12	0.28	0.30	
2005	0.63	0.63	0.024	0.024	0.14	0.15	
2009	0.63	0.63	0.024	0.024	0.08	0.08	

2.5 Catalytic converter: emission control working mechanism

Three-way catalytic converters have been used since 1981 for vehicle emission reduction in North America and later on in a number of countries [Zhang, n.d.]. Since this study is on a typical three-way ceramic monolith honeycombs type catalytic converter, here the basic working mechanisms for reducing toxic emissions with such devices are discussed. In a three-way catalytic converter, the conversion of the toxic emissions CO, NO_x and unburned HCs is performed simultaneously, including reduction of NO_x to N_2 and O_2 (equation 2.7), oxidation of CO to CO_2 (equation 2.8), and oxidation of unburnt HCs to CO_2 and H_2O (equation 2.9) [Heck et al., 2009; Zhang, n.d.].

$$2NO_x \rightarrow xO_2 + N_2 \qquad \text{(equation 2.7)}$$

$$2CO + O_2 \rightarrow 2CO_2 \qquad \text{(equation 2.8)}$$

$$C_yH_n + (1+n/4)\, O_2 \rightarrow yCO_2 + n/2\, H_2O \qquad \text{(equation 2.9)}$$

In a three-way ceramic monolith catalytic converter, two different types of catalysts perform the above mentioned conversion: (1) a reduction catalyst surface consisting of platinum (Pt) and rhodium (Rh), and (2) an oxidation catalyst surface consisting of platinum (Pt) and palladium (Pd) (equation 2.7-2.9).

While the automobile engine starts, both the engine and the catalyst are cold and so the toxic emissions are still emitted via the exhaust because a certain critical temperature (400-700ºC) is needed for the efficient functioning of the catalytic converter. But now complex and expensive catalytic converter heating systems are used in order to reach this critical temperature as quickly as possible [Technische Universität Wien, n.d.]. When a driver starts the automobile, the exhaust gradually warms up and reaches the critical temperature, known as lightoff temperature, to initiate the catalytic reactions. In the first ceramic monolith chamber, the reduction catalyst Pt and Rh reduces NO_x emissions. Pt and Rh splits NO or NO_2 into nitrogen and oxygen atoms. This results into release of the oxygen in the form of O_2 surface.. Nitrogen atoms become attached to the catalyst surface and then bond with other nitrogen atoms and form N_2. In the second ceramic monolith chamber, the oxidation catalyst Pt and Pd reduce the unburned HCs and CO by oxidizing them. Pt and Pd catalyst surfaces catalyze this reaction with the aid of the O_2 coming from the first ceramic monolith chamber, and convert CO and unburned HCs to CO_2 and H_2O (Figure 2.4) [Heck et al., 2009; Taylor, 1984; Zhang, n.d.].

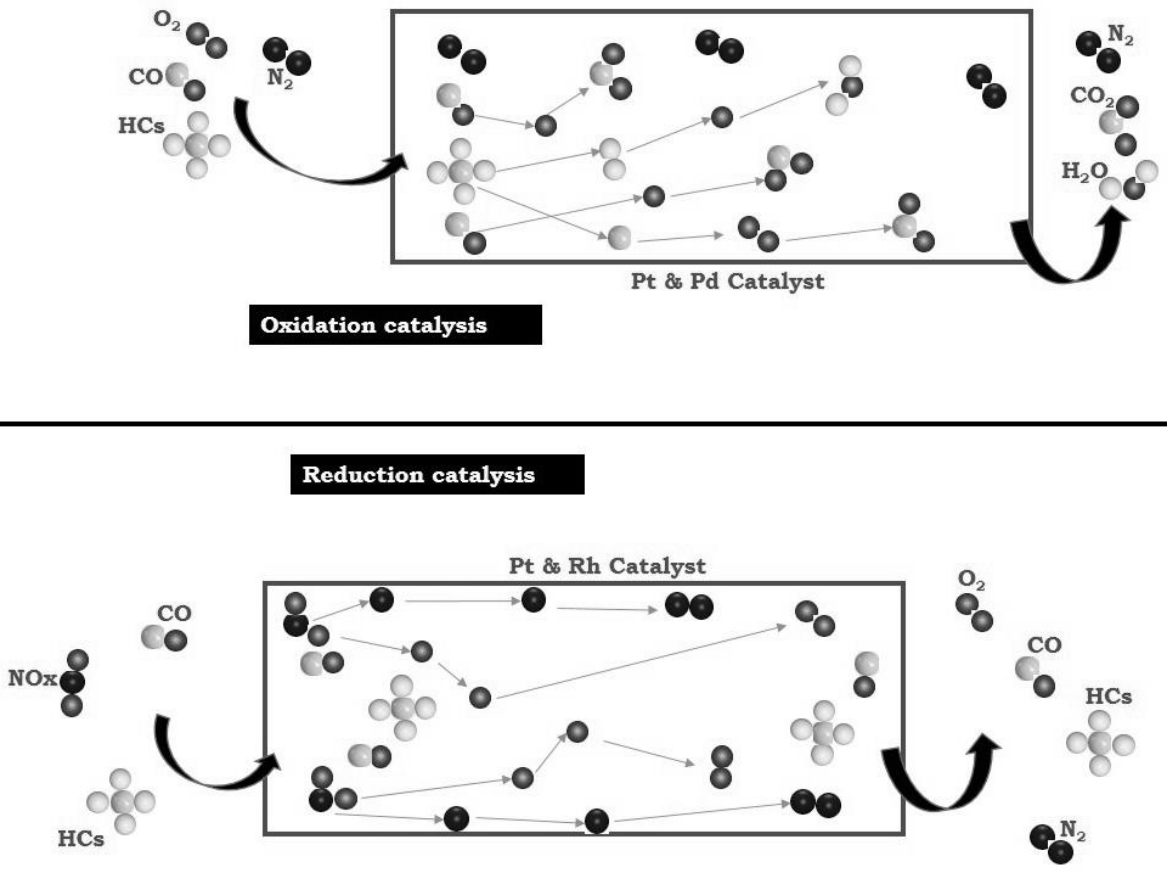


Figure 2.2: CO, NO_x and HCs conversion mechanisms in a typical three way ceramic monolith catalytic converter.

2.6 Global use and production of catalytic converter

A catalytic converter is a key component of an automobile exhaust systems and a vital component for the growing number of 920 million vehicles in 2010 [Kaspar et al., 2003]. It has been reported that the automotive catalytic converter market will be around 140 million units by 2019 [CNBC, 2015; Markets and Markets, 2015; PR Newswire, 2015]. Worldwide annual sales of catalytic converter was just over 9 million units/year during 2006, which increased to around 19 million units/year during 2012. This rate of increase over this period (from 2006 to 2012) is certainly an indication of increased use of catalytic converter in near future [SANGO, 2012].

The future emerging emission standards in the Asia-Oceania region, including China, India, South Korea, and Japan, will be the potential cause for further boasting of the automobile catalytic converter market in this region. Particularly India and China will be the dominating factors for this market rise, where the automotive industry is growing at a high rate. The upcoming emission standards, along with rising vehicle sales and production because of low production cost, increasing production capacity, and growing demand for light and heavy vehicles, would increase the demand for catalytic converters. It is expected to increase the automotive catalytic converter market in Asia-Oceania region at a CAGR (Compound Annual Growth Rate) of 8.6% from 2014-to2019. In Europe, the Euro 6 emission standard is expected to increase the demand for catalytic converters in Eastern and Western Europe, and is projected to grow at a CAGR of 6.4% from 2014 to 2019. The North American automotive catalytic converter market (consisting of USA., Canada, and Mexico), is expected to grow at a CAGR of 7.5% from 2014 to 2019 [CNBC, 2015; Markets and Markets, 2015; PR Newswire, 2015].

CHAPTER 3

Method

3.1 Social Life Cycle assessment (SLCA) framework

SLCA is the third pillar tool within LCSA, along with the two other tools known as LCA and LCC [Kloepffer, 2008]. Every-day decisions are made in companies related to product manufacturing that affect people and the environment, directly through their own operations, or indirectly through the value chain of their business. Currently, business operations are increasingly faced with questions regarding their social performances from a number of stakeholders [Dreyer et al., 2006]. Hence, companies around the world are increasingly trying to manifest their business operation as sustainable. To assess the social sustainability of the business operation, the SLCA tool is becoming increasingly popular. Simply put, SLCA can be seen as a method for assessing negative and positive consequences in society due to the use of particular goods or services from a life cycle perspective.

3.1.1 Principles

According to the "Guidelines for Social Life Cycle Assessment of Products" published by UNEP/SETAC, SLCA assesses social and socio-economic impacts originating along the life cycle, with generic and site-specific data. SLCA is quite different from other social impacts assessment methods (e.g. participatory rural appraisal, and beneficiary assessment) by its objects of study, i.e. products and services; and its scope, i.e. the entire life cycle. SLCA is also conducted to map social impacts and identify hot spots. SLCA does not have the goal, nor pretends to provide information, regarding whether a product should be produced or not [Benoit and Mazijn, 2009].

3.1.2 Product system in SLCA

The product system comprises of all the processes involved in different stages of a product life cycle, starting from the extraction of raw materials, manufacturing, use, and end of life management. SLCA is about assessing positive and negative consequences on people in a society, so the focus of SLCA when defining product system must be on those activities in the life cycle that affect people [Dreyer et al., 2006]. According to the guidelines of SLCA, positive and negative impacts on society generally have three dimensions. One is behavioral dimension, for example allowing illegal child labor. Another one is socio-economic processes dimension, for example investing in a manufacturing plant of a product leading to developed infrastructure in a community. Finally, human, social, and cultural capitals dimension, and impacts on them can either be positive or negative, for example beneficial to human health or deterioration of human health [Benoit and Mazijn, 2009]. So when defining product system for SLCA case study, the above dimension should be taken into consideration and there are different approaches to handle this dimensions.

To define social impacts of a product system, another important aspect is to understand different stakeholders. People affected directly or indirectly by a company's operation to produce a product can collectively be referred to as stakeholders of the company in relation to the product considered [Dreyer et al., 2006]. In every geographical location, positive and negative impacts on society from a

product may be observed for five main stakeholder categories: workers or employees, local community, society (national and global), consumers (covering end-consumers as well as the consumers who are part of each step of the supply chain), and value chain actors [Benoit and Mazijn, 2009].

3.1.3 Goal, scope and functional unit

The goal and scope definition of SLCA includes specifying the object and objectives of the intended study and defining the functional unit. It also includes the unit processes to be included within the system boundary, which data will be collected, which impact categories and subcategories to include in the analysis, and which stakeholders to include. The functional unit of an SLCA study must be based on the function of a product to provide a reference to which the input and output data are related. So, the functional unit must be clearly defined, measurable and consistent with the goal and scope [Benoit and Mazijn, 2009].

3.1.4 Product system boundary

The product system boundaries in SLCA must be determined on a case-to-case basis, but in general the system boundary may cover aspects such as material extraction phase, manufacturing phase, distribution of product, use phase, end of life management, and transportation between phases [Dreyer et al., 2006]. Product system boundaries should be based on the defined functional unit, and the product system to be modeled. To define the product system and the boundaries for an SLCA case study, the key processes of manufacturing the considered product and which organizations that are involved needs to be identified and located. The product system and the boundaries defining phase is an iterative process [Benoit and Mazijn, 2009].

3.1.5 SLCA inventory analysis

The aim of the inventory phase of an SLCA is to collect relevant information in relation to the specific processes for the product system identified during the scope definition [Jørgensen, et al., 2008]. The inventory phase involves gathering and summing up of life cycle inventory data (input of resources and associated elementary and other flows) for all the unit processes linked by product flows as delimited by the system boundaries [Benoit and Mazijn, 2009]. Thus, during the SLCA inventory phase, data are collected, the product system is modeled, and the inventory results related to specific unit process are obtained. According to the "Guidelines for Social Life Cycle Assessment of Products" published by UNEP/SETAC [Benoit and Mazijn, 2009], some of the operational steps of the SLCA inventory phase are: (i) data collection for prioritizing and screening, and using generic data for hotspots assessment, (ii) data needed for impact assessment, means characterization, (iii)

validation of data, (iv) functional unit and unit process relating data, and (v) refining the system boundary, if needed [Benoit and Mazijn, 2009].

3.1.6 SLCA impact assessment

The impact assessment phase of SLCA encompasses classification, aggregation and characterization of collected data in relation to the functional unit. The main steps in SLCA impact assessment are: (i) selection of the impact categories and subcategories, and the relevant characterization methods and models, (ii) relating the inventory data to particular subcategories and impact categories, also known as classification, and (iii) determining the results for the subcategory indicators. The social and socio-economic impacts in an SLCA case study can range from specific to very general, from final to preliminary, based on the level of precision to be reached in the interpretation. The UNEP/SETAC framework for SLCA includes impact categories organized into stakeholders (for example worker and consumer) and subcategories (under worker category for example child labor, fair Salary, working hours) [Benoit and Mazijn, 2009]. According to this UNEP/SETAC framework, two types of impact categories can be identified. Type 1 impact categories represent social issues of interest in relation to stakeholders affected, such as health and safety, human rights, working conditions, socio-economic repercussions, and cultural heritage. Type 2 impact categories are based on models of the social impact pathways to the endpoints human capital, cultural heritage and human well-being [Benoit and Mazijn, 2009].

3.2 Methods adopted and choice of indicator

In order to enable comparison of the catalytic converter production impacts and potential realization of use phase health benefits, the DALY indicator is used. To quantify the burden associated with premature death, disease, and injury affecting the humans in society, the indicator DALY was developed by the World Bank and the World Health Organization [Gold, et al., 2002; Havelaar et al., 2000].

The methodological approach of this study is depicted in the Figure 3.1 together with other options. The “Preston pathway” by Feschet et al., (2013) approach is based on the “Preston curve” of economics, and considers that increased economic activity related to a particular product will lead to improvements in the health of a country’s population through increased in income. Feschet and her colleagues developed this approach by considering a single country and a starting GDP per capita for the base year, which later increases due to the economic activity, resulting into better health [Feschet et al., 2013]. The “Wilkinson pathway” approach by Bocoum, et al., (2015) is based on the fact that income inequality is harmful to health and reducing the income inequality within a population could improve health quality [Bocoum et al., 2015]. Instead of the above two indirect approach, i.e., changing income status will increase health status, this study assessed the health benefit from

avoiding toxic emission as well as health impacts from environmental emissions and occupational health losses throughout the production system. This study thus employs a type 2 impact category, since a social impact pathways model is applied to assess the impacts on the endpoint human capital using the DALY indicator.

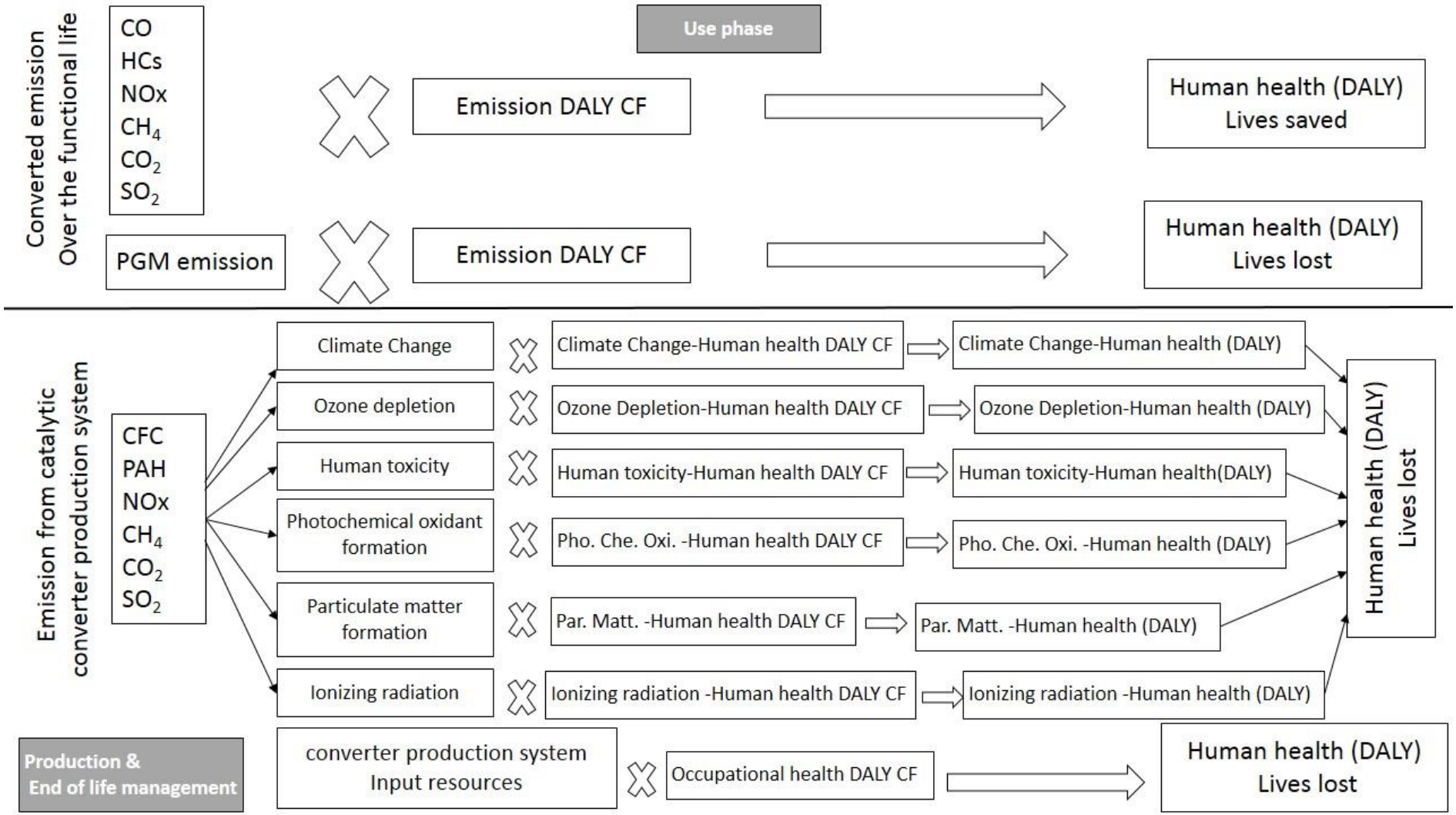


Figure 3.1: Methodological approach adopted for the catalytic converter SLCA case study.

3.3 Disability Adjusted Life Years (DALY)

DALY is an indicator developed in the 1990s to measure overall burden on human health, and expressed as the number of years lost due to illness, disability or premature death. By using equal weightings to the significance of one year of life lost for all ages (or no weighting) and without discounting, DALY is the sum of years of life lost (YLL) and years of life disabled (YLD) [Goedkoop et al., 2013; Grosse et al., 2009]. Mathematically DALY can be expressed as follows:

$DALY = YLL + YLD$ (Equation 3.1)
$YLD = W \times D$ (Equation 3.2)

Here, W=Severity factor ranging from 0 to 1, with 0 representing complete health and 1 representing death. D=Duration of the disease. In this study, lives lost during production are assessed from two sources. One is environmental emission from the product system, hereafter referred to as emission DALY, and the other one from occupational hazards, hereafter referred to as occupational DALY.

According to Dreyer et al., (2006), there are two approaches for SLCA, namely the top-down approach and the bottom-up approach. Under the former approach, the definition of assessment parameters start with the identification of social issues in the business context of the product manufacturer. In the latter approach, the assessment parameters start with the identification of what is valuable to society [Dreyer et al., 2006]. So according to Dreyer et al., (2006), through the use of the DALY indicator, this study is a bottom up approach and according to this UNEP/SETAC framework, this study thus employs a type 2 impact category.

3.4 ReCiPe 2008 impact assessment method

The ReCiPe (2008) impact assessment method is based on two approaches, one is the method proposed as the baseline method for characterization of midpoint impacts in the "Handbook on LCA" [Guinée, 2006] and another one is the method used in Eco-indicator 99 for endpoint assessment [Goedkoop and Spriensma, 2001]. This impact assessment method is named ReCiPe 2008, because like many other reports on LCIA, it provides a 'recipe' for calculating life cycle impact category indicators. The acronym also represents the initials of the institutes that were the main contributors to the project for the development of the method: RIVM and Radboud University, CML, and PRé [Goedkoop et al., 2013].

The ReCiPe (2008) impact assessment method comprises two sets of impact categories and associated sets of characterization factors. Eighteen impact categories exist at the midpoint level. At the endpoint level, the above-mentioned midpoint impact categories are further converted and

aggregated into the endpoint categories damage to human health [Goedkoop et al., 2013]. The midpoint and endpoint conversion model of ReCiPe (2008) is depicted in Figure 3.2.

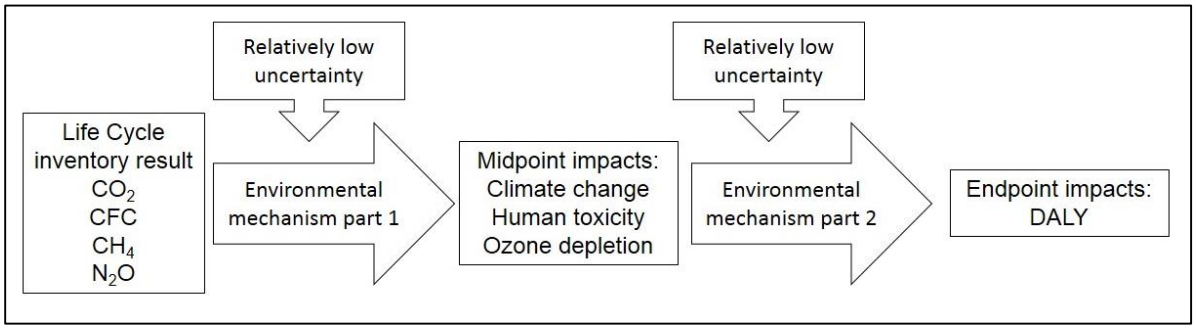


Figure 3.2: Example of a harmonized midpoint-endpoint model for climate change, human toxicity and ozone depletion linking to human health in ReCiPe (2008) impact assessment method [Source: Goedkoop et al., 2013].

To calculate the characterization factors for the midpoint categories, the adopted formula is presented in equation 3.3. In the equation 3.3, M_i is the magnitude of intervention *i*, for example, mass of CO_2 released to air. Q_{mi} is the characterization factor, which links intervention *i* with the midpoint impact category *M*, and I_m is the indicator result for the midpoint impact category *M*. To calculate the characterization factors for endpoint categories, ReCiPe (2008) used two sets of characterizations. One converts a midpoint indicator result into an endpoint indicator result, and another converts an intervention directly into an endpoint indicator result. Symbolically in equation 3.4, intervention *i* and midpoint indicator *m* are coupled with characterization factor Q_{mi}, and midpoint indicator *m* is coupled with endpoint indicator *e* with characterization factor Q_{em}. Their combined characterization factor Q_{ei} is determined in ReCiPe (2008) as shown in equation 3.5. The quantitative connection between midpoint and endpoint categories (the factors Q_{em}) for three value perspectives, known as individualist (I), hierarchist (H), and egalitarian (E), are presented in Table 3.1 [Goedkoop et al., 2013].

$$I_m = \sum Q_{mi} \times M_i \qquad \text{(Equation 3.3)}$$

$$Q_{ei} = \sum Q_{mi} \times Q_{em} \qquad \text{(Equation 3.4).}$$

In the ReCiPe (2008) impact assessment method, the underlying assumptions for the individualist (I) perspective is a short term interest (e.g. for climate change the time horizon is 20 years), impact types are certain, and for human adaptation there will be technological breakthroughs in the future. TheHierarchist (H) perspective is based on the common policy principles and an intermediate time-frame (e.g. 100 years' time horizon for climate change). Egalitarian (E) is the most precautionary

perspective, which assumes the longest time-frame (e.g. 500 years' time horizon for climate change), and impact types that are not yet fully certain [Goedkoop et al., 2013].

Table 3.1: quantitative connection between midpoint and endpoint categories (the factors Q_{em} in the equation 3.5) for three value perspectives [Source: Goedkoop et al., 2013]

Midpoint impact category	**Characterization factor name**	**Unit**	**Endpoint impact category conversion factor**
Climate change	Global warming potential	kg (CO_2 to air)	1.19×10^{-06} (I) [a] 1.40×10^{-06} (H) 3.51×10^{-06} (E)
Ozone depletion	Ozone depletion potential	kg (CFC-11 to air)	**
Human toxicity	Human toxicity potential	kg (1,4 DCB to urban air)	7.0×10^{-07} (I,H,E)
Photochemical oxidant formation	Photochemical oxidant formation potential	kg (NMVOC to urban air)	3.9×10^{-08}
Particulate matter formation	Particulate matter formation potential	kg (PM10 to air)	2.6×10^{-04}
Ionizing radiation	Ionizing radiation potential	kg (U235 to air)	1.64E-08

[a] to convert a midpoint indicator for example climate change (in kg) into an endpoint indicator for human health (in year), multiply by 1.19×10^{-06} year/kg.
** For different ozone depleting substance like CFC-11, CFC-12, CFC-113, etc., species specific endpoint characterization factors used.

To assess the human health benefit of the catalytic converter in the use phase, DALY CF of ReCiPe (2008) are used for avoided toxic emission, and the ReCiPe (2008) conversion model from environmental emissions directly into endpoint result is used. Production system environmental burdens are included in this study as midpoint impacts, and later these midpoint impacts are converted to public health burdens (endpoint impacts) using the ReCiPe (2008) impact assessment method. The included midpoint impact categories are: (i) climate change (kg CO_2 eq.), (ii) ozone depletion (kg CFC-11 eq.), (iii) human toxicity (kg 1,4-DB eq.), (iv) photochemical oxidant formation (kg NMVOC), (v) particulate matter formation (kg PM10 eq.), and (vi) ionizing radiation (kg U235 eq.). These results are not displayed as the single categories cannot be directly compared.In a second step, these midpoint categories are converted to endpoint impact categories: (i) human health - climate change, (ii) human health - ozone depletion, (iii) human health - human toxicity, (iv) human health - photochemical oxidant formation, (v) human health - particulate matter formation, and (vi) human health - ionizing radiation. All endpoint impacts are summed up as human health – total using the openLCA V. 1.4.1 software platform (GreenDelta, Berlin,

Germany). All categories have then a single comparable unit. To this, occupational DALY are added.

