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Environmental Profile of NO_x Reduction by a Photocatalytic Surface Coating and a Vehicle Catalytic Converter

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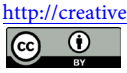

Abstract

Nitrogen oxides (NO_x) in urban air close to ground have significant health implications. Restrictions in traffic, mandatory use of catalytic converters on vehicles, and novel photocatalytic coatings on surfaces contribute to reducing the level of NO_x in cities. The aim of this study is to establish environmental profiles of NO_x removal by a Three-Way Catalyst (TWC) car converter and by a photocatalytic surface coating (for asphalt and concrete pavements) for fostering technological development in reducing the levels of NO_x in urban air. We assessed the environmental performance for the removal of 1 kg NO_x by the two technologies with Life Cycle Assessment (LCA; EF.3 impact assessment method). In order to do so, we established Life-Cycle-Inventory (LCI) data representing production, operation and end-of-life of the two technologies based on data from literature and industry. The production of photocatalytic surface coatings, used on concrete and asphalt, has environmental loads two orders of magnitude lower than the environmental benefits of NO_x reduction expressed as a reduction in Photochemical Ozone Formation (POF), Acidification (A), and Terrestrial Eutrophication (TE). The vehicle catalytic converter shows similar results except that the use of rare earth elements in the production constitutes a significant load to Freshwater Ecotoxicity (FET) and that additional use of fuel during operation induces a modest Climate Change (CC) impact. For both technologies, the environmental benefits of reducing NO_x far exceed any adverse environmental aspects of the production of the technologies.

Keywords

NO_x Removal, Photocatalytic Surfaces, Vehicle Converter, LCA, Environmental Profile

1. Introduction

Nitrogen oxides (NO_x) levels in urban air are monitored routinely in many cities around the world because of the significant effect of nitrogen dioxide (NO_2) on human health [1]. NO_x affects the quality of urban air close to ground, where traffic is the main source of NO_x [2]. The EU has since 2010 prescribed a calendar yearly average urban air quality of max 40 μg/m^3 NO_2 [3]. Nevertheless, streets with intense traffic in Europe often show significantly higher yearly values, in some cases above 80 μg NO_2 per m^3 [4]. Even if the NO_2 is kept 50% below the EU directive limit, severe health impacts are foreseen [1]. For these reasons, vehicles are in many cases met with restrictions in terms of limited access to city centers or in terms of strict exhaust standards demanding the use of catalytic converters for controlling NO_x emissions. New vehicles on the market are equipped with end-of-pipe catalytic converters [5], and even when biofuels are used in vehicles, converters would be required to control exhaust emission [6].

In recent years, the use of photocatalytic surface coatings [7] [8] on pavements, roads and buildings has been introduced with the purpose of reducing NO_x levels in urban air. This technology has, for example, been used in concrete and asphalt pavements, as well as paints [9] [10]. The photocatalytic technology has been tested in several major cities around the world and has been shown to reduce NO_x levels in urban air close to ground [11].

The catalytic converters used by vehicles and the photochemical coatings used on hard surfaces in cities are complementary NO_x-reducing technologies, one regulating NO_x emissions from vehicles, the other reducing NO_x levels in urban air close to ground. However, the two technologies are very different in terms of the resources required for their production, operation and end-of-life (life-cycle stages), as well as their effect on other air pollutants. In terms of environmental sustainability, the two technologies may have an overall different environmental performance, taking into account environmental burdens for their production, operation and end-of-life compared to the benefits of air pollution control. The environmental profile of these technologies must be quantified for a balanced development of their roles and applications in reducing the levels of NO_x in urban air.

Life Cycle Assessment (LCA [12] [13]) is a widely used standardized method for the quantification of potential environmental benefits and burdens connected to products and systems. LCA provides a stringent methodology for formulating and assessing the resources used for the life-cycle stages of products and services: production, operation and end-of-life. In this context, LCA can provide a systematic framework for the assessment of the environmental performance of NO^x-reducing technologies contributing to NO_x removal in urban air.

Few past LCA studies have assessed NO_x reduction via photocatalytic surfaces or end-of-pipe catalytic converters. An LCA study of photocatalytic coating showed environmental benefits with respect to environmental indicators such as

acidification, eutrophication, air pollution and smog formation exceeding the environmental impacts connected to the production phase [14]. Similar findings are presented in another study on highway infrastructure with photocatalytic coating [15]. A comparative LCA on the operation phase of concrete overlays for buildings with and without photocatalytic properties showed the benefits of adding photocatalytic coating with respect to traditional concrete overlays in all indicators considered in the study [16]. The environmental impacts connected to the production, operation and end-of-life of vehicle catalytic converters have also been assessed by a few studies [17] [18]. Belcastro [18] concluded that the majority of impacts were related to the use phase of the car converter, and in spite of additional fuel use, the converter reduced significantly the impacts on human health and ecosystems.

The results of the few LCA studies available in the literature cannot be generalized nor compared for assessing the environmental performance related to the function of NO_x removal. Past LCA studies are often focusing on different products (e.g. concrete overlays or highway infrastructure where NO_x removal is an additional function [15] [16]), on different life-cycle phases of the products (e.g. operational phase only [16]), or simply on different data sources and life cycle modelling assumptions.

The aim of this study is to quantify the potential environmental impacts of reducing NO_x levels in urban air close to ground with two complementary NO_x-reducing technologies: A photocatalytic surface coating and a vehicle catalytic converter. The aim of the assessment is to assess the environmental profile of the two NO_x-reducing technologies separately, in terms of resources required for production, operation and end-of-life of the technologies, opposed to the environmental benefits obtained during operation. This assessment aims to support a balanced development of both NO_x-reducing technologies contributing to the reduction of NOx levels in urban air.

2. Materials and Methods

This study quantifies with LCA the potential environmental impacts connected to two different NO_x-reducing technologies. The following paragraphs report the LCA methodology (2.1) and assessment (2.2). Principles and inventory of photocatalytic surface coatings and principles and inventories of vehicle catalytic converters are presented in the following sections (3.1 and 3.2).

2.1. LCA Methodology

The environmental assessment of the two NO_x-reducing technologies follows the principles of the LCA ISO standard procedure [12] [13]. Moreover, the environmental assessment presented follows the recommendations of the European Union for Product Environmental Footprint (PEF) studies, aiming at increasing the reproducibility, consistency and comparability of environmental assessments of products and services [19] [20] [21].

The two technologies assessed are a photocatalytic surface coating and a vehicle catalytic converter providing the service of reducing NO_x in urban air. The environmental assessment of the two technologies is not a comparative assessment. The study does not aim to benchmark one technology against the other, as they belong to different service groups (manufacture of parts and accessories for motor vehicles and manufacture of chemical products [22]). The intended application of the LCA is to support researchers and developers for both technologies for the development of technology applications for reducing the NO_x levels in urban air.

This study assesses the two technologies in terms of their environmental performance with respect to a common functional unit (FU), which describes the common function provided by both technologies. The FU is complete reduction of NO_x in urban air close to ground throughout the technology lifetime in Europe for the year 2021. The NO_x reduction principles are reported in sections 3.1 and 3.2. The technology lifetime is considered to be 10 - 15 years for both the photocatalytic surface and the vehicle catalytic converter (refer to sections 3.1 and 3.2 for more details). The reference flow represents the amount to which all the resource flows in the environmental assessment are related to: reduction of 1 kg NO_x in urban air close to ground.

Figure 1 provides a generic representation of the system boundaries of the LCA. The LCA takes into account the resources required for production, operation, and end-of-life of the technologies in a gate-to-grave perspective. Examples are materials and energy utilized for the production process. During operation, the system boundaries include removal of NO_x, as well as removal or emissions of additional substances (e.g. pollutants). In the assessment of the two technologies, we pay attention to the following aspects, albeit their significance may vary considerable between the technologies:

- Production: Materials and energy used in producing and applying the technology.
- Operation: Materials and energy used in operating and maintaining the technology.
- End of life: Recycling and final disposal after use.

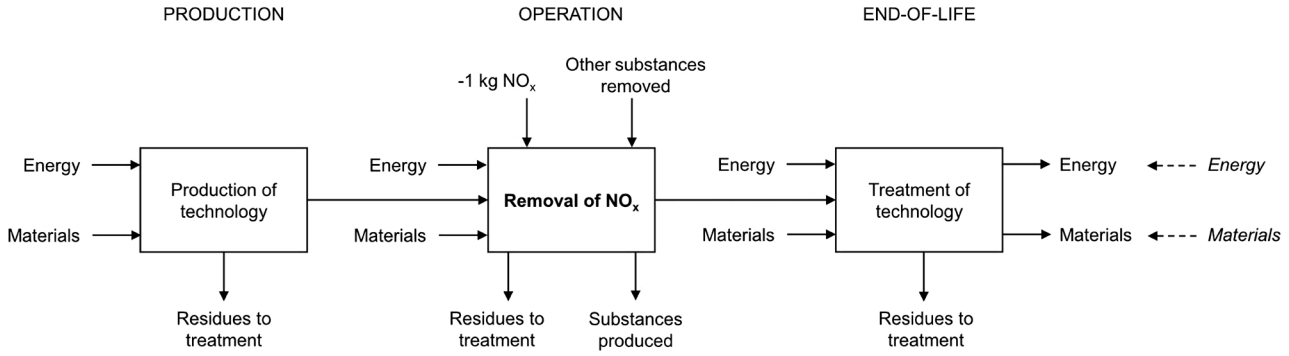

Figure 1. Representation of the system boundaries of the study and the product life-cycle phases considered.

- Removal of NO_x and other air pollutants: Amount removed and end products of removed pollutants within product lifetime.

The life cycle inventory modelling (LCI, *i.e.* the representation of the technologies by means of the flows of resources required for their production, operation, and end-of-life) for both technologies is reported in detail in the following sections (3.1 and 3.2). The LCI modelling of the technologies was compiled based on literature data and personal communication with industry. The LCI modelling approach is attributional, representing flows of resources, and their environmental footprint with average data. The inventories for the resources utilized in the life cycle of the technologies were retrieved from the Ecoinvent database, version 3.7.1, allocation at the point of substitution [23]. Multi functionality, which occurs in the model because the technologies also affect other air pollutants than NO_x, is addressed with system expansion (e.g. further substances removed during operation, recovery of energy, and materials from end-of-life treatment).

2.2. LCA Results Interpretation

The LCIs for the two NO_x-reducing technologies (Section 3) are assessed in terms of environmental impacts (life cycle impact assessment phase, LCIA). The study utilizes the European Commission's recommended Environmental Footprint LCIA methods (EF.3), including 16 midpoint impact categories [24] [25]. The impact categories included are climate change (CC), ozone depletion (OD), human toxicity (cancer, HTC and non-cancer effects, HTNC), particulate matter (PM), ionizing radiation (IR), photochemical ozone formation (POF), acidification (A), eutrophication (terrestrial, TE, aquatic freshwater, FE, and marine, ME), freshwater ecotoxicity (FET), land use (LU), water use (WU), and resource use (minerals and metals, RDM, and energy carriers, RDE). The results presented in this LCA study are generic midpoint impact potentials and do not predict impacts on category endpoints, threshold levels, safety margins or risk levels, nor impacts associated with any specific application. LCA results are further normalizes as person equivalents (PE) based on the global normalization factors of Sala *et al.* [26].

The time horizon of the inventory is the lifetime of the technologies (10 to 15 years), while the time horizon of the impact characterization is 100 years. We estimate that data collected and used for the LCIs of the two NO_x-reducing technologies is representative of their current technological performance and valid for the next 10 years (in accordance to the lifetime of the technologies).

The result assessment phase involved quantifying the relative contribution of each process involved in the life-cycle of each technology, for each impact category assessed. The results focused on the benefits of NO_x reduction versus the environmental burdens connected to provision of resources required to produce, operate, and dispose the technologies. Although characterized and normalized results are reported for all impact categories in the Supplementary Material (SM), the focus of the manuscript is placed on the impact categories of POF,

PM, A, TE, FEM ME, and CC. The results obtained are discussed with respect to assumptions adopted for the study and with respect to previous literature findings.

