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Journal of Cleaner Production 9 (2001) 395–403

Journal of Cleaner Production

www.cleanerproduction.net

Life cycle assessment of a catalytic converter for passenger cars

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Received 1 May 2000; received in revised form 1 September 2000; accepted 27 October 2000

Abstract

A life cycle assessment of a typical ceramic three-way catalytic converter manufactured for a Swedish passenger car is performed. The environmental impacts occurring in the life cycle of a catalytic converter, encompassing the extraction of raw materials, production of a catalytic converter, use phase, etc. are assessed. They are compared with the environmental benefits assessed throughout an average service lifetime of a catalytic converter. Inventory data show that several significant environmental impacts occur in the life cycle and are related to mining and production of the Platinum Group Elements (PGEs) used as the catalytic elements as well as to the use phase. At the current recycling rate, two of the three weighting methods used in this study indicate that the environmental impacts such as resource depletion and waste generation are not less important than the air emissions reduced at the car exhaust pipe. As its name implies, a “catalytic converter” is a “converter”. From a global and life cycle perspective, the catalytic converter is “converting” rather than reducing the environmental impacts. The results show that it is converting exhaust emissions from one place to environmental impacts in other places of the world. It is important that a life cycle perspective should be used for any “end of pipe” solution and the environmental impacts occurring in the life cycle should not be overlooked and should be weighed against the environmental benefits.

Keywords: Life cycle assessment (LCA); Catalytic converter; Passenger car; Platinum Group Elements (PGEs)

1. Introduction

Cars, the dominant source of road transport emissions, are one of the most important contributors to air pollution problems. To reduce the atmospheric emissions from passenger cars, the catalytic converter, an “end-of pipe” solution, was introduced and has become one of the most effective technologies. Since the introduction of cars with three-way catalytic converters, emissions of hydrocarbons, carbon monoxide, nitrogen oxides and other atmospheric pollutants from car exhausts have declined substantially. Nevertheless, it is essential not only to consider the clear benefits of a catalytic converter only at the exhaust pipe, but also to take into account the environmental impact entailed in extracting raw materials and producing a catalytic converter as part of its life cycle. From a local and global perspective, it is therefore important to investigate whether this technology is reducing the environmental impact from car exhausts locally while increasing environmental burdens globally. Life cycle assessment is the approach chosen to investigate the environmental performance of a catalytic converter. The paper starts by defining the goal, scope, and assumptions of the study. In later sections, the paper discusses the comparisons of the environmental impacts and benefits of a catalytic converter.

2. Method

2.1. Goal definition

The goal of this study is to assess and compare the environmental impacts occurring in the life cycle of a catalytic converter and the environmental benefits in terms of atmospheric emission reductions at the exhaust pipe.

2.2. Functional unit

The assessment and comparison of the total environmental impacts and benefits are based on the functional

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0959-6526/01/$ - see front matter
PII: S0959-6526(00)00082-2

unit of one catalytic converter over 160,000 kilometers (km) of use. This is the guaranteed service lifetime of catalytic converters from the manufacturer [1] and is assumed to be the average service lifetime of the catalytic converter in this study. Over this service lifetime, it is assumed that the catalytic converter is not broken or malfunctions because of damage to the catalyst through accidental impacts or engine misfires.

2.3. Studied product

Of several designs and techniques for catalytic emission control for passenger cars, the ceramic monolithic three-way catalytic converter is one of the most widely used. In this study, a typical ceramic three-way catalytic converter manufactured for a Swedish passenger car is considered. It consists essentially of three parts: 1) A monolithic ceramic support that carries the catalyst, 2) A mat that surrounds the monolithic support made of ceramic material, 3) A converter housing made out of high quality, corrosion-resistant steel [2]. Table 1 shows the catalyst formulation taken from the typical values of the upper middle segment of Swedish passenger cars [3,2]. The amount of average fuel consumption of the cars is 3.4 Megajoule (MJ)/km or 0.109 litre/km [3,4].

2.4. System boundaries

2.4.1. Geographical

It is assumed that the catalytic converter is manufactured in England using Platinum Group Elements (PGEs) mined and produced from a PGE mining company in South Africa (Fig. 1). Raw materials such as ceramic monolith and wire mesh are assumed to have been produced in Germany. Steel is assumed to be produced in Wales. The catalytic converter is installed and used in Sweden. Spent catalytic converters are recycled in Sweden but PGEs are recovered and refined by the manufacturer in England. The environmental impacts are assessed in each area where the activities in the life cycle of the catalytic converter take place.

