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TECHNOLOGY REVIEW

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The Environmental Profile of Platinum Group Metals

Interpretation of the results of a cradle-to-gate life cycle assessment of the production of pgms and the benefits of their use in a selected application

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The International Platinum Group Metals Association (IPA) carried out the first ever industry-wide life cycle assessment on platinum group metals (pgms) which included data from a majority of the industry in both primary and secondary production, as well as one major application of pgms, i.e. their use in a car exhaust catalyst. The results, discussed in this paper, identify that the major impact (72%) of the production of pgms on the environment is from power consumption during mining and ore beneficiation; they also demonstrate that the impacts of pgm production are mitigated by the use of pgm-based automotive catalysts. The exercise provides benchmarking for the industry and a greater understanding of the impacts and benefits of pgms.

Introduction

Life cycle assessment (LCA) is a reliable method used across a variety of sectors for calculating the lifetime environmental impacts of a product or service. LCA identifies environmental hot spots in products and materials and establishes the benchmark against which improvements can be measured. It provides product designers, regulators and engineers with valuable information for exploring decisions in each life stage of the material. LCA is also used in new product research and development, when environmental footprint is important to the future marketing or cost structure of a product. Companies as well as industry associations use LCA to demonstrate transparency and corporate credibility to stakeholders and customers. Industry-wide LCAs offer the benefit of providing reliable, transparent and averaged data on a global or regional level. LCA data are applied by stakeholders in order to compare the impacts of different materials used in modelled processes against each other. The growing significance of LCAs as part of life cycle thinking becomes evident in the current European Union's Circular Economy approach and related policies such as the Product Environmental Footprint (PEF) studies which involve the use of LCA data for a variety of materials.

The IPA conducted the first industry-wide assessment of the life cycle of the primary and secondary production of pgms in 2013, based on data collected during 2010. The study also looked at the impacts of producing a representative application, namely catalytic converters (autocatalysts) to control vehicle exhaust pollution and compared these to the benefits of using them. Autocatalysts were selected because they represented, in the reporting year of 2010, 51% of the end use market for pgms and have a widely recognised societal benefit. Eleven out of fifteen IPA members took part in the study, representing the primary producers of pgms (from mining to production), the secondary producers of pgms (recycling and production) as well as the fabricators of autocatalysts.

This paper looks at the industry's motivation for commissioning the study, the study's functional units and method as well as the Life Cycle Impact Assessment (LCIA), i.e. the interpretation of the results. It also briefly explains the main characteristics and usages of pgms and their production process. Note that this paper presents only aggregated data. The release of segregated data to the community is under consideration for future updates.

What are Platinum Group Metals?

The six pgms platinum, palladium, rhodium, ruthenium, iridium and osmium occur together in nature alongside nickel and copper. The annual production of pgms amounts to around 400 tonnes, several orders of magnitude lower than many common metals. Platinum and palladium are the most important metals in the pgm mix and also the main products. Rhodium, ruthenium, iridium and osmium are mined as co-products of platinum and palladium. The pgms are highly resistant to wear, tarnish, chemical attack and high temperature and have outstanding catalytic and electrical properties (1). All these unique characteristics have made them indispensable in many industrial applications. The pgms are very rare elements and most pgm-bearing ores are extremely low-grade, with mined ore grades ranging from 2 to 6 g per tonne (2). Mining the pgms is a capital, energy and labour intensive process; extraction, concentration and refining of the metals require quite complex processes that may take up to six months. Most of the largest primary producers of pgms are located in South Africa which hosts 95% of the known world reserves, currently estimated at 66,000 tonnes (3).

The pgms have catalytic qualities which make them the choice for a number of industrial applications, such as petroleum refining, nitric acid manufacturing and autocatalysts. The pgms are used rather than consumed. The high recyclability of pgms means they can be reused many times, thus ensuring that their impact on the environment is kept as low as possible. The pgm industry routinely recycles pgms from their applications. Using state-of-the art recycling technology, up to 95% of the pgm content of spent automotive catalysts (and other pgm-containing applications) can be recovered. However, the high technical recyclability of pgms is sometimes jeopardised by insufficient collection and inappropriate pretreatment of pgm-bearing materials.

Primary Production

Ore bearing the pgms is typically mined underground or, less usually, from open pits. The ore is blasted before being transported to surface. Crude ore is crushed, milled and concentrated into a form suitable for smelting, which takes place at temperatures that may be over 1500ºC (2732ºF); for a good overview on the history and sustainability of pgm mining, see (4).

Unwanted minerals such as iron and sulfur are removed leaving a matte containing the valuable metals which are separated in a series of refining processes. Nickel, copper, cobalt, gold and silver may be extracted in the refining process as co-products (5) (**Figure 1**).

Electricity consumption is high, not only for ore haulage but also to drive compressed air to the miners' hand-held pneumatic drills and, because the hard rock in platinum mines has a high thermal gradient, to refrigerate the working areas. Indeed, electricity use was found to be the main source of greenhouse gas emissions from primary production in the IPA LCA study, with a share of 85–90% of total global warming potential (GWP), depending on the pgm.

