CHALMERS

# Material Flow Analysis and Environmental Impact Assessment Related to Current and Future Use of PGM in Europe

*Master of Science Thesis in the Master Degree Programme, Industrial Ecology*

MATHIEU SAURAT

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*Division of Physical Resource Theory*
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MATHIEU SAURAT
Supervised by STEFAN BRINGEZU and ULRIKA LUNDQVIST

Department of Energy and Environment
Division of Physical Resource Theory
Chalmers University of Technology
SE-412 96 Göteborg, Sweden
Telephone + 46 (0)31-772 1000
www.ee.chalmers.se

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Material Flow Analysis and Environmental Impact Assessment Related to Current and Future Use of Platinum Group Metals in Europe
MATHIEU SAURAT
Department of Energy and Environment
Chalmers University of Technology

# SUMMARY

Platinum group metals (PGM) are essential components in a number of industrial processes and end-products of high technology, including catalytic converters fitted on cars to reduce atmospheric emissions. However, the production of these precious metals is associated with heavy environmental impacts, such as mineral waste and sulphur dioxide emissions. The present study develops a model of the use of PGM in Europe in eight industrial sectors for the period 1990-2030, coupled with an analysis of the environmental impacts of the primary and secondary production of PGM in South Africa, Russia, North America and Europe.

The material flow analysis tends to show that sulphur dioxide emissions are the prime environmental concern regarding the primary production of PGM. In this respect, secondary production emits 30 to 180 less $SO_2$ per ton PGM produced, depending on the way the emissions are allocated. Modelling results also show that increased recyling rates for autocatalysts and electronic products could lead to 30% less $SO_2$ emissions. Up to date technologies at the Russian PGM production facilities alone could reduce the $SO_2$ emissions associated with the use of PGM in Europe by 50%. The autocatalyst product group represents 60% of the demand for primary PGM in Europe, therefore the evolution of consumption patterns and the development of new technologies in the car industry have a major influence on the environmental impacts associated with PGM used in Europe. The potential future introduction of fuel cell vehicles containing platinum could take place at a large scale without jeopardizing world reserves, only under the condition of important technological improvements to reduce the amount of platinum needed per kW. Finally, the present work stresses the importance of promoting the recovery and recycling of the PGM used on the European territory, in order to save primary resources, reduce environmental impacts related to PGM production and avoid the shifting of environmental burden to other parts of the world.

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[1] *Der Dativ ist dem Genitiv sein Tod*, Bastian Sick, 256p.

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# List of Abbreviations

| | |
|---|---|
| ACEA | Association des Constructeurs Européens d'Automobiles |
| ACP | Anglo Platinum Converting Process |
| BAU | business as ususal |
| CHP | Combined Heat & Power |
| CIS | Commonwealth of Independent States |
| COMECON | Council for Mutual Economic Assistance |
| conc. | concentrate |
| conv. | converter |
| DG TREN | Directorate-General Energy and Transport |
| DM | manufacture of transport equipment (in the NACE classification system) |
| EEA | European Environment Agency |
| ELV | end-of-life vehicle |
| EOL | end-of-life |
| EU | European Union |
| EU10 | Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia |
| EU15 | Austria, Belgium, Denmark, Germany, Greece, Spain, France, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Finland, Sweden and United Kingdom |
| EU25 | EU15 + EU10 |
| EUROSTAT | Statistical Office of the European Communities |
| FC | fuel cell |
| FCV | fuel cell vehicle |
| g | gramme |
| GDP | gross domestic product |
| GEMIS | Global Emission Model of Integrated Systems |

| | |
|---|---|
| GJ | gigajoule |
| GRI | Global Reporting Initiative |
| GULAG | Chief Directorate of Corrective labour Camps and Colonies |
| ha | hectare |
| HC | rapid learning process for the platinum loading of fuel cells |
| HP | rapid learning process for the power density of fuel cells |
| HR | high registrations scenario |
| ICT | information and communication technologies |
| ISO | International Standardization Organization |
| KBA | Kraftfahrt-Bundesamt |
| kg | kilogramme |
| KGB | State Security committee |
| kW | kilowatt |
| $kW_{el}$ | electrical kilowatt |
| L | liter |
| LC | slow learning process for the platinum loading of fuel cells |
| LCD | liquid crystal display |
| LP | slow learning process for the power density of fuel cells |
| LR | low registrations scenario |
| $m^3$ | cubic meter |
| max | maximum |
| MC | moderate learning process for the platinum loading of fuel cells |
| MEA | electrodes and membrane assembly |
| MFA | material flow analysis |
| min | minimum |
| MP | moderate learning process for the power density of fuel cells |
| NACE | Classification of Economic Activities in the European Community |
| NA Palladium | North American Palladium |
| NKVD | People's Commisariat for internal Affairs |
| NMVOC | non-methane volatile organic carbon |
| NN | Norilsk Nickel |

| | |
|---|---|
| OECD | Organisation for Economic and Co-operation and Development |
| oz | ounce (28.349 g) |
| PCC | post-combustion catalyst |
| PEM | polymer electrolyte membrane |
| PEM | proton exchange membrane |
| PGM | platinum group metals |
| PM | particulate matter |
| ppb | part per billion |
| ppm | part per million |
| RER | Reed Electronics Research |
| SCENES | |
| t | metric ton |
| TC | transfer coefficient |
| TJ | terajoule |
| TMR | total material requirement |
| TREMOVE | |
| troz | troy ounce (31.1035 g) |
| UG2 reef | reef of the upper chromitite group number 2 |
| UPMR | Umicore Precious Metals Refining |
| USA | United States of America |
| USD | US dollar |
| WEEE | waste electrical and electronic equipment |

*Chemical elements*

| | |
|---|---|
| Ag | silver |
| Au | gold |
| Cu | copper |
| Fe | iron |
| Ir | iridium |
| Ni | nickel |
| Os | osmium |
| Pd | palladium |
| Pt | platinum |
| Rh | rhodium |
| Ru | ruthenium |
| S | sulphur |

*Chemical compounds*

| | |
|---|---|
| $CH_4$ | methane |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $CO_{2eq}$ | carbon dioxide equivalent |
| FeO | iron oxide |
| $Fe_3O_4$ | magnetite |
| $FeO \cdot SiO_2$ | fayalite |
| FeS | iron sulfide |
| $Fe_7S_8$ | pyrrhotite |
| HCl | chloridric acid |
| HF | fluoric acid |
| $H_2SO_4$ | sulfuric acid |
| $N_2O$ | nitrous oxide |
| $NO_x$ | nitric oxides |
| $O_2$ | oxygen |
| $SiO_2$ | silica |
| $SO_2$ | sulfur dioxide |

# Introduction

## Problem Definition

Platinum group metals (PGM)[2] have very valuable chemical and physical properties. They are, among other things, superb catalysts and highly resistant to corrosion and weathering. They are therefore utilized in a number of industrial processes (for example in chemical, petroleum or glass industry) and they constitute vital components of numerous end-products, such as catalytic converters, electronic devices or dental prostheses. PGM also have some other qualities which make them very prized for jewellery. At the European as well as the world level, most of the primary PGM currently produced are used in catalytic converters for automobiles.

The autocatalyst application is symptomatic of the problem at the core of the present study. The introduction of these devices on a large scale in OECD countries has allowed, on the one hand, an important reduction of pollutant emissions[3] (with the notable exception of carbon dioxide) in the countries where this technology has been implemented. On the other hand, the PGM are rare metals whose extraction does not go without heavy environmental impacts, such as mining waste and sulphur dioxide emissions. The latter is one of the substances responsible for acidification. Nitric oxides are another group of acidifying compounds, and catalytic converters precisely work at eliminating them. As a consequence, the development of cleaner technologies in some (rich) parts of the world is suspected to be responsible for a shift of the environmental burden towards other (often less rich) parts of the world.

This issue could become even more relevant with the rise of a promising emerging technology: the fuel cells. With a large spread of this technology in the automotive sector, local air pollution could become a problem of the past, and at the same time fuel cells could address climate change issues,

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[2] The six PGM are: platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), osmium (Os) and iridium (Ir). In the present study only the most widely used of these precious metals are considered (i.e. platinum, palladium and rhodium).

[3] carbon monoxide CO, hydrocarbons $C_nH_m$ and nitric oxides $NO_x$

provided that the fuel is produced from renewable sources. At the current state of the art, fuel cells require platinum for their catalytic parts and in the case of fuel cell vehicles (FCV) the amount needed is substantially higher than that contained in an autocatalyst.

The aim of the present study consists in modelling the environmental impacts associated with the supply of platinum group metals to Europe. For that purpose, a model of the demand side (i.e. use of PGM in Europe) will be put into relation with a model of the environmental pressures related to PGM production. This should then provide insights into the suspected problem of shifting environmental burden from Europe to other parts of the world. The model should also offer the possibility to test potential levers to mitigate environmental impacts.

## Objectives

The aim of the study implies that certain technical objectives need to be fulfilled by the modelling of the production and the use (*supply* and *demand*) of PGM. Then, based on those models, potential levers can be investigated to address environmental impacts.

The *supply* of PGM consists of both primary and secondary production, through mining of PGM ore and recycling of scrap, respectively. In this respect, the present study should deliver results covering:

- the aggregate direct and indirect environmental impacts (emissions, energy and material resource use) associated with primary and secondary productions;
- the environmental impacts detailed at the level of production processes, whenever possible;
- an allocation procedure of the environmental impacts with regard to the different products;
- an aggregation procedure of the environmental impacts of the different producing regions into a 'PGM world mix'.

The use of PGM in Europe occurs in a number of industrial and consumption sectors with their own evolutions and structures, notably concerning recycling schemes. The study of the *demand* side for PGM in the present work should provide results regarding:

- the primary and secondary PGM inputs associated with the relevant industrial and consumption sectors in Europe;
- the past and future trends of the PGM flows related to the selected sectors.

The two aforementioned sets of results should then be considered together and assembled in different combinations of scenarios. Results stemming from the *relations between demand and supply* sides should cover:

- the environmental impacts at present time associated with the use of PGM in each selected sector;
- scenarios for the future evolution of these impacts.

The last results should help understand the environmental impacts of different supply and use scenarios and thus scrutinize the sensitivity of the overall picture to some parameters. In the end, it should be possible to identify some of the levers available to:

- reduce the environmental impacts associated with the use of PGM in Europe;
- mitigate the shift of environmental burden from Europe towards other parts of the world.

## Literature Review

There are very few statistics available regarding PGM demand and supply. The world wide reference is, however, the bi-annual publication "Platinum" by Johnson Matthey. Most of the other statistics that may be published are actually based on Johnson Matthey's data. The "Platinum" reports present the yearly primary production of platinum, palladium and rhodium of the major producing countries and the demand for primary PGM from a range of application fields (autocatalysts, electronics, jewellery etc) in different regions of the world (North America, Japan, Europe, and others).

While Johnson Matthey is the hallmark for statistics regarding primary PGM, there is virtually no data published concerning secondary PGM. However, regarding the issue of PGM flows analysis, the book "Stoffströme der Platingruppenmetalle" by Hagelüken *et al.* (2005) stands as a reference. The expertise of the Öko-Institut e.V. in the fields of material flows analysis and scenario studies, coupled with the insider experience of Umicore AG & Co. KG,[4] delivered a very detailed study of the stocks and flows of PGM in Germany, taking into account the specificities of each application sector with regard to the management of the PGM life cycle. The study shows that certain product groups, such as autocatalysts and electronics, generate high PGM losses at the end of the product lifetime due to low collection rates and export towards countries with no recycling scheme in place. Hagelüken *et al.* (2005) therefore considered the scenarios of PGM secondary production usually assumed in the literature to be unrealistic.

Hagelüken *et al.* (2005) also show that, from an environmental point of view, secondary production is preferable to primary production. The comparison is essentially based on Hochfeld's (1997) study which quantified the environmental pressures associated with primary production in South Africa, Russia, Canada and USA and with PGM secondary production in 1995. Hochfeld (1997) underlines the heavy impact of Russian production, especially regarding the emission of acidifying compounds. As a consequence, the break-even-point[5] for an autocatalyst was estimated at 4900 km.

The possible introduction of fuel cell vehicles in the future raises concerns regarding the capacity of known minable reserves to match the need for primary platinum. Gordon *et al.* (2006) estimate that a world fleet of 500 million of such fuel cell vehicles could be sustained during 15 years, disregarding the competition with other applications.

The present study proposes to expand and model at the European level Hagelüken *et al.*'s (2005) results regarding PGM flows in Germany. The present work is also expected to deliver a renewed study of the environmental impacts of primary and secondary production, to update Hochfeld's (1997) results. The overall objective is to link these two sub-studies in order to analyse and discuss the sensitivity of the impacts associated with the use of PGM in Europe.

# Overview of the Methodology

The study of the PGM supply and use sides consists of two material flows analyses. In the first case it is actually a material and energy flows analysis,

[4]Umicore is a materials technology group centered on four business areas: advanced materials, precious metals products and catalysts, precious metals services and zinc specialities. Umicore Precious Metals Refining operates as one of the world's largest precious metals recycling facility.

[5]Distance driven by a car fitted with an autocatalyst at which the total amount of acidifying compounds eliminated by the catalytic convertor equals that emitted during the production of the PGM contained in the autocatalyst.

the flows investigated being, among others, those of PGM, carbon dioxide and sulphur dioxide, as well as the total material requirement.[6]

The use of PGM is modelled in a top-down analysis for seven sectors[7] in which PGM are predominantly used. The use of PGM for catalytic converters is also modelled in a more detailed way by a bottom-up analysis. The future demand of platinum for fuel cell vehicles is modelled by a similar bottom-up analysis.

### Geographical Scope

The use of PGM is modelled for the geographical area covering the EU25, Norway and Switzerland. The top-down analysis is conducted within these boundaries wheareas the bottom-up analysis uses a model designed for the EU25 only. The results of the bottom-up analysis are then adapted to the system boundaries 'EU25 + Norway + Switzerland'.

Secondary production is assumed to take place within the same geographical boundaries as for the use of PGM.

Primary production is studied for three PGM producing regions: South Africa, Russia and North America. In the last case, due to data limitations, Canada serves as a reference for the whole North American region, through PGM mining in Ontario.

### Temporal Scope

The use of PGM is modelled for the period 1990-2020 for all sectors except for fuel cells which are modelled until 2030. Prior to 2004, the model is based on empirical data. From 2005, the forecast scenarios are derived from the literature.

The environmental impacts of primary and secondary productions are calculated for the year 2004. In the base case scenario, the impact intensity (per unit of production) is supposed to remain constant after 2004.

[6] Total Material Requirement (TMR) is defined as accounting for the domestic resource extraction and the resource extraction associated with the supply of the imports (all primary materials except water and air). It comprises raw materials which are further processed and which have an economic value (= "used extraction"), as well as so-called "hidden flows" (= "unused extraction", e.g. mining waste) (Moll *et al.* 2003, p.24).

[7] industrial catalysts, autocatalysts, electronics, glass industry, dentistry, jewellery and others

## Overview of the Content

The structure of the present work reflects the overall aim of the study which is to model the environmental impacts associated with the supply of the PGM used in Europe. The report is divided into three parts.

The first part of the report presents the modelling of the material and energy flows involved in PGM primary and secondary production. Chapter 1 gives an overview of the PGM production processes. The methodology for the material and energy flows analysis is detailed in chapter 2. The context and operations of PGM primary production in South Africa, Russia and North America are presented in chapters 3, 4 and 5, respectively. The resulting flow sheets are displayed in the same chapters. The case of secondary production is dealt with in chapter 6.

The second part of the report presents the modelling of primary and secondary PGM flows in Europe. Chapter 7 treats seven industrial and consumption sectors in a bottom-up analysis, while chapter 8 deals with autocatalysts and fuel cell vehicles through bottom-up analyses.

The third part of the report compiles the results of the first two (chapter 9) and applies an allocation procedure to represent the environmental impacts from part I. The main findings of the overal final model, which links various environmental impacts to the present and future use of PGM in Europe, are then discussed in chapter 10. This chapter also reflects on some of the assumptions and parameters used in the models.

Finally, conclusions are drawn and recommendations for future research given.

# Part I

# MFA of PGM Primary and Secondary Production

# Chapter 1

# Overview of the PGM Primary Production Processes

## 1.1 Geography and Geology[1]

Platinum group metals are virtually all concentrated in the earth metallic core, unaccessible to mankind. Their concentration in the siliceous lithosphere is estimated to range between 5 ppb and 0.5 ppm. However, in some marginal zones, physical and chemical interactions combined have lead to concentration and separation effects, giving birth to primary PGM deposits. There, the six PGM[2] always occur together, though in different concentrations. Gold and silver can often be found in PGM deposits too. The precious metals also always come along with nickel, copper, cobalt and other base metals (such as chromium, selenium, tellurium etc).

The largest primary deposits are situated in South Africa (Bushveld), Russia (Norilsk, Talnakh and, to a lower extent, the Kola Peninsula), Canada (Sudbury and Lac des Iles, Ontario) and the United States (Stillwater, Montana). These four places have been chosen for the present study. The locations of the deposits as well as facilities necessary for PGM primary production are presented in figure 1.1. The reserves and shares in today's world production are also displayed.

Primary production in Zimbabwe (Great Dyke) has been under development in the past years but remains negligible at the world's level. Colombia and the Urals used to contribute significantly to the primary production but their deposits are now virtually exhausted. Development programmes are currently undertaken in western Australia and eastern China.

[1]This section is based on Renner (1992, p.81-84)

[2]platinum, palladium, rhodium, ruthenium, osmium and iridium

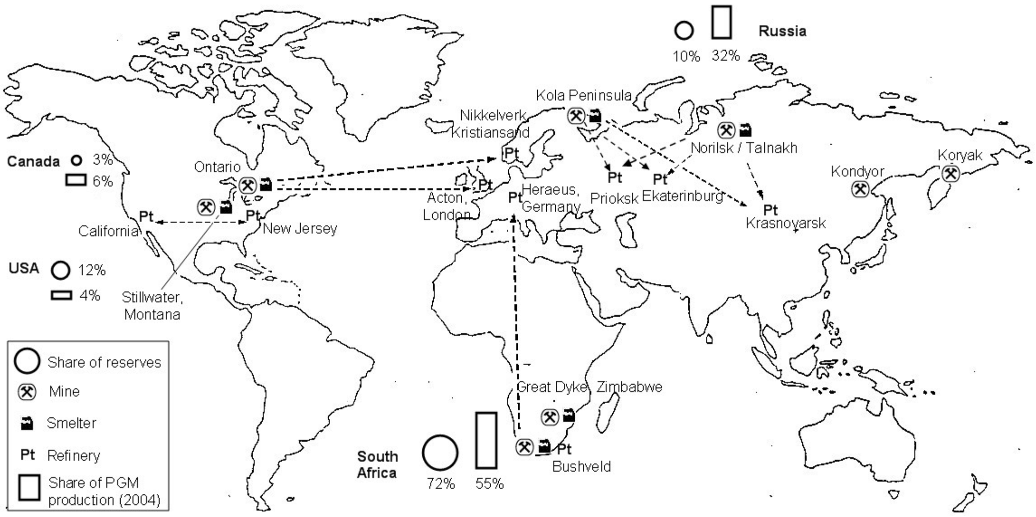



Figure 1.1: World platinum group metal primary production — reserves after Renner (1992, p.87); production after Johnson Matthey (2005)

In addition to primary deposits, there are secondary deposits which were formed by weathering and washing of primary deposits. Exploitation from such deposits in the far east of Siberia (Kondyor, Koryak) contributes to a limited extent to the Russian PGM production.

The deposits of platinum group metals can be further classified with respect to the type of ore (sulfide or chromitite layers). All the ore bodies processed today but one come with sulfides. One of the two South African deposits, the UG2 Reef (the other one being Merensky Reef), is a chromitite layer. This has an influence on the processes of the primary production. Another distinction can be drawn regarding whether PGM are mined as primary products or as joint-products of nickel and copper. Even in the former case, the concentrations of nickel and copper are higher than that of PGM, but mining PGM is then economically viable as such. This is of importance for the allocation rules of the environmental burden. The resulting classification is shown in table 1.1.

In the following sections, the principles of the processes included in the primary production of PGM are described. Some of the practical differences to the theory are presented in the following chapters which present a material and energy flows analysis of the primary production in the selected areas.

Table 1.1: A classification of the world's largest PGM deposits

| **Base metal sulfide deposits** | | **Chromite deposits** |
|---|---|---|
| **Primary PGM** | **PGM as joint-product** | **Primary PGM** |
| Merensky Reef<br>Stillwater | Sudbury<br>Noril'sk | UG2 Reef |

## 1.2 Extracting

Two main types of ore extraction from the earth crust can be distinguished: open pit and underground mining. In practice, both ways are often operated on the same seam. In both cases, the prime objective is to extract as little as possible non-valuable rocks and sand along with the metal-bearing ore in order to achieve high productivity and facilitate further ore treatment.

The two above-mentioned categories can be further divided into mechanized and non-mechanized mining methods. The latter relies on human labour. Some of the main techniques inluded in the former are called 'mechanized ramp and fill mining', 'sub-level stoping', 'mechanized cut and fill' or the more selective, less productive method of 'slusher cut and fill mining' (Stillwater 2005). Different processes are conducted depending e.g. on the incline and the width of the reef or the operating depth. Going into further details is beyond the scope of the present study. Mining represents indeed on its own a considerable part of engineering science.

Broken ore results from the extraction stage. After being transported to the adequat facilities it undergoes numerous complex treatments which are further described in the sections below.

## 1.3 Beneficiation

### 1.3.1 Milling

During the milling process broken ore is reduced to a size suitable for undertaking the next step, concentrating. It actually consists of crushing and grinding, usually wet grinding (Renner 1992, p.87). By doing so, the microstructure of the ore is revealed, and with it the small valuable PGM-bearing sulfidic minerals. The finely ground material is then fed into the concentrator.

### 1.3.2 Concentrating

Concentrating stands for the separation of milled ore into a waste stream (tailings) and a valuable stream (concentrate). Ground ores undergo a first step of gravity concentration to separate the metallic particles from the PGM-bearing minerals (Renner 1992, p.87). A first concentrate is obtained which is then used in the next concentrating process called 'flotation'.

This stage consists of a series of agitating tanks through which milled ore mixed with water (pulp or slurry) is passed. Various chemical reagents are added to the pulp in a sequence that renders the valuable minerals hydrophobic and the non-valuable minerals hydrophilic. The unwanted gangue is then removed from the sulfidic minerals with the help of air blown through the tanks. The hydrophobic particles attach to the rising air bubbles and are removed from the main volume of pulp as a soapy froth (Anglo Platinum 2004a, p.181).

Flotation cells are combined in series and are operated in association with second milling circuits to process the material which previously failed to float. This looped process-chain enables the flotation concentrate to contain several hundred parts per milion of PGM, along with a small percentage of sulphur, copper, nickel and iron (Renner 1992, p.89). The concentrate in the form of pellets is then sent to the smelter.

## 1.4 Pyro- and Hydrometallurgy

Typically, three pyrometallurgical steps are conducted, followed by hydrometallurgical treatments. Each of these stages could be further divided into different processes but this is beyond the scope of this study.

The term 'smelting' is often used to designate the pyrometallurgical process chain 'roasting – primary smelting – converting' whose purpose is to separate the metal values (nickel, copper and precious metals) from the major metallic component of the ore, namely iron (Inco 2004a, p.37). The description below is based on Kerfoot (1991, p.165-184).

### 1.4.1 Roasting

In the roasting step, the concentrate is heated in the air at 600 − 700 °C. At this temperature oxygen oxidizes sulfides, therefore part of the sulphur is removed as sulphur dioxide and part of the iron is oxidized. This step is also used to dry and preheat the material before smelting. The oxidation of iron being strongly exothermic, the process heat is reused whenever possible.

The product obtained is called calcine. Iron having greater affinity for oxygen than the other present metals, the main reaction is the oxidation of pyrrhotite ($Fe_7S_8$) to magnetite ($Fe_3O_4$), which can be represented as follows:

$$3\ Fe_7S_8 + 38\ O_2 \longrightarrow 7\ Fe_3O_4 + 24\ SO_2 \tag{1.1}$$

Normally, the process is designed to yield 50% oxidation of the pyrrhotite content of the concentrate. In this manner, less than 5% of the nickel and copper are oxidised, the balance remaining as sulfides. These values result from the necessary trade-off between the grade of the matte produced and the losses of nickel and copper to the slag phase in the subsequent smelting operation.

If most of the iron were to be oxidised in the roaster, then it would be slagged in the smelter and high-grade matte would be produced (low iron content versus high nickel and copper content). But in such a case significant amounts of the nickel and copper sulfides would also be oxidised in the roaster and thus slagged in the smelter, leading to high Ni and Cu losses.

### 1.4.2 Primary Smelting

The smelting step is actually carried out in two phases: primary smelting and converting (see next section). In primary smelting, the calcine from the roaster is melted in a furnace at a high temperature (1200 – 1300 °C) with a silica flux that combines with the oxidised iron from the roasting phase. Two immiscible phases are produced: a liquid slag which contains the iron oxide, the mineral gangue and silica, and a solution of molten sulfides containing the metals values. The slag can be discarded or recycled in the milling/concentrating process while the latter product, refered to as furnace matte, is directed to the converter.

The magnetite ($Fe_3O_4$) formed in the roaster reacts with the remaining iron sulfides and siliceous flux to form fayalite ($FeO\cdot SiO_2$). The reactions can be written as follows:

$$3\ Fe_3O_4 + FeS \longrightarrow 10\ FeO + SO_2 \tag{1.2}$$

$$2\ FeO + SiO_2 \longrightarrow 2\ FeO \cdot SiO_2 \tag{1.3}$$

The slag produced has a high iron content and a low nickel and copper grade. It floats on the furnace matte which has a high nickel and copper grade and a low iron content. The matte is then processed in the converter to remove the remaining iron.

### 1.4.3 Converting

In the converting step, air or oxygen-enriched air is blown with a silica flux through the molten furnace matte to form iron oxides and remove sulphur as sulfur dioxide. As in the roasting phase, the oxidation of iron is very exothermic and heat is recovered. The converting slag is normally made of iron silicate, but the presence of some metal values explains why the slag is often recycled in the smelting process. The main reactions are as follows:

$$2\ FeS + 3\ O_2 \longrightarrow 2\ FeO + 2\ SO_2 \tag{1.4}$$

$$2\ FeO + SiO_2 \longrightarrow 2\ FeO \cdot SiO_2 \tag{1.5}$$

Converting is a batch operation conducted in two main types of converters, known as the Pierce-Smith converter and the top blown rotary converter. However some modern installations have recently commissioned continuous converting processes (e.g. Anglo Platinum Converting Process in South Africa, 2004). The intermittent nature of traditional converting processes renders the treatment of off-gases by a sulfuric acide plant difficult (see section 1.4.4 below).

### 1.4.4 Major Environmental Aspects of the Pyrometallurgical Processes

The sulphur dioxide emissions from the roasting, smelting and converting processes represent the primary environmental concern which the nickel and PGM industries have to face. Three types of response have been put in place. First, outdated process equipments were replaced by more environmental friendly ones. Second, because the sulphur emitted by the smelter comes from the pyrrhotite ($Fe_7S_8$) contained in the ore, part of the pyrrhotite is separated from pentlandite in the concentrator and rejected. As much as $50 - 60\%$ of the pyrrhotite content of the ore is rejected in the Canadian operations in Sudbury. This, however, also leads to significant losses in metal recovery because some nickel, copper and precious metals remain trapped in the rejected minerals.

The third option is to collect the $SO_2$ bearing off-gases, clean them from dust and other particules and use them to produce sulfuric acid or elemental sulphur. Sulfuric acid production in a so-called 'contact plant' requires a stable feed with high strength off-gases. Intermittent processes or weak exhaust gases are thus not suitable. But in the modern installations continuous processes are put in place (e.g. Anglo Platinum Converting Process, South

Africa, in 2004) and plants capable to treat low strength gases for the production of weak sulfuric acid are commissioned (e.g. Implats' Sulfacid Plant, South Africa, in 2003).

### 1.4.5 Hydrometallurgy

The hydrometallurgical step aims at separating precious and base metals. Prior to that, a slow-cooling technique is applied to the molten converter matte, followed by magnetic concentration. The nickel-copper matte from the converting stage is slowly frozen with the consequence that the constituents segragate into three separate and distinct chemical phases. The major phases are nickel and copper sulfides. Due to a deficit of sulphur, the remaining nickel and copper form a magnetic alloy phase which collects virtually all the precious metals.

After magnetic separation, the nickel and copper sulfides are treated in the base metals refinery. The Cu/Ni alloy containing the PGM values is leached in a sulfate or chloride solution which in turn undergoes electrowinning processes to recover nickel and copper. The PGM are concentrated in the residue and are send to the precious metals refinery.

## 1.5 Precious Metals Refining

The refining of precious metals consists of two steps: separation and purification. There are two main techniques to separate the six different PGM and gold from one another: selective precipitation and solvent extraction.

The former is the traditional one. The precious metals concentrate is dissolved in *aqua regia*. The precious metals are then separetely and selectively precipitated and filtered. The filter cake finally undergoes several complex purifying processes.

The latter separation process uses the property of metals to form stable complexes with organic molecules. The concentrate is first dissolved in boiling hydrochloric acid with introduction of chlorine gas. The precious metals are then selectively extracted into organic solutions from which they are recovered by means of filtration or distillation. Finally, further complex purifying stages are necessary to obtain a saleable product. Solvent extraction allows a better recovery of the metal values and therefore this technique is preferred nowadays to selective precipitation.

# Chapter 2

# Methodology for the Material Flow Analysis of PGM Primary Production

The present study analyses material and energy flows related to the primary production of platinum group metals in South Africa, Russia and North America. Inputs such as energy, minerals, fossil fuels and water are considered. The outputs studied are emissions to air, solid waste and to a lesser extent emissions to water. These input and output flows are quantified either in an aggregate form for the whole system or in a more detailed way for the different processes (flows from, to and between the main processes: mining, milling, concentrating, smelting, converting, separating and refining). In part I 'MFA of PGM Primary and Secondary Production', no allocation procedure between the different products is applied to the calculated flows, which is equivalent to say that the whole environmental burden is allocated to PGM. In part III 'Results and Discussion' an allocation procedure is chosen and applied to the results of part I.

## 2.1 Aggregate Flow Sheets

The aggregate flow sheets present the inputs to and outputs from the primary production process chain considered as a whole. One can distinguish between direct and indirect flows. The former cover inputs or outputs directly used or emitted by the production processes. The latter represent flows directly linked to electricity generation and the supply of fossil fuels, which are thus indirectly associated with the PGM production process.

Whenever possible data for direct flows were taken from environmental reports of the considered mining companies. Anglo Platinum in South Africa and Inco in Canada publish such data. These are revised by third parties and can thus be considered as reliable. There are no such publications available from Norilsk Nickel, the Russian PGM mining company. When it comes to PGM in Russia it is extremely difficult to find data, let alone reliable ones. The impact of transport (of men and materials) is disregarded in the three regions.

Concerning indirect flows, two main sources were used. Emissions to air associated with electricity generation from different energy carriers were taken for each country from the GEMIS[1] database. The energy mix of each country was either found in publications from national energy agencies or again in the GEMIS database.

Fossil fuels used for electricity generation or directly by the mining companies require a certain amount of resources to be mobilized for their extraction. A researcher at the Wuppertal Institute, Dr Helmut Schütz, has developed a huge database containing, among others, indirect flows associated with raw materials imported to Germany from almost any part of the world. The data of interest here are those called "unused extraction", "abiotic resources for energy" and "abiotic resources for transport". They represent the 'hidden flows' associated with the extraction of e.g. hard coal in South Africa, which is then exported for use in Germany. In the present study, only the data concerning "unused extraction" and "abiotic resources for energy" are retained (the impact of transport is disregarded).

## 2.2 Detailed Flow Sheets

The detailed flow sheets try to display the input and output flows *per process* of the primary production chain. Due to the difficulty to obtain data at this less aggregate level, only part of the flows are studied. In the first place, mineral flows are considered: as main input/output of the metals recovery process (from rocks and ore to refined metals), as waste (waste rocks, tailings, slags) and as sulphur emissions to the air. Flows of energy and water are also calculated whenever possible.

For each process the transfer coefficients (TC) of PGM, nickel and copper into the valuable (i.e. which contains the metal values) output of the process is taken from the literature (where it is often called "recovery rate"). The PGM, nickel, copper and sulphur concentrations (or grades as they are usually referred to in the mining sector) in the input and output flows are also

[1]Global Emission Model for Integrated Systems developped by the Öko-Institut e.V. (Institute for Applied Ecology)

taken from the literature. These two sets of data allow to estimate the mass flows of minerals containing the PGM (rocks, ore, matte or concentrates for the valuable flows and tailings, slags, sulphur emissions for the waste flows). The relationship used between the parameters is as follows:

$$\frac{\sum_{i=1}^{O} \text{valuable Output}_i * \text{Output grade}_i}{\sum_{j=1}^{I} \text{Input}_j * \text{Input grade}_j} = \text{TC for PGM} \qquad (2.1)$$

The waste flows account for the difference between $\sum_{j=1}^{I} \text{Input}_j$ and $\sum_{i=1}^{O} \text{valuable Output}_i$. However, several problems mitigate the quality of the disaggregate flows. First, the quantities of auxiliary materials (e.g. silica) used in the metallurgical processes are not disclosed by the mining companies. The transfer coefficients of these substances to the valuable output or the waste are also unknown. The recycling rates of certain mineral wastes are not available either (e.g. furnace slag sent back to the milling process, or converter slag returned to smelting). These uncertainties imply that some processes do not verify the mass balance. However, when summed up, the sulphur dioxide, energy and waste flows of the detailed sheets should give the same results as displayed in the aggregate flow sheets, from which they were originally derived.

Finally, it should be considered that the flows provided in the detailed flow sheets are not quantitative data of high quality. They can, however, still be used to compare qualitatively the relevance of the different processes regarding $SO_2$ emissions, energy use or waste generation. On the other hand, all the flows of the aggregate flow sheets – if not mentioned otherwise – are reliable and can be used for quantitative comparison between producing regions or between primary and secondary producers. The aggregate data are used in the 'Results & Discussion' part of this work to assess the environmental impacts of PGM primary production.

# Chapter 3

# PGM Primary Production in South Africa

## 3.1 General Features

The so-called 'Bushveld Complex' hosts the currently exploitable South African reserves of platinum group metals. These are dispatched over the Western, Eastern and Northen Limbs, the last one being of lesser importance. Originally, all the mining activities were situated on the Western Limb but, due to the depletion of the reserves there, the production is currently moving to the east.

The reserves occur in two narrow but extensive strata referred to as the Merensky Reef and the UG2 chromitite layer. The former faces exhaustion and consequently the importance of the latter in the production volumes and development projects increases.

A number of mining companies operate in the Bushveld Complex but only a few large ones have all the facilities for mine-to-market production. These are Anglo American Platinum Corporation (Anglo Platinum), Implats, Lonmin and Northam. The first two represent 70 to 90% of the South African sales of refined PGM. Anglo Platinum alone accounts for about 55% of the output. The facilities of these companies are all situated in South Africa, except for Northam whose precious metals refinery is in Germany (see figure 1.1).

The operations of the South African producers seem to present similarities to a large extent, therefore calculations of material and energy flows are made for one of them (the main one, Anglo Platinum) and are extended to the whole country. Anglo Platinum has worked to obtain the ISO 14001 certification for its activities and publishes a 'Sustainable Development Report' applying the Global Reporting Initiative (GRI) Sustainability Guidelines. The report is reviewed by an independent assurance. The data from this report were extensively used to obtain the flow charts depicted in section 3.3.

## 3.2 Operations[1]

Open cast mining only plays a minor role nowadays (e.g. about 6% of Implats' production). At the same time, conventional (non-mechanized) mining techniques are still widely used (e.g. 8.6% of the total production is mechanized at Implats and the share is not expected to increase further than 12%).

Concentration and flotation processes are most of the time conducted in the vicinity of the mines. The treatment of UG2 ore is challenging because its high chromite content can hamper the smelting process. Therefore UG2 ore is often blended with Merensky ore in order to control the chromite content of the flotation concentrate.

There is no separate roasting step in South African smelters, only a drying phase immediately followed by smelting. The roasting is actually included in the smelting process. The main South African producers operate sulfuric acid plants to treat off-gases. Then, for each company, the converting step is often centralized in one smelter.

Anglo Platinum placed its old Pierce-Smith converters on cold stand-by in 2004 as the new Anglo Platinum Converting Process (ACP) plant was commissioned. The off-gases from the continuous converting process can be treated by a new sulfuric acid plant. As a consequence, the sulphur dioxide emissions from the Waterval smelter (where the ACP is located) decreased by 72% year-by-year (2003-2004). At Implats, Pierce-Smith converters are still in use but off-gases are, however, treated by a sulfuric acid plant, one of the few in the world which can work directly on converting exhaust gases.

After slow cooling of the converter matte and leaching of the different chemical phases, the final PGM concentrate is sent to the precious metal refinery while the base metals are directed towards the base metals refinery.

[1] The present description of PGM production in South Africa is mainly based on the operations of Anglo Platinum and Implats (Anglo Platinum 2004a, Implats 2005, Jones 1999).

## 3.3 Material and Energy Flows

Anglo Platinum is the largest platinum group metals producer in the world and, consequently, also in South Africa. As mentioned earlier, it is assumed in the present study that the material and energy flows associated with the activities of Anglo Platinum are representative for the national production. Figures 3.1, 3.2 and 3.3 show the results of the calculations for the year 2004. The numbers are all given per ton of refined PGM produced. The environmental data, directly given by Anglo Platinum or obtained after calculations, have hence been normalized by the company's PGM production in 2004 (4.42 million troy ounces,[2] i.e. about 137.7 metric tons).

### 3.3.1 Aggregate Flow Sheet

Figure 3.1 presents the aggregate results, i.e. the inputs and outputs for the whole process chain, from the mine to the saleable product. The absence of data or estimate is marked with a '?'. Anglo Platinum processes rocks mined in its own facilities but also flotation concentrates from joint-venture partners. The amount of rocks mined takes into account the upstream mining for the concentrates purchased and processed by Anglo Platinum.

However, the other input parameters given in Anglo Platinum (2004b) only refer to Anglo Platinum's operations. There was then a 8% difference in energy use between the aggregate picture (based on Anglo Platinum's data) and the results of figure 3.2 (estimate of energy use per process). Therefore, some inputs (electricity and water) in figure 3.1 were adjusted to take into account the mining, milling and concentrating operated by joint-venture partners. This means that the results for electricity and water from the per process calculations were used in the aggregate flow sheet instead of the data published by Anglo Platinum.

The flow of water reycled from the processes should not be considered as accurate. It is derived from data published by Anglo Platinum but the reporting of this indicator is neither harmonized nor extensively implemented in the company.

Some of the indirect emissions due to electricity generation are shown in the flow sheet. They were calculated based on the GEMIS database (see 2.1). Anglo Platinum also publishes estimates of its indirect $CO_2$ emissions but those are 12% lower than the results obtained with the GEMIS database. This can be explained in a similar way as above: Anglo purchases flotation concentrate from joint venture partners but the upstream processing is not

[2] 1 troz = 31.1035 g (troz is the abbreviation for troy ounce)

taken into account. Furthermore, the GEMIS data derive from a life cycle analysis approach which leads to higher emissions per unit of electricity than a direct estimate based only on the fuel used by the power plant.

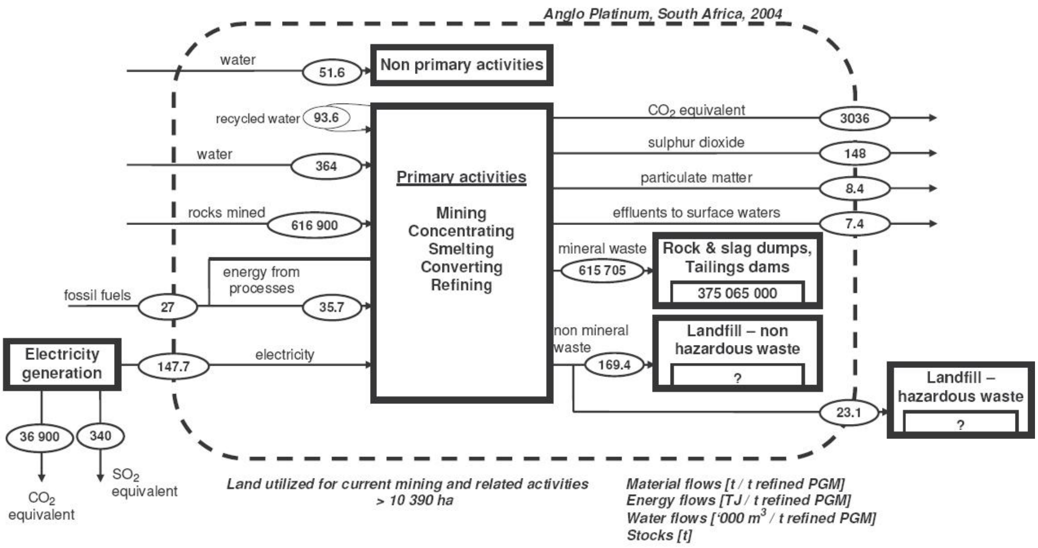



Figure 3.1: Overview of material and energy flows of PGM production in South Africa in 2004

## 3.3.2 Detailed Flow Sheet

The material flows along the production processes, from the mined rocks to the refined PGM, are presented in figure 3.2. Besides the mineral inputs, energy and water use are also calculated for each process and are presented in figure 3.3. Due to lack of data, no distinction could be made between electricity and fossil fuel use. For the same reason, mineral wastes and sulphur dioxide emissions are the only waste outputs calculated for each process.

### Flows of Minerals

Anglo Platinum publishes data for 'rocks mined' and 'ore milled', which give the input and output of the mining process. Due to lack of data (kept condidential), the chemicals used in flotation and the silica used in pyrometallurgy are not accounted for in the flow sheet. The recovery rates and PGM grades ratios used in the calculations are presented in table 3.1. The calculations themselves are detailed in appendix A.1.

The total amount of mineral wastes in dumps is given as in 2004. The year-on-year stock increase of rock dumps, tailings dams and slag dumps is lower that the amount of waste dumped. An unknown part of the mineral waste is indeed used for re-fill in the mines. The waste produced by joint-venture partners is also disposed of in facilities which are not managed by Anglo Platinum.

Table 3.1: Data for calculation of mineral flows in South African PGM production

| | PGM recovery rate (in %) | Grades ratio output:input |
|---|---|---|
| **Concentrating** | 84† | 30:1†† |
| **Smelting** | 98 | 7.5:1‡ |
| **Converting** | 98 | 3:1* |
| **Magnetic sep. & Leaching** | 100 | 200:1** |
| **PGM Refining** | 99 | 1.7:1 |

†(Implats 2005, p.61, Jones 1999)

††(Anglo Platinum 2004, p.36, Jones 1999, Kerfoot 1991, p.170, Renner 1992, p.88)

‡(Jones 1999, Kerfoot 1991, p.170)

*(Anglo Platinum 2004, p.36, Jones 1999, Kerfoot 1991, p.170)

**(Anglo Platinum 2004, p.36, Jones 1999, Renner 1992, p.88)

### Energy and Water Use

The energy and water use for smelting (Polokwane smelter) and base and precious metals refining are taken directly from Anglo Platinum (2004b, p.62, p.64). The energy and water consumption for mining/milling together is an average values over six facilities. According to Hochfeld (1997, p.51), the share of the mining process in the total mining/milling amounts 58% and 41% of energy and water use, respectively. The figures for the converting process stem from an estimation of the converting share in the energy and water consumption of the Waterval smelter which hosts both smelting and converting processes. The final values used in the study are presented in table 3.2, relatively to the valuable output of each process. Figure 3.3 shows the results.

### Flows of Sulphur

Virtually all the sulphur contained in the flotation concentrate is emitted as sulphur dioxide during the metallurgical treatment (Müller 1994, p.583). With a sulphur content of 9% (Jones 1999, Kerfoot 1991, p.170), this would

Table 3.2: Energy and water use in PGM production processes

| | Energy use (GJ) | Water use ($m^3$) |
|---|---|---|
| **Mining** (per ton of ore produced) | 0.26 | 0.52 |
| **Concentrating** (per ton of flotation concentrate) | 6.5 | 26.1 |
| **Smelting** (per ton of furnace matte produced) | 26.5 | 8.7 |
| **Converting** (per ton of converter matte produced) | 50.8 | 21.9 |
| **Base Metals Refining** (per ton of refined base metals) | 64.7 | 19.3 |
| **PGM Refining** (per ton of refined PGM) | 1.4 | 1200 |

lead to about 1388 t tons of $SO_2$ per ton PGM produced. The actual emissions measured by Anglo Platinum reach 148 t in 2004. Hence, 89% of the $SO_2$ emissions are avoided thanks to the sulfuric acid plants. Taking into account the recent investments of Anglo Platinum in cleaner technology, which lead to a 72% decrease year-on-year in $SO_2$ emissions at the waterval smelter, the result obtained seems reasonable.

The potential emissions detailed per process are calculated using the respective sulphur contents of the furnace matte (27%) and converter matte (20%) given by Kerfoot (1991, p.170). The share which is not emitted to the atmosphere is directed to the contact plant or the gas scrubbing process for production of sulfuric acid or sodium sulfate.

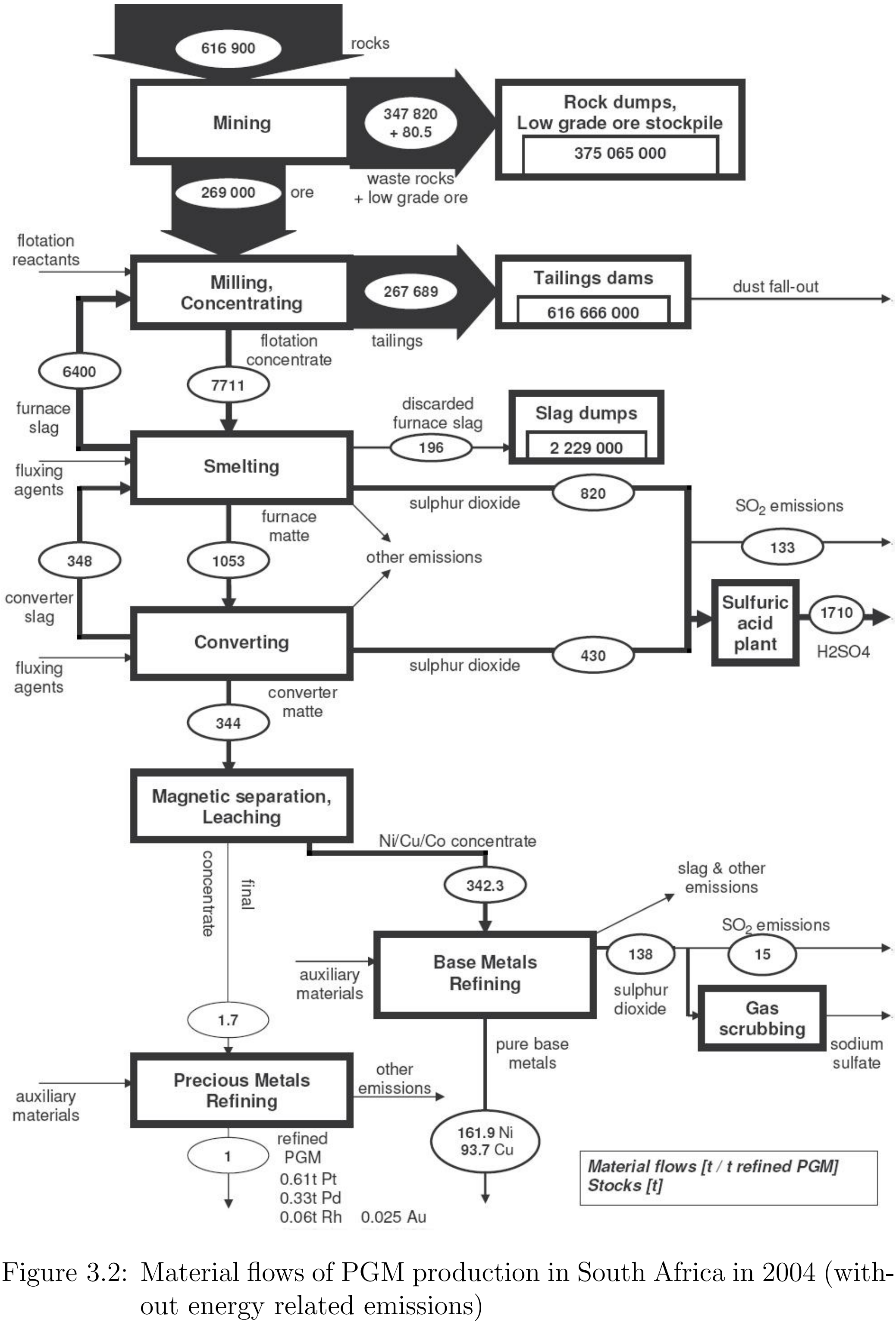



Figure 3.2: Material flows of PGM production in South Africa in 2004 (without energy related emissions)

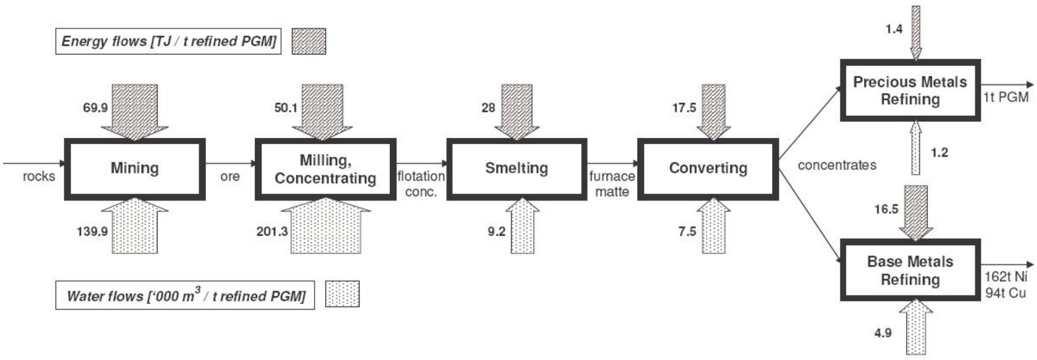



Figure 3.3: Energy and water use in PGM production in South Africa in 2004

# Chapter 4

# PGM Primary Production in Russia

## 4.1 General Features

The once significant PGM deposits of the Urals no longer contribute to Russian output of precious metals. Nowadays, Norilsk Nickel virtually accounts for all the PGM production, which in turn represents about 40% and 15% of world outputs of palladium and platinum, respectively (Johnson Matthey 2004, p.16). The company, primarily a nickel company, operates facilities in the Taimyr Peninsula (northern Siberia, the city is called Norilsk) and the Kola Peninsula. The PGM production overwhelmingly originates from the Taimyr Peninsula. On the Kola Peninsula, very little precious metals are mined along with the nickel and most of the PGM production comes from concentrates imported from Norilsk. However, the treatment of Siberian concentrates (from Norilsk) is supposed to stop in the coming years because of its high sulphur content and consequently high environmental impacts, including in the neighbouring Finland and Norway whose governments have granted subsidies to Russian industry in order to reduce pollution in the Kola Peninsula (De Man 2005, p.41)[1]. In the present study, only the production facilities in Norilsk are considered.