3.5 Occupational DALY

To assess the occupational health impacts, occupational DALY CF reported by Scanlon, et al., (2015) were used. Industry-specific occupational DALY CF were calculated by dividing industry-specific occupational DALY by the total physical output produced by that industry (equation 3.5). These occupational DALY CF are for work environments in the USA, with strict regulations for occupational health and safety in place. Scanlon and colleagues (2015) estimated the occupational DALY for a specific industry from morbidity and premature mortality based on some factors, such as (1) industry-specific number of fatal and nonfatal injuries and illnesses, (2) the age at which the of fatal and nonfatal injuries and illnesses occur, (3) the time duration of injury or illness that affected the worker, and (4) the severity of the injury or illness. Some major occupational injuries and illnesses considered include, but are not limited to, bruises, wounds, traumatic injuries, and systemic diseases. This occupational DALY CF is considered to be the same for products produced in Europe, but occupational DALY CF were doubled for the resources mined from South Africa, Russia and China. Some of the physical outputs are in the form of mass (kg), others are in the form of length (m), area (m^2), volume (l), energy (MJ), and transportation (tkm), depending on the nature of the product. Thus, the occupational DALY CF unit is DALY/kg, DALY/MJ, DALY/tkm, etc. Table A.3.1 in the appendix A.3 shows the occupational DALY CF considered in this study [Scanlon, et al., 2015].

$$\text{Industry specific occupational DALYs CF} = \frac{\text{Industry specific occupational DALY}}{\text{Industry specific Physical output}} \quad \text{(Equation 3.5)}$$

CHAPTER 4

Goal and scope definition

4.1 Goal and intended application

This SLCA case study was conducted with the aim to assess the social impacts in terms of lives lost and lives saved by a catalytic converter using the DALY indicator. This catalytic converter SLCA case study can play a vital role for identifying social hotspots of a generic catalytic converter production system. It can also be used for testing the applicability of the DALY indicator within the UNEP/SETAC framework of SLCA for complex product systems involving a number of countries and manufacturing processes. The SLCA case study is about a generic three way ceramic honeycomb catalytic converter and not related to a specific model or company that produces three way ceramic honeycomb catalytic converters. Consequently, the result should not be associated with any specific company.

4.2 Functional unit

The ceramic monolithic three-way catalytic converter is one of the most widely used catalytic converters., The service lifetime varies from 100,000 to 160,000 km [Amatayakul & Ramnäs, 2001]. In Europe, the average service life time of a catalytic converter for petrol vehicles is 160,000 km, and for diesel vehicles it is 200,000 km [Saurat & Bringezu, 2008]. In this study, the functional unit is one ceramic honeycomb three-way catalytic converter with a 160,000 km life time. However, a sensitivity analysis for service lifetimes of 100,000 and 200,000 km has also been performed.

4.3 Physical structure of a catalytic converter

A typical three way ceramic monolith honeycomb catalytic converter consists of inlet and outlet pipes, steel housing and heat shield, insulation material or mat, ceramic honeycomb substrate, wash coating on ceramic honeycomb substrate, along with catalyst and oxygen sensor and electronic fuel management system [Amatayakul & Ramnäs, 2001; Heck et al., 2009]. A stainless steel housing provides protection and structural support for the ceramic honeycomb substrate. The stainless steel is covered with a heat shield made of aluminium compound. Inside the stainless steel housing, an insulation material known as mat or wire mesh provides heat insulation and also acts as a support between the stainless steel housing and ceramic honeycomb substrate. There also exist seals to protect the mat material from being burned by the high temperature exhaust gas. The ceramic honeycomb monolith substrate is a supporting material for the catalyst consisting of numerous parallel open channels, with a density of approximately 690 thousand cells per m^2. The ceramic honeycomb monolith substrate is coated with a washcoat (mixture of silica and alumina) to increase the amount of surface area available to support the catalyst. When silica and alumina mix washcoat is added to the ceramic honeycomb substrate, it forms a rough, irregular surface with much larger surface area than the flat surfaces. The large surface area provides more sites for catalyst to react with NO_x, CO and unburned HCs. When the washcoat is in suspension, the catalyst is added to the washcoat and then this mixture is added to the ceramic honeycomb substrate.

Widely used catalyst are platinum (Pt), palladium (Pd) and rhodium (Rh) [Heck et al., 2009a; Heck et al., 2009b; Taylor, 1984].

4.4 Catalytic converter production system

To develop the product system of the catalytic converter, an in-depth review of the existing literature regarding the supply chain of the catalytic converter has been performed to identify the raw materials used in different phases to produce a typical catalytic converter. In parallel, the countries involved in different phases are also identified. The supply chain of the catalytic converter may include hundreds of different suppliers for different parts with varying degrees of integration. To avoid this complexity, a simplified product system has been developed for this study. More detailed country-specific involvement for different production stage of catalytic converter is presented in the geographical boundary section. Figure 4.1 shows the typical catalytic converter value chain system for the whole production processes starting from the platinum group metals (PGM) mining to recycling. Figure 4.2 shows the simplified baseline product system developed for this study.

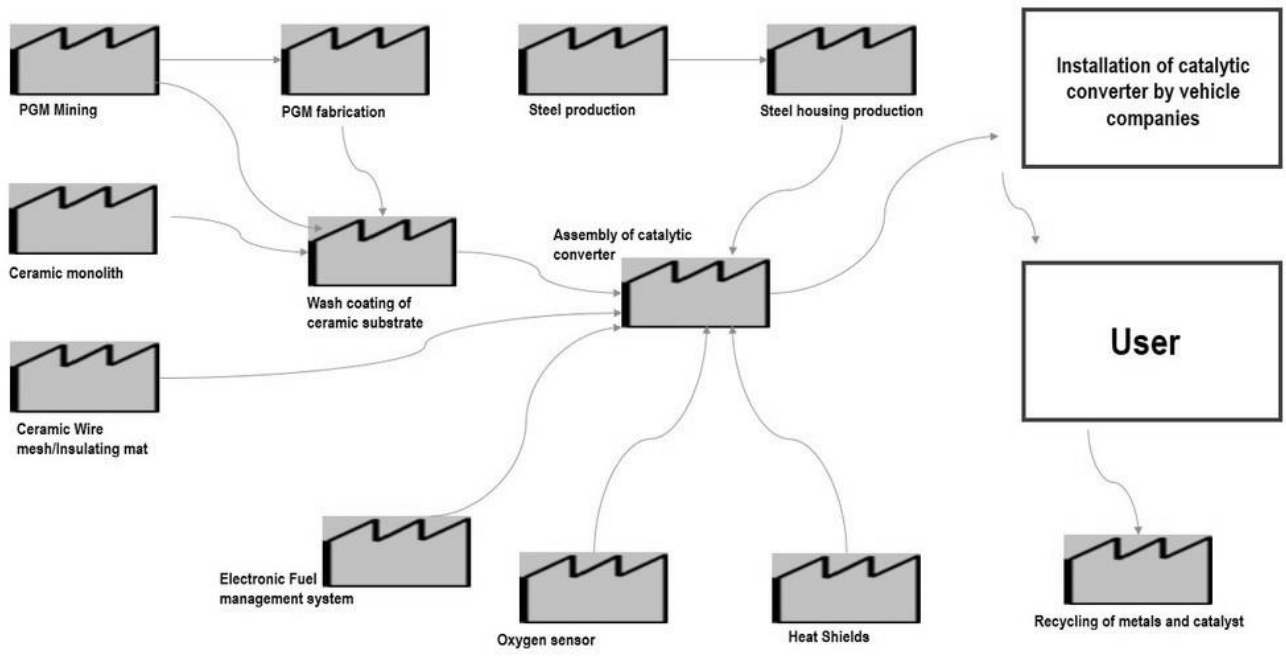


Figure 4.1: Value chain system of a typical three way catalytic converter [developed from Dewar, 2012].

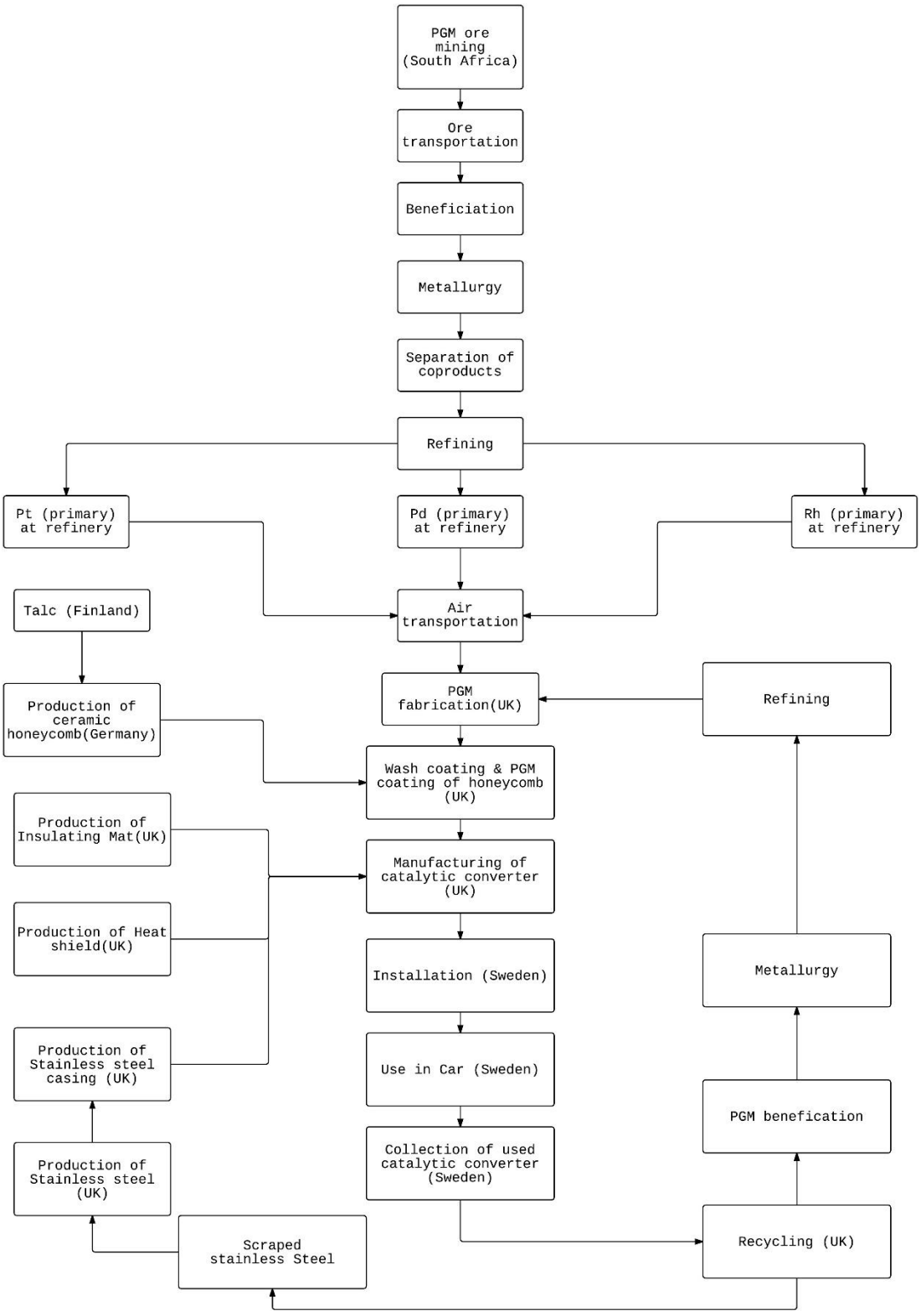


Figure 4.2: Baseline product system developed for the study.

4.4.1 PGM supply

Most of the PGMs (Pt, Rh and Pd) are sourced from either South Africa or Russia. South Africa and Russia have the largest reserves of PGMs (Table 4.1) [Steinweg, 2008]. During 2010, South Africa supplied 76% Pt, 35% Pd and 86% Rh of the global demand and Russia supplied 14% Pt, 37% Pd, and 9% Rh of the global demand [POLINARES, 2012].

Three major mining companies in South Africa are Anglo Platinum, Impala Platinum and Lonmin Platinum. In 2006, the Anglo Platinum company produced around 88 thousand kg of platinum, and 48 thousand kg of palladium; Impala Platinum produced approximately 36 thousand kg and 17 thousand kg of platinum and palladium, respectively; and Lonmin Platinum produced 31 thousand kg of platinum and 14 thousand kg of palladium. In Russia, Norilsk Nickel is the major PGM producer and accounts for more than 96% of Russia's PGM production. Another company, Krastvetmet Metal, also owns and operates a large precious metals refinery. The largest PGM fabrication company, Johnson Matthey, also has a plan to build a factory for catalytic converter on the site of Krastvetmet in the province of Krasnoyarsk, Russia. The North American companies for PGM mining are Stillwater Mining Company, USA (in this company, Norilsk Nickel has a majority share), Inco (Canada) and the North American Palladium Company (Canada) [RdM, 2005; Steinweg, 2008]. This study did not consider the North American companies in the production chain of the catalytic converter.

Table 4.1: World PGM reserves and reserve base [Source: Koek et al., 2010]

Country	Reserves (kg)	% of world total	Reserve base (kg)	% of world total
South Africa	63,000,000	89	70,000,000	88
Russia	6,200,000	8.7	6,600,000	8
United States	900,000	0.1	2,000,000	2
Canada	310,000	0.4	390,000	1
Other countries	800,000	1.1	850,000	1
World total	71,000,000		80,000,000	

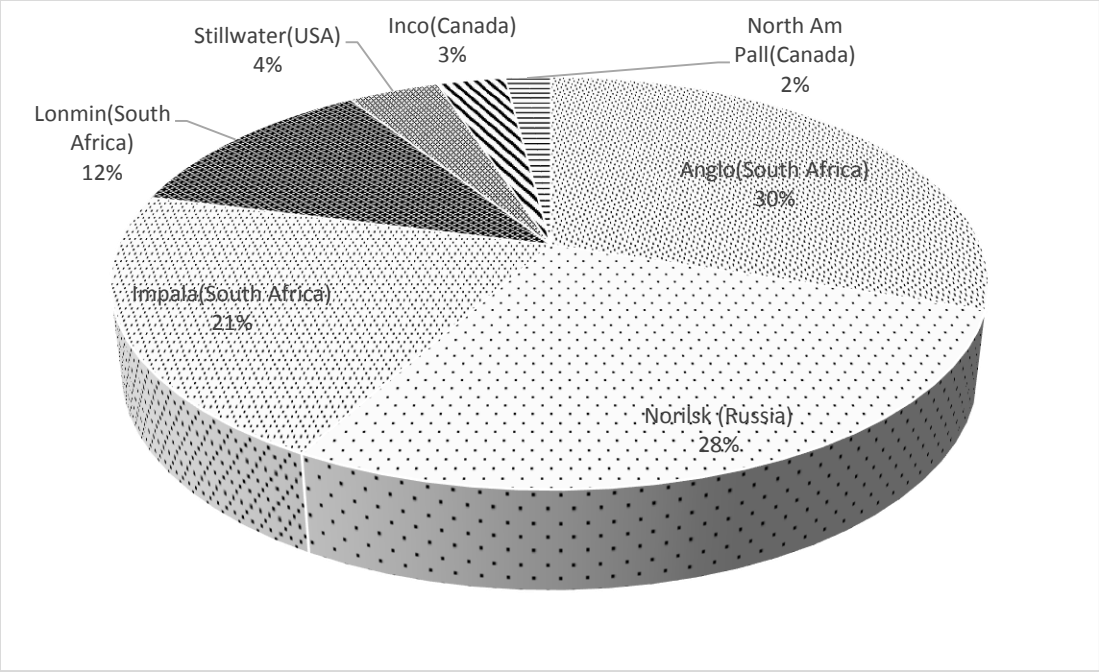


Figure 4.3: Relative market shares of PGM producing companies [Source: RdM, 2005].

4.4.2 Assembly of catalytic converter and catalytic converter components producing industry

After the PGMs are extracted and refined, they need to be processed. Catalysts are fabricated by the PGM fabricating and processing companies. These companies source the PGMs from the mining companies and also use recycled PGMs from recycled catalytic converters. The major PGM fabricating and processing companies are W.C. Heraeus GmbH, BASF Catalysts in Germany, Johnson Matthey Plc. in UK, and Umicore SA in Belgium. In addition to the PGM fabricating and processing companies for catalysts, a number of companies are involved as producer of assembled catalytic converters or different component of the catalytic converter. The manufacturing phase is the most complex phase of the catalytic converter production system, because many companies are involved in this phase. The major companies involved in either catalytic converter assembly or component manufacturing are Bosal International N.V., Friedrich Boysen GmbH & Co KG, Calsonic Kansei, Eberspacher, Emitec, Benteler AG, Faurecia, Futaba, Gustav Wahler, Katcon Global, KSPG, Magneti Marelli, Tenneco Inc, Wescast Industries Inc, Delphi Automotive LLP, and Emitec, Valeo SA (Research and Markets, 2014; Steinweg, 2008). After the catalytic converter assembly, it is transported to different automobile companies for installation into the vehicles.

4.4.3 Use phase

The catalytic converter production system of this study considers installation of the catalytic converter into a car, and the use phase is assumed take place in Sweden.

4.4.4 Recycling phase of Catalytic converter

Another important source of PGMs is from recycling of used catalytic converter. Approximately 27 thousand kg of platinum and 44 thousand kg of palladium was recovered in 2006. This accounts for 11% and 17% of total world supply, respectively. In most of the cases, the recycling operation is performed by the same PGM fabricating and processing companies that source their raw materials from PGM mining companies [Hagelüken, 2012; Steinweg, 2008].

4.5 System boundary

4.5.1 Technical boundaries

The raw materials for different catalytic converter production stages such as washcoat, ceramic honeycomb, insulating mat, steel casing and heat shield, are included in the system boundaries. The mining and production of PGMs and recycling of PGMs are included. Electricity and other fuels needed during the manufacturing are also included. Figure 4.4 shows the scope and system boundary of this SLCA case study.

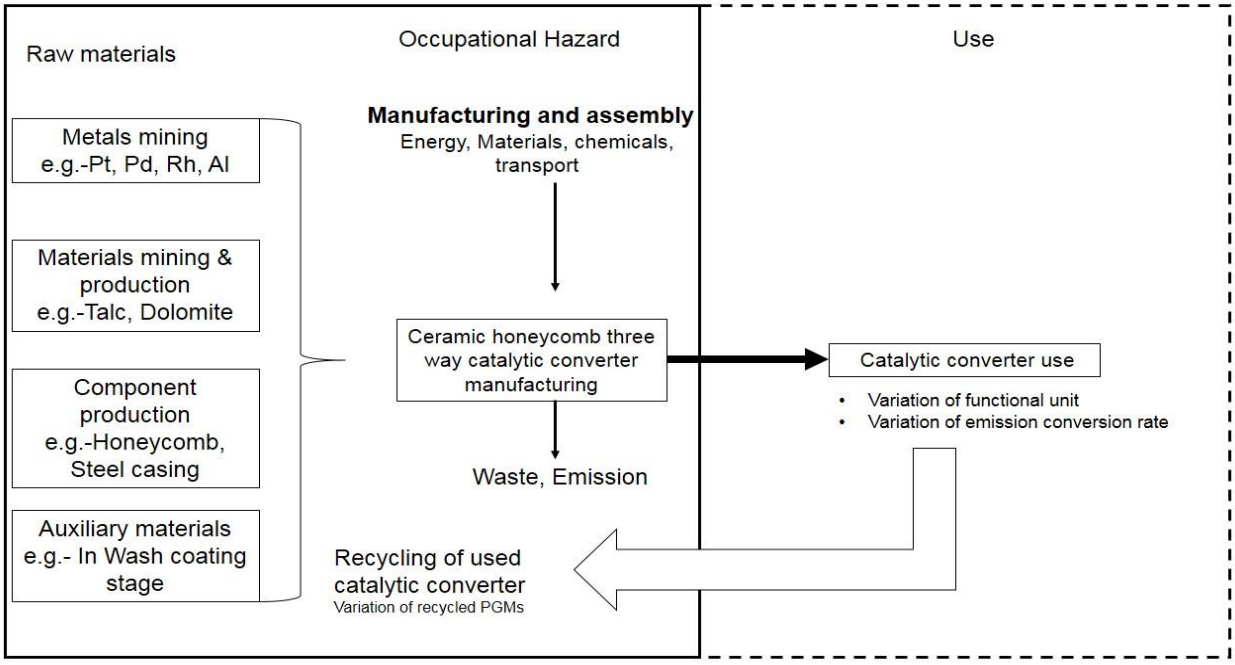


Figure 4.4: Scope and system boundary of the study. The solid line represents the boundary considered for production impact and the dotted line represents the boundary considered for use phase benefit assessment.

4.5.2 Geographical boundaries

For the baseline production system, it is assumed that the catalytic converter is manufactured in the UK using PGMs mined in South Africa. The ceramic honey comb is produced in Germany with talc imported from Finland. Wash coating and PGM coating is performed in the UK. Steel and aluminum is produced

in the UK for the baseline production system. The catalytic converter is installed and used in Sweden. Spent catalytic converters are collected in Sweden, then PGMs are recovered and refined by the PGM fabricating company in the UK for the baseline production system. Variation of geographical location is also performed for different scenarios presented in Table 4.3. Table 4.2 shows the key market actors and their manufacturing locations for catalytic converter production, and Table 4.3 shows the variation of geographical location for different production scenarios in this study.

Table 4.2: Key market actors and their manufacturing locations.

Key market players	Industrial operations locations
PGM mining	
Anglo Platinum	South Africa
Impala Platinum	
Lonmin Platinum	
Norilsk Nickel	Russia
Automotive catalysts fabrication and refining	
BASF Catalysts	Manufacturing and production in USA, Germany, China, South Africa, Japan, and India. Refining facility in UK. Recycling facility in UK and USA.
Johnson Matthey	Manufacturing and technology sites in USA, Argentina, Germany, UK, Sweden, South Africa, Russia, India, China, Japan, Korea and Macedonia. Recycling facility in UK and USA.
Umicore	Production and testing center in USA, Canada, Brazil, South Africa, France, Germany, Sweden, Japan, China, and Korea. Refining and recycling facility in Belgium.
Heraeus GmbH	Manufacturing and production in USA, Germany, China, and India. Refining and recycling facility in Germany, USA, Hong Kong, and South Africa
Catalytic converter	
Faurecia S.A, France (Market leader in Catalytic converter industry. It operates through four business segments- Automotive Seating, Emissions Control Technologies, Interior Systems, and Automotive Exteriors.)	In Europe, it has 27 Automotive Emission Control technologies production plant and located in Germany (7), France (5), Spain (5), Czech Republic (2), Slovakia (2), and 1 in each of Italy, UK, Portugal, Netherlands, Hungary, and Romania. It has production plant in Russia (2), Turkey (1). Within the South American and North American regions, 7 production plants in Brazil, 11 in USA, 3 in Maxico, 1 in Canada. In the African region, 2 production plants in South Africa. In Asia, it has 22 production plants located in China (13), India (3), South Korea (4), and Thailand (2).
Tenneco, Inc., USA	In North and South America, it has 13 emission control technologies manufacturing plants located in USA, Canada, Mexico and Brazil. In Europe, it has 20 manufacturing plants located in Belgium, Poland, Czech Republic, Germany, UK, France, Spain and Portugal. In Asia, it has 13 manufacturing plants located in India, China, Singapore and Japan. In South Africa, it has 1 manufacturing plant.
Benteler International AG,Germany.	Benteler Automotive segment has 42 production plants operated in Germany, Belgium, Czech Republic, France, UK, Italy, Spain, USA, Mexico, Canada, China, Japan, and South Africa.
Magneti Marelli S.P.A, Italy.	Its production plants, development centers and application centers for exhaust gas after-treatment are located in Italy, Spain, Poland, Serbia, Argentina, U.S., South Africa, China, India, Turkey.
Eberspaecher Holding GMBH & CO. KG, Germany	Its exhaust technology production plants are located in Germany, France, UK, France, Italy, Sweden, Czech Republic, USA, Brazil, Russia, South Africa, China, Japan and Korea.

Table 4.3: Geographical locations for catalytic converter input materials and production stages (bold ones are tested in different scenarios).

Input materials for catalytic converter components	**Baseline scenario- Geographical boundary**	**Other countries of production**
Catalytic converter manufacturing	UK	**Germany** France Belgium Spain Czech Republic Slovakia Italy Portugal
PGMs	South Africa	**Russia**
Wash coating and Auto catalyst coating	UK	**Germany** Belgium
Ceramic Honeycomb substrate	Germany	Austria France Netherlands UK
Talc for honeycomb	Finland	France Italy Austria
Steel for converter housing	UK	**Germany** Italy France Spain Belgium Sweden Netherlands Finland
Aluminium for heat shield	UK	**Norway** **Germany** France Netherlands Belgium
Insulating mat for catalytic converter	UK	**Germany** Belgium China
Recycling of used catalytic converter	UK	**Germany** Belgium

4.5.3 Temporal boundary

In this study, currently existing catalytic converters manufactured for a Swedish car are considered. For the unit process of the catalytic converter manufacturing, PGMs extraction and refining and recycling data are used from the Ecoinvent version 2.2 database, released in 2010.

4.6 Assumptions

Some important assumptions of this study are listed here:

1) In this study, packaging of all types (e.g. plastic, paper and cardboard) of the intermediate component and final catalytic converter product are not considered. It is thus assumed that impacts from packaging materials are negligible.

2) Basic components of the catalytic converter, such as ceramic monolith, wash coat and catalyst coating, insulating mat and steel housing are manufactured by different manufacturers and shipped to the final catalytic converter manufacturer. Wash coating and catalyst coating are assumed to take place in the same industrial facility. From the catalytic converter manufacturer, the final product is shipped to Sweden for installation in the car, and the car is used in Sweden.

3) The catalytic converter is assumed to not become broken or malfunction over its useful lifetime.

4) The European mix of primary and secondary PGMs is assumed here according to the Ecoinvent data base V 2.2. Thus the recycled content is 5% for platinum, 3% for palladium and 15% for rhodium [Classen et al., 2009]. This recycling rate combination of PGMs is hereafter referred to as low recycling rate. According to Graedel, et al., (2011), the current recycling rate in the vehicles sector for platinum and palladium is 50-55% and for rhodium is 45-50%. Therefore, in this study, a sensitivity analysis based on 50% recycling rate for the PGMs is conducted.

5) Because of unavailability of reliable data for talc production, ceramic monolith production, wash coating and PGMs coating, insulating mat production, steel converter casing production, and heat shield production, industrial equipment and other resources needed as inputs were estimated based on similar processes in the Ecoinvent database version 2.2 as described in Appendix A.5.