The power grid in South Africa, where the bulk of production considered in this study takes place, relies heavily on burning hard coal, leading to relatively high carbon dioxide emissions: more than 90% of electricity is generated that way. Due to the high proportion of electricity use in primary pgm production, a considerable shift to renewable energy projects like solar thermal or photovoltaics to progressively replace existing coal-based electricity could result in a significant reduction in emissions (4). However, to a great extent, the national electricity grid mix is beyond the control of South African pgm producers.

Secondary Production (Recycling)

The pgms can be recycled from a variety of end-of-life products (such as spent autocatalysts) and even from residues created during primary production. Secondary production processes can vary widely depending on the specific material or combination of materials treated. Some secondary producers of pgms

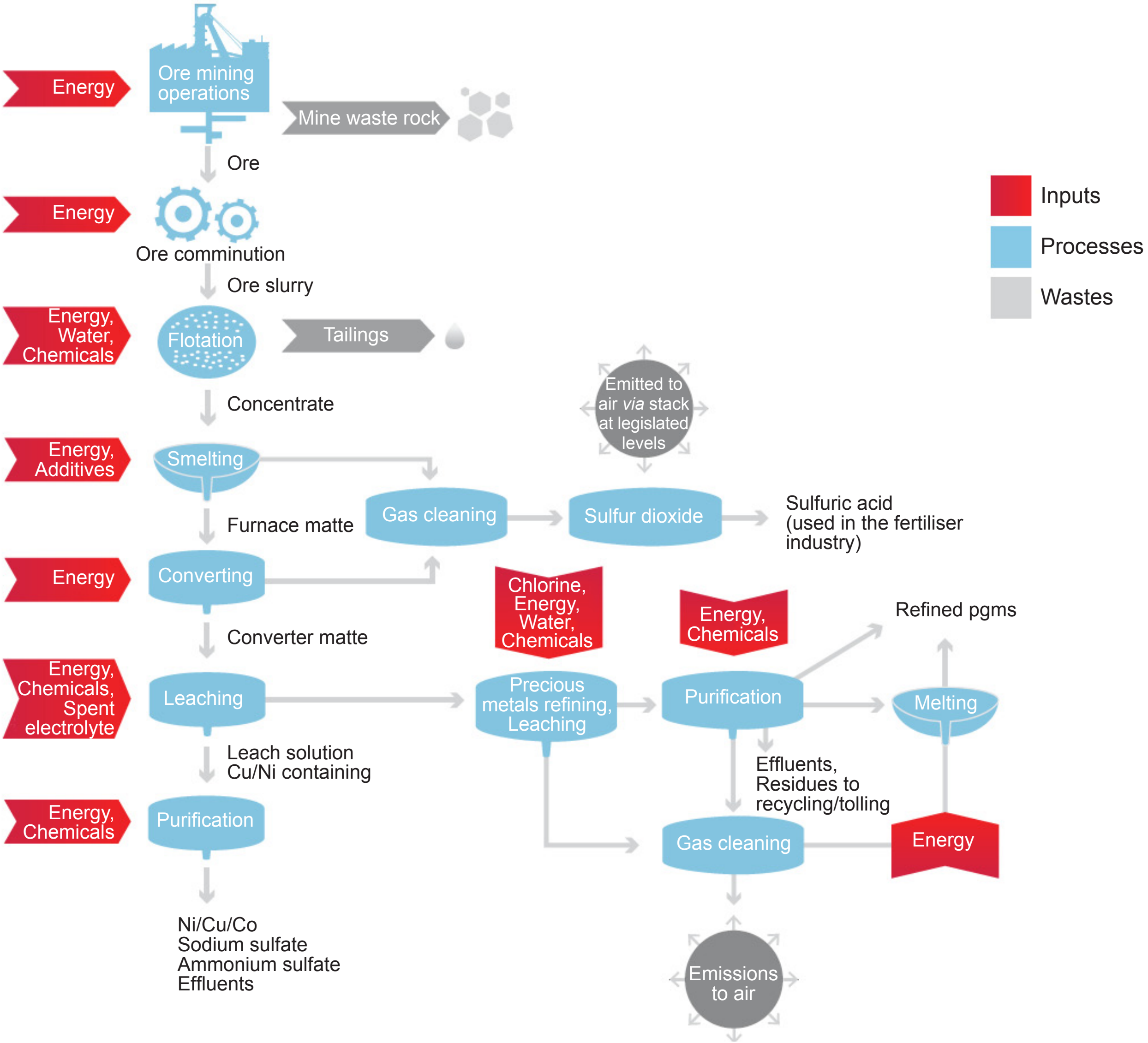

Fig. 1. Generic flow chart for pgm production in South Africa; source: Lonmin

use a dissolving process to create a pgm-rich solution for refining, while others may use a smelting process to create a matte. In both cases, the final pgm products are identical in quality and purity to those refined from mined material.

