A Comparative Life Cycle Assessment of Recycling the Platinum Group Metals from Automobile Catalytic Converter: An Australian Perspective

MARYAM GHODRAT, M. AKBAR RHAMDHANI, PEZHMAN SHARAFI,
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This study provides a comparison between environmental impacts of the recovery of platinum group metals (PGMs) from the end-of-life catalytic converters by hydrometallurgical and pyrometallurgical methods. A gate to grave life cycle assessment of a typical three-way catalytic converter manufactured for an Australian passenger car was carried out using GaBi professional environmental package. Recovery rates, as well as qualities, quantities, losses, and fugitive emissions for all materials and elements used in both methods were calculated based on the developed flowsheets. A life cycle impact assessment was then made by carrying out a mass balance calculation. Inventory data show that the hydrometallurgical route for recycling of the platinum group metals out of catalytic converter scrap has lower impacts on the environment compared with the pyrometallurgical method. In terms of emission effects, the hydrometallurgical process was found to be highly advantageous since it causes insignificant emissions to air, sea water, and fresh water. It is also found that the hydrometallurgical route performs comparatively superior in terms of acidification, eutrophication, fossil depletion, and human toxicity. The obtained results are applicable only to the Australian setting.

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I. INTRODUCTION

IN recent years, exhaust emissions from road vehicles have played a prominent role in environmental pollution. To date passenger car usage is growing at a rapid pace which directly results in the increase of emission of harmful greenhouse gases to the atmosphere. In this context, there are many modifications carried out in new generation automobiles in terms of weight reduction, using alternate materials, switching over to hybrid electric vehicles, and so on, to mitigate the serious environmental impacts. One such component is a catalytic converter which is installed in almost every vehicle to convert harmful gases emitted from the engine into a harmless one. It is made up of the ceramic monolith, stainless steel, and the platinum group metals (PGMs) like platinum, palladium, and rhodium. PGMs are used as catalysts, and it is recommended to carry out oxidation and reduction reactions with emitted gases to make them less harmful.

However, owing to the rare existence of the PGMs and their high price, it is favorable to recover these metals after their end of life from scrap converters and recycle them for secondary usage. The recovery processes already existing in practice are the hydrometallurgical and pyrometallurgical techniques, where acid leaching and furnace smelting methods are carried out, respectively. However, there are serious environmental impacts associated with these two methods in terms of energy consumption, chemical usage, wastewater emission, and greenhouse gas emission due to transportation. A recent research by Cossu and Lai[1] indicates that when an abandoned vehicle is subjected to recycling, the recovered metal content contributes nearly 75 pct of the total output, whereas the remaining portion is recovered as shredder residues.[1] Life cycle assessment (LCA) is gaining popularity in recent years to evaluate the impacts of processes and materials used over the entire life cycle of a component. LCA considers all life cycle phases right from the raw material extraction to the disposal of the component after their useful life. This type of LCA method is employed for this study to determine which of the two metal-recovery methods is environmentally more advantageous by making a

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comparison between them. The increasing trend of automobile usage leads to an increase in catalytic converters production which results in higher demand for PGMs mining. Platinum is an extremely scarce resource and if the rising consumption pattern continues the imbalance between supply and demand may possibly escalate into a crisis.[2] Many industries around the world are forced to carry out sustainable manufacturing operations to ensure the resources availability for future consumption.[3] However, primary production of precious metals is energy intensive and causes adverse effects on environment in terms of coal depletion and wastewater emission into mines. A recent study by Reference 4 reported the sustainability issues in platinum mining and predicted that production of platinum metals is expected to increase because of the globally growing demand. In his research, Reference 4 gave approximate values of energy consumption, water, and carbon dioxide emissions in the course of production of 1 t of platinum metal. Continuous decline in the quality of ore grades is attributed to the increasing greenhouse gas emissions since large amount of energy is consumed for ore refining. According to Anglo Platinum mining company, ore refining consumes 23.3 pct of direct energy and 76.7 pct of indirect energy. It is also estimated that 175 GJ of energy is consumed to produce 1 kg of PGM.[4] The secondary production of the PGMs is justified mainly by the fact that the extraction and mining of these metals from their ores consume a large amount of energy and lead to wastewater emission from the mining sites. It is estimated that for producing a ton of precious metals in European countries, nearly 300 kt of materials are required. In the case of metal production in South Africa, the material requirement has gone up even higher to a range of 600,000 t and resulted in 35,000 t of carbon dioxide emission due to the electricity generation from coal.[5] Such considerable figures justify the demand for the secondary usage of platinum, palladium, and rhodium by recovering them from the end-of-life materials especially those used as automotive catalysts. LCA results help to make design changes and adopt innovation in manufacturing technologies. The usage of lightweight materials such as aluminum and magnesium is increasing due to their ability to improve fuel efficiency. A recent study by Raugei *et al.*[6] using LCA compared various scenarios such as using steel, carbon fiber, magnesium, aluminum, and PGMs. The results showed a decrease in carbon dioxide emission while using the PGMs instead of steel which is conventionally used for automotive body and chassis parts.[6]

Performing the LCA along with life cycle costing is also favorable since this kind of studies helps to evaluate the modification implemented from an environmental point of view. For example, the results of a research by Witik *et al.*[7] show that although materials with lightweight are used due to their environmental advantage, the overall life cycle costs have escalated due to the material cost and production cost. In their study, the cost analysis is carried out along with the comparison of environmental benefits of different materials such as steel, magnesium, sheet molding compound, and other composite materials. Another study by Tharumarajah and Koltun[8] evaluated the impact of using magnesium engine blocks instead of other lightweight material such as aluminum or heavier materials such as steel. Their results indicated that this modification contributed positively when considered from the life cycle point of view compared to the previous materials and processes used.

Recycling the PGMs out of catalytic converters after their useful life involves a series of processes such as dismantling, smelting, electrorefining, leaching, and transportation. To be precise, the recovery of PGMs is currently carried out by the pyrometallurgical and hydrometallurgical methods, in which the former involves electrorefining and smelting, whereas the latter involves leaching. However, these two recycling routes during their entire life cycle cause serious threats to the environment due to the release of harmful gases and chemical wastes. In such cases, life cycle assessment (LCA) becomes an unavoidable study which is mainly used to determine the impacts on the environment caused by these recycling processes. In this paper, a life cycle assessment approach is used to investigate and compare the environmental impacts of recycling the PGMs from automobile catalytic converter caused by the hydrometallurgical and the pyrometallurgical processes. The paper starts by defining the goal, scope, and assumptions of the study. In later sections, the comparison of the environmental impacts and benefits of the recycling process of catalytic converter have been discussed.