6) For the road transportation of different input materials, the distance is assumed between port and the industrial region of a particular country producing that input materials for the whole mass. Detailed description of different transport processes in this study are presented in Appendix A.4.

7) For the final assembly of the components of the catalytic converter and installation of the catalytic converter in a car, only electricity consumption is considered as described in Appendix A.5.

4.7 Allocation

For primary PGMs and recycled PGMs, economic allocation is used based on the Ecoinvent 2.2 database.

4.8 Sensitivity analysis

Sensitivity analysis is performed by varying the following parameters:

1) Emission conversion rate: Amatayakul (1999) and Hochfeld and Jenseit (2000) reported similar emission conversion rates of catalytic converters, except for CO and HCs. A sensitivity analysis is performed based on this variation in emission rates of CO and HCs.
2) Functional lifetime: A sensitivity analysis is performed, varying the functional lifetime from 160,000 km, to 100,000 km and to 200,000 km.
3) Recycling rate: A sensitivity analysis testing the variation from a low recycling rate (5% for Pt, 3% for Pl and 15% for Rh) to a high recycling rate (50% for Pt, Pl, and Rh) is performed.
4) Sensitivity analysis based on the three impact assessment value perspective, theindividualist (I), hierarchist (H), and egalitarian (E) perspectives, is performed.
5) Sensitivity analysis based on the geographical location of different production processes is performed.

CHAPTER 5

Inventory analysis

5.1 Material composition

Different designs and materials are used for catalytic converters, but 85% of the catalytic converter manufactured globally are three way ceramic monolith type catalytic converters [Twigg, 2011]. A number of critical specifics are trade secrets to protect the unique nature of the supplier's own products, and are therefore not publicly disclosed. Different catalytic converter value chain actors held a number of patents for various components, but it is uncertain whether the disclosed or declared process description is actually practiced [Heck et al., 2009]. It is common in today's business world to maintain a unique advantage of one's own product over the competitors' products. So the process system described here for the different components of the catalytic converter production is more general and commonly used procedures, rather than specific procedures for a specific model of catalytic converter. Table 5.1 shows a general material composition of the typical catalytic converter considered in this study.

Table 5.1: Material composition and weight of a typical three way ceramic monolith catalytic converter [Source: Addiego & Melscoet-Chauvel, 2007; Amatayakul, 1999; Amatayakul & Ramnäs, 2001; Bedford & Tsang, 1994; Landon et al., 1990; Merry & Coates Jr., 1989].

Catalytic converter component	**Material composition**	**Weight (kg)**
Ceramic Honeycomb Substrate/Catalyst support	Cordierite ($MgO \cdot Al_2O_3 \cdot SiO_2$)	1.4
Insulating surrounding mat	Alumina-silica fibers, Vermiculite and Acrylic binder	0.16
Wash coats	Alumina (Al_2O_3), Cerium Oxides (CeO_2), Zirconium Oxide (ZrO_2) and Acetic acid ($C_2H_4O_2$)	0.28
PGM catalyst	Pt, Pd and Rh	0.006
Catalytic converter housing	18/8 stainless steel (stainless steel type 304)	5
Heat Shield	Aluminized steel	0.5
	Total Weight	7.3

5.2 Mining of PGM

PGMs are mined in South Africa and Russia and transported to Europe. PGMs mined in South Africa and Russia are considered to be primary PGMs. After mining, subsequent steps are beneficiation, metallurgy, separation of co-products, and refining. The co-products are copper and nickel. The Ecoinvent version 2.2 process data and system models for PGM mining are used in this study [Classen et al., 2009]. Economic allocation is used for both primary and secondary PGM production.

5.3 Ceramic honeycomb substrate production

Monolithic supports for the catalyst in a three way catalytic converter are often a thin-walled ceramic honeycomb-like structure composed mostly of synthetic cordierite ($2MgO{\cdot}2Al_2O_3{\cdot}5SiO_2$). Characteristics such as low thermal expansion, small size, fast heat-up, low back pressure, low vibration attrition, and design flexibility of ceramics makes them suitable for this purpose. Use of cordierite has a number of advantage, such as thermal shock resistance, ease of washcoat application, good washcoat adherence because of suitable porosity and pore size distribution, as well as non-reactive with washcoat and catalysts. The raw materials are kaolin [Al_2 (Si_2O_5) $(OH)_4$], talc [$Mg_3(Si_2O_5)_2(OH)_2$], alumina [Al_2O_3], aluminum hydroxide [$Al(OH)_3$], and silica [SiO_2]. These are blended into a paste, extruded and finally calcinated. The key manufacturing process are [Addiego & Melscoet-Chauvel, 2007; Heck et al., 2009; Taylor, 1984; Twigg, 2011; Williams, 2001] :

1. **Raw material processing:** The raw materials mentioned above are delivered to the manufacturing site by trucks, then weighed and checked for quality. Raw materials are mixed into a batch with water and conveyed to extrusion.
2. **Forming and drying:** The cell geometry of the honeycomb is formed by extrusion of the batch raw material and then dried.
3. **Cutting and firing:** Dried honeycomb pieces are cut to size and cleaned and then loaded in a kiln for firing at around 1000-1200^{o}C.
4. **Finishing and shipping:** The honeycomb substrates are finally packed and shipped to catalytic converter assembly site

Data on input and output amounts for the ceramic honeycomb is missing and have to be estimated. The calculation of input and output materials for the ceramic honeycomb substrate production processes is presented in Appendix 1. In addition to this calculation, for this ceramic honeycombs substrate production processes, inputs such as energy, and water, and emission output are obtain from relevant ceramic production processes in the Ecoinvent database version 2.2. For process electricity input and associated environmental burden, country-respective electricity mixes are considered in this study. The input and output masses become slightly different during the whole calculation because of

rounding (Appendix 1). The values are rounded off, so that input and output mass becomes equal, and presented in Table 5.2.

Table 5.2: The material input and output masses for a ceramic honeycomb substrate of 1 kg.

	Materials	**Mass (g)**
Input	Kaolin [$Al_2(Si_2O_5)(OH)_4$]	245
	Talc [$Mg_3(Si_2O_5)_2(OH)_2$]	445
	Alumina [Al_2O_3]	125
	Aluminum hydroxide [$Al(OH)_3$]	200
	Silica [SiO_2]	110
Output	Cordierite [$MgO \cdot Al_2O_3 \cdot SiO_2$]	1000
	Water [H_20]	125

5.4 Wash coating and PGM coating

The chemical composition and input ratio of different catalysts is the key technical know-how of the catalyst manufacturer and thus precise process descriptions are not disclosed. However, the wash coat mainly consists of alumina (Al_2O_3), cerium dioxide (CeO_2), zirconium dioxide (ZrO_2) and PGM catalysts (Pt, Pd and Rh). The usual composition is 10% Al_2O_3, 20% CeO_2, and 70% ZrO_2 [Amatayakul, 1999]. Some other minor oxides like calcium oxide (CaO), lanthanum oxide (La_2O_3) and magnesium oxides (MgO) are also used during the wash coat preparation, but for this study these minor inputs are not considered. At first, the washcoat is applied to the bare ceramic monolith and then PGM catalysts are applied. A liquid slurry is prepared containing Al_2O_3, CeO_2, ZrO_2, acetic acid ($C_2H_4O_2$) and water. Then the slurry is milled at room temperature for three hours resulting into particle size in the range of about 0.5-1 µm. The bare ceramic honeycomb monolith is dipped into the impregnating solutions. After the excess slurry is removed, the coated monolith is dried at 120°C for eight hours and calcinated at 427°C for one hour. Following the formation of the calcinated washcoat layer, it is then dipped into the mixture of Pt, Pd and Rh in a similar way as for the washcoat process. The PGM-coated honeycomb is then air-dried and calcinated at around 400-500ºC to ensure good adhesion. The final wash coat mass excluding the PGM catalyst in catalytic converter is 275 g [Bedford and Tsang, 1994; Heck et al., 2009).

The mass of the PGM catalysts Pt, Pd and Rh per catalytic converter varies with car size, engine type and country-specific emission standards. Considering three big car producing regions of the world, the average mass of PGM catalysts in catalytic converter is approximately 4 g in North America, 6 g in Europe because 55% of the cars produced are diesel driven, and 2 g in China, because of less restrict emission standards and smaller car sizes. In North America, 4 g PGM catalyst consist of approximately

3 g Pd, 0.5 g Pt and 0.5 g Rh. In Europe, 6 g PGM catalyst consist of approximately 2.75 g Pt, 2.75 g Pd and 0.5 g Rh. In China, 2 g PGM catalysts is mostly Pd [Still Water, 2012]. In this study, the input of PGM catalysts is considered to be equal to the European average. The materials input for wash coating and PGM coating are presented in Table 5.3.

Table 5.3: Material inputsconsidered in this study for wash coating and PGM coating for one catalytic converter [Source: Bedford & Tsang, 1994; STILL WATER, 2012] .

	Materials	**Mass (g)**
Wash coating	Alumina (Al_2O_3)	25
	Cerium Oxides (CeO_2)	55
	Zirconium Oxide (ZrO_2)	125
	Acetic acid ($C_2H_4O_2$)	10
	Water	60
PGM Coating	Platinum (Pt)	2.75
	Palladium (Pd)	2.75
	Rhodium (Rh)	0.5

5.5 Insulating mat production

The insulating mat used in catalytic converters is basically an intumescent (swelling up when heated) rectangular sheet having a slot on one end and a complementarily configured tab on the other end. This mat is wrapped around the outer surface of the ceramic honeycomb monolith with tab and slot engaged [Merry & Coates Jr., 1989]. Intumescent mats are the most common type of insulating surrounding mat used in catalytic converters. This type of mats are made of alumina-silica ceramic fibers and vermiculite to provide the advantage of thermal expansion. Typical compositions of these types of mats are 30-50% of alumina-silica fibers, 40-60% of vermiculite and 4-9% of binder, such as acrylic binder [Ecopoint, 2004]. The alumina-silica fibers are basically a mixture of about equal parts by weight of Al_2O_3 and SiO_2 [Langer, 1993]. Again, specific process descriptions of the manufacturing of insulating mats are not disclosed by manufacturers. However, this type of insulating mat is manufactured into suitable thickness following basic papermaking processes [Merry & Coates Jr., 1989]. So for this process, energy, water and other resources inputs is estimated from paper making process data available in the Ecoinvent database version 2.2. Key materials inputs considered in this study for 1 kg mass of insulating mat are presented in Table 5.4.

Table 5.4: Materials inputs considered in this study for insulating surrounding mat production.

Materials		Mass (g)
Alumina-silica fibers	Alumina (Al_2O_3)	250
	Silica (SiO_2)	250
Vermiculite		410
Acrylic binder		90

5.6 Catalytic converter housing and heat shield production

For catalytic converter housing, the steel used should have good oxidation resistance and low thermal expansion capability as well as high yield strength. Thus, the most common material used is the ferritic stainless steel type 409. However, for the converter housing, in which case there is a possibility of high temperature like 600°C, the classic 18/8 stainless steel, popularly known as stainless steel type 304, is also used [Belcastro, 2012; Ecopoint, 2004]. Process data for stainless steel type 409 is not available in the Ecoinvent database version 2.2, but there is process data for 18/8 stainless steel. Consequently, in this study, a catalytic converter housing made from 18/8 stainless steel is considered, with 5 kg mass input per catalytic converter (Table 5.1). Aluminized steel sheets are usually used as catalytic converter heat shields and the material used is an aluminium alloy. The estimated weight of aluminized heat shield per catalytic converter is 0.5 kg (Table 5.1), which is composed of 90% of aluminum and10% of silicon [EAA, 2011]

5.7 Assembly and installation of catalytic converter

Input resources needed for the assembly of different components of the catalytic converter and installation into the car is assumed from unit process data of light weight concept passenger car of 550 kg in the Ecoinvent database version 2.2.

5.8 Use of catalytic converter

During the use phase, the catalytic converter both reduces toxic emission such as CO, NO_x, and HCs, and also increases emission like CO_2. When the engine first starts, the catalytic converter does not work optimally to convert the emission, meaning that some emissions occur. When the temperature reaches the light-off temperature, it starts to work efficiently to convert the toxic emission. Due to this conversion delay, most of the toxic emissions are emitted during the first few minutes of engine start. The monolith in the catalytic converter causes some pressure drop or back pressure, resulting increased consumption of fuel. The weight of the catalytic converter also causes increased fuel consumption, resulting in a slightly increased exhaust gas emissions. Due to mechanical abrasion of the materials in the catalytic converter, a small amount of platinum group elements (PGE) are also emitted

[Amatayakul, 1999; Taylor, 1984]. This PGE emission varies with the type of the engine, age (km driven) of the catalytic converter, speed of the automobile, type of catalyst, and the type of fuel additives [Ravindra et al., 2004]. The emission rates for CO, NO_x, HCs, CH_4, CO_2 and SO_2 considered in this study are presented in Table 5.5 and for PGEs in Table 5.6. Amatayakul (1999) and Hochfeld & Jenseit (2000) reported almost the same emission rates for NO_x, CH_4, CO_2 and SO_2, but slightly different for CO and HCs. These variation for CO and HCs emission rate is used for sensitivity analysis in this study.

Table 5.5: Exhaust emission rate for CO, NOx, HCs, CH_4, CO_2 and SO_2 considered in this study [Source: Amatayakul, 1999; Hochfeld & Jenseit, 2000].

Emissions	**Car without catalytic converter (g/km)**	**Car with catalytic converter (g/km)**	**Amount reduced or increased (g/km)**	**Percentage (%) increase or decrease with catalyst**
CO	10[a]	0.5	-9.5	-95
	14.93[b]	3.54	-11.39	-76.3
HCs	0.9[a]	0.045	-0.855	-95
	3.09[b]	0.33	-2.76	-89.3
NO_x	2	0.2	-1.8	-90
CH_4	0.11	0.03	-0.08	-73
CO_2	200	208.53	+8.53	+4.3
SO_2	0.01	0.01005	+0.00005	+0.5

Note: [a] Amatayakul, 1999 and [b] Hochfeld & Jenseit, 2000. A sensitivity analysis is performed based on these variation of emission rate of CO and HCs. Emission decrease indicate by – and increase indicated by +.

Table 5.6: Exhaust Emission rate for PGEs as particulate considered in this study [Source: Ravindra et al., 2004]

Age of the catalytic converter	**Pt (ng/km)**		**Pd (ng/km)**		**Rh (ng/km)**	
	Range	**Mean**	**Range**	**Mean**	**Range**	**Mean**
0-30000 km	17.8-181.8	100	0-636	318	0-151.3	75
>30000 km	3.4-7.8	7.3	1.8-8.8	5.3	0.9-2.5	1.7

Note: In this study, mean values of the emission rates for PGE are used.

5.9 Recycling

Recycling of the catalytic converter yield secondary PGMs after refining. Used catalytic converters are transported to refining centers in Europe. The locations considered here are the UK and Germany.

Each refining center performs the same processes to get secondary PGMs and the process steps are collection, beneficiation-dismantle and decanning, metallurgy, and refining. The recycling rate is 5% for platinum, 3% for palladium and 15% for rhodium for the low recycling rate scenario. For the high recycling rate scenario, it is 50% for platinum, palladium, and rhodium. In this study, the Ecoinvent database version 2.2 process data and system models for recycling of used catalytic converter are used. Similar to Ecoinvent database version 2.2, for each refining center in Europe, 600 km transportation distance by lorry for collection and shipped to the refining center is assumed in this study [Classen et al., 2009].

5.10 Occupational DALY

Occupational DALY are obtained from the study by Scanlon et al., (2015). They calculated work environment DALY CF based on industry-specific occupational fatal and nonfatal injuries and illnesses occurring in the US (equation 3.5). In this study, it is assumed that similar workplace hazards and exposures are present in the European catalytic converter industry. But for mining resources from South Africa, Russia and other locations outside Europe, doubling of work environment DALY CF is done in this study.

5.11 Inventory of the catalytic converter production system

Input materials needed and associated environmental emissions from the catalytic converter baseline production system are presented in Appendix A.6 and A.7. The energy inputs for the baseline production system under both low recycling rate and high recycling rate are presented in Appendix A.8.

CHAPTER 6

Impact assessment

6.1 Life cycle impacts and benefits

Inventory results of the baseline production system and different production system scenarios of the catalytic converter were used to assess life cycle impacts and benefits. The results of direct benefit from the use of the catalytic converter in the form of lives saves during the use phase (hereafter referred to as use phase benefit) and the impacts of the production system of the catalytic converter in the form of lives lost (here after referred to as production impacts and consists of emission DALY and occupational DALY) were compared for the baseline scenario as well as for the other production scenarios. The contribution of the life cycle stages and different input materials were also analyzed. Based on the RiCiPe (2008) impact assessment method, emission DALY hotspots were also identified.

6.2 Use phase benefits

Table 6.1 shows the use phase benefit of the catalytic converter in the form of years saved during the use phase measured as DALY. For the 160,000 km functional unit, in the case of the low toxic emission conversion scenario, the use phase benefit is 1.22×10^{-2}, 1.52×10^{-2}, and 1.61×10^{-2} years for the egalitarian, hierarchist and individualist perspectives, respectively. This means that lives saved during the use phase for the 160,000 km functional unit is 4.5 days, 5.5 days and approximately 6 days for the egalitarian, hierarchist and individualist perspectives, respectively. Sensitivity analysis for the case of high toxic emission conversion rate for the same functional life resulted in 4.6 days, 5.6 days, and 6 days for the egalitarian, hierarchist and individualist perspectives, respectively (Table 6.1).

To assess the impact of the catalytic converter utilization on the use phase benefits, a sensitivity analysis was performed varying the functional unit between 100,000 km and 200,000 km. The results of the life span sensitivity analysis are also presented in the Table 6.1. For a lower utilization (100,000 km), use phase benefits are reduced to 2.8 days, 3.5 days and 3.7 days for the low toxic emission conversion scenario for egalitarian, hierarchist and individualist perspectives, respectively. For a higher utilization (200,000 km), use phase benefits increased to 5.5 days, approximately 7 days and 7.3 days for the low toxic emission conversion scenario, and 5.7 days, 7 days, and 7.5 days for the high toxic emission conversion scenario for egalitarian, hierarchist and individualist perspectives, respectively (Table 6.1).

From the sensitivity analysis of the toxic emission conversion rate, it can be concluded that higher toxic emission conversion of the catalytic converter has a positive effect on the use phase benefit. A minor increase (26% to 28%) in use phase benefit is observed from the functional life span

sensitivity analysis, when the functional life span of the catalytic converter is increased. Overall, the use phase benefits vary between 0.021 and 0.0076 years per catalytic converter.

Table 6.1: Use phase benefit from converting toxic emission during the functional life spam of the catalytic converter in the form of lives saves measured as DALY.

Emission sensitivity analysis	**Functional unit**			**Sensitivity analysis based on functional unit**					
	160000km			100000km			200000km		
	I	H	E	I	H	E	I	H	E
Emission conversion scenario 1	1.61E-02	1.52E-02	1.22E-02	1.01E-02	9.47E-03	7.60E-03	2.01E-02	1.88E-02	1.52E-02
Emission conversion scenario 2	1.64E-02	1.54E-02	1.25E-02	1.02E-02	9.65E-03	7.79E-03	2.05E-02	1.93E-02	1.56E-02

Note:

(1) Sensitivity analysis is performed based on these variation of emission rate of CO and HCs and functional unit. Two emission factor considered from Amatayakul, (1999) and Hochfeld & Jenseit, (2000). Emission factors for all the emission are almost similar, except CO and HCs as presented in Table 5.6. Emission conversion scenario 1 represent emission factor reported by Amatayakul, (1999) and emission conversion scenario 2 represent emission factor reported by Hochfeld & Jenseit, (2000).

(2) E= Egalitarian, H= Hierarchist, I= Individualist.

6.3 Production impacts from emissions

Midpoint impacts and converted endpoint impacts from ReCiPe (2008) are shown in Table 6.2. Under the low recycling rate scenario, the climate change impact is 570 kg CO_2 eq., Human toxicity is 38000 kg 1, 4-DB eq., photochemical oxidant formation is 2 kg NMVOC, particulate matter formation is 1.5 kg PM_{10} eq., and ionizing radiation is 170 kg U_{235} eq. (Table 6.2).

Table 6.2: Production impacts (midpoint and endpoint) from emissions during production and recycling for the baseline production system of the catalytic converter (Egalitarian perspective).

Recycling rate Of PGMs	**Midpoint Impact**		**Endpoint Impact**	
Low recycling rate	Climate change (kg CO_2 eq.)	574	Human health - Climate change (DALY)	2.01E-03
	Ozone depletion (kg CFC-11 eq.)	5.98E-05	Human health - Ozone depletion (DALY)	1.71E-07
	Human toxicity (kg 1, 4-DB eq.)	37672	Human health - Human toxicity (DALY)	2.64E-02
	Photochemical oxidant formation (kg NMVOC)	2	Human health - Photochemical oxidant formation (DALY)	7.70E-08
	Particulate matter formation (kg PM_{10} eq.)	1.5	Human health - Particulate matter formation (DALY)	3.70E-04
	Ionizing radiation (kg U_{235} eq.)	165	Human health - Ionizing radiation (DALY)	2.70E-06
			Human health-total (DALY)	2.88E-02
High (50%) recycling rate	Climate change (kg CO_2 eq.)	538	Human health - Climate Change (DALY)	1.89E-03
	Ozone depletion (kg CFC-11 eq.)	5.72E-05	Human health - Ozone depletion (DALY)	1.64E-07
	Human toxicity (kg 1, 4-DB eq.)	23220	Human health - Human toxicity (DALY)	1.63E-02
	Photochemical oxidant formation (kg NMVOC)	1.5	Human health - Photochemical oxidant formation (DALY)	7.06E-08
	Particulate matter formation (kg PM_{10} eq.)	1	Human health - Particulate matter formation (DALY)	2.98E-04
	Ionizing radiation (kg U235 eq.)	143	Human health - Ionizing radiation (DALY)	2.34E-06
			Human health-total (DALY)	1.84E-02

The conversion of midpoint impact categories to the endpoint impact category resulted into approximately 1 day, 10 days, 0.15 days loss of lives due to climate change, human toxicity and particulate matter, respectively. Contributions from other impact categories were minor. In total, the loss of lives is approximately 11 days for the baseline production system, of which 91% comes from human toxicity. A sensitivity analysis based on recycling rate of PGMs showed that, in case of a high recycling rate (50%), the total loss of lives is reduced to 6.7 days. Thus, a moderate decrease (36%) in production impacts is observed for high recycling rate of PGMs.

6.4 Contributions of life cycle phases to the emission DALY

Figure 6.1 and 6.2 show the contribution of the life cycle phases to the emission DALY. The highest share of the loss of lives for human toxicity, and particulate matter formation is from the PGM coating, for both the low and high recycling rates of PGMs. For the low recycling rate, the share of loss of lives due to human toxicity and particulate matter formation of the PGM coating is 83% and 45%, respectively (Figure 6.1). For the high recycling rate, still PGM coating is the largest contributor for the loss of lives, but the contribution reduced to 72% and 31 %, respectively (Figure 6.2). The share of the loss of lives because of ionizing radiation is almost similar for the installation phase (33 %), manufacturing of catalytic converter (31 %), and PGM coating (30%) for low recycling rate of PGMs (Figure 6.1). For high recycling rate of PGMs, however, the contribution of PGMs coating is reduced to 20 % (Figure 6.2). For total loss of lives, the main contributor is the PGMs coating under both low (78 %) and high (65%) recycling rate of PGMs (Figure 6.1 and 6.2). The next two contributors for total loss of lives are installation and manufacturing of catalytic converter, for low recycling rate of PGMs (11 % and 10%, respectively) and high recycling rate of PGMs (16 % and 15%, respectively). In the case of high recycling rate, reduction in the relative contribution of the impacts from PGM coating is accompanied by a relative increase in the contribution from installation and manufacturing of catalytic converter life cycle phase.

For climate change, photochemical oxidant formation and ozone depletion, the highest share in loss of lives is from the manufacturing of the catalytic converter and installation phase (for both low and high recycling rate of PGMs). For the low recycling rate, the share of loss of lives due to climate change from installation of a catalytic converter is 40%, followed by manufacturing of catalytic converter (39 %), and after that comes PGM coating (15%) (Figure 6.1). For the high recycling rate, the share of loss of lives due to climate change increased for the installation of catalytic converter (42%) and manufacturing of catalytic converter (41 %), but decreased for PGM coating (9 %) (Figure 6.2). Similar trends are also observed for the share of loss of lives due to photochemical oxidant formation and ozone depletion (Figure 6.1 and 6.2).