The electricity use in secondary production amounted to 17–23% of the GWP, other parameters of GWP were fuels, ancillary materials and process emissions.

The Main Uses of Platinum Group Metals

The pgms are found in numerous products, from hard disks to aircraft turbines, from anticancer drugs to mobile phones, from industrial catalysts to ceramic glazes. Numerous applications in which pgms are involved benefit the environment and our quality of life, such as water purification, nitrous oxide (N_2O) abatement and surgical implants, to name a few.

When pgms are used as industrial catalysts they enable chemical reactions to take place at reduced temperature and pressure compared to other materials and therefore at reduced cost and environmental impact, for example see (6). Catalysts based on pgms are used to produce ammonia, acetic acid, silicones, chlorine, nitric acid and many other chemicals which are ingredients of everyday goods, such as polyester, nylon, fertiliser and synthetic rubber. Platinum-rhenium catalysts are essential for reforming naphtha into high octane blending components for producing gasoline. Platinum-rhodium alloys which are highly resistant to corrosion are used in the production of flat screen glass for mobile phone, computer and television displays.

The pgms are also used inside the human body in devices such as pacemakers, defibrillators and catheters for the treatment of heart disease; neuromodulation devices to treat Parkinson's disease and hearing loss; and in coils and catheters for the treatment of brain aneurysms. Platinum's high resistance to corrosion makes it a good candidate for biomaterials as it is stable in the changing environment formed by the body's naturally occurring fluids. Specific compounds of platinum are effective in the treatment of a range of cancers, while palladium and other pgms are used in alloys suitable for dental inlays, crowns and bridges; for more applications, see (7, 8). The infographic in **Figure 2** shows the main uses of pgms.

By far the largest use of pgms today is for automobile catalytic converters (autocatalysts), a pollution control device fitted to cars, trucks, motorcycles and non-road mobile machinery. In catalytic converters, pgms are coated onto a substrate housed in the exhaust system where they act as catalysts to reduce harmful emissions to legislated levels. Autocatalysts convert over 90% of hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) from gasoline engines into less harmful carbon dioxide, nitrogen and water vapour. In diesel cars, oxidation catalysts are used to convert HC and CO to water and carbon dioxide, and catalysed soot filters trap and oxidise particulate matter (PM). The pgms enable car manufacturers to comply with emissions standards and help regulators to implement tightening emissions regulations. Catalytic converters reduce urban and rural air pollution which is estimated by the World Health Organization (WHO) to have caused 3.7 million premature deaths worldwide in 2012 (9).

Life Cycle Assessment Studies by Other Commodity Associations

In conducting this first industry-wide study of pgm production, IPA has aligned itself with similar studies carried out by other commodity associations. Amongst these, the Nickel Institute (10, 11) commissioned a cradle-to-gate Life Cycle Inventory (LCI) in 2012 covering 56% of world primary nickel metal production and 40% of world ferronickel production; nine companies contributed data from production sites in thirteen countries to this update of an earlier study in 2003. Similarly, the International Zinc Association (12) published in 2015 an update of its 2009 LCA on the extraction and smelting of zinc concentrates and special high grade zinc, which represented 36% of global concentrate production and 27% of global high grade zinc production. The European Copper Institute (13) has produced an LCA based on 2005 data from 25 countries in the European Union including all processes from mining to refining and semi-finished production. Another European region study was conducted by the International Lead Association, which examined primary and secondary production of lead in the European Union based on 2011 data (14) and supplemented this with LCAs on lead batteries (including a demonstration