Everything is unusual and out of proportion about Norilsk. This is at least what emerges from the reports of the few journalists who could visit

[1]This document, one of the very rare attempts to quantify Norilsk Nickel's environmental impacts, was kindly provided by Dr Reinier de Man, independant consultant in "Sustainable Business Development", even though it was still at the stage of draft. Sergey Zhavoronkin (Bellona Murmansk) and Vladimir Masloboev (Kola Science Centre) have contributed to the parts related to Norilsk Nickel cited in this chapter.

the place. It is situated some 200 miles[2] north of the Arctic circle and "hosts" about 230 000 inhabitants in dreadful conditions combining a harsh climate (-40 °C usual in winter) to a tremendous pollution of air, soil and water. Air transport is the only access to the city in winter when the river freezes up: Norilsk has no road or rail connection to "the continent" (this is how Norilsk's inhabitants call Russia, where the life expectancy is some ten years longer but the average wage is six times lower than in Norilsk – about 900 USD per month in Norilsk). The history of the place is not common either: the Norilsk mining complex was founded in 1935 by Stalin, the NKVD (future KGB) was in charge and the Gulag provided the labour force. In total some 500 000 prisoners, including a large number of political ones, worked at the construction of what became the main supplier of nickel and PGM for the Russian armaments industry. A journalist of the Washington Post (Robert G. Kaiser) once called Norilsk "a city built on bones".[3]

## 4.2 Operations[4]

The Norilsk Nikel mining complex in the Taimyr Peninsula operates seven mines feeding two enrichment plants (the Talnakh and Norilsk Enrichment Plants). The output of this concentration step consists of three types of concentrates: nickel, copper and pyrrhotite concentrates (similar to Canadian operations). The last one is heavily loaded in sulphur but to date still undergoes metallurgical processes (unlike in Canada where it is rejected). There are plans to improve the separation of the three concentrates so that the pyrrhotite could be rejected without causing too high metal losses.

The concentrates are treated on spot by three metallurgical plants (the Nadezhda Metallurgical Plant, the Nickel and Copper Plants). After smelting, the converting step occurs in Pierce Smith converters. The converter matte is then processed by 'slow cooling' and after magnetical separation nickel and copper are recovered by electrowinning. The PGM concentrates produced from the electrolysis sludge are sent to three precious metal refineries under toll refining agreement (Krasnoyarsk, Prioksk and Ekaterinburg Precious Metals Plants).

Norilsk Nickel pretends to produce elementary sulphur and sulfuric acid but never mentions the existence of a contact plant or any other system dedicated to the treatment of off gases. De Man (2005) and Hochfeld (1997)

[2] 321.8 km (1 mile = 1.609 km)

[3] This paragraph was based on De Man (2005, p.14-34) and Johnson Matthey (2004, p.16-21).

[4] This section is based on Norilsk Nickel (2005, p.28-29)

suppose that there is simply no such system. It is at least for sure that Norilsk Nickel does not have the technology today to treat the weak and intermittent gases from the Pierce Smith converters. The sulfuric acid derivatives may actually be produced from the sulphur removed from the anode sludges (residues of nickel and copper electrowinning) (Hochfeld 1997, p.89).

## 4.3 Material and Energy Flows

Probably due to its past (and still present) status of military strategic industry, Norilsk Nickel cultivates its corporate secret, especially concerning data related to PGM production and environmental issues. One example illustrates quite well the level of transparency. In 2003, a bill was approved by President Putin to relax the interdiction of publishing data about Norilsk Nickel's PGM production. The bill was due to come into force in 2004 but it is still to be approved by the parliament. Therefore Johnson Matthey's estimates are based on Norilsk Nickel's sales, which can be quite different from the actual production due to the company's and government's secret stocks.

Facing the impossibility to find environmental data about Norilsk Nickel activities in the Taimyr Peninsula it was decided to use the flow sheet produced by Hochfeld (1997, p.95). Taking into account the process analogies between Canadian and Russian productions and the age of the facilities, Hochfeld came up with results used to build figure 4.1. It is assumed that Hochfeld's data can be used to describe today's situation. Calculations needed to adapt Hochfeld's (1997, p.95) flowsheet to Russian production in 2004 are presented in appendix A.2.

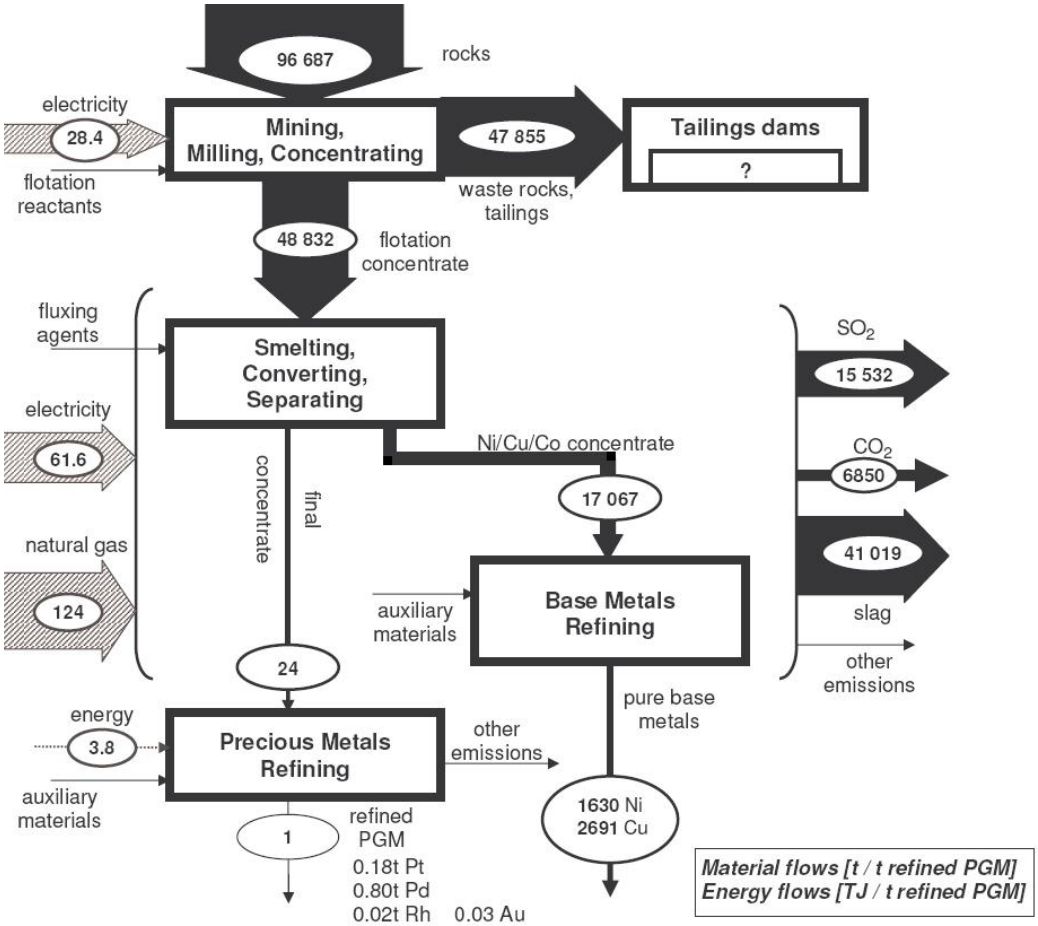
In 2003, Norilsk Nickel's management has announced huge investments (of several billion dollars) to close down the most polluting units (e.g. the Nickel Plant), change the composition of the feed ore (see section 4.2) and build facilities for the treatment of exhaust gases from smelting and converting. However, the work has yet to be done; it is therefore reasonable to assume that the situation in Norilsk is very similar to that described by Hochfeld in 1997.

The objective of highest priority of these measures is to reduce $SO_2$ emissions. These are huge, and not reported. Hochfeld and the Russian contributors to De Man's paper have had tremendous difficulties to find even total annual emissions of sulphur dioxide. They finally both cite the number of 2.3 million tons emitted in 1992. According to the authorities the figure would have decreased down to 2 million tons a year around 2002 (De Man 2005, p.24). To grasp the extent of the problem, the 1992 figure represents about the total of German $SO_2$ emissions or twenty times the Swedish ones (De Man 2005, p.30). Along with the release of heavy metals, acid rains due to sulphur dioxide have wiped out or damaged areas of forest-tundra estimated at several thousands of hectares. De Man (2005) could not find any recent exhaustive study on the subject.

Taking Johnson Matthey's estimate of Russian PGM production in 1992, 2.3 million tons of sulphur dioxide emitted that year give an intensity of 25 238 t $SO_2$ per ton PGM. Hochfeld gives a number of 29 500 t/t but he has used other estimates for Norilsk's production. However, even in the more favourable case (the first estimate), the total emissions in 2004 would reach 3 732 600 t, which is enormous. If it is assumed that 2 million tons were emitted in 2002, the intensity turns to be 21 434 t per ton PGM. Even in this better case estimate, total emissions in 2004 would still reach the colossal amount of 3 170 014 t.

Another corporate source(NN corporate magazine #7 of December 2004, published online), cited by De Man (2005, p.33), also claims that about 2 million tons of $SO_2$ are emitted every year (De Man 2005, p.33). Given that the production varies substancially year on year (at least in Johnson Matthey's estimates) this number can lead to different results. If it is considered for the year 2003, the intensity goes down to 15 532 t per ton PGM. The total emissions in 2004 would then 'only' amount 2 297 108 t. This is still a very large quantity of $SO_2$, furthermore equal to emissions twelve years earlier.

Despite the uncertainties, it is assumed that 15 532 t of sulphur dioxide are emitted per ton of PGM produced, i.e. the most favourable estimate is retained. A line in Norilsk Nickel (2004, p.72) could support this choice. It is claimed there that "in spite of a significant increase in production in the Taimyr Peninsula, the total emissions of [sulphur dioxide] in 2003 decreased by 0.3%". However, as always with Norilsk Nickel, a percentage is given but it can not be applied to any absolute figure because these are not reported. Similarly, production is said to increase but the numbers for PGM are not disclosed.




| Indirect emissions due to electricity generation | $CO_{2eq}$ | $SO_{2eq}$ |
|---|---|---|
| | 17 101 t | 119 t |

Figure 4.1: Material and energy flows of PGM production in Russia in 2004, after Hochfeld (1997, p.95)

# Chapter 5

# PGM Primary Production in North America

## 5.1 General Features

In North America, three Canadian companies and one from the USA mine PGM: Inco Limited, Falconbridge and North American Palladium, and Stillwater Mining, respectively. For Inco and Falconbridge, the platinum goup metals are by-products of the production of nickel and copper. For the two others, PGM are the primary metals: platinum for Stillwater and palladium for North American.

This distinction implies that PGM grades are higher in the Stillwater and North American's mines. As a consequence, energy intensity, emissions and waste generation ought to be lower than in the case of Inco and Falconbridge.

However, very few environmental data are available for these four companies. North American and Stillwater (in which Norilsk Nickel has recently taken a majority share) do not publish data. Falconbridge publishes an environmental report but the data are aggregated at the company level which means that mining activities in South America, where there is no PGM, are also accounted for. Finally, Inco discloses environmental information, revised by a third party, which are disaggregated enough to allow the estimation of the environmental impacts associated with Inco's mining activities in Sudbury, Ontario where about 92% of the company's PGM output is produced (Johnson Matthey 2005, p.18). Due to the lack of data from the other mining companies, it is assumed that the environmental impacts calculated for Inco can be applied to the whole North American production.

North America as a whole represented less than 10% of the world PGM production (in mass) in 2004. Inco accounted for about 28% of the North

American production (see table 5.1). The typical PGM grades at Inco's Sudbury mines are lower than those of the other North American producers: 0.75 g/t for Inco (Inco 2004b, p.11) against 7.4 g/t for North American Palladium and 12 g/t for Stillwater. Therefore, when applying the results of Inco's MFA to the three other companies one overestimates the environmental impacts of the PGM production in North America. The assumption can therefore be considered as conservative.

Table 5.1: PGM production in North America, by mining company

| '000 oz | Total | Inco | NA Palladium | Falconbridge | Stillwater |
|---|---|---|---|---|---|
| **Pt** | 385 | 183 | 25 | 47 | 130 |
| **Pd** | 1055 | 212 | 309 | 95 | 439 |
| **Rh** | 18 | 9 | n.a. | n.a. | n.a. |

Source: Johnson Matthey (2005, p.17-18)

## 5.2 Operations

Sudbury's sulfide minerals are made of pentladite (bearing nickel), chalcopyrite (bearing copper) and pyrrhotite (bearing iron). The milling and concentrating processes are designed to reveal these sulfide minerals occuring as grains in the rock matrix and to separate them. The purpose is to separate and reject as much as possible pyrrhotite before the metallurgical treatments in order to lower sulphur dioxide emissions. However, this implies necessarily loosing the inclusions of nickel in the pyrrhotite. This nickel can not be recovered if the pyrrhotite is not processed, and this is the case since the end of the 1980s when stricter restrictions on emissions to the air were implemented. Furthermore, the presence of nickel (even in small concentrations) in the rejected pyrrhotite makes the production of marketable iron from the pyrrhotite uneconomic (Kerfoot 1991, p.163).

The flotation concentrate is then directed to the Copper Cliff smelter where after drying it is smelted without a specific roasting step. The exhaust gases, heavily loaded in sulphur dioxide are treated by a sulfuric acid plant. The furnace matte is transfered to slightly modified Pierce Smith converters whose gases are not treated. The converter matte undergoes then a phase of 'slow cooling'. After separation, the magnetic nickel-copper alloy containing the PGM values is directed to the Copper Cliff nickel refinery. The precious metals are recovered in the sludge of the leaking step and a PGM concentrate is shipped to Acton precious metals refinery, London.

## 5.3 Material and Energy Flows

The material and energy flows related to the PGM primary production of the Canadian company Inco in the Sudbury region, Ontario are presented in figures 5.1 and 5.2. The data, taken from Inco's environmental report (Inco 2004a, p.45, p.49), have been normalised to obtain values per ton of refined PGM. The data relative to the company's activities in Sudbury were normalised by 10.5 t, which is the quantity of PGM produced by Inco from material originated from its Sudbury operations (Johnson Matthey 2005, p.18). The data concerning the Acton refinery were normalised by 13.1 t, which is the total PGM output of the refinery, produced from concentrates imported from Sudbury but also from other Inco's facilities or from purchased concentrates (Inco 2004b, p.2).

### 5.3.1 Aggregate Flow Sheet

The direct flows are taken from Inco's environmental report under the conditions described above. Data concerning water were not directly available however. The use of water for PGM production is estimated from aggregate data: Inco reports that its facilities worldwide use on average 155 $m^3$ of water per ton of metal produced. This figure represents the amount of water extracted from external sources and does not take into account water recycled by the processes. The production of one ton of PGM from Sudbury implies also the production of 10 381 t of nickel and 11 810 t of copper. It can therefore be estimated that 3 439 609 $m^3$ of water are necessary for the production of one ton of PGM. This figure is about ten times higher than that from South Africa: Anglo Platinum uses 366 958 $m^3$ of water (recycled water excluded) per ton PGM produced. The difference can be explained by two factors: first, the PGM grades are higher in the Merenski Reef than in Sudbury; second, water is probably considered a more scarce resource in South Africa, which would also explain why water use is reported more thoroughly by Anglo Platinum than by Inco.

### 5.3.2 Detailed Flow Sheet

#### Flows of Minerals

The calculations leading to the flows of minerals presented in figure 5.2 are detailed in appendix A.3. The data shown in table 5.2, along with the equation explained in chapter 2 make the starting point of the estimates. Due to lack of data, the auxiliary materials, such as the fluxing agents used in the

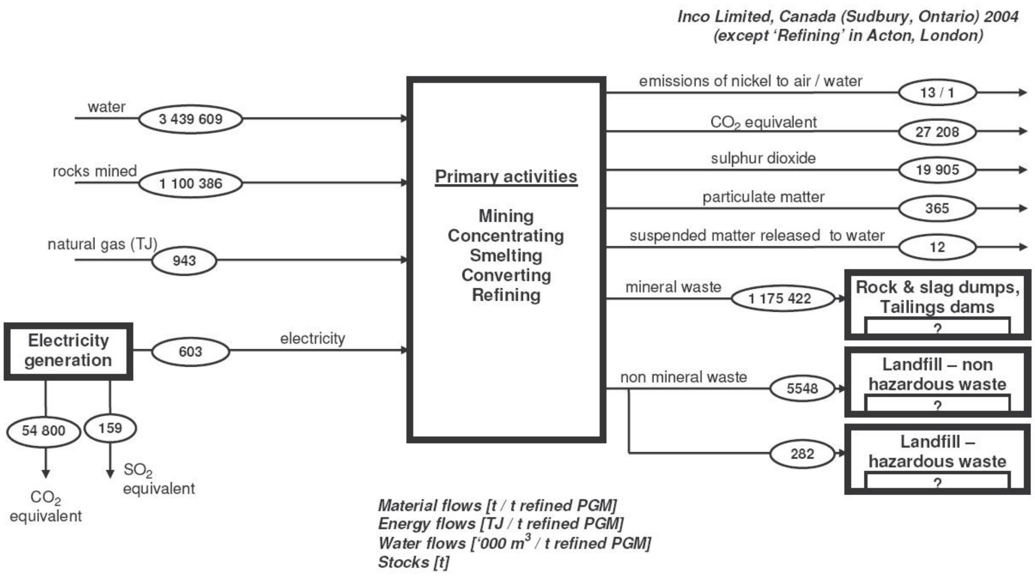



Figure 5.1: Overview of material and energy flows of PGM production in Canada in 2004

smelting and converting processes, are not accounted for. This might explain why the mass balance is not verified all along the process chain.

### Energy Use

The level of disaggregation of energy data published by Inco is limited: one can only distinguish between the energy used for precious metals refining and the energy used for the rest. The share of electricity (39%) in total energy use is taken from Hochfeld. The remaining is made of natural gas and used in the pyrometallugical processes. The distribution of electricity between mining, milling and metallurgical processes has been made in the same proportions as it was done by Hochfeld (1997, p.80): 54%, 14% and 32%, respectively.

### Flows of Sulphur

Virtually all the sulphur contained in the flotation concentrate entering the smelter is emitted as sulphur dioxide if the off gases are not treated (Müller 1994, p.583), hence the will to get rid of as much pyrrhotite as possible before the pyrometallurgical process chain. The flotation concentrate delivered to Inco's Copper Cliff smelter contains about 30% sulphur in mass (Kerfoot 1991, p.167). This could potentially release 75 986 t of $SO_2$ to the atmosphere per ton of PGM produced. Inco reports 19 905 t of emissions in 2004, which means that 74% of the potential emissions are trapped by the sulfuric acid

Table 5.2: Data for calculation of mineral flows in Canadian PGM production

| | **PGM recovery rate (in %)** | **Grades ratio output:input** |
|---|---|---|
| **Concentrating** | 89† | 8:1†† |
| **Smelting & Converting** | 96 | 5.2:1‡ |
| incl. Smelting | 98 | 2.2:1 |
| incl. Converting | 98 | 2.4:1 |
| **Magnetic sep. & Leaching** | 100 | 200:1* |
| **PGM Refining** | 99 | 142:1** |

†(Hochfeld 1997, p.77)

††(Hochfeld 1997, p.80, Kerfoot 1991, p.164)

‡(Hochfeld 1997, p.80, Kerfoot 1991, p.167, p.169)

*(Anglo Platinum 2004, p.36, Renner 1992, p.88)

**(calculated)

plant. It is 15% lower that the efficiency of Anglo Platinum in South Africa. The gap may actually be smaller because large amounts of pyrrhotite are rejected in the milling process, decreasing in this way the potential of $SO_2$ emissions from the flotation concentrate. Inco is also currently building a new off gas treatment system for the smelting operations (Inco 2004a, p.25). The potential emissions from the smelting and converting steps are calculated thanks to the concentration of sulphur remaining in the converter matte, 20% (Kerfoot 1991, p.169,p.172). The remaining is emitted by the base metals refinery.

Sulphur dioxide emissions per ton of PGM can seem quite high: 19 905 t for Inco against 148 t for Anglo and even 15 532 t for Norilsk Nickel. However, expressed per ton of nickel (the primary output of both Inco and Norilsk) the $SO_2$ intensity is five times higher in Russia. The Russian total annual emissions are also about ten times larger than those from Inco.

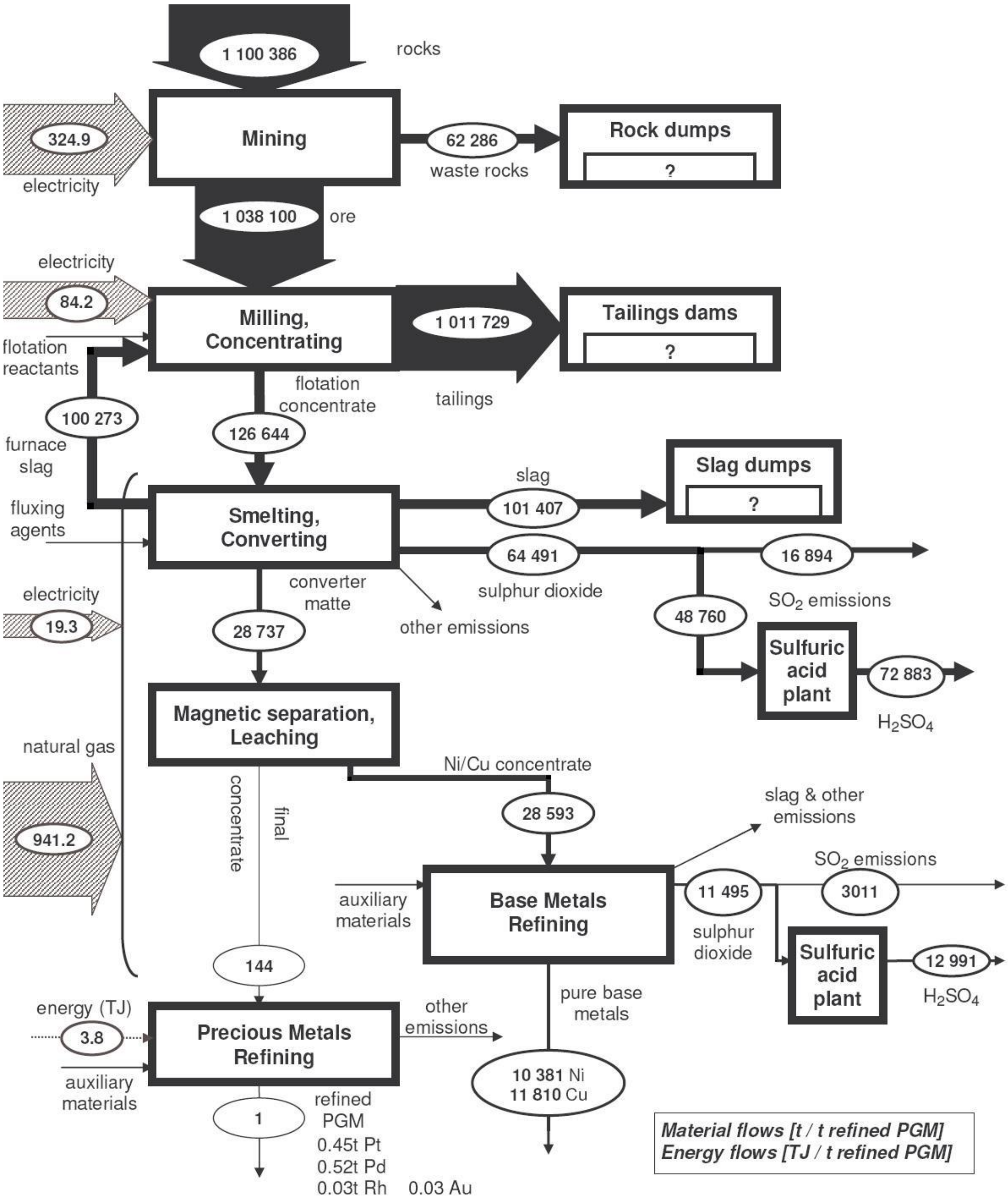



Figure 5.2: Material and energy flows of PGM production in Canada in 2004 (without energy related emissions)

# Chapter 6

# PGM Secondary Production

The multiplicity of materials which can be recycled as well as the number of actors who can take part in the recycling chain make it very challenging to grasp in a few pages the complexity of the production of secondary platinum group metals. However, the present chapter aims at providing an overview of the processes and the material flows involved. The purpose is thus to try and give a first insight into some aspects of PGM recycling in order to help to understand the choices made in part II 'PGM Use in Europe' and to enable a comparative study with primary production in part III 'Results & Discussion'.

## 6.1 Direct and Indirect Recycling Paths

Basically, platinum group metals are either used as industrial metals or incorporated in consumer goods. In the first case, the product delivered by the industrial process normally does not contain PGM. The precious metals are physically confined to the plant. Industries using PGM in their processes (as catalysts, coating etc) have usually developed a closed loop management of these metal values. In practice, contracts are signed with PGM refiners who collect the used precious metals at the plant and return refined PGM in a suitable form (salt, powder etc). The recycling rate achieved in such a rationalised precious metals management is typically higher than 90%. Figure 6.1 shows how Hagelüken (2005a) (in the name of Umicore, a PGM recycling and refining company) represents the direct recycling path.

In the second case, the PGM which enters a given plant leaves it embedded in the final product (autocatalyst, electronic device etc). Then, after an often rather long lifetime and multiple changes of ownerships, the product is called 'end-of-life (EOL) product'. It can be taken care of in three distinct ways:

dumped in a landfill or burnt in an incinerator with the rest of the domestic waste stream, exported to poorer countries where it starts a new life as second-hand product, or alternatively, collected to enter the recycling chain. The importance of the two first flows can vary greatly. It depends on factors such as the last owner's awareness of the precious metals value embedded in the product, the legislation (on export of scrap or on collection schemes) and the conscientiousness with which it is implemented.

The flow of PGM entering the recycling chain still has to undergo multiple steps including collection, sorting, dismantling, size-reduction and homogeneization before it is actually smelted and refined. Losses can occur at various stages along the way. The actors involved (especially in the first steps) are not always formally identified. Removing and processing PGM containing parts (e.g. decanning[1] or shredding[2] of an autocatayst) can lead to tremendous losses if not conducted properly (e.g. particular attention should be payed to dust collection). The dilution of PGM in the waste flow (e.g. in electronics) also hampers the recovery; the recycling chain is sometimes simply optimized for other materials. Hagelüken (2005a) represents the indirect recycling path as shown in figure 6.2.

It is beyond the scope of this study to examine in details the functioning of the PGM recycling chain. The insights given above serve, however, to estimate the efficiency of this chain in the different cases of PGM use studied in part II 'PGM Use in Europe'. The environmental impacts of the collection and pre-processing processes (i.e. up to the smelter) are disregarded (it mainly involves transport), whereas the enviromental weight of the smelting-refining processes is addressed in the following two sections.

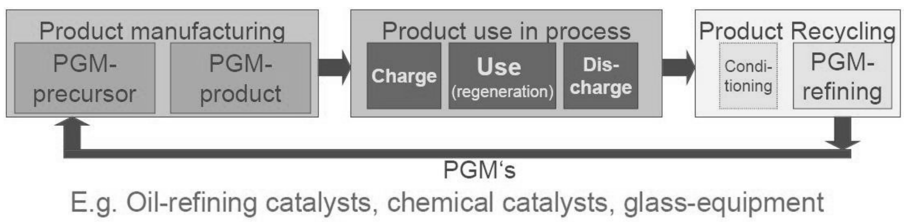



Figure 6.1: Recycling path for PGM used in industrial applications, after Hagelüken (2005a)

[1]Decanning of (ceramic) catalytic converters: opening the converter in order to separate the ceramic honeycomb from the steel can.

[2]Shredding of (metallic) converters: passing the converter through one or more different types of shredders, followed by separation of various fractions of steel scrap from the precious metal containing fraction.

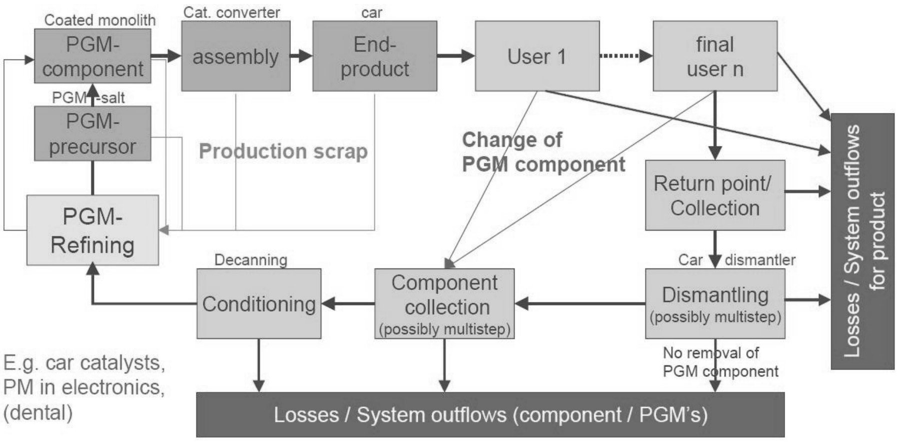



Figure 6.2: Recycling path for PGM embedded in consumer durable products, after Hagelüken (2005a)

## 6.2 Overview of the PGM Secondary Production Processes[3]

There are two important PGM recyclers in Europe: Johnson Matthey and Umicore. The particularity of the latter is that it has developed a combined smelting-refining facility in Hoboken (Belgium) where it processes virtually only secondary materials. The former on the other hand, produces PGM from both secondary materials and concentrates purchased from mining companies. The purpose being here to assess the environmental impact of producing PGM from secondary sources, Umicore's plant in Hoboken is taken as a reference.

Recycling and refining precious metals involves complex pyro and hydrometallurgical processes and technologies, which vary from one producer to the other. However, the aim is generally the same: to collect the precious metals in a base metal bullion. The possible collectors include lead, copper and nickel. The PGM remain then in the residues produced by the base metals refining, before they can in turn be refined.

Figure 6.3 presents the main steps of Umicore's PGM recycling process in its plant in Hoboken. Not shown in the figure are the shredding, sampling and assaying stages. The purpose is to obtain homogeneous samples of the incoming lots whose composition and precious metals concentration can vary greatly. These steps are essential to establish the contract with the client (How much should the client pay? How much PGM is the client supposed

[3]This section is based on UPMR (2005)

to recover at the end of the process?) as well as for a further efficient PGM recovery (the PGM content of the raw material is an important parameter to calibrate the recycling processes).

The preprocessed PGM containing material is then fed into the smelter along with by-products from the lead and copper industries, typically smelter slags and tankhouse slimes (Umicore 2004b, p.19). The output of the smelter consists of a lead slag and a bullion of impure copper. The former is directed to the lead blast furnace where, along with lead and copper containing secondary materials, it is treated and separated into three flows: impure lead bullion, speiss and copper matte (sent back to the smelter). The lead bullion and speiss both contain PGM. The latter is treated in a separate plant while the former is refined to obtain lead. Residues from both processes gather the PGM values and are fed to the precious metals concentration, along with some high grade raw secondary materials.

The residues from the leaching and electrowinning processes (applied to the copper bullion produced by the smelter) are also directed to the precious metal concentration. The following and last step is comparable to that of precious metals concentrates refining in the primary production. By-products of PGM recycling, including base metals (lead, copper, nickel, zinc etc), special metals (selenium, tellurium, indium etc) and precious metals (gold, silver), are recovered all along the process chain.

## 6.3 Material and Energy Flows

The data published by Umicore in its 2004 environmental report (Umicore 2004a, p.42) are aggregated at the "Business Segment" level. In the present study, the data concerning "Precious Metals Services" are used. This covers three recycling plants, the main one being situated in Belgium (Hoboken plant, described above). The inputs and outputs of materials and energy are normalized with respect to the secondary PGM production. In 2004, Umicore produced 37.3 t of PGM, including 15 t of platinum, 19 t on palladium and 3.3 t of rhodium. The results are presented in table 6.1.

The distribution of energy use between electricity and process fuels is made using the aggregate shares of each energy carrier at the company level (Umicore 2004a, p.40). The carbon dioxide emissions reported by Umicore include equivalent emissions for the use of electricity (Umicore 2004a, p.27). The result presented in the table below is an estimate of the direct $CO_2$ emissions. Thanks to a new ventilation system in the lead refinery, the airborne emissions of lead at the Hoboken plant fell by 82% in 2004 (63 kg instead of 355 kg the previous year). Lead emissions account in 2004 for

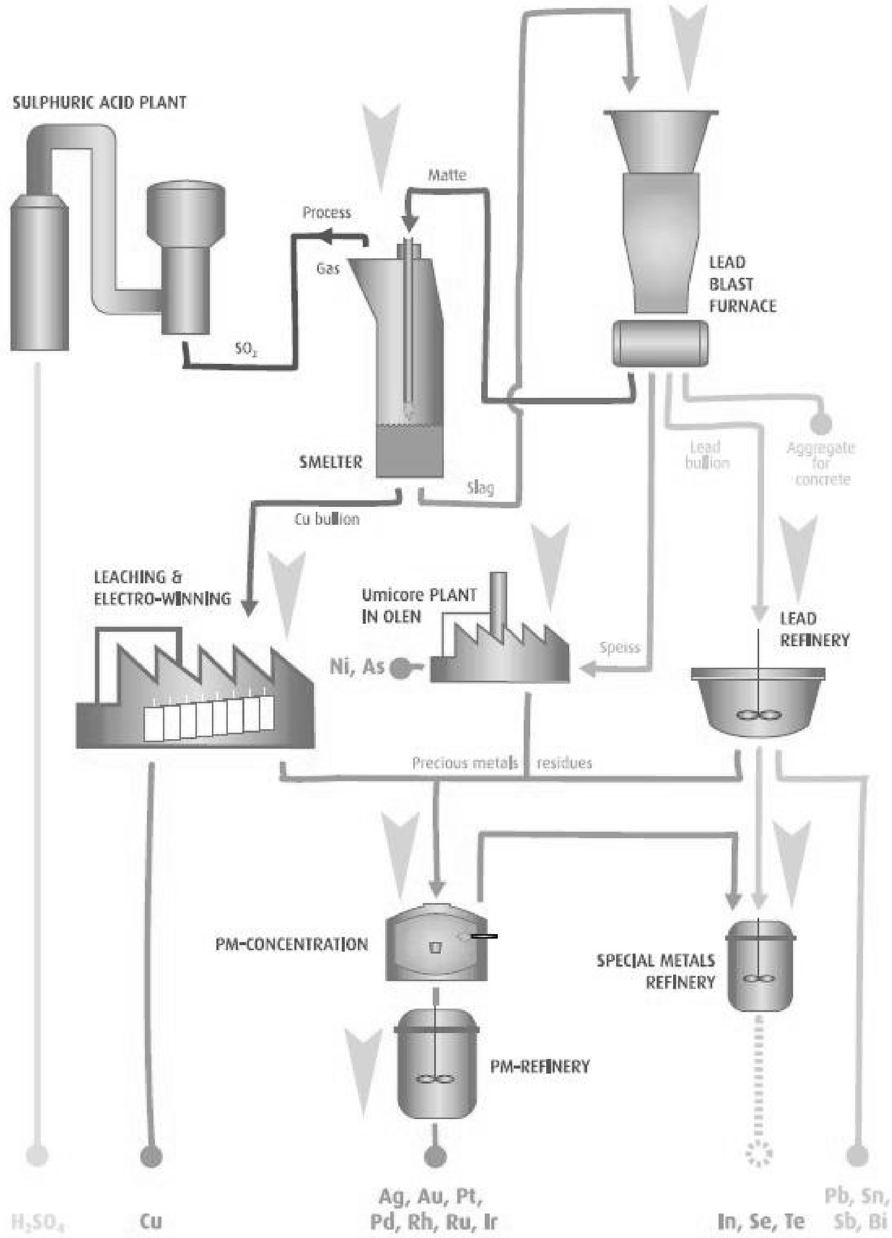



Figure 6.3: Simplified flow chart of Umicore Precious Metals Refining's plant in Hoboken (Belgium)

1.2% of the metals emissions to the air.

In part III 'Results & Discussion' of this work, the results presented here are compared to the environmental impact of primary production. The data aggregated for the whole process chain (from raw materials to refined PGM) are used both for primary and secondary production. Therefore, due to the scope of the present study, no further calculation of flows between the processes of the Hoboken plant is conducted.

Table 6.1: Direct material and energy inputs and outputs at Umicore PGM recycling plant in 2004

| **Umicore Precious Metals Recycling – 2004** (numbers given per ton of PGM produced, without allocation) | | |
|---|---|---|
| **Materials used** | metric ton | 6628.18 |
| of which secondary materials | metric ton | 6429.33 |
| **Energy use** | TJ | 64.12 |
| of which: electricity | TJ | 37.19 |
| natural gas | TJ | 15.39 |
| heavy fuel | TJ | 5.77 |
| other fuels | TJ | 5.77 |
| **Water use** | '000 $m^3$ | 37.32 |
| **Total waste** | metric ton | 3453.70 |
| of which is recovered | metric ton | 1650.87 |
| **Emissions to air:** | | |
| $CO_2$ | metric ton | 2207.46 |
| $SO_2$ | metric ton | 33.91 |
| $NO_X$ | metric ton | 3.30 |
| **Metals** | kg | 140.78 |
| **Emissions to water:** | | |
| **Metals** | kg | 84.80 |
| **PGM production:** | | |
| **Platinum** | metric ton | 0.40 |
| **Palladium** | metric ton | 0.51 |
| **Rhodium** | metric ton | 0.09 |

# Part II

# MFA of PGM Use in Europe

# Chapter 7

# Top-Down Material Flow Analysis

## 7.1 Methodology

The aggregate data of PGM input used for the top-down analysis presented in this chapter are taken from the yearly publication *Platinum* by Johnson Matthey. The geographical boundaries applying to these data are referred to as *Europe*. Johnson Matthey's explanatory notes to 'supply and demand tables' precise that "from 1993 demand numbers for *Europe* include an estimate of net consumption in the former COMECON countries of eastern Europe".[1] The General Manager of Johnson Matthey Precious Metals Marketing (J. Coombes, personal communication, Feb. 13, 2006) was asked for further information about these system boundaries and his answer clarified the borders: "prior to 1993 [Johnson Matthey's] Europe demand numbers represent purchases of PGM in the EU15 plus Norway and Switzerland" and "from 1993 [these data] include all of the former COMECON countries outside the CIS" (Commonwealth of Independent States)[2].

Therefore, the countries added to the system from 1993 are: the Baltic States (Estonia, Latvia and Lithuania), Bulgaria, Czechoslovakia, the German Democratic Republic (East Germany), Hungary, Romania and Poland. Among these states, only Bulgaria and Romania are not members of the European Union. On the other hand, Cyprus, Malta and Slovenia, which do belong to EU25, do not appear in the list. It is assumed, however, that

[1]The Council for Mutual Economic Assistance (COMECON or CMEA), 1949-1991, was an economic organisation of communist states.

[2]The CIS is an alliance consisting of 11 former Soviet Republics: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Ukraine, and Uzbekistan.

these two points can be disregarded. It is thus considered that prior to 1993 data refer only to the western European countries, i.e. the actual EU15 plus Norway and Switzerland. It is also assumed that from 1993 onwards the figures are representative for EU25 plus Norway and Switzerland.

Within the given geographical boundaries seven industrial sectors are considered. These industrial applications are studied in detail by Hagelüken *et al.* (2005) for Germany and these results are used to a large extent in the present work. The selected industrial sectors are as follows:

- Industrial catalysts
- Autocatalysts
- Electronics
- Glass industry
- Dental metals
- Jewellery
- Other industrial applications

Among these industries, some use PGM only for their processes, i.e. the final product is not supposed to contain precious metals, while PGM is embedded in the products of some other industrial sectors. In the first case, only the metals used in the industrial process are considered, no matter whether the final product is exported outside Europe or not. In the second case, our focus on PGM use in Europe implies to take into account the products containing PGM used within the geographical boundaries. These products might be produced and used in Europe; or they might be produced outside Europe, then imported and used in Europe.

The figures supplied by Johnson Matthey to represent the use of PGM in the European industry are called *net demand*. Hagelüken *et al.* (2005) also use this term (*Nettonachfrage* in German). These data estimate the "total purchases [of primary PGM] by consuming industries less any sells back to the market". Thus, "annual totals represent the amount of primary metal that is acquired by [industrial] consumers in a particular year". In the present work, the term *primary input* is used instead of net demand as it is the vocabulary adapted to the field of material flow analysis.

Having obtained the primary input from Johnson Matthey, the *total input* and the *secondary input* should be calculated for each sector. It is assumed in the present study that secondary PGM is used in the same industrial sector as the one which produced the product recycled. The relation between the three parameters is as follows:

$$\text{total input} = \text{primary input} + \text{secondary input} \tag{7.1}$$

In most cases the secondary input is calculated using what Hagelüken *et al.* (2005) call *static recycling rates* (*statische Recyclingquote* in German). The term *rate of secondary production*, which is typically used in MFA studies, is adopted as a synonym for the purpose of the present work. It is assumed that these rates, issued for Germany, can be applied at the European level. It is also assumed that the rates of secondary production are constant over time, i.e. the potential recycling improvements presented by Hagelüken *et al.* (2005) are not taken into account. The rate of secondary production can be defined as follows:

$$\text{rate of secondary production} = \frac{\text{secondary input}}{\text{total input}} \tag{7.2}$$

Therefore, given the primary input and the rate of secondary production, the following expression for the total input is obtained:

$$\text{total input} = \frac{\text{primary input}}{1 - \text{rate of secondary production}} \tag{7.3}$$

In the sole case of autocatalysts, Johnson Matthey gives demand as *gross demand*. A set of values called *recovery* is also given. For Johnson Matthey, recovery corresponds in fact to secondary input. The PGM recovery indeed covers PGM collected from used autocatalysts and, after recycling processes, reused in the production of autocatalysts. Thus, the primary input corresponds, in this case, to the gross demand less recovery.

Johnson Matthey provides input data from 1975 to 2004 for platinum, from 1980 to 2004 for palladium and from 1985 to 2004 for rhodium. In the present analysis the time period from 1990 to 2020 is considered. Between 1990 and 2004 the Johnson Matthey's data are used (either directly or after some modifications, as detailed in section 7.2 below). Concerning the scenario between 2004 and 2020, the forecasts from Hagelüken *et al.* (2005) about the market evolution of each industrial sector are applied to Europe. Hagelüken *et al.*'s (2005) forecasts stem from the literature and Umicore's own experience of the evolution of sells in relation with the economic situation and technological developments.

For platinum and palladium Johnson Matthey specifies data for a given industrial sector in a given geographical region. For rhodium, however, one can only access input data per industrial application or per geographical zones. It is then assumed that Europe accounts for the same share of rhodium input in each industrial sector as it does in the aggregate global input. This assumption is probably rather unrealistic. However, due to lack of alternative data, no better approximation could be made due to the lack of data concerning rhodium. On the other hand, European demand for Rh represented only 5.2% of Europe's total demand for PGM (in mass) in 2004 (Johnson Matthey 2005).

The method is described in detail for each sector in section 7.2 and the results for platinum, palladium, rhodium and the sum of the three are presented in section 7.3.

## 7.2 Methodology per Sector

### 7.2.1 Industrial Catalysts

Under the heading 'industrial catalysts' Hagelüken *et al.* (2005) study different applications and provide detailed results for each as well as an aggregate view of the whole sector (see Table 7.1). On the other hand, the data provided by Johnson Matthey only distinguish between chemical and petroleum applications. Therefore these two categories from Johnson Matthey are summed up and the aggregate rates of secondary production and market evolutions for platinum, palladium and rhodium calculated by Hagelüken *et al.* (2005) for Germany are applied to the present study.

In the applications considered in table 7.1 (except environmental catalysts), PGM are used as 'process catalysts' which means that the metal is normally not embedded in the final product. Therefore the possible extra-European export of final products is assumed to have no influence on the use of PGM in Europe.

Most of these industrial processes allow optimized rates of secondary production thanks to well organized logistics. The recycling loop is simple, with mainly two actors: companies, such as Umicore, deliver precursors or final metal complexes to chemical and petroleum plants; the same companies recollect PGM from their clients (e.g. embedded in an organic matrix) and recycle it (Hagelüken *et al.* 2005, p.43).

There are, however, noticeable exceptions to these high rates of secondary production: platinum and palladium use in homogeneous catalysis and platinum in environmental catalysts. In silicon production *via* homogeneous catalysis, platinum is retained in the product in such a low concentration (3–100 ppm) that it is not economically viable to recover it (Hagelüken *et al.* 2005, p.43). Similarly, only 50% of the palladium used in homogeneous catalysises is recycled because the concentrations involved in the multiple processes are considered too small and the value of the process slag is neglected.

The term 'environmental catalysts' cover mainly two fields of application: combined heat and power (CHP) plants and post-combustion catalysts (PCC) applied to exhaust gases loaded with organic particles. Environmental catalysts (without autocatalysts) contain platinum but only 10% of it is recycled because used catalysts end up most of the time with steel scrap. Users of such devices have indeed often little knowledge about their value for recycling. The picture is also complicated by the fact that these catalysts occur in many small units and are in place for a rather long lifetime (about six years).

Recycling potentials for the applications cited above are presented as very high by Hagelüken *et al.* (2005, p.45, p.48), except for platinum use in silicon production which presents no potential. Palladium recovery from homogeneous catalysis could be as high as 95% if residues from low capacity processes were treated. 90% of the platinum from environmental catalysts could be recycled if the professional paths for recollection were followed by the multiple users of small units. However, as stated in the "methodology" section, rates of secondary production as shown in table 7.1 are applied.

Hagelüken *et al.* (2005) foresee no market evolution for PGM in industrial catalysts apart from the applications in homogeneous catalysis and powder catalysts (5% increase in input per year). Many processes from fine chemistry and pharmaceutics can indeed be optimized thanks to PGM (Hagelüken *et al.* 2005, p.37, p.46).

### 7.2.2 Autocatalysts

PGM flows related to the application 'autocatalysts' are only roughly evaluated in this top-down analysis. The results can be seen as a way to control those obtained with the bottom-up analysis (see Chapter 8).

From 1990 to 2004, the total input and the secondary input (as *recovery*) are directly given by Johnson Matthey. The primary input is defined as the difference between the two. For the scenario between 2004 and 2020 the rates of secondary production proposed by Hagelüken *et al.* (2005, p.86) for end-of-life vehicles without exchanged autocatalysts are applied: 10% for platinum, 4% for palladium and 15% for rhodium. With exchanged autocatalysts – defective autocatalysts which ought to be exchanged during the lifetime of

Table 7.1: Rates of secondary production and market evolution for the industrial applications of PGM catalysts in Germany, after Hagelüken *et al.* (2005, p.50)

| **Applications** | **Rate of secondary production in %** | **Market evolution until 2020 in %/yr** |
|---|---|---|
| **Oil refining** | | |
| Pt | 97 | +/- 0 |
| Pd | 97 | +/- 0 |
| **Nitric acid** | | |
| Pt | 94 | +/- 0 |
| Pd | 70 | +/- 0 |
| Rh | 75 | +/- 0 |
| **Prussic acid** | | |
| Pt | 90 | +/- 0 |
| Pd | 90 | +/- 0 |
| **Homogeneous catalysis** | | |
| Pt | 21 | + 5 |
| Pd | 50 | + 5 |
| Rh | 87 | + 5 |
| **Powder catalysts** | | |
| Pt | 95 | + 5 |
| Pd | 95 | + 5 |
| **Solid state and fluidised bed catalysts** | | |
| Pt | 95 | +/- 0 |
| Pd | 95 | +/- 0 |
| **Environmental catalysts CHP & PCC** | | |
| Pt | 10 | +/- 0 |
| **Aggregate industrial catalysts** | | |
| **Pt** | 65 | + 2.5 |
| **Pd** | 92 | + 3.8 |
| **Rh** | 86 | + 4.3 |
| **sum PGM** | 80 | + 3.2 |

the vehicle – these values would be slightly higher; the estimate can therefore be regarded as conservative.

The market evolution is difficult to assess because it depends on the evolution of the number of new registrations and among those on the share of petrol and diesel cars and of the different cylinder capacities. A bottom-up analysis is more appropriate to make this sort of evaluation. However, the amounts of primary platinum, palladium and rhodium used in autocatalysts in Europe are assumed to increase at the same rate as new registrations in EU 25 as assumed in the bottom-up model (see Chapter 8.1.1). Thus the use of the three precious metals is considered to increase by 5% per year in 2005 and 2006, by 4% between 2007 and 2011 and by 1% between 2012 and 2016, followed by a stagnation until the year 2020.

One should note that the calculations presented here build on the data provided by Johnson Matthey which only account for the PGM as an input to the European automotive industry for the production of autocatalysts. The final products might then be exported and used outside Europe. This is not taken into account in the present top-down analysis. The bottom-up analysis, on the contrary, is designed to represent the PGM flows related to the autocatalysts effectively used in Europe.

### 7.2.3 Electronics

Platinum, palladium and, to a lesser extent, rhodium find multiple applications in the field of electronics, including contact materials, plumbs, electronic components such as varistors or multilayer capacitors. The precious metals are also used in special applications such as hard disks for computers or in metal layer technics. They are also used in sensors, such as thermo-elements, lambda sonds or gas sensors (Hagelüken *et al.* 2005, p93-94). These last applications are accounted for by Johnson Matthey under the heading 'other'. They are therefore considered in section 7.2.7.

As with autocatalysts in the previous section, electronic products contain PGM. Therefore imports and exports of electronic devices should be considered; the primary input values given by Johnson Matthey only reflect the PGM input into the European electronic industry. However, a bottom-up analysis is excluded because, on the one hand, it does not fit with the focus of the present study and since, on the other hand, 'electronic products' can take such a multitude of forms that it would be impossible to consider all the different products separetly and evaluate their PGM content.

To conduct the top-down analysis, the global PGM primary input to the electronic industry is considered and the share lying with the European consumption of electronic goods is extracted. Hagelüken *et al.* (2005, p.101) estimates that Germany accounts for 6.3% of the global electronic market. It is assumed that this share is constant over time and that the amount of PGM used for the production of electronic goods is evenly distributed among those. Then the European share in the world market for electronics is evaluated using the German share (6.3%) and the ratio between German and EU GDP (EU15 plus Norway and Switzerland before 1993, EU25 plus Norway and Switzerland thereafter) as reported by Eurostat[3] (accessed December 4, 2005). This gives, for instance, a European share of about 30% in 2004 which seems reasonable considering that in 2005 sixteen western European countries accounted for about 23% of the world electronic market (RER 2005).

The management of PGM-containing waste differs depending whether the production or use phase is considered. Producers of electric and electronic components (high PGM content) have developed a comprehensive recycling chain, so that losses are almost negligible. Producers of electronic devices, on the other hand, send their waste to electronic scrap (e-scrap). End users also dispose of their electronic waste in this manner, if not directly with domestic trash in which case the end-of-life electronic devices are burnt or dumped in a landfill. End-of-life appliances may also be exported to eastern Europe and electronic scrap might be exported (e.g. to China) and thus lost for PGM recycling. However, the share of scrap treated in Europe is not necessarily processed for PGM recovery as the recycling chain might be designed for e.g. plastic and copper recovery.