2.4.2. Life cycle

The production of raw materials for the catalytic converter production such as washcoat, ceramic monolith and ceramic wire mesh are included in the system boundaries but the extraction and transportation of the corresponding raw materials are excluded since data are not available and are assumed negligible. The mining and production of PGEs and the production of steel are included. Data regarding the extraction and production are also included for most energy carriers including electricity and fuels.

In order for the catalytic converter to be able to effectively reduce the exhaust emissions, an oxygen sensor and electronic fuel management system is required to monitor the exhaust gas composition and to control the air to fuel ratio, respectively. This sensor consists of an electrolytic cell with “platinum” electrolytes [5]. However, the environmental impacts occurring in the life cycle of the oxygen sensor and the associated control system are not included in this study.

2.5. Temporal boundaries

A catalytic converter manufactured for a Swedish car during 1997–1998 is considered. Data of the catalyst formulation, use and recycling stages are based on data of year 1998–1999. Data on the mining and production of Platinum Group Elements (PGEs) of year 1995 are investigated [6]. Data regarding the environmental impacts in the energy carrier production and transportation in the LCA database are based upon data of year 1991–1994 [4].

Table 1
The material compositions of a typical ceramic three-way catalytic converter

	Ceramic monolith	Total weight
Catalyst support	Cordierite (crystal phase) –MgO 14% –Al_2O_3 36% –SiO_2 50%	2×0.7 kg
Mat	Ceramic wire mesh	2×0.25 kg
Washcoats	Metal oxides slurry –Al_2O_3 10% –CeO_2 20% –ZrO_2 70%	0.17 kg
	Precious metals –Pt: Pd: Rh 1:14: 1	2 kg
Converter housing	Steel	5 kg
Total weight		7.1 kg