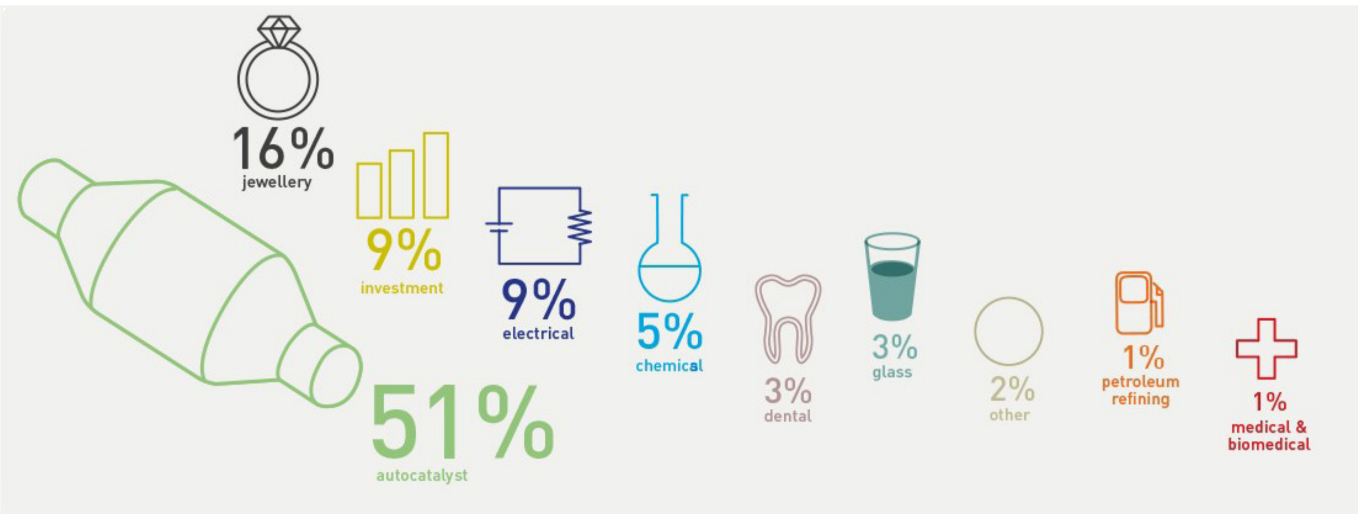

Fig. 2. PGM use per industry 2010 (time coverage of LCA Study data)

of in-use benefits) (15) and lead sheet (16). In 2014 the Aluminum Association (17) updated its 2010 cradle-to-grave study (18) on production, use, recovery and recycling of aluminium cans in North America.

Common to all these studies has been the objective of providing up-to-date and accurate environmental information useful to regulators, product designers and end-users, LCA practitioners and databases, and non-governmental organisations (NGOs). They measure the major impact categories of primary energy demand and global warming potential; the results represent a significant proportion of production in the geographical areas studied; and they all conform to International Organization for Standardization (ISO) standards. The studies do however vary in scope, with some associations limiting coverage to primary extraction and refining while others include the measurement of an end-use and recycling. The allocation of the impact of production to co-products is particular to the commodities studied: the lead and zinc industries use mass allocation and the nickel and copper industries use mass and economic allocation, while the aluminium study is for a single product and no allocation is made. Nickel, zinc, aluminium and lead data are available on the GaBi database.

The International Platinum Group Metals Association Life Cycle Assessment

The IPA LCA study covers 64% of the global pgm supply, which is widely accepted as a high industry representation. It covers 70% of world primary production of pgms (with study data from mines in South Africa, the USA and Canada), 60% of world secondary production (with data from refineries in Belgium, the UK and Japan) and 90% of world autocatalyst fabrication (with data from production sites in the UK and Germany). The results represent the global average primary and secondary production of pgms by the participating members. The pgm industry carried out this study in order to generate a reliable, current and independent dataset of the environmental footprint of pgms and pgm-containing products and to enable it to identify areas in the pgm life cycle where improvements would deliver the most benefits. The IPA LCA study data is made available to LCA practitioners and other interested stakeholders upon request and after validation through the association; application *via* web questionnaire (19).

As in every typical LCA, the IPA Study consisted of four phases (**Figure 3**) and followed the ISO standards (20, 21):

1. Goal and scope: the goal and scope outline the rationale of the study, the anticipated use of the results of the study, the boundary conditions and the assumptions used to analyse the product system under consideration
2. LCI: the life cycle inventory stage quantifies the material and energy use and environmental releases for the product system being studied. These results can be used in isolation to understand emissions, waste or resource use. Additionally, the results can provide insights which may lead to product design improvements
3. LCIA: the evaluation of the environmental relevance of the inputs and outputs of the system
4. Interpretation: interpretation of the results of the study, including recommendations and limitations of the study as well as an analysis of the validity of the results based on those limitations.

Why the Life Cycle Assessment was Conducted

In 2008, the IPA began to formulate an environmental strategy as a result of increased environmental awareness within the organisation and in response to market, customer and regulator expectations. In 2009, the membership developed the pgm industry's Sustainability Principles (22) which include improving its understanding of the environmental, social and economic impacts and benefits of its materials across

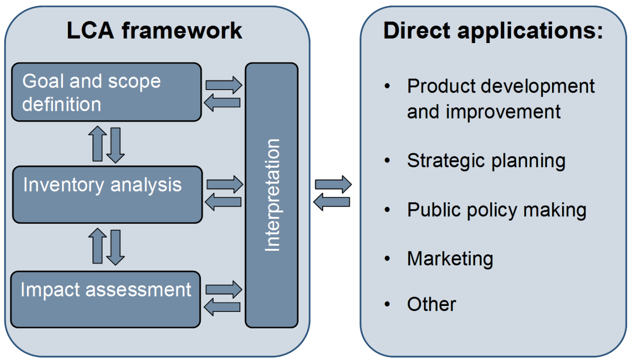

Fig. 3. Phases of an LCA (ISO 14040:2006)

their life cycle. In committing itself to a life cycle approach, the industry determined that it will:

- Collaborate with suppliers, customers and other stakeholders to understand the life cycle of its products and materials
- Contribute to a global database of life cycle information and share best practices in order to reduce the overall footprint of pgm products.