Data concerning the recycling of e-scrap are actually not available to date; this is supposed to change in the coming years, though. The EU Council and Parliament have indeed adopted the European Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE-directive) in December 2002 which sets collection and recovery (i.e. in this case, physical recycling) targets for electronic waste. In total, 4 kg of WEEE from private households should be collected per inhabitant and per year by the end of 2006, which makes a collection rate of about 25-30%. However, the first deadline proposed by the directive (August 2004 for transposition into national laws in the member states) was met only by two countries. Furthermore, the way the directive is or will be implemented by the member states may vary and differences in interpretations, rules and standards may arise (Hagelüken 2005b, p.365-366).

Therefore the estimates of Hagelüken *et al.* (2005, p.111) are based on the experience of professional recyclers. It is thus assumed that 50% of the PGM contained in the flow of WEEE are collected (as end-of-life devices, scrap etc),

[3] The Eurostat databases are available online after registration at http://epp.eurostat.cec.eu.int

that the processing of scrap leads to 20% of PGM losses and that during the further recycling and refining processes about 6% of the remaining platinum, palladium and rhodium are lost. The first figure for waste collection seems high. However, e-scrap containing precious metals (gold, silver and PGM) such as printed circuit boards have raised recyclers' interest long before the WEEE-directive was discussed.

Hagelüken *et al.* (2005, p.114) finally provide the following rates of secondary production: 15% for platinum, 91% for palladium and 26% for rhodium. The value for palladium seems particularly high considering the aforementioned restrictions to the recycling chain. The convergence of different factors might explain this number.

In 2001 the primary input of palladium into the European electronic industry dramatically dropped. This was due to the substitution of palladium by base metals, notably in the production of multilayer capacitors. The high price of palladium at this time, due to the rising demand in the automobile industry, triggered this change in inputs. At the same time, and since the mid-90s, the volume of WEEE increases three times faster than average municipal waste. This is mainly due the boom of the information and communication technologies in the 1990s, combined with the decreasing lifetime of electronic consumer goods such as computers and cell phones. Therefore, a lower demand in some sectors of the electronic industry combined with potentially increasing quantities of secondary palladium might explain why Hagelüken *et al.* (2005) considered a rate of secondary production as high as 91% in Germany.

However, to apply this rate to the whole European Union would not be realistic. Hagelüken *et al.* (2005, p.112) also give values for recycling rates (which they call *dynamic* rates of secondary production or *dynamische Recyclingquote* in German): 38% for platinum, 38% for palladium and 19% for rhodium. Distinct from the rate of secondary production, the recycling rate can be defined as follows:

$$\begin{aligned} \text{recycling rate} &= \frac{\text{recycled material}}{\text{waste}} \\ &= \frac{\text{secondary input } \textit{at end of lifetime}}{\text{total input } \textit{at time of production}} \end{aligned} \tag{7.4}$$

Hagelüken *et al.* (2005) consider a lifetime of ten years. However, if the lifetime of a computer in the 1980s was indeed ten years, it was closer to five years in the second half of the 1990s; the lifetime of a cell phone being even shorter. The given recycling rates, with a lifetime of five or ten years, were applied to European primary input of palladium between 1995 and 2004 to calculate the secondary input. Then, on this basis, the rates of secondary production (as defined in section 7.1) were calculated. This estimation is rather rough because it is only based on the recycling of the primary metal at the end of the lifetime of the product it is contained in and not on the recycling of the total input. However, on the average, the rate of secondary production was estimated at 30% before 2001 and at 70% after (against 91% given above for the same period). The results shown in section 7.3 were obtained with the two calculated values.

The recycling potential from electronic products can not be clearly stated. On the one hand, a large amount of the embedded PGM is not recovered and measures could be taken such as incentives to return electronic devices to the producer or product design oriented towards an easy and maximal recovery of precious metals. On the other hand, miniaturisation implies that the PGM content decreases (Hagelüken *et al.* 2005, p.113).

After Hagelüken *et al.* (2005, p.114) it is assumed that the input of palladium and rhodium remain constant between 2004 and 2020. To smooth out the quick variations observed in the use of platinum in the electronic sector it is considered that between 2004 and 2020 the input is constant and equal to the average input between 2000 and 2004.

### 7.2.4 Glass Industry

In a very schematic way, the process chain of glass production can be described as a succession of ovens. The extremly high temperatures and the agressive fluid glass flowing through them explain why the oven-walls made of ceramics are entirely lined with layers of PGM-alloys. For the same reasons the stirrers, thermometers and other devices used in the production are plated with platinum-rhodium alloys. These alloys present in general the following composition: 95% platinum and 5% rhodium. These protections are especially necessary for the production of highly agressive special and technical glasses (Hagelüken *et al.* 2005, p.122-123). The previous description corresponds to the use of PGM as a process material.

The production of optical glasses and fiber glasses also requires oven-walls and tools plated with PGM-alloys. But in this case rhodium can not be used, otherwise the glass would be tinted. Optical glasses represent a growing market due to the rising demand of LCD-displays.[4] The dozzles for fiber glass are also plated with Pt-Rh alloys.

Hagelüken *et al.* (2005, p.126) assume a slight market increase of 2% per year for the German glass industry, which is applied in the present study for

[4]The production of LCDs at a European level is negligible whereas their use is not.

the whole of Europe. Glass producers have put in place a comprehensive life cycle management of the PGM used in the production process or platered on tools. In addition, the recovery rates in PGM refineries are already at a maximal level for this kind of residues. The typical lifetime of platinum and rhodium in the glass industry is two years, so that every year half of the stock has to be renewed. Primary inputs therefore compensate the (low) losses occuring during the recycling of the two year old PGM and cover the market increase. The overall recycling rate attains 98% and there is practically no room for further recycling improvements (Hagelüken *et al.* 2005, p.124-125). Due to the relative homogeneity of the sector and the rather well determined lifetime, the recycling rate (98%) is used in the present study instead of the rate of secondary production. The latter oscillates then between 96.5% (in 1996) and 99% (in 1993).

### 7.2.5 Dental Metals

In the field of dentistry, palladium is the only PGM which can be used as a base for prostheses (bridges, crowns, implants). The others have indeed a too high melting point which prevents them from being melted, poured and casted in the desired shape (Hagelüken *et al.* 2005, p.128). One can distinguish three types of alloys for dental applications: high gold content alloys, gold reduced alloys and palladium based alloys. The first two are based on a Au-Ag-Cu alloy, whereas the third one is based on Pd. These three categories can be further divided under two other specifications: alloys which can be faced with synthetic material or which are used without any coating and alloys which can be flared up for plating of a ceramic coating. The high melting point of ceramics imposes an even higher melting point for the metallic alloy base. There are around one hundred different kinds of Pd based dental alloys which are almost all to be used with a ceramic coating. An overview of the composition of the different types of dental alloys is presented in tables 7.2 and 7.3.

Because of lack of relevant data, imports to and exports from Europe are disregarded for dental prostheses. Therefore, palladium primary input for dental applications is directly taken from Johnson Matthey. Platinum input in dental applications is not accounted for by Johnson Matthey. Thus, a rough estimation is made, based on the fact that platinum is used in combination with gold in high gold content dental alloys (to increase the resistance to weathering). Therefore, the gold input for dental prostheses in Germany, Italy, Netherlands and Switzerland is considered and it is assumed that this amount was all supposed to be used in high gold content prostheses with a weight-ratio Au:Pt of 5.5:1. This ratio is an average value, the upper limit being 7.5:1 (Hagelüken 2005, p.128, p.134). Data from 1997 to 2002 could only be used, thus for 1990-1996 and 2003-2004 the average value of the period 1997-2002 is applied.

Hagelüken *et al.* (2005, p.136) considers that 50% of dentists' work consists of replacing old or damaged dental prostheses. Therefore the potential recycling accounts for half of the total input. A replaced prosthese or inlay is given back to the patient who can sell it to a precious metal collecting-recycling company or donate it to a caritative organisation which will in turn sell it. It is assumed that 50% of the replacements do not enter the recycling chain, mainly because the patients are not aware of the value of their old prostheses. Thus, the effective recycling attains only 25% of the total input. Since losses during the production and implant (at the dentist's) phases are minimal due to the constant recovery of residues, the only potential to increase recycling can come through improved information and education of patients.

The market evolution for PGM in the dental sector is assumed to be nil. Different parameters can influence this evolution but in the end it is assumed that they compensate each other. For instance, better tooth health, a postponement of teeth losses into later stages of life or investments in ceramics and non-precious metals based prostheses would have a negative influence on the PGM demand. On the contrary, the age structure of the population, the increasing use of one-tooth-prostheses for young people or the increasing share of prostheses in comparison to inlays would lead to a higher demand for PGM (Hagelüken *et al.* 2005, p.137).

Table 7.2: Composition of gold based alloys for dental applications, after Hagelüken *et al.* (2005, p.128-131)

| | **High Au content alloys** | | **Au reduced alloys** | |
|---|---|---|---|---|
| **Element (weight %)** | **synthetic or no coating** | **ceramic coating** | **synthetic or no coating** | **ceramic coating** |
| **Pt** | 1-10% | 10-13% | no | no |
| **Pd** | no | 0-8% | 5% | 35-40% |
| **Au** | 70-75% | 70-75% | 60% | 50-60% |
| **Ag** | present | present | 20% | present |
| **Cu** | present | present | present | present |

Table 7.3: Composition of palladium based alloys for dental applications, after Hagelüken *et al.* (2005, p.128-131)

| **Element** | **Pd based alloys** | | |
|---|---|---|---|
| **(weight %)** | **Pd-Ag** | **Pd-Ag-Au** | **Pd-Cu** |
| **Pt** | no | no | no |
| **Pd** | 50-65% | 52-78% | 72-80% |
| **Au** | no | 4-19% | no |
| **Ag** | 20-40% | 6-20% | no |
| **Cu** | no | no | 5-14% |

### 7.2.6 Jewellery

There are mainly two kinds of PGM-containing jewels: Pt-jewels, which are mainly made in Europe and contain 95% Pt and 5% of a base metal (cobalt most of the time), and white gold alloys, containing a minimum of 10% of palladium along with gold and often silver, copper and zinc. Germany is the largest market in Europe for the PGM jewellery, Italy produces and exports light platinum chains to the USA and Japan, whereas as much as 90% of the British market is dominated by weddings jewels.

Due to lack of relevant data imports and exports of PGM jewels to/from Europe are disregarded. Therefore platinum and palladium primary input are directly derived from the tables published by Johnson Matthey. The production of jewels is divided between the goldsmith workshops and industrial manufacturers. In the former case, definitive losses account for 2% of the inputs, while for the latter they represent 5%. It is highly unlikely that such low losses might be further reduced in the future. Hagelüken *et al.* (2005, p.147) gives rates of secondary production of 38% for Pt and 28% for Pd. The remaining, i.e. inputs which are neither lost nor recycled, goes to the stock made up by the end users. The present economic circumstances tend to plead in favour of a stagnating market for jewels containing PGM.

### 7.2.7 Other

According to Hagelüken *et al.* (2005, p.157) the main 'other' applications would be *lambda-sonds* (also see section 7.2.3) and *spark ignition plugs*. They are both used in vehicles with petrol engines, where lambda-sonds are needed in vehicles equipped with three-ways catalysts for regulating the air-petrol mix.

The palladium and rhodium primary inputs for the 'other industrial applications' are directly obtained from Johnson Matthey, disregarding imports or exports. Concerning platinum, the values issued by Johnson Matthey include the use of this metal for dental applications (Johnson Matthey 2003, p.32). The results for Pt obtained in section 7.2.5 are therefore substracted.

Such sonds and spark plugs are quite complicated to dismantle and they contain low amounts of PGM (about 30mg of Pt per lambda sond and 15 mg of Pt for a spark plug) rendering their recycling uneconomic. The rate of secondary production is therefore set to nil which is consistent with the assumptions made by Hagelüken *et al.* (2005, p157). The number of sonds per car is expected to increase in the future as well as the number of new registrations. Due to the large variety of products entailed in the 'other' category, it is difficult to make precise assumptions regarding a possible market evolution. An increase of 2% per year between 2004 and 2020 is nevertheless assumed.

## 7.3 Results

This section presents the results from the top-down analysis both for the sum of the three PGM (subsection 7.3.1) as well as in a more disaggregate manner, separately for platinum, palladium and rhodium (subsections 7.3.2, 7.3.3 and 7.3.4, respectively). In each case, the figures display the European[5] primary input, total input (i.e. the sum of primary input and secondary input) and secondary input (i.e. the use of PGM from recycling of scrap and residues). The time span considered extends from 1990 to 2020. Between 1990 and 2004, the results are based on empirical data and own calculations. From 2004 onwards, forecasts stemming from the literature are applied.

### 7.3.1 Aggregate Results

In the period up to 2004, primary and total input both reach a maximum in 2000 with 132.2 t and 242.3 t, respectively.[6] Secondary input peaks in 2004 (119.6 t) while reaching a minimum in 2000 (88.8 t). Due to the assumptions made for the future scenario, the three parameters increase steadily after 2004, with the primary input increasing from 122.6 t to 167.3 t, the total input rising from 242.2 t to 312 t and the secondary input going up from 119.6 t to 144.7 t.

[5]'Europe' still refers to EU15 plus Norway and Switzerland prior to 1993 and to EU25 plus Norway and Switzerland afterwards.

[6]The ton-unit used is 'metric ton'.

At the aggregate level, the primary input is clearly dominated by autocatalysts, as shown in figure 7.1. Starting with 29% of the European primary input in 1990, the share of this application increased to 75% in 2001 and is expected to range from 70 to 75% between 2002 and 2020. The picture presented in figure 7.2 has a bit more nuances. Total input for autocatalysts indeed represented 41% of the European total in 2001 and is expected to remain between 40 and 45% until 2020. These shares calculated for the future scenario rely directly on the assumptions concerning the market evolutions. Other results may stem from the bottom-up analysis.

However, the fact that the glass industry, industrial catalysts, and electronics account respectively for 21%, 16% and 14% of European total input for the three PGM in 2004 whereas they represent merely 0.5%, 5% and 10% of the primary input reflects the performance in recycling. The glass production, industrial catalysts and to a lower extent electronics present high rates of secondary production, in contrast to the autocatalyst sector where, from 2004 onwards, secondary input only backs up around 10% of the total input (which corresponds to the rate of secondary production). Figure 7.3 shows the large differences in volume of secondary PGM being at the disposal of the industrial sectors. Overall between 1995 and 2020, primary input accounts for 47 to 55% of the total input. This is consistent with Hagelüken *et al.* (2005, p.10) who estimate that global secondary input is of a similar magnitude that primary input.

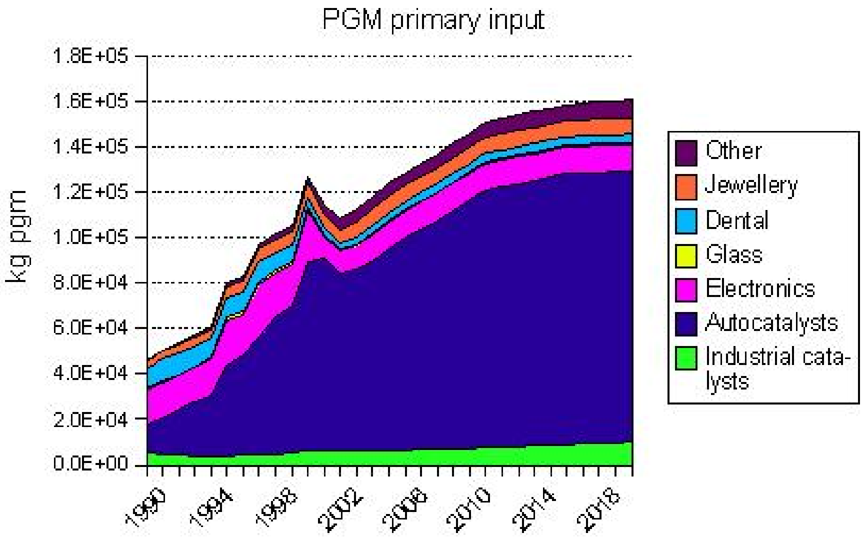



Figure 7.1: PGM primary input per sector in Europe

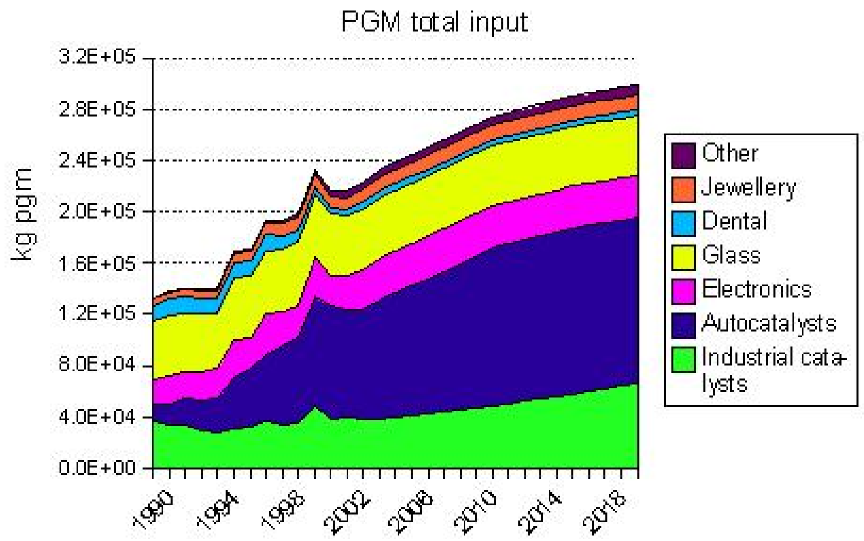



Figure 7.2: PGM total input per sector in Europe

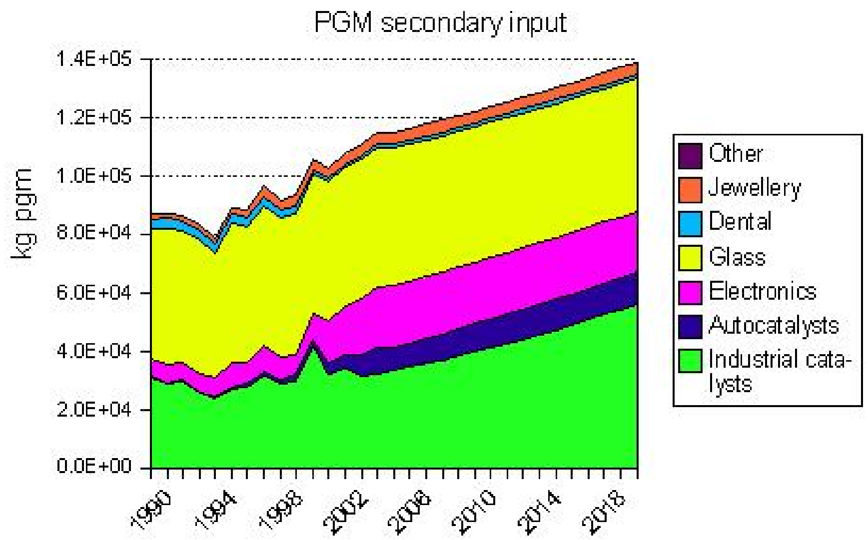



Figure 7.3: PGM secondary input per sector in Europe

### 7.3.2 Platinum

The overall evolution patterns of primary and total inputs of platinum are similar. Both curves present a steep slope at the beginning of the 21$^{st}$ century (see figures 7.4 and 7.5). For instance, primary input was 17% higher in 2000 than the previous year and increased again by 23% in 2001. In absolute terms, primary input went up from 21.1 t in 1990 to 31 t in 1999 and then reached 66.6 t in 2004. Total input increased from 74.9 t in 1990 to 86.8 t in 1999 and reached 127.7 t in 2004.

The strong increase after 2000 is mainly due to the rising platinum inputs to the automobile sector. This period coincides with more stringent norms for emissions from diesel vehicles (Euro II to Euro III standards). As a consequence, the platinum content of diesel autocatalysts (which contain only platinum) more than doubled (see table 8.2). This, coupled with a rapidly increasing demand for diesel vehicles in Europe,[7] explains the steep slopes of the primary and total input curves between 2000 and 2004. After 2004, both inputs increase steadily but at a lower pace, due to the assumptions made regarding the market evolutions of the different sectors (see table 7.4). Primary input is expected to reach 89.4 t in 2020 while total input should amount 151.9 t.

The distribution of inputs varies greatly between the sectors, however. Primary input is heavily dominated by the applications from the automotive industry. The lowest share of autocatalysts in the 1990s still amounts 52% of platinum primary input (in 1999) and the value climbs to 71% in 2004 (it is expected to remain between 71 and 75% until 2020). Other relevant sectors lag far behind the autocatalysts. In 2004, for example, jewellery, 'other' industrial applications (which are often linked to the automotive sector), industrial catalysts and electronics accounted respectively for 9%, 7%, 6% and 4% of the European primary input.

The picture is quite different when considering total input. After a steady increase in the 1990 (19% in 1991), autocatalysts represent 40% of platinum total input in 2004 and their share is not expected to exceed 48% in the coming fifteen years. The other aforementionned sectors (jewellery, 'other' applications, industrial catalysts and electronics) accounted in 2004 for 8%, 4%, 9% and 3% of total input, respectively. The gap is filled in by the glass industry which represents 35% of platinum total input in Europe in 2004 whereas its share in primary input is negligible.

The large share of the glass industry in secondary input (85% in 1990,

[7] The share of diesel vehicles among new registrations in EU15 went up from 29% in 1999 to 37% in 2001 and reached 49% in 2004 (source: Association des Constructeurs Européens d'Automobiles).

73% in 2004 and 63% expected in 2020) also explains the smooth evolution of the curve presented in figure 7.6. Due to a longer lifetime and hampered by a low recycling rate, autocatalysts are expected to account for 10% of secondary input for the first time in 2009.

Table 7.4: Rates of secondary production and market evolutions assumed for platinum in industrial catalysts in Europe

| | **rate of secondary production in %** | **market evolution 2004 − 2020 in % per year** |
|---|---|---|
| **industrial catalysts** | 65 | + 2.5 |
| **autocatalysts** | 10 | (2005-2006) + 5 |
| | | (2007-2011) + 4 |
| | | (2012-2016) + 1 |
| | | (2017-2020) +/- 0 |
| **electronics** | 15 | +/- 0 |
| **glass** | 98 | + 2 |
| **dental** | 27 | +/- 0 |
| **jewellery** | 38 | +/- 0 |
| **other** | 0 | + 2 |

### 7.3.3 Palladium

The evolution of palladium inputs illustrates quite well the market interactions between the different applications. The share of autocatalysts in Pd primary input increased steadily and sharply from 1990 (0.6%) to 2001 (83%). The year 2000 is marked by a maximum in both primary and total input (86.2 t and 130.7 t respectively; see figures 7.7 and 7.8). These unusually high values are not expected to be reached again before long (primary input: 48.2 t and 66.3 t in 2004 and 2020; total input: 97.6 t and 130 t in 2004 and 2018). These peaks stem from the sky rocketting equipment rate of ignition cars with Pd-containing autocatalysts. As a consequence, the price of palladium exploded as well. The other sectors responded strongly to the stimulus in 2001, for instance Pd primary input for electronics fell by 69%, mainly due to a substitution of palladium by base metals in the production of multi-layer ceramic capacitors (Johnson Matthey 2001, p.35). The dental sector also favoured alloys without or with low Pd content. The use of palladium for autocatalysts declined as well, due to substitution with platinum,

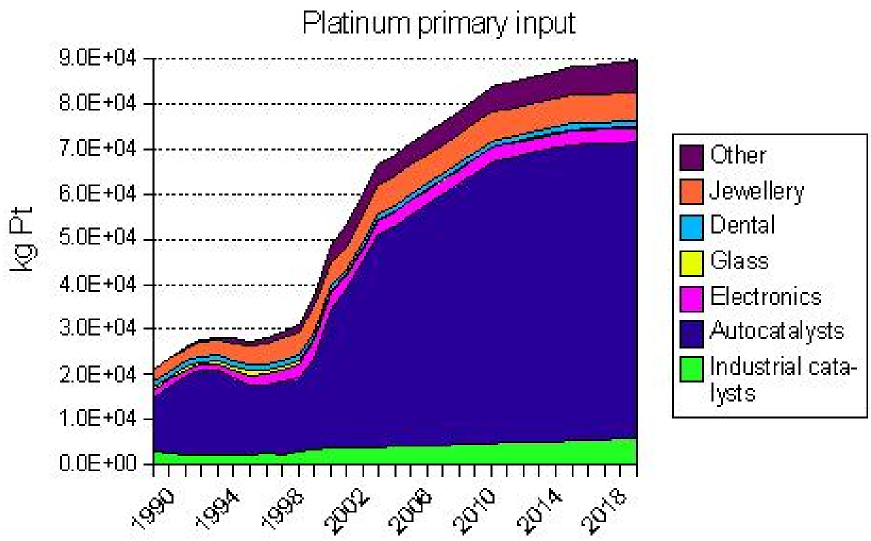



Figure 7.4: Platinum primary input per sector in Europe

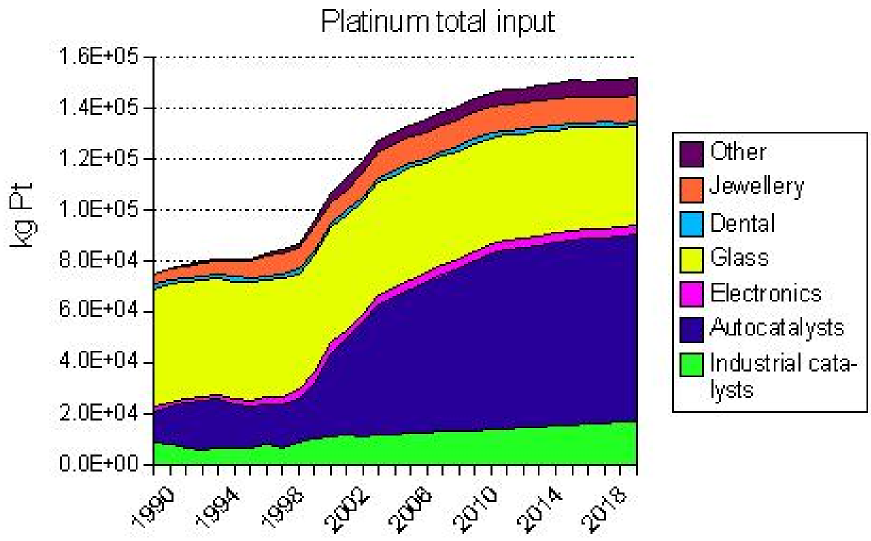



Figure 7.5: Platinum total input per sector in Europe

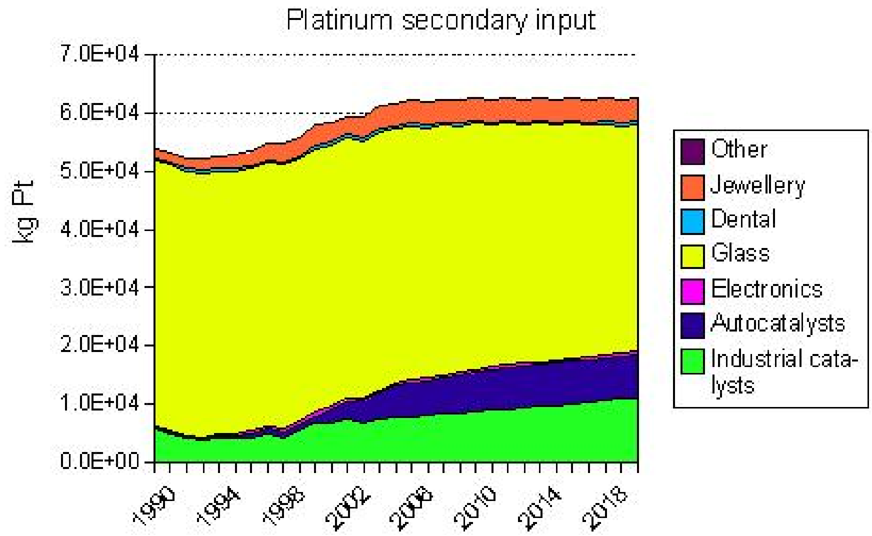



Figure 7.6: Platinum secondary input per sector in Europe

but still remained relatively high.

From the year 2000 onwards, the share of autocatalysts in Pd total input oscillates between 38% and 52%, which makes a large difference with regard to the share in primary input (over 70%). The two other main sectors among the total input are electronics and industrial catalysts, which accounted respectively for 31% and 26% in 2004. The two sectors have indeed high rates of secondary production as shown in table 7.5. The overwhelming importance of these two sectors in secondary input is illustrated in figure 7.9. In the first place, industrial catalysts represented 47% of total recycling in 2004. The recovery from the electronic sector comes second with a 43% share. It is about twice the value obtained at the end of the 1990s. This reflects the choice made in the present study to apply different rates of secondary production before and after 2001 (see table 7.5). In this way, the model is expected to reproduce the combined influences of two factors: decreasing palladium primary input in the electronic sector and increasing electronic waste stream containing palladium (which could be recycled).

### 7.3.4 Rhodium

In this top-down analysis, five application fields have a predominant role in the case of rhodium inputs. Rh primary input is virtually only shaped by the needs for autocatalysts (85% of primary input in 2004; see figure 7.10), whereas total input shows the importance of autocatalysts, glass industry

Table 7.5: Rates of secondary production and market evolutions assumed for palladium in industrial catalysts in Europe

| | rate of secondary production in % | market evolution 2004 – 2020 in % per year |
|---|---|---|
| **industrial catalysts** | 92 | + 3.8 |
| **autocatalysts** | 4 | (2005-2006) + 5 |
| | | (2007-2011) + 4 |
| | | (2012-2016) + 1 |
| | | (2017-2020) +/- 0 |
| **electronics** | (1990-2000) 30 | +/- 0 |
| | (2001-2020) 70 | +/- 0 |
| **dental** | 27 | +/- 0 |
| **jewellery** | 28 | +/- 0 |
| **other** | 0 | + 2 |

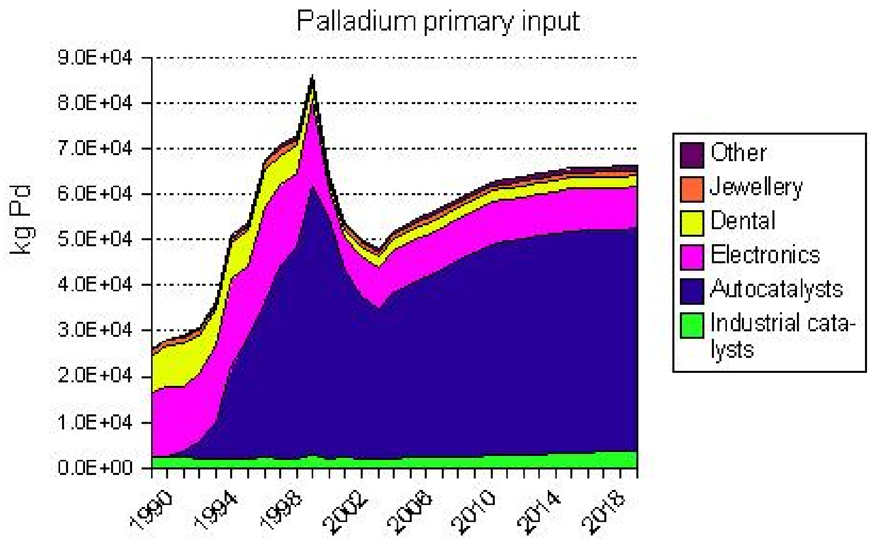



Figure 7.7: Palladium primary input per sector in Europe

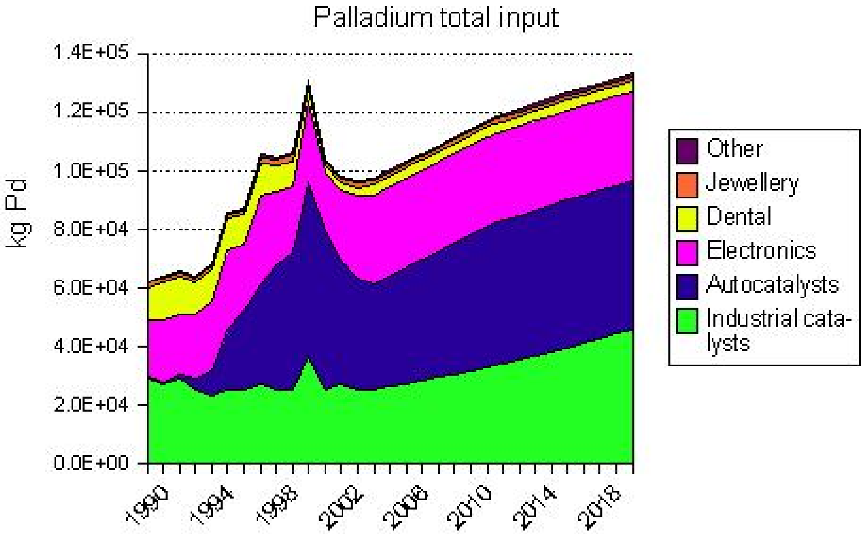



Figure 7.8: Palladium total input per sector in Europe

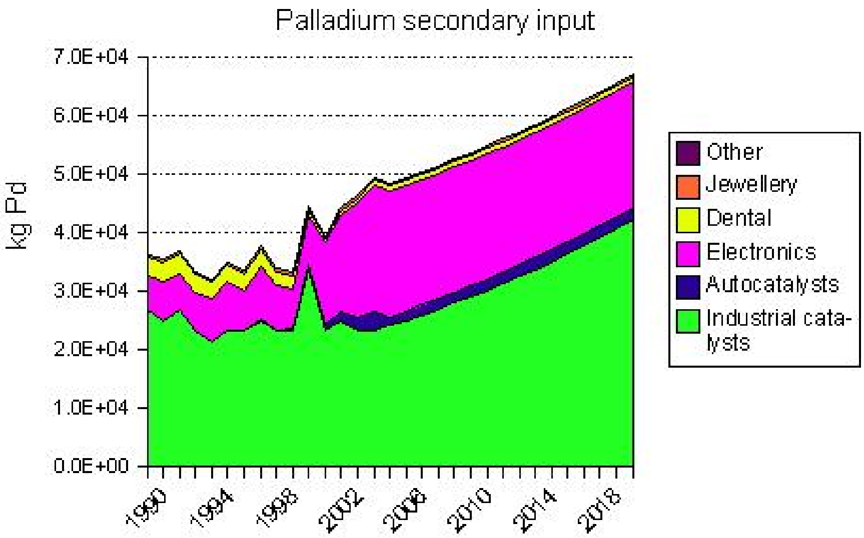



Figure 7.9: Palladium secondary input per sector in Europe

and, to a lesser extent, industrial catalysts. These three sectors represented respectively 48%, 32% and 18% of total input in 2004. Secondary input reflects primarily the activity of the glass industry (54% in 2004). Industrial catalysts and autocatalysts are of lower significance with 29% and 16%, respectively, of the secondary input in 2004.

The share of the automotive sector in the primary input never falls below 80% in the studied time period. Glass production never accounts for less than 31% of the total input and 54% of the secondary input. In the first case (autocatalysts), an indirect recycling path yielding low recycling rates and in the second case (glass industry), a direct recycling path allowing a very high recovery (see table 7.6 for the rates of secondary production), are the main explanations to the relative importance of these two application fields in the different categories of inputs.

The autocatalyst sector under fast development explains, as in the previous section, the primary input peak in 2000 (8.5 t). This value is overtaken in 2006 because of the assumed evolution of the rhodium market. These assumptions, especially for the glass industry, also explain the steady increase of the total and secondary input, respectively from 16.9 t to 26.8 t and from 9 t to 15.2 t between 2004 and 2020.

Table 7.6: Rates of secondary production and market evolutions assumed for rhodium in industrial catalysts in Europe

| | **rate of secondary production in %** | **market evolution 2004 – 2020 in % per year** |
|---|---|---|
| **industrial catalysts** | 86 | + 4.3 |
| **autocatalysts** | 15 | (2005-2006) + 5 |
| | | (2007-2011) + 4 |
| | | (2012-2016) + 1 |
| | | (2017-2020) +/- 0 |
| **glass** | 98 | + 2 |
| **electronics** | 26 | +/- 0 |
| **other** | 0 | 2 |

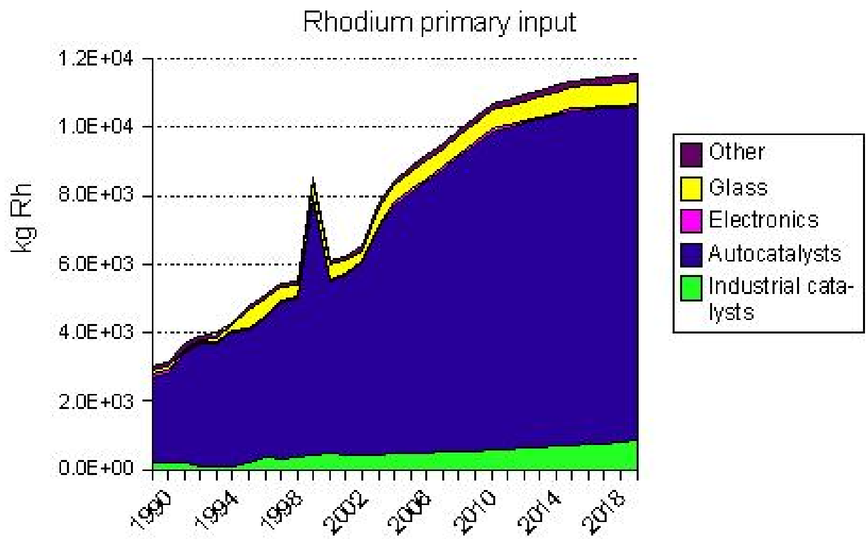



Figure 7.10: Rhodium primary input per sector in Europe

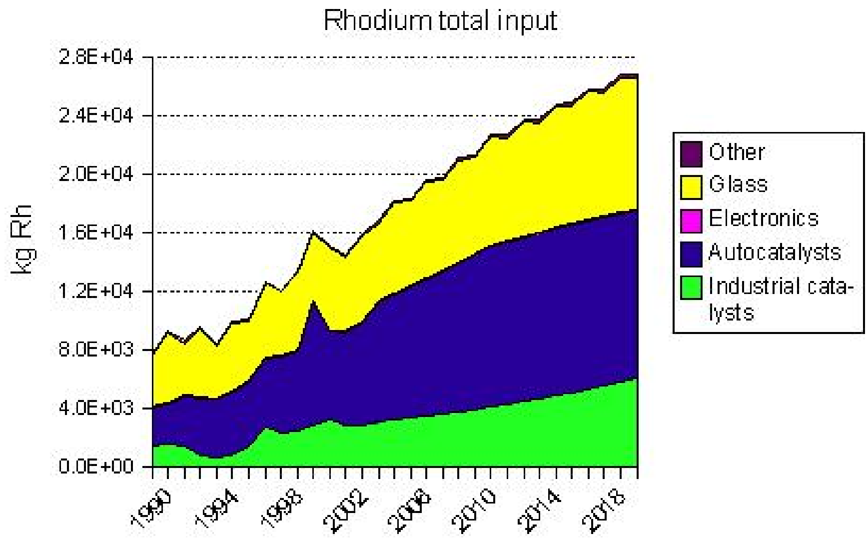



Figure 7.11: Rhodium total input per sector in Europe

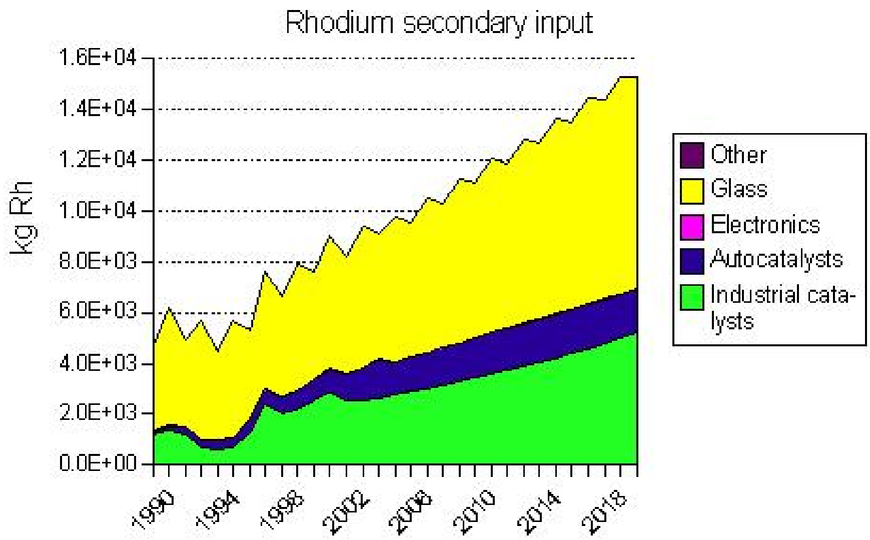



Figure 7.12: Rhodium secondary input per sector in Europe

# Chapter 8

# Bottom-Up Material Flow Analysis

## 8.1 Autocatalysts

The use of PGM in autocatalysts in the European Union is modelled with the help of the simulation of a dynamic system representing the European fleet of passenger cars. The evolution of the car fleet is coupled with the EU-regulations concerning the exhaust gas emissions.

A first detailed model has been built and tested for Germany. The methodology and the results, compared with empirical data from the literature, are presented in Appendix B. The same framework was used to develop the model at the European level. However, due to missing data and to save some time, the model for the entire EU is somewhat less detailed than the one for Germany.

### 8.1.1 Methodology

#### Fleet of Passenger Cars and Autocatalysts

The evolution of the passenger car fleet is modelled between 1990 and 2020 for the EU15 and between 1995 and 2020 for the ten new EU members (EU10). The two sets of modelling results are then combined to obtain the overall picture. The resolution of the dynamic system is programmed with a numerical calculation software called Scilab.[1]

The fleet is divided between petrol and diesel cars whose evolutions are modelled separetely and whose sum gives the aggregate picture. No comprehensive data set could be found about the structure of the EU car fleet

[1]Scilab is a Free Scientific Software Package available from www.scilab.org

with respect to the cylinder capacity. Therefore, it is assumed that all petrol cars range between 1.4 and 2 L of cylinder capacity, while the diesel vehicles are assumed to have a cylinder capacity lower or equal to 2 L.[2] The values for cylinder capacity fit with the average numbers given by the European Automobile Manufacturers Association (ACEA 2005) for new car registrations which range between 1.6 and 1.75 L for the past ten years. Separated between petrol and diesel cars, the fleet in a given year is in turn divided into 25 age categories: from 0-1 year old cars to 24-25 year old cars.

The model implemented is of the 'survival type' which means that the car fleet in a given year is calculated as the sum of the new registrations and the cars registered in the previous years still in use. The latter figure is obtained as the number of cars which 'survived' from the previous year. The model is therefore iterative from one year to the next. The 'survival rates' differ according to the age and the motor type. On the other hand, they are taken as constant with time.

The survival rates for EU15 were derived from data used by Bourdeau (1998, p.220) for the modelling of the French car fleet between 1970 and 2020. These rates were adapted for the ten new members with a three year time lag: e.g. the survival rates applying to new cars in EU15 apply to three year old cars in the Central European EU members. The average age of the vehicle fleet was indeed 11.5 years at the end of the 1990s in the "Accession Countries", compared to 7.3 years in the EU15 (EEA 2002a, p.2). The difference is likely to be slightly lower between the ten new members and the EU15 because non-EU25 members such as Bulgaria are included in the "Accession Countries" (the average age of the Bulgarian car fleet is more than 15 years according to EEA (2002a, p.2), another source (Janischewski *et al.* 2003, p.51) even states more than 20 years).

Data concerning new registrations up to the year 2004 were taken from ACEA (2005) for EU15 and from Eurostat (accessed Dec. 4, 2005) for the new members. For the forecast scenario it is assumed that the curves remain at a constant value after 2010 for the old member states and after 2015 for the new ones. Hagelüken *et al.* (2005) assume a constant number of new registrations from 2008 in Germany.

In both parts of the EU, between 2004 and the first year of stagnation, the curves for new registrations are assumed to evolve in a linear way. The final values have been calibrated so that the resulting car fleet fits with an existing model called TREMOVE. TREMOVE is a policy assessment model to study the effects of different transport and environment policies on the emissions

[2]By comparison with the model for Germany, it means that only two technological categories are considered: 'petrol inf' and 'diesel sup' (see Appendix B).

of the transport sector. The final version of TREMOVE has been delivered in February 2005 to the DG Environment of the European Commission. The forecast of the stock (fleet) of passenger cars applied in the base case of this model uses data from the SCENES model (DG TREN SCENES project) (De Ceuster *et al.* 2005, p.58). After adjustments, the relative error between the car fleet of EU25 in 2020 as issued by the model of the present study and the stock of passenger cars as used in SCENES for the TREMOVE model is lower than 1%. The relative errors for EU15 or the new EU members are both below 5% in absolute values.

In addition to new cars a number of second-hand cars is imported from western Europe to the new EU members from Central Europe. The number of cars involved is estimated on the basis of German data which is by far the biggest exporter of second-hand cars to those countries (Janischewski *et al.* 2003).

Very little data is available concerning the age and technological structures of the exports of second-hand vehicles by EU15 countries to the east. This growing market can hardly be qualified as transparent. However, based on figures from Janischewski *et al.* (2003), it is assumed that diesel cars account for a constant share of 25%. The probability density function of the age structure for these second-hand vehicles is modelled by a normal distribution, its parameters mean and standard deviation be taken equal to 8 (years old) and 2 (years). It seems that most of the new members have adopted legislations to prevent the import of cars older than a given age, e.g. 3 years in Poland (Janischewski *et al.* 2003, p.42). But, the author's personal experience tells that those regulations are yet to be implemented into practice.

Starting from a given initial state, the programme calculates the successive stock and flows of vehicles and PGM until 2020. The set of initial conditions was obtained from different sources. The age structure of the car fleet is derived from Austrian data for EU15 (Gabriel *et al.* 2000, p.37) and from Polish data for EU10 (Janischewski *et al.* 2003, p.51). The initial distribution between petrol and diesel cars is calculated from Eurostat data. By applying the survival rates to the car fleet, the model calculates each year the number of de-registrations.

The fleet of cars equipped with an autocatalyst is divided in four 'environmental categories' corresponding to the legal requirements for emissions from passenger cars (Table 8.1). These regulations are set by directives from the EU Commission. Some countries may have introduced earlier standards (e.g. G-Kat in Germany) but there was at the time no obligation made to the EU members and no harmonization either. Due to a lack of data regarding the PGM content of these early autocatalysts as well as concerning the equipment rate of the newly registered cars, it is assumed that autocatalysts have been introduced in Europe in 1992 with the Euro I standard. In reality, about 7% of the car fleet of EU15 were already equipped with autocatalysts in 1990 (EEA 2002b, p.48). However, this error made on the PGM stock at the beginning of the 1990s should be barely noticeable fifteen years later (i.e. at the present time) when most of the cars involved have been already de-registered.

The legal dispositions apply to EU15 as well as to the new member states. However, a delay of six years was introduced in the model between old and new members. It is extremely difficult to find data concerning the state of compliance of the new EU members to the EU directives regarding catalytic converters. The European Environment Agency, however, indicates a six year backlog in this respect for the year 1996 (EEA 2002b, p.48).

It should be noted that this distinction applies only to new cars; second-hand cars exported from the EU15 to Central Europe comply with the western EU-norms at the time of their first registration. The evolution of each category is modelled following the same principle as above but from the first year of application of each regulation and with initial conditions equal to zero. This reflects the following two assumptions:

- Prior to its first year of application, no car complies with the regulation.
- A given regulation stops to be applied to new cars when a new one comes into force.

Table 8.1: The four environmental categories used in the model

| | no regulation | Euro I | Euro II | Euro III | Euro IV |
|---|---|---|---|---|---|
| EU 15 | before 1991 | 1992-1995 | 1996-1999 | 2000-2004 | 2005-2020 |
| EU10 | before 1997 | 1998-2001 | 2002-2005 | 2006-2010 | 2011-2020 |

**PGM Flows**

In order to model the PGM total input for new vehicles as well as the potential PGM secondary input from de-registered cars it is assumed, after Hagelüken *et al.* (2005, p.71), that there is a correlation between the motor type (petrol, diesel), the cylinder capacity, the environmental category (Table 8.1) and the PGM content of the vehicle.

Hagelüken *et al.* (2005) conducted a detailed study in Germany to quantify this correlation. In his calculations the share of the different car brands (and thus different 'corporate' PGM contents in autocatalysts) was considered for each technological category of the new registrations in Germany. The aggregate results are presented in appendix B in table B.3. They are extensively used in the model built for Germany. It is assumed that these data can be applied at the European level. However, due to the simplifications made concerning the different types of cars, only part of these results is effectively used (Table 8.2). The given values are said to correspond to vehicles at the end of the use phase but it is assumed in the present work that the PGM losses during this phase are negligible and table 8.2 is used to calculate the PGM input for new registrations as well as the PGM potential recycling from de-registrations.

Hagelüken *et al.* (2005, p.80) write that for the modern and well maintained autocatalysts in western Europe losses during the use phase are significantly lower than 5% of the PGM content. However, (Hochfeld 1997, p.117) and De Man (2005, p.49) cite a much higher figure (25%) but it is precised then that the major causes for high losses are poor maintenance and accidental damages to the autocatalysts. This issue is currently raising concern for economic and health reasons. On the one hand, PGM accumulation along some busy roads approaches concentrations that would be economically viable to recover (De Man 2005, p.50). On the other hand, very little is known about the toxicity and bioavailability of PGM.

The secondary PGM input is estimated as 30% of the potential recycling. This rather low value is taken from Hagelüken *et al.* (2005, p.87) who conducted a field study of the recycling chain for autocatalysts in Germany. The 70% losses are for a major part (almost 60% of all losses) due to 'unknown' reasons. These mysterious reasons can probably be explained to a large extent by exports of second-hand cars to countries of Central and Eastern Europe or Africa. The same rate was assumed for the new member states for which no quantitative data concerning the recycling of end-of-life vehicles could be found. However, the EU states from Central and Eastern Europe have various facilities, often in the form of small workshops, where de-registered cars can be dismantled, including the autocatalysts which are then exported to Germany (Janischewski *et al.* 2003, p.51). The possibility of exporting de-registered vehicles further east also remains. For instance, Bulgaria (not yet a EU member) has a flourishing import business of cars which would have been scrapped in any other country of western or Central Europe. The average age of the Bulgarian car fleet is consequently more than 20 years old (Janischewski *et al.* 2003, p.42).

Table 8.2: PGM content of ELV in EU25 wrt the environmental norms and motor types, after Hagelüken (2005, p.72)

| **PGM content** | **Petrol cars** | | | | | **Diesel cars** | |
|---|---|---|---|---|---|---|---|
| | **cylinder capacity** | **g/vehicle** | | | | **cylinder capacity** | **g/vehicle** |
| | | **Pt** | **Pd** | **Rh** | **sum** | | **Pt** |
| Euro I | 1.4 - 2 L | **1.71** | **0.00** | **0.33** | **2.04** | < 2 L | |
| Euro II | 1.4 - 2 L | **0.38** | **2.00** | **0.29** | **2.66** | < 2 L | **1.43** |
| Euro III | 1.4 - 2 L | **0.48** | **2.76** | **0.29** | **3.52** | < 2 L | **4.09** |
| Euro IV | 1.4 - 2 L | **0.67** | **2.85** | **0.48** | **3.99** | < 2 L | **4.75** |

### 8.1.2 Results

#### Fleet of Passenger Cars and Autocatalysts

Starting from the registrations shown in figure 8.1 and an assumed initial state, as described in the previous section, the model calculates the evolution of the car fleet in the EU15 and in the new member states. The aggregate picture for the EU25 is consequently the sum of the two sets of curves.