II. PROCESS DESCRIPTION

The common industrial methods used to recover precious metals from catalytic converters are the hydrometallurgical and the pyrometallurgical routes. The process is performed through leaching the components in acidic environment and melting them in electric furnaces, respectively. The usual procedure is to dismantle the converters from scrapped vehicles and prepare them for melting by grinding and milling. In the pyrometallurgical technique, the precious metal-bearing component extracted from the catalytic converter is then melted in a furnace along with copper. The platinum is dissolved in copper, whereas the other molten materials are removed as slag. The copper-platinum alloy is used as the anode and is subjected to an electrorefining process where platinum is recovered in the form of powder.[9] The second method that has gained popularity in recent years is the hydrometallurgical process. The literature shows that nearly 90 pct recovery rate is possible by subjecting the scrap converter to acid-leaching medium and microwave heating.[10] The component is leached using hydrochloric acid (HCl) and aqua regia ($HNO_3 + 3\,HCl$) at different temperatures, and the optimal one was found to be 120 °C.[11] The residue left behind after the leaching process is treated with chemicals like Triton and Mercaptobenzothiazole (C_6H_4SNCSH) for separating platinum, palladium, and rhodium.[12] Jimenez de Aberasturi *et al*.[11] proposed a new alternative method that included the addition of H_2O_2 as the oxidizing agent. Their proposed method reduced the pollutant gases, and hence, the environmental impacts due to the chemical process decreased.

III. LCA METHODOLOGY

Life cycle analysis was carried out using GaBi professionals' environmental software.[13] The database incorporated in GaBi covers a wide range of data such as flows, processes, and emission data for a range of materials. The data for life cycle inventory (LCI) were taken from the literature and ecoinvent databases. Once the modeling process was carried out and the flow sheets for both the processes were developed, a life cycle impact assessment was made by carrying out the mass balance calculation. The scenario-modeling feature of the GaBi software allows us to create different models for different scenarios, which helps to analyze and compare the results independently.

A. *Goal Definition*

The goal of this study is to assess and compare the environmental impacts occurring in the life cycle of recycling the PGMs from the end-of-life catalytic converter through the pyrometallurgical and the hydrometallurgical routes. The core aim of the research was to determine a superior option for recycling the PGMs in terms of reduction in the overall environmental impacts. This study is an approach from an Australian perspective since it was assumed that all the dismantling and recycling activities for both the methods were carried out in state of Victoria, Australia.

B. *Scope of the Study*

The scope of this study includes the processes that take place after the catalytic converter assembly was transported for installation in the cars, their used phase, and the entire recycling processes. The other processes such as extraction of raw materials, manufacturing of catalytic converters, and the transportation activities associated with these processes were excluded from this study.

C. *Functional Unit*

In this study, the recycling of catalytic converter ultimately results in the recovery of precious metals in powder form. Hence, platinum was chosen as the precious metal to be recovered, and the mass of the metal obtained was considered to be fixed as 1 g. The life cycle impact parameters determined from the study, such as the carbon dioxide equivalent and other emission quantities, compare the results of recovery of 1 g of platinum from the end-of-life catalytic converter between the two studied methods. The functional unit is similar for both the hydrometallurgical and the pyrometallurgical methods of recovery.

D. *System Boundary*

It is assumed that the catalytic converter is manufactured in Australia using platinum group metals mined and produced from a PGMs mining company in South Africa. Raw materials such as ceramic monolith are produced in Austria and steel is assumed to be produced in Australia. The installation process and usage phase take place in Australia. The PGMs are recycled and refined in Victoria, Australia.

The environmental impacts are evaluated in each area where the activities in the life cycle of recycling the PGMs out of catalytic converter scrap take place. The production and transportation of raw materials for the catalytic converter are excluded from the system boundaries. Data related to the extraction and productions of the PGMs are also excluded from this study.

The system boundaries for the pyrometallurgical and the hydrometallurgical routes are shown in Figures 1 and 2, respectively. As a result of the electrorefining process, the slime with platinum and other PGMs were obtained which needed to be further processed.

E. *Assumption*

The LCA analysis of PGMs recovery out of catalytic converter scrap includes several commercial- and industrial-based zones such as car manufacturing, recycling, leaching, and smelting. Some of the data needed for this study are hence not available in Australian context. Given the rather unique population distribution of Australia (clustering, insularity, major cities all on the coast), ratios between different factors for different substances are likely to be quite different between Australia's major population centers. The used data were mainly derived from the updated existing literature, the industrial professionals, and the LCA database. The distance and transportation mode out of the recycling site are determined based on the location of the assumed recycling and dismantling sites.

1. *Electricity production in Australia*

- Electricity in Australia is mainly generated by coal-fired power stations. A production mix related to Australian standards is chosen for all processes involving electricity usage.
- The electricity consumption data for the vehicle dismantling, decanning, and crushing machines are taken from the technical specifications of the machine. A 10-pct increase in electrical usage of the machine is considered.