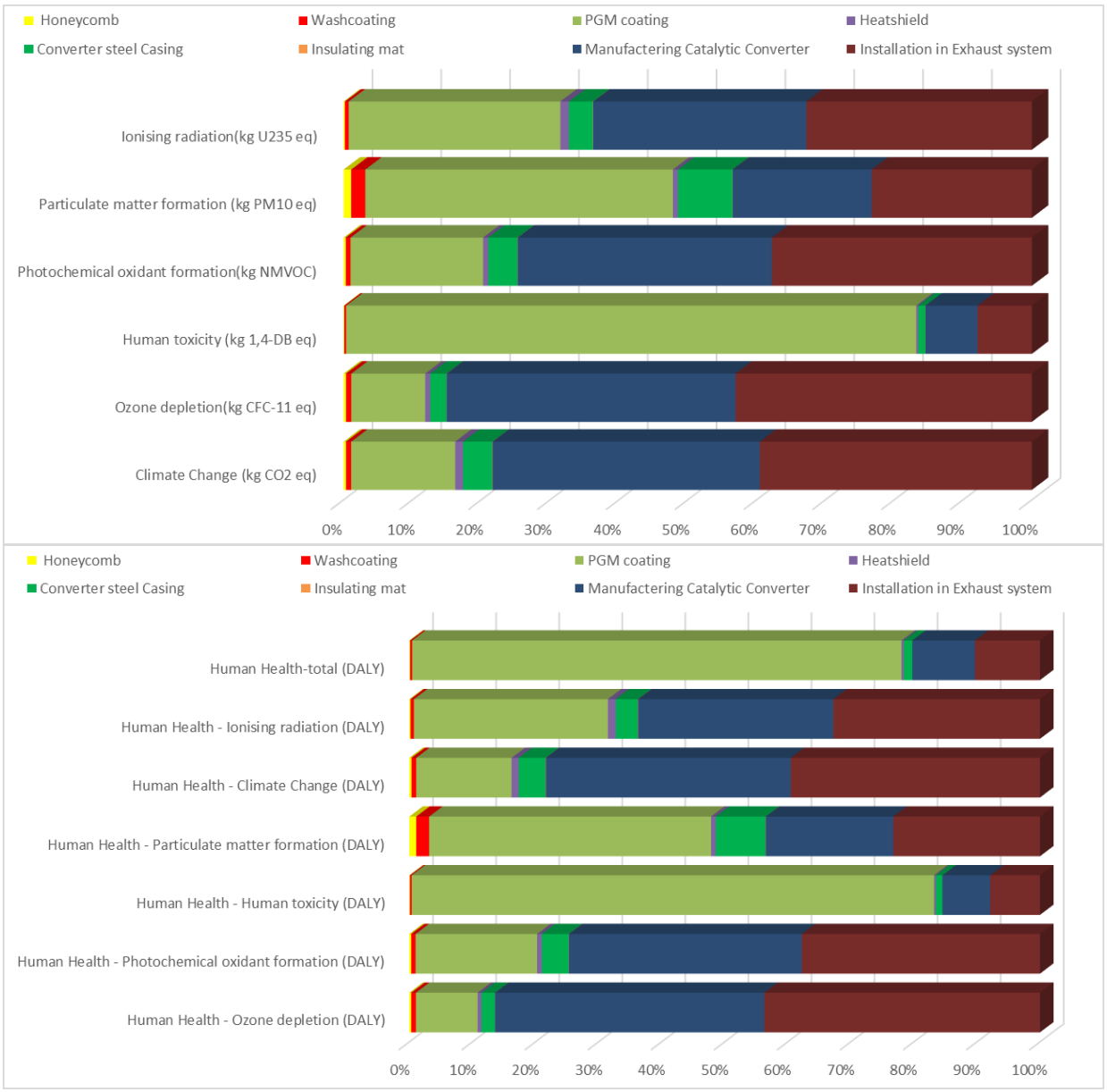


Figure 6.1: Horizontally stacked plots of the life cycle impacts associated with the manufacturing processes of a catalytic converter organized by life cycle phase for low recycling rate of PGMs, for the egalitarian perspective and the baseline production system. The upper panel and lower panel depicts midpoint categories and endpoint category, respectively.

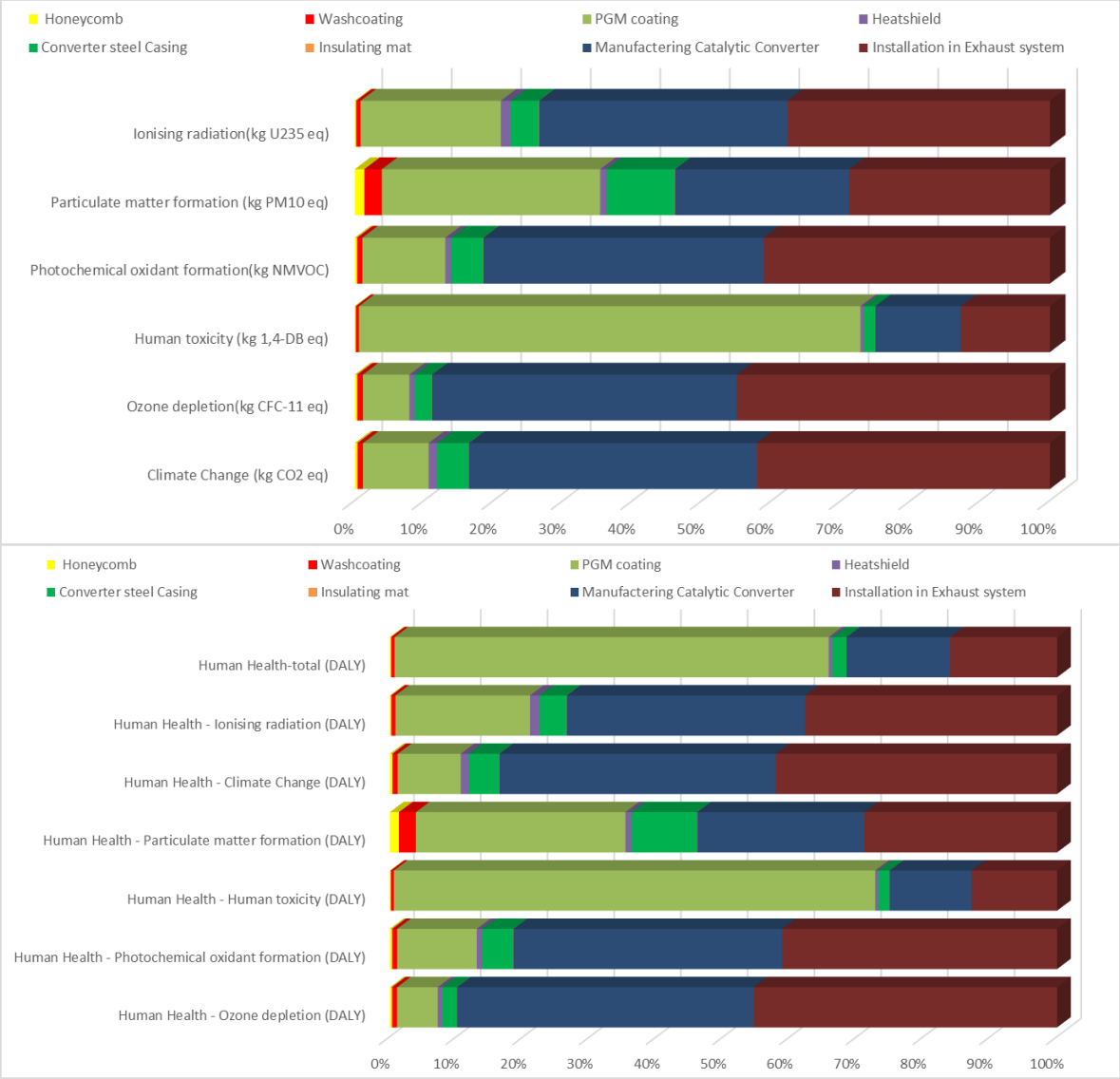


Figure 6.2: Horizontally stacked plots of the life cycle impacts associated with the manufacturing processes of a catalytic converter organized by life cycle phases for high recycling rate (50%) of PGMs, for the egalitarian perspective and the baseline production system. The upper panel and lower panel shows midpoint categories and endpoint category, respectively.

6.5 Contributions of input materials to the emission DALY

Figure 6.3 and 6.4 show the input materials' share of the emission DALY. The largest share of loss of lives for human toxicity and particulate matter formation is from the PGMs input, for both low and high recycling rate of PGMs. For the low recycling rate, the share is 81% for human toxicity and 33% for particulate matter formation, and under high recycling rate, the share reduces to 72% and 22%, respectively (Figure 6.3 and 6.4). Again, the main contributor is the PGMs input to the production system under both low and high recycling rate of PGMs, which is 75% and 64%, respectively. The

second largest contributor is the energy input under low and high recycling rate, which is 19 % and 26%, respectively (Figure 6.3 and 6.4). Again, it is observed that in the case of a high recycling rate, reduction in the relative contribution of the impacts from PGMs input into the production system is accompanied by relative increase in the contribution from energy input as well as chemical and materials input.

The largest share of the loss of lives for ionizing radiation, climate change and ozone depletion is the energy consumption, for both low and high recycling rate of PGMs. For the low and high recycling rates, the share of loss of lives due to ionizing radiation comes to 99% from energy inputs into the production system. The share of loss of lives because of climate change due to energy input is 65 %, followed by chemicals and materials input (31%), under the low recycling rate (Figure 6.1). This trend is also observed in case of high recycling rate. The share of loss of lives due to ozone depletion also shows a similar trend for energy input (56%) and chemicals and materials input (43%), under both low and high recycling rate (Figure 6.3 and 6.4).

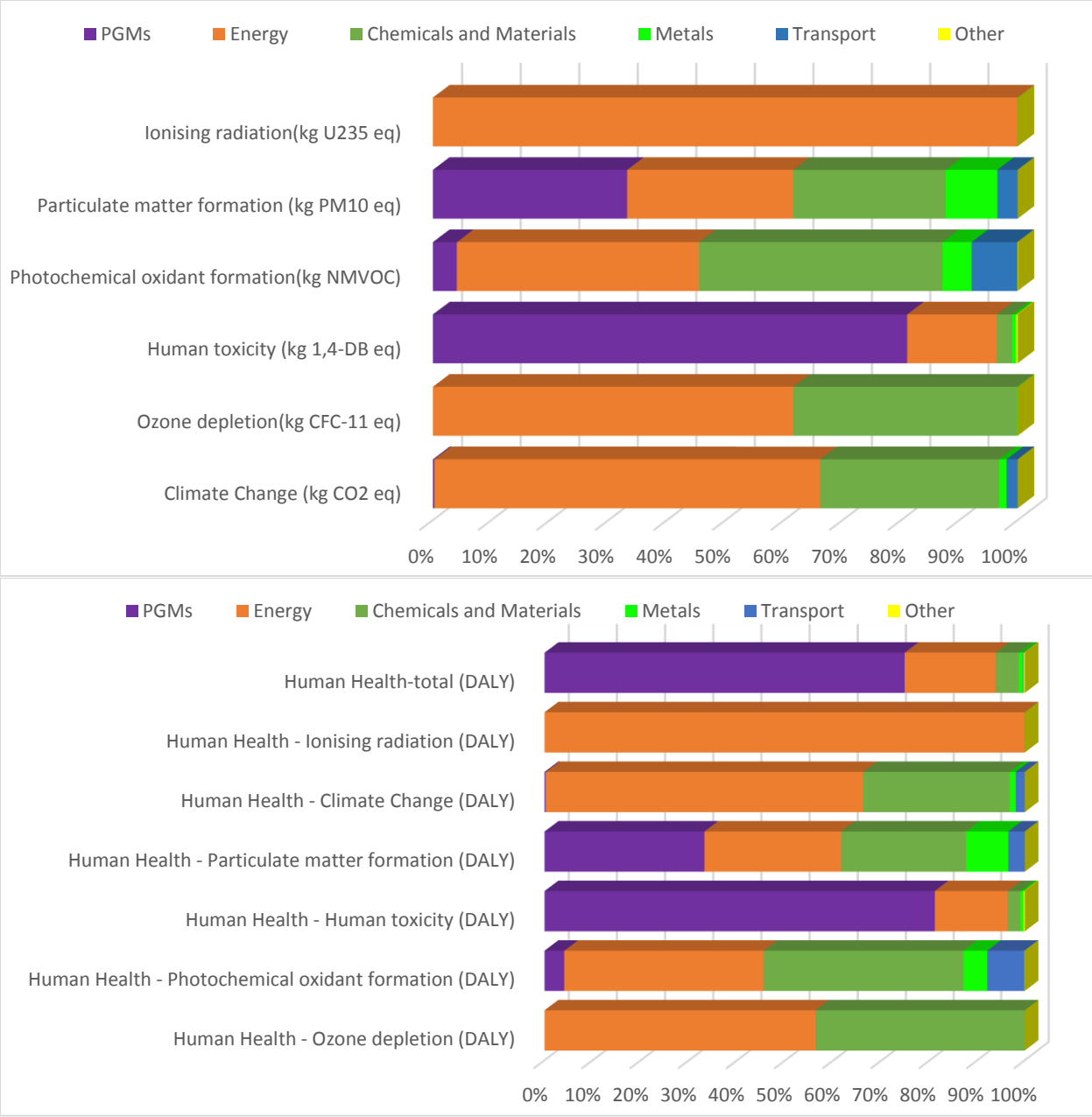


Figure 6.3: Horizontally stacked plots of the life cycle impacts associated with the material and energy inputs of the catalytic converter for low recycling rate of PGMs, under the egalitarian perspective and the baseline production system. The upper panel and lower panel depict midpoint categories and endpoint category, respectively.

Figure 6.4: Horizontally stacked plots of the life cycle impacts associated with the material and energy inputs of the catalytic converter for high recycling rate (50%) of PGMs, for the egalitarian perspective and the baseline production system. The upper panel and lower panel depict midpoint categories and endpoint category, respectively.

6.6 Geographical location of production emission

The result of the geographical location of emission analysis is shown here for the baseline production system. For all other inputs into the production system, the identified emission region did not vary as much as it did for PGMs sourcing. Therefore, the Figure 6.5 (a-g) and 6.6 (a-c) show identified emission areas for different endpoint impact categories in ReCiPe (2008) as well as total lives lost, when PGMs is sourced from South Africa (Figure 6.5, a-g) and Russia (Figure 6.6, a-c).

Emissions that cause an impact equivalent to lives lost due to particulate matter formation and human toxicity, the highest shares of emissions are observed in South Africa as 32.5% and 32%, respectively. The next identified hotspot is Europe, for which both categories have the share of 26% and 28%, respectively (Figure 6.5, c & e). The highest share (55%) of emissions contributing to lives lost due to climate change is observed in Europe. Within Europe, the identified hotspots are Germany (18%) and Poland (7.5%) (Figure 6.5, a). Lives lost due to ozone depletion is observed to be highest in Europe (49%), followed by Russia (27.5%) (Figure 6.5, b). In terms of total loss of lives throughout the production system when PGMs is sourced from South Africa, country specific highest burden falls in South Africa , where the lost is half of a day in a year (Figure 6.5, g).

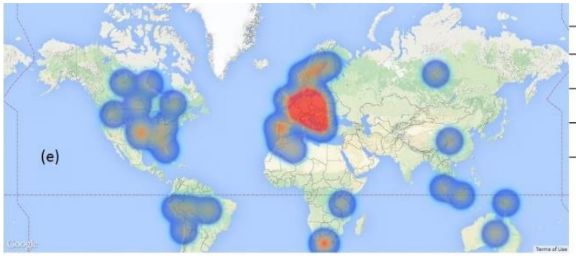
When the PGMs is sourced from Russia, the highest share of lives lost due to particulate matter formation and photochemical formation, is observed in Russia with around 94% and around 76%, respectively (Figure 6.6, a & b). In view of total loss of lives throughout the production system when PGMs is sourced from Russia, the highest share is in Russia (62%) with approximately 3 days lost. Interestingly, when PGMs is sourced from Russia, the total lives lost impacts is spread almost exclusively within Russia and Europe (Figure 6.6, c), whereas when the PGMs are sourced from South Africa, the share in total lives lost is distributed worldwide (Figure 6.5, g). It is an also a matter of fact that, when PGMs is sourced from South Africa, lives lost throughout the production system due to environmental emission is approximately 11 days lost per catalytic converter for baseline production system, with low recycling rate of PGMs and egalitarian value perspective. On the other hand, when PGMs is sourced from Russia, lives lost is approximately 5 days due to the production of the catalytic converter for baseline production system with low recycling rate of PGMs and egalitarian value perspective (Table 6.3).

Human Health - Climate Change	
Region/Country	DALY
Europe	0.00111 (55%)
Germany	0.00019 (18%)
Poland	8.29E-05 (7.5%)

Human Health - Ozone depletion	
Region/Country	DALY
Europe	8.35E-08 (49%)
Russia	4.66E-08 (27.5%)
Middle East	1.10E-08 (6.5%)
Africa	6.96E-09 (4%)
Algeria	5.44E-09 (3.2%)

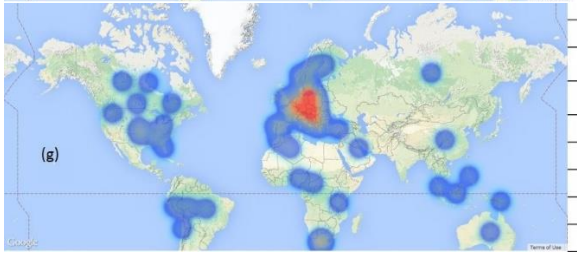
Human Health - Particulate matter formation	
Region/Country	DALY
South Africa	1.20E-04 (32.5%)
Europe	9.56E-05 (26%)

Human Health - Photochemical oxidant formation	
Region/Country	DALY
Europe	4.27E-08 (56%)
Spain	2.80E-09 (6.5%)
Germany	2.70E-09 (6.3%)
South Africa	3.16E-09 (4.9%)



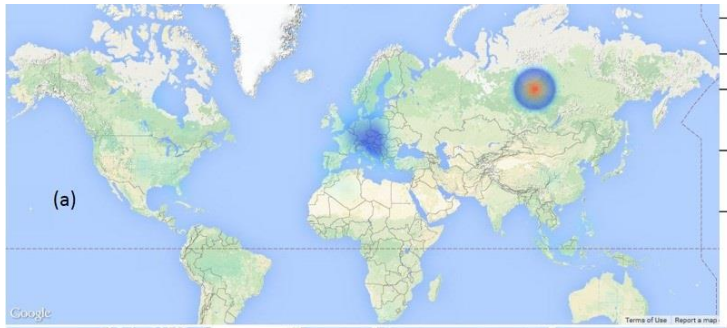
Human Health - Human toxicity	
Region/Country	DALY
South Africa	7.70E-04(32%)
Europe	6.80E-04(28%)

Human Health - Ionizing radiation	
Region/Country	DALY
Europe	8.51E-07(49%)
Northern America	4.55E-08 (4%)

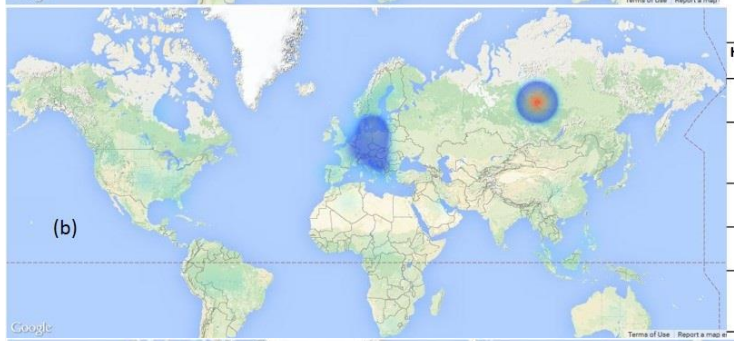


Human Health - total	
Region/Country	DALY
Europe	1.88E-03 (8%)
Germany	3.00E-04 (16%)
Poland	2.60E-04 (14%)
Switzerland	2.60E-04 (14%)
Spain	1.00E-04 (5.5%)
South Africa	9.00E-04 (4%)

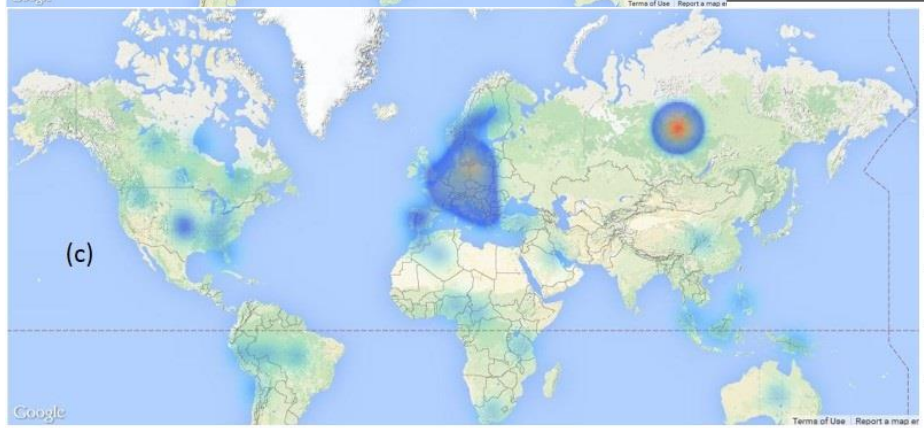
Figure 6.5 (a-g): Regions with the highest share of lost lives in the life cycle of a catalytic converter for baseline production system with PGMs mined in South Africa and an egalitarian perspective. Only those regions that have a comparatively large share of the lost lives are highlighted. The percentage of the total share of the respective impact category is presented in the parentheses. Countries within regions, mostly for Europe, are also included for some impacts categories. All the geographical hotspot assessment figures were obtained openLCA V. 1.4.1 (GreenDelta, Berlin, Germany).



Human Health - Particulate matter formation	
Region/Country	DALY
Russia	3.52E-03 (93.62%)
Europe	1.00E-04 (2.66%)



Human Health - Photochemical oxidant formation	
Region/Country	DALY
Europe	4.38E-08 (15.48%)
Germany	2.64E-09 (6 %)
Spain	2.48E-09 (5.66%)
Russia	2.15E-07 (75.97%)



Human Health - total	
Region/Country	DALY
Europe	1.99E-03 (34%)
Germany	2.70E-04 (13.6%)
Poland	2.30E-04 (11.56%)
Switzerland	2.40E-04 (12%)
Spain	9.13E-05 (4.6%)
Russia	3.61E-03 (62%)

Figure 6.6 (a-g): Regions with the highest share of lost lives in the life cycle of a catalytic converter for base line production system with PGMs mined in Russia and an egalitarian perspective. Only those regions that have a comparatively large share of the lost lives are highlighted. The percentage of the total share of the respective impact category is presented in the parentheses. Countries within regions, mostly for Europe, are also included for some impacts categories. All the geographical hotspot assessment figures were obtained openLCA V. 1.4.1 (GreenDelta, Berlin, Germany).

6.7 Production impacts for different scenarios and value perspectives

Table 6.3 shows the total loss of lives measured as DALY, calculated from the environmental emission and occupational DALY throughout the production system of the catalytic converter for low and high recycling rate of PGMs and for the three value perspectives (egalitarian, hierarchist, and individualist). For the recycling rate sensitivity analysis, occupational DALY do not shows much variation, but emission DALY vary considerably between the value perspectives. For the baseline production system, with low recycling rate and when PGMs is sourced from South Africa, the total lives lost (both emission DALY and occupational DALY) is 11 days, approximately 1 day, and 0.6 days under the egalitarian, hierarchist, and individualist perspectives, respectively. For high recycling rate of PGMs, the total loss of lives is reduced to approximately 6.5 days, 0.73 days, and 0.6 days under the egalitarian, hierarchist, and individualist perspectives, respectively. For the baseline production system with PGMs sourced from Russia (Scenario A) under low recycling rate, the total lives lost (emission DALY and occupational DALY) varies mainly because of value perspective, which is approximately 5 days, approximately 2 days and 1.8 days for the egalitarian, hierarchist, and individualist perspectives, respectively. For high recycling rate of PGMs, the total loss of lives reduced to 3.7 days, 1.3 days, and 1 days for the egalitarian, hierarchist, and individualist perspectives, respectively (Table 6.3).

When the catalytic converter is manufactured in Germany, but the PGMs are sourced from either South Africa (scenario B) or Russia (Scenario C), the total lives lost (emission DALY and occupational DALY) is higher than for the baseline scenario. For the egalitarian perspective, when the catalytic converter is manufactured in Germany and PGMs are sourced from South Africa (Scenario B), the total lives lost are approximately 12 days with low recycling rate and approximately 7.5 days with high recycling rate. For the egalitarian perspective, when the catalytic converter is manufactured in Germany and PGMs are sourced from Russia (Scenario C), the total lives lost are approximately 5.5 days with low recycling rate and approximately 4.5 days with high recycling rate (Table 6.3).

When the aluminium used for the heat shield is imported from Norway, the total lives lost (emission DALY and occupational DALY) for all the production scenarios (Scenarios D-G), the do not show much variation. The lives lost impacts remain almost same (Table 6.3).

Overall, the DALY varies between 1.7×10^{-3} and 3.1×10^{-2} years, mainly due to difference in value perspective.

Table 6.3: Lives lost measured as DALY from environmental emissions and occupational hazards over the life cycle of a catalytic converter.

Geographical location of key manufacturing stage and key resource input	Production system scenario	DALY	Eco-invent data base defined recycling rate of PGMs			50% recycling rate of PGMs		
			I	H	E	I	H	E
Catalytic converter and components is manufactured in UK and PGMs from South Africa.	Baseline	Emission	1.29E-03	1.97 E-03	2.88 E-02	1.16 E-03	1.62 E-03	1.85 E-02
		Occupational	4.00E-04	4.00E-04	4.00E-04	3.99E-04	3.99E-04	3.99E-04
		Total	1.69E-03	2.37E-03	2.92 E-02	1.56 E-03	2.02 E-03	1.88 E-02
Catalytic converter and components is manufactured in UK and PGMs from Russia.	Scenario A	Emission	4.65 E-03	4.93 E-03	1.29 E-02	2.96 E-03	3.2 E-03	9.97 E-03
		Occupational	4.01E-04	4.01E-04	4.01E-04	4.00E-04	4.00E-04	4.00E-04
		Total	5.05 E-03	5.33 E-03	1.33 E-02	3.35 E-03	3.6 E-03	1.03 E-02
Catalytic converter and components is manufactured in Germany and PGMs from South Africa.	Scenario B	Emission	1.54 E-03	2.27 E-03	3.04 E-02	1.41 E-03	1.92 E-03	2.01 E-02
		Occupational	4.04E-04	4.04E-04	4.04E-04	4.03E-04	4.03E-04	4.03E-04
		Total	1.95 E-03	2.67 E-03	3.08 E-02	1.82 E-03	2.32 E-03	2.05 E-02
Catalytic converter and components is manufactured in Germany and PGMs from Russia.	Scenario C	Emission	4.91 E-03	5.23 E-03	1.5E-02	3.21 E-03	3.5 E-03	1.16 E-02
		Occupational	4.04E-04	4.04E-04	4.04E-04	4.03E-04	4.03E-04	4.03E-04
		Total	5.3 E-03	5.63 E-03	1.49 E-02	3.61 E-03	3.90 E-03	1.20 E-02
Catalytic converter and components is manufactured in UK and aluminium imported from Norway, and PGMs from South Africa.	Scenario D	Emission	1.28 E-03	1.96 E-03	2.9 E-02	1.15 E-03	1.61 E-03	1.84 E-02
		Occupational	4.00E-04	4.00E-04	4.00E-04	3.99E-04	3.99E-04	3.99E-04
		Total	1.68 E-03	2.36 E-03	2.91 E-02	1.55 E-03	2.00 E-03	1.88 E-02
Catalytic converter and components is manufactured in UK and aluminium imported from Norway, and PGMs from Russia.	Scenario E	Emission	4.64 E-03	4.92 E-03	1.28 E-02	2.95 E-03	3.19 E-03	9.88 E-03
		Occupational	4.00E-04	4.00E-04	4.00E-04	4.00E-04	4.00E-04	4.00E-04
		Total	5.04 E-03	5.32 E-03	1.32 E-03	3.35 E-03	3.59 E-03	1.03 E-02
Catalytic converter and components is manufactured in Germany and aluminium imported from Norway, and PGMs from South Africa.	Scenario F	Emission	1.53 E-03	2.27 E-03	3.03 E-02	1.41 E-03	1.91 E-03	2.00 E-02
		Occupational	4.04E-04	4.04E-04	4.04E-04	3.97E-04	3.97E-04	3.97E-04
		Total	1.93 E-03	2.67 E-03	3.07 E-02	1.81 E-03	2.31 E-03	2.04 E-03
Catalytic converter and components is manufactured in Germany and aluminium imported from Norway, and PGMs from Russia.	Scenario G	Emission	4.9 E-03	5.22 E-03	1.44 E-03	3.2 E-03	3.49 E-03	1.15 E-02
		Occupational	4.04E-04	4.04E-04	4.04E-04	4.03E-04	4.03E-04	4.03E-04
		Total	5.30 E-03	5.62 E-03	1.48 E-03	3.60 E-03	3.89 E-03	1.19 E-02

Note:

(1) The Ecoinvent data base defined recycling rate is 5% for Platinum, 3 % for Palladium and 15% for Rhodium for European region as reported in Classen et al., (2009). According to Graedel, et al., (2011), the recycling rate in the vehicles sector for Platinum and Palladium is 50-55% and for Rhodium is 45 -50%. In this study, a sensitivity analysis based on 50% recycling rate for the PGMs is conducted.