New registrations in the EU15 increased from 13 million vehicles in 1990 (14% of which were diesel cars) to 14 million in 2004 (49% diesel) and are assumed to reach 18 million in 2020 (forecast: 60% of diesel vehicles). In the EU10, new registrations decreased from 1.2 million passenger cars in 1995 (6% diesel) to 0.9 million in 2004 (14.6% diesel) and are assumed to amount to 2.8 million vehicles in 2020 (25% diesel). At the EU25 level, the share of diesel cars among new registrations went up from 21% in 1995 to 47% in 2004 and is assumed to attain 55.3% in 2020.

Figure 8.2 represents the evolution of the two fleets of passenger cars, while the shares of vehicles equipped with an autocatalyst are presented in figure 8.3. The number of de-registered cars, some of which fitted with autocatalysts that can be used for recycling, is calculated by the model and shown in figure 8.4.

According to the modelling results, the car fleet in EU15 expands from 143 million units in 1990 (17% diesel) to 156 million in 2004 (32.6% diesel) and could reach 212 million in 2020 (58% diesel). The fleet of EU10 is smaller by about an order of magnitude: from 16.6 million vehicles in 1995 (10% diesel), the model proposes that it slightly increases to 17.3 million in 2004 (12.8% diesel), and finally attains 36 million units in 2020 (22.6% diesel).

The car fleet in EU10 slightly increases between 1995 and 2004, even though the difference between new registrations and de-registrations is negative, due to the import of second-hand vehicles. According to the modelling results, the share of diesel passenger cars in the fleet of EU25 increases from 18.5% in 1995 to 30.6% in 2004 and finally reaches 53% in 2020.

For de-registrations the model features an increase from 12.2 million in 1990 to 12.6 million in 2004 and 15.7 million in 2020 for the EU15. In 2004, 64% of the de-registered cars are fitted with an autocatalyst, among which, 16% are diesel cars. In 2020 virtually all the de-registered vehicles are equipped with a catalytic converter (48% of them are diesel catalysts). De-registrations in EU10 decrease from 1.7 million in 1995 to 1.3 million in 2004 and finally increase again up to about 2 million in 2020. End-of-life autocatalysts represent 15% of the de-registrations in 2004 and 93% in 2020. Diesel autocatalysts represent 24% of the EOL catalytic converters in 2004 and 45% in 2020. The large share in 2004 is probably due to the fact that, at this time in the EU10, a large part of the de-registrated cars equipped with autocatalysts are second-hand cars formerly imported from the EU15. It was indeed assumed in the model that diesel cars constitute a higher share (25%, constant) of the imported second-hand vehicles than among the new registrations (from 6% to 15% between 1995 and 2004).

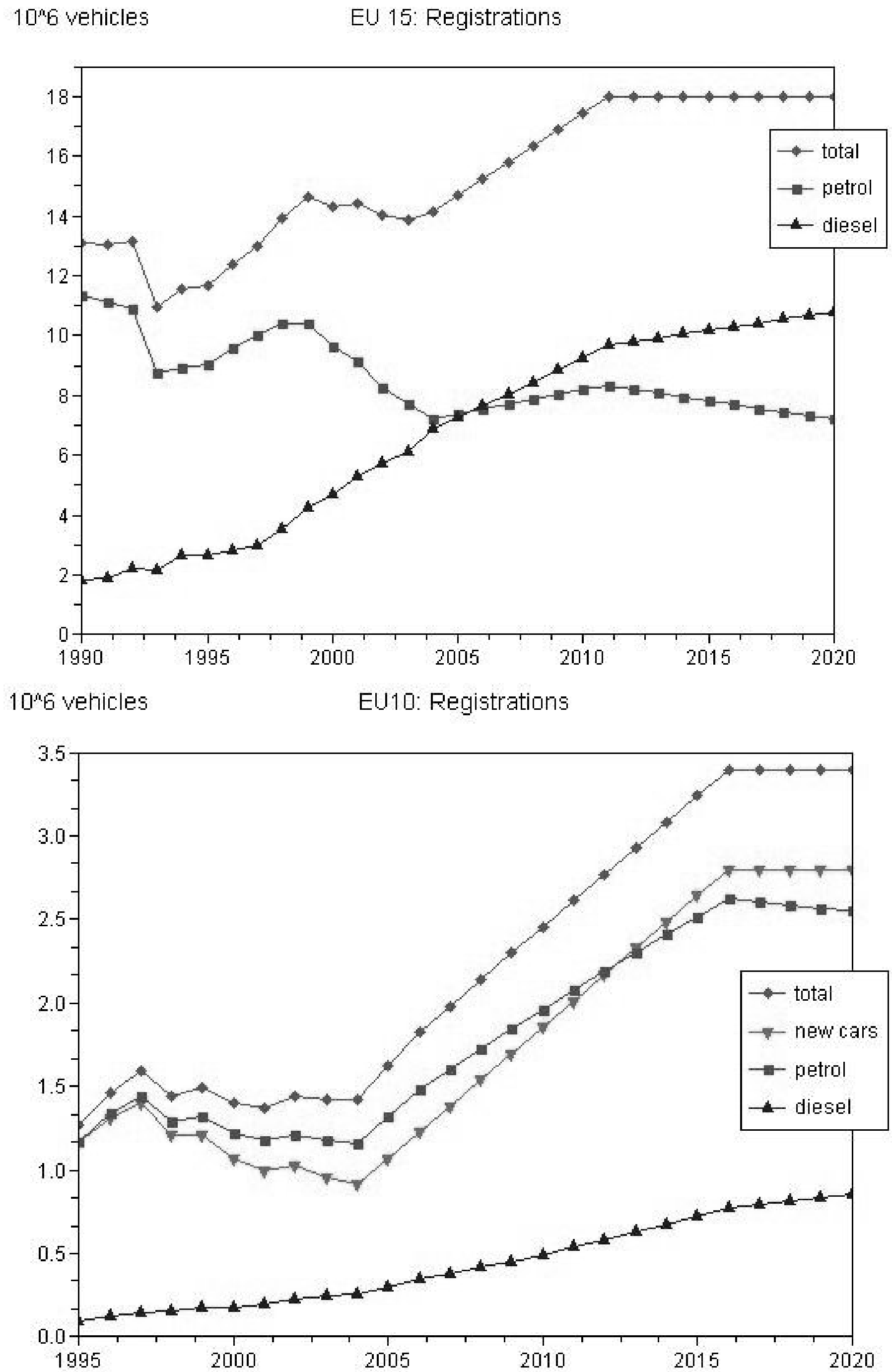



Figure 8.1: Registrations of passenger cars in Europe, existing data and forecast. *Up:* EU15. *Down:* EU10.

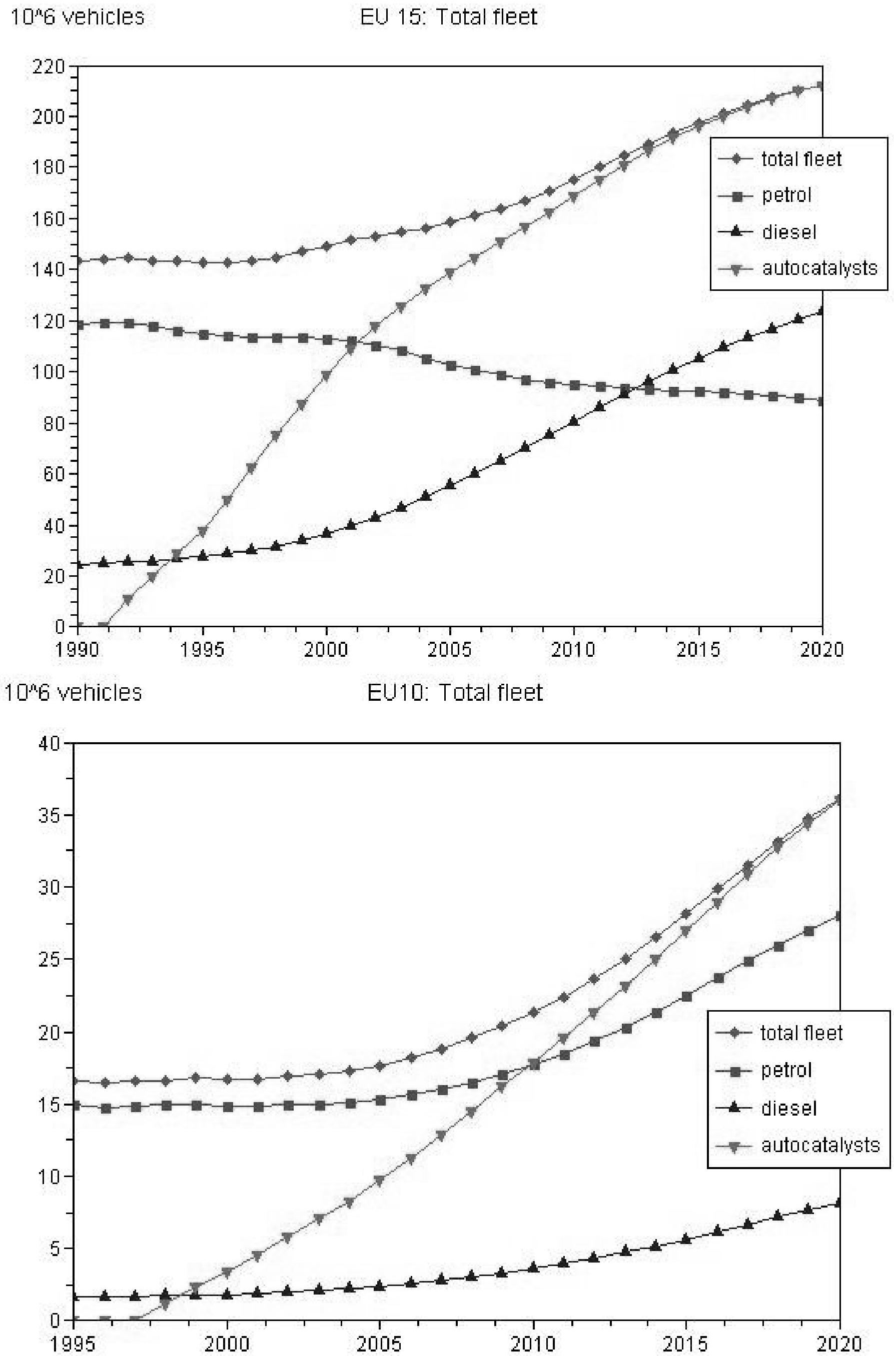



Figure 8.2: European fleet of passenger cars. *Up:* EU15. *Down:* EU10.

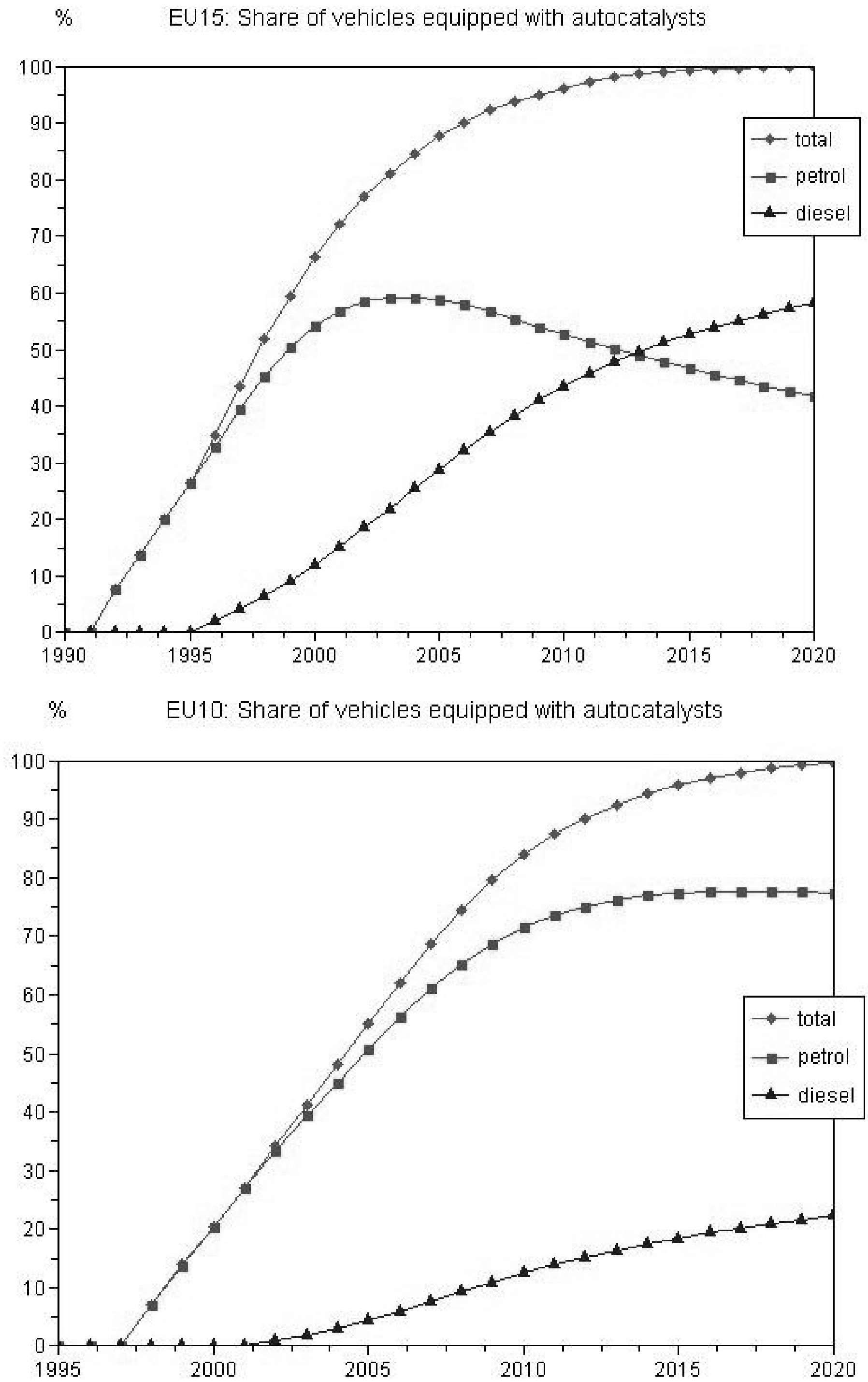



Figure 8.3: Share of cars equipped with an autocatalyst in Europe. *Up:* EU15. *Down:* EU10.

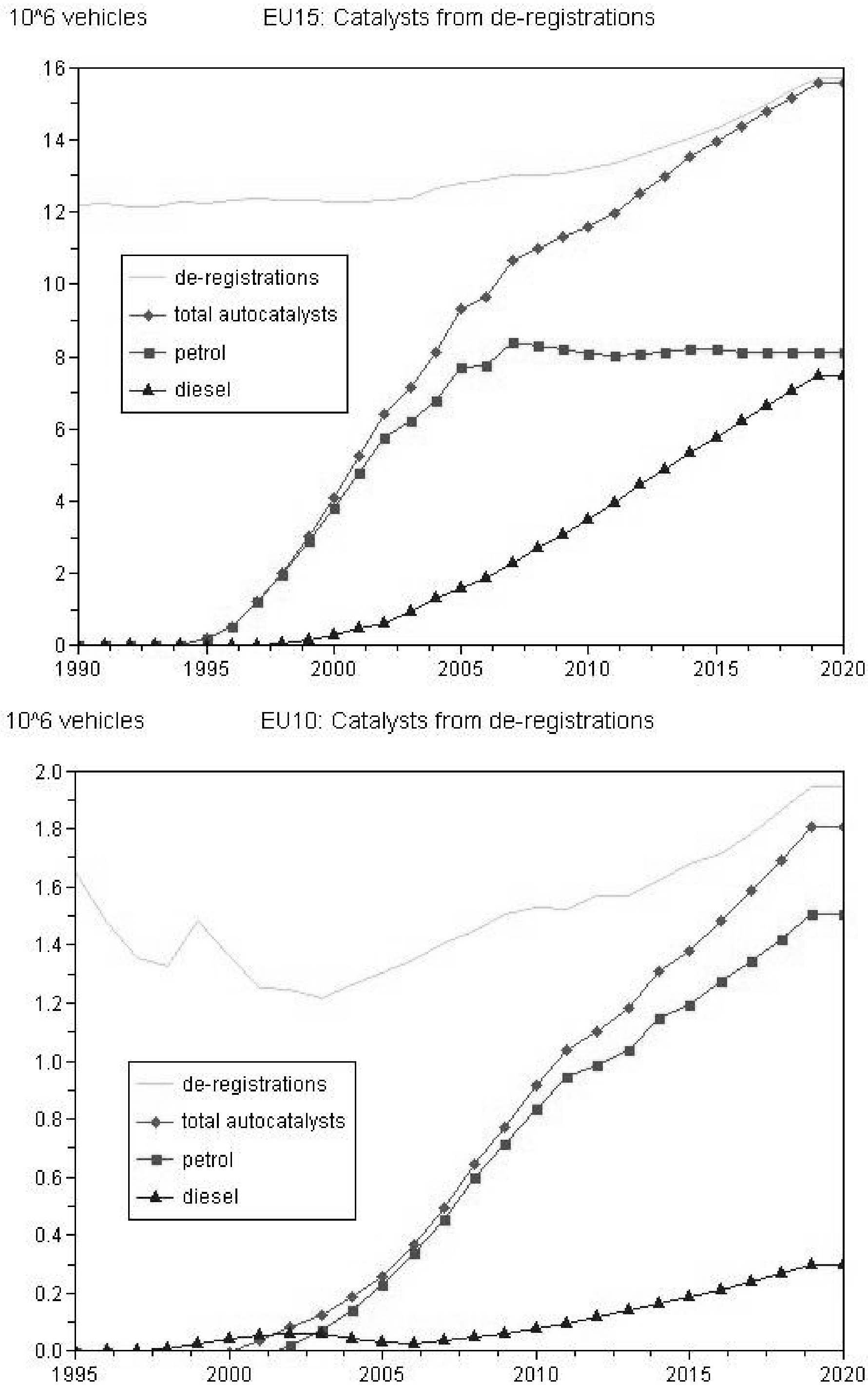



Figure 8.4: De-registrations and amount of autocatalysts available from de-registered cars in Europe. *Up:* EU15. *Down:* EU10.

### PGM Flows Related to New Registrations and End-of-Life Vehicles

De-registered cars equipped with an autocatalyst can potentially constitute a source of secondary PGM. This potential is shown in figure 8.5 and it steadily increases from 0.5 t in 1995 to 24.8 t in 2005 and 72.6 t in 2020. At the same time, new registrations of vehicles imply a higher demand for primary and secondary PGM by the automobile industry. The sum, i.e. the total input, is presented in figure 8.6. When comparing these figures with the results from the model for Germany (see figure B.8), it emerges that Germany accounts for about one fourth of the PGM total input. This is consistent with the other results which show that Germany hosts slightly less than one fourth of the European car fleet.

The increasing stock of PGM in the European vehicles in use is presented in figure 8.7. It expands from 76.9 t in 1995 to 471.8 t in 2005 and reaches 1074.5 t in 2020. The share of PGM primary input used for the manufacture of the autocatalysts in European cars is shown in figure 8.8. Primary input of PGM rises from 18.3 t in 1995 to 59.4 t in 2005 and 70.1 t in 2020. In the same period, the amount of PGM secondary input goes up from 0.14 t in 1995 to 7.5 t in 2005 and 21.8 t in 2020.

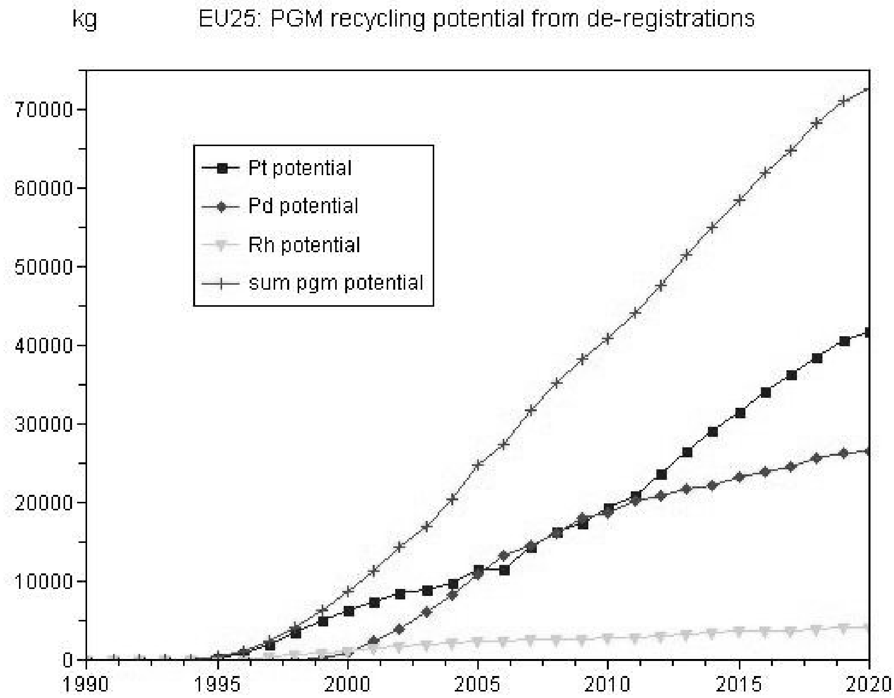



Figure 8.5: Theoretical amount of PGM available from de-registered cars in EU25 (in the model, 25 members from 1995)

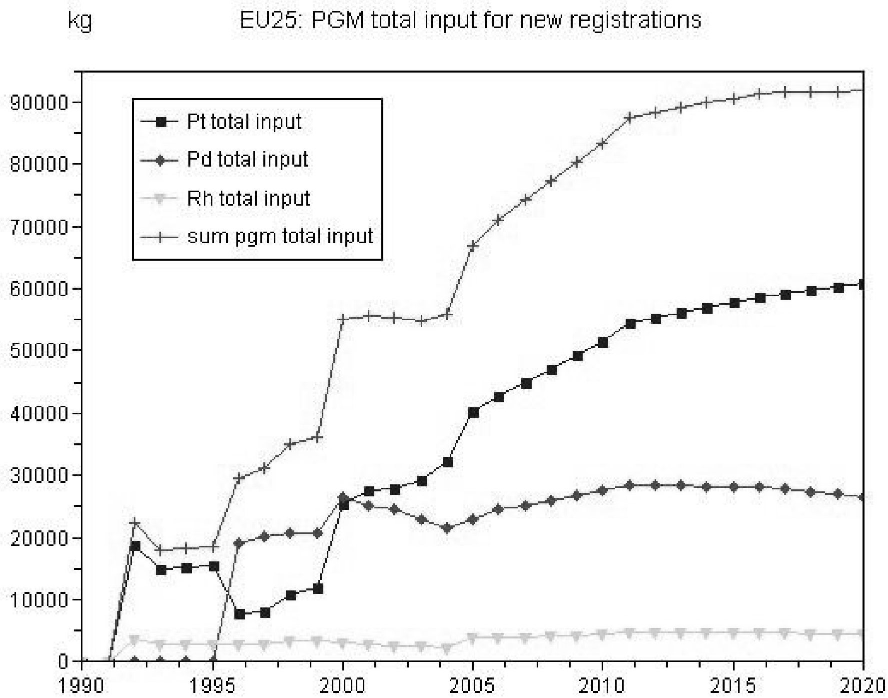



Figure 8.6: PGM total input for new registrations of passenger cars in EU25 (in the model, 25 members from 1995)

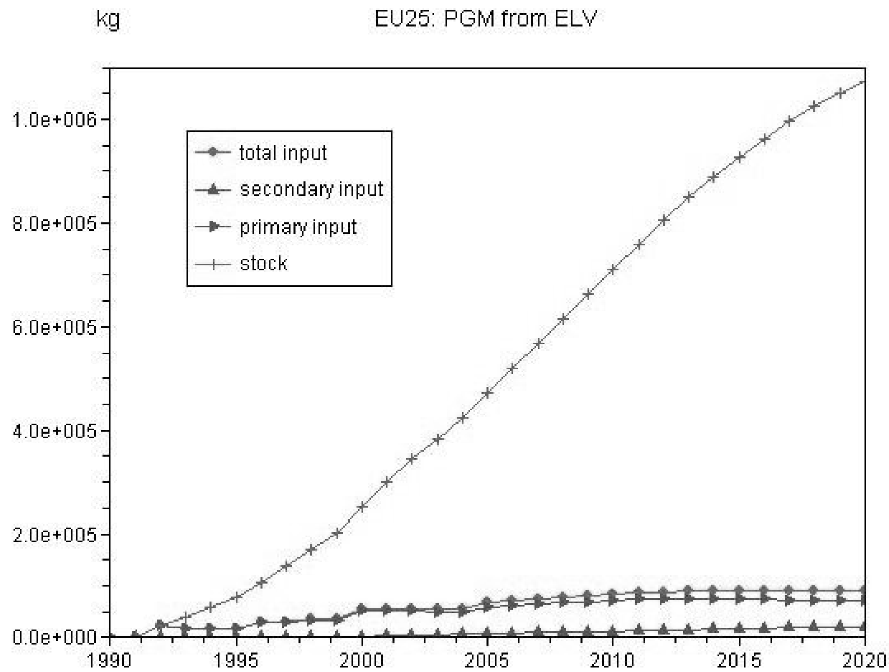



Figure 8.7: Stock of PGM for the passenger car fleet in EU25 (without exchanged autocatalysts; in the model, 25 members from 1995)

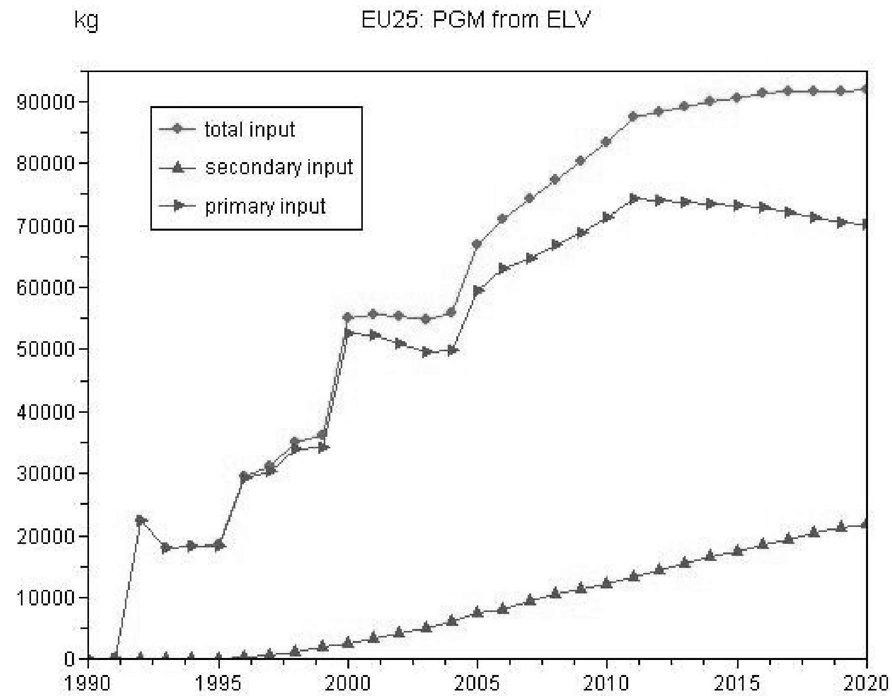



Figure 8.8: Comparison of PGM total and secondary input in EU25 (without exchanged autocatalysts, with constant recycling rate; in the model, 25 members from 1995)

## 8.2 Fuel Cells

### 8.2.1 Methodology

#### Fleet of Fuel Cell Vehicles

Two scenarios for the introduction of fuel cell vehicles (FCV) in Europe are considered. They are referred to as HR and LR scenarios, which stand for high and low registrations scenarios, respectively. The yearly numbers of new registrations are higher and increase faster in the former scenario than in the latter. Mass production of fuel cell vehicles starts in 2013 in HR scenario and in 2016 in LR scenario. Data were provided by the Fraunhofer Institute for Systems and Innovation Research and correspond to those used in the European *HyWays 'Hydrogen Roadmap'* project.

In accordance with HyWays, an average lifetime of twelve years is considered for the fuel cell vehicles. Therefore, twelve years after being registered, FCV are de-registered and can endure dismantling and recycling processes. It is assumed that 75% of the total PGM contained in the de-registered vehicles is recovered and reused for the production of new vehicles. Such a recycling rate is much higher than the 30% used in the autocatalyst model (see section 8.1). Two reasons may back this choice. First, it is likely that the collecting-recycling chain for end-of-life vehicles will be more efficient in the future than it is today. Second, it is assumed that the FCV will be fuelled exclusively with pure hydrogen, which requires an infrastructure for hydrogen supply in the EU, at the time when mass production starts. It was underlined in section 8.1 that the prime reason for the low recycling rate of end-of-life autocatalysts is the exportation of vehicles towards (poorer) countries which do not have implemented recycling schemes. In the case of FCV tanking pure hydrogen, such exportation effects would virtually not exist assuming that no hydrogen infrastructure is put into place outside the EU and OECD countries before 2030.

In both scenarios, the average power of the fuel cell stack is assumed to increase from 75 $kW_{el}$ to 100 $kW_{el}$. With a motor conversion efficiency of 80% (Weiß 2004, p.81), 75 $kW_{el}$ from the stack corresponds to 60 kW available from the electric engine. As a comparison, the average power of newly registered cars in EU15 increased from 63 kW in 1994 to 80 kW in 2004. To have an effective power of 80 kW at the engine, a fuel cell stack of 100 $kW_{el}$ is needed with a consequent higher platinum content than for a 75 $kW_{el}$ stack (at a given platinum content per unit of power).[3]

[3] In order to propose policy oriented results and discussion, two other scenarios have been modelled: the fuel cell stack power either remains constant at 75 $kW_{el}$ or decreases

### PGM Flows Related to Fuel Cell Vehicles

In the present study, the fuel cells considered are of the PEM type (Proton Exchange Membrane) and tank pure hydrogen. It means that options with on-board reforming of another fuel are not considered and that platinum is the only PGM used (Weiß 2004, p.79).

The amount of platinum contained in a fuel cell stack depends on its total power, its power density and its platinum loading. The last two parameters are given per unit of surface, in kW/m$^2$ and g/m$^2$, respectively. These two parameters cannot be taken as constant with time. Technological improvements thus ought to be accounted for in the model. Therefore, the total platinum content of a fuel cell stack, at a given time (i.e. for a given FCV power and technology level), is obtained using the following formula:

$$\text{FCV Pt content [g]} \quad = \quad \frac{\text{FC power [kW]}}{\text{Power density [kW/m}^2\text{]}} * \text{Pt loading [g/m}^2\text{]} \tag{8.1}$$

The technology evolution for the PEM fuel cells installed in passenger cars is modelled using learning curves. This tool was primarily developed to represent the relation between cumulative production of a given product and the reduction of the marginal production costs. In this respect, the general equation is as follows:

$$Y_i = Y_0 * (X_i)^{-r} \tag{8.2}$$

$X_i$ represents the cumulative number of products at i$^{\text{th}}$ production, $Y_i$ stands for the cost of a product at i$^{\text{th}}$ production. $Y_0$ can be interpretated as the cost of the first unit produced. The last parameter $r$ is used to build the so called progress ratio (PR), defined as follows:

$$\text{PR} = 2^{-r} \tag{8.3}$$

$$r = -\frac{ln\text{PR}}{ln2} \tag{8.4}$$

The expression $1 - 2^{-r}$ represents the rate of cost reduction for each doubling of production. In the present study, the same concepts as presented

from 75 kW$_{el}$ to 50 kW$_{el}$ (the results are shown and commented in chapter 10 of the present study).

above are used to model the increasing power density and the decreasing platinum loading of fuel cells. The equations are as follows:

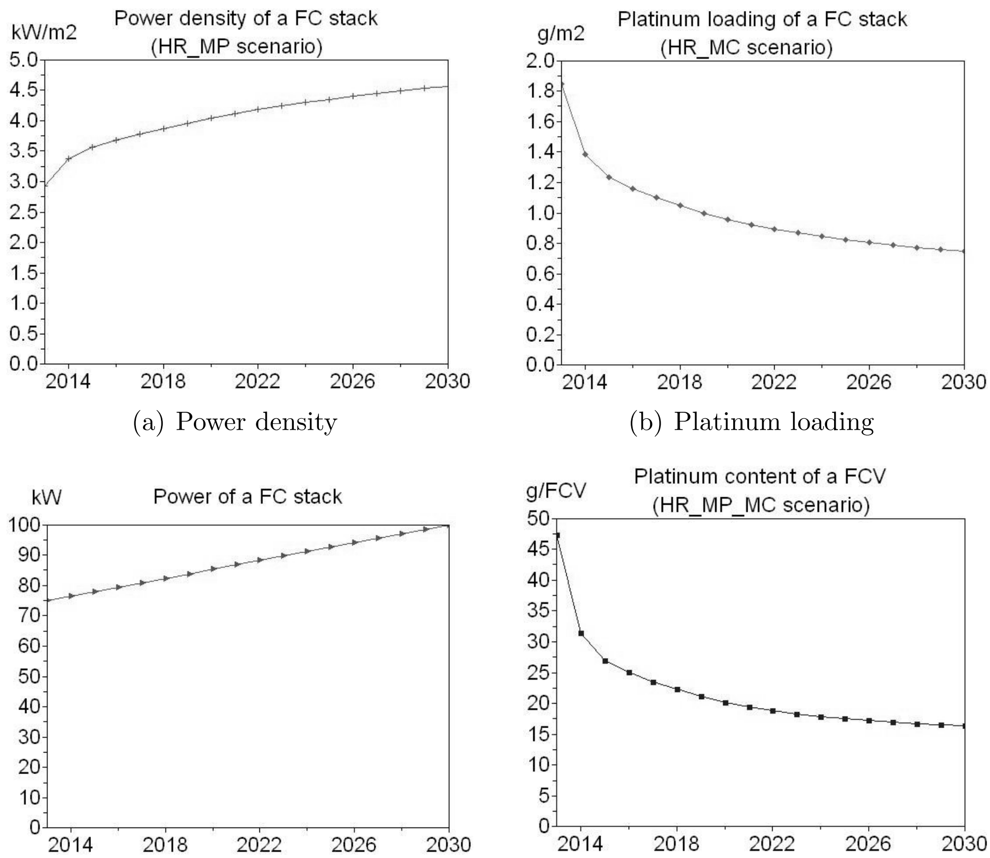
$$(\text{power density})_i^{-1} = (\text{power density})_0^{-1} * (X_i)^{-r} \quad (8.5)$$
$$(\text{platinum content})_i = (\text{platinum content})_0 * (X_i)^{-r} \quad (8.6)$$

Tshuchiya and Kobayashi (2002) propose three progress ratios for the power density and another three for the platinum content. They also provide estimates for the power density (2 kW/m$^2$) and the platinum loading (4 g/m$^2$) for Japan in 2000, i.e. at a time when the cumulative production amounted fourty units. These data were fed into the model, resulting in three scenarios for the evolution of power density (rapid increase, medium increase and slow increase of the power density, referred to as HP, MP and LP scenarios, respectively) and three scenarios for the improvements of platinum content (rapid decrease, medium decrease and slow decrease of the platinum content, referred to as HC, MC and LC scenarios, respectively).

Figure 8.9 illustrates the modelling of the platinum content of a FCV with learning curves. This example uses the following combination of scenarios (the values for progress ratios are taken from Tshuchiya and Kobayashi (2002)):

- high registration scenario (HR);
- medium power density (MP; PR = 96%);
- medium platinum loading (MC; PR = 82%).

The combination of the scenarios regarding the evolution of mass production presented in the previous section and the scenarios concerning technological improvements gives a total of eighteen scenarios. An overview of the range of values obtained for the platinum content of fuel cell vehicles, with a power increase from 75 kW$_{el}$ to 100 kW$_{el}$ over the simulation period (2013-2030 for HR scenario and 2016-2030 for LR scenario), is shown in table 8.3. As a comparison, Weiß (2004, p.80) assumed for her study a platinum content of 29 g for a vehicle powered by a fuel cell stack of 75 kW$_{el}$.




(a) Power density

(b) Platinum loading

(c) FC power

(d) Result: FCV Pt content

Figure 8.9: The three steps to model the platinum content of a FCV: learning curve for FC power density, learning curve for FC platinum loading and evolution of total power.

Table 8.3: Platinum content of a fuel cell vehicle according to 18 different scenarios (in grammes per vehicle)

| scenarios g Pt / FCV | **HP** PR = 94.5% | **MP** PR = 96% | **LP** PR = 97.5% |
|---|---|---|---|
| **HC** PR = 89% | 30 – 6.1<br>31.7 – 8.1 | 34.8 – 8.4<br>36.6 – 10.9 | 40 – 11.4<br>41.9 – 14.4 |
| **MC** PR = 92% | 40.9 – 11.9<br>42.7 – 15 | 47.4 – 16.4<br>49.3 – 20.2 | 54.5 – 22.2<br>56.4 – 26.7 |
| **LC** PR = 96% | 60.5 – 27.9<br>62.5 – 32.9 | 70.2 – 38.4<br>72 – 44.1 | 80.7 – 52.2<br>82.4 – 58.3 |

Upper numbers for **HR** scenario 2013 – 2030
Lower numbers for **LR** scenario 2016 – 2030

### 8.2.2 Results

#### Fleet of Fuel Cell Vehicles

The two scenarios of the HyWays project for the penetration of fuel cell vehicles on the European market are illustrated in figure 8.10. Given the twelve year life time of fuel cell vehicles and the new registrations from the two scenarios, the evolution of the fleet of hydrogen cars is represented in figure 8.11.

Mass production starts in 2013 with 25 000 vehicles for the HR scenario and in 2016 with 20 000 units for the LR scenario. In the first case, the fleet represents 44 200 000 vehicles in 2030 and the cumulative production reaches 47 050 000 units. In the second case, the fleet is made of 14 080 000 fuel cell cars in 2030 and the cumulative production represents 14 660 000 vehicles.

#### Platinum Flows Related to Fuel Cell Vehicles

In terms of platinum input, the modelling leads to a large range of results. The primary platinum input is presented in figure 8.12 for the nine combinations of technological evolution in the two registrations scenarios. Total and primary inputs are actually equal in the first twelve years of each scenario, corresponding to the assumed average lifetime of fuel cell vehicles.

For the high registrations scenario, primary platinum input increases on average from 1.3 t in 2013 to 112.8 t in 2030. Cumulative primary input reaches 1018.8 t on average. The two extreme HR scenarios are HR_HP_HC (best case) and HR_LP_LC (worst case). Primary input of platinum rises

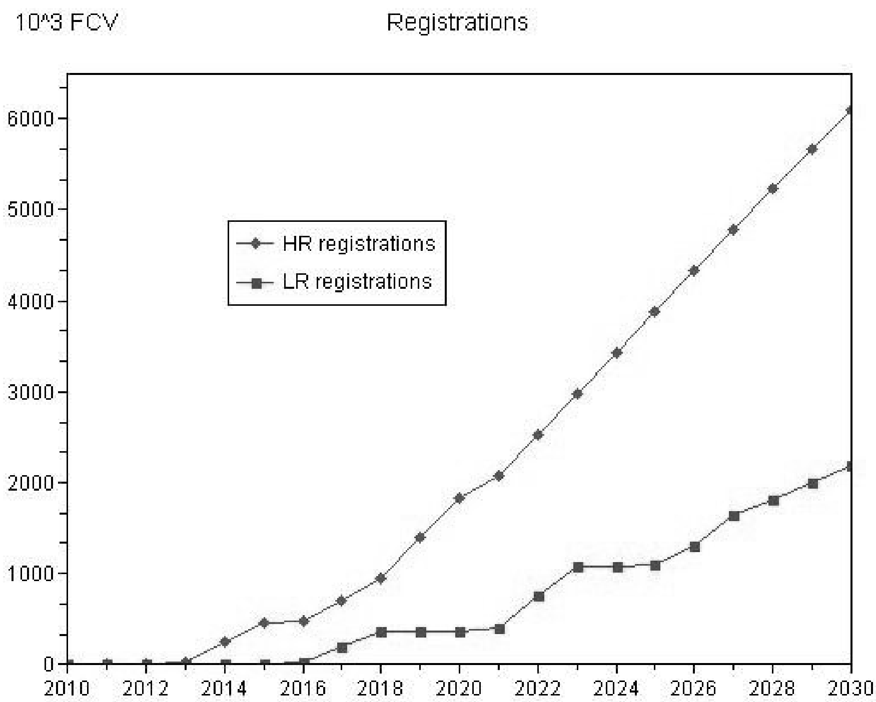



Figure 8.10: Two scenarios for fuel cell vehicles registrations in EU25

from 0.8 t to 29.9 t in the best case scenario (cumulative input corresponding to 312.2 t), while it goes up from 2 t to 278.1 t in the latter scenario (cumulative input: 2360.7 t).

In the low registrations case, primary platinum input climbs up on average from 1.1 t in 2016 to 47.1 t in 2030. The cumulative primary input reaches 381.5 t on average. Similarly to the HR case, the two extreme LR scenarios are LR_HP_HC (best case) and LR_LP_LC (worst case). Primary input of platinum goes up from 0.6 t to 13.9 t in the best case scenario (cumulative input: 132.1 t), while it increases from 1.7 t to 110.3 t in the worst case scenario (cumulative input: 832.3 t).

The increase of the stock of platinum in the fuel cell car fleet is shown in figure 8.13 for the same sets of scenarios. In the HR scenarios, the Pt stock reaches 997.9 t in 2030 on average. The extreme HR scenarios are again HR_HP_HC and HR_LP_LC, resulting in stocks of 303.7 t and 2318.9 t in 2030, respectively. The average platinum stock of the LR scenarios equals 376.4 t in 2030. The LR best and worst cases are the same as for primary input (LR_HP_HC and LR_LP_LC, respectively). The stocks amount then to 129.8 t and 822.9 t in 2030.

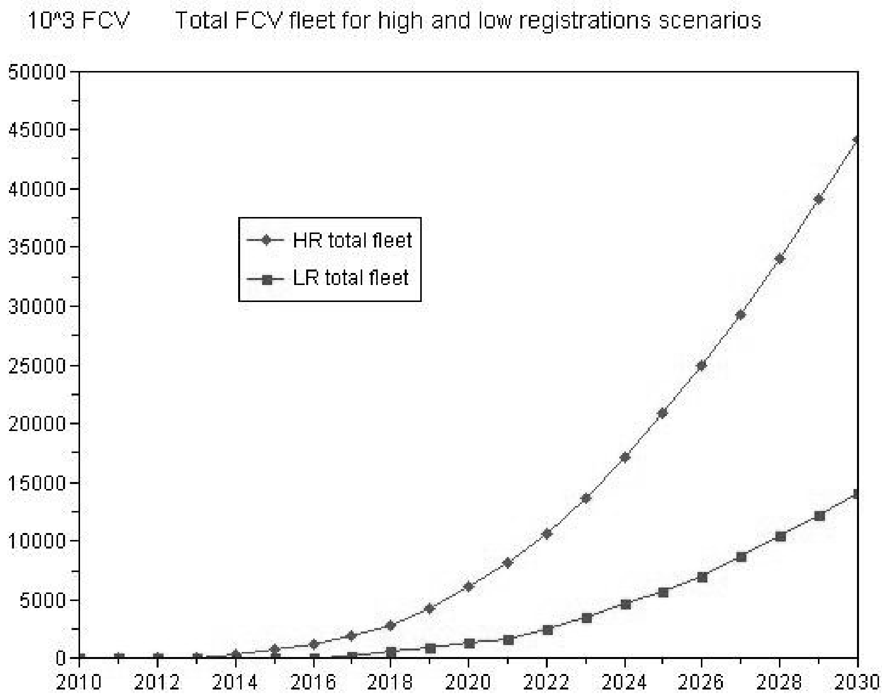



Figure 8.11: Two scenarios for the fleet of fuel cell vehicles in EU25

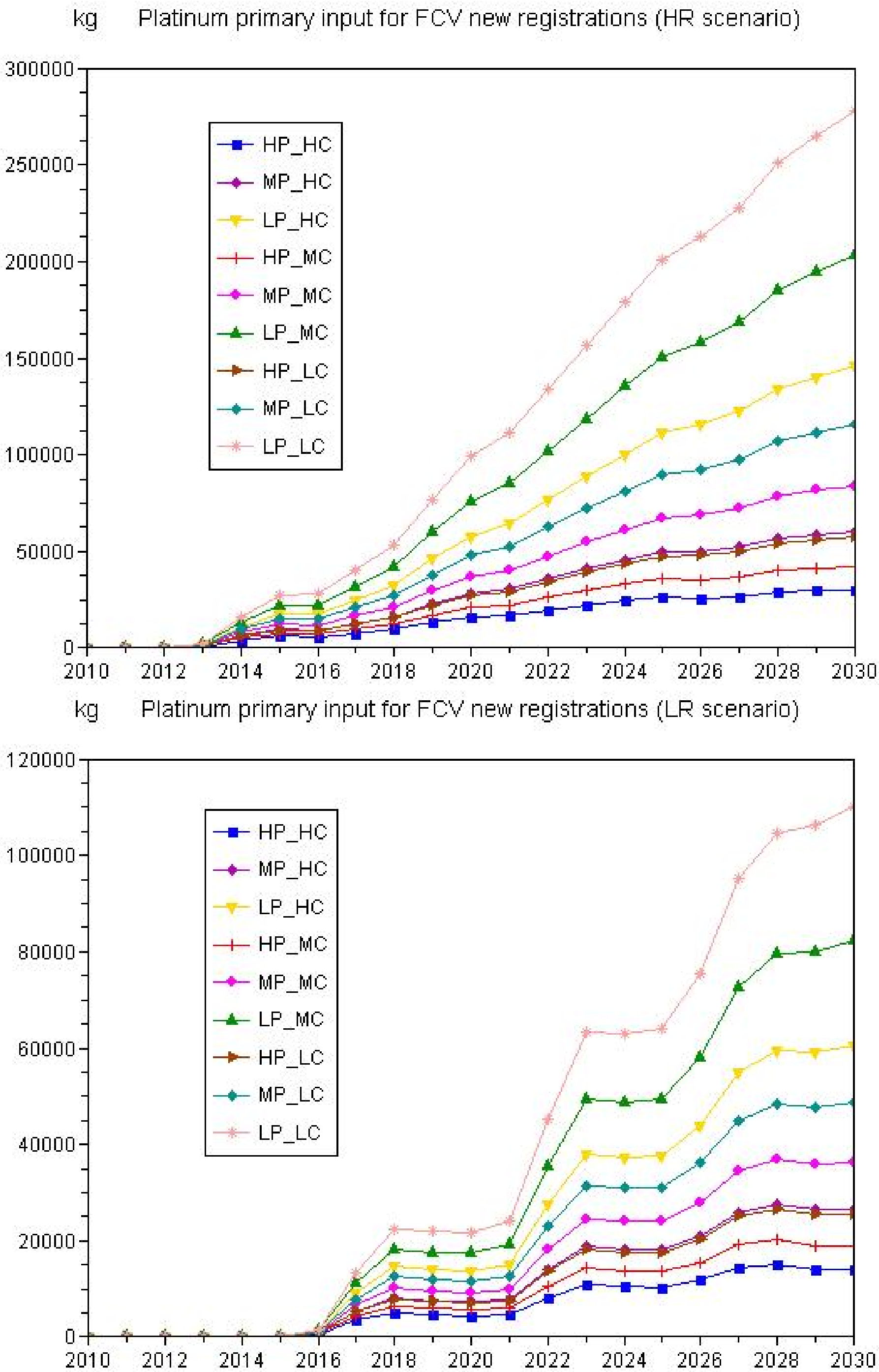
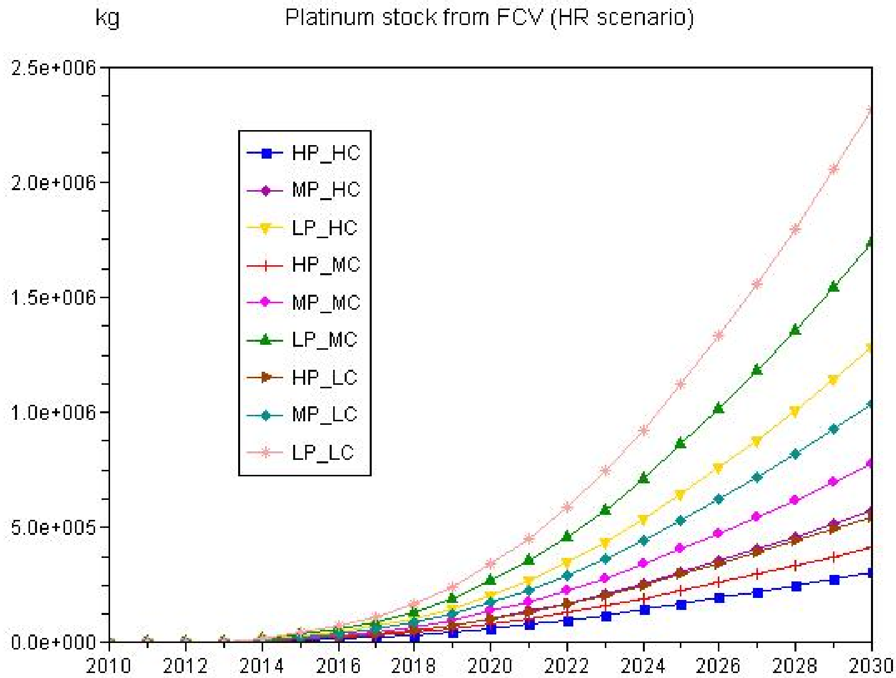



Figure 8.12: Platinum total input for new registrations of fuel cell vehicles in EU25. *Up:* Scenario high registrations (HR). *Down:* Scenario low registrations (LR).



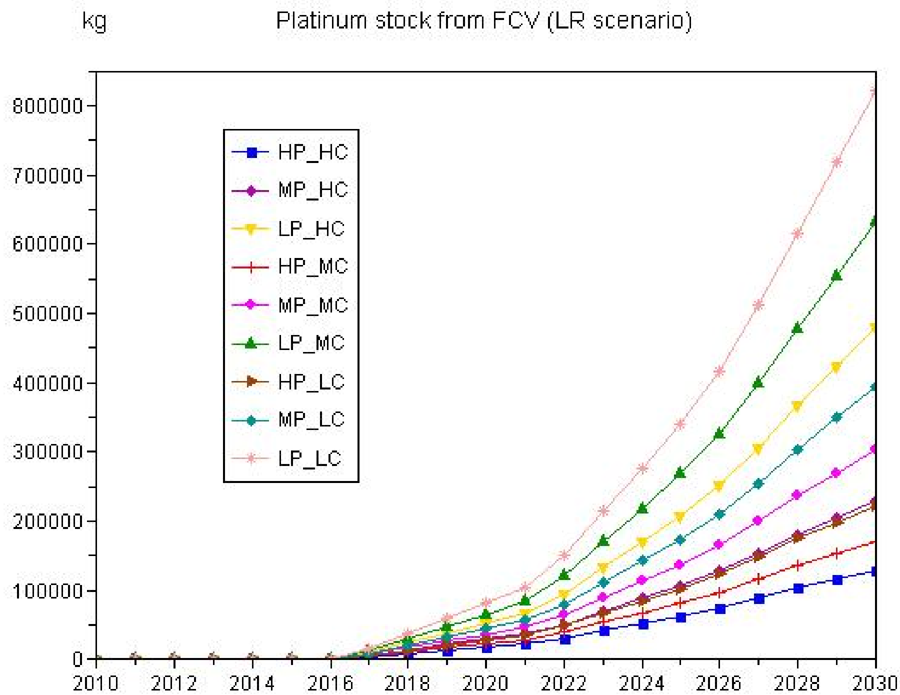




Figure 8.13: Stock of platinum for the fleet of fuel cell vehicles in EU25. *Up:* Scenario high registrations (HR). *Down:* Scenario low registrations (LR).