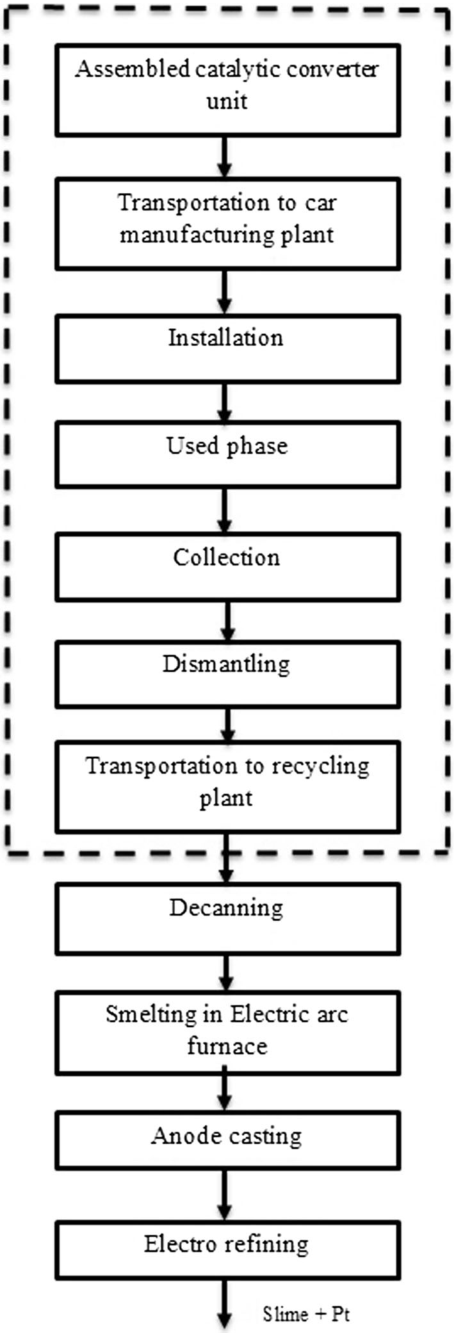

Fig. 1—System boundary—pyrometallurgical route.

2. *Transportation*

- The rates of fuel consumption and emission released to the environment during the transportation are based on the LCA database version 2.0 (1994).
- The vehicle dismantling yard and recycling companies are considered to be situated in Victoria.
- For the pyrometallurgical route of recycling, the vehicle dismantling plant and the recycling company are assumed to be as close as possible to each other in order to reduce the environmental impacts due to the transportation.

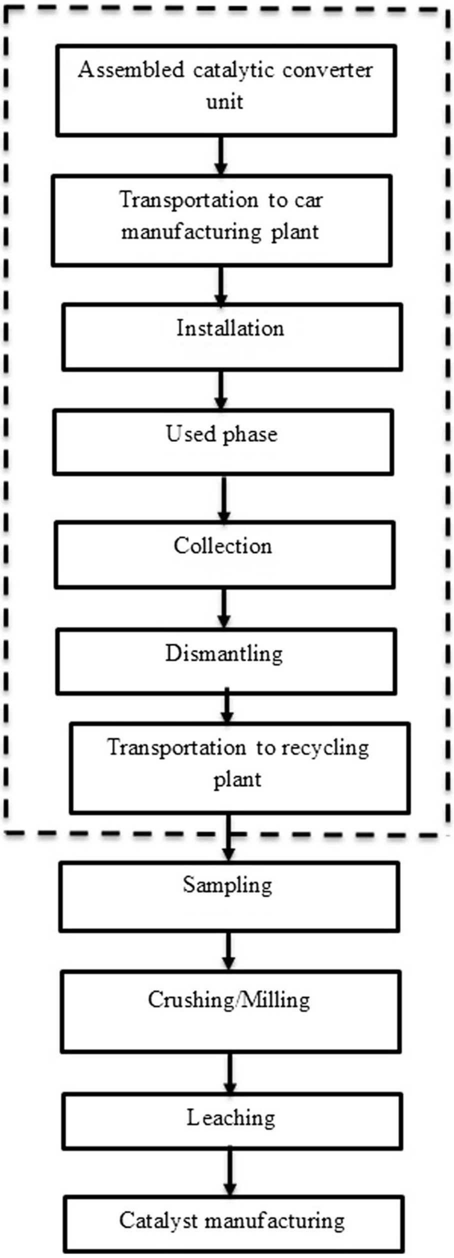

Fig. 2—System boundary—hydrometallurgical route.

Some general assumptions made in this study include

- The leaching and the recovery of PGMs are assumed to be performed in the recycling company located at Western Australia (Perth).
- The recovered PGMs are assumed to be returned to a catalyst-manufacturing company operating in Victoria in order to close the recycling loop.

F. *Reference Process*

In this study, the precious metal (mostly platinum) is recovered from automotive catalyst by two different methods, and it can be termed as the valuable output. Hence, considering this factor, electrorefining and leaching are fixed as the reference processes since they are considered as the final steps in the entire life cycle of pyrometallurgical and hydrometallurgical methods. On average, a three-way catalytic converter emits 120 ng of platinum, 0.3 ng of palladium, and 20 ng of Rhodium at an average speed of 140 km per hour.[14] The emitted metals have a detrimental impact on human health and can cause serious respiratory problems. Soil, fresh water, and plants have also been shown to accumulate great amount of PGMs which raised serious environmental concerns.[15]

G. *Data Collection*

1. *Pyrometallurgical route*

The pyrometallurgical route of recycling involves a series of steps including dismantling; decanning, and smelting the interior at a smelting plant (EAF smelting) followed by separation of the PGMs by means electrorefining process. EAF smelting outputs an iron collector holding the PGMs, and slags used for construction purposes. The collector is exported and treated by means of refining the PGMs where the individual PGMs are isolated and slags are produced, typically involving numerous refining processes.[5,16,17] Aforementioned data serve as the basis for the modeling. Dismantling is mainly done by removing the reusable parts which can be processed further for recycling. The removal of catalytic converter is carried out using hydraulic cutters for breaking the fastening bonds. The overall dismantling process is based on electricity usage with an average power consumption of 38 kW that is subject to changes based on the number of vehicles dismantled.[18] The above-mentioned power consumption is just for dismantling, and it can be still higher when hammer mill data for shredding operations are also included. The initial step to remove the catalyst from converter assembly or to separate it from the steel is called decanning. Decanning operation is usually carried out by a hydraulic shear machine which consists of a blade operated by a hydraulic power pack. The blade is used to cut/shear the outer steel so that the inner core component called catalyst can be obtained. The catalyst is then subjected to subsequent operations in order to recover the metals. The decanning machine has a motor with a capacity of 10 HP/7.5 kW.[19] It is assumed that the machine is operating for almost 5 hours to obtain the catalysts. The catalysts are then smelted further, and the process consumes 600 kWh at the lowest temperature of 1573 K (1300 °C) and 1100 kWh at the highest temperature of 1773 K (1500 °C) for every ton of precious metal recovered.[20] In the smelting process, catalysts are melted with some base metals and subjected to anode casting and electrorefining operations. Electrorefining is defined as the corrosion of an anode due to application of electricity and metal moving from the anode to the cathode through the appropriate electrolyte solution. Once the impure metals are removed or corroded, the required metal can be obtained in a pure form. In this case, the base metal copper is deposited on the cathode by passing the materials through a copper sulfate solution which resulted in obtaining platinum in powder form.[21] The other considerable activity is the transportation which needed to be included in the LCA study due to its significant impact on the environment. In the pyrometallurgical method of recycling, the required transportation activities are as follows: Catalytic converter assemblies are transported to the vehicle manufacturing plant, the dismantled scrap converters sent to the recycling company, and the finally recovered precious metals sent to the catalyst manufacturing plant. Table I summarizes the LCI data of the pyrometallurgical method of catalytic converter recycling.