(2) E= Egalitarian, H= Hierarchist, I= Individualist.

6.8 Comparison of use phase benefits and production impacts

To compare the use phase benefit of using a catalytic converter with the production impacts of different production system scenarios, an impact-benefit analysis was performed. Figure 6.7 shows the impact-benefit analysis of the catalytic converter for the included production system scenarios. When the impact-benefit ratio (IBR) is less than 1, the use phase benefit outweighs the production impacts, meaning that the catalytic converter saves more lives in the use phase than loss of lives caused during the production. When the IBR is greater than 1, production impacts outweigh the use phase benefit, meaning that the catalytic converter production causes more loss of lives than it saves in the use phase.

For low recycling rate and all three tested life spans (160,000 km, 100,000 km and 200,000 km), most scenarios result in more loss of lives than it saves for the egalitarian perspective. Exceptions to this are scenario A, C, E, and G. For these four scenarios, the catalytic converter saves more lives in the use phase than are lost during the production. From the sensitivity analysis of emission conversion rate, it is observed that the IBR does not vary much with this parameter, which is because the variation is relatively small (Figure 6.7 upper panel).

For high recycling rate, scenario A, C, E, and G save more lives in the use phase than are lost during production for the egalitarian perspective, given a functional life of 160,000 km or 200,000 km (Figure 6.7 lower panel). Thus, both the recycling rate and functional life time of the catalytic converter have considerable influences on the net health impact given an egalitarian perspective. For the hierarchist and individualist perspectives, all scenarios save more lives in the use phase than are lost during the production (Figure 6.8 and 6.9). Thus, it can be say that the choice of value perspective for the impact assessment of emissions have a profound influence on the net health impact.

The differences in net health impact due to different value perspectives is likely because of different time horizons and assumption of future technological advancement for human adaptation [Goedkoop et al., 2013].

From this IBR analysis with a focus on the egalitarian, hierarchist, and individualist perspectives, it is clear that the choice of perspective can alter the net health impact balance of a product system. In view of this, it can be inferred that when comparing results from different production system scenarios in a human health-focused SLCA case study, not only the different system boundaries

and underlying assumptions are important to report, but also the value perspective used for impact assessment.

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	2.39	3.84	1.92	2.33	3.74	1.87
Scenario A	1.09	1.74	0.87	1.06	1.70	0.85
Scenario B	2.53	4.06	2.03	2.47	3.96	1.98
Scenario C	1.22	1.96	0.98	1.19	1.92	0.96
Scenario D	2.38	3.83	1.91	2.33	3.73	1.86
Scenario E	1.08	1.73	0.87	1.05	1.69	0.84
Scenario F	2.52	4.04	2.02	2.46	3.95	1.97
Scenario G	1.22	1.95	0.98	1.19	1.90	0.95

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	1.54	2.48	1.24	1.51	2.42	1.21
Scenario A	0.85	1.36	0.68	0.83	1.33	0.66
Scenario B	1.68	2.70	1.35	1.64	2.63	1.31
Scenario C	0.99	1.58	0.79	0.96	1.54	0.77
Scenario D	1.54	2.47	1.23	1.50	2.41	1.20
Scenario E	0.84	1.35	0.68	0.82	1.32	0.66
Scenario F	1.67	2.69	1.34	1.63	2.62	1.31
Scenario G	0.98	1.57	0.79	0.95	1.53	0.76

$$\frac{Upstream\ Impact}{Downstream\ Benefit} = Impact\ Benefit\ Ratio\ (IBR)$$

<1 Downstream lives saving benefit outweigh the upstream lives lost impact from production system

=1 Net neutral impact

>1 Upstream lives lost impact from production system outweigh the downstream lives saving benefit

Figure 6.7: Impact-benefit analysis of a catalytic converter for the included scenarios. Sensitivity is tested for different emission conversions, functional life time, and recycling rate of PGMs. Results are for the egalitarian value perspective. The upper panel show the IBR for low recycling rate and lower panel for high recycling rate.

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	0.16	0.25	0.13	0.15	0.25	0.12
Scenario A	0.35	0.56	0.28	0.35	0.55	0.28
Scenario B	0.18	0.28	0.14	0.17	0.28	0.14
Scenario C	0.37	0.59	0.30	0.37	0.58	0.29
Scenario D	0.16	0.25	0.13	0.15	0.24	0.12
Scenario E	0.35	0.56	0.28	0.35	0.55	0.28
Scenario F	0.18	0.28	0.14	0.17	0.28	0.14
Scenario G	0.37	0.59	0.30	0.36	0.58	0.29

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	0.13	0.21	0.11	0.13	0.21	0.10
Scenario A	0.24	0.38	0.19	0.23	0.37	0.19
Scenario B	0.15	0.24	0.12	0.15	0.24	0.12
Scenario C	0.26	0.41	0.21	0.25	0.40	0.20
Scenario D	0.13	0.21	0.11	0.13	0.21	0.10
Scenario E	0.24	0.38	0.19	0.23	0.37	0.19
Scenario F	0.15	0.24	0.12	0.15	0.24	0.12
Scenario G	0.26	0.41	0.21	0.25	0.40	0.20

$$\frac{Upstream\ Impact}{Downstream\ Benefit} = Impact\ Benefit\ Ratio\ (IBR)$$

<1 Downstream lives saving benefit outweigh the upstream lives lost impact from production system

=1 Net neutral impact

>1 Upstream lives lost impact from production system outweigh the downstream lives saving benefit

Figure 6.8: Impact-benefit analysis of a catalytic converter for the included scenarios. Sensitivity is tested for different emission conversions, functional life time, and recycling rate of PGMs. Results are for the hierarchist value perspective. The upper panel show the IBR for low recycling rate and lower panel for high recycling rate.

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	0.10	0.17	0.08	0.10	0.17	0.08
Scenario A	0.31	0.50	0.25	0.31	0.50	0.25
Scenario B	0.12	0.19	0.10	0.12	0.19	0.10
Scenario C	0.33	0.52	0.26	0.32	0.52	0.26
Scenario D	0.10	0.17	0.08	0.10	0.16	0.08
Scenario E	0.31	0.50	0.25	0.31	0.49	0.25
Scenario F	0.12	0.19	0.10	0.12	0.19	0.09
Scenario G	0.33	0.52	0.26	0.32	0.52	0.26

Production scenario	Emission conversion scenario 1 & 160000 km life time	Emission conversion scenario 1 & 100000 km life time	Emission conversion scenario 1 & 200000 km life time	Emission conversion scenario 2 & 160000 km life time	Emission conversion scenario 2 & 100000 km life time	Emission conversion scenario 2 & 200000 km life time
Base line	0.10	0.15	0.08	0.10	0.15	0.08
Scenario A	0.21	0.33	0.17	0.20	0.33	0.16
Scenario B	0.11	0.18	0.09	0.11	0.18	0.09
Scenario C	0.22	0.36	0.18	0.22	0.35	0.18
Scenario D	0.10	0.15	0.08	0.09	0.15	0.08
Scenario E	0.21	0.33	0.17	0.20	0.33	0.16
Scenario F	0.11	0.18	0.09	0.11	0.18	0.09
Scenario G	0.22	0.36	0.18	0.22	0.35	0.18

$$\frac{Upstream\ Impact}{Downstream\ Benefit} = Impact\ Benefit\ Ratio\ (IBR)$$

<1 Downstream lives saving benefit outweigh the upstream lives lost impact from production system

=1 Net neutral impact

>1 Upstream lives lost impact from production system outweigh the downstream lives saving benefit

Figure 6.9: Impact-benefit analysis of a catalytic converter for the included scenarios. Sensitivity is tested for different emission conversions, functional life time, and recycling rate of PGMs. Results are for the individualist value perspective. The upper panel show the IBR for low recycling rate and lower panel for high recycling rate.

CHAPTER 7

Discussion & Conclusion

7.1 Uncertainties and data quality

The study is based on a number of assumptions, as mentioned in section 4.5. All those assumptions could reduce the reliability and validity of the results. Most of the input and output data for different processes for catalytic converter production system has been taken from the Ecoinvent database version 2.2. For processes where process-specific data is not available, input and output data has been obtained from similar process available in the Ecoinvent database version 2.2, as mentioned in the appendix A.5. Consequently, these data approximations could reduce the reliability of the results. Since the study is not about a specific catalytic converter model, but rather about a generic catalytic converter, different material inputs for the catalytic converter is assumed from relevant catalytic converter LCA studies and relevant patent. These material input approximations could also reduce the reliability of the results.

The ReCiPe (2008) impact assessment method has DALY characterization factors for a number of environmental emissions from the production system, except for PGM emissions. So in order to account for lives lost from PGM emission during the use phase, in this study, PGM emission were considered as particulate matter emissions and relevant particulate DALY characterization factors were used. This approximation for the PGMs DALY CFs could also reduce the reliability of the results. But from the impact assessment it is observed that the negative contribution of PGMs emissions during the use phase is very minor, and outweighed by the reduction in emissions.

The lives lost consist of emission DALY and occupational DALY. The ReCiPe (2008) impact assessment method has DALY characterization factors for environmental emission, but not for occupational DALY. In order to account the lives lost due to occupational hazards within the production system, occupational DALY characterization factors reported by Scanlon, et al., (2015) were considered. But the occupational DALY characterization factors reported by Scanlon and colleagues (2015) for different input materials represent US production. But from the inventory analysis of this study it is observed that, most of the mined resources needed for the catalytic converter is from South Africa, Russia and China. So, in this study a doubling of occupational DALY Characterization factor is considered for the resources sourced from South Africa, Russia and China and for Europe the occupational DALY Characterization factor is considered similar like US. From the impact assessment, it can be noted that the share of occupational DALY of the total DALY is 1.4%, 17%, and 24% for the egalitarian, hierarchist, and individualist perspectives, respectively. This indicates that the contribution from occupational DALY is effectively negligible. However, these contributions may increase if the worst working conditions in the mines located in South Africa, Russia and China would be considered. It would thus be relevant to develop occupational DALY CFs

for other countries than the US to be used in human health life cycle assessments, as a part of social life cycle assessment (SLCA) study.

7.2 Conclusions

This study presents an SLCA case study of a generic catalytic converter production system, using DALY as indicator of social impacts. The production impacts in terms of lives lost consist of DALY from environmental emissions and DALY from occupational hazards throughout the production system of the catalytic converter. A catalytic converter saves more lives than are lost during its production for some production system scenarios. But for some of the cases, the net health impact is negative, chiefly because of increased recycling rate and value perspective. Some specific findings of this study are listed here:

1. For the baseline production scenario with 160,000 km functional life, during the use phase, a catalytic converter saves 4.5 days, 5.5 days and approximately 6 days for the egalitarian, hierarchist and individualist perspectives, respectively. However, it caused the loss of 11 days, approximately 1 day, and 0.6 days for the egalitarian, hierarchist, and individualist perspectives, respectively. This means that a catalytic converter is a net health provider given the individualist and hierarchist perspectives, but not for the egalitarian perspective.
2. Increased use of recycled PGM has a positive influence on the health impact. For example, for production scenario A under low recycling rate (5% for Pt, 3% for Pd and 15% for Rh), the lives lost is approximately 5 days, approximately 2 days, and 1.8 days for the egalitarian, hierarchist, and individualist perspectives, respectively. For high recycling rate (50% for Pt, Pd, and Rh), the lives lost are reduced to 3.65 days, 1.3 days, and approximately 1 day for the egalitarian, hierarchist, and individualist perspectives, respectively.
3. The lives saved in the use phase over the functional life of the catalytic converter range from around 5 to 6 days for 160,000 km functional life, to around 6 to 8 days for 200,000 km functional life given the different value perspectives (egalitarian, hierarchist and individualist).
4. Hotspot analysis revels that while the catalytic converter saves lives in the use phase in Sweden, it causes loss of lives elsewhere in the world.

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APPENDICES

Appendix A. 1: Ceramic honeycomb substrate production process material inputs and outputs

For the ceramic honeycomb substrate production process raw material composition and weight calculation, extruded ceramic cordierite batch composition as reported by Belcastro, (2012) from Lachman et al., (1981), presented in Table A.1.1, is used in this study. All the raw materials mentioned in Table A.1.1 form cordierite, which is combination of magnesia (MgO), alumina (Al_2O_3), and silica (SiO_2), through equation A.1.1. The formed water is emitted into the environment as vapor during the heating processes.

Table A.1.1: Extruded ceramic cordierite honeycomb substrate batch composition.

Raw materials	**Weight Percentage (%)**
Kaolin [Al_2 (Si_2O_5) $(OH)_4$]	21.74
Talc [$Mg_3(Si_2O_5)_2(OH)_2$]	39.24
Alumina [Al_2O_3]	11.23
Aluminum hydroxide [$Al(OH)_3$]	17.80
Silica [SiO_2]	9.99
Total	100

Al_2 (Si_2O_5) $(OH)_4$ [Kaolin] + $Mg_3(Si_2O_5)_2(OH)_2$ [Talc] + Al_2O_3 [Alumina] + $Al(OH)_3$ [Aluminum hydroxide] + SiO_2 [Silica] → $MgO{\cdot}Al_2O_3{\cdot}SiO_2$ [Cordierite] + H_2O [water]---(Equation A.1.1)

Assuming 100 g weight of the batch input of ceramic cordierite production and individual weight percentage of Table A.1.1, the moles of each raw material input is calculated in Table A.1.2

Table A.1.2: Moles of raw materials for ceramic cordierite production, assuming 100 g of batch input.

Raw materials [1]	**Mass (g) [2]**	**Molar mass (g/mol) [3]**	**Moles (mol) [4=2÷3]**
Kaolin $Al_2(Si_2O_5)$ $(OH)_4$	21.74	260	0.085
Talc $Mg_3(Si_2O_5)_2(OH)_2$	39.24	380	0.105
Alumina Al_2O_3	11.23	102	0.11
Aluminum hydroxide $Al(OH)_3$	17.8	78	0.23
Silica SiO_2	9.99	60	0.167
Total	100		

Now the masses of each element in each raw materials input is calculated below:

Raw materials	Element	Molecular weight (g/mol)	Mass (g)
Kaolin $Al_2(Si_2O_5)(OH)_4$	Aluminum	27	0.085×2×27= 4.515
	Silicon	28	0.085×2×28= 4.682
	Oxygen	16	0.085×9×16= 12.041
	Hydrogen	1	0.085×4×1= 0.334
Talc $Mg_3(Si_2O_5)_2(OH)_2$	Magnesium	24	0.105×3×24= 7.435
	Silicon	28	0.105×4×28= 11.565
	Oxygen	16	0.105×12×16= 19.827
	Hydrogen	1	0.105×2×1= 0.207
Alumina Al_2O_3	Aluminum	27	0.11×2×27= 5.945
	Oxygen	16	0.11×3×16= 5.285
Aluminum hydroxide $Al(OH)_3$	Aluminum	27	0.23×1×27= 6.162
	Oxygen	16	0.23×3×16= 10.954
	Hydrogen	1	0.23×3×1= 0.685
Silica SiO_2	Silicon	28	0.167×1×28= 4.662
	Oxygen	16	0.167×2×16= 5.328

The total mass of each input element can now be calculated:

Aluminum=4.515+5.945+6.162= 16.622 g
Silicon=4.682+11.565+4.662=20.910 g
Oxygen=12.041+19.827+5.285+10.954+5.328=53.434 g
Hydrogen= 0.334+0.207+0.685=1.226 g
Magnesium= 7.435 g

According to mass balance law, input masses of each element are equal to output masses of each element. So the moles of output elements are calculated in Table A.1.3.

Table A.1.3: Moles of output elements for ceramic cordierite production assuming 100 g of batch input.

Output element [1]	Mass (g) [2]	Molar mass (g/mol) [3]	Moles (mol) [4=2÷3]
Aluminum	16.622	27	0.616
Silicon	21.910	28	0.747
Oxygen	53.434	16	3.35
Hydrogen	1.226	1	1.226
Magnesium	7.435	24	0.310

Moles of each output elements presented in Table A.1.3 can now be used to calculate the moles of each output compound. From equation A.1.1, cordierite ($MgO{\cdot}Al_2O_3{\cdot}SiO_2$) can be written as MgO (magnesia) + Al_2O_3 (alumina) + SiO_2 (silica). Since there is one mole of magnesium in magnesia, the moles of magnesia and magnesium are equal. Assuming 100 g of batch input, in cordierite for the output of ceramic cordierite production, the mole of magnesia is 0.31. Similarly, in 1 mole of alumina, there are 2 moles of aluminum and hence the mole of alumina are half of the moles of aluminum. So, in the cordierite output for ceramic cordierite production, assuming 100 g of batch input, the mole of alumina is 0.31 (0.616÷2). In 1 mole of silica there are 1 mole of silicon and hence the moles of silica and silicon are equal. So, in cordierite output for ceramic cordierite production assuming 100 g of batch input, the moles of silica is 0.75. Another product of the cordierite-forming reaction is water (H_2O) according to equation A.1.1. There are 2 moles of hydrogen in 1 mole of water, so the mole of water are half of the moles of hydrogen and thus the moles of water produced during ceramic cordierite production assuming 100 g of batch input, is 0.62 (1.226÷2). Equation A.1.2 is the verification of the computed moles of the output, using the input 3.35 moles of oxygen (53.4 g÷16 g/mol).

Output moles of oxygen= moles of Al_2O_3 × moles of O + moles of MgO × moles of O + moles of SiO_2 × moles of O + moles of H_2O × moles O ---------- (Equation A.1.2)

= 0.31× 3 + 0.31 × 1 + 0.75 × 2 + 0.62 × 1

= 3.36 (Which is nearly the input moles of oxygen. A small difference exist because of rounding of the number of moles to three decimal place).

So the right hand side of the equation A.1.1 can be written as using balanced moles for 100 g batch input:

$MgO{\cdot}Al_2O_3{\cdot}SiO_2 + H_2O = 0.31\ Al_2O_3 + 0.31\ MgO + 0.75\ SiO_2 + 0.62\ H_2O$ ---------- (Equation A.1.3)
$MgO{\cdot}Al_2O_3{\cdot}SiO_2 + H_2O = Al_2O_3 + MgO + 2.5\ SiO_2 + 2\ H_2O$ (dividing with 0.31) ----- (Equation A.1.4)
$MgO{\cdot}Al_2O_3{\cdot}SiO_2 + H_2O = 2\ Al_2O_3 + 2\ MgO + 5\ SiO_2 + 4\ H_2O$ (multiplied by 2) ----- (Equation A.1.5)

Masses of each output is computed in Table A.1.4.
Table A.1.4: Masses of each output for ceramic cordierite production assuming 100 g of batch input.

Output [1]		**Moles (mol) [2]**	**Molar mass (g/mol) [3]**	**Mass (g) [4=2×3]**	**Mass percentage for cordierite (%)**	**Mass percentage of total output (%)**
Cordierite $MgO{\cdot}Al_2O_3{\cdot}SiO_2$	Alumina Al_2O_3	0.31	102	31.62	35.5	----
	Silica SiO_2	0.75	60	45	50.5	----
	Magnesia MgO	0.31	40	12.4	14	----
Total cordierite mass				89.02	------	89
Water H_2O		0.61	18	10.98	------	11
Total Output mass				100		

For 1000 g cordierite output, total output would be

Total output= 1000/89%

= 1125 g

So for 1125 g total output, cordierite mass is 1000 g and water mass is 125 g and mass of alumina is 355 g, mass of silica is 505 g, mass of magnesia is 140 g, out of 1000 g cordierite mass. Therefore output moles are:

Alumina= 355 g ÷ 102 g/mol = 3.5 moles

Silica= 505 g ÷ 60 g/mol = 8.4 moles

Magnesia= 140 g ÷ 40 g/mol = 3.5 moles

Water= 125 g ÷ 18 g/mol = 7 moles

The output moles for 1 kg (1000 g) mass of cordierite are about 11 times higher than the output moles for the ceramic cordierite production assuming 100 g of batch input. For 100 g, batch input equation A.1.1 can be written as follows using the number of moles for each compound mentioned in Table A.1.2 and equation A.1.3.

0.085 Al_2 (Si_2O_5) $(OH)_4$ [Kaolin] + 0.105 $Mg_3(Si_2O_5)_2(OH)_2$ [Talc] + 0.11 Al_2O_3 [Alumina] + 0.23 $Al(OH)_3$ [Aluminum hydroxide] + 0.167 SiO_2 [Silica] → 0.31 MgO + 0.31 Al_2O_3 + 0.75 SiO_2 [Cordierite] + 0.62 H_2O [water]---(Equation A.1.6)

For the output mass of 1 kg (1000 g) of cordierite, using the scale factor 11, equation A.1.6 can be written as

0.935 Al_2 (Si_2O_5) $(OH)_4$ [Kaolin] + 1.155 $Mg_3(Si_2O_5)_2(OH)_2$ [Talc] + 1.21 Al_2O_3 [Alumina] + 2.53 $Al(OH)_3$ [Aluminum hydroxide] + 1.837 SiO_2 [Silica] → 3.41 MgO + 3.41 Al_2O_3 + 8.25 SiO_2 [Cordierite] + 6.82 H_2O [water]---(Equation A.1.6)

Therefor, input masses of the raw materials for 1000 g mass of ceramic (cordierite) honeycomb monolith output or 1125 g total output to be used as resource input in openLCA are presented in Table A.1.5

Table A.1.5: Masses of each input for ceramic cordierite output of 1000 g and total output of 1125 g.

Raw materials [1]	**Moles (mol) [2]**	**Molar mass (g/mol) [3]**	**Mass (g) [4=2×3]**
Kaolin $Al_2(Si_2O_5)$ $(OH)_4$	0.935	260	245
Talc $Mg_3(Si_2O_5)_2(OH)_2$	1.155	380	445
Alumina Al_2O_3	1.21	102	125
Aluminum hydroxide $Al(OH)_3$	2.53	78	200
Silica SiO_2	1.837	60	110
Total			1125

Appendix A. 2: Talc production process material inputs and outputs

The Ecoinvent database version 2.2 has no unit process data base for talc production processes. But it does have production processes data of dolomite [$CaMg(CO_3)_2$], and silica [SiO_2] sand. Talc is produced via the reaction shown in equation A.2.1, from dolomite and silica. So the process data is developed based on this reaction. All the other resources input like machinery, energy is estimated from similar processes in the Ecoinvent database version 2.2. The computation of materials input and output relative to 1 kg talc production is described here. The input and output mass is slightly different because of rounding off throughout the calculation.

3 $CaMg(CO_3)_2$ [Dolomite] + 4 SiO_2 [Silica] + H_2O [Water] → $Mg_3Si_4O_{10}(OH)_2$ [Talc] + 3 $CaCO_3$ [Calcite] + 3 CO_2 [Carbon dioxide] ---(Equation A.2.1)

Molecular mass of the inputs and outputs are as follows:

Inputs	Outputs
$CaMg(CO_3)_2$ [Dolomite] 40.078+ 24.305+2×12.0107+6×15.9994 =184.37 g	$Mg_3Si_4O_{10}(OH)_2$ [Talc] 3×24.305+4×28.0855+12×15.9994+2×1.008 =379.27 g
SiO_2 [Silica] 28.0855+2×15.9994=60.08 g	$CaCO_3$ [Calcite] 40.078+12.0107+3×15.9994 =100.09 g
H_2O [Water] 2×1.008+15.9994=18.02 g	CO_2 [Carbon dioxide] 12.0107+2×15.9994 =44 g

379.27 g talc production require 3× 184.37 g Dolomite
So, 1000 g talc production require $\frac{3\times184.37}{379.27} \times 1000 = 1458.35$ g Dolomite

379.27 g talc production require 4× 60.08 g Silica
So, 1000 g talc production require $\frac{4\times60.08}{379.27} \times 1000 = 633.64$ g Silica

379.27 g talc production require 18.02 g Water
So, 1000 g talc production require $\frac{18.02}{379.27} \times 1000 = 47.52$ g Water

3×184.37 g Dolomite produce 3× 100.09 g Calcite
So, 1458.35 g Dolomite produce $\frac{3\times100.09}{3\times184.37} \times 1458.35 = 791.70$ g Calcite

3×184.37 g Dolomite produce 3× 44 g CO_2
So, 1458.35 g Dolomite produce $\frac{3\times44}{3\times184.37} \times 1458.35 = 348$ g CO_2

Appendix A. 3: Occupational DALY CF

Occupational DALY CF considered in this study is based on the study of Scanlon et al., (2015). Table A.3.1 shows the industry specific occupational DALY CF relevant to the catalytic converter life cycle.

Table A. 3.1: Industry-specific occupational DALY CF considered in this study.