# Part III

# Results & Discussion

# Chapter 9

# Results

The use of platinum group metals has been modelled for Europe[1] for the period 1990–2020. The environmental impacts per unit of primary and secondary production of PGM have been calculated for the year 2004. These two sets of data are combined to obtain the total environmental impacts due to the use of PGM in Europe in 2004.

## 9.1 PGM Flows

The very starting point of the present work was to study the environmental impacts, wherever they might occur in the world, of the *use* of PGM in Europe. It has been explained earlier in the present work (see chapter 7.1) that depending on the application the *use* phase corresponds either to an industrial process (for industrial catalysts and the glass industry) or to the consumption by the end-users (for autocatalysts and electronics). It was also shown that this distinction had implications on the recycling paths: direct for the former applications, indirect for the latter (see chapter 6).

In the first case, the data concerning the inputs of primary precious metals were directly taken from Johnson Matthey's publications. The rates of secondary production had been well established for Germany by Hagelüken *et al.* (2005) and they have been used at the European level in the present study. One should remember that the jewellery and dentistry sectors, as well as the 'other industrial applications', have been treated in the same way as industrial catalysts and the glass industry, due to lack of data concerning the European consumption of, among others, PGM containing jewels or dental metals.

[1] *Europe* refers to EU15 + Norway + Switzerland prior to 1993 and to EU25 + Norway + Switzerland thereafter.

The second case (indirect recycling path) appears to be more problematic. The amount of PGM contained in electronic devices or catalytic converters effectively in *use* in Europe (and not necessarily or only *produced* in Europe) had to be determined. This has been done *via* a top-down analysis for electronics (see chapter 7.2.3) and *via* a bottom-up modelling for autocatalysts (see chapter 8). The future of the PGM at the end of the lifetime of the product it was contained in is much less certain than in the case of process PGM. The recycling rates and rates of secondary production were, however, estimated and modelled.

Figure 9.1 presents the final results of the combined top-down and bottom-up analyses for the year 2004. Only data concerning the autocatalysts come from the latter. They were adapted to the broader system boundaries of the top-down analysis (EU25 plus Norway and Switzerland instead of EU25 alone) relatively to the ratio of GDPs of the two geographical ensembles. Results regarding fuel cell vehicles do not appear here as only the year 2004 is considered. In the next chapter, however, the long term influence of the introduction of FCV will be discussed.

As stated above, the inputs of primary and secondary PGM in figure 9.1 do not refer to the same stage in the production-consumption chain. Figure 9.2 is therefore an attempt to represent the flows of PGM from the primary production to, first, the industrial processes (which also correspond to the end-users for the industrial catalysts and the glass industry), then the use phase and, finally, secondary production or definitive losses.

The flows related to industrial catalysts, glass industry, jewellery, dentistry and 'other' are direct representations of the results of the top-down analysis. The picture is more complex, however, concerning autocatalysts and electronics because the PGM containing products used in Europe may or may not have been produced in Europe and the amounts of precious metals available from end-of-life devices are uncertain. It is assumed that secondary PGM is used in the same industrial sector as the one which produced the product recycled.

The construction of the flows displayed in figure 9.2 is detailed in appendix C. The assumptions are precised there and the limitations of the representation are pointed out.

## 9.2 Environmental Impacts

PGM used as process metals or contained in products used in Europe can come from different suppliers: from South African, Russian or North American primary producers, or from secondary producers (assumed to be situated

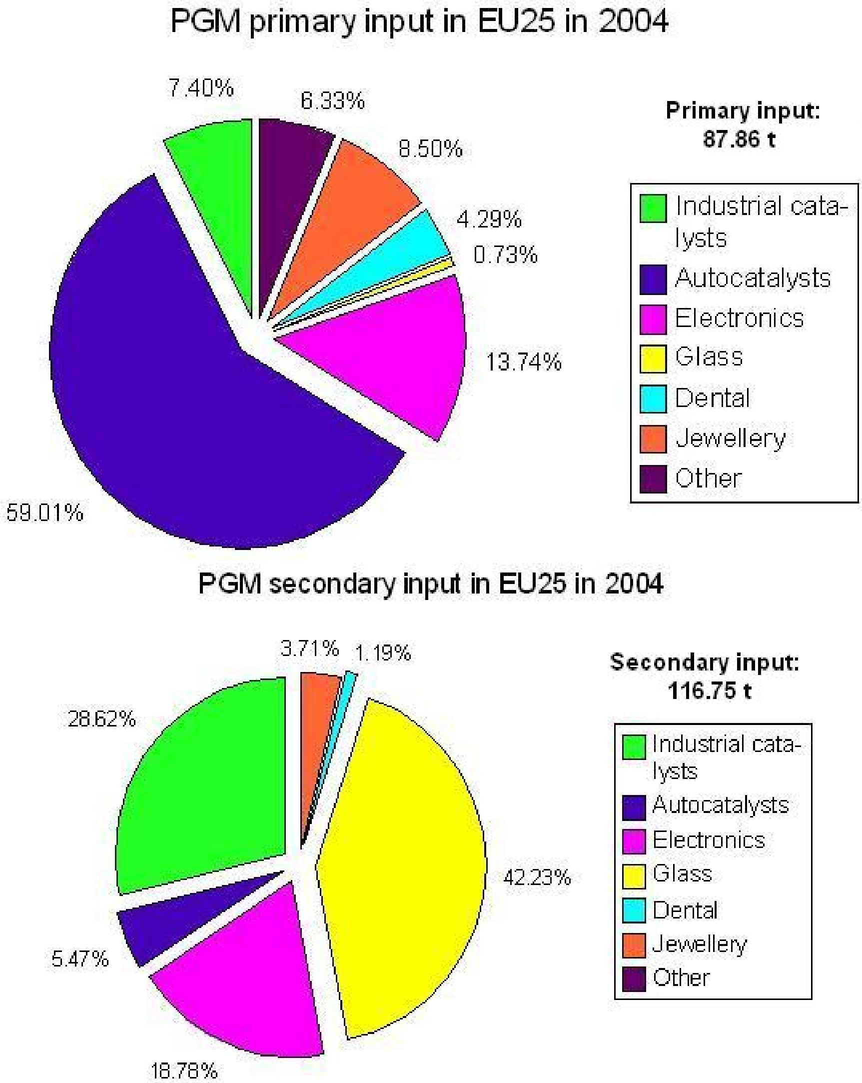



Figure 9.1: Inputs of platinum group metals related to their use in Europe in 2004. *Up:* Primary input. *Down:* Secondary input

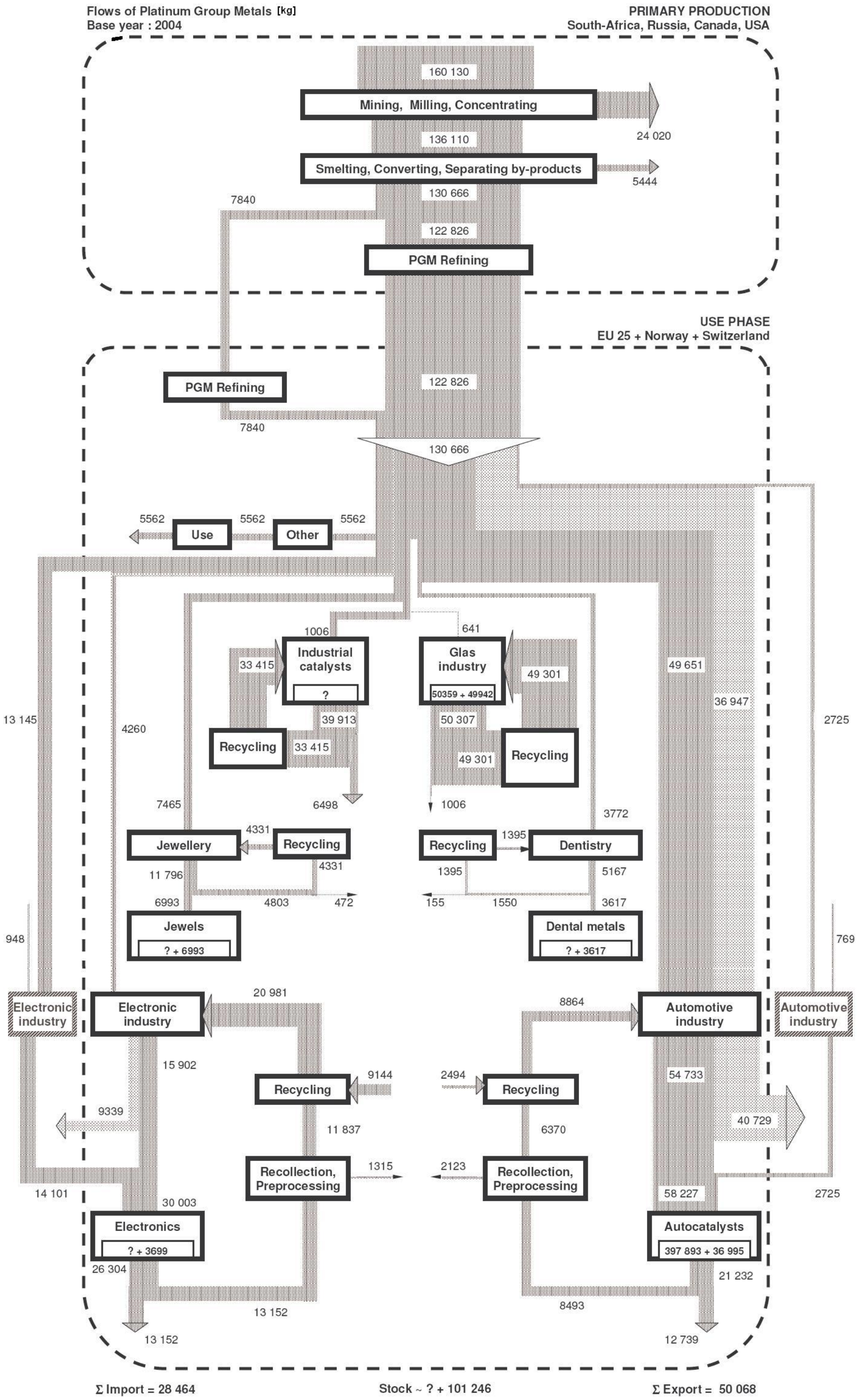



Figure 9.2: Flows of Platinum Group Metals in Europe

in Europe). In the second part of the present study inputs to and outputs from the production processes likely to have environmental impacts have been calculated. The results have been represented in flow charts per ton of PGM produced (see figures 3.1, 5.1 and 4.1, and table 6.1).

However, the three PGM considered in the present work (platinum, palladium and rhodium) never come alone when extracted from ore or recycled from waste. The main joint-products are two base metals, nickel and copper. Small quantities of gold are also extracted in the mining process. The problem arising at this point is to find the means to fairly allocate the burden of the impacts on the environment between the different outputs of the PGM production process.

There are mainly three allocation methods available for such metal production: no allocation (i.e. all the burden is on PGM, as in part I of this study) and allocations based on the mass or the monetary value of the production. An allocation based on the relative mass of the different products is excluded because due to the small quantities of PGM in relation to the other metals their contribution would be negligible. Even in South African mines where platinum is the metal of prime interest PGM production represents only about 0.4% in mass of total production (PGM + nickel + copper).

The inputs and outputs related to metal production are therefore allocated to the three PGM (altogether or separate) with respect to their share in the total value of the production. The joint-products considered alongside PGM are nickel, copper and gold. Cobalt and silver are not taken into account because of the absence of data concerning the quantities produced. The major drawback of this allocation method is that results may vary greatly due to the volatility of the metal prices. In the present case, the average price over the year 2004 is retained for each metal. The prices are presented in table 9.1.

To build an allocation factor, e.g. for platinum, two parameters are needed:

- the share of platinum in the monetary value of the production corresponding to the extraction of 1 t PGM
- the mass of platinum production per ton PGM extracted

The ratio of the two parameters make the allocation factors (e.g. $\frac{0.698}{0.61}$ in the case of platinum in South Africa). Table 9.2 presents the list of parameters needed. The environmental burden allocated to the production of 1 t platinum is obtained by applying the allocation factor to the environmental burden given per ton PGM (without allocation).

In the case of secondary production, base metals and precious metals also occur as joint-products of PGM. However, Umicore does not publish production data from its plant in Hoboken for other metals than PGM. The recycling process is primarily designed and optimized for platinum group metals and the ratio between main products (PGM) and joint-products can probably vary from year to year depending on the secondary materials fed into the process. In the present study, metals other than platinum, palladium and rhodium are not taken into account for the allocation for secondary production. By doing this, the allocation process is less favourable to secondary production than to primary production.

Table 9.1: Average prices of PGM and some joint-products for the year 2004

| $ per troz – Year 2004 | platinum† | palladium† | rhodium† | gold†† |
|---|---|---|---|---|
| **Yearly average price** | 848.08 | 232.33 | 979.83 | 409.16 |
| (in $ per ton) | (27 266 492) | (7 469 685) | (31 502 350) | (13 154 736) |
| **Min. monthly average** | 810 | 193 | 508 | 400.48 |
| **Max. monthly average** | 901 | 300 | 1329 | 441.76 |

| $ per ton – Year 2004 | nickel‡ | copper‡ | cobalt‡ |
|---|---|---|---|
| **Yearly average price** | 13 823 | 2866 | 52 756 |

†(Johnson Matthey)

††(Kitco 2006)

‡(USDI 2006, p.116, p.56, p.52)

Table 9.2: Parameters for allocation factors: shares of metal products in the monetary value of the production and mass of each product in the production (both per ton PGM produced)

| per ton PGM produced | South Africa (Anglo Platinum) % price | South Africa (Anglo Platinum) mass | Russia (Norilsk Nickel) % price | Russia (Norilsk Nickel) mass | North America (Inco, Sudbury) % price | North America (Inco, Sudbury) mass |
|---|---|---|---|---|---|---|
| **PGM** | 88.1 | 1 | 27.3 | 1 | 8.8 | 1 |
| **of which Pt** | 69.8 | 0.61 | 11.6 | 0.18 | 6.3 | 0.45 |
| **Pd** | 10.3 | 0.33 | 14.2 | 0.80 | 2 | 0.52 |
| **Rh** | 7.9 | 0.06 | 1.5 | 0.02 | 0.5 | 0.03 |
| **nickel** | 9.4 | 162 | 53.4 | 1630 | 73.6 | 10 381 |
| **copper** | 1.1 | 94 | 18.3 | 2691 | 17.4 | 11 810 |
| **gold** | 1.4 | 0.03 | 0.9 | 0.03 | 0.2 | 0.03 |

In the present study, the recycling of PGM is studied in one European case (Hoboken, Belgium). The results regarding environmental impacts per unit of secondary production are then considered applicable to all secondary inputs to European use of PGM. Primary production on the other hand clearly stems from different regions of the world with different impacts on the environment. Therefore, in order to compare directly the environmental burdens of primary and secondary productions, the former needs to be aggregated in one set of data representative of the world's PGM mining industry as a whole.

For this purpose, the results of the MFA of PGM primary production in South Africa, Russia and North America are weighted with respect to the shares of these regions in the world's production of primary PGM. Table 9.3 presents the factors used for the aggregation of the MFA results according to a 'PGM world mix'. It appears in this table that 3.5% of the world mix is produced from 'other' sources which were not studied in the present work. It appears from Johnson Matthey (2005, p.18-19) that about 62% of this rather undefined share is covered by production in Zimbabwe which is in turn often operated by companies already installed in South Africa (notably Impala Platinum) where the matte from Zimbabwean smelters is treated. Due to a lack of complementary data for primary production from 'other' sources it is assumed that its weight can be combined with that of South Africa and applied to South African MFA results.

Table 9.3: Share of the main producing regions in the world production in 2004 (in mass)

| % of world prod. | South Africa | Russia | North America | Other |
|---|---|---|---|---|
| **Platinum** | 77.4 | 13.1 | 5.9 | 3.6 |
| **Palladium** | 32.8 | 49.9 | 13.8 | 3.5 |
| **Rhodium** | 80.8 | 14.5 | 2.5 | 2.2 |
| **PGM** | 54.7 | 32.0 | 9.8 | 3.5 |

Source: Johnson Matthey (2005)

For each producing region, the environmental burden of primary production has been allocated to the platinum group metals. The results have then been aggregated using the 'world primary PGM mix'. The simplification made for North America to consider only Inco to represent the whole region increases its environmental burden per ton of PGM produced because of the low grade ore (regarding PGM) processed by Inco. However, the allocation of this burden with respect to the value of the different productions (the share of PGM in the value of Inco's production is lower than it is for Stillwater or

North American Palladium) is likely to offset this effect.

Results are presented in tables D.1 and D.2. The former table consists of inputs and outputs directly related to mining, smelting and refining processes whereas the latter shows the indirect impacts of these activities due to electricity generation and the supply of fossil fuels.

The effect of allocation can be seen in the burden allocated to palladium which is lower than for platinum and rhodium. However, it is interesting to notice that the direct $SO_2$ emissions allocated to Pd are not as low as could be expected when considering its price relatively to Pt and Rh, which are about four times more expensive. The reason is that Russia, which presents a high $SO_2$ intensity, accounts for about 50% of palladium world production. The allocation results for secondary production are presented in appendix D.4.

Table 9.6 shows the environmental impact ratio between primary and secondary production. The ratios of the non-allocated impacts are about one order of magnitude lower than those presented by Hochfeld (1997, p.122). Hochfeld's data are representative of primary production more than ten years ago. This would imply that PGM mining is much 'cleaner' today than at that time. This is certainly the case in South Africa for instance. For Russia, on the other hand there still seem to be large potentials for impact reduction. Hochfeld's modelling of secondary production also suffered from a lack of data from professional recyclers. Therefore, it might be that the impacts of secondary production had been underestimated. In contrast, the environmental pressures associated with PGM secondary production have been overestimated in the present study: due to lack of data concerning the production volumes of metals other than PGM, the environmental impacts could only be allocated to PGM, whereas significant amounts of gold, nickel and copper (among others) are probably produced as well. Allocating the environmental impacts over this larger range of products would significantly reduce the environmental burden associated with recycled PGM.[2]

[2]Dr Christian Hagelüken, from Umicore Precious Metals Refining, has been contacted (by e-mail and phone) and he accepted, in principle, to disclose some production data for other metals than PGM. These data were still not available at the time when the final report of the present study was submitted.

Table 9.4: Direct inputs and outputs related to the primary production of 1 t of PGM world mix

| Allocation | | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | |
| **Rocks mined** | | t | 471 915 | 586 979 | 83 169 | 691 292 | 331 679 |
| **Energy** | | TJ | 328.4 | 201.4 | 48.4 | 231.3 | 126.4 |
| of which | electricity | TJ | 175.2 | 149.9 | 28.3 | 174.8 | 89.1 |
| | fossil fuels | TJ | 148.0 | 43.3 | 19.0 | 46.8 | 32.8 |
| **Output** | | | | | | | |
| **$CO_2$-eq** | | t | 9058.9 | 3824.2 | 1226.3 | 4282.7 | 2602.0 |
| **$SO_2$** | | t | 7015.6 | 1616.0 | 1495.1 | 1921.1 | 1606.2 |
| **Mineral waste** | | t | 495 055 | 587 998 | 83 819 | 690 901 | 332 991 |

Table 9.5: Indirect environmental burden related to the primary production of 1 t of PGM world mix

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Electricity generation** | | | | | | |
| **$CO_2$-eq** | t | 32 292 | 36 068.5 | 5995.3 | 42 546.6 | 20 849.1 |
| **$SO_2$-eq** | t | 251.5 | 326.9 | 50.1 | 387.3 | 186.1 |
| **TMR** | | | | | | |
| **Electricity** | t | 115 483 | 92 059 | 15 843 | 106 159 | 54 213 |
| **Fossil fuels** | t | 5692 | 4527 | 879 | 5257 | 2711 |

Table 9.6: Compared environmental impacts of primary and secondary productions

| Ratio Primary:Secondary | | No allocation | After allocation to | | | |
|---|---|---|---|---|---|---|
| | | | Pt | Pd | Rh | PGM |
| **Direct impacts** | | | | | | |
| **Material input** | | 71.2 | 57 | 29.5 | 58.1 | 50 |
| **Energy** | | 5.1 | 2 | 1.8 | 2 | 2 |
| of which | electricity | 4.7 | 2.6 | 1.8 | 2.6 | 2.4 |
| | fossil fuels | 7.3 | 1.3 | 2.1 | 1.2 | 1.6 |
| **$CO_2$-eq** | | 4.1 | 1.1 | 1.3 | 1.1 | 1.2 |
| **$SO_2$-eq** | | 207 | 30.7 | 103.8 | 31.6 | 47.4 |
| **Total waste** | | 143.6 | 109.7 | 57.1 | 111.5 | 96.5 |
| **Indirect impacts** | | | | | | |
| **$CO_2$-eq** | | 14.7 | 10.6 | 6.4 | 10.8 | 9.5 |
| **$SO_2$-eq** | | 41.9 | 35.5 | 20 | 36.2 | 31 |
| **TMR** | | 16.5 | 8.5 | 5.4 | 8.5 | 7.8 |
| **Total impacts** | | | | | | |
| **$CO_2$-eq** | | 9.4 | 5.8 | 3.9 | 5.9 | 5.3 |
| **$SO_2$-eq** | | 182.1 | 31.4 | 91.4 | 32.2 | 44.9 |
| **TMR** | | 42.4 | 31.5 | 16.8 | 32 | 27.8 |

# Chapter 10

# Discussion

## 10.1 Relevance, Objectives & Limitations

### 10.1.1 Indicators

The purpose of the present discussion is to investigate the sensitivity of the environmental pressures associated with the use of PGM in Europe with respect to some influencing factors. This can be done by relating the results concerning the environmental impacts of primary and secondary productions of PGM (see Part I and chapter 9.2) and those regarding the amounts of primary and secondary PGM used in Europe (see Part II and chapter 9.1). This relation is considered for different combinations of scenarios, providing insights into the sensitivity of the environmental pressures with regard to the influencing factors. This, in turn, can be used to investigate the potential levers – technological, economic, political etc – likely to drive the 'influencing factors' in a way that would mitigate the environmental impacts associated with the use of PGM in Europe.

The variations of the environmental pressures need to be represented by a set of indicators. As it appears from the results presented in the previous chapter, three indicators are available to reflect the environmental impacts of primary and secondary production: carbon dioxide emissions, sulphur dioxide emissions and the total material requirement (TMR). In practice, the sum of direct and indirect $CO_2$ and $SO_2$ emissions are considered. These indicators can be considered at an aggregate level or attributed to the different producing regions.

The other indicator used in the present discussion is the 'PGM primary input' (mass) associated with the use of PGM in Europe. Even though this indicator can be interpreted in a number of ways, it remains that, as for the three aforementioned indicators, the higher the 'PGM primary input' is, the stronger the pressures on the environment. The extraction of non renewable resources – unsustainable as such – indeed goes along with higher pollution levels (represented by the three previous indicators) than in the case of secondary production (as shown in the previous chapter).

### 10.1.2 PGM Primary Input

The indicator 'PGM primary input' is actually an aggregate of the three 'sub-indicators' platinum, palladium and rhodium primary inputs. The PGM, Pt, Pd and Rh primary input indicators can be further attributed to the seven industrial and consumption sectors[1] considered for PGM use in the present work.

Figure 9.2 (previous chapter) shows that the autocatalyst and electronic sectors are the prime contributors to the demand for primary PGM. This is a direct consequence of the high losses occuring in these application fields. Only the 'mining and concentrating' stage of primary production presents higher losses (the PGM recovery rate at this stage can be as low as 80%; the potential improvements for this process are not discussed in the present study). Reducing the losses from the autocatalyst and electronic sectors through increased recycling would have a direct impact on PGM primary input. This constitutes therefore a first potential lever to study, which is further investigated in section 10.2.1.

Fuel cells (in automobiles for the present study) are also a future potentially relevant product group for the use of primary PGM. As it appears in chapter 8.2, a combination of factors drives the PGM demand for FCV. In the present work, the platinum density of the fuel cell stack (in g/kW) is modelled through learning curves. The total platinum content of the FCV is determined in the end by its power, which is another potential lever to consider (see section 10.5.1).

### 10.1.3 $CO_2$, $SO_2$ and TMR

In absolute terms, some of the quantities represented by the indicators $CO_2$ emissions, $SO_2$ emissions and TMR may be more relevant to address than others at the European level. Table 10.1 compares the three indicators to the (direct) $CO_2$ and $SO_2$ emissions and the TMR of the EU15. 'Europe' in the present study refers to EU25 plus Norway and Switzerland. The results of the present work are thus compared to data regarding a smaller geographical

[1] industrial catalysts, autocatalysts, electronics, glass industry, dentistry, jewellery and others

scope, and limited to direct $CO_2$ and $SO_2$ emissions. Therefore, the relevance is probably lower than that depicted in table 10.1.

It appears that the environmental pressures associated with the use of PGM in Europe are not of major relevance when compared with European totals. However, sulphur dioxide emissions related to PGM use in Europe in 2004 reached 3% of EU15 emissions in 2003. Although this still seems rather low, one has to bear in mind that, at that time, the final use of primary PGM in Europe amounted to less than a hundred tons (see figure 9.1 of the previous chapter). Therefore, it is considered that the $SO_2$ emissions associated with PGM production cannot be disregarded. At the same time, the TMR associated with PGM use seems three times more relevant than $CO_2$, when assigning equal importance to those environmental pressures, based on the comparison with EU15 totals for TMR and $CO_2$ emissions.

Table 10.2 gives insights into some possible adjustments to tackle the problem of sulphur dioxide. It appears clearly that the Russian production of primary PGM is tremendously more polluting than that of other regions. Cleaning the production of primary PGM in Russia therefore represents another potential lever, which is further analysed in section 10.2.2. Russia is also the largest producer of palladium, which could potentially imply that the use of this metal leads to important environmental impacts. However, the $SO_2$ emissions associated with the production of 1 t Pd in Russia are about four times lower than those of platinum or rhodium. This suggests that the allocation procedure, i.e. metal prices, could have a non-negligible influence on the representation of the environmental pressures by the indicators. This issue is further treated in section 10.3.

Furthermore, the autocatalyst sector is the largest consumer of primary palladium. The strong development of diesel vehicles in Europe, which until a recent technological breakthrough contained only platinum, however seems to prevent palladium demand from exploding. The impact of the two parameters 'new registrations of diesel cars' and 'PGM content of diesel autocatalysts' on PGM primary input and on environmental pressures are investigated in section.

The study of PGM primary production in South Africa showed that indirect emissions of $SO_2$ due to electricity generation represent 70% of the South African total (see figure 3.1 in chapter 3.3). By looking at table 10.2, one can notice, however, that South Africa has a much cleaner production than Russia and North America when it comes to sulphur dioxide emissions ($SO_2$ intensity allocated to PGM is four times higher in North America and ten times in Russia). But South Africa also remains by far the largest PGM producer in the world and, consequently, its contribution to $SO_2$ emissions allocated to 1 t of 'PGM world mix' represents 5% of direct emissions, 94%

of indirect ones and 14% of the sum. This is not negligible and electricity generation in South Africa is a potential lever which is considered in section 10.2.2.

Table 10.2 also shows that PGM secondary production presents a $SO_2$ intensity one order of magnitude lower (almost two orders of magnitude in the case of palladium) than that of primary production (see also table 9.6 in previous chapter). This confirms the importance of the PGM recycling rate as a potential lever to mitigate environmental pressures.

It apppears that sulphur dioxide emissions associated with PGM production constitute a more relevant issue at the European level than carbon dioxide or TMR. Russia presents in this respect the worst environmental performance among the three producing regions. This country however seems better than South Africa and North America when it comes to $CO_2$ and TMR. Taking these remarks into consideration, figure 10.1 is an attempt to answer the question "From which producer should a 'green' company buy its primary PGM?". Figure 10.1 was obtained by, first, dividing the results of table 10.2 by the EU15 totals presented in table 10.1. This is a way to weight environmental impacts according to their relevance at the EU level. Second, the numbers (which have no unit anymore) obtained for $CO_2$, $SO_2$ and TMR are summed up for each region and each PGM. Finally, the country with the highest result (i.e. with the worst environmental performance) is normalized to 1, and the other regions are normalized proportionally. Hence, the region with the highest environmental impact per ton of Pt, Pd or Rh produced (the results are virtually all the same for the three metals) is given the value 1, and it is Russia.

### 10.1.4 Objectives

The rest of the discussion presented in the following sections consists in studying the sensitivity of the indicators 'PGM primary input', '$CO_2$ emissions', '$SO_2$ emissions' and 'TMR' with regard to the influencing factors defined in sections 10.1.2 and 10.1.3. The influencing factors and their relevance regarding the different indicators are summarized in table 10.3. A further distinction between environmental impacts exerted within or outside the borders of the EU could be made, under the assumption that primary production occurs outside the EU, whereas secondary input comes from materials recycled in the EU.

For reasons of clarity, only part of the the results are presented in tables and figures in the present discussion. However, for transparency purposes, the results from all scenarios used in the discussion are presented in appendix E.1 and E.2).

Table 10.1: Relevance of environmental pressures associated with PGM use in Europe

| **Indicator** | **Unit** | **Total EU15** | **Production of PGM** | | |
|---|---|---|---|---|---|
| | | | **Primary** | **Secondary** | **Total** |
| **$CO_2$**† | ton | 4 179 613 044 | 2 372 668 | 566 325 | 2 938 993 |
| | % | 100 | 0.06 | 0.01 | 0.07 |
| **$SO_2$**†† | ton | 5 420 778 | 157 722 | 5122 | 162 844 |
| | % | 100 | 2.91 | 0.09 | **3.00** |
| **TMR**‡ | ton | 19 069 483 512 | 39 815 615 | 1 795 608 | 41 611 223 |
| | % | 100 | 0.21 | 0.01 | 0.22 |

†in 2003 for EU15; in 2004 for PGM production

††in 2003 for EU15; in 2004 for PGM production

‡in 2000 for EU15; in 2004 for PGM production

Table 10.2: Comparison of the environmental pressures stemming from the different PGM producing regions

| **Year: 2004** | *Primary production* | | | | *Secondary prod.* |
|---|---|---|---|---|---|
| **Unit: ton** | **World Mix** | **South Africa** | **Russia** | **North America** | **Belgium** |
| ***Impact associated with the production of 1 t PGM (after allocation)*** | | | | | |
| **$CO_{2eq}$** | 23 451.1 | 35 143.2 | 6542.2 | 9365.8 | 4407.4 |
| **$SO_{2eq}$** | 1792.3 | 430.2 | **4274.9** | 1760.8 | **39.9** |
| **$TMR_{eq}$** | 388 602.2 | 628 255 | 35 036.8 | 122 677.1 | 13 974.3 |
| ***Impact associated with the production of 1 t Platinum (after allocation)*** | | | | | |
| **$CO_{2eq}$** | 39 892.7 | 45 656.8 | 15 493 | 14 934.7 | 6844.8 |
| **$SO_{2eq}$** | 1942.9 | 558.9 | **10 123.7** | 2807.8 | **61.9** |
| **$TMR_{eq}$** | 683 564.9 | 816 207.2 | 82 972.9 | 195 621.3 | 21 702.3 |
| ***Impact associated with the production of 1 t Palladium (after allocation)*** | | | | | |
| **$CO_{2eq}$** | 7221.6 | 12 507.7 | 4244.3 | 4091.4 | 1875.1 |
| **$SO_{2eq}$** | 1545.1 | 153.1 | **2773.4** | 769.2 | **17** |
| **$TMR_{eq}$** | 99 891.1 | 223 600.8 | 22 730.5 | 53 590.7 | 5945.4 |
| ***Impact associated with the production of 1 t Rhodium (after allocation)*** | | | | | |
| **$CO_{2eq}$** | 46 829.4 | 52 749.7 | 17 899.9 | 17 254.8 | 1908.1 |
| **$SO_{2eq}$** | 2308.4 | 645.8 | **11 696.5** | 3244 | **72** |
| **$TMR_{eq}$** | 802 707.9 | 943 005.2 | 95 862.7 | 226 011.2 | 25 073.8 |

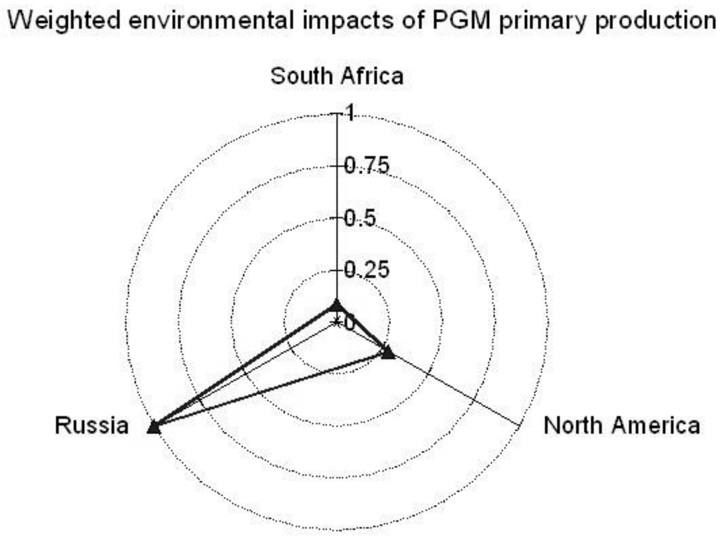



Figure 10.1: Comparison of the environmental impact of the three PGM producing regions (the weighted and normalized results, as presented in this figure, are the same for Pt, Pd and Rh)

Table 10.3: Indicators and potential levers

| see section | Indicators → ↓ Influencing factors | Use of primary PGM | Environmental impacts $CO_2$ | $SO_2$ | TMR |
|---|---|---|---|---|---|
| 10.2.1 | **Recycling rates** | × | × | × | × |
| 10.2.2 | **Pyrometallurgy in Russia** | | | × | |
| 10.2.2 | **Electricity generation in South Africa** | | | × | |
| 10.4.2 | **Share of diesel cars in new registrations** | × | × | × | × |
| 10.4.2 | **Palladium content of diesel autocatalysts** | × | × | × | × |
| 10.3 | **PGM prices (*via* allocation factors)** | × | × | × | × |
| 10.5.1 | **Power of FCVs** | × | × | × | × |

### 10.1.5 Limitations

The results discussed in the present chapter rely on the calculations of the material and energy flows involved in PGM primary and secondary production (Part I), and on the modelling of PGM use in Europe (Part II). The limitations inherent to these calculations and models need to be kept in mind when analysing the outcome of scenarios based on the results of Parts I and II.

#### PGM production

The results regarding production in Russia (chapter 4) suffer from low quality data when it comes to the actual quantities of PGM produced, the estimate of environmental impacts or of material and energy flows. The carbon dioxide emissions, sulphur dioxide emissions and TMR results are therefore probably underestimated.

North American production (chapter 5) has been modelled based only on data from Inco Limited (Ontario, Canada). There are however three other producers[2] in North America, including two (Stillwater Mining and North American Palladium) operating in rather different conditions compared to Inco. These two companies are indeed primary producers of platinum and palladium, respectively, while Inco's PGM are by-products of nickel mining.

The absence of data regarding the joint-products (gold, nickel, copper etc) of PGM secondary production renders the allocation procedure less favourable for recycling than for primary production. The comparative advantage of PGM secondary production compared to primary metal mining is therefore probably higher than shown in table 9.6.

#### PGM use in Europe

The top-down analysis presented in chapter 7 relies on the extrapolation at the European level of Hagelüken *et al.*'s (2005) findings for Germany. The lack of reliable data made it also difficult to set the rate of secondary production in the electronic sector, or to estimate imports to and exports from the EU of consumer goods or scrap containing PGM (mainly for the autocatalysts and electronics product groups).

Due to the lack of data, the bottom-up analysis modelling the use of PGM in autocatalysts (chapter 8.1) considers only one category of cylinder capacity for European automobiles, whereas the PGM content of a catalytic

[2]Stillwater Mining, North American Palladium and Falconbridge do not publish detailed environmental reports, unlike Inco Limited

converter can vary two folds between small and big cars (see table B.3). The model also suffers from often low quality data regarding the structure of the car fleet in EU10.

The model concerning the future European fleet of FCVs takes into account only vehicles powered by PEM-FC and tanking pure hydrogen. The former assumption serves to justify the high recycling rate (no export to non OECD countries). Due to the lack of quantitative data, the alternative introduction of other technologies, such as Direct Methanol or Ethanol Fuel Cells, is not considered.

## 10.2 Primary and Secondary Production

### 10.2.1 Potentially Increased Recycling Rates

The autocatalyst and electronics sectors present the highest PGM losses among the seven sectors considered in the present study. This fact stems from the low collection and recycling rates of end-of-life products. For autocatalysts, it is assumed that, to date, only 30% of the PGM contained in end-of-life catalytic convertors are recovered. No more than 40% of the palladium present in European electronic waste is assumed to be recycled and this rate is even considered to be about two times lower for platinum and rhodium (both less common in electronics where palladium represented about 75% of the primary input in 2004).

There is thus theoretically some potential to increase recycling. The EU Council and Parliament have adopted the ELV and WEEE directives, in 2000 and 2002 respectively, dealing with reuse, recovery and recycling in the automotive and electronics sectors. The former directive sets minimum targets for "reuse and recycling" of parts from end-of-life vehicles as high as 80% from the year 2006 and 85% from 2015. The directive does not specify targets for autocatalysts and their PGM but it does cite the removal of the catalytic converter among the minimum technical requirements (Van Maele and Hagelüken 2005). The WEEE directive sets targets for "reuse and recycling" ranging from 50% to 80% depending on the type of waste.

In the present work, three scenarios (R1, R2 and R3) are tested. The recycling rates are assumed to increase linearily until 2020. At this date, they reach the values presented in table 10.4. A lower target has been set for rhodium in electronic waste because it is more diluted (lower quantities used) and more problematic to recycle than palladium and platinum. In the 'business as usual' case (BAU), all recycling rates are assumed to remain constant at 2004 levels, as described in chapters 7 and 8.

Table 10.4: Recycling rates for the scenarios involving increased recycling

| | Recycling rates in 2020 | | |
|---|---|---|---|
| | **Scenario R1** | **Scenario R2** | **Scenario R3** |
| **Autocatalysts** | | | |
| Pt | 0.70 | 0.80 | 0.90 |
| Pd | 0.70 | 0.80 | 0.90 |
| Rh | 0.70 | 0.80 | 0.90 |
| **Electronics** | | | |
| Pt | 0.80 | 0.80 | 0.80 |
| Pd | 0.80 | 0.80 | 0.80 |
| Rh | 0.60 | 0.60 | 0.60 |

### PGM Primary Input

Table 10.5 presents PGM primary input in the BAU case. Table 10.6 displays the same results for the three scenarios. 'Min 2005-2020', 'Avg 2005-2020' and 'Max 2005-2020' stand for the minimum, the average and the maximum values delivered for a given scenario over the period between 2005 and 2020. 'Cumul. 2005-2020' represents the sum of the modelling results issued for a given scenario over the same period. The absolute and relative savings of primary PGM due to increased recycling can be seen in appendix E.1, as well as results for Pt, Pd and Rh. Relatively to the BAU PGM use, increased recycling allows a higher share of palladium to be saved (compared to platinum or rhodium). Pd represents indeed about three fourth of the PGM inputs for electronics.

The aggregate PGM results are quite different for autocatalysts and electronics. In the former case, the three recycling scenarios respectively allow savings of 18%, 22% and 26% of the cumulative use of primary PGM with respect to the BAU scenario. The maxima are reached in 2020 with 41%, 52% and 62% savings. For the three scenarios, the relative savings are lower than those obtained for electronics (58% of cumulative primary PGM and 94% at the maximum), even for scenario R3 where the assumed recycling rate for autocatalyst is higher.

This reflects the fact that, even with a very high recycling rate, primary input is needed to sustain market growth. In the present study the automotive sector is indeed assumed to expand in Europe after 2004, while the electronics sector is expected to stagnate. In the latter case, primary input only serves to compensate losses, which are low when recycling is high. Considering all the sectors, the three scenarios result respectively in cumulative PGM savings of 18%, 21% and 23% with regard to BAU. The maximum savings in 2020 are about twice as high: 36%, 43% and 49% for the three recycling scenarios. The yearly relative PGM savings (with respect to BAU) in autocatalysts, electronics and in total (all seven sectors) are shown in figure 10.2 for scenario R1, the least ambitious scenario among the three, which makes it somewhat more probable (the same assumptions regarding recycling rates for autocatalysts are used by Hagelüken *et al.* (2005)). The modelling results suggest for instance that, in 2015, 22% of the primary PGM used in autocatalysts in the BAU scenario could be saved. Similarly, in the R1 scenario only 19% of the primary PGM used in electronics in the BAU scenario would still be necessary (i.e. 81% savings) in 2015. Considering the seven sectors, it is 23% of the BAU primary PGM that could be spared in 2015.

Table 10.5: PGM input in the BAU scenario (in tons)

| **Primary & Secondary PGM Inputs** | **Autocatalysts** *Primary* | *Secondary* | **Electronics** *Primary* | *Secondary* | **All sectors** *Primary* | *Secondary* |
|---|---|---|---|---|---|---|
| **Min 2005-2020** | 61.76 | 7.75 | 12.42 | 21.99 | 98.46 | 119.42 |
| **Avg 2005-2020** | 72.73 | 15.47 | 12.42 | 21.99 | 112.46 | 136.98 |
| **Max 2005-2020** | 77.33 | 22.64 | 12.42 | 21.99 | 116.94 | 156.3 |
| **Cumul. 2005-2020** | 1163.71 | 247.44 | 198.65 | 351.82 | 1799.42 | 2191.6 |

Table 10.6: PGM input in the recycling scenarios R1, R2 and R3 (in tons)

| **Primary & Secondary PGM Inputs** | **Autocatalysts** *Primary* | *Secondary* | **Electronics** *Primary* | *Secondary* | **All sectors** *Primary* | *Secondary* |
|---|---|---|---|---|---|---|
| ***PGM inputs for recycling scenario R1*** | | | | | | |
| **Min 2005-2020** | 42.68 | 8.39 | 0.78 | 22.88 | 74.21 | 120.96 |
| **Avg 2005-2020** | 59.96 | 28.24 | 5.18 | 29.22 | 92.45 | 156.99 |
| **Max 2005-2020** | 69.3 | 52.82 | 11.52 | 33.63 | 101.85 | 198.12 |
| **Cumul. 2005-2020** | 959.31 | 451.84 | 82.88 | 467.59 | 1479.25 | 2511.76 |
| **Cumul. R1 / BAU** | 82% | 183% | 42% | 133% | 82% | 115% |
| ***PGM inputs for recycling scenario R2*** | | | | | | |
| **Min 2005-2020** | 35.13 | 8.56 | 0.78 | 22.88 | 66.66 | 121.12 |
| **Avg 2005-2020** | 56.76 | 31.43 | 5.18 | 29.22 | 89.26 | 160.18 |
| **Max 2005-2020** | 67.3 | 60.36 | 11.52 | 33.63 | 99.85 | 205.67 |
| **Cumul. 2005-2020** | 908.22 | 502.94 | 82.88 | 467.59 | 1428.16 | 2562.86 |
| **Cumul. R2 / BAU** | 78% | 203% | 42% | 133% | 79% | 117% |
| ***PGM inputs for recycling scenario R3*** | | | | | | |
| **Min 2005-2020** | 27.59 | 8.72 | 0.78 | 22.88 | 59.12 | 121.28 |
| **Avg 2005-2020** | 53.57 | 34.63 | 5.18 | 29.22 | 86.07 | 163.37 |
| **Max 2005-2020** | 65.29 | 67.91 | 11.52 | 33.63 | 98.98 | 213.21 |
| **Cumul. 2005-2020** | 857.12 | 554.03 | 82.88 | 467.59 | 1377.06 | 2613.96 |
| **Cumul. R3 / BAU** | 74% | 224% | 42% | 133% | 77% | 119% |

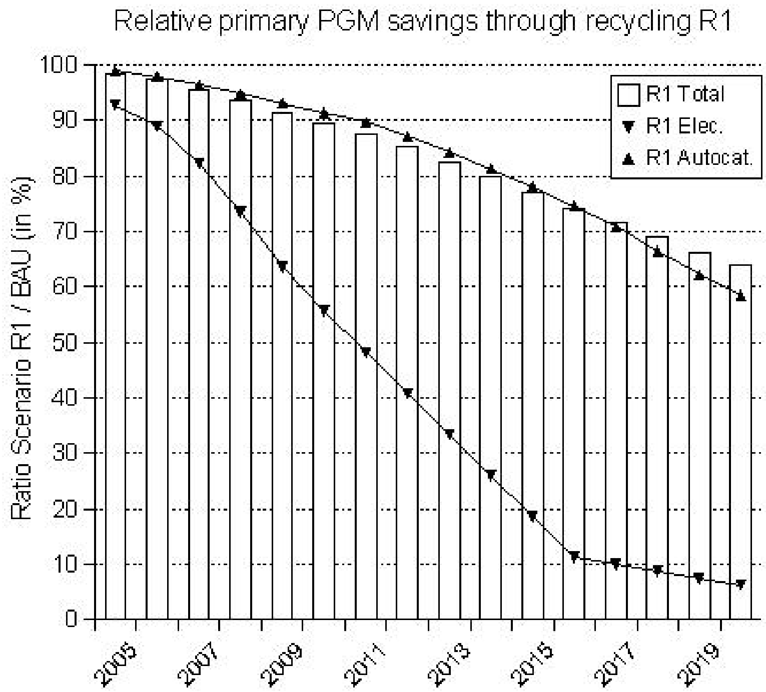



Figure 10.2: Potential savings of primary PGM through increased recycling in scenario R1, relatively to BAU

### $CO_2$, $SO_2$ and TMR

Table 10.7 presents the total $SO_2$ emissions of all sectors in the BAU case. Table 10.8 shows the same indicator for the three recycling scenarios. The absolute and relative amounts of $SO_2$ emissions avoided through increased recycling are shown in appendix E.1, along with the tables for the $CO_2$ and TMR indicators.

The cumulative $SO_2$ emissions associated with the total PGM input for the period 2005-2020 are reduced by 16%, 19% or 21% when comparing the three recycling scenarios to the BAU case. The maxima reached in 2020 are, here again, about twice as much: 33%, 39% and 45%. The results for $CO_2$ and TMR present lower variations in the different scenarios than those for $SO_2$ (cumulative savings reach 9%, 11% and 13% for $CO_2$ and 12%, 15% and 17% for TMR, in scenarios R1, R2 and R3 respectively). Secondary production of PGM is indeed about 45 times 'cleaner' than primary production with regard to $SO_2$ emissions whereas the ratio primary:secondary production amounts only about 5 for $CO_2$ and 30 for TMR (see table 9.6 in the previous chapter).

The aforementioned figures correspond to a global reduction of $SO_2$ emissions. It is interesting to note that, under the assumption that secondary production takes place in Europe, the cumulative $SO_2$ emissions in Europe increase by 13%, 15% or 18%. The maximum increases (in 2020) compared to BAU, could be as high as 26%, 31% or 37% (shown in appendix E.1).

The problem of shifting environmental impacts from Europe, where e.g. the emissions from cars are reduced, towards other parts of the world, where the PGM are mined, can be mitigated by increased recycling rates. Environmental pressures associated with PGM use in Europe decrease in South Africa, Russia and North America; they are also reduced at the global level. But, if recycling occurs in Europe, the pressures increase there. However, for sulphur dioxide, which is the most relevant at the EU level (see section 10.1.3), it also means that diffuse sources of acidifying compounds (e.g. $NO_x$ from cars) are replaced by point sources (PGM recyclers-refiners), which are possibly easier to control.

Table 10.7: Sulphur dioxide emissions in the BAU scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| **Min 2005-2020** | 178 540.1 | 5222.3 | 183 762.4 |
| **Avg 2005-2020** | 205 201.4 | 5827.9 | 211 029.4 |
| **Max 2005-2020** | 213 769.8 | 6524.8 | 219 910.3 |
| **Cumul. 2005-2020** | 3 283 223 | 93 246.9 | 3 376 470 |

## 10.2.2 Potentially Cleaner Primary Production

### Reduction of Direct Sulphur Dioxide Emissions in Russia

The sulphur dioxide intensity of Russian production of primary PGM is a problem that has been underlined a number of times in the present study. The Russian company Norilsk Nickel communicates a lot about its project to reduce the environmental impacts of its activities, especially concerning the emissions of acidifying substances. The billions of dollars planned to be invested in this issue should lead to a 70% reduction of $SO_2$ emissions in 2010 with respect to today's emissions level (which is, to date, not officially disclosed).

In the scenario proposed in the present section, it has been assumed that, between 2004 and 2009, $SO_2$ emissions per ton PGM remain equal to those in 2004. It is then assumed that in 2010 new installations are operational and that emissions per ton PGM decrease by 70% with regard to emissions in 2004. The scenario is named RU scenario and the results are presented in table 10.9.

Table 10.8: Sulphur dioxide emissions in R1, R2 and R3 scenarios

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| ***$SO_2$ emissions in recycling scenario R1*** | | | |
| **Min 2005-2020** | 138 839.2 | 5274.4 | 147 059.6 |
| **Avg 2005-2020** | 170 403.4 | 6579.9 | 176 983.3 |
| **Max 2005-2020** | 187 581 | 8220.4 | 193 728.6 |
| **Cumul. 2005-2020** | 2 726 455.1 | 105 278.3 | 2 831 733.4 |
| **Cumul. R1 / BAU** | 83% | 113% | 84% |
| ***$SO_2$ emissions in recycling scenario R2*** | | | |
| **Min 2005-2020** | 125 119.9 | 5281.4 | 133 687.1 |
| **Avg 2005-2020** | 164 629.7 | 6772.6 | 171 352.3 |
| **Max 2005-2020** | 183 997.7 | 8567.1 | 190 229.5 |
| **Cumul. 2005-2020** | 2 634 075.3 | 107 561.2 | 2 741 636.5 |
| **Cumul. R2 / BAU** | 80% | 115% | 81% |
| ***$SO_2$ emissions in recycling scenario R3*** | | | |
| **Min 2005-2020** | 111 400.6 | 5288.4 | 120 314.6 |
| **Avg 2005-2020** | 158 856 | 6865.3 | 165 721.2 |
| **Max 2005-2020** | 180 414.4 | 8913.9 | 186 730.5 |
| **Cumul. 2005-2020** | 2 541 695.5 | 109 844.2 | 2 651 539.7 |
| **Cumul. R3 / BAU** | 77% | 118% | 79% |

The cumulative reduction of sulphur dioxide emissions over the period 2005-2020 compared to BAU (37%) is 1.7 to 2.3 times higher than that achieved with increased recycling (see tables 10.7 and 10.8 in previous section). One can therefore imagine that a combination of increased recycling and technological improvement in Russian production could lead to an interesting reduction of environmental pressures. This is further investigated in section 10.2.3. Secondary production is intrinsically cleaner than primary production (e.g. it does not need to extract PGM from sulfides), which means that the more secondary input, the better. However, in a growing economy, primary input is needed and, therefore, the environmental impact of primary production is important to look at.