To support the industry's commitment to understand and improve the sustainability performance of pgms, at the end of 2011, the IPA commissioned the consultancy and software firm PE International (now thinkstep) to carry out an LCA study with the aims to:

- Generate current life cycle data on pgms and their application in autocatalysts
- Provide data to determine the benefits of pgms (for example in applications and through recycling)
- Identify areas (in the pgm life cycle) where the industry can improve its performance
- Support benchmarking within the industry.

To achieve these aims, the study used the most up-to-date and robust industrial data on pgm mining, production, fabrication and recycling. As a result, at the end of 2013, the IPA had concluded the first industry-wide assessment of the life cycle of primary and secondary pgm production.

Goal and Scope of the International Platinum Group Metals Association Life Cycle Assessment Study

The IPA LCA followed the 'cradle-to-gate' approach which covers the processes from the extraction of the raw materials in the earth (i.e. the cradle) to the finished products ready to be shipped from the factories (i.e. the gate). For pgms it includes all aspects of ore extraction, the production of other raw materials, energy supply and the production of the pgms themselves. The cradle-to-gate LCI also includes the production of fuel and ancillary materials, and represents all resource use and emissions caused by primary and secondary pgm production. It does not include the manufacture of downstream co-products, their use, end of life and scrap recovery schemes.

Whereas each participating company received its own LCA report with regard to its production results, the IPA LCA study report covers their global average primary and secondary pgm production data.

When talking about 'an LCA for pgms' it is important to understand that no single LCA can accurately cover every pgm product. Hence, in the study, an example application had been chosen that represents the largest use of pgms today: autocatalysts. The study analyses the in-use benefits of pgms in two different (modelled) systems using autocatalysts.

The functional units for the study were:

- 1 kg of platinum, 1 kg of palladium and 1 kg of rhodium (production phase)
- One three-way catalyst (TWC) in a EURO 5 1.6 l gasoline engine vehicle over 160,000 km lifetime (use phase)
- One diesel oxidation catalyst (DOC) and one catalysed soot filter (CSF) in a EURO 5 2.0 l diesel engine vehicle over 160,000 km lifetime (use phase).

Method

The LCA model was created using the GaBi 5 software system for life cycle engineering developed by PE International AG, now thinkstep. In the study, site-specific data (primary data) representative of current processes used in the pgm and fabrication industry for the fiscal year 2009/2010 were collected and analysed. The GaBi database 2010 provided the LCI data for the upstream production processes (non-primary data) of the ancillary materials.

The primary production of pgms typically yields several other base metal products such as nickel, copper and cobalt and other precious metals such as iridium, osmium, ruthenium, gold and silver, as these metals are a component of the pgm ore body. The secondary production of pgms also yields other co-products due to the variation in raw material feed. These products are not included within the scope of this study and are therefore treated as co-products and separated from the system using a combination of economic and mass allocation.

A particular challenge posed by the high economic value of pgms was how to allocate the environmental impact of production between the base metals and the pgms. Guided discussions by LCA experts supported the pgm industry in determining this. For the phases of production up to the separation of the base metals from the pgms, economic allocation based on market value of the products was applied (see **Figure 4**). Within the refinery where the different pgms are separated the environmental impact was allocated to the different pgms by mass. The reason for that is that the effort to separate the pgms can be assumed to be the same for

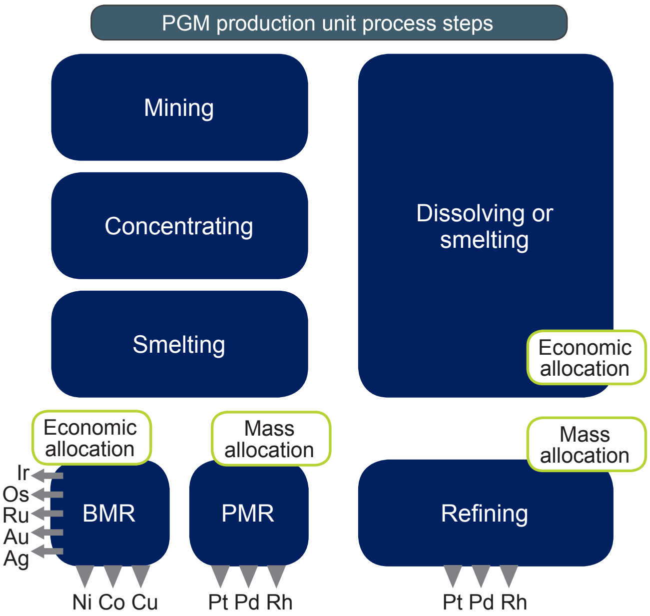

Fig. 4. General depiction of the allocation process applied to the pgm product

all pgms and therefore the impact was not allocated by the market value.

The graph in **Figure 5** shows the calculation methods used to determine the economic and mass allocation factors.