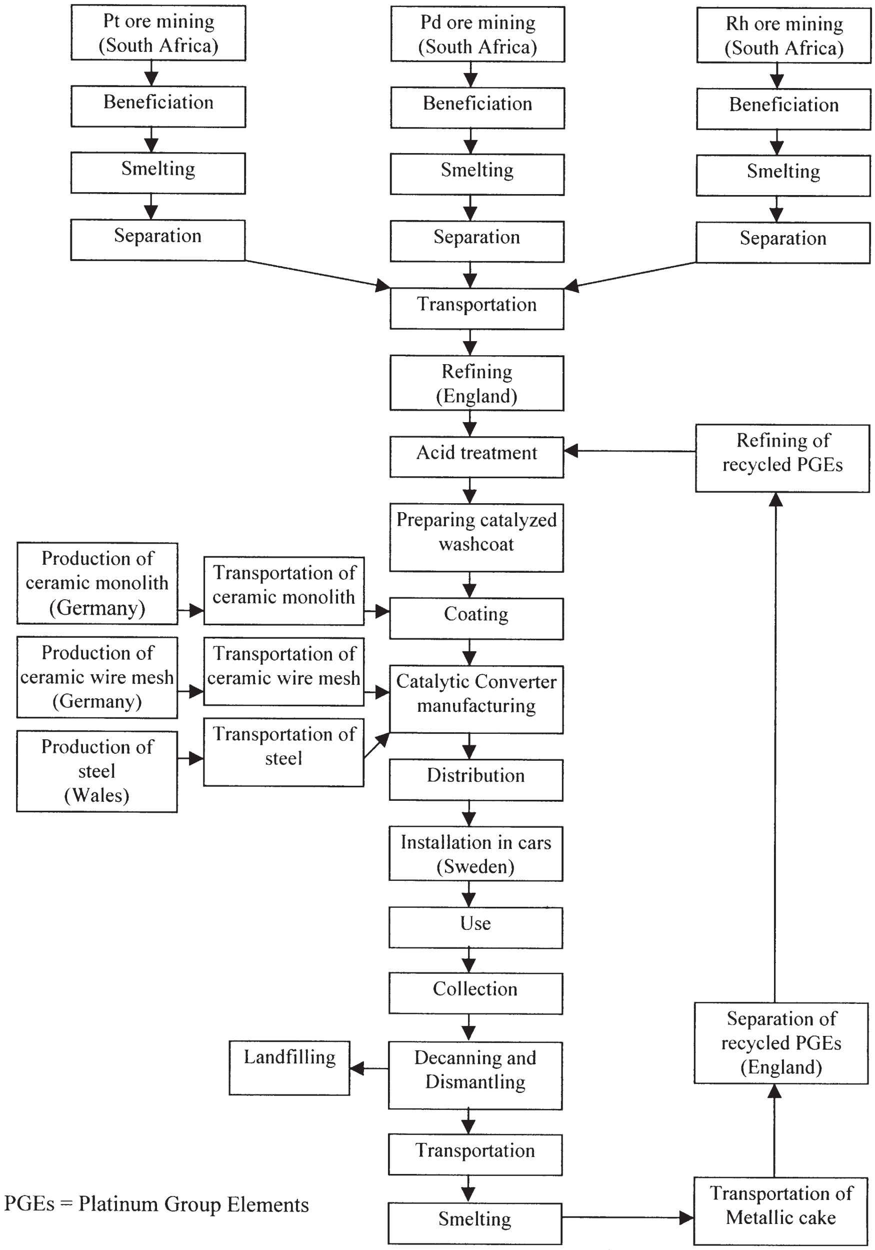

Fig. 1. Life-cycle diagram of a catalytic converter.

2.6. Data types

The life cycle of a catalytic converter involves many competitive business areas such as manufacturers of cars, PGEs and monolith. Part of the data required for this study is therefore not accessible. Data obtained from updated available literature, personal communications and estimations by industrial experts, and the LCA database are acceptable. Most data available are 4–8 years old except that the data of the catalyst formulation, use and recycling stage are of years 1998–1999.

South Africa and Russia are among the most important producers of PGEs [7]. The data of PGEs mining and production in South Africa are more collected and documented. In this study, the data of PGEs mining and production are taken from a collection of data in the literature obtained from a large mining company in South Africa in 1995 [6]. The data regarding manufacturing of catalytic converters and their raw materials such as monoliths and washcoats are, where applicable, estimated and based on the production process descriptions availiable in the literature [8].

Literature data are used for steel production [9]. Data on recycling of catalytic converters are obtained from a Swedish catalytic converter recycling company. Transportation data included in the recycling stage are also estimated by the company [10,11]. Data on recovering and refining of PGEs from spent catalytic converters are estimated by data of similar operations in the primary production of PGEs [6]. Data of the catalyst formulation are suggested by a Swedish car catalyst expert (Table 1) [3]. Car exhaust emissions and emissions reductions are estimated by the Swedish Motor Test Center and the car catalyst expert (Table 2) [12,3]. The distance and mode of transportation outside the recycling stage are estimated and based upon the location of the assumed production sites.

2.7. Assumptions for up-stream processes.

2.7.1. Electricity production in South Africa

Electricity in South Africa is mainly generated by coal-fired power stations [13]. It is assumed that the electricity use in the mining and production of PGEs in South Africa is based only upon coal-fired power stations.

2.7.2. Transportation

The amount of fuel consumption and emissions released during the transportation and the environmental impacts associated with its production are based on the LCA database [4].

2.7.3. Increased fuel consumption

When car exhaust flows through the monolithic catalytic converter inserted in the exhaust pipe, the catalytic converter causes a certain amount of pressure drop or back pressure, resulting in an increased consumption of the fuel to overcome the back pressure. This is therefore considered as energy loss due to the use of the catalytic converter. A range of 0.5–3% increased fuel consumption due to the back pressure is estimated [3,14]. For this reason, metallic monolith catalytic converters are used in some Swedish passenger cars to reduce the back pressure. It is noted, however, that these cars require about 3.2 g of PGEs per catalytic converter [15]. In addition, in order for efficient reduction of exhaust emissions the air to fuel ratio of a car equipped with a catalytic converter needs to be adjusted to be close to the stoichiometric ratio, (i.e. 14.7 to 1). The effect of the lower air to fuel ratio and the back pressure collectively leads to 10% increased fuel consumption [14]. However, in this study, the lowest value of the increased fuel consumption is chosen. Thus, 0.017 MJ/km or 0.00055 litre/km of gasoline is the additional consumption. The increased fuel consumption also results in increased exhaust emissions. The amounts of increased emissions are based on the car exhaust emissions presented in Table 2[3,12].

2.7.4. Energy carriers production

To quantify the environmental burdens associated with the extraction and final use of the energy carrriers, emissions factors are used [4].