2. *Hydrometallurgical route*

The recovery of the PGMs through the hydrometallurgical method involves chemical-treatment processes. The preprocessing activities such as collection and dismantling are similar in both the pyro- and hydrometallurgical methods. Unlike the pyrometallurgical route in which all the activities are carried out in Victoria, in the hydrometallurgical method, the scrap converters have to be sent to Perth (Western Australia) for recovery of the PGMs due to the unavailability of recycling companies that implemented such method in Victoria. The scrap converters are collected together and sent *via* roadways using a truck with a payload capacity of 17 t to a distance of around 3200 km. The recycling company in Perth carries out the other processes such as crushing, sampling, and leaching.

In the hydrometallurgical method, since leaching is the main activity involved, the honeycomb brick or ceramic substrate is separated from the outer steel casing and crushed. The crushing activity is usually carried out using a crusher or grinder with an average power consumption of 85 kW (Grinding Mobile Crusher by SCM machinery Ltd.)[19] if the operation is assumed to be carried out for 5 hours. The most important step in the hydrometallurgical method is the leaching process in which various chemicals are used for metal recovery.

The main problem of using chemicals is that they generate wastewater and can have negative effects on environment due to their corrosive nature. Given the fact that precious metals are chemically relatively inert, they call for strong acids for the effective dissolution

Table I. LCI Data—Pyrometallurgical Method

Component/Process	Input/Output	References
Use Phase	platinum, palladium, and rhodium emissions	14
Dismantling	38 kWh	18
Decanning	40 kWh	19
Smelting	600 to 1100 kWh	20
Transportation	Distances in the order of 50, 10, and 70 km	23

instead of basic acids. However, this problem is eliminated by using hydrogen or thermal treatment, which is proven to maximize the extraction rate when the treatment is carried out at certain temperatures. This method along with composition determination has paved the way for using fewer amounts of reagents. The final process is treating the sample with chemicals like hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and most importantly, hydrogen peroxide (H_2O_2) for its ability to carry out oxidation reaction, whereas HCl is used for stabilization. Finally, it is found that the mentioned chemicals with concentrations of 80, 5, and 5 ml, respectively, can result in the nearly 95 pct recovery of platinum and other metals (44 mg Pt, 0.6 mg Pd, and 6 mg Rh).[11]

IV. MODELING

Once the life cycle inventory (LCI) phase is completed, the GaBi software model using the overall process information is developed. The creation of model in GaBi is associated with the usage of information from the in-built database and creating new processes. Upon process creation, the input and output flows such as electricity and material incoming and leaving the system are also generated. The valuable output is created as tracked flow which means it will be used in the next process, and most importantly, it enables the connection of two processes. The electricity production mix applied to Australian standards is used for the dismantling, decanning, and smelting operations. The transportation details are added between the processes using the information from the database and the distances considering that the recycling process is carried out in the state of Victoria. Once the model is created, balance calculation will be carried out which is the final part of the LCA study. This stage provides the entire life cycle impacts of the model. The obtained results are interpreted and reported according to various impact categories. The generated GaBi models for the pyrometallurgical and the hydrometallurgical routes are presented in Figures 3 and 4, respectively.

V. RESULTS AND DISCUSSION

The life cycle impacts of a component/product can be assessed using different methods. The adopted methodology determines the way in which the results are presented and analyzed. The method used for this study is ReCiPe[22] which included 18 midpoint and 3 endpoint indicators. Most of these midpoint impact categories are further converted and combined into three midpoint categories. The complete characterization factors and detailed methodology for ReCiPe are obtainable on the website of Institute of Environmental Science in Leiden University of Nederland (http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/recipe.html).

A. *Life Cycle Impact Assessment (LCIA)*

The general assumption for both the recycling routes is the same in order to maintain neutrality in the comparison between the methods. The life cycle phases differ in many ways with the only similarity being the dismantling of the converter unit. After dismantling in the hydrometallurgical route, the component is transported to a recycling plant located in Perth (Western Australia). The components are then subjected to crushing activity so that the ceramic substrate that contains the precious metals forms powder. The powder is then subject to a leaching process in which chemicals like hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), and sulfuric acid (H_2SO_4) are used in certain proportions. The main difference is that the impacts in the hydrometallurgical route are comparatively lower since electricity consumption is reduced due to the absence of smelting process. Of the two introduced processes, the pyrometallurgical process is more effective for extracting the PGMs from catalytic scrap by a larger-scale treatment. In this study, 17 t of catalytic converter scrap has been used to carry out the recycling process.

In the pyrometallurgical route, the main processes involved are electric arc smelting and transportation along with other operations such as dismantling and decanning. The flows associated with these processes are