Due to the limitations of the modelling in the present study, the implementation of $SO_2$-oriented end-of-pipe solutions at Norilsk Nickel seems not to affect the $CO_2$ and TMR indicators. In practice, however, the commissioning of such measures would tend to increase the TMR and carbon dioxide emissions, through e.g. increased energy use or lower overall process efficiency.

Table 10.9: Sulphur dioxide emissions in the RU scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| **Min 2005-2020** | 98 700.5 | 5222.3 | 104 256.6 |
| **Avg 2005-2020** | 129 799.1 | 5827.9 | 135 627 |
| **Max 2005-2020** | 200 000.5 | 6524.8 | 205 498.5 |
| **Cumul. 2005-2020** | 2 076 785.68 | 93 246.9 | 2 170 032.6 |
| **Cumul. RU / BAU** | 63% | 100% | 64% |

### Reduction of Indirect Sulphur Dioxide Emissions in South Africa

Power is cheap in South Africa (Hochfeld 1997, p.47) and, consequently, South African PGM producers use for their processes electricity rather than fossil fuel when possible (e.g. electric furnaces). Direct emissions are therefore reduced. However, in the South African energy mix, 92% of the electricity is generated from hard coal, which implies high indirect emissions of $CO_2$, but also $SO_2$, because the thermal power plants do not seem to have high environmental standards in this field (which might also partly explain why power is cheap).

Even though South Africa presents an overall low $SO_2$ intensity (t/t PGM) compared to Russia and North America, its largely dominant position on the PGM supply side[3] implies that it accounts for about 14% of the world $SO_2$ intensity (t/t world mix PGM). In the present scenario (named SA scenario), it is assumed that from 2005 onwards, the $SO_2$ emission factor for coal fired electricity generation used for secondary production in Europe (Belgium) is applied to South Africa. The results are shown in table 10.10.

Cumulative emissions for the period 2005-2020 decrease by 9% compared to the BAU case, which is significant. Each year, about 9% of BAU sulphur dioxide emissions are avoided. It appeared from table 10.2 that industries should buy, if possible, PGM from South Africa because of its lower $SO_2$ intensity. However, if this intensity were to be further decreased (e.g. by applying European standards to South African coal fired power plants), $SO_2$ emissions reduction would still significantly decrease because of the dominant share of South Africa in PGM primary production. The same remarks as in the Russian case can be made regarding TMR and $CO_2$, which would probably tend to increase if end-of-pipe measures are applied to South African electricity generation.

[3]South Africa represented in 2004 about 77% of Pt production, 33% of Pd production and 81% of Rh production (in mass).

Table 10.10: Sulphur dioxide emissions in the SA scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| **Min 2005-2020** | 163 264.8 | 5222.3 | 168 487.2 |
| **Avg 2005-2020** | 187 136.9 | 5827.9 | 192 964.9 |
| **Max 2005-2020** | 194 795.2 | 6524.8 | 200 935.7 |
| **Cumul. 2005-2020** | 2 994 190.7 | 93 246.9 | 3 087 437.6 |
| **Cumul. SA / BAU** | 91% | 100% | 91% |

### 10.2.3 Combinations of Scenarios

The combination of the first recycling scenario (70% in 2020 for autocatalysts and 80% for electronics) with the scenarios for environmentally improved production in Russia and South Africa delivers the results presented in table 10.11 (the scenario is referred to as R1-RU-SA scenario). For the period 2005-2020 about 50% less sulphur dioxide would be emitted than in the BAU case, with the same total PGM used in Europe. In 2020, it is 71% of the $SO_2$ emissions that could be avoided. Not surprisingly, considering the results from section 10.1.2, the same combination but with the third recycling scenario (90% recycling for autocatalysts) instead of the first one, would improve the emissions reduction by a few percents more (results not shown).

The contributions of the R1, RU and SA scenarios to the R1-RU-SA scenario are presented in figure 10.3. It shows the share of the BAU sulphur dioxide emissions which could be avoided each year through increased recycling and environmentally improved production in Russia and South Africa. The model suggests that 67% of the BAU $SO_2$ emissions could be avoided in 2015 with the R1-RU-SA scenario. This is lower than the sum of the savings achieved separately in 2015 by the scenarios R1 (21%), RU (50%) and SA (9%) because, for a given total PGM input, increased recycling implies a lower primary production and therefore the effects of the RU and SA scenarios are less visible.

As explained in the previous sections, the RU and SA scenarios have no implications in the modelling results regarding the $CO_2$ and TMR indicators, even though in reality end-of-pipe solutions are likely to make them increase. On the other hand, increased recycling reduces $CO_2$ emissions and TMR. Therefore, the gains (as modelling results) concerning these two indicators are the same as those presented in section 10.2.1 (9% and 12% cumulative savings for $CO_2$ and TMR, respectively).

Table 10.11: Sulphur dioxide emissions in the R1-RU-SA scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| **Min 2005-2020** | 55 428.2 | 5274.4 | 63 648.6 |
| **Avg 2005-2020** | 96 852.8 | 6579.9 | 103 432.7 |
| **Max 2005-2020** | 167 407.8 | 8220.4 | 173 218.6 |
| **Cumul. 2005-2020** | 1 549 645.3 | 105 278.3 | 1 654 923.6 |
| **Cumul. R1-RU-SA / BAU** | 47% | 113% | 49% |

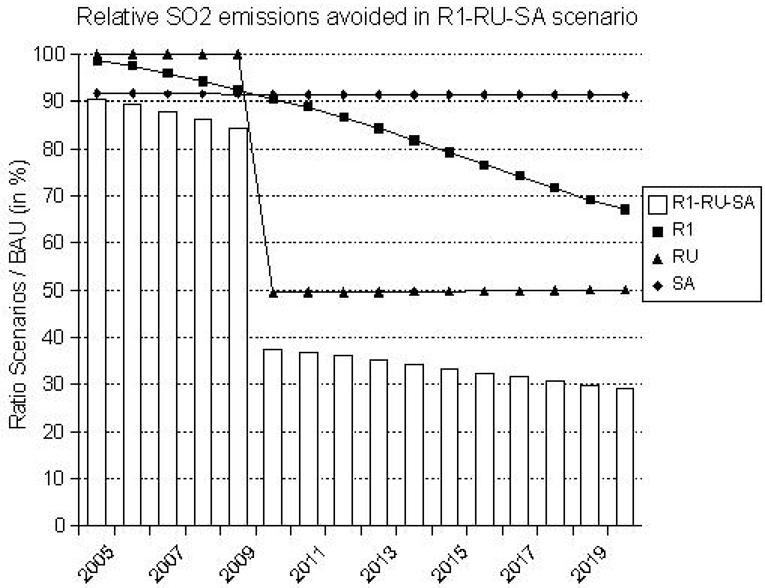



Figure 10.3: Potential savings of $SO_2$ emissions through increased recycling and cleaner production scenario R1-RU-SA, relatively to BAU

## 10.3 PGM Prices & Allocation Procedure

For a given share (in mass) in a production total, the cheaper a metal, the lower its environmental impacts after allocation. This effect is well illustrated in the case of palladium. The world largest Pd producer is Russia (about 50% in mass) and it is also the country with the worst environmental record regarding sulphur dioxide emissions. But, as shown in table 10.2, $SO_2$ emissions (after allocation) associated with the production of 1 t 'world mix' primary palladium, appear finally more than 20% lower than in the case of platinum or rhodium. The reason for that is that on average, palladium prices amounted to only 27% of platinum prices and 24% of rhodium prices in 2004. Therefore, given the allocation procedure used in the present study (see chapter 9.2), it is simply logical that palladium seems better from an environmental point of view.

However, palladium prices have the particularity to be very volatile[4] compared to platinum and rhodium (about twice as much for the 1998-2004 period). The present situation with the price of palladium at about one fourth of that of platinum is only relatively recent. In 2000 and 2001, palladium was on average more expensive than platinum. At its maximum in 2001, palladium costed more than twice the average price of platinum for the same year.

The high palladium prices had been triggered off by the substitution of this metal for platinum in autocatalysts, which were a technology in rapid expansion at the time. The prices then fell by 87% in thirty months, mainly because of the substitution of base metals for palladium in some important electronic components. But what if a new application for palladium suddenly increases the demand? One could speculate that prices would go up. It is actually really hard to tell as it mostly depends on Russia, which is often depicted as a price maker in the market, through the world largest producer (Norilsk Nickel) and the state stockpiles sales. One could also assume that in case of a big rise in palladium demand, Norilsk would not be able to match it as it would imply an increase in nickel production (palladium is 'only' a "by-product" of nickel at Norilsk) and thus a decline in nickel prices.

Table 10.12 show the environmental pressures allocated to 1 t of PGM for the different producing regions and for the world mix, with four different palladium prices. In each case, the prices of platinum and rhodium are taken equal to their 2004 average value. The price of palladium is set equal to:

- its average in 2004 (base case scenario, 27% of platinum price);

[4]The volatility is a relevant index of the instability of prices.

- 50% of platinum price (scenario A1);
- 75% of platinum price (scenario A2);
- 100% of platinum price (scenario A3);

Figure 10.4 shows that a doubling of palladium price, while platinum and rhodium prices remain constant, would imply that 23% more $SO_2$ is emitted per ton PGM produced in the world (and correspondingly less for nickel produced from PGM containing ore). In such a scenario, the price of palladium would still remain half that of platinum and it would still be far from the extremes of the year 2001. Logically, scenarios A2 and A3 would lead to 44% and 61% higher $SO_2$ intensities of the PGM world production, respectively. The other two indicators ($CO_2$ and TMR) show a much lower degree of variation, confirming that an increase in palladium price would stress the need for improvement of the Russian PGM production regarding sulphur dioxide emissions. It can finally be concluded from the present section that the assumptions made for metal prices have a heavy influence on the allocation procedure and hence on the results regarding environmental impacts associated with PGM use.

Table 10.12: Influence of the allocation procedure on the environmental impacts associated with PGM production

| | *Primary production* | | | | *Secondary prod.* |
|---|---|---|---|---|---|
| **Unit: ton** | **World Mix** | **South Africa** | **Russia** | **North America** | **Belgium** |
| ***BAU prices: impact associated with the production of 1 t PGM (after allocation)*** | | | | | |
| $\mathbf{CO}_{2eq}$ | 23 451.1 | 35 143.2 | 6542.2 | 9365.8 | 4407.4 |
| $\mathbf{SO}_{2eq}$ | 1792.3 | 430.2 | 4274.9 | 1760.8 | 39.9 |
| $\mathbf{TMR}_{eq}$ | 377 227.9 | 610 781.5 | 32 479 | 118 663.5 | 12 712 |
| ***A1 prices: impact associated with the production of 1 t PGM (after allocation)*** | | | | | |
| $\mathbf{CO}_{2eq}$ | 24 407.1 | 35 516.9 | 8365.4 | 10 941.3 | 4407.4 |
| $\mathbf{SO}_{2eq}$ | 2205.6 | 434.8 | 5466.3 | 2057 | 39.9 |
| $\mathbf{TMR}_{eq}$ | 385 864.4 | 617 276.8 | 41 530.2 | 138 625.2 | 12 712 |
| ***A2 prices: impact associated with the production of 1 t PGM (after allocation)*** | | | | | |
| $\mathbf{CO}_{2eq}$ | 25 294.4 | 35 867.3 | 9983.2 | 12 625.4 | 4407.4 |
| $\mathbf{SO}_{2eq}$ | 2577.8 | 439.1 | 6523.4 | 2373.7 | 39.9 |
| $\mathbf{TMR}_{eq}$ | 394 073 | 623 365.6 | 49 561.9 | 159 962.8 | 12 712 |
| ***A3 prices: impact associated with the production of 1 t PGM (after allocation)*** | | | | | |
| $\mathbf{CO}_{2eq}$ | 26 048.3 | 36 165.7 | 11 296.8 | 14 251.3 | 4407.4 |
| $\mathbf{SO}_{2eq}$ | 2884.9 | 442.7 | 7381.7 | 2679.3 | 39.9 |
| $\mathbf{TMR}_{eq}$ | 401 200.7 | 628 552.1 | 56 083 | 180 563 | 12 712 |

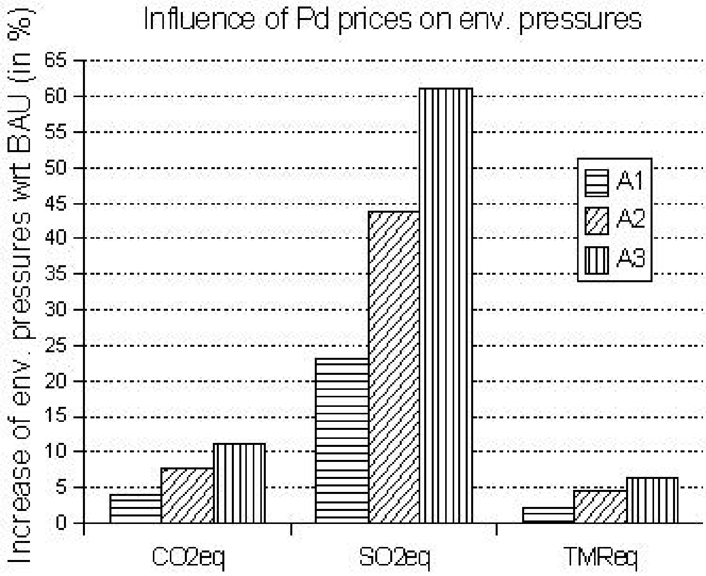



Figure 10.4: Increase of environmental pressures, compared to BAU levels, in A1, A2 and A3 palladium prices scenarios

## 10.4 Autocatalysts

### 10.4.1 Influence of EU Enlargement and Car Fleet Growth

The model predicts a steady decrease of the share of the EU15 in the PGM stock and flows of the EU25 for the period 2000-2020. However, the new members are still expected to account for less than 15% of PGM primary inputs in 2020. These results are illustrated in table 10.13.

If the European car fleet were to stop expanding after 2004 (scenario 'NG' for 'No Growth'), primary input would start to decrease, while secondary input would increase (because of a higher recycling potential). Total input in the NG scenario would still slightly go up due to the increasing share of diesel vehicles among the new registrations. At equivalent cylinder capacity, diesel autocatalysts indeed require a heavier PGM loading than petrol cars. This influence of the car fleet growth can be seen in figure 10.5.

Table 10.13: Evolution of the share of the EU15 in the PGM stock and flows associated with use of autocatalysts in the EU25

| EU15 / EU25 (in %) | **2000** | **2005** | **2010** | **2015** | **2020** |
|---|---|---|---|---|---|
| **Primary input** | 96 | 96 | 91 | 87 | 86 |
| **Secondary input** | 98 | 97 | 95 | 93 | 91 |
| **Stock** | 97 | 95 | 92 | 89 | 87 |

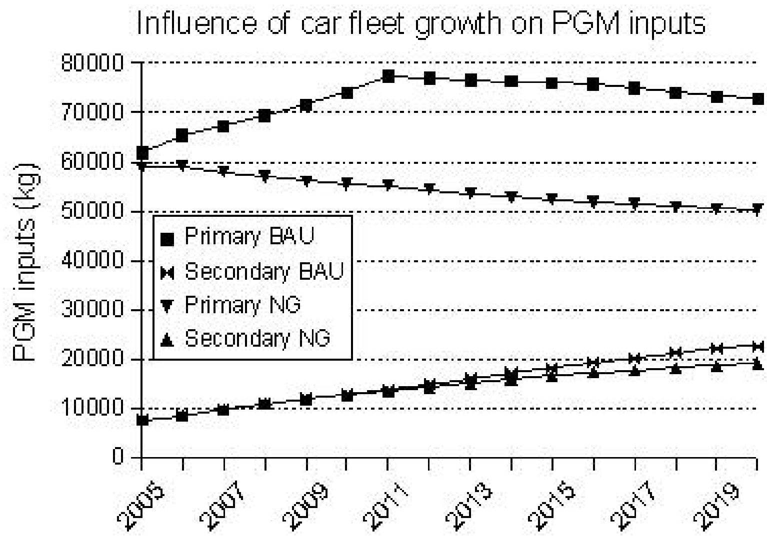



Figure 10.5: Comparison of PGM inputs in BAU and NG scenarios

### 10.4.2 Evolution of Environmental Pressures Associated with PGM Use in Autocatalysts

#### Base Case

The "base case" for autocatalysts corresponds to the assumptions regarding new registrations, share of diesel vehicles and recycling rates presented in chapter 8.1 and applied in the overall BAU scenario.[5] In the base case, new registrations of passenger vehicles stagnate after 2015 in EU25, the share of diesel cars among the new registrations increases from 49% in 2004 to 60% in 2020 in the EU15 and from 14% to 25% in the EU10, and the recycling rate is set to 30% (constant).

The evolution of the primary and secondary inputs of the three PGM are presented in table 10.14. Figure 10.6 compares the yearly PGM primary

[5]In the following, the base case for autocatalysts will be indifferently referred to as "base case" or "BAU"

inputs between 2005 and 2020 to the 2005 level. For instance, the overall PGM primary input has increased by 18% in 2020 compared to 2005, while the primary inputs of platinum and rhodium have increased by 32% and 3%, respectively, and the primary input of palladium has decrased by 6%. The main aspects of these developments are well reflected in the results regarding $SO_2$ emissions, displayed in table 10.15. The evolutions of carbon dioxide emissions and of TMR, shown in appendix E.2, present similar patterns as those of sulphur dioxide.

Sulphur dioxide emissions due to primary input increase by about 19.5% between 2005 and 2020 while emissions associated with PGM secondary production go up more than three folds between 2005 and 2020. This increase, however, represents less than 1% of the 20% of the total increase of $SO_2$ emissions. This shows again that recycling should be preferred over the use of primary metals. In this case, secondary input increases even though recycling rates do not, because the share of de-registered vehicles fitted with an autocatalyst increases with time, and so does the potential for recycling.

Between 2005 and 2020, the sulphur dioxide emissions associated with the use of palladium in autocatalysts decrease by almost 6% (consistent with the results presented in figure 10.6). This can be explained by the combined effects of the rising demand for diesel vehicles, whose catalytic convertors contain only platinum, and the stagnation of the total number of new registrations after 2015. For the same reason, the impact allocated to rhodium increases only slightly (3%) while $SO_2$ related to platinum use increases by 33% (to be compared with results shown by figure 10.6).

Diesel autocatalysts indeed contain only Pt, and they do so in higher quantities than the sum of the three PGM in catalytic convertors for petrol cars (for a given cylinder capacity). This also explains why total PGM input increases between 2015 and 2020 even though the number of new registrations remains constant. Total $SO_2$ emissions, however, tend to decrease in this period of market saturation, because the share of secondary input increases (the share of autocatalysts among de-registrations virtually reaches 100% and the share of de-registered diesel catalytic converters also increases).

It appears that many (positive or negative) aspects of the development of PGM use and its environmental impacts can be linked, at least partly, to the increasing demand for diesel cars. This parameter is therefore further investigated in the following sections.

### Influence of the Share of Diesel Cars Among New Registrations

There is a large disparity between the member states of the EU15 regarding the demand for diesel vehicles: only 8% of the newly registered passenger cars

Table 10.14: PGM inputs for autocatalysts in BAU scenario

| PGM inputs (in tons) | **Primary inputs** | **Secondary inputs** | **Total inputs** |
|---|---|---|---|
| ***PGM inputs for autocatalysts (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 61.76 | 7.75 | 69.5 |
| **Avg 2005-2020** | 72.73 | 15.47 | 88.2 |
| **Max 2005-2020** | 77.33 | 22.64 | 95.5 |
| **Cumul. 2005-2020** | 1163.71 | 247.44 | 1411.15 |
| ***Platinum inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 38.12 | 3.61 | 41.72 |
| **Avg 2005-2020** | 47.48 | 8.06 | 55.55 |
| **Max 2005-2020** | 50.3 | 13 | 63.29 |
| **Cumul. 2005-2020** | 759.75 | 129.01 | 888.77 |
| ***Palladium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 19.25 | 3.38 | 23.81 |
| **Avg 2005-2020** | 21.63 | 6.38 | 28.01 |
| **Max 2005-2020** | 23.18 | 8.32 | 29.49 |
| **Cumul. 2005-2020** | 346.04 | 102.08 | 448.11 |
| ***Rhodium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 3.21 | 0.76 | 3.97 |
| **Avg 2005-2020** | 3.62 | 1.02 | 4.64 |
| **Max 2005-2020** | 4.05 | 1.33 | 4.97 |
| **Cumul. 2005-2020** | 57.92 | 16.35 | 74.27 |

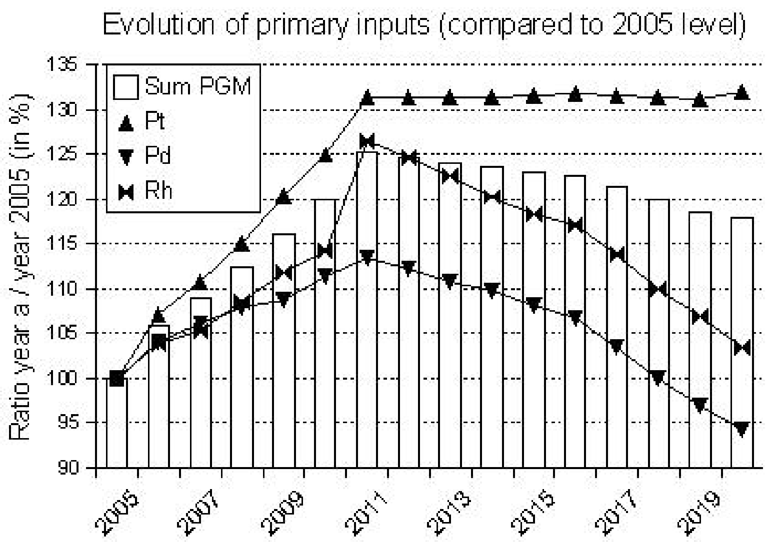



Figure 10.6: Evolution of Pt, Pd and Rh primary inputs in BAU scenario, with respect to 2005 levels

Table 10.15: Sulphur dioxide emissions associated with the use of PGM in autocatalysts in BAU scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| ***Emissions associated with PGM production (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 113 030.1 | 335.1 | 113 365.2 |
| **Avg 2005-2020** | 134 031.5 | 680.5 | 134 712.0 |
| **Max 2005-2020** | 142 512.2 | 1040.4 | 143 089.6 |
| **Cumul. 2005-2020** | 2 144 504.5 | 10 887.6 | 2 155 392.1 |
| ***Emissions associated with platinum production*** | | | |
| **Min 2005-2020** | 74 057.5 | 223.3 | 74 280.8 |
| **Avg 2005-2020** | 92 258.6 | 499.2 | 92 757.7 |
| **Max 2005-2020** | 97 719.3 | 804.5 | 98 523.8 |
| **Cumul. 2005-2020** | 1 476 136.9 | 7986.9 | 1 484 123.8 |
| ***Emissions associated with palladium production*** | | | |
| **Min 2005-2020** | 29 743.0 | 57.3 | 29 884.0 |
| **Avg 2005-2020** | 33 416.7 | 108.2 | 33 524.9 |
| **Max 2005-2020** | 35 820.4 | 141.0 | 35 927.4 |
| **Cumul. 2005-2020** | 534 667.7 | 1731.2 | 536 398.9 |
| ***Emissions associated with rhodium production*** | | | |
| **Min 2005-2020** | 7398.7 | 54.5 | 7453.2 |
| **Avg 2005-2020** | 8356.2 | 73.1 | 8429.3 |
| **Max 2005-2020** | 9355.8 | 94.8 | 9421.2 |
| **Cumul. 2005-2020** | 133 699.9 | 1169.6 | 134 869.5 |

were powered by a diesel engine in Sweden in 2004, this share reached 44% in Germany, while it was about 70% in France, Austria, Belgium and Luxembourg. According to ACEA, the share of diesel cars in new registrations more than doubled in ten years in EU15 (from 23% in 1994 to 49% in 2004). The increasing oil prices play in favour of the diesel engine, being more efficient than the petrol one. The now mature technologies of particulate filters and catalytic converters have also contributed to reduce the pollution problems linked to diesel.

In the base case, it is assumed that the share of diesel cars among new registrations in the EU15 will reach 60% in 2020 (and 25% in the EU10). A second scenario has been tested where the diesel share attains 80% in 2020 in the EU15 and 50% in the EU10 (HD scenario). A last scenario where demand for diesel cars actually remains constant after 2005 has also been tested (LD scenario). The results are presented in table E.14 in appendix E.2.

When looking at a particular metal, the changes can be substantial. For instance, in the HD scenario, where demand for diesel explodes, 19% more primary platinum is required for the period 2005-2020 than in the base case (see table E.14). At the same time, primary input of palladium and rhodium decrease by 30%. But at the aggregate level, the change is negligible: slightly above 2% more primary PGM is needed for the period. Consequently, the increase in cumulative $SO_2$ emissions over 2005-2020 associated with primary PGM production only reaches 4%.

#### Potential Introduction of a New Technology for Diesel Autocatalysts

The steadily rising interest for diesel cars sustains a growing demand for primary platinum and thus, high prices. Until recently, platinum was indeed the only PGM used in diesel autocatalysts because of its properties of resistance to sulphur and oxidation. However, research and development work undertaken by autocatalyst manufacturers, associated with the growing availability of low-sulphur diesel fuel and the increasing sophistication of modern engine management systems, led to a technological breakthrough. On the $2^{nd}$ of April 2006, Umicore published indeed a press release announcing that it had developed a new technology allowing the use of palladium in diesel autocatalysts. For a start, about 25% of the actual platinum content could be replaced by palladium (Umicore 2006).

A new scenario (DPd scenario) has been tested, applying the renewed PGM content to diesel autocatalysts from 2006 onwards (and holding all other things equal to the base case). The results are presented in table E.15 in appendix E.2. Palladium cumulative primary input for the period 2005-2020 increases by 50% while platinum primary input decrease by 23%. Of course, at the PGM aggregate level no difference can be noted. As a consequence, cumulative $SO_2$ emissions even decrease by 3%. This is due to the fact that the $SO_2$ intensity of palladium ($SO_2$ emissions allocated to the production of 1 t of Pd) is lower than that of platinum. Pd is indeed cheaper than Pt and this makes the difference after the allocation procedure.

### 10.4.3 Combinations of Scenarios

Shortly after Umicore's announcement of a technological breakthrough regarding diesel autocatalysts, palladium price reached a seventeen month high, while the price for platinum decreased by 20 USD. The price ratio Pd:Pt was actually not strongly modified but it might be the case when this new generation of autocatalysts is put on the market. It has already been mentioned (see section 10.3) that palladium prices are particularly volatile and analysts seem to agree upon the fact that increasing sales of diesel vehicles in Europe and in China (where diesel is strong), coupled with the use of palladium in diesel catalytic converters, should sustain a rise of palladium prices .

A new scenario is developed, combining the assumption for diesel used in section 10.4.2 (80% of new registrations in 2020 in EU15) with diesel autocatalysts containing 25% of palladium from 2006 onwards, and finally applying from 2006 palladium prices at half that of platinum (scenario A1 in section 10.3). The scenario is called HD-DPd-A1 and the results in terms of PGM inputs are presented in table 10.16, while the impact on $SO_2$ emissions are shown in table 10.17.

Table 10.16: PGM inputs for autocatalysts in HD-DPd-A1 scenario

| PGM inputs (in tons) | **Primary inputs** | **Secondary inputs** | **Total inputs** |
|---|---|---|---|
| ***PGM inputs for autocatalysts (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 61.99 | 7.62 | 69.61 |
| **Avg 2005-2020** | 74.63 | 15.29 | 89.92 |
| **Max 2005-2020** | 78.91 | 22.44 | 98.85 |
| **Cumul. 2005-2020** | 1194.12 | 244.66 | 1438.78 |
| **Cumul. HD-DPd-A1 / BAU** | 103% | 99% | 102% |
| ***Platinum inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 32.54 | 3.50 | 36.07 |
| **Avg 2005-2020** | 43.12 | 7.41 | 50.53 |
| **Max 2005-2020** | 50.48 | 11.50 | 61.98 |
| **Cumul. 2005-2020** | 689.85 | 118.58 | 808.43 |
| **Cumul. HD-DPd-A1 / BAU** | 91% | 92% | 91% |
| ***Palladium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 19.85 | 3.35 | 23.21 |
| **Avg 2005-2020** | 28.94 | 6.92 | 35.86 |
| **Max 2005-2020** | 32.26 | 9.79 | 38.82 |
| **Cumul. 2005-2020** | 463.11 | 110.65 | 573.76 |
| **Cumul. HD-DPd-A1 / BAU** | 134% | 108% | 128% |
| ***Rhodium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 1.35 | 0.76 | 2.5 |
| **Avg 2005-2020** | 2.57 | 0.96 | 3.54 |
| **Max 2005-2020** | 3.16 | 1.15 | 4.06 |
| **Cumul. 2005-2020** | 41.16 | 15.44 | 56.59 |
| **Cumul. HD-DPd-A1 / BAU** | 71% | 94% | 76% |

Compared to the base case, cumulative primary input of palladium increases by 34% while demand for primary platinum decreases by 10% (see table 10.18). In the same time, cumulative sulphur dioxide emissions (2005-2020) associated with the use of primary palladium more than double. Total $SO_2$ emissions, i.e. corresponding to the use of the three metals, increase by

Table 10.17: Sulphur dioxide emissions associated with the use of PGM in autocatalysts in HD-DPd-A1 scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| ***Emissions associated with PGM production (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 113 682.6 | 328.0 | 114 010.6 |
| **Avg 2005-2020** | 154 397.6 | 629.9 | 155 027.5 |
| **Max 2005-2020** | 165 489.1 | 930.5 | 166 038.8 |
| **Cumul. 2005-2020** | 2 470 360.7 | 10 079.1 | 2 480 439.8 |
| **Cumul. HD-DPd-A1 / BAU** | 115% | 93% | 115% |
| ***Emissions associated with platinum production*** | | | |
| **Min 2005-2020** | 57 456.6 | 185.5 | 57 642.1 |
| **Avg 2005-2020** | 76 572.9 | 391.3 | 76 964.2 |
| **Max 2005-2020** | 89 151.8 | 603.9 | 89 755.7 |
| **Cumul. 2005-2020** | 1 225 166.6 | 6250.0 | 1 231 426.6 |
| **Cumul. HD-DPd-A1 / BAU** | 83% | 78% | 82.97% |
| ***Emissions associated with palladium production*** | | | |
| **Min 2005-2020** | 30 671.0 | 56.9 | 30 727.9 |
| **Avg 2005-2020** | 72 411.5 | 179.64 | 72 591.2 |
| **Max 2005-2020** | 82 097.9 | 257.1 | 82 270.0 |
| **Cumul. 2005-2020** | 1 158 584.6 | 2874.2 | 1 161 458.8 |
| **Cumul. HD-DPd-A1 / BAU** | 217% | 166% | 217% |
| ***Emissions associated with rhodium production*** | | | |
| **Min 2005-2020** | 2819.4 | 46.4 | 2888.9 |
| **Avg 2005-2020** | 5413.1 | 59.1 | 5472.2 |
| **Max 2005-2020** | 7165.4 | 69.5 | 7219.9 |
| **Cumul. 2005-2020** | 86 609.5 | 944.9 | 87 554.4 |
| **Cumul. HD-DPd-A1 / BAU** | 65% | 81% | 65% |

15%, which is not negligible (see table 10.19).

A scenario with the share of diesel increasing up to 80% of new registrations in EU15 in 2020 (HD scenario) is actually not the most favourable one for increased palladium prices. The base case (60% of diesel registrations in 2020 in EU15) combined with the DPd scenario indeed implies a 50% rise in primary palladium input and a 23% drop in primary platinum input (against 34% and 10%, respectively, in the HD scenario). However, in such a case, and with Pd half the price of Pt (A1 scenario), the increase in cumulative $SO_2$ emissions would remain at 15% compared to BAU. The changes in emissions allocated to platinum and palladium indeed compensate each other.

The HD-DPd-A1 scenario is re-run after introducing a 70% recycling rate for autocatalysts in 2020 (as in scenario R1 in section 10.2.1). This new scenario is named HD-DPd-A1-R1 and the results can be seen in tables 10.18 and 10.19. In such a scenario, cumulative palladium primary input only goes up by 7% over the 2005-2020 period. Cumulative platinum primary input is down by 23% compared to the base case. Instead of increasing by 15% as in the scenario with low recycling, total cumulative $SO_2$ emissions actually decrease by 5%. Figure 10.7 shows the year-by-year comparison of the base case with the $SO_2$ emissions as calculated in scenarios HD-DPd-A1 and HD-DPd-A1-R1. For instance, in 2015 and 2020, sulphur dioxide emissions associated with the use of PGM in autocatalysts in the HD-DPd-A1 scenario are 15% and 14% higher than in the base case, respectively. At the same time, the HD-DPd-A1-R1 scenario gives emissions lower than BAU by 9% and 31%.

To sum up the modelling results of the last three sections, one could start by saying that the substitution of palladium for platinum (25% of it) in diesel autocatalysts would lead to an increase in demand for primary palladium and a decrease in demand for platinum. Under the assumptions and limitations of the present modelling, however, the total $SO_2$ emissions would remain virtually unchanged, if metal prices remain constant as well. But if the price of palladium happens to increase as high as 50% of that of platinum, $SO_2$ emissions associated with the use of PGM in autocatalysts might significantly rise (15% for 2005-2020 cumulative emissions). This would be the consequence of a suddenly higher $SO_2$ intensity of palladium due to the allocation factors reflecting metal prices. The problem would be offset if recycling increased. Higher secondary input indeed implies that demand for primary palladium would drop, therefore reducing the impact of Russian production (50% of the world primary palladium production).

Table 10.18: PGM inputs for autocatalysts in HD-DPd-A1-R1 scenario

| PGM inputs (in tons) | **Primary inputs** | **Secondary inputs** | **Total inputs** |
|---|---|---|---|
| ***PGM inputs for autocatalysts (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 46.50 | 8.25 | 69.61 |
| **Avg 2005-2020** | 61.99 | 27.94 | 89.92 |
| **Max 2005-2020** | 70.97 | 52.35 | 98.85 |
| **Cumul. 2005-2020** | 991.80 | 446.98 | 1438.78 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 85% | 181% | 102% |
| ***Platinum inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 31.95 | 3.79 | 36.07 |
| **Avg 2005-2020** | 36.85 | 13.68 | 50.53 |
| **Max 2005-2020** | 39.90 | 26.83 | 61.98 |
| **Cumul. 2005-2020** | 589.58 | 218.84 | 808.43 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 78% | 170% | 91% |
| ***Palladium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 11.52 | 3.63 | 23.21 |
| **Avg 2005-2020** | 23.30 | 12.56 | 35.86 |
| **Max 2005-2020** | 29.65 | 22.85 | 38.82 |
| **Cumul. 2005-2020** | 372.77 | 200.99 | 573.76 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 108% | 197% | 128% |
| ***Rhodium inputs for autocatalysts*** | | | |
| **Min 2005-2020** | 0 | 0.83 | 2.5 |
| **Avg 2005-2020** | 1.84 | 1.7 | 3.54 |
| **Max 2005-2020** | 3.04 | 2.67 | 2.5 |
| **Cumul. 2005-2020** | 29.63 | 27.15 | 56.59 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 51% | 166% | 76% |

Table 10.19: Sulphur dioxide emissions associated with the use of PGM in autocatalysts in HD-DPd-A1-R1 scenario

| $SO_2$ emissions (in tons) | **Primary Production** | **Secondary Production** | **Total** |
|---|---|---|---|
| ***Emissions associated with PGM production (Pt+Pd+Rh)*** | | | |
| **Min 2005-2020** | 91 400.2 | 355.3 | 93 571.4 |
| **Avg 2005-2020** | 127 448.3 | 1151.8 | 128 600.1 |
| **Max 2005-2020** | 148 328.5 | 2171.2 | 149 198.8 |
| **Cumul. 2005-2020** | 2 039 542.4 | 18 428.2 | 2 057 970.6 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 95% | 169% | 95% |
| ***Emissions associated with platinum production*** | | | |
| **Min 2005-2020** | 56 417.0 | 216.4 | 56 633.4 |
| **Avg 2005-2020** | 65 502.8 | 720.5 | 66 223.3 |
| **Max 2005-2020** | 75 279.6 | 1409.0 | 75 514.3 |
| **Cumul. 2005-2020** | 1 048 044.2 | 11 528.4 | 1 059 572.6 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 71% | 144% | 71% |
| ***Emissions associated with palladium production*** | | | |
| **Min 2005-2020** | 29 323.6 | 61.6 | 29 923.6 |
| **Avg 2005-2020** | 58 061.0 | 327.7 | 58 388.7 |
| **Max 2005-2020** | 75 449.7 | 600.0 | 75 597.6 |
| **Cumul. 2005-2020** | 928 975.5 | 5243.9 | 934 219.4 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 174% | 303% | 174% |
| ***Emissions associated with rhodium production*** | | | |
| **Min 2005-2020** | 0 | 54.2 | 162.2 |
| **Avg 2005-2020** | 3884.6 | 103.5 | 3988.1 |
| **Max 2005-2020** | 7018.9 | 162.2 | 7077.9 |
| **Cumul. 2005-2020** | 62 522.7 | 16556.0 | 64 178.7 |
| **Cumul. HD-DPd-A1-R1 / BAU** | 47% | 142% | 48% |

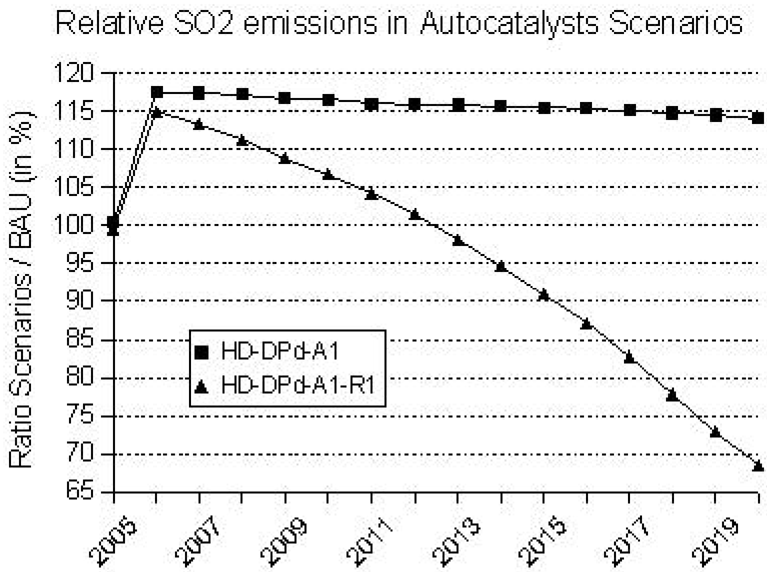



Figure 10.7: $SO_2$ emissions associated with PGM use in autocatalysts in scenarios HD-DPd-A1 and HD-DPd-A1-R1, relatively to BAU

### 10.4.4 Potential Introduction of Autocatalysts at the World Level

A simple model is used to roughly assess the consequences of the introduction of autocatalysts at the world level. The forecast for vehicles sales worldwide is taken from the IEA/SMP Transportation Model. Sales go up from 49.8 million in 2000 to 141.4 million in 2050. The share of diesel remains constant at around 18%. The IEA/SMP model considers light duty vehicles (LDV), i.e. it includes light trucks and SUVs as it is the custom in North America. The LDV fleet is assumed to expand from 683.4 million in 2000 to slightly over 2 billion in 2050, which would make a car density of about 200 cars for 1000 people if world population reaches 10 million in 2050. It remains far lower than today's equipment rate in OECD countries. It is assumed that from 2006 onwards each new car is fitted with a catalytic converter containing about 4 g of PGM (equivalent to a medium cylinder capacity Euro IV vehicle: 71% Pd, 17% Pt and 12% Rh for a petrol engine). The PGM recycling rate and the car average lifetime are set to 30% and ten years, respectively.

The use of primary PGM and the associated environmental impacts are presented in tables 10.20 and 10.21. Gordon *et al.* (2006, p.1213) estimate the world minable PGM resources at 53 000 t, including 29 000 t of platinum. Therefore, table 10.20 shows that the cumulative use of primary PGM until 2050, as estimated by this simple model, would require 25% of PGM resources, including 9% of the platinum resources.

If one assumes that the car fleet remains constant from 2050 (2 billion units), that the average lifetime of a vehicle is still ten years and that at the time recycling rate attains 50%, then the maintenance of the fleet requires $2.10^9 * \frac{1}{10} * \frac{1}{2} * 4.10^{-6} = 400$ tons of PGM per year. This rough estimate would indicate that the remaining resources could last another hundred years, if only autocatalysts are considered and if environmental and economic implications are disregarded.

Table 10.20: Use of primary PGM in the World-Autocat scenario

| Primary inputs (in t) | **Platinum** | **Palladium** | **Rhodium** | **PGM** |
|---|---|---|---|---|
| **2010** | 68.97 | 118.65 | 19.05 | 206.67 |
| **2020** | 79.49 | 139.95 | 22.47 | 241.92 |
| **2030** | 95.35 | 171.71 | 27.57 | 294.63 |
| **2040** | 104.74 | 214.68 | 34.47 | 353.90 |
| **2050** | 131.82 | 277.96 | 44.64 | 454.41 |
| **Cumul. 2006-2020** | 2645.24 | 7776.27 | 1248.77 | 13 370.85 |

Table 10.21: Environmental pressures associated with PGM production (after allocation) in the World-Autocat scenario

| Unit: ton | **$CO_{2eq}$** | **$SO_{2eq}$** | **$TMR_{2eq}$** |
|---|---|---|---|
| **2010** | 4 846 733.6 | 370 424.9 | 77 963 257.9 |
| **2020** | 5 673 308.4 | 433 598.2 | 91 259 319.0 |
| **2030** | 6 909 459.8 | 528 074.4 | 111 143 718.4 |
| **2040** | 8 299 286.7 | 634 295.8 | 133 500 101.2 |
| **2050** | 10 656 469.4 | 814 449.9 | 171 417 110.4 |

## 10.5 Fuel Cell Vehicles

### 10.5.1 Potential Environmental Pressures Associated with PGM Use in Fuel Cells

The model developed in the present study to simulate the development of fuel cell vehicles in Europe between 2010 and 2030 (see chapter 8.2) consists of a total of eighteen scenarios. Two forecasts (HR and LR) for future registrations of FCVs are combined with nine scenarios regarding the evolution of the platinum content of the fuel cell stack. This content also depends on the power needed for the vehicle. The model is run for three scenarios with differing levels of stack power. In the "base case", the power increases linearily from 75 kW to 100 kW. In the two other scenarios, the power either remains constant (75 kW) or decreases (from 75 kW to 50 kW). The average power of newly registered cars powered by an internal combustion engine has increased by about one third over the past ten years, this is why the scenario with increasing power is taken as a base case in the fuel cell model.

Table 10.22 shows the results for the three power scenarios, in the case of a high market penetration of FCVs in Europe (results for $CO_2$ and TMR are displayed in appendix E.3). For each power scenario, the best, average and worst cases among the nine HR scenarios are presented. By keeping the power of the fuel cell stack constant, 20% of the cumulative primary input of platinum could be saved compared to the base case (increasing power). In 2030, the savings would almost reach 30% of the yearly primary input. Comparable shares (19-20%) of cumulative $CO_2$, $SO_2$ and TMR could be spared. The cumulative and yearly savings could attain 40% and 53% of the 75-100 kW scenario if the FCV power decreased instead of increasing. On the one hand, given the evolution observed today for the power of thermal engines, such an option seems unlikely. A legislation could, on the other hand, restrict the power of the stacks. Such a measure could however have undesirable effects such as hampering the market penetration of the product or reducing the incentives for the constructors to reduce platinum density (in g/kW).

### 10.5.2 Potential Introduction of Fuel Cells at the World Level

A simple model is used to estimate the impact of the introduction of fuel cells at the world level. Two penetration scenarios are considered where the new registrations of FCVs are taken as a share of the total car sales (taken from the IEA model as in section 10.4.4 and named wHR and wLR scenarios, which stands for high and low world registrations, respectively). Combined to that, three scenarios concerning the improvement of the fuel cell platinum content are tested (see table 10.23). In this somewhat rough model, the technological improvement is stated, using previous simulations of technological progression *via* learning curves. The three scenarios for the reduction of FCV Pt content (called HPt, MPt and LPt) correspond indeed to the best, the average and the worst cases observed in the model developed in chapter 8.2 under the assumptions 'high registrations' and 'FC stack constant

Table 10.22: Platinum primary input and associated $SO_{2eq}$ emissions in the HR 75-100 kW, HR 75 kW and HR 75-50 kW scenarios

| **Scenario HR 75-100 kW** | **Yearly Figures (in tons)** | | | **Cumulative 2010-2030 (in tons)** |
|---|---|---|---|---|
| | **Min** | **Avg** | **Max** | |
| ***Platinum primary inputs*** | | | | |
| **Best Case** | 0.75 | 17.34 | 29.86 | 312.21 |
| **Avg Case** | 1.27 | 56.60 | 112.84 | 1018.82 |
| **Worst Case** | 2.02 | 131.15 | 278.07 | 2360.72 |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | |
| **Best Case** | 1457.2 | 33 787.5 | 58 465.6 | 608 174.6 |
| **Avg Case** | 2476.3 | 110 186.6 | 220 417.9 | 1 983 358.1 |
| **Worst Case** | 3918.2 | 255 247.3 | 542 744.3 | 4 594 450.9 |

| **Scenario HR 75 kW** | **Yearly Figures (in tons)** | | | **Cumulative 2010-2030 (in tons)** | **Cumul. 75 kW / 75-100 kW** |
|---|---|---|---|---|---|
| | **Min** | **Avg** | **Max** | | |
| ***Platinum primary inputs*** | | | | | |
| **Best Case** | 0.75 | 14.02 | 21.52 | 252.43 | 81% |
| **Avg Case** | 1.27 | 45.55 | 81.59 | 819.85 | 80% |
| **Worst Case** | 2.02 | 105.31 | 202.11 | 1895.6 | 80% |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 1457.2 | 27 329.2 | 42 054.0 | 491 926.0 | 81% |
| **Avg Case** | 2476.3 | 88 695.9 | 159 572.2 | 1 596 526.8 | 81% |
| **Worst Case** | 3918.2 | 205 014.9 | 394 950.2 | 3 690 268.9 | 80% |

| **Scenario HR 75-50 kW** | **Yearly Figures (in tons)** | | | **Cumulative 2010-2030 (in tons)** | **Cumul. 75-50 kW / 75-100 kW** |
|---|---|---|---|---|---|
| | **Min** | **Avg** | **Max** | | |
| ***Platinum primary inputs*** | | | | | |
| **Best Case** | 0.75 | 10.70 | 15.96 | 192.64 | 62% |
| **Avg Case** | 1.27 | 34.49 | 54.06 | 620.87 | 61% |
| **Worst Case** | 2.02 | 79.47 | 129.65 | 1430.48 | 61% |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 1457.2 | 20 871.0 | 31 044.0 | 375 677.4 | 62% |
| **Avg Case** | 2476.3 | 67 205.3 | 105 386.9 | 1 209 695.4 | 61% |
| **Worst Case** | 3918.2 | 154 782.6 | 253 057.8 | 2 786 087.0 | 61% |

power' (75 kW). In the best case, the platinum content of the stack in 2030 is similar to that of an autocatalyst today. FCVs are assumed to have an average lifetime of ten years and the recycling rates in set to 75% as in chapter 8.2.

In the 'high registrations scenario', FCVs represent 35% of the 2 billion passenger car fleet in 2050. Depending on the evolution considered for FCVs' Pt content, the cumulative use of primary platinum would represent 18%, 63% or 150% of the world resources, as estimated in 2005 by Gordon *et al.* (2006, p.1213) (see table 10.24). Even though it is likely that known resources will increase in the future, it remains that an important technological improvement is needed (such as the one considered in the best case) in order to be able to introduce FCV at a world scale without jeopardizing the world platinum resources, not to mention environmental and economic implications of depletion.

Table 10.23: Scenarios for the introduction of FCVs at the world level

| **Scenarios** | **Units** | **2010** | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|---|
| **H Pt** | g Pt / FCV | 80.67 | 46.28 | 41.52 | 39.11 | 39.11 |
| **M Pt** | g Pt / FCV | 50.98 | 20.95 | 17.76 | 16.23 | 16.23 |
| **L Pt** | g Pt / FCV | 30 | 7.06 | 5.32 | 4.55 | 4.55 |
| **wHR** | % of sales | 2 | 10 | 30 | 70 | 80 |
| **wLR** | % of sales | 0 | 2 | 5 | 15 | 20 |
| **wHR** | % of car fleet | 0 | 2.2 | 12.1 | 27.9 | 35.7 |
| **wLR** | % of car fleet | 0 | 0.6 | 2.2 | 5.4 | 9.1 |

Table 10.24: Use of primary platinum for the introduction of FCV at the world level and relevance regarding world Pt resources

| **Modelling Results 2010-2050** | | **Cumulative use of primary Pt (in tons)** | **Share of world resources (in %)** |
|---|---|---|---|
| **H Pt** | **wHR** | 43 557.57 | 150 |
| | **wLR** | 9958.47 | 34 |
| **M Pt** | **wHR** | 18 154.59 | 63 |
| | **wLR** | 4 146.36 | 14 |
| **L Pt** | **wHR** | 5156.82 | 18 |
| | **wLR** | 1173.77 | 4 |

# Conclusions

Platinum group metals, especially platinum, palladium and rhodium, are essential inputs for a number of industrial processes or consumer goods. The PGM primary and secondary inputs of seven industrial sectors and product groups have been scrutinized and forecasted in Europe for the time period 1990-2020. The environmental pressures associated with the primary or secondary production of these precious metals to be used in Europe have been studied in four regions of the world (three for primary production and one for secondary production). Part of the environmental burden is allocated to each metal produced, according to its market value.

An overall model was finally developed, accordingly to the aim of the study, to represent the environmental impacts associated with the use of PGM in Europe. Still in accordance with the aim of the study, the model allows to compare the environmental impacts of primary and secondary production[6] and to investigate potential levers available, at the production or use level, to mitigate environmental pressures. The conclusions presented below cover these three aspects defined by the aim of the study: modelling environmental impacts, providing insights into the issue of shifting environmental burden outside Europe and investigating potential levers available to mitigate environmental impacts associated with the use of PGM in Europe.

- Among the three investigated environmental pressures ($CO_{2eq}$, $SO_{2eq}$ and $TMR_{eq}$), it seems that the sulphur dioxide emissions associated with the production of PGM used in Europe can be considered as relevant when compared with total $SO_2$ emissions at the EU level. The same sort of comparison shows that carbon dioxide and TMR are of lesser relevance at the European level. It appears, however, that the TMR related to PGM use in Europe represents a share of the EU total TMR at least three times larger than that of $CO_2$ emissions associated with PGM use in Europe when compared to EU total $CO_2$ emissions.