2.8. Allocations

2.8.1. PGEs production

As PGEs always occur in deposits associated with base metals like copper and nickel, the material and energy flows have to be divided between the PGEs and these metals. In this study, the allocation is based on the average price of the metals in 1995. It is believed that this allocation reflects the motivation to mine the ores. The energy and material flows of each PGEs production are therefore allocated proportional to its contribution to the total sales of the metals of the mining company [6,16].

2.8.2. Steel production

Steel production comprises multi-output processes. The economic allocation was chosen where the environmental loads are assigned to each product according to the price and the amount produced [9].

2.8.3. Steel recycling

The steel scraps from the decanning process are recycled for secondary steel production. It is assumed that the secondary steel production carries all of the impacts associated with the production and the final disposal after use. Thus, in this study, data on recycling of steel are excluded.

Table 2
Average exhaust emissions of a Swedish car without a catalyst and with a catalyst[a]

Emissions	A car (without catalyst) (g/km)	Relative change (with catalyst)	A car (with catalyst) (g/km)	Changed amount (g/km)	Euro standard 1996 (g/km) [2]
CO	10	−95%	0.5	−9.5	2.2
NOx	2	−90%	0.2	−1.8	}
HC	0.9	−95%	0.045	−0.855	}*0.5
CH_4	0.1	−70%	0.03	−0.07	}
CO_2	200	+0.5%	201	+1	–
SO_2	0.01	+0.5%	0.01005	+0.00005	–

[a] The emissions limit for a total of emissions of NOx, HC and CH_4 is 0.5 g/km

2.9. PGEs recycling scenarios

The mining and primary production of PGEs is a significant contributor to environmental impacts occuring in the life cycle of a catalytic converter. The recycling rates of PGEs are therefore a significant factor in reducing environmental impacts. In 1997, 10% of spent catalytic converters are recycled in Europe and a higher percentage in the US [7]. In this study, two scenarios of PGEs recycling rates (10% and 90%) are investigated.

3. Results

Environmental impacts and benefits occurring in the life cycle of the catalytic converter with the assumed current recycling rate of PGEs (10%) are discussed and presented in Table 3. Three comparisons of the environmental impacts and benefits and the comparisons of the results of 10% and 90% PGEs recycling rate are made.

3.1. Direct comparison of the total environmental impacts and benefits

3.1.1. Environmental impacts

Due to the scarce natural occurrence of PGEs, several significant environmental impacts occur during the mining and production of the precious metals used as the catalytic elements. The ore mined and produced in South Africa occurs naturally in low concentrations (about 8 g/ton); therefore, the mining and production processes are complex and require substantial amounts of energy and material resources and consequentially generate a large amount of solid wastes. For example, electricity consumption of 110 MJ/catalytic converter is used mainly for the mining processes since the ore is mined underground below 1000 m. Electricity production in South Africa is mainly based on coal-fired power stations; thus, it contributes significantly to a substantial amount of coal use corresponding to 11 kg/catalytic converter. The burning of coal gives rise to a significant amount of carbon dioxide and sulphur dioxide emissions. Moreover, substantial emissions of sulphur dioxide into air are generated chiefly from the smelting process. However, it should be noted that most of the air emissions including metals emissions generated directly from the mining and production of PGEs are not included in this study since data are not obtainable.

To produce gasoline for the increased consumption to overcome the back pressure, non-renewable energy resources such as 66 kg of crude oil/catalytic converter and 9 kg of natural gas/catalytic converter are exploited over the use phase. Natural gas is used during the refining processes of crude oil and production of additives for the gasoline. The additional gasoline consumption also results in increased exhaust emissions of carbon monoxide, nitrogen oxides, hydrocarbons and methane. Furthermore, a large amount of emissions of carbon dioxide to air corresponding to 390 kg/catalytic converter is generated principally due to the additional com-

Table 3
Environmental benefits and some environmental impacts occurring in the life cycle of a catalytic converter. (10% reycling rate of PGEs)

Parameter	Amount of environmental benefits	Amount of environmental impacts	Unit
Energy resource use			
Crude oil	–	66	kg
Natural gas	–	9	kg
Coal	–	11	kg
Material resource use			
PGEs	–	1.8	g
Air emissions			
CO	1500	0.4	kg
NOx	290	0.3	kg
HC	140	0.2	kg
CH_4	11	0.2	kg
CO_2	–	390	kg
SOx	–	0.7	kg
PGEs	–	3.2	mg
Zn	–	1.5	g
Water emissions			
Zn	–	15	mg
Mn	–	1.5	mg
Pb	–	2	mg
Waste generation			
Solid waste	–	253	kg
Slag	–	8.3	kg
Waste	–	5.4	kg

bustion of gasoline as well as the catalytic conversion of carbon monoxide and hydrocarbons to carbon dioxide by the catalytic converter over the use phase. Also, during driving, PGEs are emitted from the catalytic converter due to mechanical abrasion in small amounts (nanograms (ng)/km) or about 3.2 mg/catalytic converter [17]. The biological effects of their increased distribution on the ecosystems, however, should be of concern.