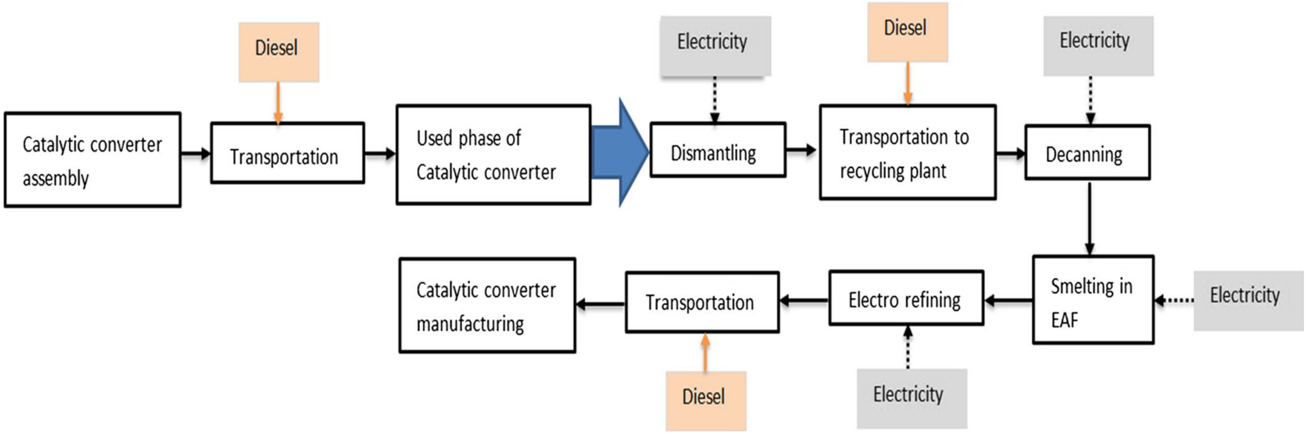

Fig. 3—GaBi model—pyrometallurgical route.

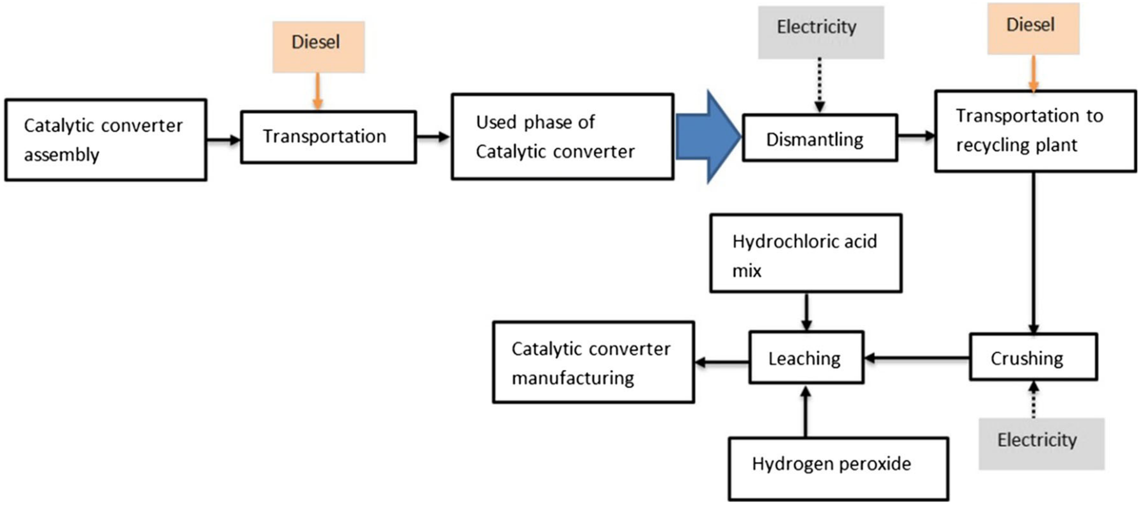

Fig. 4—GaBi model—hydrometallurgical route.

the electricity and diesel usage which both affect the environment due to the burning of the fossil fuel for electricity generation and emissions related to transportation. These emissions are the main causes for global warming and have serious negative consequences on the environment. Apart from global warming, the environmental load indices could be interpreted in terms of acidification, eutrophication, toxicity, and marine aquatic bodies. The amounts of contribution to the overall value or impact from each of these processes differ since these values depend on the input values or data used in the GaBi model.

B. *Main Contributors*

1. *Global warming potential (GWP)*

Global warming is measured in terms of the number of kilograms of carbon dioxide released to the atmosphere. In the pyrometallurgical route of recycling the PGMs, this emission is associated with relatively higher records due to the higher electricity consumption of the smelting operation. The results indicate that approximately 97 kg of carbon dioxide was emitted in hundred years of time for recovery of 1 g of platinum. The smelting operation holds one of the major shares in contributing to total emission since it emits 17 kg of carbon dioxide due to the melting of ceramic substrates. Other operations such as dismantling and decanning emit 39 and 0.000655 kg, respectively. The values and impact are comparatively higher than the impact caused by the hydrometallurgical route (the estimated carbon dioxide released from the hydrometallurgical process is 37 kg). Crushing process is the major contributor in the hydrometallurgical route as it emits 33 kg of carbon dioxide, whereas the remaining amount goes to dismantling activity. Apart from this, a negligible amount (0.096 kg) of carbon dioxide is released during the transportation of the dismantled converter to the recycling site. In spite of the pyrometallurgical route having a series of transportation activities, the impact of carbon dioxide emission is lower than that in the hydrometallurgical route due to the long distance the dismantled converter traveled in the hydrometallurgical method.

2. *Acidification potential*

Apart from the emission of carbon dioxide, there are some other pollutants like nitrogen oxide and sulfur dioxide that affects the environment in terms of reducing the soil fertility. In the pyrometallurgical route, smelting and electrorefining contribute to the majority of sulfur dioxide emission with values of 0.0443 and 0.106 kg, respectively, followed by decanning. The emission of sulfur dioxide contributes nearly 68 pct, whereas the remaining 32 pct, comes from nitrogen oxides accounting for the overall environmental impact of acidification. For the hydrometallurgical route, on the other hand, considering the fact that acidification potential is associated with sulfur dioxide and nitrogen dioxide emissions, the only possible process that contributed to this category is dismantling. The results indicate that sulfur dioxide emissions are 1.2×10^{-10} and 1.22×10^{-9} kg due to dismantling and crushing activities, respectively. The obtained values are relatively small due to the absence of electricity consumption for the smelting process and chemical usage for the leaching activity. The emission of sulfur dioxide accounts for 56.3 pct, whereas for nitrogen dioxide, it is 43.4 pct. The major contribution to the total emission is from the crushing process as it results in almost 51 pct of emission.