For the average result for the production of pgms the model was created using a weighted average on relative production volume of participating companies. Within the boundaries of this study, the primary producers contribute 90%, 75% and 80% to the production volume of Pt, Pd and Rh respectively, with the balance being made up by recycled metals.

For the purpose of the study, the use phase was modelled using data for gasoline and diesel autocatalyst systems for typical vehicles manufactured in the European region. The model was created using a EURO 5 model vehicle (gasoline and diesel) from the GaBi database (2010), with emissions lowest at 133 g CO_2 km^{-1} driven. It was assumed that each travelled a total distance of 160,000 km in its lifetime (EURO 5 standard life expectancy) and the catalytic converter system is assumed to last this vehicle lifetime.

A typical catalyst is made up of a mix of pgms sourced from both primary and secondary production. The pgm mix in the study is assumed to be approximately 72% primary pgms and 28% recycled pgms (typical market mix), based on the gross weight of pgms used in autocatalysts and the gross weight of pgms recycled from end-of-life autocatalysts in 2010 (data collection year). The manufacture of downstream co-products, the canning process and the collection of spent autocatalysts are not included in this study.

The LCA has been conducted according to the requirements of the ISO 14040 (20) and ISO 14044 (21) to withstand evaluation by a critical review panel if required by IPA. Furthermore, data quality checks were performed by an external technical expert and mass

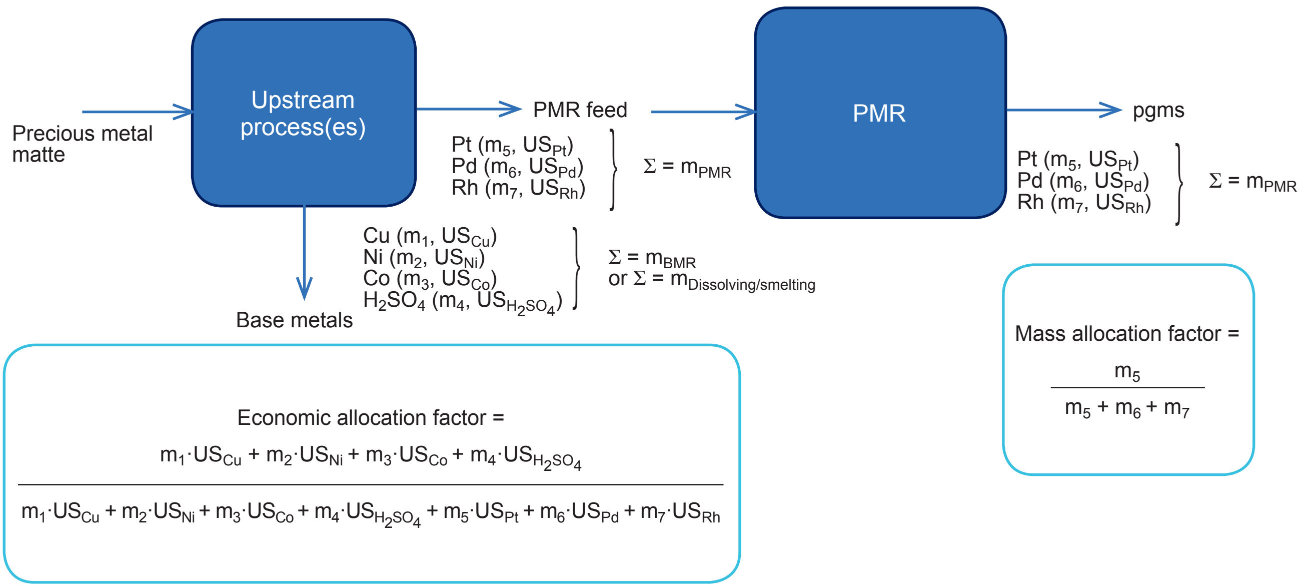

Fig. 5. Establishing the economic and mass allocation factors

and energy balances were performed to detect any anomalies.

Key Findings Based on Life Cycle Inventory and Life Cycle Assessment Results

Power consumption during mining and ore beneficiation has been identified as the major impact (72%) of the production of pgms on the environment; these two energy intensive processes precede the final separation of metals during refining, thereby producing not only platinum, palladium and rhodium but also several other base metal products such as nickel, copper and cobalt, and other precious metal products such as iridium, osmium, ruthenium, gold and silver. The reason for the high impact from power consumption is a combination of the high electricity demand in the mines and concentrators and the composition of the South African power grid mix where more than 90% of electricity is produced from the combustion of hard coal which has a high carbon and sulfur content.

A further 27% of the impact comes from smelting and refining of pgms. Only 1% of impacts are attributed to recycling, based on the production volumes considered in this study, which represent 60% of global pgm recycling from all secondary sources: therefore, the low footprint of recycling compensates for the higher footprint of primary production. This is expected for various reasons, including the vast difference in the concentration of pgms between primary and secondary sources. For the recycling of pgms, less than 30% of the overall impact is allocated to electricity production. The higher impacts derive from the fuel (thermal energy for smelting) and the ancillary materials used (i.e. the environmental impact of the production of ancillary materials).