Industry/Services	DALY CF
Iron Ore Mining	2.23E-09 DALY/kg
Copper Ore and Nickel Ore Mining	8.39E-09 DALY/kg
Lead Ore and Zinc Ore Mining	6.43E-10 DALY/kg
Uranium-Radium-Vanadium Ore Mining	3.41E-05 DALY/kg
Miscellaneous Metal Ore Mining	2.10E-07 DALY/kg
Bituminous Coal Underground Mining	3.32E-09 DALY/kg
Construction Sand and Gravel Mining	4.57E-10 DALY/kg
Kaolin and Ball Clay Mining	6.40E-09 DALY/kg
Clay, Ceramic and Refractory Minerals Mining	1.38E-09 DALY/kg
Miscellaneous non-metallic Minerals Mining	2.31E-12 DALY/kg
Dimension Stone Mining and Quarrying	3.44E-08 DALY/kg
Crude Petroleum and Natural Gas Extraction	5.35E-11 DALY/MJ
Petroleum Refineries	5.00E-10 DALY/kg
Industrial Gas Manufacturing	1.50E-08 DALY/kg
Fossil Fuel Electric Power Generation	1.40E-10 DALY/MJ
Other Electric Power Generation	1.87E-09 DALY/MJ
Miscellaneous basic Inorganic Chemical Manufacturing	3.40E-09 DALY/kg
Miscellaneous basic Organic Chemical Manufacturing	3.94E-09 DALY/kg
Paint and Coating Manufacturing considered for wash and catalyst coating	2.25E-07 DALY/kg
Brick and Structural Clay Tile Manufacturing considered for ceramic honeycomb monolith	1.59E-08 DALY/kg
Miscellaneous Nonmetallic Mineral Product Manufacturing	6.43E-08 DALY/kg
Iron and Steel Mills	2.91E-08 DALY/kg
Primary Aluminum Production	7.65E-08 DALY/kg
Secondary Smelting and Alloying of Aluminum	3.45E-07 DALY/kg
Motor Vehicle Parts Manufacturing	1.85E-04 DALY/item
Timber Tract Operations	6.44E-11 DALY/m^3
Freight Air Transportation	1.02E-07 DALY/tkm
Freight Railroads Transportation	7.85E-10 DALY/tkm
Deep Sea Freight Transportation	7.51E-10 DALY/tkm
General Freight Trucking, Local	2.20E-08 DALY/tkm
General Freight Trucking, Long-Distance, Truckload	1.10E-08 DALY/tkm
Materials Recovery Facilities	1.78E-08 DALY/kg

Appendix A. 4: Transport distance and types considered

For the road transportation, transport distances are determined from the total length of the respective producing countries. Transport distances are then multiplied with the whole mass of different component and materials to determine the ton-kilometer (tkm). For sensitivity analysis of transport, doubling (which corresponds to production further away) and halving (which correspond to production in quite close proximity) of transport distances was performed. Rail transport is considered for minerals and rocks which are mined for different materials. For different mined materials, unless it is present in the Ecoinvent V 2.2, transport variables are estimated from similar process data in Ecoinvent V 2.2. For inter-country shipment, transport distances considered are port-to-port travel distances for ship transport. For other transport mode, the distances are described in the comments section of Table A.4.1.

Table A.4.1: Country specific transport distance and type considered for different processes.

Processes	**Producing Country**	**Transportation variables**		
		Distance	Types	Comments
Talc production	Finland		Road transport by lorry >16t fleet average for Europe region.	
Honeycomb ceramic monolith production	Germany	Total length of Germany considered is 1100 km. Half of this distance is considered for Talc transport from port to industry. Transport distance within Finland from Talc manufacturing plant to Helsinki port is 560 km. Transport distance within France from Talc manufacturing plant to La Rochelle port is 420 km. Transport distance within Japan from Talc manufacturing plant to Tokyo port is 335 km. Around 50% of processed talc exported from Liaoning province, China, among the three Talc producing provinces of China. Transport distance within China from Talc manufacturing plant to nearby Dalian sea port is 400 km. For export of Talc from Finland, port (Helsinki) to port (Hamburg) distance is 2245 km; from France, port (La Rochelle) to port (Hamburg) distance is 1700 km; port (Dalian) to port (Hamburg) distance is 23800 km; port (Dalian) to port (Tokyo) distance is 2600 km	Road transport by lorry >16t fleet average for Europe region. Transoceanic freight ship for marine transport.	Freight transport by rail is assumed from ceramic tiles production in Germany of Ecoinvent V 2.2. Transoceanic freight ship-OCE of Ecoinvent V 2.2. is used.
Wash coat and PGMs coating	UK	Total length of UK considered is 750 km. Half of this distance is taken as transport distance for transportation of honeycomb from port to industry site. For export of ceramic honeycomb from Germany, port (Hamburg) to port (Felixstowe) distance is 763 km.	Road transport by lorry >16t fleet average for Europe region. Transoceanic freight ship for marine transport. Air freight for PGMs.	Transoceanic freight ship-OCE of Ecoinvent V 2.2. is used.

		Total length of Germany considered is 1100 km. Half of this distance is considered for transport from industry to port. For export of ceramic honeycomb from Japan, port (Tokyo) to port (Hamburg) distance is 21225 km. For PGMs, air freight for European region as presented in Ecoinvent V 2.2 is used.		
Stainless steel housing and heat shield	UK	Total length of UK considered is 750 km. Half of this distance is taken as transportation distance for transport of input materials to the manufacturing site. For export of Aluminium, industry to port (Bergen) distance in Norway is 400 km. Port (Felixstowe) to port (Bergen) distance is 990 km and Port (Hamburg) to port (Bergen) distance is 990 km and	Road transport by lorry >16t fleet average for Europe region.	
Insulating mat	UK	Total length of UK considered is 750 km. Half of this distance is taken as transportation distance for transport of input materials to the manufacturing site.	Road transport by lorry >16t fleet average for Europe region.	
Catalytic converter component assembly	UK	Total length of UK considered is 750 km. Half of this distance is taken as transportation distance for transport of different components to the manufacturing site.	Road transport by lorry >16t fleet average for Europe region.	
Installation into the car in Sweden	Sweden	For export of Catalytic converter from UK, port (Felixstowe) to port (Goteborg) distance is 980 km. For export of Catalytic converter from Germany, port (Hamburg) to port (Goteborg) distance is 580 km. Total length of UK considered is 750 km. Half of this distance is taken as transportation distance for transport of catalytic converter from industry to port. Total length of Germany considered is 1100 km. Half of this distance is considered for transport from industry to port. In Sweden the port to industry distance is 10 km.	Transoceanic freight ship for marine transport.	Transoceanic freight ship-OCE of Ecoinvent V 2.2. is used.

Appendix A.5: Data quality and sources of the study

For most of the unit processes, the data used are from the Ecoinvent V 2.2 database. Whenever a specific unit process is not available in the Ecoinvent V 2.2, input and output materials were determined using stoichiometric ratios and process input resources like energy, equipment, and fuel consumption were estimated based on similar processes in Ecoinvent V 2.2, as described in Table A.5.1.

Table A.5.1: Data sources for different components and materials of a catalytic converter.

***Components* and materials**	**Data source**
Ceramic honeycomb substrate	Materials inputs and outputs are calculated from stciometric ratio. Energy, other resources and transport freight-rail input and emissions are assumed from the ceramic tiles production unit processes data of Ecoinvent V 2.2. Details of Transport input is presented in Appendix A.4.
Materials for ceramic honeycomb substrate production	
Talc	In this study input and output data are developed for talc based on the following reaction dolomite + silica + water → talc + calcite + carbon dioxide $3\ CaMg(CO_3)_2 + 4\ SiO_2 + H_2O \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3\ CaCO_3 + 3\ CO_2$ Ecoinvent has data related to dolomite production at plant. Industrial machineries and other resources as input as well as emissions for the production of Talc are assumed from the 1 kg dolomite production at plant from Ecoinvent database V 2.2.
Kaolin Alumina Aluminum hydroxide Silica	Ecoinvent V 2.2 unit process database is used. The unit processes used are-kaolin, at plant; aluminium oxide, at plant; aluminium hydroxide, at plant; and silica sand, at plant.
Wash coating and PGM coating of ceramic monolith	Process input resources and emissions data are assumed from ceramic tiles production of Ecoinvent database.
Materials for Wash coating and PGM coating	
Alumina Zirconium oxide Cerium oxide Acetic acid Water	Ecoinvent unit process database V 2.2 is used. The unit processes for materials used are aluminium oxide, at plant; zirconium oxide, at plant; cerium oxide, at plant; acetic acid, at plant.
Platinum Palladium Rhodium	Ecoinvent unit process database V 2.2 is used. The unit processes for materials used are platinum, primary and secondary; palladium, primary and secondary; and rhodium, primary and secondary.
Insulating mat production	Energy and other resources input as well as emissions from production assumed from tube insulation materials process data of Ecoinvent V 2.2.

Component/Materials	Data base source and processes
Materials for insulating mat	
Acrylic binder Alumina Silica Vermiculite	Ecoinvent unit process database V 2.2 is used. The unit processes for materials used are acrylic binder, alumina, ailica sand, and vermiculite.
Steel housing and heat shield manufacturing	Process input resources are assumed from average metal working of stainless steel and aluminium of Ecoinvent V 2.2.
Materials for steel housing and heat shield	
Stainless steel Aluminized steel (Composition 90% aluminium, and 10% silicon)	Ecoinvent unit process data base V 2.2 is used. The unit processes for materials used are chromium 18/8 stainless steel, Aluminium production mix, and Silica sand at plant.
Assembly of catalytic converter component and installation into the car.	Electricity needed for the assembly of different component of catalytic converter and installation into the car is assumed from total electricity (891.67 KWh) needed for light weight concept passenger car of 550 kg in Ecoinvent V 2.2. The average weight percentage different component of catalytic converter is 0.5%, hence electricity input assumed for this processes is 4.5 KWh (891.67×0.5%)

Appendix A.6: Input materials for the baseline production system.

Input materials	Unit	Quantity
Aluminium, 24% in bauxite, 11% in crude ore, in ground	kg	1.733383
Anhydrite, in ground	kg	0.000372
Barite, 15% in crude ore, in ground	kg	0.25846
Basalt, in ground	kg	0.065359
Borax, in ground	kg	0.000433
Cadmium, 0.30% in sulfide, Cd 0.18%, Pb, Zn, Ag, In, in ground	kg	2.67E-05
Calcium carbonate, in ground	kg	39.50757
Cerium, 24% in bastnasite, 2.4% in crude ore, in ground	kg	0.040839
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	kg	1.319681
Chrysotile, in ground	kg	0.000695
Cinnabar, in ground	kg	6.42E-05
Clay, bentonite, in ground	kg	0.285943
Clay, unspecified, in ground	kg	37.13134
Coal, brown, in ground	kg	71.94004
Coal, hard, unspecified, in ground	kg	71.88562
Cobalt, in ground	kg	0.00018
Colemanite, in ground	kg	29.25925
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	kg	0.01354
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	kg	0.074395
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	kg	0.019734
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	kg	0.098464
Diatomite, in ground	kg	1.18E-08
Dolomite, in ground	kg	0.970588
Europium, 0.06% in bastnasite, 0.006% in crude ore, in ground	kg	0.000102
Feldspar, in ground	kg	1.09E-07
Fluorine, 4.5% in apatite, 1% in crude ore, in ground	kg	0.008131
Fluorine, 4.5% in apatite, 3% in crude ore, in ground	kg	0.003569
Fluorspar, 92%, in ground	kg	0.531631
Gadolinium, 0.15% in bastnasite, 0.015% in crude ore, in ground	kg	0.000255
Gallium, 0.014% in bauxite, in ground	kg	1.2E-09
Gas, mine, off-gas, process, coal mining	m3	0.669204
Gas, natural, in ground	m3	110.2726
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	kg	4.58E-07
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	kg	8.4E-07
Gold, Au 1.4E-4%, in ore, in ground	kg	1.01E-06
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	kg	1.54E-06
Gold, Au 4.3E-4%, in ore, in ground	kg	3.81E-07
Gold, Au 4.9E-5%, in ore, in ground	kg	9.12E-07

Input materials	Unit	Quantity
Gold, Au 6.7E-4%, in ore, in ground	kg	1.41E-06
Gold, Au 7.1E-4%, in ore, in ground	kg	1.59E-06
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	9.54E-08
Granite, in ground	kg	6.65E-10
Gravel, in ground	kg	75.02931
Gypsum, in ground	kg	0.000102
Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd, in ground	kg	5.05E-07
Iron, 46% in ore, 25% in crude ore, in ground	kg	21.04545
Kaolinite, 24% in crude ore, in ground	kg	0.381756
Kieserite, 25% in crude ore, in ground	kg	5.21E-06
Lanthanum, 7.2% in bastnasite, 0.72% in crude ore, in ground	kg	0.012243
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	kg	0.002853
Lithium, 0.15% in brine, in ground	kg	9.46E-10
Magnesite, 60% in crude ore, in ground	kg	0.307585
Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	kg	0.014602
Metamorphous rock, graphite containing, in ground	kg	0.001656
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground	kg	0.00183
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground	kg	0.000259
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground	kg	0.00018
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground	kg	0.00095
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground	kg	0.000359
Neodymium, 4% in bastnasite, 0.4% in crude ore, in ground	kg	0.006734
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76% in crude ore, in ground	kg	0.000668
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	kg	3.168887
Oil, crude, in ground	kg	64.01204
Olivine, in ground	kg	0.000147
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	0.002964
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	2.9E-07
Phosphorus, 18% in apatite, 12% in crude ore, in ground	kg	0.037083
Phosphorus, 18% in apatite, 4% in crude ore, in ground	kg	0.032524
Praseodymium, 0.42% in bastnasite, 0.042% in crude ore, in ground	kg	0.000714
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	3.97E-09
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	0.002902
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3E+0%, Cu 3.2E+0% in ore, in ground	kg	1.13E-09
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%, Cu 5.2E-2% in ore, in ground	kg	0.000473
Rhenium, in crude ore, in ground	kg	1.04E-09
Samarium, 0.3% in bastnasite, 0.03% in crude ore, in ground	kg	0.00051

Input materials	Unit	Quantity
Sand, unspecified, in ground	kg	0.006791
Shale, in ground	kg	0.001053
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In, in ground	kg	1.02E-05
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te, in crude ore, in ground	kg	7.3E-06
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	kg	6.74E-07
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	kg	1.54E-06
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	kg	1.51E-06
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%, Pb 0.014%, in ore, in ground	kg	9.96E-07
Sodium chloride, in ground	kg	24.62992
Sodium nitrate, in ground	kg	5.15E-10
Sodium sulphate, various forms, in ground	kg	0.070416
Stibnite, in ground	kg	1.23E-09
Sulfur, in ground	kg	0.607154
Sylvite, 25 % in sylvinite, in ground	kg	0.00089
Talc, in ground	kg	0.000173
Tantalum, 81.9% in tantalite, 1.6E-4% in crude ore, in ground	kg	8.06E-06
Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag, in crude ore, in ground	kg	1.1E-06
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	kg	0.00644
TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	kg	0.128585
TiO2, 95% in rutile, 0.40% in crude ore, in ground	kg	5.84E-08
Ulexite, in ground	kg	5.8E-05
Uranium, in ground	kg	0.003147
Vermiculite, in ground	kg	0.07467
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	kg	0.052354
Zirconium, 50% in zircon, 0.39% in crude ore, in ground	kg	0.102665
Bromine, 0.0023% in water	kg	2.69E-07
Iodine, 0.03% in water	kg	6.94E-08
Magnesium, 0.13% in water	kg	4.05E-06
Peat, in ground	kg	0.037516
Wood, hard, standing	m3	0.002078
Wood, primary forest, standing	m3	1.55E-06
Wood, soft, standing	m3	0.006055
Wood, unspecified, standing	m3	2.76E-05

Appendix A.7: Environmental emission from the baseline production system.

Flow	Category	Sub-category	Unit	Quantity
1,4-Butanediol	air	high population density	kg	2.71E-09
1-Pentanol	air	high population density	kg	1.79E-11
1-Pentene	air	high population density	kg	1.35E-11
2-Aminopropanol	air	high population density	kg	2.18E-12
2-Methyl-1-propanol	air	high population density	kg	3.65E-11
2-Methyl-2-butene	air	high population density	kg	3E-15
2-Nitrobenzoic acid	air	high population density	kg	3.76E-12
2-Propanol	air	high population density	kg	4.98E-05
Acenaphthene	air	high population density	kg	5.14E-10
Acetaldehyde	air	high population density	kg	0.001911
Acetic acid	air	high population density	kg	0.009058
Acetone	air	high population density	kg	0.000117
Acrolein	air	high population density	kg	3.36E-08
Acrylic acid	air	high population density	kg	1.29E-07
Aldehydes, unspecified	air	high population density	kg	5.77E-05
Aluminium	air	high population density	kg	0.002609
Ammonia	air	high population density	kg	0.009644
Ammonium carbonate	air	high population density	kg	3.96E-07
Aniline	air	high population density	kg	1.71E-10
Anthranilic acid	air	high population density	kg	2.74E-12
Antimony	air	high population density	kg	0.002212
Arsenic	air	high population density	kg	0.001337
Arsine	air	high population density	kg	1.5E-12
Barium	air	high population density	kg	3.1E-05
Benzaldehyde	air	high population density	kg	1.75E-08
Benzene	air	high population density	kg	0.023806
Benzene, dichloro	air	high population density	kg	9.38E-11
Benzene, ethyl-	air	high population density	kg	6.12E-05
Benzene, hexachloro-	air	high population density	kg	1.75E-09
Benzene, pentachloro-	air	high population density	kg	4.39E-09
Benzo(a)pyrene	air	high population density	kg	5.97E-08
Beryllium	air	high population density	kg	3.16E-07
Boron	air	high population density	kg	0.00012
Boron trifluoride	air	high population density	kg	2.05E-14
Bromine	air	high population density	kg	6.22E-06
Butadiene	air	high population density	kg	1.15E-11
Butane	air	high population density	kg	0.003377
Butanol	air	high population density	kg	1.5E-11
Butene	air	high population density	kg	3.3E-05

Butyrolactone	air	high population density	kg	7.73E-10
Cadmium	air	high population density	kg	0.000447
Calcium	air	high population density	kg	0.000637
Carbon dioxide, biogenic	air	high population density	kg	7.028338
Carbon dioxide, fossil	air	high population density	kg	307.3641
Carbon disulfide	air	high population density	kg	5.21E-09
Carbon monoxide, biogenic	air	high population density	kg	0.001024
Carbon monoxide, fossil	air	high population density	kg	0.346318
Chloramine	air	high population density	kg	6.71E-11
Chlorine	air	high population density	kg	0.027089
Chloroacetic acid	air	high population density	kg	8.79E-09
Chloroform	air	high population density	kg	1.8E-07
Chlorosilane, trimethyl-	air	high population density	kg	3.46E-08
Chlorosulfonic acid	air	high population density	kg	2.54E-11
Chromium	air	high population density	kg	0.000175
Chromium VI	air	high population density	kg	7.51E-07
Cobalt	air	high population density	kg	1.28E-05
Copper	air	high population density	kg	0.000199
Cumene	air	high population density	kg	0.006334
Cyanide	air	high population density	kg	2.24E-05
Cyanoacetic acid	air	high population density	kg	2.08E-11
Diethylamine	air	high population density	kg	7.7E-11
Dimethyl malonate	air	high population density	kg	2.6E-11
Dinitrogen monoxide	air	high population density	kg	0.04333
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	air	high population density	kg	2.42E-11
Dipropylamine	air	high population density	kg	4.79E-11
Ethane	air	high population density	kg	0.001589
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air	high population density	kg	1.49E-08
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	air	high population density	kg	6.11E-09
Ethane, 1,1-difluoro-, HFC-152a	air	high population density	kg	1.56E-07
Ethane, 1,2-dichloro-	air	high population density	kg	3.16E-05
Ethane, hexafluoro-, HFC-116	air	high population density	kg	4.25E-07
Ethanol	air	high population density	kg	0.000124
Ethene	air	high population density	kg	0.002622

Ethene, chloro-	air	high population density	kg	9.41E-06
Ethene, tetrachloro-	air	high population density	kg	0.00015
Ethyl acetate	air	high population density	kg	0.000248
Ethyl cellulose	air	high population density	kg	4.68E-07
Ethylamine	air	high population density	kg	4.17E-11
Ethylene diamine	air	high population density	kg	4.44E-10
Ethylene oxide	air	high population density	kg	0.000123
Ethyne	air	high population density	kg	0.000122
Fluorine	air	high population density	kg	2.66E-06
Fluosilicic acid	air	high population density	kg	1.6E-05
Formaldehyde	air	high population density	kg	0.000636
Formamide	air	high population density	kg	3.27E-11
Formic acid	air	high population density	kg	2.89E-07
Heat, waste	air	high population density	MJ	5336.47
Heptane	air	high population density	kg	0.000326
Hexane	air	high population density	kg	0.001216
Hydrocarbons, aliphatic, alkanes, cyclic	air	high population density	kg	0.000299
Hydrocarbons, aliphatic, alkanes, unspecified	air	high population density	kg	0.011719
Hydrocarbons, aliphatic, unsaturated	air	high population density	kg	0.000296
Hydrocarbons, aromatic	air	high population density	kg	0.007789
Hydrocarbons, chlorinated	air	high population density	kg	1.45E-05
Hydrogen	air	high population density	kg	0.019882
Hydrogen chloride	air	high population density	kg	0.015299
Hydrogen fluoride	air	high population density	kg	0.002576
Hydrogen peroxide	air	high population density	kg	3.47E-07
Hydrogen sulfide	air	high population density	kg	1.12E-06
Iodine	air	high population density	kg	2.83E-06
Iron	air	high population density	kg	0.001108
Isocyanic acid	air	high population density	kg	2.73E-06
Isopropylamine	air	high population density	kg	9.48E-12
Lactic acid	air	high population density	kg	3.75E-11
Lead	air	high population density	kg	3.52E-05
Lead-210	air	high population density	kBq	0.011333
m-Xylene	air	high population density	kg	6.31E-06
Magnesium	air	high population density	kg	0.000943
Manganese	air	high population density	kg	1.7E-05
Mercury	air	high population density	kg	1.76E-05

Methane, biogenic	air	high population density	kg	0.001486
Methane, bromotrifluoro-, Halon 1301	air	high population density	kg	5.63E-13
Methane, chlorodifluoro-, HCFC-22	air	high population density	kg	2.37E-07
Methane, dichloro-, HCC-30	air	high population density	kg	1.35E-08
Methane, dichlorodifluoro-, CFC-12	air	high population density	kg	2.16E-07
Methane, dichlorofluoro-, HCFC-21	air	high population density	kg	4.25E-11
Methane, fossil	air	high population density	kg	0.647749
Methane, monochloro-, R-40	air	high population density	kg	2.09E-06
Methane, tetrachloro-, R-10	air	high population density	kg	3.08E-05
Methane, tetrafluoro-, R-14	air	high population density	kg	8.03E-09
Methane, trichlorofluoro-, CFC-11	air	high population density	kg	6.9E-11
Methane, trifluoro-, HFC-23	air	high population density	kg	1.35E-08
Methanesulfonic acid	air	high population density	kg	2.1E-11
Methanol	air	high population density	kg	0.0002
Methyl acetate	air	high population density	kg	8.7E-13
Methyl acrylate	air	high population density	kg	1.46E-07
Methyl amine	air	high population density	kg	3.02E-10
Methyl borate	air	high population density	kg	6.86E-12
Methyl ethyl ketone	air	high population density	kg	0.000231
Methyl formate	air	high population density	kg	5.75E-10
Methyl lactate	air	high population density	kg	4.12E-11
Molybdenum	air	high population density	kg	4.81E-06
Monoethanolamine	air	high population density	kg	6.9E-06
Nickel	air	high population density	kg	0.000435
Nitrate	air	high population density	kg	6.61E-07
Nitrobenzene	air	high population density	kg	2.32E-10
Nitrogen oxides	air	high population density	kg	0.669033
NMVOC, non-methane volatile organic compounds, unspecified origin	air	high population density	kg	0.241398
o-Nitrotoluene	air	high population density	kg	3.24E-12
Ozone	air	high population density	kg	4.18E-06

PAH, polycyclic aromatic hydrocarbons	air	high population density	kg	2.49E-05
Particulates, < 2.5 um	air	high population density	kg	0.035613
Particulates, > 10 um	air	high population density	kg	0.049824
Particulates, > 2.5 um, and < 10um	air	high population density	kg	0.05284
Pentane	air	high population density	kg	0.005083
Phenol	air	high population density	kg	0.004413
Phenol, 2,4-dichloro	air	high population density	kg	1.94E-11
Phenol, pentachloro-	air	high population density	kg	9.07E-10
Phosphine	air	high population density	kg	1.11E-10
Phosphorus	air	high population density	kg	3.24E-05
Platinum	air	high population density	kg	2.38E-12
Polonium-210	air	high population density	kBq	0.020717
Polychlorinated biphenyls	air	high population density	kg	4.69E-12
Potassium	air	high population density	kg	0.001539
Potassium-40	air	high population density	kBq	0.003289
Propanal	air	high population density	kg	2.05E-08
Propane	air	high population density	kg	0.002461
Propanol	air	high population density	kg	5.7E-09
Propene	air	high population density	kg	0.018364
Propionic acid	air	high population density	kg	4.76E-05
Propylamine	air	high population density	kg	1.04E-11
Propylene oxide	air	high population density	kg	0.02048
Radioactive species, other beta emitters	air	high population density	kBq	0.018988
Radium-226	air	high population density	kBq	0.002925
Radium-228	air	high population density	kBq	0.015813
Radon-220	air	high population density	kBq	0.000361
Radon-222	air	high population density	kBq	0.00031
Scandium	air	high population density	kg	3.07E-07
Selenium	air	high population density	kg	4.9E-06
Silicon	air	high population density	kg	0.003929
Silver	air	high population density	kg	2.54E-08
Sodium	air	high population density	kg	0.000366
Sodium chlorate	air	high population density	kg	2.71E-06
Sodium dichromate	air	high population density	kg	6.34E-07
Sodium formate	air	high population density	kg	4.58E-08
Sodium hydroxide	air	high population density	kg	1.29E-06
Strontium	air	high population density	kg	4.62E-05
Styrene	air	high population density	kg	2.72E-06