The LCA was carried out with the LCA model EASETECH, developed at the Technical University of Denmark [27]. Microsoft Excel was used for calculating the LCIs and for the interpretation and analysis of the results of the LCA model.

3. NO_x Removal Principles and LCIs

The following sections summarize the principles of photocatalytic reduction for the two NO_x-reducing technologies (3.1.1 and 3.2.1), the technologies and their life-cycle phases (3.1.2 and 3.2.2), and the LCIs utilized for the LCA (3.1.3 and 3.2.3).

3.1. Photocatalytic Surface Coating

3.1.1. Principle

The basic principle of photocatalysis was first discovered five decades ago by Fujishima and Honda [28], and the possibilities for using titanium dioxide (TiO_2)-based photocatalysis for removal of various pollutants have since been the subject of various studies [29] [30] [31]. The photocatalytic properties of TiO_2 are based on the semi-conducting properties of the crystalline form of the mineral. TiO_2 nanoparticle exists in three polymorphs, anatase, rutile and brookite. However, the anatase form is the most widely used for photocatalytic purposes [7]. The complex process of NO_x absorption and degradation at the TiO_2 surface is described in detail elsewhere [32] [33]. Illuminated by UV light, the anatase in contact with air and water produces hydroxyl radicals OH·, which oxidize NO_2 to nitrate (NO_3^-):

$$NO + 2OH\cdot \rightarrow NO_2 + H_2O \quad (1)$$

$$NO_2 + H_2O \rightarrow NO_3^- + H^+ \quad (2)$$

The resulting NO_3^- is extremely soluble in water; hence it is easily washed away. Since the main catalytic property of the TiO_2 surface is the effective formation of OH radicals, the levels of ozone (O_3), volatile organic compounds (VOCs), and sulphur oxide (SO_x) in the air may also be affected by the contact to the catalytic surface [34] [35] [36]. However, Mothes *et al.* [37] did not find photocatalytic degradation of the studied toluene and isoprene.

3.1.2. Photocatalytic Surface Technology and Life-Cycle Phases

We establish the background data for the LCI for the product NOxOFF supplied by Photocat (Denmark) and consider its application as part of a pre-fabricated concrete element used as pavement and as a sprayed coating on asphalt road.

The production of the NOxOFF products is based on commercial raw materials that are ground and mixed; a SiO_2 product serves as a binder material and ammonia acts as a buffer to stabilize pH. Production of 1 kg of product is summarized in **Table 1**.

Table 1. Production data for 1 kg NOxOFF product for two applications (data from Photocat).

1 kg of product	Concrete pavement element	Asphalt road
Water, gram	902	888
TiO_2, gram	75	50
SiO_2 (binder), gram	19	60
NH_3 (pH stabilizer), gram	4	2
Energy consumption, Wh	19	45
Area covered, m^2	7.5	10

The product is transported to the application in black plastic containers (IBC) holding 1000 kg. The container consists of high density polyethylene (HDPE) and weighs 59 kg. The containers are used 5 - 10 times and afterwards sent to a municipal waste incinerator with energy recovery.

When used in concrete elements, the product is introduced during the manufacturing of the concrete product before the product is cured and the NOxOFF catalyst is integrated into the top 2 mm of the final product used for the final surfaces.

When used on asphalt roads and parking lots, the product is sprayed applied when the initial surface bitumen is worn off and the NOxOFF product can adhere and bind to the mineral granulates in the surface of the asphalt. The product is spray-applied on existing asphalt pavements using common equipment. We neglect any environmental burdens from the application process.

Modelling of operation of photocatalytic surfaces is based on full-scale experiences with the photocatalytic surface has been tested during the last 15 years [11] [38]. Pedersen *et al.* [11] proposed a scheme for evaluation the different real-world studies including lifetime and durability. The lifetime not only depends on the quality of the coating but also on the quality of the material to which the coating adheres. We estimate that the lifetime of the photocatalytic concrete pavement elements is 15 years and in case of the asphalt road 10 years. We do not expect any maintenance during the lifetime and we do not expect that the photocatalytic surface coating affects other kinds of maintenance that may routinely take place on the surfaces. Faraldos *et al.* [39] and Bendix *et al.* [40] showed that the coating has a cleaning effect on the surface but we have not been able to quantify this additional effect into a format suitable for the LCA.

For the NOxOFF product, three major real-world demonstrations were performed during 2012-2019 [41]. From the study in the city of Roskilde in Denmark, it was calculated that the NOxOFF product removed 13.8 g of NO_x/m^2 per year. This was based on laboratory ISO test results, which were correlated to real-life results with good approximation. The tests showed a NO_x removal efficiency of approximately 4.83 mg/m^2 per hour. The UV influx in Denmark is around 50 kWh/m^2 per year. NO_3^- is the oxidized product. This means that 10

m^2 of coated surface during a 10 year lifetime removes 1.38 kg NO_x and produces around 2.65 kg NO_3^-. We assume that the NO_3^- is dissolved into water and that the associated acidity production is only of marginal significance in the water that washes the surface during the lifetime of the product. We take into account the produced NO_3^- and, although the destination may vary, we assume that marine surface water will be ultimately affected.

In the LCA modelling we also considered effects on other air pollutants. Baral *et al.* [16] as well as Hernández-Alonso *et al.* [42] quantified the removal of SO_x by photocatalytic surfaces. By scaling the removals of SO_x and NO_x observed over a 15 year life time [16], we include a removal of 0.033 kg SO_x per kg NO_x removed. The SO_x is converted to sulphate that is washed off. The data on O_3 removal is scarce [36] and not yet quantified relatively to the NO_x removal, hence we did not include it.

The photocatalytic surface is not reused or recycled after its lifetime. We assume that the main product amended with surface coating after the end-of-life of the main product will enter into traditional material recycling and disposal and that the presence of the coating will not affect the environmental aspects of the material recycling and disposal. The photocatalytic effect is assumed lost when the material is being recycled. We assume that the final disposal of the photocatalytic coating occurs together with the concrete and asphalt pavement to which it is bound, and that the environmental profile of the recycling is not affected by the presence of the photocatalytic material.

3.1.3. LCI Inventory for Photocatalytic Surface Coating Removing 1 kg of NO_x

Based on the above data compilation, the LCI for 1 kg NO_x removed by photocatalytic surface coating has been developed as presented in **Table 2**. **Table 2** summarizes resources in terms of materials and energy required for each life-cycle phase of the technology. The inventory differs with respect to photocatalytic surface coating applied to concrete or to asphalt pavement. The corresponding Ecoinvent processes utilized for the modelling of photocatalytic surface coating are reported in the SM, **Table S1** and **Table S2**.

3.2. Catalytic Converters in Vehicles

3.2.1. Principle

The knowledge about the ability of certain surfaces to enhance chemical reactions is very old and has been used in catalytic converters applied as end-of-pipe technologies for vehicles since 1975 in US and since 1985 in Europe [43] [44]. Today new cars are supplied with catalytic converters as emission control technologies. This applies to passenger cars, vans, and trucks as well as to gasoline and diesel driven vehicles. Several types of catalytic converters exist [5], but we have been able to build stringent LCI data only for the TWC (Three-Way Catalyst) which is often used on gasoline-driven passenger cars. Diesel cars and trucks use other types of after treatment systems, for example the Urea-Selective

Table 2. LCI inventory for 1 kg of NO_x removed by photocatalytic surface coating. Positive values are uses and negative values are savings.

Reference flow: 1 kg of NO_x removed by photocatalytic surface coating	LCI phase	Concrete pavement element	Asphalt pavement
Materials and energy—inputs from techno sphere			
Water, gram	Production	577	645
TiO_2, gram	Production	48	35
SiO_2 (binder), gram	Production	12	45
NH_3 (pH stabilizer), gram	Production	2.5	1.5
Energy consumption, Wh	Production	12	33
Plastic, HDPE, gram	Production	9	10
Emissions to air			
NO_x, gram	Operation	−1000	−1000
SO_x, gram	Operation	−33	−33
Emission to surface water			
NO_3^-, gram	Operation	1900	1900
Residues			
Plastic, HDPE, to incineration, gram	End-of-life	9	10
Waste product, to sanitary landfill, gram	End-of-life	94	74

Catalytic Reduction (Urea-SCR) which uses urea additive to convert NO_x to N_2 and water [45]. The TWC-converter creates reductive and oxidative reactions at elevated temperature that decrease/remove the content of air pollutants in the engine exhaust. Several reactions take place [46] and many air pollutants are affected. The dominating overall catalytic conversions are:

$$NO_x \rightarrow N_2 + H_2O \quad (3)$$

$$CO \rightarrow CO_2 \quad (4)$$

$$THC \rightarrow CO_2 + H_2O \quad (5)$$

where THC is total hydrocarbons.

The TWC converter has first a reductive section where NO_x is removed and a second oxidative section where CO and THC are removed. During the NO_x reduction, oxygen is generated and hence additional oxidation reactions may take place in the reductive section. Some oxygen will feed into the oxidative section of the converter and contribute to the oxidation of CO and THC. The catalytic converter increases the fuel consumption because of the pressure loss in the converter.

3.2.2. Catalytic Converter and Life-Cycle Phases

Laboratory test as well as in-situ measurements on vehicles in operation have documented the effect of catalytic converters on vehicle emissions [47], but the studies have also demonstrated that the effect depends on many technical factors

as well as temperature and mode of operation [46].

We establish the background data for the LCI for the TWC converter based on information in the literature. Due to the complexity of the reactions and the integrated function of the reductive and the oxidative sections of the converter, we establish two sets of data. A first data set for the whole converter considering the combined effect of the converter, and a second data set for the first part of the converter assuming that the reductive section only removes NO_x. We aim at establishing robust LCIs of general value and, although we rely on specific data from Belcastro [18], we assume that the data can be generally representative of the performance of a generic catalytic converter, irrespective of vehicle, product or driving conditions.

A vehicle catalytic converter is contained in a steel canister and operates typically around 350˚C with a conversion efficiency above 90% [48]. The exhaust gas is routed through two chambers with honeycomb structures with coated surfaces providing large catalytic surfaces sustaining the reactions. The catalytic elements are typically rhodium in the reductive section and platinum and palladium in the oxidative section. However, variations exist in both the construction, the catalyst, and their catalytic metal composition. Typical data are compiled in **Table 3**.

The cordierite is specifically produced as the honeycomb structure and no database offers an LCI for this product. We use data based on the compilation provided by Belcastro [18] as presented in **Table 4** for a Cordierite honeycomb structure

Table 3. Production data for 1 TWC converter (compiled with data from various studies [18] [49] [50] [51]).

Production of 1 TWC converter	Both sections (1 TWC)	NO_x-reduction (1/2 TWC)*
Weight, gram	7000 - 8000 [18]	3500 - 4000
Heat shield, gram Aluminized steel	500 [50]	250
Canister, gram 18/8 stainless steel (type 304)	5000 [50] [51]	2500
Insulation, gram Alumina-silica fibers, vermiculite and acryl binder	160 [50] - 500 [51]	80 - 250
Ceramic honeycomb, gram Cordierite ($1.4MgO{\cdot}3.6Al_2O_3{\cdot}5SiO_2$)	1400 [50] [51]	700
Wash coat/catalytic coating, gram		
Aluminum oxide (Al_2O_3)	17 - 28	8 - 14
Cerium oxide (CeO_2)	34 - 56	17 - 28
Zirconium oxide (ZrO_2)	120 - 195	60 - 98
Acetic acid (CH_3COOH)	10	5
Platinum (Pt)	0.2 [18] [49]	0
Palladium (Pd)	1.4 [49] - 2.5 [18]	0
Rhodium (Rh)	0.2 [18] [49]	0.2
Cardboard packaging, gram**	1000	500

**Data are half the data from the TWC converter except the rare elements, which are distributed according to their function; **Coarse estimates based on data used by Belcastro [18].

Table 4. Production data for a 1400 gram cordierite honeycomb structure for a TWC converter (based on data reported in Belcastro [18]).