3. *Eutrophication potential (EP)*

Eutrophication is defined as the overabundance of nutrients such as phosphorous and nitrogen oxide in the lakes and rivers, leading to algal bloom which affects living species. Australia is facing serious problems regarding eutrophication in recent years due to agricultural run-off which makes the fertilizers rich in phosphorous nutrients. In the GaBi model, the eutrophication potential is measured in terms of kilogram equivalent of phosphate emitted. In the pyrometallurgical route of recycling the PGMs out of catalytic converter scrap, electricity is the main contributor and the impacts of electrorefining and smelting are in the range of 1.5 to 3.58×10^{-13} kg, whereas the decanning process has comparatively lower effect since it emits 5.6×10^{-18} kg during the entire life cycle of the pyrometallurgical process. In the hydrometallurgical route, the crushing activity has the major share with an emission of 4.3×10^{-13} kg of phosphate and phosphorous. The next process is dismantling which emits nearly 4.25×10^{-14} kg of the above-mentioned nutrients. Also due to the large distance involved in transportation, a noticeable yet less amount of emission is observed from the truck used, and the value is almost 9.25×10^{-15} kg. On the other hand, chemicals like hydrochloric acid and hydrogen peroxide account for 4.62×10^{-15} and 3.15×10^{-15} kg of emissions, respectively, in terms of wastewater.

4. *Ozone-depletion potential (ODP)*

The Ozone layer is affected considerably due to the release of ozone-depleting substances such as chlorofluorocarbons (CFC). Apart from chlorofluorocarbons (CFC), the depletion of ozone layer can also be due to the release of greenhouse gases to the atmosphere. In this recycling process, electricity is the major contributor to cause most of the impacts including ODP. The obtained results indicated that dichlorotetrafluoroethane (R114) is the dominant emitted gas, and the amount is relatively lower compared with other impact categories. The electrorefining process has the highest share since it caused an emission of 5.7×10^{-14} kg equivalent of R114 followed by 5.43×10^{-14} kg equivalent of R114 in the dismantling and 2.39×10^{-14} kg in the smelting processes. In the hydrometallurgical process, chlorofluorocarbons are the main source in affecting the ozone layer. Crushing has the highest share due to the high electric consumption of machinery used for crushing and grinding the ceramic substrates into the powder form. The crushing process emits 4.62×10^{-14} kg of CFC followed by the dismantling activity which releases 4.56×10^{-15} kg of CFC. The transportation activities carried out for moving the converter from the manufacturing site to the car-assembling plant and the used converter to the recycling plant does not cause considerable impact, and the values are negligible compared with other processes. Since the hydrometallurgical method relies entirely on leaching, the impacts arising due to usage of the chemical are critical. The CFC emissions of 1.03×10^{-15} and 8.37×10^{-16} kg have been observed during the leaching process. The obtained values are mainly attributed to the usage of acids such as hydrochloric acid and hydrogen peroxide.

5. *Fossil depletion*

Unlike the pyrometallurgical method which consisted of the processes which consume a large amount of energy and in turn resulted in huge exploitation of natural resources, the hydrometallurgical method consumes relatively fewer amounts of energy and resources. Although this recycling activity is carried out in an area outside Victoria, depletion of natural resources is a common factor in both the routes considering the fact that electricity generation in Australia is carried out by burning the fossil fuels. The crushing process consumes almost 9 kg of oil equivalent during the electricity generation, and the total consumption is nearly 10 kg including the remaining involved processes. The FD values in the hydrometallurgical process are lower than those of the pyrometallurgical method in which the total consumption is approximately 26 kg oil equivalent.

6. *Abiotic depletion potential*

The other important impact category associated with life cycle stages of any process is the depletion of natural resources. The resource can be both renewable and nonrenewable, and resource depletion usually occurred due to the electricity generation. Australia is rich in natural resources; however, exploitation of the natural resources accounts for a fair share of environmental impacts due to greenhouse gas emission. Electricity consumption is the main source of resource depletion in the pyrometallurgical method. The smelting and electrorefining processes have the highest shares since they consume 4.75 and 11 kg equivalent of oil for their operation. These rates are considered to be relatively a high consumption rate for recovery of 1 g of PGMs. The other two pyrometallurgical processes that hold the next consumption rates are dismantling and decanning. The hydrometallurgical method has comparatively lower impacts and energy consumption due to the replacement of the smelting process by leaching.

7. *Freshwater ecotoxicity*

Freshwater ecotoxicity data provide details regarding the metals and their possible quantities released to the water bodies. Some of the emitted metals as a result of this recycling process are arsenic, antimony, chromium, copper, lead, manganese, cobalt, mercury, vanadium, zinc, tin, barium, beryllium, and cyanide, yet the overall emission is lower in comparison with the electrorefining operation which contributes 5.19×10^{-13} kg of heavy metals. The smelting and dismantling processes led to 2.17×10^{-13} and 4.94×10^{-13} kg of metal emissions during the entire life cycle of the pyrometallurgical route. Overall, the freshwater ecotoxicity values are higher in the pyrometallurgical process compared with the hydrometallurgical process. This is mainly due to the higher electricity consumption of the smelting process in the pyrometallurgical process along with a series of transportation activities involved. Tables II and III present life cycle impact assessment data obtained for the pyrometallurgical and the hydrometallurgical methods for the recovery of the PGMs out of catalytic converter scrap. As seen from the presented data, the hydrometallurgical method contributes lower amounts of emissions of carbon dioxide, sulfur dioxide, phosphate, and CFC compared with the pyrometallurgical route.

VI. DISCUSSION

The main input involved in both the hydro- and pyrometallurgical methods is electricity; however, the