The environmental impacts of pgm production have been quantified for a variety of categories; the two most requested categories, GWP and primary energy demand (PED), are presented in **Figure 6**. The results for GWP and PED are representative of the global average primary and secondary production of pgms by the IPA members participating in the study. GWP is calculated in CO_2 equivalents (CO_2-Eq), i.e. the greenhouse potential of an emission is given in relation to CO_2. PED is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere or energy source.

However, the study also illustrates that the impacts of pgm production are significantly mitigated by the in-use benefits: over 1.3 tonnes of toxic and harmful pollutants including CO, HC, NOx and PM are avoided by the use of catalytic converter systems in one EURO 5 gasoline plus one EURO 5 diesel vehicle in use over 160,000 km each; this is equivalent to a reduction in these emissions of up to 97%. Emissions of CO_2 are increased by between 2% and 6% through the use of autocatalysts; this is due to the conversion of CO and HCs into CO_2 during vehicle use; however, this increase is small when compared to CO_2 emissions from the combustion of the fuel used to drive the vehicle. The calculation is based on stoichiometry. The reactions governing the conversion of carbon monoxide and hydrocarbons to carbon dioxide are (Equations (i) and (ii)):

$$2CO + O_2 \rightarrow 2CO_2 \quad \text{(i)}$$

Here, the hydrocarbon is assumed to be pentane (C_5H_{10}), yielding the equation:

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O \quad \text{(ii)}$$

The reduction in emissions of HC, CO, NOx and PM as a result of the use of a catalytic converter outweigh the emissions generated during the production of the catalyst including pgms and other related materials used to support the functionality of the catalyst. For all investigated EURO 5 systems the break-even point for emissions of CO, HC, NOx and PM is reached after at most 40,000 km and in some cases (for example CO and HC in a TWC) after only a few kilometres of driving. The 'break-even' point is the driving distance of the

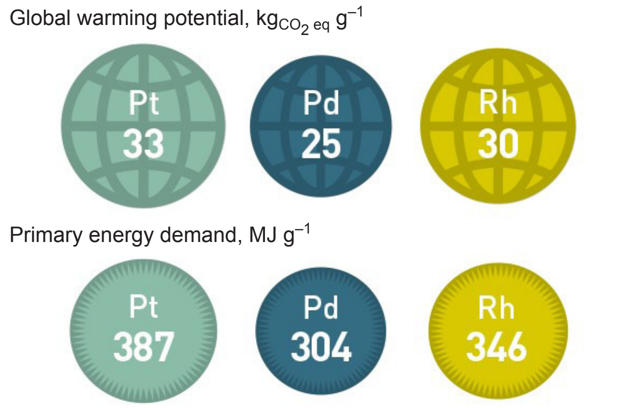

Fig. 6. Summary result of the Life Cycle Impact Assessment for the average production of 1 g of pgms (data in round figures): this is the IPA study mix representing the global average primary and secondary production of pgms by the participating members. Source: IPA LCA study 2013

vehicle in which the additional environmental burden of producing the catalytic converter is counteracted by the role of the catalytic converter in reducing vehicle emissions. For example, in a vehicle equipped with a DOC + CSF catalytic system, the break-even point for CO is reached after 100 km, hence at that distance the CO emissions from producing the catalyst (including the pgm loading) have been cancelled out by the reduction of CO emissions from the vehicle.

Examples of Use Phase Benefits

The production of a TWC emits 0.60 kg NOx. This figure has been calculated by adding up the NOx emissions of the three relevant steps to produce a TWC, namely pgm production, substrate and coating. The coating process alone contributes 55% to the total NOx emissions of the TWC. The coating process is a chemical intensive process and requires, among others, inputs of ammonia, acetic acid and aluminium oxide which contribute to these NOx emissions. The electricity and natural gas consumption in the coating processes are the major contributing factor towards NOx emissions, while the ancillary materials upstream processes are minor contributing factors; the benefit during the use phase, however, is that the catalyst in the vehicle reduces emissions by 332 kg over the vehicle's lifetime. The break-even point for NOx emissions is reached after a driving distance of approximately 250 km (**Figure 7**).

During the cradle-to-gate production of the catalyst system used in a diesel engine, 0.25 kg of PM is emitted; however, the use of these catalysts reduces the vehicle engine PM emissions by 18 kg over the vehicle's lifetime. The break-even point for PM is achieved after a driving distance of approximately 2200 km (**Figure 8**).

Impacts Over the Full Life Cycle

The extraction and refining of pgms is a capital, energy and labour intensive process which, like all mining activities, has an impact on the environment. When assessing the impacts of pgm production it is, however, essential to examine the full life cycle of the metals in order to acknowledge several important offsetting factors. The pgms are produced in low volumes, amounting to 430 tonnes of combined Pt, Pd and Rh in 2011 (23), several orders of magnitude lower than many common metals. Also, pgms are used in very tiny quantities: for instance, the average pgm loading for a EURO 5 European light duty diesel (LDD) catalyst system is 7–8 g and for a EURO 5 European light duty gasoline (LDG) catalyst it is 2–3 g (average pgm content as used in the IPA LCA study for Europe).