Input	1400 gram cordierite honeycomb
Kaolin, $Al_2(Si_2O_5)(OH)_4$, gram	325
Talc, $Mg_3(Si_2O_5)2(OH)_2$, gram	600
Aluminum oxide, Al_2O_3, gram	170
Aluminum hydroxide, $Al(OH)_3$, gram	285
Silica, SiO_2, gram	160
Electricity, kWh	2.2 (1.6 - 3.2)

at 1400 gram. The weight of input materials exceeds the final weight of the cordierite by approximately 10% because of the water content of the input materials (deducted from Belcastro [18]).

The production of the canister from the steel requires energy, which we estimate as the energy needed with the energy required for the steel deep drawing process, as assumed by Belcastro [18].

Catalytic converters are typically manufactured based on components produced by specialized industries on commercial raw materials. The converters are in large quantities transported to the car assembly facilities. We do not have specific information on the packaging and transport of the individual components but we assume that the cardboard box for the converter weighs around 1 kg based on information in Belcastro [18].

As far as the operation phase is concerned, we assume that a converter has a lifetime corresponding to 160,000 km driven [49] [50]. The converter is estimated to increase the fuel consumption due to lower air-to-fuel ratio and back pressure by 2% - 10% depending on the driving conditions [51]. Assuming an emission of 150 - 220 g CO_2 per km for a typical gasoline-driven passenger car [47], we estimate that the additional fuel consumption for the TWC converter amounts to approximately 2000 kg CO_2. We assume that the converters require no maintenance during their lifetime.

Estimating the amount of NO_x and other air pollutants removed during the lifetime of the converter requires data on average composition of the exhaust gas before and after the converter.

Several studies have addressed the removal of air pollutants by catalytic converters [46], but, since the engine technology as well as the catalytic converters constantly develop, only recent data should be applied. Fanick *et al.* [52] measured the exhaust gas composition before and after the converter on two Toyota models. The results are summarized in SI units in **Table 5**. As baseline for the LCA modelling over the TWC lifetime, we use a removal of 250 kg NO_x, 1150 kg CO, 180 kg THC. In addition, the CO_2 emissions increase with 2350 kg due to the conversion of THC and CO into CO_2.

For the end-of-life phase of vehicle catalytic converters, we assumed that the majority of the converters are dismantled and properly managed. The energy

Table 5. Removal of NO_x and other air pollutants by a TWC converter during a lifetime of 160,000 km (based on Fanick *et al.* [54]).

Pollutant	Exhaust without converter g/km	Exhaust with converter g/km	Removal during lifetime kg/lifetime	Converted to during lifetime kg/lifetime
NO_x	1.3 - 2.1	0.004 - 0.016	200 - 320	N_2 (not counted)
CO	6.5 - 8.1	0.125	1025 - 1280	1610 - 2010 kg CO_2
THC	1.0 - 1.2	0.014 - 0.017	160 - 200	480 - 610 kg CO_2

and material requirements for the treatment of spent catalytic converters were taken from the Ecoinvent database. Platinum, rhodium and palladium may be recycled [53], and the remaining parts are landfilled. We considered two scenarios, one where the metals are not recycled, and one where the metals can be fully recycled, and later discuss how this affects in the LCA results for the catalytic converter.

3.2.3. LCI Inventory for a Vehicle Catalytic Converter Removing 1 kg of NO_x

Based on the above data compilation, the LCI for 1 kg NO_x removed by the catalytic car converter has been developed as presented in **Table 6**. **Table 6** summarizes resources in terms of materials and emission involved in each life-cycle phase of the technology. The inventory column TWC represents a whole converter including both the first part where the NO_x reduction take place and the second part where the reduction of THC and CO primarily takes place. The inventory column 1/2 TWC represents only the first part of the converter and is ascribed the NO_x removal, the use of rhodium plus a proportional part of the materials for the honeycomb and the canister as well as the additional fuel use. This approach is used to bracket the environmental profile of the NO_x removal, since the processes cannot be separated as stringently as done here. The corresponding Ecoinvent processes utilized for the modelling of catalytic car converter are reported in the SM, **Table S3** and **Table S4**.

4. Results and Discussion

This section reports the main results of the LCA for NO_x reduction via photocatalytic surface coating (4.1) and vehicle catalytic converter (4.2). Complete list of characterized and normalized results can be found in the SM (**Tables S5-S8** for characterized, **Tables S9-S12** for normalized).

The results are presented as normalized environmental impacts in sixteen impact categories (**Figure 2** and **Figure 3**). Burdens or loads are positive values, while benefits or savings are negative values. The results are divided according to the life-cycle phased described in Section 3: Production, operation, NO_x removal, and end-of-life. The unit is mPE per kg of NO_x removed. Net values are marked by diamonds.

For both technologies, the direct effect of the NO_x removal is quantified as

Table 6. LCI inventory for 1 kg of NO_x removed by a passenger car TWC-converter. The column "1/2 TWC converter" is a proxy representation of the first reductive section of the converter where the NO_x removal takes place. The data is basically half the values of the TWC, except from differences in rare earth element content and pollutant conversion. Positive values are burdens and negative values are savings.

1 kg of NO_x removed by vehicle converter	LCI phase	TWC converter	1/2 TWC converter
Materials and energy—input from techno sphere			
Aluminized steel, gram	Production	2	1
Stainless steel, gram	Production	20	10
Canister manufacturing, gram	Production	20	10
Aluminum oxide—silica fibres (proxy for isolation), gram	Production	1	0.5
Kaolin, gram	Production, cordierite	1.3	0.65
Talc, gram	Production, cordierite	2.4	1.2
Aluminum oxide, gram	Production, cordierite	0.7	0.35
Aluminium hydroxide, gram	Production, cordierite	1.1	0.55
Silica, gram	Production, cordierite	0.6	0.3
Electricity, Wh	Production, cordierite	9	4.5
Aluminum oxide, gram	Production, wash coat	0.10	0.05
Cerium oxide, gram	Production, wash coat	0.20	0.10
Zirconium oxide, gram	Production, wash coat	0.60	0.30
Acetic acid, gram	Production, wash coat	1*	0.5*
Platinum (Pt), gram	Production, wash coat	0.001	0
Palladium (Pd), gram	Production, wash coat	0.010	0
Rhodium (Rh), gram	Production, wash coat	0.001	0.001
Emission to air			
NO_x, gram	Operation, FU	−1000	−1000
CO removed in converter, gram	Operation	−4600	0
THC removed in converter, gram	Operation	−700	0
CO_2 from converted pollutants	Operation	9400	0
CO_2 from additional fuel use	Operation	8000	4000
Waste			
TWC unit to treatment: recycling and disposal, gram	End-of-life	30	15

*Estimate.

savings in the categories PM, POF, A, TE, and ME (see **Figure 2** and **Figure 3**). The categories PM and POF are proxies for the health effect of NO_x, acidification is due to the acidity produced when NO_x is oxidized to NO_3^-, and TE and ME reflect that NO_3^- is a nutrient both in terrestrial and in marine environments. NO_3^- is also a nutrient in freshwaters, but we have chosen to allocate the emission to the marine environment; thus savings due to NO_x removal is zero in the impact category FE.

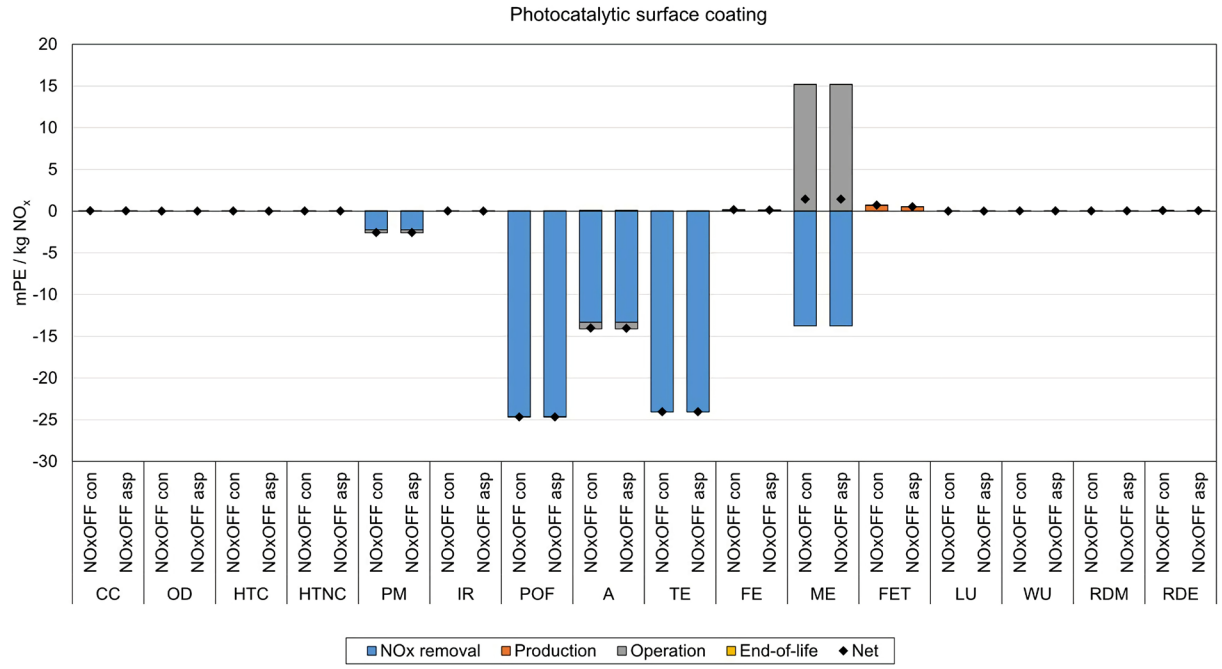

Figure 2. Normalized environmental profile in mPE per kg of NO_x removed for photocatlytic surface coating on concrete (con) and asphalt (asp). The 16 impact categories are: CC: Climate change; OD: Ozone depletion; HTc: Human toxicity, cancer effects; HTnc: Human toxicity, non-caner effects; PM: Particulate matter; IR: Ionizing radiation; POF: Photochemical ozone formation; A: Acidification; TE: Terrestrial eutrophication; FE: Freshwater eutrophication; ME: Marine eutrophication; FET: Freshwater eco toxicity; LU: Land use; WU: Water use; RDM: Resource use, minerals and metals; RDE: Resource use, energy carrier.

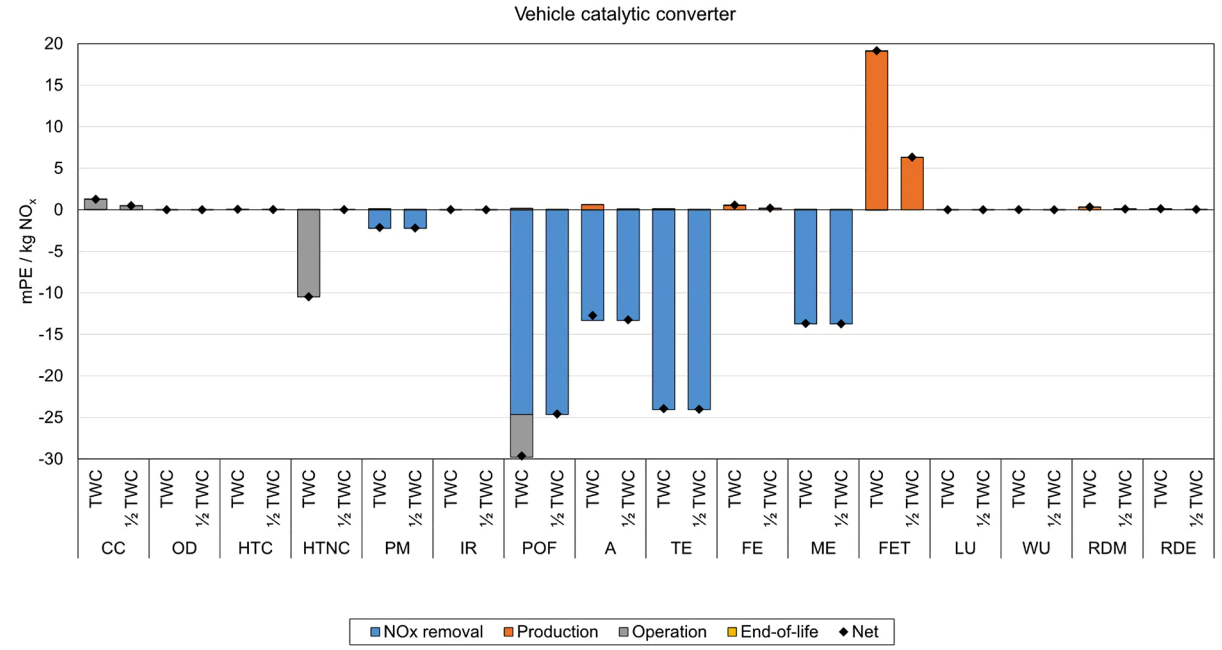

Figure 3. Normalized environmental profile in mPE per kg of NO_x removed for catalytic car converter (TWC: whole converter; 1/2 TWC: NO_x-reducing part of converter). The 16 impact categories are: CC: Climate change, OD: Ozone depletion, HTc: Human toxicity, cancer effects, HTnc: Human toxicity, non-caner effects; PM: Particulate matter; IR: Ionizing radiation; POF: Photochemical ozone formation; A: Acidification; TE: Terrestrial eutrophication; FE: Freshwater eutrophication; ME: Marine eutrophication; FET: Freshwater eco toxicity; LU: Land use; WU: Water use; RDM: Resource use, minerals and metals; RDE: Resource use, energy carrier.