Table II. LCIA Data—Pyrometallurgical Method

Impact Category	Dismantling	Decanning	Smelting	Electrorefining	Transportation
GWP (kg CO_2 Equiv.)	39.4 (40 pct)	0.00065 (0.0007 pct)	17.3 (17.7 pct)	41.3 (42.2 pct)	0.003 (0.003 pct)
AP (kg SO_2 Equiv.)	0.10 (22.6 pct)	1.7e−6 (0.0004 pct)	0.04 (9.95 pct)	0.1 (23.7 pct)	1.04E−05 (0.002 pct)
EP (Phosphate Equiv.)	3.4 e−13 (27 pct)	5.7e−18 (0.00045 pct)	1.5e−13 (11.9 pct)	3.6e−13 (28.4 pct)	2.3E−15 (0.18 pct)
ODP (R114)	5.4e−14 (39.7 pct)	9e−19 (0.0006 pct)	2.4e−14 (17.5 pct)	5.7e−14 (41.7 pct)	5E−18 (0.004 pct)
Fossil Depletion (kg Oil Equiv.)	10.8 (40.1 pct)	0.0002 (0.0007 pct)	4.7 (17.7 pct)	11.3 (42.2 pct)	8.6E−03 (0.03 pct)
Freshwater Ecotoxicity	0.001 (16.2 pct)	1.7e−8 (0.0003 pct)	0.00045 (7.1 pct)	0.0012 (17 pct)	1.3E−06 (0.02 pct)
Human Toxicity	46.6 (38.5 pct)	0.0008 (0.0006 pct)	20.5 (16.9 pct)	48.9 (40.4 pct)	1.07E−03 (0.0009 pct)
Marine Eutrophication	0.0004 (3.2 pct)	6.2e−9 (5.3e−5)	0.00016 (1.4 pct)	0.0004 (3.4 pct)	1.6E−06 (0.014 pct)

Table III. LCIA Data—Hydrometallurgical Route

Impact Category	Dismantling	Crushing	Leaching HCl	Leaching H_2O_2	Transportation
GWP (kg CO_2 Equiv.)	3.27 (8.87 pct)	33.1 (89.7 pct)	0.0144 (0.039 pct)	0.0161 (0.0435 pct)	0.09344 (0.25 pct)
AP (kg SO_2 Equiv.)	1.2e−10 (5.06 pct)	1.2e−9 (51.2 pct)	1.6e−13 (0.00674 pct)	1.33e−13 (0.00559 pct)	8.78e−15 (0.000365 pct)
EP (Phosphate Equiv.)	4.25e−14 (8.68 pct)	4.3e−13 (87.8 pct)	4.62e−15 (0.943 pct)	3.15e−15 (0.644 pct)	1.04e−15 (0.0233 pct)
ODP (R114)	4.56e−15 (8.57 pct)	4.62e−14 (86.8 pct)	1.03e−15 (0.00047 pct)	8.37e−16 (0.0381 pct)	2.06e−17 (1.94 pct)
Fossil Depletion (kg Oil Equiv.)	0.907 (8.95 pct)	9.18 (90.6 pct)	0.0071 (0.0701 pct)	0.00765 (0.0755 pct)	3.49E−2 (0.00419 pct)
Freshwater Ecotoxicity	8.66e−5 (3.59 pct)	0.000876 (36.3 pct)	1.26e−5 (0.52 pct)	8.84e−6 (0.366 pct)	5.48E−6 (0.00277 pct)
Human Toxicity	3.91 (8.6 pct)	39.6 (87 pct)	5.28e−5 (0.026 pct)	0.00428 (0.0186 pct)	2.03E−2 (0.000116 pct)
Marine Eutrophication	3.13e−5 (0.711 pct)	0.000317 (7.2 pct)	1.06e−6 (0.024 pct)	6.03e−7 (0.0137 pct)	6.62E−6 (0.00183 pct)

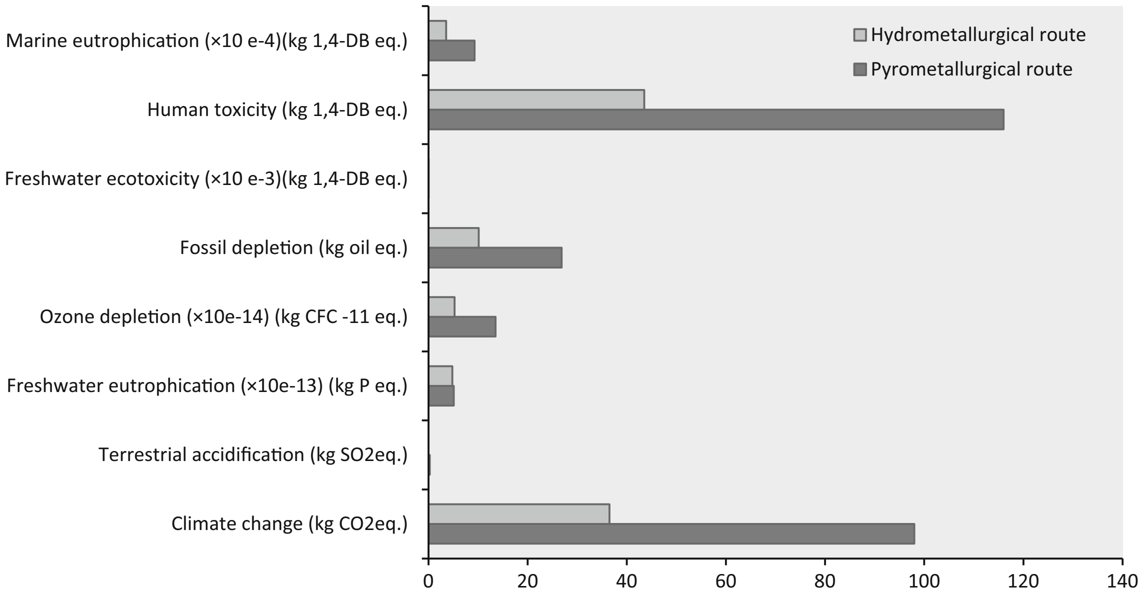

Fig. 5—Comparison of impact categories between the pyrometallurgical and hydrometallurgical processes.