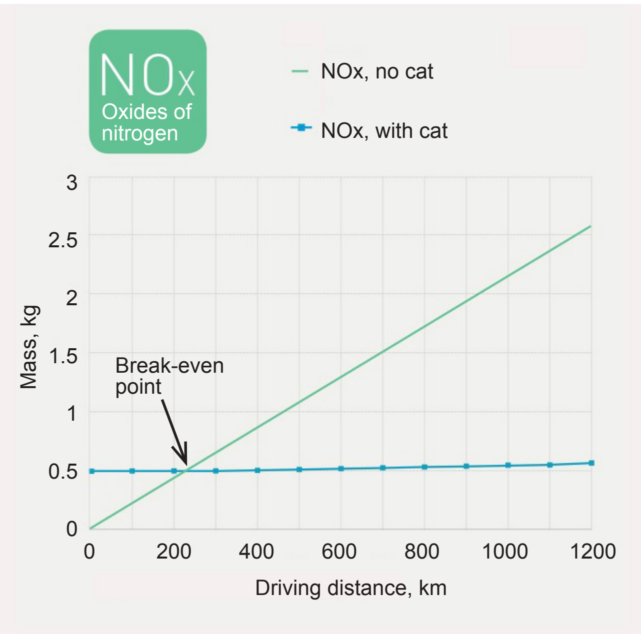

Fig. 7. A graph showing the break-even point for NOx emissions

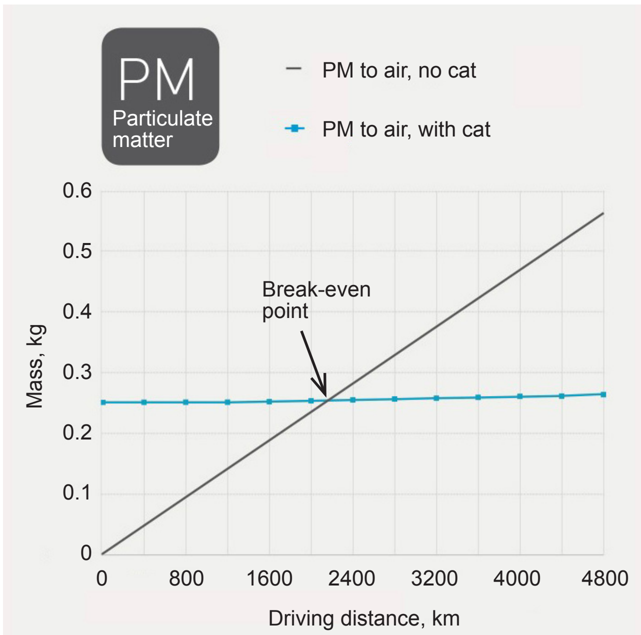

Fig. 8. A graph showing the break-even point for PM

The pgms are almost indefinitely recyclable. This high and repeatable recyclability reduces the environmental impact of pgm production with each recycling round, meaning that the investment in producing a primary ounce of pgms can in theory last in perpetuity.

Due to the effective environmental benefits of pgms in autocatalysts, it has been possible to progressively tighten regulatory limits on air pollution from vehicles around the world. Consequently, it would on average take just one car sold in the 1960s to equal the exhaust emissions from 100 of today's automobiles with catalytic converters. The IPA study underlines and helps to qualify the improvements in air quality achieved through the use of pgm-based emissions controls.

Conclusions

In carrying out a first comprehensive life cycle study of primary and secondary production of pgms, IPA has generated life cycle data which will assist the pgm industry to better understand its environmental impacts and set a benchmark from which pgm companies can work to improve their environmental performance. The study aligns the industry in terms of its objectives and scope with other commodity associations which have commissioned similar studies. The inclusion in the study of the main end-use for pgms has provided evidence for the environmental benefits of pgms in downstream applications which help to mitigate the impacts of primary production.

As the pgm industry is committed to ensure the steady supply of pgms to meet society's current and future needs, both increased levels of recycling and ongoing investments in primary production will be required. In the case of the latter and as the study identifies, reduction of energy demand remains a key challenge.

The LCA data of global average pgm production compiled by the IPA in the course of the study has been made available to a variety of stakeholders conducting LCA studies or other research projects. This has also allowed IPA to open up a dialogue with these stakeholders and to better understand their needs and expectations. As a result of the IPA LCA study, a number of case studies should appear that apply consistent methodology and utilise up-to-date data. This will result in a better understanding of the impacts and benefits of pgm materials.

Acknowledgements

The authors would like to thank Jeremy Coombes, Precious Metals Consultant, for his valuable contributions to this article.

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