4.1. Photocatalytic Surface Coating

Figure 2 shows the environmental profile of the concrete and asphalt coatings. The results are close to identical for the two applications and the presentation below applies to both applications.

4.1.1. Results: Photocatalytic Surface Coating

The direct effect of the NO_x removal dominates the environmental profile of the photocatalytic coatings, showing significant savings in POF, A, and TE ranging approximately from −12 to −24 mPE per kg NO_x. Some savings are also seen in PM (−2 mPE per kg NO_x). The net value for ME is close to zero; this reflects that the NO_x, with and without the photocatalytic surface, always ends up as NO_3^-.

The burdens from the production of the coatings are minor. Only a small burden of approximately 1 mPE per kg NO_x is observed in FET due to the provision of TiO_2.

The associated benefits of removal of SO_x are marginal and do not provide a large contribution to the results (not visible contribution in Figure 3). No significant impacts are seen from the end-of-life phase.

4.1.2. Dicussion: Photocatalytic Surface Coating

The overall results obtained for the photocatalytic coatings showing that the benefits of removing the NO_x far outbalances any environmental impacts from the production of the coating and is in accordance with what has been the main outcome of a few previous studies [15] [16]. The main environmental impact connected to the production phase is due to the provision of TiO_2. We include accurately the main materials and process in the production of the coating, and we follow standard procedures in quantifying the benefits of removing the NO_x. Thus, we find the overall result robust, although we cannot judge their general representability due to the few data sets available. However, we may not fully cover the additional benefits of using the photocatalytic coating on surfaces. This is primarily due to lack of clear evidence and data. SO_x removal seems of no importance for the results, but we neglect any effects related to removal of O_3, oxidation of volatile hydrocarbons, effects related to the cleanness of the surface, and the potential increase in uptake of CO_2 in the concrete due to the presence of TiO_2. These aspects have been addressed in the literature [36] [40] [54] [55], but are all still very new and characterization factors and methods to account for these aspects in an LCA are still not available. However, although not possible to quantify at the moment, we believe that these additional functions (removal of O_3, oxidation of VOCs, effects related to the cleanness of the surface, and the potential increase in uptake of CO_2) all potentially would increase the benefits of reduction of NO_x via catalytic surface coating.

4.2. Vehicle Catalytic Converter

Figure 3 shows the environmental profile of the whole converter (TWC) and for the first part of the converter responsible for the NO_x reduction (1/2 TWC). This

is done in an attempt to identify the environmental profile solely of the NO_x removal in spite of the fact that many interlinked processes are taking place in the converter including removal of THC and CO. In both cases, we assume removal of 1 kg of NO_x and the environmental profile of the NO_x removal is in between the two cases presented in **Figure 3**.

4.2.1. Results: Vehicle Catalytic Converter

The direct effect of the NO_x removal dominates the environmental profile also of the catalytic converter. The effects in PM, POF, A, and TE are identical to the benefits also seen for removal of 1 kg NO_x by the photocatalytic surface coating, but the converter also shows a significant saving in ME (−13 mPE per kg NO_x). This is due to the fact that the catalytic converter produces N_2 and not NO_3^-, and N_2 has no environmental impacts. In addition, the TWC shows additional benefits in HTNC (10 mPE per kg NO_x) and in POF (5 mPE per kg NO_x). These additional benefits are not observed for the 1/2 TWC; they are caused by THC and CO reduction that primarily takes place in the second half of the converter, while NO_x removal takes place in the first part of the converter.

The converter also reveals a minor burden in CC (2 mPE per kg NO_x), due to the additional CO_2 emissions from the conversion of THC and CO to CO_2 and from the additional fuel use. Overall, the CC impacts connected to the provision of materials and energy for the NOx removal function of the converter is only 1/4 of the CC impact for the whole converter.

The burdens from the production of the converter are significant in the FET (TWC: 19 mPE per kg NO_x; 1/2 TWC: 7 mPE per kg NO_x). The provisions of the rare earth elements for the catalytic honeycomb coating are the cause. The NO_x removal takes place in the first part of the converter where only rhodium is used (7 mPE per kg NO_x), while platinum and palladium are used only in the second part of the converter (12 mPE per kg NO_x). The other burdens for the production are very small (A and FE: <1 mPE per kg NO_x). The end-of-life shows a small burden in RDM: around 1 mPE per kg NO_x), due to the management of the spent converter.

Recycling of rare earth elements from the spent converter is not included in the main results because we have no reliable data on how frequently the converters are recycled nor on the efficiency of the recycling process regarding the actual recovery of the individual elements. Work is in progress in this area [56], and when data are established this impact can be reduced proportionally to actual recovery of each metal. A sensitivity analysis considering potential full recovery of metals shows that impacts connected to the provision of rhodium, palladium and platinum is counter-balanced by their full recovery as secondary raw materials, which reduces the impacts for the FET to <1 mPE.

4.2.2. Discussion: Vehicle Catalytic Converter

The overall results obtained for the vehicle catalytic converter showing that the benefits of removing the NO_x well outbalance the environmental impacts from

the production of the converter, is in accordance with what has been the main outcome of a few previous studies. Nevertheless, different approaches and assessments methods make direct comparison difficult [17] [18] [57].

The fact that the benefits of the NO_x removal have a relatively higher contribution to the overall results and the fact that the NO_x removal even may claim some of the benefits from the removal of THC and CO (since the NO_x removal provides oxygen for the second part of the converter), we believe that the overall results are robust, although several assumptions were made regarding the production of the converter and several proxies were use where datasets were missing.

The impacts from the production of the converter are related to the use of rare earth elements. The fact that we did not consider recovery of the rare earth elements, may mean that we overestimate the environmental burden from producing the converter. Recovery will reduce the impact proportional to the recovery efficiency because the burden is linked to the mining and refinement of virgin resources. Some of the rare earth elements are produced as by-products in other mining operations and the allocation of environmental burdens for virgin materials as well as the environmental savings form recovery depend on the development in the markets both in terms of supplies and prices, but it is likely that they are related, and thus recovery always will reduce the burden of producing the converter.

4.3. Development of NO_x-Reducing Technologies

The strength of the present study resides in the novel, balanced and robust datasets obtained for the NO_x-reducing technologies in focus. The environmental profiles obtained for the two NO_x-reducing technologies are positive in the way that the environmental burdens of the production, operation and end-of-life phases is much less that the benefits obtained by fulfilling its purpose of removing NO_x from the urban air at ground level. The environmental profile of the photocatalytic surface coating is characterized by having less environmental burdens connected to production and operation. However, we believe that they both technologies will be relevant in the years to come since they are complementary in obtaining low level of NO_x in urban air.

The limitations of the study reside in the limited sources of data and studies from which the LCIs were built. In particular, limited data were available for the TWC. Even though built on scarce data, the LCIs obtained and their environmental profiles suggest areas to be considered for further improvement.

With respect to the photocatalytic surface coating, the highest burden derives from provision of TiO_2. Furthermore, the potential benefits from reducing other pollutants should be better quantified and assessed in the future; in particular data are need for O_3 degradation and THC removal.

With respect to the vehicle catalytic converter, the composition and concentration of coating liquids used should be further assessed, balancing removal ef-

ficiencies versus environmental burdens of producing the rare earth elements including their actual recovery. Our study has addressed one commonly used coating, but a variety of coatings are available, and they should all be assessed. The additional fuel use induced by the converter is significant but still minor compared to the benefit of the NO_x removal and the other burdens and savings. However, the additional fuel use should always be kept low when possible.

5. Conclusions

Focusing on the removal of nitrogen oxides (NO_x), which is a major urban air pollutant, we have compiled life-cycle-inventory (LCI) data for a photocatalytic surface coating containing TiO_2 nanoparticles and for a vehicle catalytic converter employing the rare earth elements palladium, platinum, and rhodium. Although the two NO_x-reducing technologies differ and are complementary in their application, we have addressed their life-cycle phases (production, operation, and end-of-life) with respect to the common function of NO_x removal. We have obtained novel balanced datasets that we consider robust regarding the main contributions to the life cycle of these technologies, which we did not find in previous literature. However, we have identified potential areas where more and better data are in demand.

The environmental profiles of the two technologies assessed with the life cycle assessment (LCA) methodology with respect to sixteen impact categories show that the overall benefits of using the technologies in both cases are much higher than the burdens from their production, operation, and end-of-life. Thus, they are environmentally sound technologies for removing NO_x, which would otherwise decrease the quality of urban air near the ground. The environmental profiles also indicate where further development should focus from an environmental point of view. While the burden from producing the photocatalytic surface coating is negligible, the use of rare earth elements in the vehicle catalytic converter is the main burden and, as also suggested by other studies, should be the focus in future developments.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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The Supplementary Material

Life Cycle Inventory (LCI) Modelling

Table S1. LCI modelling for the photocatalytic surface coating, concrete pavement element.

Reference flow: 1 kg of NO_x removed by photocatalytic surface coating	LCI phase (Manuscript reference 2.2.2)	Concrete pavement element	Ecoinvent 3.7.1 (2020), APOS
Materials and energy—inputs from techno sphere			
Water, gram	Production	577	Tap water, market for tap water, Europe without Switzerland
TiO_2, gram	Production	48	titanium dioxide, market for titanium dioxide, RER
SiO_2 (binder), gram	Production	12	silica sand, market for silica sand, GLO
NH_3 (pH stabilizer), gram	Production	2.5	ammonia, anhydrous, liquid, market for ammonia, anhydrous, liquid, RER
Energy consumption, Wh	Production	12	electricity, medium voltage, market for electricity medium voltage, DK
Plastic, HDPE, gram	Production	9	polyethylene, high density, granulate, market for polyethylene, high density, granulate, GLO
Emissions to air			
NO_x, gram	Operation, FU	−1000	-
SO_x, gram	Operation	−33	-
Emission to surface water			
NO_3^-, gram	Operation	1900	-
Residues			
Plastic, HDPE, to incineration, gram	Production	9	waste polyethylene, treatment of waste polyethylene, municipal incineration, CH
Waste product, to sanitary landfill, gram	End-of-life	94	waste cement, hydrated, treatement of waste cement, hydrated, residual material landfill, Europe without Switzerland

Table S2. LCI modelling for the photocatalytic surface coating, asphalt pavement.