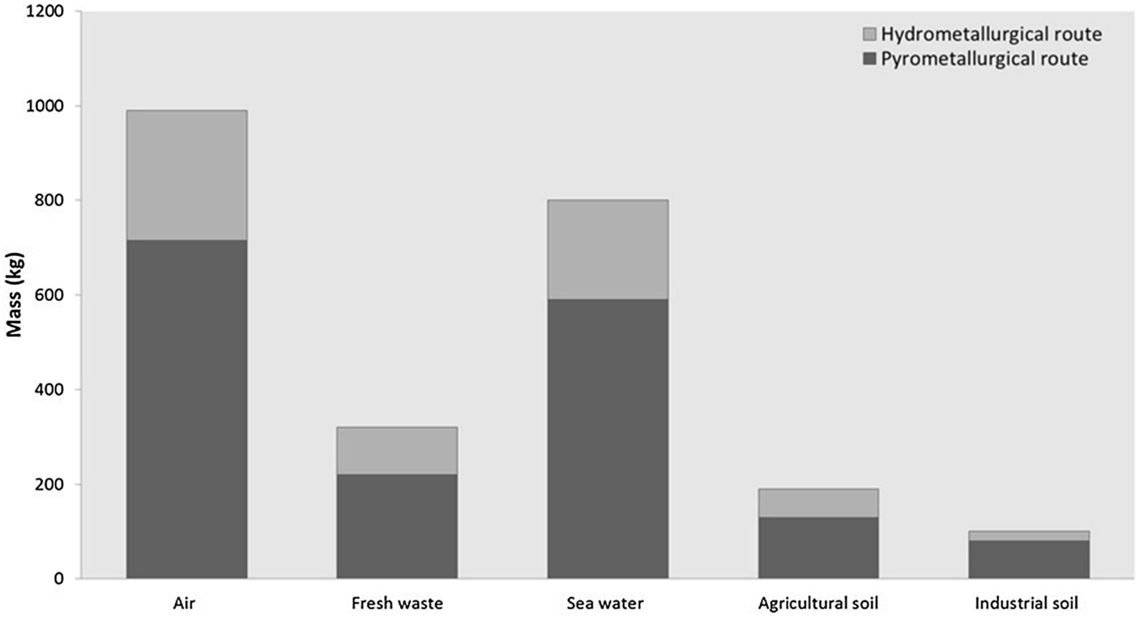

Fig. 6—General comparison of the recycling routes.

hydrometallurgical route also involved chemical usage. In order to carry out life cycle assessment of catalytic converter recycling, two sets of GaBi models are designed which included all the activities taking place during the recycling process. The results of the modeling showed that the overall impacts caused by the hydrometallurgical method are lower compared with the pyrometallurgical route. The highest environmental impact is triggered by electrorefining and high power-consuming smelting operations. It is also revealed that the impacts due to the transportation activities are insignificant. Carbon dioxide and chlorofluorocarbon emissions which are critical indicators for any product's environmental impact are lower in the hydrometallurgical route compared with the pyrometallurgical method. This makes the hydrometallurgical method a preferable option. Apart from the main categories such as global warming and ozone depletion, the hydrometallurgical process has comparatively superior performance in terms of acidification, eutrophication, fossil depletion, and human toxicity. It is worthwhile to mention that the obtained results are applicable only to the Australian setting since the life cycle stages are assumed to be carried out in Victoria and Perth. In addition to this, the truck details and transportation information considered the real distances between recycling plant and manufacturing site.

A. *Comparison of Impact categories*

Figure 5 shows a comparison between different environmental impact categories caused by the pyrometallurgical and the hydrometallurgical routes for recycling the PGMs out of catalytic converter scrap. As seen from Figure 5, the hydrometallurgical method emitted lower amounts of carbon dioxide, sulfur dioxide, phosphate, and CFCs compared with the pyrometallurgical route. Since the pyrometallurgical method consumes a large amount of electricity during the entire recycling process, this creates problems such as resource depletion and increased ozone-layer damage. Analyzing the values obtained from the results for all the impact categories, the hydrometallurgical method is considered as the preferred option for the catalytic converter recycling. Even though the hydrometallurgical route uses chemicals, proper disposal of the residues can mitigate the problems caused by wastewater from the leaching process.

B. *General Comparison*

Apart from the main impact categories, the life cycle assessment of any product or process involves calculations of the resource depletion, heavy metal emissions to air, and also other emissions to fresh water, sea water, and so on. In this context, the comparison of the two recycling routes in respect of these aspects is shown in Figure 6. The effects on environment included the ozone-layer depletion and the climate change as well as the imbalance of the nutrient levels in fresh water and sea water. The high environmental impact concerning the pyrometallurgical method indicates that the consequences on the entire life cycle phases are considerable and needed to be mitigated. The heavy metals emitted to air include antimony, arsenic, cadmium, copper, lead, molybdenum, and mercury emitted to fresh water, which affect the living organisms. Although it is not possible to avoid these emissions completely, it is essential to keep them as low as possible. Considering all the above-mentioned factors and the local conditions prevailing in Australia, it is concluded that the hydrometallurgical method is considered to be a preferable option over the pyrometallurgical method to recover the PGMs from catalytic converters in terms of the decreased environmental impacts.

VII. CONCLUSION

Since resource exploitation has become a major concern in recent years, it is inevitable to recycle the components for the recovery of the metals which have reusable value. Recycling is also associated with some negative effects on the environment due to the series of processes involved. In this context, the life cycle stages of recovery of the PGMs out of automobile catalytic converter scrap are assessed using the GaBi software from an Australian perspective. The two most commonly used recycling routes, pyrometallurgical and hydrometallurgical, are investigated. It is concluded that the hydrometallurgical route for recycling the PGMs out of the end-of-life catalytic converter has lower impacts on the environment compared with the pyrometallurgical method. It is also revealed that the hydrometallurgical route is superior to the pyrometallurgical one in all the aspects such as lower contribution to global warming effects, ozone-layer depletion, eutrophication, and the human toxicity. In terms of emission effects, the hydrometallurgical process is found to be highly advantageous since it involves negligible emissions to air, sea water, and fresh water. It is also noted that the environmental impacts of recycling the PGMs from catalytic converter scrap are increasingly expanding depending on the increased distance of the used phase to the recycling plant. It should be noted that the impact assessment in this study has its limitation since it is based on the presumptions that the environmental impacts are all observed and evaluated to date. In fact, the results of the environmental impacts of the two recycling methods assessed in this study should be treated with caution since the study is based on many estimations and assumptions. In order to achieve more precise information, data from the catalytic converter production and some of its components that are not investigated in this research should be further explored. The results obtained in this paper are applicable only to the Australian scenario since most of the life cycle stages are assumed to be carried out in Victoria and Perth. In addition to this, the truck details and transportation data are used considering the real distances between the recycling plant and the manufacturing site. Moreover, it is fairly a difficult task to obtain accurate information on the recovery of the PGMs out of the Australian Catalytic Converters' scrap, since the manufacturers generally keep the information on the exact composition of their products as confidential, and the contents of the PGMs, especially of the Australian Catalytic Converters (ACCs), vary from model to model.

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