Sulfate	air	high population density	kg	0.088457
Sulfur dioxide	air	high population density	kg	0.832274
Sulfuric acid	air	high population density	kg	2.71E-07
Sulphur trioxide	air	high population density	kg	1.88E-09
t-Butyl methyl ether	air	high population density	kg	1.61E-07
t-Butylamine	air	high population density	kg	2.38E-11
Thallium	air	high population density	kg	3.85E-07
Thorium	air	high population density	kg	4.62E-07
Thorium-228	air	high population density	kBq	0.001339
Thorium-232	air	high population density	kBq	0.000853
Tin	air	high population density	kg	3.7E-07
Titanium	air	high population density	kg	9.26E-05
Toluene	air	high population density	kg	0.000698
Toluene, 2-chloro	air	high population density	kg	7.27E-11
Trimethylamine	air	high population density	kg	1.55E-12
Uranium	air	high population density	kg	6.15E-07
Uranium-238	air	high population density	kBq	0.002437
Vanadium	air	high population density	kg	0.00049
Water	air	high population density	kg	2.240075
Xylene	air	high population density	kg	0.0002
Zinc	air	high population density	kg	0.0002
Acenaphthene	air	low population density	kg	1.34E-11
Acetaldehyde	air	low population density	kg	5.91E-07
Acetic acid	air	low population density	kg	3.89E-06
Acetone	air	low population density	kg	1.85E-05
Acetonitrile	air	low population density	kg	1.63E-07
Acrolein	air	low population density	kg	2.96E-08
Actinides, radioactive, unspecified	air	low population density	kBq	5.44E-05
Aerosols, radioactive, unspecified	air	low population density	kBq	0.001308
Aldehydes, unspecified	air	low population density	kg	2.4E-06
Aluminium	air	low population density	kg	0.00013
Ammonia	air	low population density	kg	0.00099
Antimony	air	low population density	kg	0.000116
Antimony-124	air	low population density	kBq	7.1E-09
Antimony-125	air	low population density	kBq	7.41E-08
Argon-41	air	low population density	kBq	0.663177
Arsenic	air	low population density	kg	9.26E-05
Barium	air	low population density	kg	2.81E-05
Barium-140	air	low population density	kBq	4.82E-06

Benzene	air	low population density	kg	0.000843
Benzene, ethyl-	air	low population density	kg	2.47E-09
Benzo(a)pyrene	air	low population density	kg	3.69E-06
Beryllium	air	low population density	kg	1.49E-06
Boron	air	low population density	kg	0.001855
Bromine	air	low population density	kg	0.000205
Butadiene	air	low population density	kg	2.13E-08
Butane	air	low population density	kg	0.000681
Cadmium	air	low population density	kg	1.83E-05
Calcium	air	low population density	kg	1.66E-05
Carbon dioxide, biogenic	air	low population density	kg	0.913976
Carbon dioxide, fossil	air	low population density	kg	145.0836
Carbon dioxide, land transformation	air	low population density	kg	0.01699
Carbon disulfide	air	low population density	kg	0.138537
Carbon monoxide, biogenic	air	low population density	kg	0.001536
Carbon monoxide, fossil	air	low population density	kg	0.076395
Carbon-14	air	low population density	kBq	5.318773
Cerium-141	air	low population density	kBq	1.17E-06
Cesium-134	air	low population density	kBq	5.6E-08
Cesium-137	air	low population density	kBq	9.92E-07
Chlorine	air	low population density	kg	7.08E-07
Chloroform	air	low population density	kg	2.57E-09
Chromium	air	low population density	kg	0.004584
Chromium VI	air	low population density	kg	0.000113
Chromium-51	air	low population density	kBq	7.49E-08
Cobalt	air	low population density	kg	0.000107
Cobalt-58	air	low population density	kBq	1.04E-07
Cobalt-60	air	low population density	kBq	9.21E-07
Copper	air	low population density	kg	0.000431
Cumene	air	low population density	kg	1.43E-10
Cyanide	air	low population density	kg	5.18E-05
Dinitrogen monoxide	air	low population density	kg	0.002521
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	air	low population density	kg	4.88E-11
Ethane	air	low population density	kg	0.013316
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air	low population density	kg	1.28E-07

Ethane, 1,1,1-trichloro-, HCFC-140	air	low population density	kg	5.25E-10
Ethane, 1,2-dichloro-	air	low population density	kg	1.05E-09
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	air	low population density	kg	2.2E-06
Ethanol	air	low population density	kg	6.74E-07
Ethene	air	low population density	kg	0.00037
Ethene, tetrachloro-	air	low population density	kg	1.13E-09
Ethylene oxide	air	low population density	kg	2.06E-07
Ethyne	air	low population density	kg	1.19E-05
Fluorine	air	low population density	kg	0.000535
Formaldehyde	air	low population density	kg	8.57E-05
Formic acid	air	low population density	kg	1.09E-06
Furan	air	low population density	kg	3.09E-07
Heat, waste	air	low population density	MJ	2483.901
Helium	air	low population density	kg	8.04E-05
Hexane	air	low population density	kg	5.14E-05
Hydrocarbons, aliphatic, alkanes, cyclic	air	low population density	kg	1.52E-08
Hydrocarbons, aliphatic, alkanes, unspecified	air	low population density	kg	0.001022
Hydrocarbons, aliphatic, unsaturated	air	low population density	kg	0.00029
Hydrocarbons, aromatic	air	low population density	kg	0.000386
Hydrocarbons, chlorinated	air	low population density	kg	9.25E-07
Hydrogen chloride	air	low population density	kg	0.012172
Hydrogen fluoride	air	low population density	kg	0.002827
Hydrogen sulfide	air	low population density	kg	0.002119
Hydrogen-3, Tritium	air	low population density	kBq	30.76714
Iodine	air	low population density	kg	0.00011
Iodine-129	air	low population density	kBq	0.005372
Iodine-131	air	low population density	kBq	0.262359
Iodine-133	air	low population density	kBq	1.23E-05
Iodine-135	air	low population density	kBq	1.42E-05
Iron	air	low population density	kg	8.17E-05
Isoprene	air	low population density	kg	1.43E-08
Krypton-85	air	low population density	kBq	2.076358
Krypton-85m	air	low population density	kBq	0.102683
Krypton-87	air	low population density	kBq	0.040672
Krypton-88	air	low population density	kBq	0.040145

Krypton-89	air	low population density	kBq	0.010329
Lanthanum-140	air	low population density	kBq	4.12E-07
Lead	air	low population density	kg	0.000349
Lead-210	air	low population density	kBq	0.028788
Magnesium	air	low population density	kg	4.71E-05
Manganese	air	low population density	kg	0.000561
Manganese-54	air	low population density	kBq	3.84E-08
Mercury	air	low population density	kg	6.55E-06
Methane, biogenic	air	low population density	kg	0.004047
Methane, bromochlorodifluoro-, Halon 1211	air	low population density	kg	3.88E-06
Methane, bromotrifluoro-, Halon 1301	air	low population density	kg	9E-07
Methane, chlorodifluoro-, HCFC-22	air	low population density	kg	1.47E-05
Methane, dichloro-, HCC-30	air	low population density	kg	7.61E-09
Methane, dichlorodifluoro-, CFC-12	air	low population density	kg	1.32E-08
Methane, fossil	air	low population density	kg	0.823757
Methane, monochloro-, R-40	air	low population density	kg	1.39E-08
Methanol	air	low population density	kg	0.001429
Molybdenum	air	low population density	kg	1.65E-06
Nickel	air	low population density	kg	0.000275
Niobium-95	air	low population density	kBq	4.55E-09
Nitrate	air	low population density	kg	7.3E-06
Nitrogen oxides	air	low population density	kg	0.305316
NMVOC, non-methane volatile organic compounds, unspecified origin	air	low population density	kg	0.0811
Noble gases, radioactive, unspecified	air	low population density	kBq	51623.91
Ozone	air	low population density	kg	4.39E-08
PAH, polycyclic aromatic hydrocarbons	air	low population density	kg	4.65E-06
Particulates, < 2.5 um	air	low population density	kg	0.139282
Particulates, > 10 um	air	low population density	kg	0.541174
Particulates, > 2.5 um, and < 10um	air	low population density	kg	0.3475
Pentane	air	low population density	kg	0.00019

Phenol	air	low population density	kg	9.78E-06
Phenol, pentachloro-	air	low population density	kg	1.45E-06
Phosphorus	air	low population density	kg	1.01E-06
Platinum	air	low population density	kg	7.24E-11
Plutonium-238	air	low population density	kBq	7.33E-10
Plutonium-alpha	air	low population density	kBq	1.68E-09
Polonium-210	air	low population density	kBq	0.050624
Potassium	air	low population density	kg	1.63E-05
Potassium-40	air	low population density	kBq	0.006416
Propane	air	low population density	kg	0.003899
Propene	air	low population density	kg	4.5E-05
Protactinium-234	air	low population density	kBq	0.000733
Radioactive species, other beta emitters	air	low population density	kBq	3.06E-05
Radium-226	air	low population density	kBq	0.032209
Radium-228	air	low population density	kBq	0.002421
Radon-220	air	low population density	kBq	0.293608
Radon-222	air	low population density	kBq	2258.368
Ruthenium-103	air	low population density	kBq	1E-09
Scandium	air	low population density	kg	4.64E-08
Selenium	air	low population density	kg	2.05E-05
Silicon	air	low population density	kg	0.000308
Silicon tetrafluoride	air	low population density	kg	2.46E-07
Silver	air	low population density	kg	1.22E-10
Silver-110	air	low population density	kBq	9.91E-09
Sodium	air	low population density	kg	8.74E-06
Strontium	air	low population density	kg	2.77E-05
Styrene	air	low population density	kg	1.91E-08
Sulfate	air	low population density	kg	5.51E-05
Sulfur dioxide	air	low population density	kg	1.692165
Sulfur hexafluoride	air	low population density	kg	1.73E-08
Sulfuric acid	air	low population density	kg	1.55E-10
Terpenes	air	low population density	kg	1.35E-07
Thallium	air	low population density	kg	8.24E-09
Thorium	air	low population density	kg	3E-08
Thorium-228	air	low population density	kBq	0.001305
Thorium-230	air	low population density	kBq	0.003156
Thorium-232	air	low population density	kBq	0.006498
Thorium-234	air	low population density	kBq	0.000733
Tin	air	low population density	kg	4.44E-05
Titanium	air	low population density	kg	4.62E-06
Toluene	air	low population density	kg	0.000175

Tungsten	air	low population density	kg	2.19E-09
Uranium	air	low population density	kg	1.53E-08
Uranium alpha	air	low population density	kBq	0.039834
Uranium-234	air	low population density	kBq	0.00897
Uranium-235	air	low population density	kBq	0.000414
Uranium-238	air	low population density	kBq	0.014024
Vanadium	air	low population density	kg	8.38E-06
Water	air	low population density	kg	0.001398
Xenon-131m	air	low population density	kBq	0.18728
Xenon-133	air	low population density	kBq	5.97447
Xenon-133m	air	low population density	kBq	0.025196
Xenon-135	air	low population density	kBq	2.448316
Xenon-135m	air	low population density	kBq	1.44575
Xenon-137	air	low population density	kBq	0.028314
Xenon-138	air	low population density	kBq	0.248569
Xylene	air	low population density	kg	0.00121
Zinc	air	low population density	kg	0.000895
Zinc-65	air	low population density	kBq	1.92E-07
Zirconium	air	low population density	kg	3.7E-07
Zirconium-95	air	low population density	kBq	1.87E-07
Aluminium	air	low population density, long-term	kg	0.002473
Antimony	air	low population density, long-term	kg	2.23E-07
Arsenic	air	low population density, long-term	kg	1.31E-05
Barium	air	low population density, long-term	kg	1.43E-05
Beryllium	air	low population density, long-term	kg	3.12E-07
Boron	air	low population density, long-term	kg	4.16E-06
Cadmium	air	low population density, long-term	kg	3.38E-07
Calcium	air	low population density, long-term	kg	0.000804
Chlorine	air	low population density, long-term	kg	3.07E-05
Chromium VI	air	low population density, long-term	kg	1.59E-06
Cobalt	air	low population density, long-term	kg	1.99E-06
Copper	air	low population density, long-term	kg	2.09E-05
Fluorine	air	low population density, long-term	kg	0.000151
Iron	air	low population density, long-term	kg	0.002689

Lead	air	low population density, long-term	kg	2.22E-05
Magnesium	air	low population density, long-term	kg	0.000247
Manganese	air	low population density, long-term	kg	5.56E-05
Mercury	air	low population density, long-term	kg	1.7E-07
Molybdenum	air	low population density, long-term	kg	4.3E-06
Nickel	air	low population density, long-term	kg	4.54E-06
Nitrate	air	low population density, long-term	kg	2.12E-05
Particulates, < 2.5 um	air	low population density, long-term	kg	0.001973
Particulates, > 10 um	air	low population density, long-term	kg	0.004933
Particulates, > 2.5 um, and < 10um	air	low population density, long-term	kg	0.00296
Phosphorus	air	low population density, long-term	kg	4.16E-06
Potassium	air	low population density, long-term	kg	0.000423
Radon-222	air	low population density, long-term	kBq	94597.95
Scandium	air	low population density, long-term	kg	8.85E-06
Selenium	air	low population density, long-term	kg	1.24E-06
Silicon	air	low population density, long-term	kg	0.000551
Silver	air	low population density, long-term	kg	3.7E-07
Sodium	air	low population density, long-term	kg	0.000145
Strontium	air	low population density, long-term	kg	8.99E-06
Sulfate	air	low population density, long-term	kg	0.002277
Tin	air	low population density, long-term	kg	5.16E-07
Titanium	air	low population density, long-term	kg	0.000161
Tungsten	air	low population density, long-term	kg	1E-06
Vanadium	air	low population density, long-term	kg	1.53E-05
Zinc	air	low population density, long-term	kg	1.59E-05
Benzene	air	lower stratosphere + upper troposphere	kg	1.37E-07
Butadiene	air	lower stratosphere + upper troposphere	kg	1.3E-07

Cadmium	air	lower stratosphere + upper troposphere	kg	6.85E-11
Carbon dioxide, fossil	air	lower stratosphere + upper troposphere	kg	0.021585
Carbon monoxide, fossil	air	lower stratosphere + upper troposphere	kg	2.54E-05
Chromium	air	lower stratosphere + upper troposphere	kg	3.43E-10
Copper	air	lower stratosphere + upper troposphere	kg	1.16E-08
Dinitrogen monoxide	air	lower stratosphere + upper troposphere	kg	2.06E-07
Ethylene oxide	air	lower stratosphere + upper troposphere	kg	1.25E-06
Formaldehyde	air	lower stratosphere + upper troposphere	kg	1.08E-06
Heat, waste	air	lower stratosphere + upper troposphere	MJ	0.312461
Hydrogen chloride	air	lower stratosphere + upper troposphere	kg	5.89E-09
Lead	air	lower stratosphere + upper troposphere	kg	1.37E-10
Mercury	air	lower stratosphere + upper troposphere	kg	4.8E-13
Methane, fossil	air	lower stratosphere + upper troposphere	kg	3.43E-07
Nickel	air	lower stratosphere + upper troposphere	kg	4.8E-10
Nitrogen oxides	air	lower stratosphere + upper troposphere	kg	9.59E-05
NMVOC, non-methane volatile organic compounds, unspecified origin	air	lower stratosphere + upper troposphere	kg	4.6E-06
Particulates, < 2.5 um	air	lower stratosphere + upper troposphere	kg	2.6E-07
Selenium	air	lower stratosphere + upper troposphere	kg	6.85E-11
Sulfur dioxide	air	lower stratosphere + upper troposphere	kg	6.85E-06
Water	air	lower stratosphere + upper troposphere	kg	0.008497
Zinc	air	lower stratosphere + upper troposphere	kg	6.85E-09
Acenaphthene	air	unspecified	kg	1.35E-13
Acetaldehyde	air	unspecified	kg	1.47E-05
Acetic acid	air	unspecified	kg	0.021958
Acrolein	air	unspecified	kg	7.82E-11
Aldehydes, unspecified	air	unspecified	kg	5.75E-10
Aluminium	air	unspecified	kg	0.014617
Ammonia	air	unspecified	kg	0.008185

Antimony	air	unspecified	kg	5.75E-09
Arsenic	air	unspecified	kg	3.46E-08
Barium	air	unspecified	kg	6.41E-11
Benzal chloride	air	unspecified	kg	9.92E-15
Benzene	air	unspecified	kg	8.14E-05
Benzene, hexachloro-	air	unspecified	kg	2.1E-07
Benzo(a)pyrene	air	unspecified	kg	1.62E-06
Beryllium	air	unspecified	kg	8.62E-09
Boron	air	unspecified	kg	3.7E-10
Bromine	air	unspecified	kg	3.02E-10
Butadiene	air	unspecified	kg	3.02E-07
Butane	air	unspecified	kg	1.42E-07
Cadmium	air	unspecified	kg	7.92E-07
Carbon dioxide	air	unspecified	kg	0.33019
Carbon dioxide, biogenic	air	unspecified	kg	0.34171
Carbon dioxide, fossil	air	unspecified	kg	42.62546
Carbon disulfide	air	unspecified	kg	1.84E-15
Carbon monoxide, fossil	air	unspecified	kg	0.714713
Chlorine	air	unspecified	kg	3.67E-08
Chloroform	air	unspecified	kg	8.37E-16
Chromium	air	unspecified	kg	2.81E-05
Chromium VI	air	unspecified	kg	1.77E-09
Cobalt	air	unspecified	kg	1.15E-08
Copper	air	unspecified	kg	2.62E-05
Cumene	air	unspecified	kg	7.51E-17
Cyanide	air	unspecified	kg	3.54E-14
Dinitrogen monoxide	air	unspecified	kg	0.372812
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	air	unspecified	kg	1.7E-10
Ethane	air	unspecified	kg	2.1E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	air	unspecified	kg	1.57E-05
Ethane, 1,1,1-trichloro-, HCFC-140	air	unspecified	kg	1.55E-15
Ethane, hexafluoro-, HFC-116	air	unspecified	kg	1.37E-05
Ethene, chloro-	air	unspecified	kg	5.67E-16
Ethene, tetrachloro-	air	unspecified	kg	1.23E-12
Ethylene oxide	air	unspecified	kg	2.92E-06
Ethyne	air	unspecified	kg	2.86E-06

Fluorine	air	unspecified	kg	2.78E-09
Formaldehyde	air	unspecified	kg	0.000109
Furan	air	unspecified	kg	1.2E-16
Heat, waste	air	unspecified	MJ	714.6321
Helium	air	unspecified	kg	1.34E-12
Hexane	air	unspecified	kg	1.22E-07
Hydrocarbons, aliphatic, alkanes, unspecified	air	unspecified	kg	0.002495
Hydrocarbons, aliphatic, unsaturated	air	unspecified	kg	1.14E-10
Hydrocarbons, aromatic	air	unspecified	kg	0.00081
Hydrocarbons, chlorinated	air	unspecified	kg	7.35E-06
Hydrogen	air	unspecified	kg	0.0013
Hydrogen chloride	air	unspecified	kg	0.00194
Hydrogen fluoride	air	unspecified	kg	0.00057
Hydrogen sulfide	air	unspecified	kg	0.000339
Iodine	air	unspecified	kg	1.54E-10
Iron	air	unspecified	kg	0.000171
Isoprene	air	unspecified	kg	1.61E-15
Lead	air	unspecified	kg	8.66E-05
Lead-210	air	unspecified	kBq	6.41E-08
Magnesium	air	unspecified	kg	2.91E-10
Manganese	air	unspecified	kg	2.24E-05
Mercury	air	unspecified	kg	2.49E-05
Methane, biogenic	air	unspecified	kg	0.006545
Methane, bromo-, Halon 1001	air	unspecified	kg	2.27E-15
Methane, dichlorodifluoro-, CFC-12	air	unspecified	kg	1.51E-15
Methane, fossil	air	unspecified	kg	0.02306
Methane, tetrachloro-, R-10	air	unspecified	kg	6.74E-13
Methane, tetrafluoro-, R-14	air	unspecified	kg	0.000123
Methanol	air	unspecified	kg	0.011067
Molybdenum	air	unspecified	kg	2.14E-10
Nickel	air	unspecified	kg	1.54E-05
Nitrogen oxides	air	unspecified	kg	0.281692
NMVOC, non-methane volatile organic compounds, unspecified origin	air	unspecified	kg	0.038741
Ozone	air	unspecified	kg	0.00187

PAH, polycyclic aromatic hydrocarbons	air	unspecified	kg	6.85E-05
Particulates, < 2.5 um	air	unspecified	kg	0.042783
Particulates, > 10 um	air	unspecified	kg	0.005907
Particulates, > 2.5 um, and < 10um	air	unspecified	kg	0.005627
Pentane	air	unspecified	kg	1.76E-07
Phenol	air	unspecified	kg	6.31E-07
Phosphorus	air	unspecified	kg	3.89E-08
Polonium-210	air	unspecified	kBq	1.17E-07
Polychlorinated biphenyls	air	unspecified	kg	3.53E-07
Potassium-40	air	unspecified	kBq	1.58E-08
Propanal	air	unspecified	kg	5.38E-15
Propane	air	unspecified	kg	1.08E-07
Propene	air	unspecified	kg	1.36E-10
Propionic acid	air	unspecified	kg	2.45E-09
Radium-226	air	unspecified	kBq	1.65E-08
Radium-228	air	unspecified	kBq	4.9E-09
Radon-220	air	unspecified	kBq	3.44E-07
Radon-222	air	unspecified	kBq	1.93E-07
Selenium	air	unspecified	kg	6.17E-08
Silicon	air	unspecified	kg	5.3E-12
Sodium	air	unspecified	kg	8.81E-09
Strontium	air	unspecified	kg	5.85E-11
Styrene	air	unspecified	kg	3.54E-16
Sulfate	air	unspecified	kg	3.61E-08
Sulfur dioxide	air	unspecified	kg	0.035632
Sulfur hexafluoride	air	unspecified	kg	2.79E-05
Thallium	air	unspecified	kg	3.74E-08
Thorium-228	air	unspecified	kBq	2.64E-09
Thorium-232	air	unspecified	kBq	4.15E-09
Tin	air	unspecified	kg	1.08E-06
Titanium	air	unspecified	kg	2.72E-07
Toluene	air	unspecified	kg	2.28E-05
Uranium-238	air	unspecified	kBq	1.38E-08
Vanadium	air	unspecified	kg	7.62E-07
Water	air	unspecified	kg	0.042284
Water vapour	air	unspecified	kg	0.175
Xylene	air	unspecified	kg	2.02E-05
Zinc	air	unspecified	kg	0.000288
2,4-D	soil	agricultural	kg	5.48E-08

Aclonifen	soil	agricultural	kg	3.14E-08
Aldrin	soil	agricultural	kg	3.31E-09
Aluminium	soil	agricultural	kg	0.000252
Antimony	soil	agricultural	kg	1.08E-05
Arsenic	soil	agricultural	kg	4.83E-06
Atrazine	soil	agricultural	kg	8.69E-10
Barium	soil	agricultural	kg	0.000207
Benomyl	soil	agricultural	kg	3.48E-10
Bentazone	soil	agricultural	kg	1.6E-08
Boron	soil	agricultural	kg	1.89E-05
Cadmium	soil	agricultural	kg	1.96E-06
Calcium	soil	agricultural	kg	0.002317
Carbetamide	soil	agricultural	kg	6.13E-09
Carbofuran	soil	agricultural	kg	1.91E-07
Carbon	soil	agricultural	kg	0.002327
Chloride	soil	agricultural	kg	2.19E-05
Chlorothalonil	soil	agricultural	kg	4.46E-07
Chromium	soil	agricultural	kg	1.99E-05
Cobalt	soil	agricultural	kg	1.82E-07
Copper	soil	agricultural	kg	3.1E-05
Cypermethrin	soil	agricultural	kg	2.71E-08
Fenpiclonil	soil	agricultural	kg	1.86E-08
Glyphosate	soil	agricultural	kg	7.09E-07
Iron	soil	agricultural	kg	0.001145
Lead	soil	agricultural	kg	3.38E-05
Linuron	soil	agricultural	kg	2.43E-07
Magnesium	soil	agricultural	kg	0.000262
Mancozeb	soil	agricultural	kg	5.8E-07
Manganese	soil	agricultural	kg	0.000139
Mercury	soil	agricultural	kg	1.12E-08
Metaldehyde	soil	agricultural	kg	1.27E-09
Metolachlor	soil	agricultural	kg	1.75E-06
Metribuzin	soil	agricultural	kg	2.04E-08
Molybdenum	soil	agricultural	kg	6.02E-08
Napropamide	soil	agricultural	kg	2.24E-09
Nickel	soil	agricultural	kg	1.54E-05
Orbencarb	soil	agricultural	kg	1.1E-07
Phosphorus	soil	agricultural	kg	6.72E-05
Pirimicarb	soil	agricultural	kg	1.52E-09
Potassium	soil	agricultural	kg	0.000374
Silicon	soil	agricultural	kg	0.000785

Strontium	soil	agricultural	kg	4.91E-08
Sulfur	soil	agricultural	kg	0.000177
Sulfuric acid	soil	agricultural	kg	1.67E-10
Tebutam	soil	agricultural	kg	5.32E-09
Teflubenzuron	soil	agricultural	kg	1.36E-09
Thiram	soil	agricultural	kg	6.17E-10
Tin	soil	agricultural	kg	2.15E-05
Titanium	soil	agricultural	kg	9.46E-06
Vanadium	soil	agricultural	kg	2.71E-07
Zinc	soil	agricultural	kg	4.27E-05
Oils, biogenic	soil	forestry	kg	9.23E-05
Oils, unspecified	soil	forestry	kg	0.099212
Aluminium	soil	industrial	kg	0.001028
Arsenic	soil	industrial	kg	4.11E-07
Barium	soil	industrial	kg	0.000514
Boron	soil	industrial	kg	1.03E-05
Calcium	soil	industrial	kg	0.004113
Carbon	soil	industrial	kg	0.003085
Chloride	soil	industrial	kg	0.003599
Chromium	soil	industrial	kg	5.14E-06
Copper	soil	industrial	kg	3.58E-06
Fluoride	soil	industrial	kg	5.14E-05
Glyphosate	soil	industrial	kg	5.61E-06
Heat, waste	soil	industrial	MJ	0.078515
Iron	soil	industrial	kg	0.002057
Magnesium	soil	industrial	kg	0.000823
Manganese	soil	industrial	kg	4.11E-05
Oils, unspecified	soil	industrial	kg	0.000326
Phosphorus	soil	industrial	kg	5.14E-05
Potassium	soil	industrial	kg	0.00036
Silicon	soil	industrial	kg	0.000103
Sodium	soil	industrial	kg	0.002057
Strontium	soil	industrial	kg	1.03E-05
Sulfur	soil	industrial	kg	0.000617
Zinc	soil	industrial	kg	1.54E-05
Boron	soil	unspecified	kg	1.58E-05
Cadmium	soil	unspecified	kg	1.32E-08
Chloride	soil	unspecified	kg	0.016594
Chromium	soil	unspecified	kg	6.29E-08
Chromium VI	soil	unspecified	kg	8.94E-05
Copper	soil	unspecified	kg	5.67E-05