Reference flow: 1 kg of NO_x removed by photocatalytic surface coating	LCI phase (Manuscript reference 3.1.2)	Asphalt pavement	Ecoinvent 3.7.1 (2020), APOS
Materials and energy—inputs from techno sphere			
Water, gram	Production	645	Tap water, market for tap water, Europe without Switzerland
TiO_2, gram	Production	35	titanium dioxide, market for titanium dioxide, RER
SiO_2 (binder), gram	Production	45	silica sand, market for silica sand, GLO
NH_3 (pH stabilizer), gram	Production	1.5	ammonia, anhydrous, liquid, market for ammonia, anhydrous, liquid, RER
Energy consumption, Wh	Production	33	electricity, medium voltage, market for electricity medium voltage, DK
Plastic, HDPE, gram	Production	10	polyethylene, high density, granulate, market for polyethylene, high density, granulate, GLO

Continued

Emissions to air			
NO_x, gram	Operation, FU	−1000	-
SO_x, gram	Operation	−33	-
Emission to surface water			
NO_3^-, gram	Operation	1900	-
Residues			
Plastic, HDPE, to incineration, gram	Production	10	waste polyethylene, treatment of waste polyethylene, municipal incineration, CH
Waste product, to sanitary landfill, gram	End-of-life	74	asphalt, waste asphalt, treatment in sanitary landfill, CH

Table S3. LCI modelling for the vehicle catalytic converter, three-way catalyst (TWC).

Reference flow: 1 kg of NO_x removed by vehicle converter	LCI phase (Manuscript reference 3.2.2)	TWC converter	Ecoinvent 3.7.1 (2020), APOS
Materials and energy—input from techno sphere			
Aluminized steel, gram	Production	2	Steel, low-alloyed, hot rolled, steel production, low-alloyed, hot rolled, RER
Stainless steel, gram	Production	20	Steel, chromium steel 18/8, hot rolled, market for steel, chromium steel 18/8, hot rolled, GLO
Canister manufacturing, gram	Production	20	Deep drawing, steel, 38,000 kN press, automode, RER
Aluminum oxide—silica fibres, (proxy for isolation), gram	Production	1	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Kaolin, gram	Production, cordierite	1.3	Kaolin, market for kaolin, GLO
Talc, gram	Production, cordierite	2.4	Magnesium oxide, market for magnesium oxide, GLO
Aluminum oxide, gram	Production, cordierite	0.7	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Aluminium hydroxide, gram	Production, cordierite	1.1	Aluminium hydroxide, market for aluminium hydroxide, GLO
Silica, gram	Production, cordierite	0.6	Silica sand, market for silica sand, GLO
Electricity, Wh	Production, cordierite	9	Electricity, medium voltage. Market for electricity, medium voltage, DE
Aluminum oxide, gram	Production, wash coat	0.10	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Cerium oxide, gram	Production, wash coat	0.20	Cerium oxide, market for cerium oxide, GLO
Zirconium oxide, gram	Production, wash coat	0.60	Zirconium oxide, market for zirconium oxide, GLO
Acetic acid, gram	Production, wash coat	1*	Acetic acid, without water, in 98% solution state, market for acetic acide, without water, in 98% solution state, GLO
Platinum (Pt), gram	Production, wash coat	0.001	Metal catalyst for catalytic converter, platinum for generic market for catalytic converter, GLO
Palladium (Pd), gram	Production, wash coat	0.010	Metal catalyst for catalytic converter, palladium for generic market for catalytic converter, GLO
Rhodium (Rh), gram	Production, wash coat	0.001	Metal catalyst for catalytic converter, rhodium for generic market for catalytic converter, GLO

Continued

Emission to air			
NO_x, gram	Operation, FU	−1000	−1000
CO removed in converter, gram	Operation	−4600	0
THC removed in converter, gram	Operation	−700	0
CO_2 from converted pollutants	Operation	9400	0
CO_2 from additional fuel use	Operation	8000	4000
Waste			
TWC unit to treatment: recycling and disposal, gram	End-of-life	30	Spent automobile catalyst, treatment of automobile catalyst, RER

*Estimate.

Table S4. LCI modelling for half the vehicle catalytic converter, 1/2 three-way catalyst (1/2 TWC).

Reference flow: 1 kg of NO_x removed by vehicle converter	LCI phase (Manuscript reference 3.2.2)	TWC converter	Ecoinvent 3.7.1 (2020), APOS
Materials and energy – input from techno sphere			
Aluminized steel, gram	Production	1	Steel, low-alloyed, hot rolled, steel production, low-alloyed, hot rolled, RER
Stainless steel, gram	Production	10	Steel, chromium steel 18/8, hot rolled, market for steel, chromium steel 18/8, hot rolled, GLO
Canister manufacturing, gram	Production	10	Deep drawing, steel, 38,000 kN press, automode, RER
Aluminum oxide—silica fibres, (proxy for isolation), gram	Production	0.5	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Kaolin, gram	Production, cordierite	0.65	Kaolin, market for kaolin, GLO
Talc, gram	Production, cordierite	1.2	Magnesium oxide, market for magnesium oxide, GLO
Aluminum oxide, gram	Production, cordierite	0.35	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Aluminium hydroxide, gram	Production, cordierite	0.55	Aluminium hydroxide, market for aluminium hydroxide, GLO
Silica, gram	Production, cordierite	0.3	Silica sand, market for silica sand, GLO
Electricity, Wh	Production, cordierite	4.5	Electricity, medium voltage. Market for electricity, medium voltage, DE
Aluminum oxide, gram	Production, wash coat	0.05	Aluminium oxide, metallurgical, market for aluminium oxide, metallurgical, IAI Area, EU27 & EFTA
Cerium oxide, gram	Production, wash coat	0.10	Cerium oxide, market for cerium oxide, GLO
Zirconium oxide, gram	Production, wash coat	0.30	Zirconium oxide, market for zirconium oxide, GLO
Acetic acid, gram	Production, wash coat	0.5*	Acetic acid, without water, in 98% solution state, market for acetic acide, without water, in 98% solution state, GLO
Platinum (Pt), gram	Production, wash coat	0	Metal catalyst for catalytic converter, platinum for generic market for catalytic converter, GLO
Palladium (Pd), gram	Production, wash coat	0	Metal catalyst for catalytic converter, palladium for generic market for catalytic converter, GLO
Rhodium (Rh), gram	Production, wash coat	0.001	Metal catalyst for catalytic converter, rhodium for generic market for catalytic converter, GLO

Continued

Emission to air			
NO_x, gram	Operation, FU	−1000	-
CO removed in converter, gram	Operation	0	-
THC removed in converter, gram	Operation	0	-
CO_2 from converted pollutants	Operation	0	-
CO_2 from additional fuel use	Operation	4000	-
Waste			
TWC unit to treatment: recycling and disposal, gram	End-of-life	15	Spent automobile catalyst, treatment of automobile catalyst, RER

*Estimate.

Characterized Results

Table S5. Characterized results for the photocatalytic surface coating, concrete pavement element.

C	OD
O_2-eq	kg CFC-11 eq
-01	**3.1E−08**
-04	1.5E−11
-01	2.9E−08
-04	6.9E−11
-03	8.5E−10
-02	4.2E−10
-03	1.2E−10
-02	1.9E−11
-04	3.4E−10
+00	0.0E+00
+00	0.0E+00
+00	0.0E+00

etion, HTc: human
cation, FE: freshwat

[redacted]

HTc	HTnc	PM	
CTUh	CTUh	Disease incidences	kBq
2.4E−10	**9.1E−09**	**−1.6E−06**	**3.3**
7.6E−13	1.1E−11	1.1E−11	6.9
2.0E−10	8.1E−09	2.5E−08	3.0
2.6E−13	6.1E−12	8.3E−11	2.4
1.3E−12	1.7E−11	4.4E−11	1.3
5.2E−12	8.5E−11	6.4E−10	1.2
1.5E−12	3.8E−11	8.2E−11	8.6
3.2E−12	2.4E−11	2.4E−11	6.2
2.3E−11	8.2E−10	1.2E−10	1.1
0.0E+00	0.0E+00	−1.6E−06	0.0
0.0E+00	0.0E+00	0.0E+00	0.0
0.0E+00	0.0E+00	−2.6E−07	0.0

toxicity, cancer effects, HTnc: human
er eutrophication, ME: marine eutroph

[redacted]

IR	POF	A	TE
U-235 eq.	kg NMVOC eq.	mol H+ eq	mol N e
E−02	**−1.0E+00**	**−7.3E−01**	**−4.3E+0**
E−03	6.0E−05	6.2E−05	1.2E−0
E−04	7.1E−06	1.2E−05	3.2E−0
E−06	4.2E−06	3.0E−06	1.6E−0
E−04	6.8E−06	6.7E−06	2.3E−0
E+00	−1.0E+00	−7.4E−01	−4.3E+0
E+00	0.0E+00	0.0E+00	0.0E+0
E+00	−2.7E−03	−4.3E−02	0.0E+0
E−05	6.4E−07	1.1E−06	2.0E−0
E−02	1.2E−03	5.3E−03	3.0E−0
E−05	3.5E−06	4.5E−06	1.2E−0
E−04	8.1E−06	1.1E−05	2.3E−0

toxicity, non-caner effects, PM: particu
ication, FET: freshwater eco toxicity, I

[redacted]

	FE	ME	FET	I
q	kg P eq.	kg N eq	CTUe	
00	**1.2E−04**	**4.1E−02**	**8.5E+00**	**4.3**
5	5.0E−06	2.1E−06	2.7E−01	9.1
00	0.0E+00	−3.9E−01	0.0E+00	0.0
0	0.0E+00	4.3E−01	0.0E+00	0.0
0	0.0E+00	0.0E+00	0.0E+00	0.0
6	1.4E−07	2.2E−07	3.8E−03	2.2
3	1.1E−04	3.3E−04	8.0E+00	3.8
5	9.9E−08	1.1E−06	1.3E−02	2.7
5	3.5E−07	2.2E−06	3.2E−02	1.1
4	2.8E−06	1.2E−05	1.1E−01	5.7
5	2.1E−06	2.9E−06	8.8E−02	2.7
5	2.6E−08	1.5E−06	6.3E−03	6.0

late matter, IR: ionizing radiation, PO
U: land use, WU: water use, RDM: re

[redacted]

LU	WU	RDM	RDE
–	m^3 water eq	kg SB eq	MJ
E+00	**3.8E−01**	**1.9E−06**	**5.0E+00**
E−03	2.5E−02	1.0E−09	4.1E−03
E+00	3.4E−01	1.8E−06	4.2E+00
E−02	1.5E−04	1.3E−09	7.5E−03
E−02	6.0E−03	3.5E−08	1.2E−01
E−02	9.4E−03	1.2E−07	6.7E−01
E−01	5.7E−03	1.4E−08	5.7E−02
E−04	2.1E−04	5.4E−10	1.4E−03
E−02	1.2E−03	2.1E−09	2.4E−02
E+00	0.0E+00	0.0E+00	0.0E+00
E+00	0.0E+00	0.0E+00	0.0E+00
E+00	0.0E+00	0.0E+00	0.0E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

Table S6. Characterized results for the photocatalytic surface coating, asphalt pavement.

-03	2.3E−10	4.
+00	0.0E+00	0.
+00	0.0E+00	0.
+00	0.0E+00	0.

pletion, HTc: human
hication, FE: freshwat

C	OD	
O_2-eq	kg CFC-11 eq	C
-01	**2.3E−08**	1.
-04	1.6E−11	8.
-01	2.1E−08	1.
-03	2.6E−10	9.
-03	5.1E−10	8.
-02	4.7E−10	5.
-03	3.3E−10	4.
-02	2.2E−11	3.