Due to their scarce natural occurrence, much attention should be drawn to the exploitation of such metals as platinum (Pt), palladium (Pd) and rhodium (Rh) used as the catalytic elements. Although only about 2 g per catalytic converter are used, the depletion of these metals could be of critical importance in the future.

Based on the inventory data, no significant impacts from emissions to water are of concern. However, due to vast volume of water utilized in the mine and PGEs production, it could be estimated from a material balance that substantial amounts of wastewater are released.

Concerning waste generation, the mining of PGEs, occurring naturally in low concentrations, involves the removal, processing and disposal of vast volumes of rock and wastes. As a result, a large amount of solid wastes of about 250 kg/catalytic converter is released. The wastes are mainly from tailings in the beneficiation process and slag from the smelting process.

3.1.2. Environmental benefits

Substantial benefits are gained through atmospheric emisssions reduction at the exhaust pipes. Concerning significant emissions, over 160,000 km of the use of a catalytic converter, about 1500 kg of carbon monoxide, 290 kg of nitrogen oxides, 140 kg of hydrocarbons and 11 kg of methane are reduced from the exhaust emissions.

3.2. Comparison by characterization of the environmental loads

Since different environmental loads cannot directly be compared in terms of amounts, comparisons are carried out by characterization of the environmental loads. The relative potential contributions of each input and output to its asssigned impact catagories, such as global warming and ozone depletion, are assessed by a characterization index, and the contributions to the same impact catagory are summated [18].

Table 4 shows that environmental benefits with respect to impact categories; photochemical ozone creation potential (POCP) of emissions of hydrocarbons and carbon monoxide, and eutrofication and acidification potential of emissions of nitrogen oxides are substantially greater than the environmental impacts. However, the environmental impacts due to global warming potential (GWP) of increased emissions of carbon dioxide and methane are greater than the environmental benefits. It should be noted that GWP of carbon dioxide, methane, carbon monoxide and nitrogen oxides are 1, 24.5, 0, 0, respectively [18]. Resource depletion and waste generation are also the significant environmental impacts that should be of concern.

3.3. Impact assessment (comparison by three weighing methods)

In order to weigh the relative importance of different environmental impacts, each environmental impact is assigned with a valuation index calculated according to the methodology of each weighing method. The environmental load indices for the three weighing methods used in Life Cycle Assessment (LCA) have been updated for Swedish conditions (EPS 1996 [19], Environmental Theme 1995 [18], Ecoscarcity 1995 [18]). In this study, the three weighing methods are used to compare the total environmental impacts and benefits.

3.3.1. EPS method

The EPS method assesses impacts on the environment in terms of ecological and health consequences. Five safeguard subjects that mean “the environment” are defined, i.e, human health, biological diversity, production, resources, and aesthetic values. Environmental impacts are valued according to the willingness to pay for protecting the safeguard subjects [19].

Assessment by the EPS method suggests that the use of platinum, palladium and rhodium is of most concern. Although they are utilized in small amounts, a total of 2 g per catalytic converter, these precious metals are assigned with high indices due to their scarcity (Table 5).

Other impacts such as energy resource use, air and water emissions collectively contribute to a small Environmental Load Unit (ELU). Among air emissions, carbon dioxide is the most significant contribution to ELU. ELU of water emissions are relatively negligible. It is, however, noted that water emissions might significantly increase ELU, if those from mining are included and the indices for releases of metals to water are at present available.

Waste is not evaluated in this method, but the emissions from the waste, energy and land used for the landfill are evaluated. The system boundaries of this study are restricted to the waste, excluding the emissions of waste in the landfill, therefore, there are no ELU results from the waste generation. It should be considered that the emissions from the waste, energy and land used for the landfill, if included, can lead to a substantial increase in ELU since there is an enormous amount of waste.