Fluoride	soil	unspecified	kg	6.05E-05
Heat, waste	soil	unspecified	MJ	10.17851
Iron	soil	unspecified	kg	0.010659
Lead	soil	unspecified	kg	5.43E-07
Nickel	soil	unspecified	kg	1.7E-07
Oils, biogenic	soil	unspecified	kg	6.03E-05
Oils, unspecified	soil	unspecified	kg	0.000457
Sodium	soil	unspecified	kg	0.001841
Zinc	soil	unspecified	kg	3.73E-05
Aluminium	water	ground water	kg	0.001554
Ammonium, ion	water	ground water	kg	5E-05
Antimony	water	ground water	kg	2.73E-05
Arsenic, ion	water	ground water	kg	0.000128
Barium	water	ground water	kg	1.03E-05
Beryllium	water	ground water	kg	3.71E-06
BOD5, Biological Oxygen Demand	water	ground water	kg	9.99E-06
Boron	water	ground water	kg	0.020366
Bromine	water	ground water	kg	5.34E-05
Cadmium, ion	water	ground water	kg	1.21E-05
Calcium, ion	water	ground water	kg	0.164313
Chloride	water	ground water	kg	0.659206
Chromium VI	water	ground water	kg	7.07E-05
Chromium, ion	water	ground water	kg	4.63E-06
Cobalt	water	ground water	kg	3.27E-05
COD, Chemical Oxygen Demand	water	ground water	kg	9.99E-06
Copper, ion	water	ground water	kg	7.31E-05
Dissolved solids	water	ground water	kg	0.010737
Fluoride	water	ground water	kg	0.00152
Iodide	water	ground water	kg	6.45E-06
Iron, ion	water	ground water	kg	0.118625
Lead	water	ground water	kg	1.16E-05
Lead-210	water	ground water	kBq	7.85E-05
Magnesium	water	ground water	kg	0.052114
Manganese	water	ground water	kg	0.002125
Mercury	water	ground water	kg	1.38E-07
Molybdenum	water	ground water	kg	0.000272
Nickel, ion	water	ground water	kg	5.51E-05
Nitrate	water	ground water	kg	0.012931
Phosphate	water	ground water	kg	0.514247
Phosphorus	water	ground water	kg	2.63E-08

Polonium-210	water	ground water	kBq	0.000119
Potassium, ion	water	ground water	kg	0.020728
Potassium-40	water	ground water	kBq	9.49E-06
Radium-226	water	ground water	kBq	0.000122
Scandium	water	ground water	kg	1.42E-05
Selenium	water	ground water	kg	3.03E-05
Silicon	water	ground water	kg	0.01233
Silver, ion	water	ground water	kg	9.77E-07
Sodium, ion	water	ground water	kg	0.039433
Solids, inorganic	water	ground water	kg	0.253323
Strontium	water	ground water	kg	0.001232
Sulfate	water	ground water	kg	4.901877
Suspended solids, unspecified	water	ground water	kg	6.73E-05
Thallium	water	ground water	kg	8.52E-07
Thorium-228	water	ground water	kBq	9.63E-07
Thorium-232	water	ground water	kBq	0.00017
Tin, ion	water	ground water	kg	8.06E-06
Titanium, ion	water	ground water	kg	1.28E-05
TOC, Total Organic Carbon	water	ground water	kg	2.02E-08
Tungsten	water	ground water	kg	0.000117
Uranium-238	water	ground water	kBq	4.07E-05
Vanadium, ion	water	ground water	kg	1.06E-05
Zinc, ion	water	ground water	kg	0.000508
Aluminium	water	ground water, long-term	kg	1.114208
Ammonium, ion	water	ground water, long-term	kg	5.84E-05
Antimony	water	ground water, long-term	kg	0.003017
Arsenic, ion	water	ground water, long-term	kg	0.009035
Barium	water	ground water, long-term	kg	0.010268
Beryllium	water	ground water, long-term	kg	0.001359
BOD5, Biological Oxygen Demand	water	ground water, long-term	kg	0.114704
Boron	water	ground water, long-term	kg	0.215216
Bromine	water	ground water, long-term	kg	0.000224
Cadmium, ion	water	ground water, long-term	kg	0.00546
Calcium, ion	water	ground water, long-term	kg	12.84063
Chloride	water	ground water, long-term	kg	0.460507
Chromium VI	water	ground water, long-term	kg	0.006511
Cobalt	water	ground water, long-term	kg	0.022885
COD, Chemical Oxygen Demand	water	ground water, long-term	kg	0.3398
Copper, ion	water	ground water, long-term	kg	0.045733

DOC, Dissolved Organic Carbon	water	ground water, long-term	kg	0.138519
Fluoride	water	ground water, long-term	kg	0.456043
Heat, waste	water	ground water, long-term	MJ	1.075622
Hydrogen sulfide	water	ground water, long-term	kg	0.000148
Iodide	water	ground water, long-term	kg	2.64E-10
Iron, ion	water	ground water, long-term	kg	2.425991
Lead	water	ground water, long-term	kg	0.004922
Magnesium	water	ground water, long-term	kg	7.421158
Manganese	water	ground water, long-term	kg	0.771891
Mercury	water	ground water, long-term	kg	7.18E-05
Molybdenum	water	ground water, long-term	kg	0.005938
Nickel, ion	water	ground water, long-term	kg	0.043924
Nitrate	water	ground water, long-term	kg	0.259953
Nitrite	water	ground water, long-term	kg	3.18E-06
Nitrogen, organic bound	water	ground water, long-term	kg	9.53E-05
Phosphate	water	ground water, long-term	kg	1.282693
Potassium, ion	water	ground water, long-term	kg	4.2347
Scandium	water	ground water, long-term	kg	0.002337
Selenium	water	ground water, long-term	kg	0.00457
Silicon	water	ground water, long-term	kg	8.663938
Silver, ion	water	ground water, long-term	kg	0.000301
Sodium, ion	water	ground water, long-term	kg	3.031513
Strontium	water	ground water, long-term	kg	0.149916
Sulfate	water	ground water, long-term	kg	43.84408
Thallium	water	ground water, long-term	kg	0.000514
Tin, ion	water	ground water, long-term	kg	0.004973
Titanium, ion	water	ground water, long-term	kg	0.039801
TOC, Total Organic Carbon	water	ground water, long-term	kg	0.138519
Tungsten	water	ground water, long-term	kg	0.007235
Vanadium, ion	water	ground water, long-term	kg	0.00546
Zinc, ion	water	ground water, long-term	kg	0.30092
Arsenic, ion	water	lake	kg	5.98E-12
Cadmium, ion	water	lake	kg	5.08E-12
Calcium, ion	water	lake	kg	4.05E-05
Copper, ion	water	lake	kg	2.31E-10
DOC, Dissolved Organic Carbon	water	lake	kg	0.000637
Lead	water	lake	kg	1.51E-11
Mercury	water	lake	kg	1.3E-13
Nickel, ion	water	lake	kg	2.04E-11

Zinc, ion	water	lake	kg	1.48E-11
Acenaphthene	water	ocean	kg	2.89E-09
Acenaphthylene	water	ocean	kg	1.81E-10
Actinides, radioactive, unspecified	water	ocean	kBq	0.008726
Aluminium	water	ocean	kg	0.000325
Ammonium, ion	water	ocean	kg	5.24E-05
AOX, Adsorbable Organic Halogen as Cl	water	ocean	kg	2.06E-07
Arsenic, ion	water	ocean	kg	2.61E-06
Barite	water	ocean	kg	0.01655
Barium	water	ocean	kg	0.000405
Benzene	water	ocean	kg	3.86E-05
Benzene, ethyl-	water	ocean	kg	1.12E-05
BOD5, Biological Oxygen Demand	water	ocean	kg	0.055874
Boron	water	ocean	kg	4.33E-06
Bromine	water	ocean	kg	0.000325
Cadmium, ion	water	ocean	kg	9.74E-07
Calcium, ion	water	ocean	kg	0.049914
Carboxylic acids, unspecified	water	ocean	kg	0.002755
Cesium	water	ocean	kg	4.65E-07
Cesium-137	water	ocean	kBq	0.99988
Chloride	water	ocean	kg	0.23336
Chlorinated solvents, unspecified	water	ocean	kg	1.34E-13
Chromium, ion	water	ocean	kg	2.92E-06
Cobalt	water	ocean	kg	3.01E-08
COD, Chemical Oxygen Demand	water	ocean	kg	0.056477
Copper, ion	water	ocean	kg	9.74E-06
Cyanide	water	ocean	kg	1.61E-05
DOC, Dissolved Organic Carbon	water	ocean	kg	0.018095
Fluoride	water	ocean	kg	0.000418
Glutaraldehyde	water	ocean	kg	2.04E-06
Heat, waste	water	ocean	MJ	0.032188
Hydrocarbons, aliphatic, alkanes, unspecified	water	ocean	kg	6.04E-05
Hydrocarbons, aliphatic, unsaturated	water	ocean	kg	5.58E-06
Hydrocarbons, aromatic	water	ocean	kg	0.000273

Hydrocarbons, unspecified	water	ocean	kg	0.000309
Hydrogen-3, Tritium	water	ocean	kBq	2077.392
Hypochlorite	water	ocean	kg	6.24E-05
Iodide	water	ocean	kg	4.65E-05
Iron, ion	water	ocean	kg	2.64E-05
Lead	water	ocean	kg	5.03E-06
Lead-210	water	ocean	kBq	0.09229
Magnesium	water	ocean	kg	0.002594
Manganese	water	ocean	kg	2.2E-05
Mercury	water	ocean	kg	3.01E-08
Methanol	water	ocean	kg	5.2E-05
Molybdenum	water	ocean	kg	1.08E-07
Nickel, ion	water	ocean	kg	2.34E-06
Nitrate	water	ocean	kg	0.000741
Nitrite	water	ocean	kg	1.35E-05
Nitrogen	water	ocean	kg	3.41E-06
Nitrogen, organic bound	water	ocean	kg	0.000115
Oils, unspecified	water	ocean	kg	0.017743
PAH, polycyclic aromatic hydrocarbons	water	ocean	kg	3.73E-06
Phenol	water	ocean	kg	5.94E-05
Phosphate	water	ocean	kg	0.001557
Phosphorus	water	ocean	kg	4.45E-06
Polonium-210	water	ocean	kBq	0.140842
Potassium, ion	water	ocean	kg	0.001983
Potassium-40	water	ocean	kBq	0.011155
Radioactive species, Nuclides, unspecified	water	ocean	kBq	5.216767
Radium-224	water	ocean	kBq	0.023236
Radium-226	water	ocean	kBq	0.141105
Radium-228	water	ocean	kBq	0.046473
Rubidium	water	ocean	kg	4.65E-06
Selenium	water	ocean	kg	1.62E-07
Silicon	water	ocean	kg	5.06E-07
Silver, ion	water	ocean	kg	2.79E-07
Sodium, ion	water	ocean	kg	0.142658
Strontium	water	ocean	kg	0.000844
Strontium-90	water	ocean	kBq	0.111167
Sulfate	water	ocean	kg	0.080868
Sulfide	water	ocean	kg	2.17E-06

Sulfur	water	ocean	kg	1.06E-05
Suspended solids, unspecified	water	ocean	kg	0.058758
t-Butyl methyl ether	water	ocean	kg	3.43E-06
Thorium-228	water	ocean	kBq	0.094077
Titanium, ion	water	ocean	kg	8.07E-08
TOC, Total Organic Carbon	water	ocean	kg	0.018094
Toluene	water	ocean	kg	6.92E-05
Tributyltin compounds	water	ocean	kg	5.09E-06
Triethylene glycol	water	ocean	kg	4.33E-05
Uranium-238	water	ocean	kBq	0.047349
Vanadium, ion	water	ocean	kg	3.24E-07
VOC, volatile organic compounds, unspecified origin	water	ocean	kg	0.000163
Xylene	water	ocean	kg	5.53E-05
Zinc, ion	water	ocean	kg	0.000845
1,4-Butanediol	water	river	kg	1.08E-09
1-Pentanol	water	river	kg	4.29E-11
1-Pentene	water	river	kg	3.24E-11
2-Aminopropanol	water	river	kg	5.45E-12
2-Methyl-1-propanol	water	river	kg	8.76E-11
2-Methyl-2-butene	water	river	kg	7.19E-15
2-Propanol	water	river	kg	5.25E-11
Acenaphthene	water	river	kg	6.44E-09
Acenaphthylene	water	river	kg	4.03E-10
Acetaldehyde	water	river	kg	0.009377
Acetic acid	water	river	kg	0.131335
Acetone	water	river	kg	1.75E-09
Acetonitrile	water	river	kg	1.74E-11
Acetyl chloride	water	river	kg	3.37E-11
Acidity, unspecified	water	river	kg	8.86E-05
Acrylate, ion	water	river	kg	3.05E-07
Aluminium	water	river	kg	0.068916
Ammonium, ion	water	river	kg	0.012284
Aniline	water	river	kg	4.11E-10
Antimony	water	river	kg	0.00017
Antimony-122	water	river	kBq	2.86E-06
Antimony-124	water	river	kBq	0.001443
Antimony-125	water	river	kBq	0.001348

AOX, Adsorbable Organic Halogen as Cl	water	river	kg	6.22E-06
Arsenic, ion	water	river	kg	0.002567
Barium	water	river	kg	0.000943
Barium-140	water	river	kBq	1.25E-05
Benzene	water	river	kg	0.010789
Benzene, chloro-	water	river	kg	7.42E-06
Benzene, ethyl-	water	river	kg	2.48E-05
Beryllium	water	river	kg	5.15E-08
BOD5, Biological Oxygen Demand	water	river	kg	2.531593
Borate	water	river	kg	3.47E-09
Boron	water	river	kg	0.001257
Bromate	water	river	kg	0.003663
Bromide	water	river	kg	2.42E-07
Bromine	water	river	kg	0.001363
Butanol	water	river	kg	8.4E-07
Butene	water	river	kg	9.71E-07
Butyl acetate	water	river	kg	1.09E-06
Butyrolactone	water	river	kg	1.86E-09
Cadmium, ion	water	river	kg	0.000253
Calcium, ion	water	river	kg	0.642412
Carbon disulfide	water	river	kg	2.02E-09
Carbonate	water	river	kg	0.004513
Carboxylic acids, unspecified	water	river	kg	0.00381
Cerium-141	water	river	kBq	5.02E-06
Cerium-144	water	river	kBq	1.53E-06
Cesium	water	river	kg	1.04E-06
Cesium-134	water	river	kBq	0.001243
Cesium-136	water	river	kBq	8.9E-07
Cesium-137	water	river	kBq	0.004101
Chloramine	water	river	kg	6.01E-10
Chlorate	water	river	kg	0.028145
Chloride	water	river	kg	27.31993
Chlorinated solvents, unspecified	water	river	kg	1.12E-05
Chlorine	water	river	kg	6.32E-05
Chloroacetic acid	water	river	kg	3.7E-07
Chloroacetyl chloride	water	river	kg	7.28E-12
Chloroform	water	river	kg	1.71E-08
Chlorosulfonic acid	water	river	kg	6.32E-11

Chromium VI	water	river	kg	0.001166
Chromium, ion	water	river	kg	0.000445
Chromium-51	water	river	kBq	0.0016
Cobalt	water	river	kg	0.000773
Cobalt-57	water	river	kBq	2.83E-05
Cobalt-58	water	river	kBq	0.011743
Cobalt-60	water	river	kBq	0.009213
COD, Chemical Oxygen Demand	water	river	kg	2.65706
Copper, ion	water	river	kg	0.006371
Cumene	water	river	kg	0.015221
Cyanide	water	river	kg	0.00543
Dichromate	water	river	kg	2.33E-06
Diethylamine	water	river	kg	1.85E-10
Dimethylamine	water	river	kg	2.39E-10
Dipropylamine	water	river	kg	1.15E-10
Dissolved solids	water	river	kg	0.025807
DOC, Dissolved Organic Carbon	water	river	kg	0.73485
Ethane, 1,2-dichloro-	water	river	kg	1.83E-06
Ethanol	water	river	kg	4.24E-05
Ethene	water	river	kg	0.000432
Ethene, chloro-	water	river	kg	7.97E-08
Ethyl acetate	water	river	kg	6.52E-06
Ethylamine	water	river	kg	1E-10
Ethylene diamine	water	river	kg	1.07E-09
Ethylene oxide	water	river	kg	1.46E-07
Fluoride	water	river	kg	0.008406
Fluosilicic acid	water	river	kg	2.88E-05
Formaldehyde	water	river	kg	2.75E-07
Formamide	water	river	kg	7.85E-11
Formate	water	river	kg	7.35E-09
Formic acid	water	river	kg	2.28E-11
Heat, waste	water	river	MJ	282.0393
Hydrocarbons, aliphatic, alkanes, unspecified	water	river	kg	0.000135
Hydrocarbons, aliphatic, unsaturated	water	river	kg	1.24E-05
Hydrocarbons, aromatic	water	river	kg	0.000545
Hydrocarbons, unspecified	water	river	kg	0.00137
Hydrogen peroxide	water	river	kg	3.49E-06

Hydrogen sulfide	water	river	kg	1.97E-05
Hydrogen-3, Tritium	water	river	kBq	223.1609
Hydroxide	water	river	kg	9.71E-06
Hypochlorite	water	river	kg	5.95E-05
Iodide	water	river	kg	0.000119
Iodine-131	water	river	kBq	0.000264
Iodine-133	water	river	kBq	7.87E-06
Iron, ion	water	river	kg	0.226146
Iron-59	water	river	kBq	2.16E-06
Isopropylamine	water	river	kg	2.28E-11
Lactic acid	water	river	kg	9.01E-11
Lanthanum-140	water	river	kBq	1.34E-05
Lead	water	river	kg	0.002243
Lead-210	water	river	kBq	0.012885
Lithium, ion	water	river	kg	1.5E-09
m-Xylene	water	river	kg	8.38E-11
Magnesium	water	river	kg	0.009246
Manganese	water	river	kg	0.019248
Manganese-54	water	river	kBq	0.000726
Mercury	water	river	kg	3.21E-05
Methane, dichloro-, HCC-30	water	river	kg	2.6E-05
Methanol	water	river	kg	5.45E-06
Methyl acetate	water	river	kg	2.09E-12
Methyl acrylate	water	river	kg	2.86E-06
Methyl amine	water	river	kg	7.24E-10
Methyl formate	water	river	kg	2.3E-10
Molybdenum	water	river	kg	7.42E-05
Molybdenum-99	water	river	kBq	4.61E-06
Nickel, ion	water	river	kg	0.018936
Niobium-95	water	river	kBq	0.00012
Nitrate	water	river	kg	0.016595
Nitrite	water	river	kg	8.01E-05
Nitrobenzene	water	river	kg	9.28E-10
Nitrogen	water	river	kg	0.005312
Nitrogen, organic bound	water	river	kg	0.018282
o-Dichlorobenzene	water	river	kg	3.6E-07
Oils, unspecified	water	river	kg	0.081191
PAH, polycyclic aromatic hydrocarbons	water	river	kg	5.87E-06
Phenol	water	river	kg	0.004094

Phosphate	water	river	kg	0.000529
Phosphorus	water	river	kg	0.000287
Polonium-210	water	river	kBq	0.012885
Potassium, ion	water	river	kg	0.014257
Potassium-40	water	river	kBq	0.016174
Propanal	water	river	kg	6.21E-11
Propanol	water	river	kg	8.23E-11
Propene	water	river	kg	0.043649
Propionic acid	water	river	kg	5.9E-11
Propylamine	water	river	kg	2.48E-11
Propylene oxide	water	river	kg	0.049279
Protactinium-234	water	river	kBq	0.013514
Radioactive species, alpha emitters	water	river	kBq	0.000277
Radioactive species, Nuclides, unspecified	water	river	kBq	0.015464
Radium-224	water	river	kBq	0.051766
Radium-226	water	river	kBq	8.496977
Radium-228	water	river	kBq	0.103532
Rubidium	water	river	kg	1.04E-05
Ruthenium-103	water	river	kBq	9.72E-07
Scandium	water	river	kg	7.61E-06
Selenium	water	river	kg	1.58E-05
Silicon	water	river	kg	0.014922
Silver, ion	water	river	kg	1.03E-06
Silver-110	water	river	kBq	0.008486
Sodium formate	water	river	kg	1.1E-07
Sodium, ion	water	river	kg	8.562665
Sodium-24	water	river	kBq	3.49E-05
Solids, inorganic	water	river	kg	0.050108
Strontium	water	river	kg	0.001878
Strontium-89	water	river	kBq	0.00016
Strontium-90	water	river	kBq	7.143766
Sulfate	water	river	kg	2.431381
Sulfide	water	river	kg	1.04E-05
Sulfite	water	river	kg	0.000332
Sulfur	water	river	kg	0.000272
Suspended solids, unspecified	water	river	kg	0.03439
t-Butyl methyl ether	water	river	kg	2.79E-09
t-Butylamine	water	river	kg	5.72E-11
Technetium-99m	water	river	kBq	0.000107
Tellurium-123m	water	river	kBq	0.000159

Tellurium-132	water	river	kBq	2.67E-07
Thallium	water	river	kg	6.84E-07
Thorium-228	water	river	kBq	0.207063
Thorium-230	water	river	kBq	1.843853
Thorium-232	water	river	kBq	0.005517
Thorium-234	water	river	kBq	0.013516
Tin, ion	water	river	kg	4.3E-05
Titanium, ion	water	river	kg	5.3E-05
TOC, Total Organic Carbon	water	river	kg	0.737289
Toluene	water	river	kg	0.00012
Toluene, 2-chloro	water	river	kg	1.48E-10
Trimethylamine	water	river	kg	3.72E-12
Tungsten	water	river	kg	6.64E-06
Uranium alpha	water	river	kBq	0.778569
Uranium-234	water	river	kBq	0.016217
Uranium-235	water	river	kBq	0.026758
Uranium-238	water	river	kBq	0.047124
Urea	water	river	kg	7.33E-11
Vanadium, ion	water	river	kg	2.93E-05
VOC, volatile organic compounds, unspecified origin	water	river	kg	0.000396
Xylene	water	river	kg	9.81E-05
Zinc, ion	water	river	kg	0.058818
Zinc-65	water	river	kBq	0.000473
Zirconium-95	water	river	kBq	5.47E-06
Benzene, chloro-	water	river, long-term	kg	7.92E-11
Chloride	water	river, long-term	kg	3.99E-07
4-Methyl-2-pentanone	water	unspecified	kg	5.88E-11
Acetone	water	unspecified	kg	1.4E-10
Acidity, unspecified	water	unspecified	kg	2.95E-09
Aluminium	water	unspecified	kg	4.77E-06
Ammonium, ion	water	unspecified	kg	1.73E-07
Antimony	water	unspecified	kg	1.58E-10
AOX, Adsorbable Organic Halogen as Cl	water	unspecified	kg	2.62E-06
Arsenic, ion	water	unspecified	kg	1.59E-06
Barium	water	unspecified	kg	4E-06
Benzene	water	unspecified	kg	2.35E-08
Benzene, ethyl-	water	unspecified	kg	1.32E-09
Beryllium	water	unspecified	kg	1.41E-10

BOD5, Biological Oxygen Demand	water	unspecified	kg	0.00416
Boron	water	unspecified	kg	4.41E-08
Bromine	water	unspecified	kg	3.01E-06
Cadmium, ion	water	unspecified	kg	5.54E-06
Calcium carbonate	water	unspecified	kg	0.4984
Calcium, ion	water	unspecified	kg	4.51E-05
Chloride	water	unspecified	kg	0.001082
Chromium VI	water	unspecified	kg	2.38E-06
Chromium, ion	water	unspecified	kg	1.43E-05
Cobalt	water	unspecified	kg	3.11E-10
COD, Chemical Oxygen Demand	water	unspecified	kg	0.00497
Copper, ion	water	unspecified	kg	1.65E-05
Cyanide	water	unspecified	kg	1.59E-05
Dissolved solids	water	unspecified	kg	0.000624
DOC, Dissolved Organic Carbon	water	unspecified	kg	0.001139
Fluoride	water	unspecified	kg	0.00015
Formaldehyde	water	unspecified	kg	0.000262
Heat, waste	water	unspecified	MJ	1.195073
Hydrocarbons, unspecified	water	unspecified	kg	4.98E-05
Iron, ion	water	unspecified	kg	0.00052
Lead	water	unspecified	kg	1.16E-05
Lead-210	water	unspecified	kBq	4.06E-06
Lithium, ion	water	unspecified	kg	1.51E-05
m-Xylene	water	unspecified	kg	4.25E-10
Magnesium	water	unspecified	kg	8.8E-06
Manganese	water	unspecified	kg	1.61E-05
Mercury	water	unspecified	kg	9.5E-07
Methanol	water	unspecified	kg	7.87E-05
Molybdenum	water	unspecified	kg	3.23E-10
Nickel, ion	water	unspecified	kg	3.05E-05
o-Xylene	water	unspecified	kg	3.1E-10
Oils, unspecified	water	unspecified	kg	0.000218
Phenol	water	unspecified	kg	2.63E-05
Phosphorus	water	unspecified	kg	2.63E-05
Radium-226	water	unspecified	kBq	1.86E-05
Radium-228	water	unspecified	kBq	2.61E-05
Selenium	water	unspecified	kg	3.12E-11
Silver, ion	water	unspecified	kg	2.94E-08
Sodium, ion	water	unspecified	kg	0.015017

Strontium	water	unspecified	kg	7.65E-07
Sulfate	water	unspecified	kg	4.44E-06
Sulfur	water	unspecified	kg	3.72E-08
Suspended solids, unspecified	water	unspecified	kg	0.004964
Thallium	water	unspecified	kg	3.34E-11
Tin, ion	water	unspecified	kg	1.54E-09
Titanium, ion	water	unspecified	kg	2.42E-09
TOC, Total Organic Carbon	water	unspecified	kg	0.001139
Toluene	water	unspecified	kg	2.23E-08
Vanadium, ion	water	unspecified	kg	3.81E-10
Xylene	water	unspecified	kg	1.12E-08
Zinc, ion	water	unspecified	kg	7.51E-05

Appendix A.8: Energy input (upstream and catalytic converter production processes) for the baseline production system under low and high recycling rate of PGM.

Energy input	Unit	Low recycling rate (5% Pt, 3% Pd and 15% Rh)	High recycling rate (50% Pt, Pd and Rh)
Non-renewable resources - fossil	MJ	9266.65	8788.74
Non-renewable resources - nuclear	MJ	1762.44	1540.68
Renewable resources - solar	MJ	0.43	0.37
Renewable resources - biomass	MJ	88.14	77.80
Non-renewable resources - primary forest	MJ	0.017	0.015
Renewable resources - hydro	MJ	267.94	241.93
Renewable resources - wind	MJ	29.62	25.54