[redacted]

0E+00	0.0E+00	−1.6E−06	0.0E
0E+00	0.0E+00	0.0E+00	0.0E
0E+00	0.0E+00	−2.6E−07	0.0E

toxicity, cancer effects, HTnc: human
er eutrophication, ME: marine eutroph

HTc	HTnc	PM	I
CTUh	CTUh	Disease incidences	kBq U-
6E−10	**6.2E−09**	**−1.8E−06**	**2.6E**
5E−13	1.3E−11	1.3E−11	7.7E
5E−10	5.9E−09	1.8E−08	2.2E
7E−13	2.3E−11	3.1E−10	8.9E
0E−13	1.0E−11	2.7E−11	8.0E
7E−12	9.5E−11	7.1E−10	1.3E
1E−12	1.0E−10	2.2E−10	2.4E
6E−12	2.7E−11	2.6E−11	6.9E
7E−13	5.1E−12	1.2E−10	1.0E

[redacted]

+00	−2.7E−03	−4.3E−02	0.0E+

toxicity, non-caner effects, PM: particu
ication, FET: freshwater eco toxicity, I

R	POF	A	TE
235 eq.	kg NMVOC eq.	mol H+ eq	mol N
-02	**−1.0E+00**	**−7.8E−01**	**−4.3E**
-05	7.1E−07	1.2E−06	2.3E-
-02	8.5E−04	3.9E−03	2.2E-
-05	1.3E−05	1.7E−05	4.6E-
-05	4.9E−06	6.5E−06	1.4E-
-03	6.7E−05	6.8E−05	1.4E-
-03	2.0E−05	3.3E−05	8.8E-
-06	4.6E−06	3.3E−06	1.7E-
-04	6.4E−06	5.6E−06	2.2E-
+00	−1.0E+00	−7.4E−01	−4.3E
+00	0.0E+00	0.0E+00	0.0E+

[redacted]

late matter, IR: ionizing radiation, PO
U: land use, WU: water use, RDM: re

	FE	ME	FET	
I eq	kg P eq.	kg N eq	CTUe	
+00	**8.9E−05**	**4.1E−02**	**6.3E+00**	**3.8**
-06	1.6E−07	2.4E−07	4.3E−03	2.5
-03	7.9E−05	2.4E−04	5.8E+00	2.8
-05	3.7E−07	4.3E−06	5.0E−02	1.0
-05	2.1E−07	1.3E−06	1.9E−02	6.4
-04	3.1E−06	1.3E−05	1.2E−01	6.3
-05	5.7E−06	7.8E−06	2.4E−01	7.4
-05	2.9E−08	1.6E−06	7.0E−03	6.7
-05	5.9E−08	8.8E−06	1.0E−02	4.4
+00	0.0E+00	−3.9E−01	0.0E+00	0.0
00	0.0E+00	4.3E−01	0.0E+00	0.0
00	0.0E+00	0.0E+00	0.0E+00	0.0

[redacted]

LU	WU	RDM	RDE
–	m^3 water eq	kg SB eq	MJ
3E+00	**3.0E−01**	**1.5E−06**	**4.1E+00**
5E−03	2.8E−02	1.1E−09	4.6E−03
3E+00	2.5E−01	1.3E−06	3.0E+00
0E−01	5.8E−04	4.8E−09	2.8E−02
4E−03	3.6E−03	2.1E−08	7.1E−02
3E−02	1.0E−02	1.4E−07	7.4E−01
4E−01	1.6E−02	3.9E−08	1.6E−01
7E−04	2.3E−04	6.0E−10	1.5E−03
4E−02	8.7E−04	2.0E−09	1.7E−02
0E+00	0.0E+00	0.0E+00	0.0E+00
0E+00	0.0E+00	0.0E+00	0.0E+00
0E+00	0.0E+00	0.0E+00	0.0E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

Table S7. Characterized results for the vehicle catalytic converter, three-way catalyst (TWC).

ɔd, steel production,
nts
ɔone depletion, HTc: huma
eutrophication, FE: freshw
ed by vehicle catalytic converter
) kN press, automode, RER
GLO
for magnesium oxide, GLO
rket for aluminium hydroxide,
ɔa sand, GLO
ɔerium oxide, GLO
or zirconium oxide, GLO
ı 98% solution state, market for ɓ solution state, GLO
ɔnverter, platinum to generic lytic converter, GLO
ɔnverter, palladium to generic lytic converter, GLO
ɔnverter, rhodium to generic lytic converter, GLO
treatment of automobile
arket for aluminium oxide, EFTA
ɔet for electricity, medium
ɔlled, market for steel, GLO

[redacted]

kg CO_2-eq	kg CFC-11 eq	CTUh	CTUh
1.1E+01	**4.3E−08**	**2.2E−09**	**−5.0E−06**
6.0E−03	5.0E−10	6.1E−12	7.9E−11
2.4E−04	2.5E−11	7.4E−14	2.3E−12
2.8E−03	4.8E−11	9.0E−12	1.6E−10
1.1E−03	9.3E−11	5.1E−12	8.5E−11
2.8E−05	3.4E−12	1.3E−14	3.1E−13
4.1E−03	4.5E−10	2.5E−12	1.4E−10
2.2E−03	7.5E−10	1.3E−12	3.3E−11
1.7E−03	4.2E−10	8.2E−13	2.7E−11
7.0E−02	4.0E−09	3.7E−11	1.7E−09
1.3E−01	2.4E−08	9.6E−11	3.3E−09
8.2E−02	4.7E−09	4.8E−11	2.1E−09
4.5E−02	3.0E−09	1.6E−11	6.2E−10
2.0E−03	3.7E−10	8.7E−12	1.6E−10
5.3E−03	3.1E−10	1.4E−12	4.6E−11
9.0E−02	4.6E−09	1.9E−09	2.4E−09
3.3E−03	2.0E−10	4.9E−11	1.0E−10
0.0E+00	0.0E+00	0.0E+00	0.0E+00
−7.2E+00	0.0E+00	0.0E+00	−5.0E−06
0.0E+00	0.0E+00	0.0E+00	−2.8E−09
9.4E+00	0.00E+00	0.00E+00	0.00E+00
8.0E+00	0.00E+00	0.00E+00	0.00E+00

an toxicity, cancer effects, HTnc: huma
ater eutrophication, ME: marine eutro

CC	OD	HTc	HTnc

[redacted]

6.8E−11	2.1E−04	6.8E−06	8.6E−06
1.4E−08	4.0E−03	1.4E−03	5.0E−03
3.4E−08	9.1E−03	3.1E−03	2.3E−02
1.5E−08	4.6E−03	1.6E−03	4.3E−03
7.2E−10	1.9E−02	9.5E−05	2.1E−04
1.8E−10	9.1E−05	7.6E−06	1.5E−05
4.7E−11	9.1E−04	6.9E−06	1.2E−05
8.3E−09	6.8E−03	3.3E−04	5.7E−04
2.5E−10	2.9E−04	1.3E−05	1.5E−05
−1.6E−06	0.0E+00	−1.0E+00	−7.4E−01
0.0E+00	0.0E+00	−2.1E−01	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00

n toxicity, non-caner effects, PM: partic
phication, FET: freshwater eco toxicity,

PM	IR	POF	A
Disease incidences	kBq U-235 eq.	kg NMVOC eq.	mol H+ eq
−1.5E−06	**4.7E−02**	**−1.2E+00**	**−7.1E−01**
3.3E−10	4.1E−04	1.3E−05	2.2E−05
1.3E−11	3.0E−05	6.4E−07	1.4E−06
5.9E−10	6.5E−05	5.2E−06	6.6E−06
1.5E−10	2.9E−05	4.6E−06	1.0E−05
4.1E−12	1.2E−06	1.7E−07	2.2E−07
9.2E−10	8.6E−04	2.1E−05	2.8E−05
1.2E−10	2.2E−04	7.7E−06	1.3E−05

[redacted]

1.1E−03	3.2E−05	1.1E−04	3.2E+00
3.3E−05	1.6E−06	3.8E−06	9.3E−02
−4.3E+00	0.0E+00	−3.9E−01	0.0E+00
0.0E+00	0.0E+00	0.0E+00	−1.1E−01
0.0E+00	0.0E+00	0.0E+00	−2.7E−03
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00

ulate matter, IR: ionizing radiation, PO
LU: land use, WU: water use, RDM: re

TE	FE	ME	FET
mol N eq	kg P eq.	kg N eq	CTUe
−4.2E+00	**4.1E−04**	**−3.9E−01**	**2.3E+02**
6.3E−05	1.6E−06	1.0E−05	3.2E−01
2.3E−06	9.7E−08	2.2E−07	4.8E−03
1.8E−05	2.1E−07	1.6E−06	1.1E−01
1.7E−05	5.7E−07	1.5E−06	5.9E−02
6.2E−07	5.0E−09	5.7E−08	6.7E−04
8.5E−05	1.2E−06	4.3E−05	4.6E−01
2.9E−05	1.1E−06	2.8E−06	5.5E−02
1.7E−05	5.3E−07	1.6E−06	4.1E−02
5.8E−03	8.8E−05	4.0E−04	6.1E+01
8.7E−03	1.4E−04	6.0E−04	8.8E+01
6.9E−03	1.0E−04	4.7E−04	7.2E+01
3.5E−04	3.7E−05	3.8E−05	9.0E−01
2.8E−05	6.8E−07	2.5E−06	6.7E−02
2.8E−05	8.0E−06	4.1E−06	9.1E−02

[redacted]

LU	WU	RDM	RDE
–	m^3 water eq	kg SB eq	MJ
4.4E+00	**1.4E−01**	**2.1E−05**	**8.4E+00**
1.5E−01	2.4E−03	3.1E−08	5.9E−02
1.4E−03	1.6E−04	9.8E−10	4.1E−03
3.7E−03	1.8E−04	1.3E−09	9.4E−03
4.3E−03	1.9E−04	1.7E−09	1.4E−02
1.3E−03	7.7E−06	6.3E−11	3.7E−04
5.7E−02	1.5E−03	7.4E−08	5.5E−02
1.9E−02	1.6E−03	3.2E−08	3.4E−02
1.1E−02	1.9E−03	2.0E−08	5.0E−02
7.3E−01	1.6E−02	3.6E−06	1.4E+00
1.2E+00	4.3E−02	8.9E−06	2.6E+00
8.8E−01	1.9E−02	4.1E−06	1.7E+00
5.2E−01	2.7E−02	1.1E−06	9.3E−01
5.9E−03	4.5E−04	3.5E−09	3.2E−02
6.9E−02	2.6E−03	1.5E−08	9.7E−02
6.7E−01	2.6E−02	3.2E−06	1.3E+00
2.5E−02	7.1E−04	3.6E−08	4.6E−02
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

Table S8. Characterized results for the ½ vehicle catalytic converter, three-way catalyst (1/2 TWC).

et for electricity, medium
lled, market for steel,
GLO
d, steel production,
nts
one depletion, HTc: hum
eutrophication, FE: freshw
ved by vehicle catalytic
kN press, automode, RER
GLO
for magnesium oxide, GLO
rket for aluminium
a sand, GLO
erium oxide, GLO
or zirconium oxide, GLO
n 98% solution state, market
98% solution state, GLO
onverter, platinum to
for catalytic converter, GLO
onverter, palladium to
for catalytic converter, GLO
onverter, rhodium to generic
ytic converter, GLO
treatment of automobile
market for aluminium
U27 & EFTA

[redacted]

.66E−04	4.66E−11	2.56E−12	4.25E−11	7.
.41E−05	1.71E−12	6.47E−15	1.53E−13	2.
.06E−03	2.25E−10	1.25E−12	6.79E−11	4.
.08E−03	3.75E−10	6.48E−13	1.66E−11	6.
.44E−04	2.10E−10	4.08E−13	1.36E−11	3.
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
.25E−02	4.73E−09	4.75E−11	2.06E−09	1.
.24E−02	1.51E−09	8.21E−12	3.10E−10	3.
.01E−03	1.83E−10	4.34E−12	7.97E−11	8.
.64E−03	1.56E−10	6.88E−13	2.32E−11	2.
.51E−02	2.31E−09	9.42E−10	1.21E−09	4.
.66E−03	1.00E−10	2.47E−11	5.09E−11	1.
.00E+00	0.00E+00	0.00E+00	0.00E+00	−1
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
.00E+00	0.00E+00	0.00E+00	0.00E+00	0.

an toxicity, cancer effects, HTnc: huma
water eutrophication, ME: marine eutro

CC	OD	HTc	HTnc	
g CO_2-eq	kg CFC-11 eq	CTUh	CTUh	I in
.16E+00	**1.01E−08**	**1.04E−09**	**3.99E−09**	**−1**
.01E−03	2.50E−10	3.07E−12	3.96E−11	1.
.21E−04	1.24E−11	3.75E−14	1.16E−12	6.
.40E−03	2.40E−11	4.48E−12	8.13E−11	2.