The assessment indicates substantial benefits gained through a significant reduction of the emissions of carbon monoxide, nitrogen oxides, hydrocarbons and methane. Reduction of ELU is due to appreciable abatement of carbon monoxide, nitrogen oxides and emissions, respectively.

Table 4
Characterization results of the environmental loads (10% recycling rate of PGEs)

Impact category	Amount of reduced environmental loads	Amount of increased environmental loads	Unit
GWP 100 [18]	269.5	394.9	kg CO_2-eq.
POCP (average ozone, low NOx) [18]	197.9	0.2	kg Ethene
Eutrofication [18]	37.4	0.4	kg NOx-eq.
Acidification [18]	202	0.9	kg SO_2-eq.
Resource [18]	0	1.8	use to reserve ratio
Waste	0	266.7	kg waste

Table 5
Environmental impacts and benefits weighted by the EPS method[a]

	ELU (impacts)			
Environmental impacts	PGER*=10%	PGER=90%	Environmental benefits	ELU (benefits)
Energy (oil, gas, coal)	38.3	38.5	CO	290
Material (Pt, Pd, Rh)	831	144	NOx	114
Air emissions (CO_2)	25.8	25.7	HC	95.8
Water emissions (COD)	8.1e-4	8.6e-4	CH_4	17.4
Waste	–	–		
	895.1	208		517.2

[a] PGER=PGEs recycling

Summarizing, the total environmental benefits of the catalytic converter are, however, weighted significantly lower than the total ELU to which the exploitation of platinum, palladium, rhodium and non-renewable energy resources substantially contributes.

3.3.2. Environmental Theme (ET) method

The ET method groups environmental loads into environmental themes or impact categories such as global warming, ozone depletion, and acidfication. Weighting is based on assumed critical loads in a geographical area and defined period of time for different impact categories [18].

Concerning the environmental impacts, most significant contributions to ET-points evaluated by the ET-method are due to air emissions, generation of waste, and use of energy resource, respectively. Among air emissions, global warming effect of carbon dioxide and acidification effect of sulphur dioxide are of high concern (Table 6).

The assessment indicates substantial benefits of the catalytic converter due to a significant reduction of carbon monoxide, nitrogen oxides and hydrocarbons emissions.

Summarizing, as a result, the total environmental benefits are weighted significantly higher than the total environmental impacts dominated chiefly by the emissions into air of carbon dioxide and sulphur dioxide as well as the generation of solid wastes.

3.3.3. Eco-scarcity method

The Eco-scarcity method values each environmental load based on the relation between the critical annual load and the actual annual load for a given area [18].

Assessment by the Eco-scarcity method values solid waste generation as the most critical impact and the other impacts are comparatively much less important (Table 7).

The assessment indicates substantial benefits gained through a large reduction of gaseous emissions reduced at the exhaust pipe. Reduction of Ecopoints is owing to only nitrogen oxides and hydrocarbons emissions because carbon monoxide and methane are not assigned with an index.

Summarizing, the total environmental benefits, however, are weighted significantly lower than the total environmental impacts dominated by the tremendous amount of solid waste.

3.3.4. Comparisons of the results of 10% and 90% PGEs recycling rate

Three weighting methods illustrate that by increasing the recycling rate of PGEs, the environmental impacts of the use of material resources and the generation of solid waste can be diminished substantially (Table 5–7). However, other environmental impacts such as energy resource use, and emissions to air and water are to some extent increased. The reason for this is because the additional use of crude oil and natural gas due to the

Table 6
Environmental impacts and benefits weighted by the Environmental theme method

Environmental impacts	ET-points (impacts) PGER=10%	PGER= 90%	Environmental benefits	ET-points (benefits)
Energy (oil, gas, coal)	9.93e+3	1.04e+4	CO	1.25e+6
Material (Pt, Pd, Rh)	–	–	NOx	1.14e+6
Air emissions (CO_2, SO_2)	2.06e+4	2.20e+4	HC	1.03e+6
Water emissions (Zn)	4.38e+2	2.70e+3	CH_4	1.06e+4
Waste	1.11e+4	2.70e+3		
	4.21e+4	3.73e+4		3.43e+6