[6] Assuming that the former occurs outside Europe while the latter occurs within Europe, this point constitutes an aspect of the problem of shifting environmental burden from Europe to other parts of the world.

- Assuming that PGM secondary production takes place in Europe, while primary production occurs in South Africa, Russia and North America, it seems that the problem shifting of environmental pressures from Europe to other parts of the world is here again more relevant for sulphur dioxide (the difference between the primary and secondary production paths is 1.5 and 9 times larger than in the case of TMR and carbon dioxide, respectively).

- The amount of $SO_2$ emissions, as well as the problem shifting issue, could be addressed through increased recycling, which couples the advantages of low sulphur dioxide intensity and preservation of primary resources. Autocatalysts and electronic products present promising potentials for enhanced recyling. Primary metals are however needed in a growing economy, hence the necessity to also improve the environmental performance of primary production (especially in Russia when considering $SO_2$ emissions).

- The automobile sector, producing catalytic convertors, is the largest consumer of PGM. Therefore, the consumers' demand patterns (e.g. concerning diesel cars) or the technological evolution (e.g. the introduction of diesel autocatalysts containing palladium) could heavily impact the use of PGM in the EU and the environmental impacts associated with it. Catalytic convertors represent indeed today over 60% of the European use of primary PGM and the same share of the $SO_2$ emissions related to the use of PGM in Europe.

- Regarding the potential future introduction of fuel cell vehicles, it appears that important technological improvements are needed to reduce the PGM content of the fuel cell stack and thus allow a wide scale development. Independently from technological progress, the power of a FCV seems a major parameter concerning the total amount of PGM aboard the vehicle.

- From a methodological point of view, the allocation procedure has a decisive influence on the final values of the environmental indicators. It could be shown in the present study that the prices for platinum group metals, which make the core of the allocation procedure, are essential assumptions in this respect and need to be handled carefully.

### Recommendations for future research

The technologies involved in PGM production, especially those designed to mitigate environmental impacts, are constantly evolving. The analysis of

PGM production (primary and secondary) could therefore be regularly updated. More reliable data need also to be found for the Russian production. The study of PGM production in North America could be expanded to more producers.

The modelling of PGM use in Europe could be further developed towards more details and accuracy. For instance, the model for autocatalysts in Europe should consider more than one average cylinder capacity. The industrial efficiency in the manufacturing of PGM containing products or in processes using PGM could be investigated at the European level as Hagelüken *et al.* (2005) did for Germany. This would, however, require considerable effort and seems rather like an impossible task for non-insiders of the PGM business.

# Appendix

# Appendix A

# Calculations for the MFA of PGM Primary Production

## A.1 South Africa

This section presents the calculations conducted to estimate the flows of minerals in Anglo Platinum's PGM primary production. The results make up the 'detailed' flow sheet as depicted in figure 3.2.

The amount of rocks mined per ton of PGM (616 900 t) is directly obtained by normalization of the data published by Anglo Platinum. The total inputs (ore and recycled furnace slag; 275 400 t) of the process 'milling and concentrating' are obtained in the same manner.

The shares of ore and furnace slag cannot be estimated at this step and the calculations are thus not pursued further downstream. Instead, the mineral flows are calculated upstream starting from the output of refined nickel and copper. Kerfoot (1991, p.170) indeed indicates that the converter matte analyses 75% of nickel and copper together.

Applying the transfer coefficients of the processes 'separating and leaching' ($TC_1$) and 'base metals refining' ($TC_2$) (see table 3.1), the mass of the flow 'converter matte' (344 t) can be estimated. The use of auxiliary materials in these two processes is disregarded due to lack of data. Equation 2.1 described in the methodology (chapter 2) is applied:

$$\text{converter matte} * \text{grade (Ni+Cu)} = \frac{\text{refined (Ni+Cu)}}{\text{TC}_1 * \text{TC}_2} \qquad \text{(A.1)}$$

Following the same procedure, the flows further upstream are calculated. Furnace matte constitutes the input to the process 'converting'. Using the previous result, equation 2.1 and the data displayed in table 5.2, the mass flow can be estimated:

$$\frac{\text{furnace matte} * \text{TC}}{\text{grades ratio output:input}} = \text{conv. matte} \tag{A.2}$$

The same method is then applied to the result (1053 t of furnace matte) to calculate the inputs to the process 'smelting' (flotation concentrate and converter slag):

$$\frac{(\text{flotation conc.} + \text{conv. slag}) * \text{TC}}{\text{grades ratio output:input}} = \text{furnace matte} \tag{A.3}$$

To calculate the share of the converter slag in the previous result (8059 t), the mass balance is applied to the process 'converting'. Due to lack of data, the quantities of fluxing agents (notably silica) used in this process are not considered. The relationship between input and output of the converting process is assumed as follows:

$$\text{furnace matte} = \text{conv. matte} + \text{conv. slag} + \text{S emissions} \tag{A.4}$$

The sulphur emissions (215 t) are estimated as the difference between total sulphur contents of furnace matte and converter matte (sulphur content of the slag is disregarded). The calculated mass of converter slag (494 t) gives the mass of flotation concentrate (7565 t). Starting from this last value, the inputs to the process 'milling and concentrating' can be estimated:

$$\frac{(\text{ore} + \text{furnace slag}) * \text{TC}}{\text{grades ratio output:input}} = \text{flotation conc.} \tag{A.5}$$

The result (270 179 t of ore and recycled furnace slag) is lower than the mass obtained at the beginning of this section directly from data published by Anglo Platinum (275 400 t). It is considered that the corporate figure is more reliable than the other estimate. Therefore the latter value is retained. Some of the previous results need now to be adjusted.

Applying again equation A.5, the mass of flotation concentrate is now assumed to be 7711 t. Consequently, the quantity of converter slag is now 348 t. The values for furnace and converter mattes remain unchanged. The mass of furnace slag recycled in the milling process is finally calculated using the following relationship:

$$\text{flotation conc.} + \text{conv. slag} = \text{recycled furnace slag} + \text{discarded furnace slag} + \text{furnace matte} + \text{S emissions} \quad (A.6)$$

The amount of discarded slag is taken from Anglo Platinum's data (196 t). The sulphur emissions (410 t) are calulated as previously described: difference of sulphur content between flotation concentrate and furnace matte. Finally, the mass of recycled furnace slag (6400 t) gives the mass of ore stemming from the mining process (269 000 t). Starting from the quantity of converter matte, the last mineral flows (PGM and base metals concentrates) are simply calculated using the equation 2.1 and the transfer coefficients of table 3.1.

## A.2 Russia

This section presents the calculations conducted to adapt Hochfeld's (1997, p.95) flowsheet to the year 2004. The assessment of sulphur dioxide emissions is done in chapter 4.3 and will not be repeated here.

PGM production from the Taimyr Peninsula (147.9 t) is taken from Johnson Matthey (2005, p.16). Nickel and copper productions from the Siberian ore (i.e. excluding the production from metal scrap) amounted to 241 000 t and 398 000 t in 2004, respectively (Norilsk Nickel 2005, p.4). Normalized by PGM production, this makes 1630 t/t PGM and 2691 t/t PGM, respectively. Similarly, gold production from Norilsk reached 0.03 t per ton PGM produced.

Johnson Matthey (2005, p.17) indicates that, in 2004, about 13 million tons of ore have been processed in the Taimyr Peninsula. This means that 87 897 t of ore are produced and milled for each ton of PGM produced. Hochfeld (1997, p.95) assumes that 100 kg of waste rocks are discarded per ton of valuable ore produced. It can therefore be estimated that, in 2004, 96 687 t of rocks were mined and 8790 t of waste rocks were dumped per ton of PGM produced.

In the same manner, Hochfeld (1997, p.95) indicates that about 0.8 t of tailings are rejected for each ton of flotation concentrate produced. Disregarding the use of auxiliary materials and applying the mass balance, it can therefore be assumed that, in 2004, 48 832 t of flotation concentrate were produced. For the pyro- and hydrometallurgical processes (including base metals refining but excluding precious metals refining), Hochfeld (1997, p.95) estimates that 0.84 t of slag are discarded per ton of flotation concentrate treated, which, in the present study, gives a mass of slag of 41 019 t.

Still using Hochfeld's flowsheet, the amount of converter matte produced per ton PGM is estimated at 17 091 t (i.e. 0.35 times the mass of flotation concentrate). The converter matte is then treated to separate base and precious metals. The latter are recovered in anode slimes, which are the waste output of base metals electrowinning. Hochfeld (1997, p.94) precises that, in 1994, 3300 t of PGM containing anode slimes were produced. Using Johnson Matthey's Russian production estimates from this period (136.5 t), it can be assumed that 24 t of PGM concentrate (as anode slimes) are produced per ton refined PGM produced. Assuming a 100% yield in the separation process, the mass of Ni/Cu concentrate reaches 17 067 t per ton PGM (i.e. mass of converter matte − mass of anode slimes).

Hochfeld (1997, p.95) presents the following power uses per production process: 63 kWh/t ore produced, 48 kWh/t flotation concentrate produced and 17 100 MWh/t PGM for the metallurgical steps. In 2004, this gives a power consumption of 28.4 TJ/t PGM for the combined mining-milling-concentrating processes. The pyro- and hydrometallurgical processes use 61.6 TJ/t PGM, excluding precious metal refining which is assumed to use 3.8 TJ/t PGM (value taken from Inco in Canada because of a lack of data).

The use of fossil fuel (natural gas) in the pyrometallurgical processes is taken equal to that applied by Hochfeld (124 TJ/t PGM). Since carbon dioxide emissions are directly derived from the use of natural gas, Hochfeld's value is taken (6850 t/t PGM).

## A.3 North America

The present section shows part of the calculations conducted to draw the 'detailed' flow sheet in figure 5.2. Only the flows of minerals are addressed here.

Contrary to the South African case, no data is available concerning the amount of rocks mined. However, the final outputs of nickel (10 381 t) and copper (11 810 t) are known. Kerfoot (1991, p.169) precises that the converter matte from Copper Cliff smelter contains 78% of nickel and copper altogether. Given the transfer coefficients of the processes 'separating and leaching' and 'base metals refining' (see table 5.2), and disregarding the auxiliary materials used for these steps, it is possible to estimate the mass of the flow 'converter matte': 28 737 t. Equation 2.1 described in the methodology (chapter 2) is applied:

$$\text{converter matte} * \text{grade (Ni+Cu)} \quad = \quad \frac{\text{refined (Ni+Cu)}}{\text{TC}_1 * \text{TC}_2} \qquad \text{(A.7)}$$

Based on the same method, the flows further upstream are calculated. The inputs to the process 'smelting and converting' are called flotation concentrate (output from 'milling and concentrating') and converter slag (waste output from the converting process recycled in the smelter; this flow is not drawn on the flow sheet). They are calculated using equation 2.1 and the data displayed in table 5.2:

$$\frac{(\text{flotation conc. + conv. slag}) * \text{TC}}{\text{grades ratio output:input}} = \text{conv. matte} \qquad (A.8)$$

The result (155 659 t) allows to calculate the output of the smelting process, the furnace matte (not drawn on the flow sheet):

$$\frac{(\text{flotation conc. + conv. slag}) * \text{TC}}{\text{grades ratio output:input}} = \text{furnace matte} \qquad (A.9)$$

Applying the mass balance to the converting process, it is then assumed that:

$$\text{furnace matte} = \text{conv. matte} + \text{conv. slag} + \text{S emissions} \qquad (A.10)$$

This relationship disregards the fluxing agents applied to the process. The quantity used is most probably not negligible but data are not available. The sulphur emissions (11 587 t) are estimated as the difference between the total sulphur content of the furnace matte (25%) and of the converter matte (20%). It gives an estimate for the converter slag (29 015 t) and consequently for the flotation concentrate (126 644 t). Using this last result, the inputs to the process 'milling and concentrating' (ore and recycled furnace slag) can be estimated:

$$\frac{(\text{ore + furnace slag}) * \text{TC}}{\text{grades ratio output:input}} = \text{flotation conc.} \qquad (A.11)$$

There are no data regarding recycling rates, therefore the share of recycled furnace slag included in the last result (1 138 373 t) has to be determined indirectly. Johnson Matthey (2005, p.18) indicates that in its Sudbury facilities the Canadian mining company Falconbridge processes 100 000 t of ore to produce 1 t of nickel. This ratio is applied to Inco's nickel production (10 381 t / t PGM) which actually stems from the same region. It can thus be estimated that 1 038 100 t of ore should be milled to extract one ton of

PGM. According to Hochfeld (1997, p.77) the mining process leads to 60 kg of waste rocks per ton of ore. Therefore, it appears that 1 100 386 t of rocks are mined per ton PGM produced.

Consequently, the estimate for the recycled furnace slag amounts to 100 273 t. The quantity of discarded furnace slag is given by Inco: 101 407 t, but this figure probably includes slag from other processes than smelting (e.g. base metals refining). However, the estimated mass of slag (recycled and discarded) exceeds the mass of inputs to the pyrometallurgical processes. This incoherence can be explained by the large amount of fluxing agents (e.g. silica) used in the smelting and converting processes. These materials indeed end up in the slag.

In his study Hochfeld (1997, p.80) estimated the amount of rocks being mined per ton PGM as 1 410 000 t. This figure is higher than the one used in this study (1 100 386 t, see above). However, even with this lower number, the calculated quantity of waste (rocks and talings) exceeds by far the figure reported by Inco: 1 175 422 t against 468 571 t. One explanation might be that the pyrrhotite rejected is not, or partially not, counted as waste. It could indeed theoretically be treated to recover the metal values if a clean process was available.

Applying equation 2.1 and the transfer coefficients of table 3.1 to the mass flow of converter matte, the last mineral flows (PGM and base metals concentrates) are finally calculated. The method is the same as for the calculation of the previous mineral flows.

# Appendix B

# Validation of the Model for the Bottom-Up Material Flow Analysis

## B.1 Autocatalysts

### B.1.1 Methodology

#### Fleet of Passenger Cars and Autocatalysts

The evolution of the passenger car fleet in Germany is modelled between 1985 and 2020. The resolution of the dynamic system is programmed with a numerical calculation software called Scilab.[1] The fleet is divided into five technological categories (Table B.1) whose evolutions are modelled separetely and whose sum gives the aggregate picture. For each technological category, the fleet in a given year is in turn divided into 25 age categories: from 0-1 year old cars to 24-25 years old cars.

Table B.1: The five technological categories used in the model

<table>
<tr><td colspan="3">cylinder capacity</td></tr>
<tr><td>$< 1.4$ L</td><td>1.4 - 2 L</td><td>$> 2$ L</td></tr>
<tr><td>petrol inf</td><td>petrol int</td><td>petrol sup</td></tr>
<tr><td colspan="2">diesel inf</td><td>diesel sup</td></tr>
</table>

The model implemented is of the 'survival type' which means that the car

[1] Scilab is a Free Scientific Software Package available from www.scilab.org

fleet in a given year is calculated as the sum of the new registrations and the cars registered in the previous years still in use. The latter figure is obtained as the number of cars which 'survived' from the previous year. The model is therefore iterative from one year to the next. The 'survival rates' differ according to the age and technological categories. On the other hand, they are taken as constant with time. The survival rates were derived from data used by Bourdeau (1998, p.220) for the modelisation of the French car fleet between 1970 and 2020.

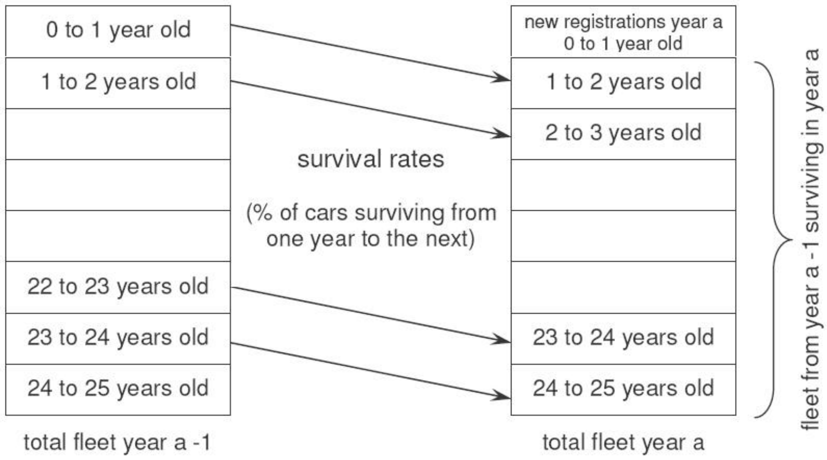



Figure B.1: Dynamic evolution of a car fleet, after Glaude and Moutardier (1978)

The modelisation of the car fleet is actually analog to that of a population – provided that one replaces 'registrations' by 'births' and 'de-registrations' by 'deaths'. Figure B.1 illustrates the iterative calculation which is at the core of the model. Now, to be programmed and simulated, the dynamic system has to be written mathematically:

$$\mathcal{N}_k(t+1) = \begin{pmatrix} 0 & 0 & \dots & 0 & 0 \\ r_{k,1}(t) & \ddots & \ddots & \ddots & 0 \\ 0 & r_{k,2}(t) & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \dots & r_{k,2}(t) & 0 \end{pmatrix} \mathcal{N}_k(t) + \begin{pmatrix} Reg_k(t) \\ 0 \\ \vdots \\ \vdots \\ 0 \end{pmatrix} \quad \text{(B.1)}$$

where $\mathcal{N}_k(t+1)$ is the column vector representing the car population of the technological category $k$ in year $t+1$. $\mathcal{N}_k$ has 25 rows corresponding to the 25 age categories. $r_{k,j}(t)$ is the survival rate between years $t$ and $t+1$ of cars from age category $j$ and technological category $k$. $Reg_k(t)$ corresponds to the new registrations of cars of the technological category $k$ in year $t$.

The new registrations curve was taken identical to the one used by Hagelüken *et al.* (2005, p.63). On the other hand, de-registrations were calculated each year by the model by applying the survival rates to the car fleet. The initial conditions needed to run the solver were obtained from different sources. The age structure of the car fleet in 1985 was derived from data for Austria (Gabriel *et al.* 2000, p.37). The distribution of the technological categories was extrapolated from German data (KBA 2005).

The fleet of cars equipped with an autocatalyst is divided in five 'environmental categories' corresponding to the legal requirements for emissions from passenger cars (Table B.2). The evolution of each category is modelled following the same principle as above but from the first year of application of each regulation and with initial conditions equal to zero. This reflects the following two assumptions:

- Prior to its first year of application, no car complies with the regulation.
- A given regulation stops to be applied to new cars when a new one comes into force.

Table B.2: The five environmental categories used in the model

| before 1986 | 1987 - 1991 | 1992 - 1995 | 1996 - 1999 | 2000 - 2004 | 2005 - 2020 |
|---|---|---|---|---|---|
| no regulation | G-Kat 87-90 | Euro I | Euro II | Euro III | Euro IV |

### PGM Flows

In order to model the PGM total input for new vehicles as well as the potential PGM recycling from de-registered cars it is assumed, after Hagelüken *et al.* (2005, p.71), that there is a correlation between the motor type (petrol, diesel), the cylinder capacity, the environmental category (Table B.2) and the PGM content of the vehicle.

Hagelüken *et al.* (2005) conducted a detailed study in Germany to quantify this correlation. In his calculations the share of the different car brands (and thus different 'corporate' PGM contents in autocatalysts) was considered for each technological category of the new registrations in Germany. The aggregate results are presented in table B.3. The given values are said to correspond to vehicles at the end of the use phase but it is assumed in the present work that the PGM losses during this phase are negligible and table B.3 is used to calculate the PGM inputs for new registrations as well as the PGM potential recovery from de-registrations.

Hagelüken *et al.* (2005, p.80) write that for the modern and well maintained autocatalysts in western Europe losses during the use phase are significantly lower than 5% of the PGM content. However, (Hochfeld 1997, p.117) and De Man (2005, p.49) cite a much higher figure (25%) but it is precised then that the major causes for high losses are poor maintenance and accidental damages to the autocatalysts. This issue is currently raising concern for economic and health reasons. On the one hand, PGM accumulation along some busy roads approaches concentrations that would be economically viable to recover (De Man 2005, p.50). On the other hand, very little is known about the toxicity and bioavailability of PGM.

The secondary input is estimated as 30% of the potential recycling. This rather low value is taken from Hagelüken *et al.* (2005, p.87) who conducted a field study of the recycling chain for autocatalysts in Germany. The 70% losses are for a major part (almost 60% of all losses) due to 'unknown' reasons. These mysterious reasons can probably be explained to a large extent by exports of second-hand cars to countries of middle and eastern Europe or Africa.

## B.1.2 Comparison with the Literature

The purpose of this section is to test the model. Therefore the results obtained with the programme are compared with the data stemming from the study in Hagelüken *et al.* (2005, Chapter 4.2, p.51-92).

#### Fleet of Passenger Cars and Autocatalysts

The aggregate curve for new registrations has been taken identical to the representation in Hagelüken *et al.* (2005, p.63, Abb.4.16), except for the period 1985-1991 which was assumed to evolve linearily from 2.5 to 4.1 million. The share of each technological category has been adapted from official German data (KBA 2005) to fit with the assumptions made by Hagelüken *et al.* (2005). The consecutive evolution assumed for the share of diesel vehicles among the new registrations is presented in Table B.4. The remaining values were obtained by linear interpolation. Figure B.2 compares the results obtained with those presented in Hagelüken *et al.* (2005, p.63, Abb. 4.16). The evolution of the curves looks rather similar (the share of diesel cars really takes off after 1997; the number of new registrations evolves towards 2.5 million for petrol cars and to over 1.5 million for diesel vehicles). However,

Table B.3: PGM content of ELV in Germany wrt the environmental and technological categories, after Hagelüken (2005, p.72)

| PGM content | Petrol cars | | | | | Diesel cars | |
|---|---|---|---|---|---|---|---|
| | cylinder capacity | g/vehicle | | | | cylinder capacity | g/vehicle |
| | | Pt | Pd | Rh | sum | | Pt |
| G-Kat 87-90 | < 1.4 L | **0.95** | **0.00** | **0.19** | **1.14** | | |
| | 1.4 - 2 L | **1.43** | **0.00** | **0.29** | **1.71** | < 2 L | |
| | > 2 L | **2.09** | **0.00** | **0.43** | **2.52** | > 2 L | |
| Euro I | < 1.4 L | **0.95** | **0.00** | **0.19** | **1.14** | | |
| | 1.4 - 2 L | **1.71** | **0.00** | **0.33** | **2.04** | < 2 L | |
| | > 2 L | **2.76** | **0.00** | **0.57** | **3.33** | > 2 L | |
| Euro II | < 1.4 L | **0.29** | **1.14** | **0.19** | **1.62** | | |
| | 1.4 - 2 L | **0.38** | **2.00** | **0.29** | **2.66** | < 2 L | **1.43** |
| | > 2 L | **2.09** | **3.04** | **0.67** | **5.80** | > 2 L | **4.28** |
| Euro III | < 1.4 L | **0.10** | **2.47** | **0.29** | **2.85** | | |
| | 1.4 - 2 L | **0.48** | **2.76** | **0.29** | **3.52** | < 2 L | **4.09** |
| | > 2 L | **0.57** | **3.71** | **0.67** | **4.94** | > 2 L | **8.55** |
| Euro IV | < 1.4 L | **0.57** | **0.95** | **0.29** | **1.81** | | |
| | 1.4 - 2 L | **0.67** | **2.85** | **0.48** | **3.99** | < 2 L | **4.75** |
| | > 2 L | **0.48** | **4.75** | **0.67** | **5.89** | > 2 L | **8.55** |

the assumptions made here were designed to fit with the literature. Another set of assumptions, notably concerning the share of diesel cars, would lead to quite different results.

Table B.4: Assumptions concerning the share of diesel cars among the new registrations

| **Year of new registration** | 1985 | 1997 | 2004 | 2020 |
|---|---|---|---|---|
| **Share of diesel cars** | 5% | 13% | 34% | 40% |

With the set of new registrations presented above, the survival rates extracted from Bourdeau (1998, p.220) and the initial conditions derived from Gabriel *et al.* (2000, p.37) and KBA (2005), the model gives the curves presented in figure B.3. This figure should be compared with Abbildung 4.17 in Hagelüken *et al.* (2005, p.63), shown in the upper part of figure B.3. Here again, the shapes are rather similar (the total fleet increases up to slightly over 50 million in 2020). Under other assumptions (e.g. for the share of

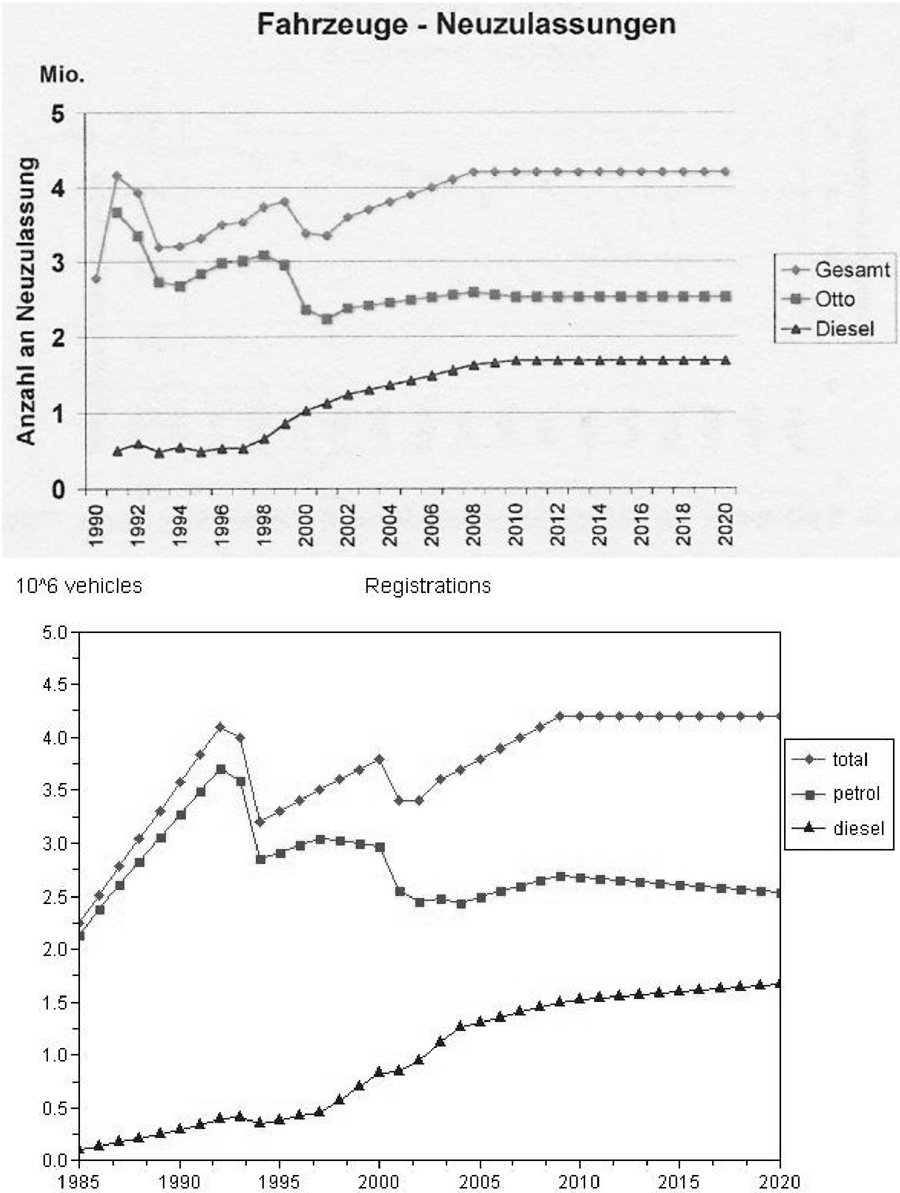



Figure B.2: New vehicles registrations in Germany, existing data and forecast. *Up:* Abbildung 4.16 in Hagelüken *et al.* (2005, p.63). *Down:* Data used for the model.

diesel cars) the aggregate picture does not change but the shares of petrol and diesel vehicles vary greatly.

Figure B.5 is an aggregate picture of the evolution of each environmental category as presented in Figure B.4. The lower part of figure B.5 can be compared to Abbildung 4.19 in Hagelüken *et al.* (2005, p.64), shown in the upper part of figure B.5. The penetration of autocatalysts in the car fleet as calculated by the model fits well with the results presented in the literature (in both cases 100% of autocatalysts is reached around 2010).

According to how many vehicles 'survive' from one year to the next, the model calculates a number of de-registrations, among which a proportion of cars are equipped with an autocatalyst. These results are shown in Figure B.6 and should be compared to Abbildung 4.21 in Hagelüken *et al.* (2005, p.65). The curve obtained from the model is smoother than the one from the literature because the model applied the survival rates to the car fleet each year, and therefore does not reflect the real unpredictable fluctuations of the de-registrations. From around 1998 onwards, the model fits rather well with the literature but prior to that, especially between 1985 and 1990, the programme calculates more de-registrations than actually occured (2.3 million against a mere 1 million). The reason behind that might be that the same survival rates were applied to the whole German car fleet, which is probably inaccurate for the period before the reunification: the survival rates of East-German cars were probably close to one (almost) irrespective of the cars' age.

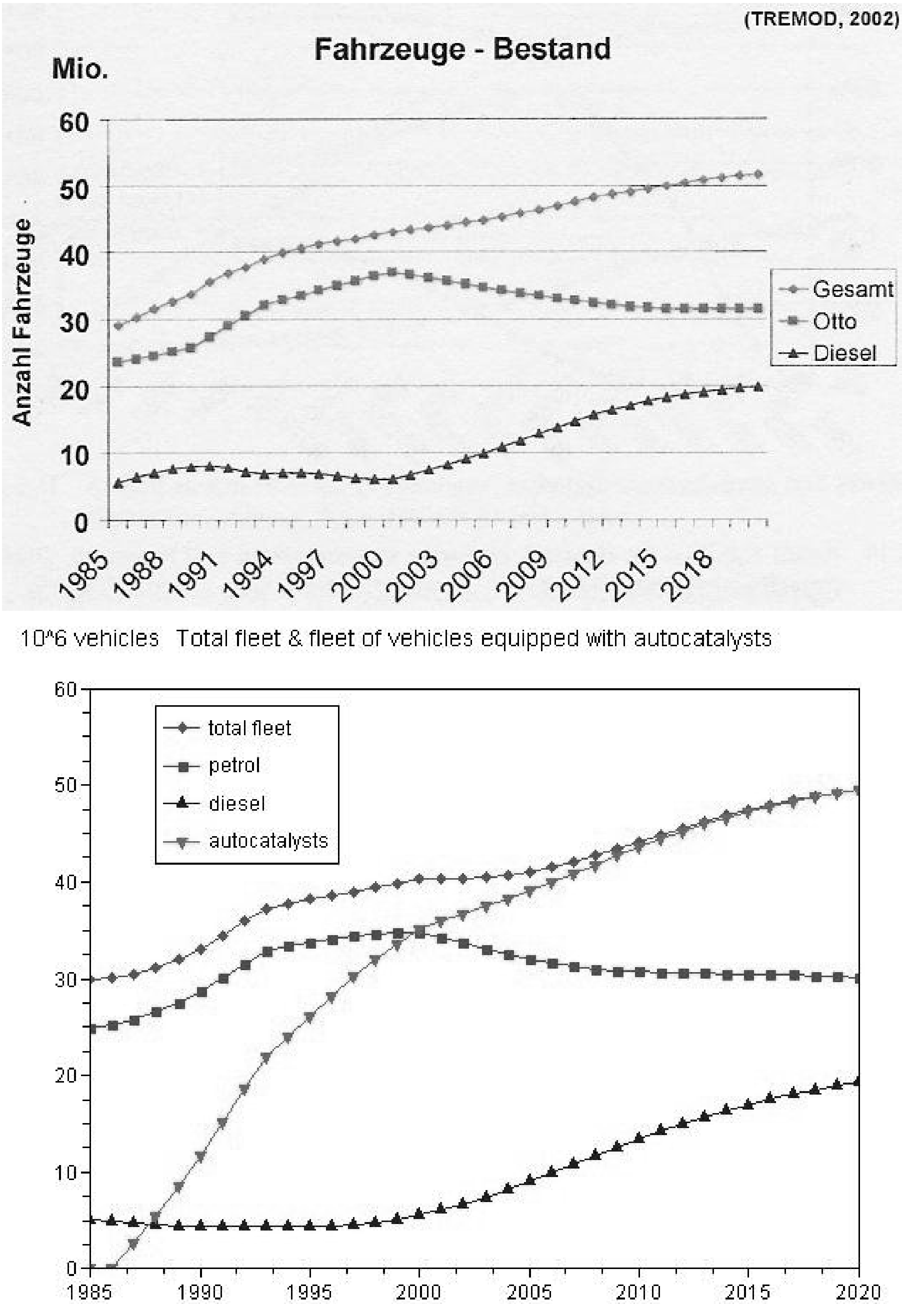



Figure B.3: German fleet of passenger cars. *Up:* Abbildung 4.17 in Hagelüken *et al.* (2005, p.63). *Down:* Modelling results.

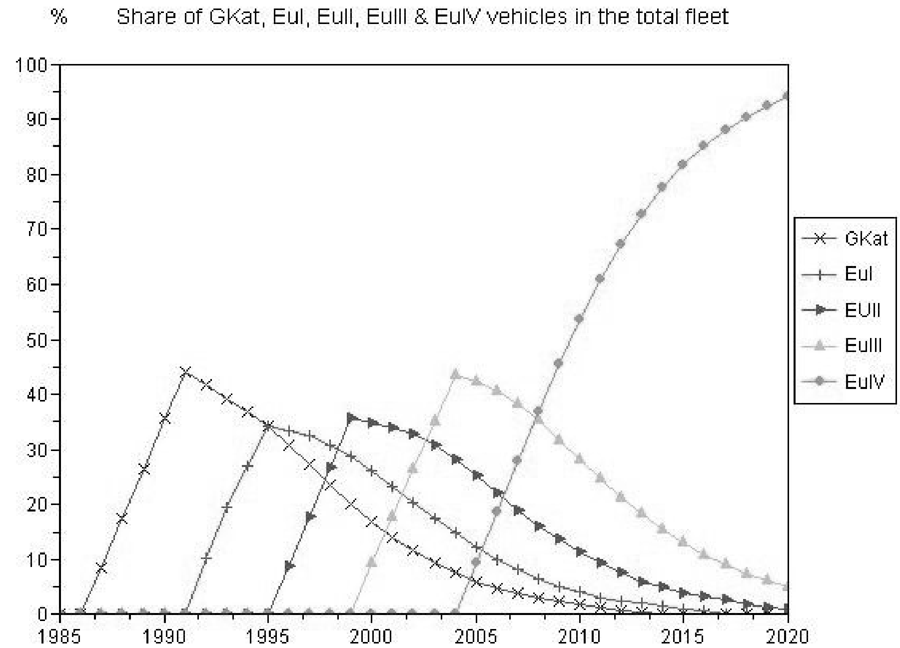



Figure B.4: Evolution of each environmental category in Germany, modelling results.

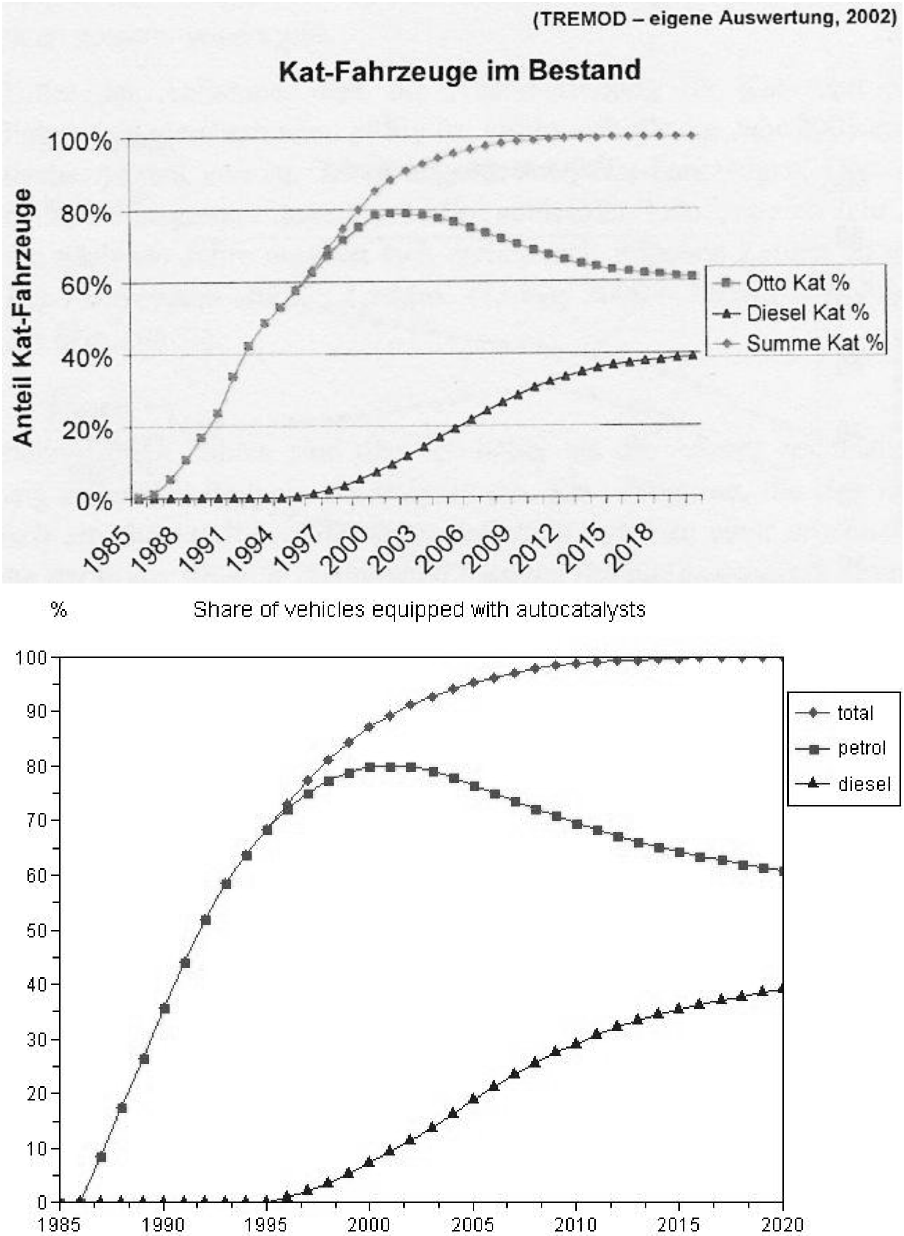



Figure B.5: Share of cars equipped with an autocatalyst for the whole German fleet. *Up:* Abbildung 4.19 in Hagelüken *et al.* (2005, p.64). *Down:* Modelling results.

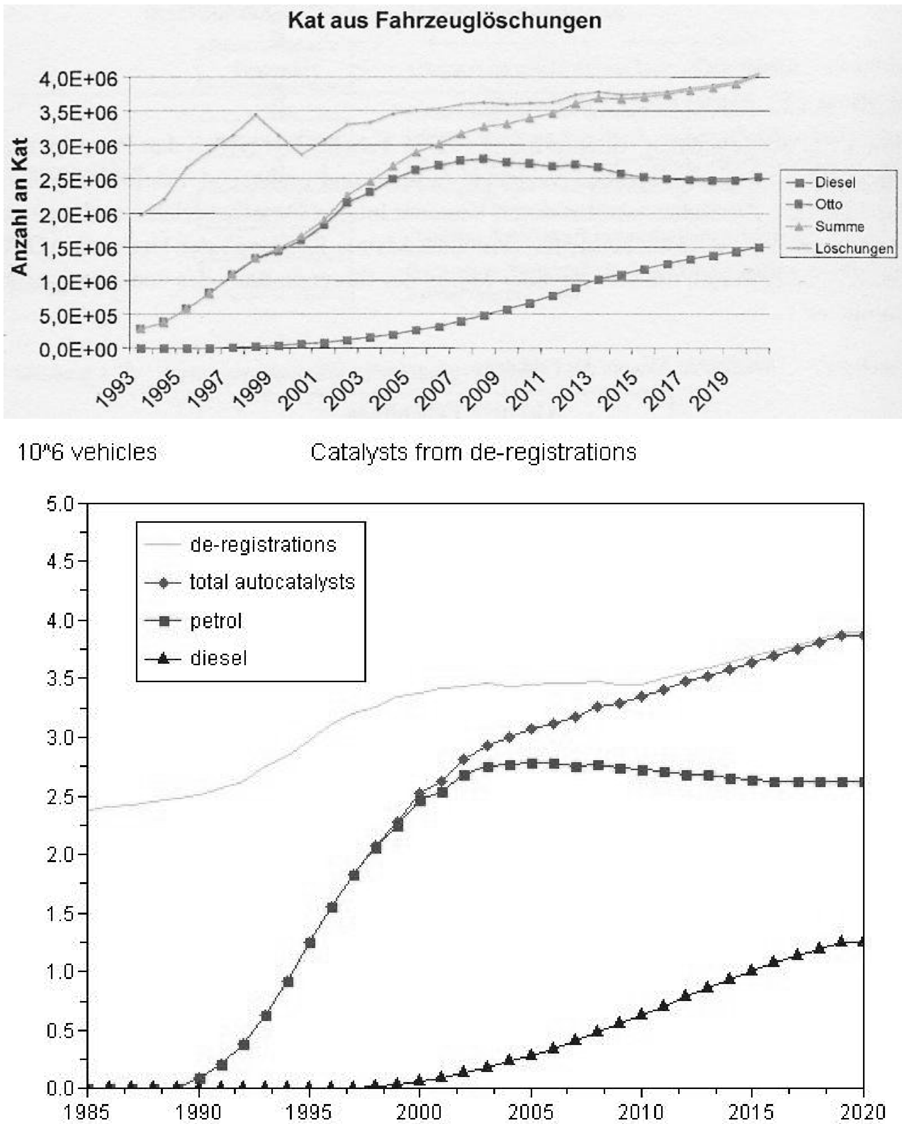



Figure B.6: De-registrations and amount of autocatalysts available from de-registered cars in Germany. *Up:* Abbildung 4.21 in Hagelüken *et al.* (2005, p.65). *Down:* Modelling results.

### PGM Flows Related to New Registrations and End-of-Life Vehicles

Beyond the modelling of the fate of the German car fleet, the aim of the programme is to provide a bottom-up estimation of PGM flows and stocks linked with vehicles in use in Germany. A potential flow of PGM stems from de-registered cars equipped with an autocatalyst. Figure B.7 shows the evolution of the amount of PGM which could theoretically be recovered from de-registered vehicles if those were disposed of *via* a proper recycling chain.

This representation is to be compared to Abbildung 4.26 in Hagelüken *et al.* (2005, p.75), shown in the upper part of figure B.7. The aggregate curve (sum of PGM) fits well with the literature. The curves for platinum and palladium follow similar evolutions as those in the literature even though the potential for palladium exceeds that for platinum at around 2010, whereas in Hagelüken *et al.* (2005) the curves do not intersect. This difference is most probably due to the fact that the non aggregate figures are very sensitive to the shares of each technological categories (petrol/diesel and cylinder capacity). Since Hagelüken *et al.* (2005) do not provide details on e.g. the share of petrol cars with less than 2 L of cylinder capacity, the present study may use different assumptions.

Newly registered cars contain an amount of PGM related to the technological category they belong to and to the enviromental regulation in force at the time. Using this correlation the model calculates the PGM total input due to new registrations. The results are presented in Figure B.8 and can be compared to Abbildung 4.27 in Hagelüken *et al.* (2005, p.75). Here again the aggregate curve matches with the literature. The slight differences in the evolutions of platinum and palladium, notably between 1995 and 2000, as compared to the results presented in the literature may be explained, as already mentioned above, by a different distribution of technological categories.

Each year new registrations of vehicles equipped with autocatalysts add to the PGM stock of the car fleet. This increase is shown in Figure B.9 and has a similar shape to Abbildung 4.28 in Hagelüken *et al.* (2005, p.76) even though the final value for 2020 is lower than the one obtained in the literature (around 213 tonnes against 225).

Figure B.10 is composed of Figures B.8 (total input) and B.7 (potential recycling). The effective amount of PGM recycled is assumed to be 30% of the potential recycling (see Section B.1.1). It seems that the curve for total input in Abbildung 4.33 in Hagelüken *et al.* (2005, p.88) has been smoothed out to get rid of the quick variations of the new registrations between 1993 and 2000. Apart from this remark, the results issued from the model fit well with the literature to the extent that Figures B.8 and B.7 did.

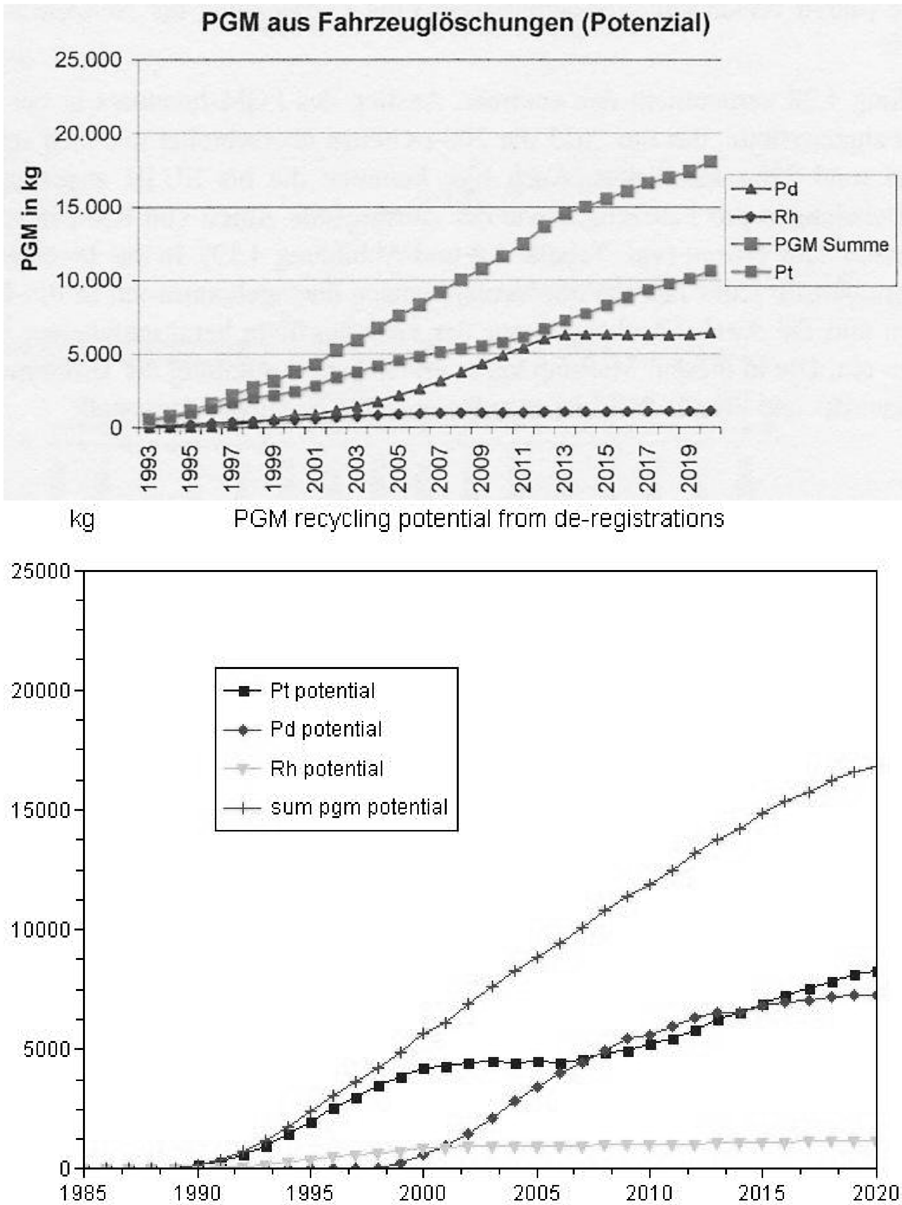



Figure B.7: Theoretical amount of PGM available from de-registered cars in Germany. *Up:* Abbildung 4.26 in Hagelüken *et al.* (2005, p.75). *Down:* Modelling results.

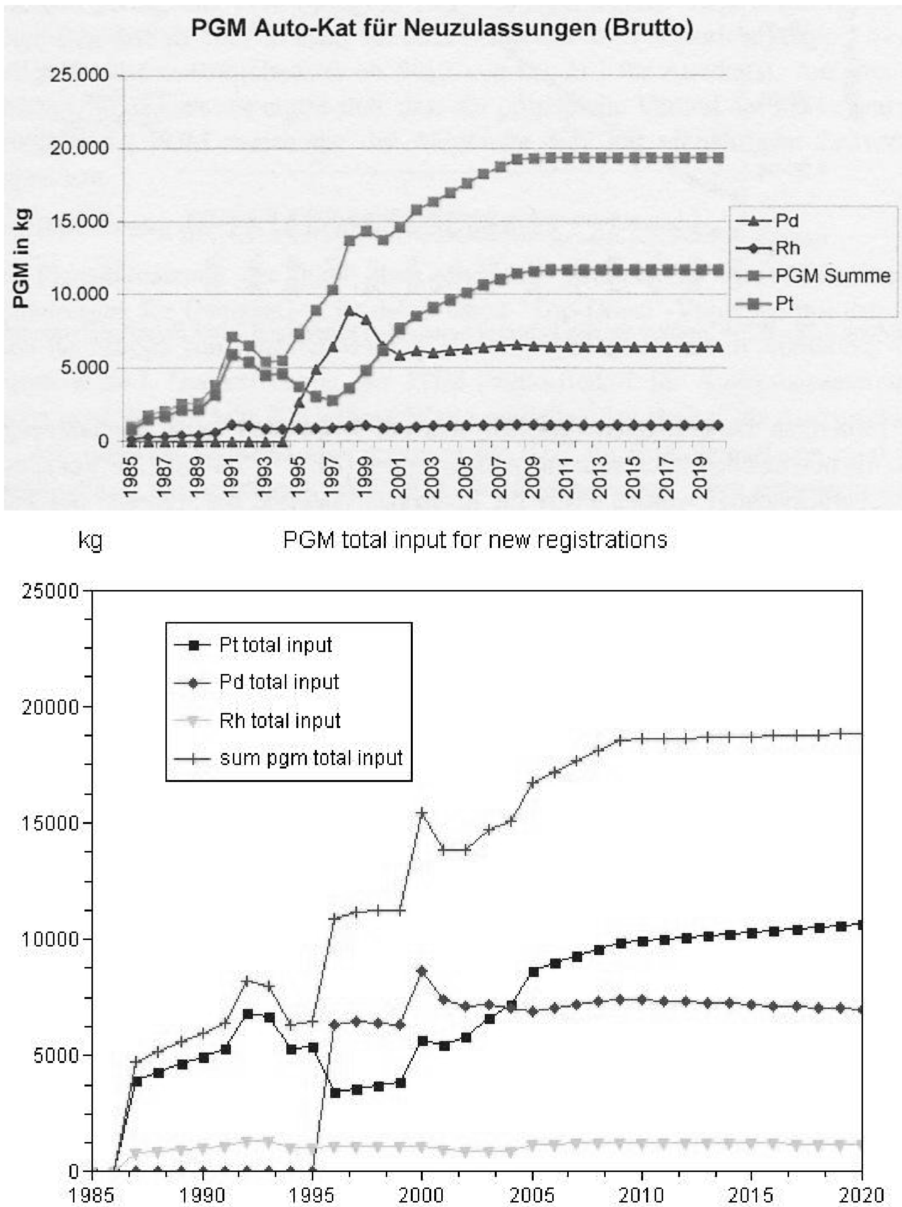
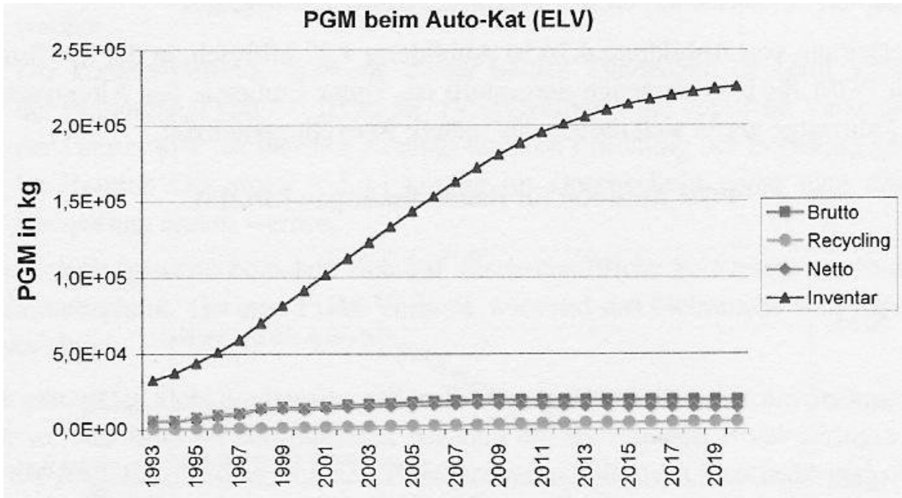



Figure B.8: PGM total input for new registrations of passenger cars in Germany. *Up:* Abbildung 4.27 in Hagelüken *et al.* (2005, p.75). *Down:* Modelling results.