[redacted]

00E+00	0.00E+00	0.00E+00	0.00E+00
00E+00	0.00E+00	0.00E+00	0.00E+00
00E+00	0.00E+00	0.00E+00	0.00E+00
00E+00	0.00E+00	0.00E+00	0.00E+00

n toxicity, non-caner effects, PM: partic
phication, FET: freshwater eco toxicity,

PM	IR	POF	A
Disease cidences	kBq U-235 eq.	kg NMVOC eq.	mol H+ eq
.58E−06	**1.90E−02**	**−9.98E−01**	**−7.35E−01**
66E−10	2.06E−04	6.73E−06	1.11E−05
38E−12	1.54E−05	3.25E−07	6.82E−07
93E−10	3.24E−05	2.60E−06	3.31E−06
43E−11	1.45E−05	2.30E−06	4.99E−06
07E−12	5.92E−07	8.63E−08	1.12E−07
60E−10	4.32E−04	1.05E−05	1.40E−05
03E−11	1.12E−04	3.86E−06	6.61E−06
38E−11	1.05E−04	3.42E−06	4.31E−06
00E+00	0.00E+00	0.00E+00	0.00E+00
00E+00	0.00E+00	0.00E+00	0.00E+00
54E−08	4.57E−03	1.57E−03	4.26E−03
60E−10	9.47E−03	4.73E−05	1.04E−04
87E−11	4.53E−05	3.80E−06	7.28E−06
36E−11	4.53E−04	3.46E−06	5.91E−06
15E−09	3.42E−03	1.65E−04	2.85E−04
25E−10	1.46E−04	6.44E−06	7.39E−06
.60E−06	0.00E+00	−1.00E+00	−7.40E−01

[redacted]

0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.87E−03	1.03E−04	4.69E−04	7.20E+01
1.74E−04	1.85E−05	1.90E−05	4.50E−01
1.38E−05	3.42E−07	1.24E−06	3.34E−02
1.39E−05	4.00E−06	2.04E−06	4.57E−02
5.73E−04	1.58E−05	5.35E−05	1.59E+00
1.67E−05	8.19E−07	1.89E−06	4.64E−02
−4.26E+00	0.00E+00	−3.89E−01	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00

culate matter, IR: ionizing radiation, PC
LU: land use, WU: water use, RDM: re

TE	FE	ME	FET
mol N eq	kg P eq.	kg N eq	CTUe
−4.25E+00	**1.45E−04**	**−3.88E−01**	**7.46E+01**
3.17E−05	7.75E−07	5.12E−06	1.61E−01
1.15E−06	4.89E−08	1.13E−07	2.41E−03
9.10E−06	1.07E−07	8.01E−07	5.25E−02
8.37E−06	2.85E−07	7.71E−07	2.94E−02
3.09E−07	2.48E−09	2.85E−08	3.36E−04
4.24E−05	5.83E−07	2.17E−05	2.32E−01
1.45E−05	5.29E−07	1.42E−06	2.77E−02
8.28E−06	2.63E−07	7.92E−07	2.06E−02

[redacted]

LU	WU	RDM	RDE
–	m^3 water eq	kg SB eq	MJ
1.64E+00	**5.12E−02**	**6.31E−06**	**2.99E+00**
7.29E−02	1.22E−03	1.57E−08	2.94E−02
7.01E−04	8.30E−05	4.95E−10	2.06E−03
1.87E−03	8.87E−05	6.48E−10	4.69E−03
2.13E−03	9.61E−05	8.58E−10	7.10E−03
6.73E−04	3.84E−06	3.17E−11	1.87E−04
2.87E−02	7.59E−04	3.72E−08	2.77E−02
9.74E−03	7.82E−04	1.61E−08	1.72E−02
5.26E−03	9.30E−04	1.00E−08	2.48E−02
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.78E−01	1.88E−02	4.07E−06	1.68E+00
2.58E−01	1.34E−02	5.46E−07	4.65E−01
2.94E−03	2.25E−04	1.77E−09	1.58E−02
3.47E−02	1.30E−03	7.44E−09	4.83E−02
3.36E−01	1.31E−02	1.59E−06	6.50E−01
1.24E−02	3.55E−04	1.78E−08	2.30E−02
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00E+00	0.00E+00	0.00E+00	0.00E+00

OF: photochemical ozone formation, A:
esource use, minerals and metals, RDE:

Normalized Results

Table S9. Normalized results for the photocatalytic surface coating, concrete pavement element.

icity, cancer effects, HTnc: human
eutrophication, ME: marine eutroph

D	HTc	HTnc	PM
PE	PE	PE	PE
−06	**6E−06**	**2E−05**	**−3E−0**
−10	2E−08	2E−08	2E−08
−06	5E−06	2E−05	3E−05
−09	7E−09	1E−08	1E−07
−08	3E−08	4E−08	6E−08
−08	1E−07	2E−07	9E−07
−09	4E−08	8E−08	1E−07
−10	8E−08	5E−08	3E−08
−08	6E−07	2E−06	2E−07
+00	0E+00	0E+00	−2E−0
+00	0E+00	0E+00	0E+00
+00	0E+00	0E+00	−4E−0

[redacted]

	1E−09	1E−07	5E−08	9E−
	3E−08	2E−07	1E−07	1E−
3	0E+00	−2E−02	−1E−02	−2E−
	0E+00	0E+00	0E+00	0E+
4	0E+00	−7E−05	−8E−04	0E+

toxicity, non-caner effects, PM: particu
ication, FET: freshwater eco toxicity, I

	IR	POF	A	TE
	PE	PE	PE	PE
3	**8E−06**	**−2E−02**	**−1E−02**	**−2E−**
	2E−08	2E−08	2E−08	1E−
	7E−06	3E−05	1E−04	2E−
	6E−09	9E−08	8E−08	7E−
	3E−08	2E−07	2E−07	1E−
	3E−07	1E−06	1E−06	7E−
	2E−07	2E−07	2E−07	2E−

[redacted]

08	1E−07	4E−08	1E−06	2
07	5E−07	8E−08	3E−06	8
07	4E−06	4E−07	9E−06	4
07	3E−06	1E−07	7E−06	2
08	4E−08	5E−08	5E−07	4
07	7E−06	7E−08	2E−05	7
−02	0E+00	−1E−02	0E+00	0
00	0E+00	2E−02	0E+00	0
00	0E+00	0E+00	0E+00	0

late matter, IR: ionizing radiation, PO
U: land use, WU: water use, RDM: res

E	FE	ME	FET	
E	PE	PE	PE	
−02	**2E−04**	**1E−03**	**7E−04**	**3**
08	2E−07	8E−09	3E−07	2
05	1E−04	1E−05	7E−04	3

[redacted]

LU	WU	RDM	RDE
PE	PE	PE	PE
E−06	**3E−05**	**3E−05**	**8E−05**
E−09	2E−06	2E−08	6E−08
E−06	3E−05	3E−05	6E−05
E−08	1E−08	2E−08	1E−07
E−09	5E−07	5E−07	2E−06
E−08	8E−07	2E−06	1E−05
E−07	5E−07	2E−07	9E−07
E−10	2E−08	8E−09	2E−08
E−08	1E−07	3E−08	4E−07
E+00	0E+00	0E+00	0E+00
E+00	0E+00	0E+00	0E+00
E+00	0E+00	0E+00	0E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

Table S10. Normalized results for the photocatalytic surface coating, asphalt pavement.

0	9.3E−08	5.7E−08	3.7E−08
9	1.2E−08	1.1E−08	1.7E−07
0	0.0E+00	0.0E+00	−2.2E−03
0	0.0E+00	0.0E+00	0.0E+00
0	0.0E+00	0.0E+00	−3.7E−04

icity, cancer effects, HTnc: human
eutrophication, ME: marine eutroph

	HTc	HTnc	PM
	PE	PE	PE
7	**4.2E−06**	**1.3E−05**	**−2.6E−03**
0	2.2E−08	2.7E−08	1.8E−08
7	3.8E−06	1.2E−05	2.5E−05
8	2.5E−08	4.8E−08	4.3E−07
8	2.1E−08	2.1E−08	3.7E−08
8	1.5E−07	2.0E−07	9.9E−07
8	1.1E−07	2.2E−07	3.1E−07

[redacted]

PE	PE	PE	PE
.2E−06	**−2.5E−02**	**−1.4E−02**	**−2.4E−**
.8E−08	1.7E−08	2.2E−08	1.3E−0
.2E−06	2.1E−05	7.0E−05	1.2E−0
.1E−08	3.2E−07	3.0E−07	2.6E−0
.9E−08	1.2E−07	1.2E−07	7.9E−0
.2E−07	1.6E−06	1.2E−06	7.7E−0
.6E−07	4.8E−07	6.0E−07	4.9E−0
.6E−09	1.1E−07	6.0E−08	9.8E−0
.4E−08	1.6E−07	1.0E−07	1.2E−0
.0E+00	−2.5E−02	−1.3E−02	−2.4E−
.0E+00	0.0E+00	0.0E+00	0.0E+0
.0E+00	−6.6E−05	−7.8E−04	0.0E+0

toxicity, non-caner effects, PM: particu
ication, FET: freshwater eco toxicity, I

IR	POF	A	TE

[redacted]

7	7.8E−06	2.8E−07	2.0E−05	5.3
8	3.9E−08	5.8E−08	5.9E−07	4.8
7	8.0E−08	3.1E−07	8.8E−07	3.1
02	0.0E+00	−1.4E−02	0.0E+00	0.0
0	0.0E+00	1.5E−02	0.0E+00	0.0
0	0.0E+00	0.0E+00	0.0E+00	0.0

late matter, IR: ionizing radiation, PO
U: land use, WU: water use, RDM: res

	FE	ME	FET	I
	PE	PE	PE	I
02	**1.2E−04**	**1.4E−03**	**5.3E−04**	**2.7**
8	2.2E−07	8.6E−09	3.6E−07	1.8
5	1.1E−04	8.6E−06	4.9E−04	2.0
7	5.1E−07	1.5E−07	4.3E−06	7.2
8	2.9E−07	4.6E−08	1.6E−06	4.6
7	4.2E−06	4.6E−07	9.9E−06	4.5

[redacted]

LU	WU	RDM	RDE
PE	PE	PE	PE
E−06	**2.6E−05**	**2.3E−05**	**6.2E−05**
E−09	2.4E−06	1.8E−08	7.0E−08
E−06	2.1E−05	2.0E−05	4.6E−05
E−08	5.0E−08	7.5E−08	4.3E−07
E−09	3.2E−07	3.3E−07	1.1E−06
E−08	9.1E−07	2.1E−06	1.1E−05
E−07	1.4E−06	6.2E−07	2.4E−06
E−10	2.0E−08	9.4E−09	2.3E−08
E−08	7.6E−08	3.2E−08	2.6E−07
E+00	0.0E+00	0.0E+00	0.0E+00
E+00	0.0E+00	0.0E+00	0.0E+00
E+00	0.0E+00	0.0E+00	0.0E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

Table S11. Normalized results for the vehicle catalytic converter, three-way catalyst (TWC).