Table 7
Environmental impacts and benefits weighted by the Eco-scarcity method

Environmental impacts	Eco-points (impacts) PGER=10%	PGER=90%	Environmental benefits	Eco-points (benefits)
Energy (oil, gas, coal)	2.64e+3	2.73e+3	CO	–
Material (Pt, Pd, Rh)	–	–	NOx	1.37e+6
Air emissions (CO_2, SO_2)	1.83e+4	5.21e+4	HC	1.44e+6
Water emissions (Zn)	2.53e+2	1.88e+3	CH_4	–
Waste	8.92e+6	1.72e+6		
	8.94e+6	1.78e+6		2.81e+6

increased electricity consumption during the recycling stage influences the total environmental loads more than the decreased use of coal during the PGEs production. It is noted that higher indices are assigned by the three weighing methods for crude oil and natural gas than for coal. For the increased environmental loads of air and water emissions, it is noted that data of most water and air emissions during the PGEs production are not available whereas those of the recycling stage are.

4. Discussion

The assessment of the total environmental benefits and impacts depends on several factors such as the amount of PGEs used in a catalytic converter, the country of PGEs production, allocation procedure, emissions factors of a car, service lifetime of a catalytic converter, increased fuel consumption due to the use of a catalytic converter, data quality, and the recycling rate of PGEs. It is noted that in this study most of the air and water emissions from the PGEs production and the environmental impacts from the life cycle of the oxygen sensor and other control systems are not included since data are not available. It should be also noted that the impact assessment in this study is based on the assumptions that the environmental impacts and benefits are all occurred and valued today. In fact, the environmental benefits of a catalytic converter are increasingly gained depending on the increased distance of use while the environmental impacts during the mining and production of PGEs occur before a catalytic converter is used.

Inventory data show that several significant environmental impacts occur in the life cycle of a catalytic converter and are related to mining and production of PGEs as well as to the use phase. At the current recycling rate, two of the three weighing methods used in this study indicate that the environmental impacts such as resource depletion and waste generation are not less important than the air emissions reduced at the car exhaust pipe. In other words, the results of the inventory data or the weighing methods show that part of its life cycle entails several significant environmental impacts. As its name implies, a catalytic converter is a “converter”. From a global perspective and a life cycle perspective, the catalytic converter is “converting” rather than reducing the environmental impacts. The results show that it diminishes the environmental impact occurring in one place by reducing significant exhaust emissions, but it also increases significant environmental impacts in other places especially during the extracting of raw materials and production. It is worth noting that people in some “developing” countries to which the environmental burdens are moved are enjoying the economic gain of the production while also suffering the consequent environmental problems and the costs of fixing the problems. The “converted and moved” impacts may appear later as local or global problems as chain effects of the “end of pipe” solution. Thus, the character of the pollution problems of car exhaust emissions may be converted but critically these environmental problems may not in fact be effectively solved.

Furthermore, more stringent emissions limits which are expected to further increase local emissions reduction from car exhaust pipes can be of critical concern. Due to the possibility of forcing further advances in catalyst or other technology for the stricter emissions limits, the solution may be concluded with a higher use of precious metals [7]. From a global and life cycle perspective, the environmental impacts may outweigh the environmental benefits because a small additional use of the PGEs may generate more environmental impacts than the further reduced emissions. For instance, a fuel cell vehicle under current development as an alternative for almost Zero car exhaust emissions requires at least 10 grams of PGEs, significantly more than that of a car installed with a catalytic converter [7]. Substantially more environmental impacts occurring during the mining and production of PGEs may outweigh the further benefits of reduced exhaust emissions.

It is worth noting that the purpose of the study is not to obtain an absolute answer as to whether a net environmental benefit can be achieved. The study is based on many estimations and assumptions and should be considered as a lesson for future development. Since the production of PGEs is associated with significant environmental impacts, an increased recycling rate of PGEs will lead to a significant reduction of the associated environmental impacts. It is more important that a life cycle perspective be used for any “end of pipe” solutions. The environmental impacts occurring in the life cycle should not be overlooked and should be weighted against the environmental benefits in order for more local and global improvement for the environment and sustainable development. It is also important that non “end of pipe” solution be considered.

This paper is based on a study on life cycle assessment of a catalytic converter for passenger cars [20]. In order to obtain better and more detailed information, data from the production of the PGEs, the catalytic converter and some of its components that are not accessible at present should be further investigated. The environmental impacts from the life cycle of an oxygen sensor and other control systems should as well be included. Also, the effects of increased emissions and distribution of PGEs on the ecosystems should be investigated.

Acknowledgements

The authors would like to thank Morgan Fröling, their colleague at the Department of Chemical Environmental Science, Chalmers University of Technology, Sweden for his useful comments.

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