hicle catalytic converter		CC	OD	HTc	HTnc	PM	IR	POF	A	TE	FE	ME	FET	LU	WU	RDM	RDE
		PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE
		1.3E−03	**1.9E−06**	**5.6E−05**	**−1.0E−02**	**−2.1E−03**	**1.1E−05**	**−3.0E−02**	**−1.3E−02**	**−2.4E−02**	**5.6E−04**	**−1.4E−02**	**1.9E−02**	**3.1E−06**	**1.2E−05**	**3.3E−04**	**1.3E−04**
ss, automode, RER		7.2E−07	2.1E−08	1.6E−07	1.7E−07	4.6E−07	9.8E−08	3.3E−07	4.0E−07	3.6E−07	2.1E−06	3.6E−07	2.7E−05	1.0E−07	2.1E−07	4.9E−07	9.0E−07
		2.9E−08	1.0E−09	1.9E−09	4.8E−09	1.8E−08	7.2E−09	1.6E−08	2.4E−08	1.3E−08	1.3E−07	7.9E−09	4.0E−07	9.9E−10	1.4E−08	1.5E−08	6.3E−08
nesium oxide, GLO		3.3E−07	2.1E−09	2.3E−07	3.4E−07	8.2E−07	1.5E−08	1.3E−07	1.2E−07	1.0E−07	2.9E−07	5.7E−08	8.9E−06	2.7E−09	1.5E−08	2.0E−08	1.4E−07
aluminium hydroxide,		1.3E−07	4.0E−09	1.3E−07	1.8E−07	2.1E−07	6.9E−09	1.1E−07	1.8E−07	9.5E−08	7.8E−07	5.4E−08	5.0E−06	3.0E−09	1.7E−08	2.7E−08	2.2E−07
GLO		3.4E−09	1.5E−10	3.4E−10	6.5E−10	5.8E−09	2.8E−10	4.3E−09	4.0E−09	3.5E−09	6.8E−09	2.0E−09	5.7E−08	9.6E−10	6.7E−10	1.0E−09	5.7E−09
xide, GLO		4.9E−07	1.9E−08	6.5E−08	2.9E−07	1.3E−06	2.0E−07	5.2E−07	5.0E−07	4.8E−07	1.6E−06	1.5E−06	3.9E−05	4.1E−08	1.3E−07	1.2E−06	8.5E−07
ium oxide, GLO		2.6E−07	3.2E−08	3.4E−08	7.0E−08	1.7E−07	5.3E−08	1.9E−07	2.4E−07	1.6E−07	1.4E−06	1.0E−07	4.7E−06	1.4E−08	1.4E−07	5.1E−07	5.3E−07
olution state, market for n state, GLO		2.0E−07	1.8E−08	2.1E−08	5.7E−08	9.4E−08	5.0E−08	1.7E−07	1.6E−07	9.4E−08	7.2E−07	5.6E−08	3.5E−06	7.5E−09	1.6E−07	3.2E−07	7.6E−07
er, platinum to generic verter, GLO		8.3E−06	1.7E−07	9.7E−07	3.7E−06	2.0E−05	9.4E−07	3.5E−05	9.0E−05	3.3E−05	1.2E−04	1.4E−05	5.2E−03	5.2E−07	1.4E−06	5.7E−05	2.2E−05
er, palladium to generic verter, GLO		1.6E−05	1.0E−06	2.5E−06	7.0E−06	4.7E−05	2.2E−06	7.6E−05	4.2E−04	4.9E−05	1.9E−04	2.1E−05	7.4E−03	8.7E−07	3.7E−06	1.4E−04	4.0E−05
er, rhodium to generic verter, GLO		9.8E−06	2.0E−07	1.2E−06	4.3E−06	2.1E−05	1.1E−06	3.9E−05	7.7E−05	3.9E−05	1.4E−04	1.7E−05	6.1E−03	6.3E−07	1.6E−06	6.4E−05	2.6E−05
nt of automobile catalyst,		5.3E−06	1.3E−07	4.3E−07	1.3E−06	1.0E−06	4.5E−06	2.3E−06	3.7E−06	2.0E−06	5.0E−05	1.3E−06	7.6E−05	3.7E−07	2.3E−06	1.7E−05	1.4E−05
or aluminium oxide,		2.4E−07	1.6E−08	2.3E−07	3.4E−07	2.5E−07	2.1E−08	1.9E−07	2.6E−07	1.6E−07	9.3E−07	8.8E−08	5.7E−06	4.2E−09	3.9E−08	5.6E−08	4.8E−07
ectricity, medium		6.3E−07	1.3E−08	3.6E−08	9.8E−08	6.6E−08	2.1E−07	1.7E−07	2.1E−07	1.6E−07	1.1E−05	1.4E−07	7.8E−06	5.0E−08	2.3E−07	2.3E−07	1.5E−06
rket for steel, chromium		1.1E−05	2.0E−07	4.9E−05	5.1E−06	1.2E−05	1.6E−06	8.1E−06	1.0E−05	6.5E−06	4.3E−05	3.8E−06	2.7E−04	4.8E−07	2.3E−06	5.0E−05	2.0E−05
production, low-alloyed,		4.0E−07	8.6E−09	1.3E−06	2.1E−07	3.5E−07	6.9E−08	3.2E−07	2.7E−07	1.9E−07	2.2E−06	1.3E−07	7.9E−06	1.8E−08	6.2E−08	5.6E−07	7.1E−07
		0.0E+00	0.0E+00	0.0E+00	0.0E+00	−2.2E−03	0.0E+00	−2.5E−02	−1.3E−02	−2.4E−02	0.0E+00	−1.4E−02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
		−8.6E−04	0.0E+00	0.0E+00	−1.0E−02	0.0E+00	0.0E+00	−5.2E−03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	−8.9E−06	0.0E+00	0.0E+00	0.0E+00	0.0E+00
		0.0E+00	0.0E+00	0.0E+00	−5.8E−06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	−2.3E−07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
		1.1E−03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
		9.5E−04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

pletion, HTc: human toxicity, cancer effects, HTnc: human toxicity, non-caner effects, PM: particulate matter, IR: ionizing radiation, POF: photochemical ozone formation, A: er eutrophication, ME: marine eutrophication, FE: freshwater eco toxicity, FET: freshwater eco toxicity, LU: land use, WU: water use, RDM: resource use, minerals and metals, RDE:

Table S12. Normalized results for the 1/2 vehicle catalytic converter, three-way catalyst (1/2 TWC).

LU	WU	RDM	RDE
PE	PE	PE	PE
1.2E−06	**4.5E−06**	**9.9E−05**	**4.6E−05**
5.2E−08	1.1E−07	2.5E−07	4.5E−07
5.0E−10	7.2E−09	7.8E−09	3.2E−08
1.3E−09	7.7E−09	1.0E−08	7.2E−08
1.5E−09	8.4E−09	1.3E−08	1.1E−07
4.8E−10	3.3E−10	5.0E−10	2.9E−09
2.1E−08	6.6E−08	5.8E−07	4.2E−07
7.0E−09	6.8E−08	2.5E−07	2.6E−07
3.8E−09	8.1E−08	1.6E−07	3.8E−07
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
6.3E−07	1.6E−06	6.4E−05	2.6E−05
1.8E−07	1.2E−06	8.6E−06	7.1E−06
2.1E−09	2.0E−08	2.8E−08	2.4E−07
2.5E−08	1.1E−07	1.2E−07	7.4E−07
2.4E−07	1.1E−06	2.5E−05	1.0E−05
8.9E−09	3.1E−08	2.8E−07	3.5E−07
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00

F: photochemical ozone formation, A:
source use, minerals and metals, RDE:

[redacted]

3.9E−05	1.4E−04	1.7E−05	6.1E−03
9.8E−07	2.5E−05	6.7E−07	3.8E−05
7.8E−08	4.7E−07	4.4E−08	2.8E−06
7.9E−08	5.4E−06	7.2E−08	3.9E−06
3.2E−06	2.1E−05	1.9E−06	1.3E−04
9.4E−08	1.1E−06	6.7E−08	3.9E−06
−2.4E−02	0.0E+00	−1.4E−02	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00

culate matter, IR: ionizing radiation, PC
LU: land use, WU: water use, RDM: re

TE	FE	ME	FET
PE	PE	PE	PE
−2.4E−02	**2.0E−04**	**−1.4E−02**	**6.3E−03**
1.8E−07	1.1E−06	1.8E−07	1.4E−05
6.5E−09	6.7E−08	4.0E−09	2.0E−07
5.1E−08	1.5E−07	2.8E−08	4.5E−06
4.7E−08	3.9E−07	2.7E−08	2.5E−06
1.7E−09	3.4E−09	1.0E−09	2.8E−08
2.4E−07	7.9E−07	7.7E−07	2.0E−05
8.2E−08	7.2E−07	5.0E−08	2.3E−06
4.7E−08	3.6E−07	2.8E−08	1.7E−06
0.0E+00	0.0E+00	0.0E+00	0.0E+00
0.0E+00	0.0E+00	0.0E+00	0.0E+00

[redacted]

n toxicity, non-caner effects, PM: partic
phication, FET: freshwater eco toxicity,

	PM	IR	POF	A
	PE	PE	PE	PE
6	**−2.2E−03**	**4.5E−06**	**−2.5E−02**	**−1.3E−02**
3	2.3E−07	4.9E−08	1.7E−07	2.0E−07
9	8.9E−09	3.6E−09	8.0E−09	1.2E−08
7	4.1E−07	7.7E−09	6.4E−08	6.0E−08
3	1.0E−07	3.4E−09	5.7E−08	9.0E−08
0	2.9E−09	1.4E−10	2.1E−09	2.0E−09
7	6.4E−07	1.0E−07	2.6E−07	2.5E−07
3	8.4E−08	2.6E−08	9.5E−08	1.2E−07
3	4.7E−08	2.5E−08	8.4E−08	7.8E−08
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
5	2.1E−05	1.1E−06	3.9E−05	7.7E−05
7	5.0E−07	2.2E−06	1.2E−06	1.9E−06
7	1.2E−07	1.1E−08	9.4E−08	1.3E−07
3	3.3E−08	1.1E−07	8.5E−08	1.1E−07
5	5.8E−06	8.1E−07	4.1E−06	5.1E−06
7	1.7E−07	3.5E−08	1.6E−07	1.3E−07
0	−2.2E−03	0.0E+00	−2.5E−02	−1.3E−02
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00
0	0.0E+00	0.0E+00	0.0E+00	0.0E+00

[redacted]

	0.0E+00	0.0E+00	0.0E+00	0.0E+0
ic	0.0E+00	0.0E+00	0.0E+00	0.0E+0
	9.8E−06	2.0E−07	1.2E−06	4.3E−0
yst,	2.7E−06	6.5E−08	2.1E−07	6.5E−0
	1.2E−07	7.8E−09	1.1E−07	1.7E−0
	3.1E−07	6.7E−09	1.8E−08	4.9E−0
um	5.4E−06	9.9E−08	2.4E−05	2.5E−0
ed,	2.0E−07	4.3E−09	6.4E−07	1.1E−0
	0.0E+00	0.0E+00	0.0E+00	0.0E+0
	0.0E+00	0.0E+00	0.0E+00	0.0E+0
	0.0E+00	0.0E+00	0.0E+00	0.0E+0
	0.0E+00	0.0E+00	0.0E+00	0.0E+0
	4.8E−04	0.0E+00	0.0E+00	0.0E+0

an toxicity, cancer effects, HTnc: huma
water eutrophication, ME: marine eutro

r	CC	OD	HTc	HTnc
	PE	PE	PE	PE
	5.0E−04	**4.3E−07**	**2.7E−05**	**8.4E−0**
	3.6E−07	1.1E−08	8.0E−08	8.3E−0
	1.4E−08	5.3E−10	9.7E−10	2.4E−0
	1.7E−07	1.0E−09	1.2E−07	1.7E−0
	6.7E−08	2.0E−09	6.7E−08	9.0E−0
	1.7E−09	7.3E−11	1.7E−10	3.2E−1
	2.5E−07	9.6E−09	3.3E−08	1.4E−0
	1.3E−07	1.6E−08	1.7E−08	3.5E−0
for	1.0E−07	9.0E−09	1.1E−08	2.9E−0

[redacted]

one depletion, HTc: hum
eutrophication, FE: freshw

ed by vehicle catalytic converte
) kN press, automode, RER
GLO
for magnesium oxide, GLO
rket for aluminium hydroxide
a sand, GLO
erium oxide, GLO
or zirconium oxide, GLO
in 98% solution state, market
solution state, GLO
converter, platinum to generi
lytic converter, GLO
converter, palladium to gener
lytic converter, GLO
converter, rhodium to generic
lytic converter, GLO
treatment of automobile catal
market for aluminium oxide,
EFTA
et for electricity, medium
lled, market for steel, chromiu
d, steel production, low-alloy
nts