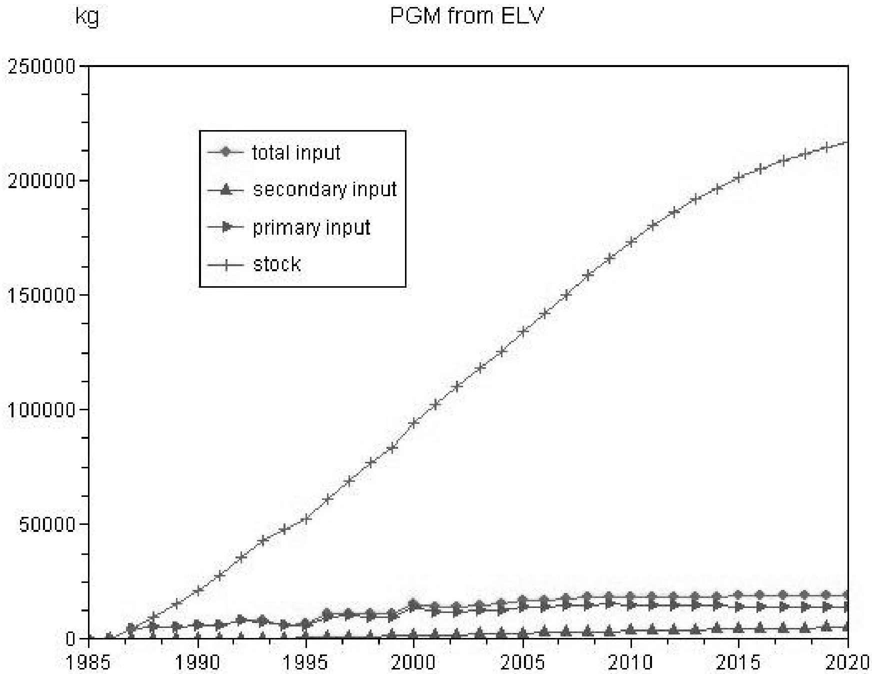
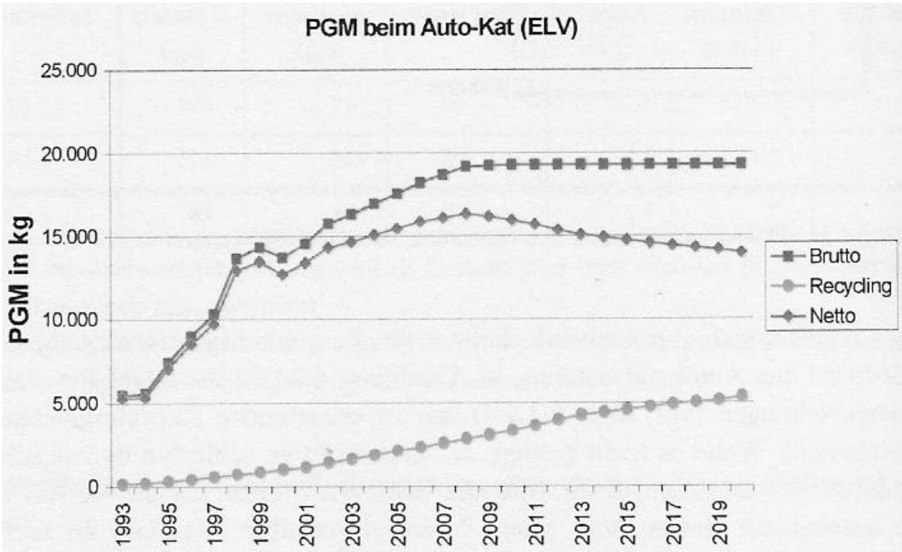




Figure B.9: Stock of PGM for the passenger car fleet in Germany (without exchanged autocatalysts). *Up:* Abbildung 4.28 in Hagelüken *et al.* (2005, p.76). *Down:* Modelling results.



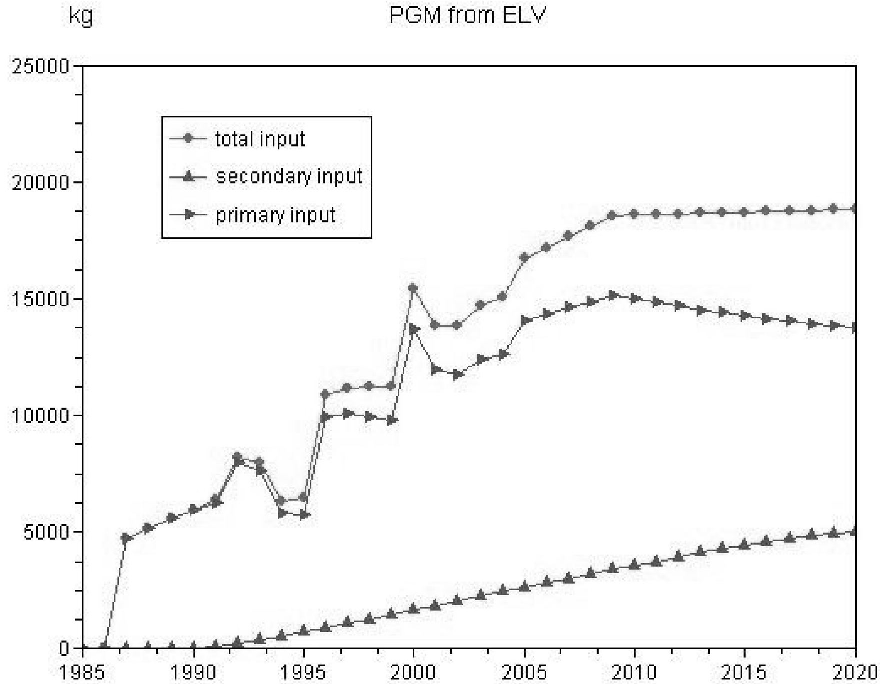




Figure B.10: Comparison of PGM total and secondary input in Germany (without exchanged autocatalysts, with constant recycling rate). *Up:* Abbildung 4.33 in Hagelüken *et al.* (2005, p.88). *Down:* Modelling results.

### PGM Flows Related to Exchanged Autocatalysts

Besides the PGM quantities required for new registrations and those stemming from end-of-life vehicles, Hagelüken *et al.* (2005, p.70) identifies exchanged autocatalysts – i.e. defective autocatalysts which ought to be exchanged during the life time of the vehicle – as another source for total and secondary input of PGM. Specific statistics about these exchanged autocatalysts being unavailable, Hagelüken *et al.* (2005, p.70) uses statistics from the exhaust gas controls conducted in Germany.

German cars are supposed to be inspected every two years (for a new car, the first control occurs three years after registration) which means that each year 50% of the fleet is controlled. Then between 1 and 2% of the vehicles fail the control with the autocatalysts having to be replaced. On average, the autocatalysts to be exchanged are four years old. The PGM content of an exchanged autocatalyst therefore corresponds to the state of the art four years before. It is also assumed that an autocatalyst is replaced by an equivalent device regarding the PGM content. Hagelüken *et al.* (2005, p.70, p.76) calculates that each year 300 000 autocatalysts are exchanged in Germany. This number is assumed to remain constant over time (in the future, more reliable devices will fail the exhaust gas control less often).

In the model it is assumed that half of the fleet is inspected every year and that 1.5% of the controlled autocatalysts have to be replaced. Contrary to Hagelüken *et al.* (2005), a dynamic approach to the number of exchanged autocatalysts is applied which therefore increases in the future as the car fleet also expands. Concerning the recycling rate of the replaced devices it is considered to be 87% and to remain constant over time (Hagelüken *et al.* 2005, p.70). The fact that a large share of autocatalysts is being exchanged in garages under contract with car manufacturers explains this rather high figure (in comparison to ELV recycling).

Figure B.11 presents the PGM total input for exchanged autocatalysts. The curves issued by the model are not as smooth as those displayed by Abbildung 4.29 in Hagelüken *et al.* (2005, p.77), shown in the upper part of figure B.11. They also increase steadily whereas in the literature the curves reach a constant value at around 2010. The dynamic – and constantly increasing – amount of exchanged autocatalysts in our model is responsible for this difference.

The same remarks can be made regarding figure B.12 which shows a comparison between total and secondary input of PGM related to exchanged autocatalysts. In both figures, the values reached by the total input are higher than those given in the literature, for the same reasons given above.

However, exchanged autocatalysts play a limited role when considering the aggregate picture, both in the literature (Abbildung 4.32 in Hagelüken *et al.*, p.88) as well as in our model. Figure B.13 shows that, when compared to figure B.7, PGM from exchanged autocatalysts have a minor impact on the overall PGM potential and effective recycling.

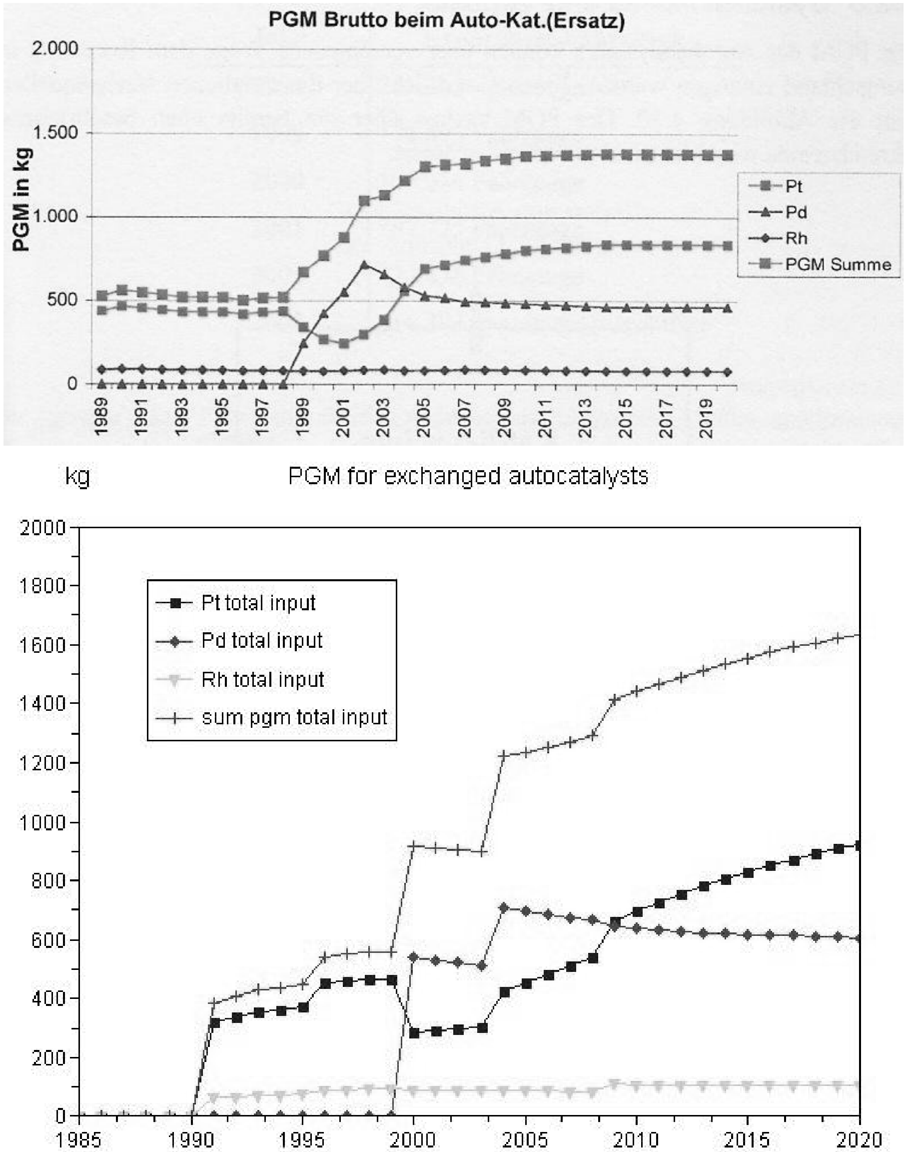



Figure B.11: PGM total input for exchanged autocatalysts in Germany. *Up:* Abbildung 4.29 in Hagelüken *et al.* (2005, p.77). *Down:* Modelling results.

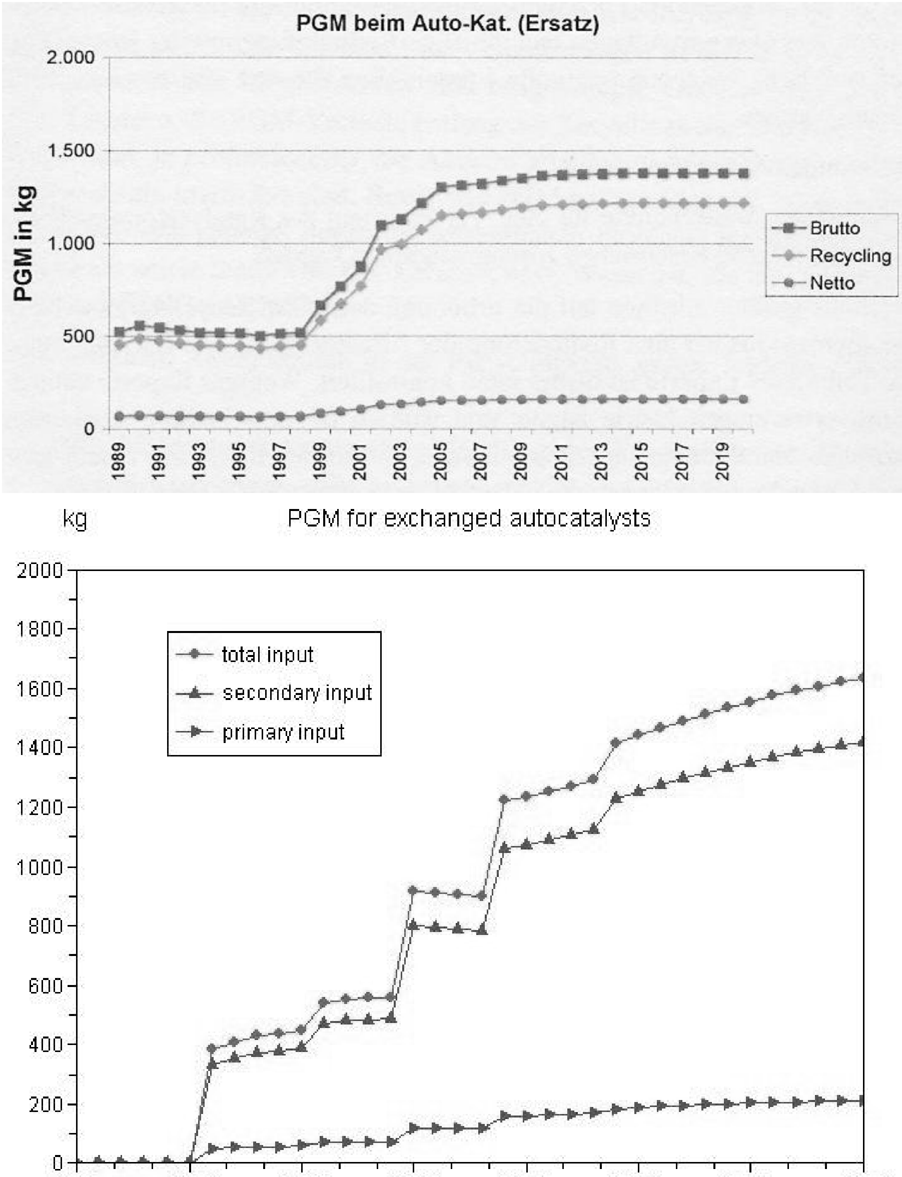



Figure B.12: Comparison of PGM total and secondary input for exchanged autocatalysts in Germany. *Up:* Abbildung 4.34 in Hagelüken *et al.* (2005, p.89). *Down:* Modelling results.

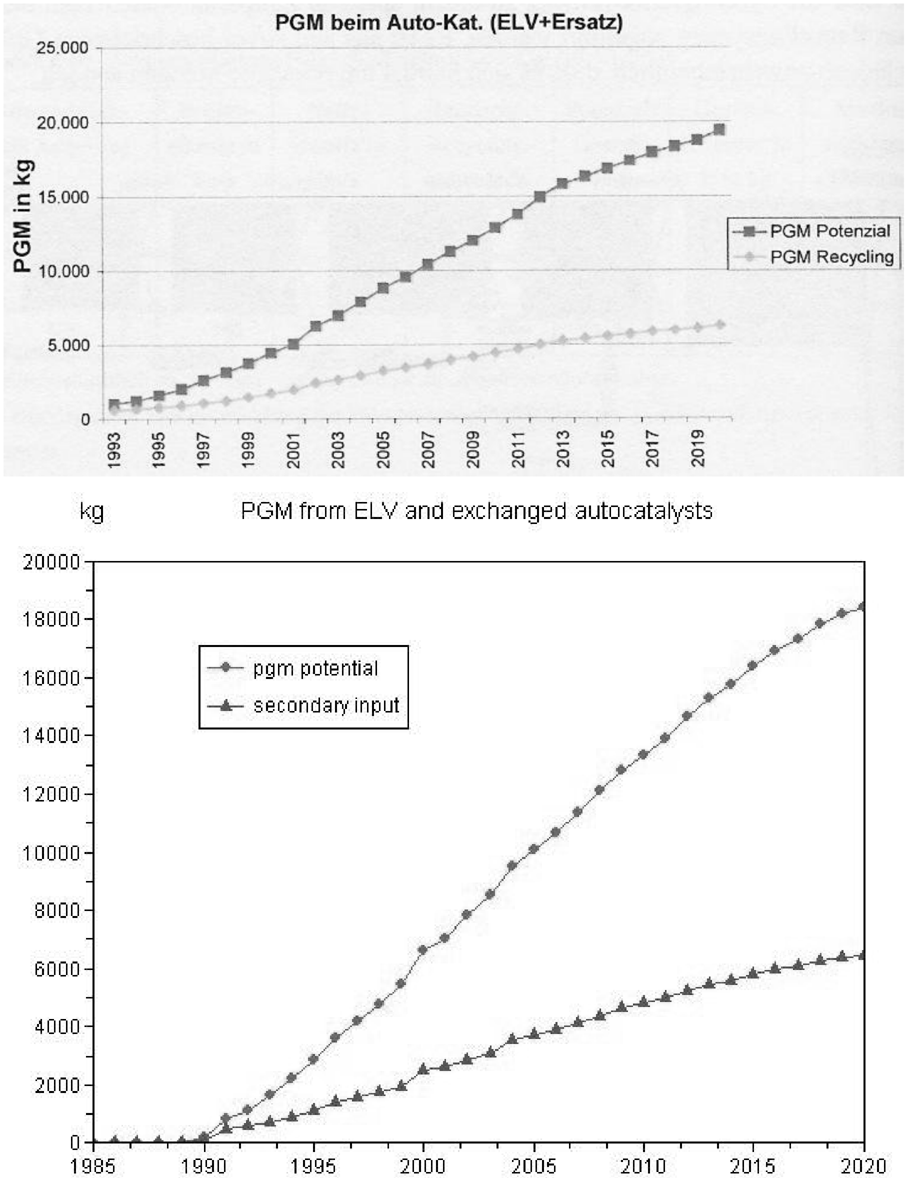



Figure B.13: Potential PGM recycling and expected actual recycling in Germany (from ELV and exchanged autocatalysts). *Up:* Abbildung 4.32 in Hagelüken *et al.* (2005, p.88). *Down:* Modelling results.

# Appendix C

# PGM Flows in Europe

The present chapter details the assumptions and calculations made to build figure 9.2 of chapter 9.1.

The transfer coefficients of PGM to the main output applied to the processes of the primary production are those used in the first part of this study (85% for milling-concentrating, 96% for pyrometallurgy, 100% for refining). The last step of the recycling chain (called recycling in figure 9.2 and corresponding in fact to smelting-refining) is also described by a TC of 100% (due to lack of data for smelting and by symmetry with primary production for refining).

The flows related to industrial catalysts, glass industry, jewellery, dentistry and 'other' are direct representations of the results of the top-down analysis. The picture is more complex, however, concerning autocatalysts and electronics because the products containing PGM used in Europe may or may not have been produced in Europe and the amounts of precious metals available from end-of-life devices are uncertain. It is assumed that secondary PGM is used in the same industrial sector as the one which produced the product recycled.

### Autocatalysts

The total input to the 'Autocatalysts' box (passenger cars equipped in Europe) is taken from the bottom-up model, as is the ouput of the same box, representing the de-registrations in 2004 of vehicles fitted with a catalytic converter. The share of this 'potential recycling' which effectively enters the European recycling chain and finally returns to European production also reflects the assumptions of the bottom-up model (30% recycling rate). The secondary input to the European production of autocatalysts is given by Johnson Matthey (see chapter 7.2.2). Therefore, the difference between Johnson Matthey's data and the estimate from the bottom-up model is supposed to come from unknown sources. These could be, for example, autocatalysts collected in North America and recycled in Europe (e.g. Umicore operates such a recycling path).

The primary input to the European autocatalyst industry is also taken from Johnson Matthey. Due to a lack of data, the losses of the process 'Automotive industry' are disregarded. The output of the production process is then disaggregated between exports and use in Europe. The share of the latter flow in the total input to 'Autocatalysts' is roughly estimated at 94%. Carlsson-Aubry (2005, p.2, Tab. 2) gives the figure of 643.550 billion euros for the turnover of the EU25 "motor vehicles and trailers industry".[1] Berthomieu (2005, p.2, Tab. 2) estimates imports and exports of "cars and other land vehicles, parts and accessories"[2] in 2001 at 37.6 and 84.2 billion euros, respectively. If assumed that the total PGM input to 'Autocatalysts' is reflected by (turnover - exports) + imports, then the imports represent 6% of this total. This is the value used in figure 9.2. However, the share of the exports in the turnover (i.e. total output of the 'Automotive industry') implied by this choice is much higher than what is suggested by Carlsson-Aubry (2005) and Berthomieu (2005). Due to the lack of specific data for autocatalysts, this incoherence could not be solved.

The share of secondary input to the prodution of autocatalysts outside the EU25 is roughly estimated thanks to Johnson Matthey's data: outside Europe it could be calculated that secondary PGM represented 22% of the total input to the autocatalyst industry.

### Electronics

The method for the construction of the PGM flows related to electronic equipment in use in Europe is similar to that applied for autocatalysts. Total input to the 'Electronics' box is determined by the top-down analysis. The output flows are calculated with a 50% recycling rate and a lifetime of five years. Losses at the 'Recollection, preprocessing' step (10%) are taken from Hagelüken *et al.* (2005, p.111) and further losses due to smelting and refining are disregarded.

The primary input to the European electronic industry is taken from Johnson Matthey. The output from this process is calculated starting from the total input to electronic use. According to Orgalime (2005, p.3), the total

[1]Corresponds to the section DM 34 "Manufacture of motor vehicles, trailers and semi-trailers" of the NACE Rev. 1 system of classification.

[2]This product classification corresponds to the chapter 87 of the Harmonised System (CN XVII 87 cars and other land vehicles, parts and accessories).

production of "the electrical- electronics-, ICT- and instrument industry" reached 541 billion euros in 2004 including 200 billion euros of exports extra-EU. Van den Eynde-Coppin (2005, p.6) precises that "in 2003, the value of the EU's imports of electrical and electronic equipment was 52% higher than the value of its corresponding exports". Therefore imports amount 304 billion euros and represent 47% of the input to 'Electronics'.

Secondary inputs, as calculated in the top-down analysis, reach 21 929 kg. It has been estimated that through recycling of e-scrap in Europe 11 837 kg of secondary PGM can be produced. Given the primary input (4260 kg), the balance needed to obtain the wanted output for the European electronic industry (25 241 kg) is 9144 kg (due to lack of data, losses in production are disregarded). The remaining secondary input is attributed to the electronic industry outside Europe. The balance with the output gives the primary input for the extra-European production.

### Limitations

Particularly two sectors (autocatalysts and electronics) suffer from low quality results. Two types of flows related with these applications should be considered as nothing more than rough estimations: imports to and exports from Europe and secondary inputs from external sources (to a lesser extent in the case of autocatalysts thanks to some of Johnson Matthey's data).

# Appendix D

# Allocated Results for the MFA of PGM Production

## D.1 South Africa

Table D.1: Direct inputs and outputs related to the primary production of 1 t of PGM in South Africa

| **Allocation** | | **Unit** | **Not allocated** | **Allocated to** | | | |
|---|---|---|---|---|---|---|---|
| | | | **Unit / t PGM** | **1 t Pt** | **1 t Pd** | **1 t Rh** | **1 t PGM** |
| **Input** | | | | | | | |
| **Rocks mined** | | t | 616 900 | 706 002 | 193 410 | 815 679 | 543 427 |
| **Energy** | | TJ | 183.5 | 210 | 57.5 | 242.6 | 161.7 |
| of which: | electricity | TJ | 147.7 | 169 | 46.3 | 195.3 | 130.1 |
| | fossil fuels | TJ | 27 | 31 | 8.5 | 35.7 | 23.8 |
| **Water** | | $m^3$ | 364 000 | 416 570 | 114 120 | 481 290 | 320 650 |
| **Output** | | | | | | | |
| ***to air*** | | | | | | | |
| **$CO_2$-eq** | | t | 3036 | 3474.5 | 951.8 | 4014.3 | 2674.4 |
| **$SO_2$** | | t | 148 | 169.4 | 46.4 | 195.7 | 130.4 |
| **PM** | | t | 8.4 | 9.6 | 2.6 | 11.1 | 7.4 |
| ***to water*** | | | | | | | |
| **Effluents** | | t | 7.4 | 8.47 | 2.3 | 9.8 | 6.5 |
| ***solid waste*** | | | | | | | |
| **Mineral** | | t | 616 348 | 705 370 | 193 237 | 814 949 | 542 941 |
| **Non-mineral** | | t | 192.5 | 220.3 | 60.3 | 254.5 | 169.6 |
| of which: | non-hazardous | t | 169.4 | 193.9 | 53.1 | 224 | 149.2 |
| | hazardous | t | 23.1 | 26.4 | 7.2 | 30.5 | 20.4 |

Table D.2: Indirect environmental burden related to the primary production of 1 t of PGM in South Africa

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Electricity generation** | | | | | | |
| **$CO_2$-eq** | t | 36 859 | 42 182 | 11 556 | 48 735 | 32 469 |
| **$SO_2$-eq** | t | 340.4 | 389.6 | 106.7 | 450.1 | 299.9 |
| **$CO_2$** | t | 36 255 | 41 492 | 11 367 | 47 937.8 | 31 937 |
| **$SO_2$** | t | 212.9 | 243.7 | 66.8 | 281.5 | 187.6 |
| **$NO_x$** | t | 159.7 | 182.7 | 50.1 | 211.1 | 140.7 |
| **HCl** | t | 15.7 | 17.9 | 4.9 | 20.7 | 13.8 |
| **HF** | t | 1.6 | 1.8 | 0.5 | 2.1 | 1.4 |
| **PM** | t | 101.3 | 115.9 | 31.7 | 133.9 | 89.2 |
| **CO** | t | 20 | 22.8 | 6.3 | 26.4 | 17.6 |
| **NMVOC** | t | 0.6 | 0.7 | 0.2 | 0.8 | 0.5 |
| **$CH_4$** | t | 0.6 | 0.7 | 0.2 | 0.8 | 0.5 |
| **$N_2O$** | t | 2 | 2.3 | 0.6 | 2.5 | 1.8 |
| **Ash** | t | 1.9 | 2.2 | 0.6 | 2.6 | 1.7 |
| **Nuclear waste** | t | 0.01 | 0.01 | 0 | 0.02 | 0.01 |
| **TMR** | | | | | | |
| **Electricity** | t | 91 880 | 105 150 | 28 806 | 121 485 | 80 937 |
| **Fossil fuels** | t | 4417 | 5055 | 1385 | 5841 | 3891 |

## D.2 Russia

Table D.3: Direct inputs and outputs related to the primary production of 1 t of PGM in Russia

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Input** | | | | | | |
| **Rocks mined** | t | 96 687 | 62 543 | 17 134 | 72 259 | 26 410 |
| **Energy** | TJ | 218 | 141 | 38.6 | 162.9 | 59.6 |
| of which: electricity | TJ | 94 | 60.8 | 16.7 | 70.3 | 25.7 |
| fossil fuels | TJ | 124 | 80.2 | 22 | 92.7 | 33.9 |
| **Output** | | | | | | |
| ***to air*** | | | | | | |
| **$CO_2$** | t | 6850 | 4431 | 1213.9 | 5119.3 | 1871.1 |
| **$SO_2$** | t | 15 532 | 10 047 | 2752.4 | 11 607.8 | 4242.5 |
| ***solid waste*** | | | | | | |
| **Mineral** | t | 88 874 | 57 489 | 15 749 | 66 420 | 24 276 |

Table D.4: Indirect environmental burden related to the primary production of 1 t of PGM in Russia

| **Allocation** | **Unit** | **Not allocated Unit / t PGM** | **Allocated to 1 t Pt** | **1 t Pd** | **1 t Rh** | **1 t PGM** |
|---|---|---|---|---|---|---|
| **Electricity generation** | | | | | | |
| **$CO_2$-eq** | t | 17 101 | 11 062 | 3030 | 12 781 | 4671 |
| **$SO_2$-eq** | t | 118.7 | 76.8 | 21 | 88.7 | 32.4 |
| **$CO_2$** | t | 16 921 | 10 945 | 2998 | 12 646 | 4622 |
| **$SO_2$** | t | 84.2 | 54.5 | 14.9 | 62.9 | 23 |
| **$NO_x$** | t | 39.2 | 25.4 | 7 | 29.3 | 10.7 |
| **HCl** | t | 0.6 | 0.4 | 0.1 | 0.4 | 0.2 |
| **HF** | t | 261.7 | 169.3 | 46.4 | 195.6 | 71.5 |
| **PM** | t | 8.7 | 5.6 | 1.5 | 6.5 | 2.4 |
| **CO** | t | 16.5 | 10.7 | 2.9 | 12.4 | 4.5 |
| **NMVOC** | t | 0.5 | 0.3 | 0.1 | 0.4 | 0.1 |
| **$CH_4$** | t | 0.6 | 0.4 | 0.1 | 0.4 | 0.2 |
| **$N_2O$** | t | 0.6 | 0.4 | 0.1 | 0.4 | 0.2 |
| **Ash** | t | 261.7 | 169.3 | 46.4 | 195.6 | 71.5 |
| **Nuclear waste** | t | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 |
| **TMR** | | | | | | |
| **Electricity** | t | 28 657 | 18 537 | 5078 | 21 416 | 7827 |
| **Fossil fuels** | t | 2927 | 1893 | 519 | 2188 | 800 |

## D.3 North America

Table D.5: Direct inputs and outputs related to the primary production of 1 t of PGM in North America

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Input** | | | | | | |
| **Rocks mined** | t | 837 177 | 117 158 | 32 096 | 135 359 | 73 472 |
| **Energy** | TJ | 1546 | 216.4 | 59.3 | 250 | 135.7 |
| of which: electricity | TJ | 603 | 84.4 | 23.1 | 97.5 | 52.9 |
| fossil fuels | TJ | 943 | 132 | 36.2 | 152.5 | 82.8 |
| **Output** | | | | | | |
| ***to air*** | | | | | | |
| **$CO_2$-eq** | t | 51 925 | 7266.6 | 1990.7 | 8395.5 | 4557 |
| **$SO_2$** | t | 19 905 | 2785.6 | 763.1 | 3218.3 | 1746.9 |
| **PM** | t | 365 | 51.1 | 14 | 59 | 32 |
| **Nickel** | t | 13 | 1.8 | 0.5 | 2.1 | 1.1 |
| ***to water*** | | | | | | |
| **Suspended matter** | t | 12 | 1.7 | 0.5 | 1.9 | 1.1 |
| **Nickel** | t | 1 | 0.1 | 0 | 0.2 | 0.1 |
| ***solid waste*** | | | | | | |
| **Mineral** | t | 1 101 552 | 154 156 | 42 232 | 178 105 | 96 674 |
| **Non-mineral** | t | 5838 | 817 | 223.8 | 943.9 | 512.4 |
| of which: non-hazardous | t | 5548 | 776.4 | 212.7 | 897 | 486.9 |
| hazardous | t | 282 | 39.5 | 10.8 | 45.6 | 24.8 |

Table D.6: Indirect environmental burden related to the primary production of 1 t of PGM in North America

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Electricity generation** | | | | | | |
| **$CO_2$-eq** | t | 54 794 | 7668 | 2101 | 8859 | 4809 |
| **$SO_2$-eq** | t | 158.8 | 22.2 | 6.1 | 25.7 | 13.9 |
| **$CO_2$** | t | 53 962 | 7552 | 2069 | 8725 | 4736 |
| **$SO_2$** | t | 52.5 | 7.4 | 2 | 8.5 | 4.6 |
| **$NO_x$** | t | 148.9 | 20.8 | 5.7 | 24.1 | 13.1 |
| **HCl** | t | 2.7 | 0.4 | 0.1 | 0.4 | 0.2 |
| **HF** | t | 0.2 | 0 | 0 | 0 | 0 |
| **PM** | t | 0.4 | 0.1 | 0 | 0.1 | 0 |
| **CO** | t | 29.2 | 4.1 | 1.1 | 4.7 | 2.6 |
| **NMVOC** | t | 10.4 | 1.5 | 0.4 | 1.7 | 0.9 |
| **$CH_4$** | t | 1.5 | 0.2 | 0.1 | 0.2 | 0.1 |
| **$N_2O$** | t | 2.7 | 0.4 | 0.1 | 0.4 | 0.2 |
| **Ash** | t | 1312 | 183.6 | 50.3 | 212.2 | 115.2 |
| **Nuclear waste** | t | 0.4 | 0.1 | 0 | 0.1 | 0 |
| **TMR** | | | | | | |
| **Electricity** | t | 538 410 | 75 348 | 20 642 | 87 053 | 47 252 |
| **Fossil fuels** | t | 22 261 | 3115 | 853 | 3599 | 1954 |

## D.4 Secondary Production

Table D.7: Direct inputs and outputs related to the primary production of 1 t of secondary PGM (Hoboken plant, Belgium)

| Allocation | | Unit | Not allocated | Allocated to | | | |
|---|---|---|---|---|---|---|---|
| | | | Unit / t PGM | 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
| **Input** | | | | | | | |
| **Materials used** | | t | 6628 | 10 294 | 11 893 | 1052 | 6628 |
| **Energy** | | TJ | 64.1 | 99.6 | 27.3 | 115.1 | 64.1 |
| of which: | electricity | TJ | 37.2 | 57.8 | 15.8 | 66.7 | 37.2 |
| | fossil fuels | TJ | 20.2 | 32.9 | 9 | 38 | 20.2 |
| **Water** | | $m^3$ | 37 320 | 57 960 | 15 880 | 66 960 | 37 320 |
| **Output** | | | | | | | |
| ***to air*** | | | | | | | |
| **$CO_2$-eq** | | t | 2207 | 3428 | 939 | 3961 | 2207 |
| **$SO_2$** | | t | 33.9 | 52.7 | 14.4 | 60.9 | 33.9 |
| **$NO_x$** | | t | 3.3 | 5.1 | 1.4 | 5.9 | 3.3 |
| **Metals** | | kg | 140.8 | 218.6 | 59.9 | 252.6 | 140.8 |
| ***to water*** | | | | | | | |
| **Metals** | | kg | 84.8 | 131.7 | 36.1 | 152.2 | 84.8 |
| ***solid waste*** | | | | | | | |
| **Total waste** | | t | 3453 | 5364 | 1469 | 6197 | 3453 |

Table D.8: Indirect environmental burden related to the primary production of 1 t of secondary PGM (Hoboken plant, Belgium)

| Allocation | Unit | Not allocated Unit / t PGM | Allocated to 1 t Pt | 1 t Pd | 1 t Rh | 1 t PGM |
|---|---|---|---|---|---|---|
| **Electricity generation** | | | | | | |
| **$CO_2$-eq** | t | 2200 | 3417 | 934 | 3947 | 2200 |
| **$SO_2$-eq** | t | 6 | 9.2 | 2.5 | 10.7 | 6 |
| **$CO_2$** | t | 2166 | 3364 | 922 | 3886 | 2166 |
| **$SO_2$** | t | 1.3 | 2.1 | 0.6 | 2.4 | 1.3 |
| **$NO_x$** | t | 6.6 | 10.3 | 2.8 | 11.9 | 6.6 |
| **HCl** | t | 0 | 0 | 0 | 0 | 0 |
| **HF** | t | 0 | 0 | 0. | 0 | 0 |
| **PM** | t | 0.1 | 0.1 | 0.0 | 0.1 | 0.1 |
| **CO** | t | 1 | 1.6 | 0.4 | 1.8 | 1 |
| **NMVOC** | t | 0.1 | 0.2 | 0.0 | 0.2 | 0.1 |
| **CH4** | t | 0.1 | 0.2 | 0.0 | 0.2 | 0.1 |
| **$N_2O$** | t | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 |
| **Ash** | t | 54.6 | 84.7 | 23.2 | 98 | 54.6 |
| **Nuclear waste** | t | 0.03 | 0.04 | 0.01 | 0.05 | 0.03 |
| **TMR** | | | | | | |
| **Electricity** | t | 6767 | 10 509 | 2879 | 12 142 | 6767 |
| **Fossil fuels** | t | 579 | 900 | 246 | 1039 | 579 |

# Appendix E

# Results of the Scenarios Utilized in the Discussion

## E.1 Potentially Increased Recycling Rates

Table E.1: PGM inputs in the BAU scenario

| ***PGM use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 61.76 | 7.75 | 12.42 | 21.99 | 98.46 | 119.42 |
| **2010** | 74.03 | 12.78 | 12.42 | 21.99 | 112.61 | 130.02 |
| **2015** | 76.01 | 18.25 | 12.42 | 21.99 | 116.73 | 143.03 |
| **2020** | 72.86 | 22.64 | 12.42 | 21.99 | 116.03 | 156.3 |
| **Min 2005-20** | 61.76 | 7.75 | 12.42 | 21.99 | 98.46 | 119.42 |
| **Average 2005-20** | 72.73 | 15.47 | 12.42 | 21.99 | 112.46 | 136.98 |
| **Max 2005-20** | 77.33 | 22.64 | 12.42 | 21.99 | 116.94 | 156.3 |
| **Cumul. 2005-20** | 1163.71 | 247.44 | 198.65 | 351.82 | 1799.42 | 2191.6 |
| ***Platinum use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 38.12 | 3.61 | 3.17 | 0.56 | 58 | 59.92 |
| **2010** | 47.63 | 6.03 | 3.17 | 0.56 | 68.7 | 61.94 |
| **2015** | 50.13 | 9.87 | 3.17 | 0.56 | 72.53 | 64.95 |
| **2020** | 50.3 | 13 | 3.17 | 0.56 | 74.17 | 68.18 |
| **Min 2005-20** | 38.12 | 3.61 | 3.17 | 0.56 | 58 | 59.92 |
| **Average 2005-20** | 47.48 | 8.06 | 3.17 | 0.56 | 69.26 | 63.64 |
| **Max 2005-20** | 50.3 | 13 | 3.17 | 0.56 | 74.17 | 68.18 |
| **Cumul. 2005-20** | 759.75 | 129.01 | 50.79 | 8.96 | 1108.2 | 1018.18 |
| ***Palladium use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 20.43 | 3.38 | 9.17 | 21.4 | 36.08 | 50.26 |
| **2010** | 22.74 | 5.87 | 9.17 | 21.4 | 38.9 | 57.7 |
| **2015** | 22.08 | 7.24 | 9.17 | 21.4 | 38.85 | 65.03 |
| **2020** | 19.25 | 8.32 | 9.17 | 21.4 | 36.74 | 73.29 |
| **Min 2005-20** | 19.25 | 3.38 | 9.17 | 21.4 | 36.08 | 50.26 |
| **Average 2005-20** | 21.63 | 6.38 | 9.17 | 21.4 | 38.12 | 61.52 |
| **Max 2005-20** | 23.18 | 8.32 | 9.17 | 21.4 | 39.45 | 73.29 |
| **Cumul. 2005-20** | 346.04 | 102.08 | 146.78 | 342.48 | 609.9 | 984.4 |
| ***Rhodium use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 3.21 | 0.76 | 0.07 | 0.02 | 4.38 | 9.24 |
| **2010** | 3.66 | 0.88 | 0.07 | 0.02 | 5.01 | 10.39 |
| **2015** | 3.79 | 1.15 | 0.07 | 0.02 | 5.35 | 13.05 |
| **2020** | 3.32 | 1.33 | 0.07 | 0.02 | 5.12 | 14.83 |
| **Min 2005-20** | 3.21 | 0.76 | 0.07 | 0.02 | 4.38 | 8.95 |
| **Average 2005-20** | 3.62 | 1.02 | 0.07 | 0.02 | 5.08 | 11.81 |
| **Max 2005-20** | 4.05 | 1.33 | 0.07 | 0.02 | 5.44 | 14.86 |
| **Cumul. 2005-20** | 57.92 | 16.35 | 1.08 | 0.38 | 81.32 | 189.02 |

Table E.2: PGM inputs in the R1 scenario

| ***PGM use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 61.11 | 8.39 | 11.52 | 22.88 | 96.91 | 120.96 |
| **2010** | 67.64 | 19.17 | 6.9 | 27.5 | 100.71 | 141.92 |
| **2015** | 59.28 | 34.98 | 2.31 | 32.09 | 89.9 | 169.86 |
| **2020** | 42.68 | 52.82 | 0.78 | 33.63 | 74.21 | 198.12 |
| **Min 2005-20** | 42.68 | 8.39 | 0.78 | 22.88 | 74.21 | 120.96 |
| **Average 2005-20** | 59.96 | 28.24 | 5.18 | 29.22 | 92.45 | 156.99 |
| **Max 2005-20** | 69.3 | 52.82 | 11.52 | 33.63 | 101.85 | 198.12 |
| **Cumul. 2005-20** | 959.31 | 451.84 | 82.88 | 467.59 | 1479.25 | 2511.76 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.65 | 0.65 | -0.9 | 0.9 | -1.54 | 1.54 |
| **2010** | -6.39 | 6.39 | -5.51 | 5.51 | -11.9 | 11.9 |
| **2015** | -16.73 | 16.73 | -10.1 | 10.1 | -26.83 | 26.83 |
| **2020** | -30.18 | 30.18 | -11.64 | 11.64 | -41.82 | 41.82 |
| **Min 2005-20** | -30.18 | 0.65 | -11.64 | 0.9 | -41.82 | 1.54 |
| **Average 2005-20** | -12.77 | 12.77 | -7.24 | 7.24 | -20.01 | 20.01 |
| **Max 2005-20** | -0.65 | 30.18 | -0.9 | 11.64 | -1.54 | 41.82 |
| **Cumul. 2005-20** | -204.39 | 204.39 | -115.77 | 115.77 | -320.16 | 320.16 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.95 | 108.33 | 92.79 | 104.07 | 98.43 | 101.29 |
| **2010** | 91.37 | 150 | 55.61 | 125.06 | 89.43 | 109.15 |
| **2015** | 77.99 | 191.67 | 18.62 | 145.95 | 77.01 | 118.76 |
| **2020** | 58.58 | 233.33 | 6.27 | 152.93 | 63.96 | 126.76 |
| **Min 2005-20** | 58.58 | 108.33 | 6.27 | 104.07 | 63.96 | 101.29 |
| **Average 2005-20** | 82.82 | 170.83 | 41.72 | 132.91 | 82.66 | 113.91 |
| **Max 2005-20** | 98.95 | 233.33 | 92.79 | 152.93 | 98.43 | 126.76 |
| **Cumul. 2005-20** | 82.44 | 182.6 | 41.72 | 132.91 | 82.21 | 114.61 |
| ***Platinum use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 37.82 | 3.91 | 2.98 | 0.76 | 57.5 | 60.42 |
| **2010** | 44.61 | 9.04 | 2.26 | 1.47 | 64.77 | 65.87 |
| **2015** | 41.09 | 18.91 | 1.51 | 2.23 | 61.82 | 75.66 |
| **2020** | 32.97 | 30.32 | 0.75 | 2.99 | 54.42 | 87.94 |
| **Min 2005-20** | 32.97 | 3.91 | 0.75 | 0.76 | 54.42 | 60.42 |
| **Average 2005-20** | 40.57 | 14.98 | 1.9 | 1.84 | 61.07 | 71.83 |
| **Max 2005-20** | 46.28 | 30.32 | 2.98 | 2.99 | 66.54 | 87.94 |
| **Cumul. 2005-20** | 649.16 | 239.61 | 30.33 | 29.43 | 977.14 | 1149.24 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.3 | 0.3 | -0.2 | 0.2 | -0.5 | 0.5 |
| **2010** | -3.01 | 3.01 | -0.91 | 0.91 | -3.92 | 3.92 |
| **2015** | -9.04 | 9.04 | -1.67 | 1.67 | -10.71 | 10.71 |
| **2020** | -17.33 | 17.33 | -2.43 | 2.43 | -19.75 | 19.75 |
| **Min 2005-20** | -17.33 | 0.3 | -2.43 | 0.2 | -19.75 | 0.5 |
| **Average 2005-20** | -6.91 | 6.91 | -1.28 | 1.28 | -8.19 | 8.19 |
| **Max 2005-20** | -0.3 | 17.33 | -0.2 | 2.43 | -0.5 | 19.75 |
| **Cumul. 2005-20** | -110.6 | 110.6 | -20.46 | 20.46 | -131.06 | 131.06 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 99.21 | 108.33 | 93.81 | 135.07 | 99.14 | 100.83 |
| **2010** | 93.67 | 150 | 71.32 | 262.5 | 94.29 | 106.34 |
| **2015** | 81.96 | 191.67 | 47.43 | 397.92 | 85.23 | 116.5 |
| **2020** | 65.55 | 233.33 | 23.53 | 533.33 | 73.37 | 128.97 |
| **Min 2005-20** | 65.55 | 108.33 | 23.53 | 135.07 | 73.37 | 100.83 |
| **Average 2005-20** | 86.08 | 170.83 | 59.72 | 328.27 | 88.66 | 112.49 |
| **Max 2005-20** | 99.21 | 233.33 | 93.81 | 533.33 | 99.14 | 128.97 |
| **Cumul. 2005-20** | 85.44 | 185.72 | 59.72 | 328.27 | 88.17 | 112.87 |

Continued on next page

**Table E.2 – continued from previous page**

| ***Palladium use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 20.15 | 3.66 | 8.48 | 22.1 | 35.1 | 51.24 |
| **2010** | 19.81 | 8.8 | 4.59 | 25.99 | 31.38 | 65.21 |
| **2015** | 15.45 | 13.87 | 0.76 | 29.81 | 23.8 | 80.07 |
| **2020** | 8.16 | 19.4 | 0 | 30.58 | 16.48 | 93.55 |
| **Min 2005-20** | 8.16 | 3.66 | 0 | 22.1 | 16.48 | 51.24 |
| **Average 2005-20** | 16.56 | 11.45 | 3.24 | 27.34 | 27.11 | 72.53 |
| **Max 2005-20** | 20.58 | 19.4 | 8.48 | 30.58 | 35.29 | 93.55 |
| **Cumul. 2005-20** | 264.96 | 183.15 | 51.77 | 437.48 | 433.82 | 1160.47 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.28 | 0.28 | -0.7 | 0.7 | -0.98 | 0.98 |
| **2010** | -2.93 | 2.93 | -4.59 | 4.59 | -7.52 | 7.52 |
| **2015** | -6.63 | 6.63 | -8.41 | 8.41 | -15.04 | 15.04 |
| **2020** | -11.09 | 11.09 | -9.17 | 9.17 | -20.26 | 20.26 |
| **Min 2005-20** | -11.09 | 0.28 | -9.17 | 0.7 | -20.26 | 0.98 |
| **Average 2005-20** | -5.07 | 5.07 | -5.94 | 5.94 | -11 | 11 |
| **Max 2005-20** | -0.28 | 11.09 | -0.7 | 9.17 | -0.98 | 20.26 |
| **Cumul. 2005-20** | -81.07 | 81.07 | -95 | 95 | -176.07 | 176.07 |
| ***Ratio wrt BAU*** | | | | | | |
| | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| (in %) | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.62 | 108.33 | 92.4 | 103.26 | 97.29 | 101.95 |
| **2010** | 87.1 | 150 | 50 | 121.43 | 80.67 | 113.03 |
| **2015** | 69.96 | 191.67 | 8.33 | 139.29 | 61.28 | 123.13 |
| **2020** | 42.4 | 233.33 | 0 | 142.86 | 44.85 | 127.64 |
| **Min 2005-20** | 42.4 | 108.33 | 0 | 103.26 | 44.85 | 101.95 |
| **Average 2005-20** | 76.07 | 170.83 | 35.27 | 127.74 | 71.18 | 116.93 |
| **Max 2005-20** | 98.62 | 233.33 | 92.4 | 142.86 | 97.29 | 127.64 |
| **Cumul. 2005-20** | 76.57 | 179.42 | 35.27 | 127.74 | 71.13 | 117.89 |

| ***Rhodium use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 3.14 | 0.83 | 0.07 | 0.03 | 4.31 | 9.3 |
| **2010** | 3.22 | 1.32 | 0.05 | 0.04 | 4.56 | 10.84 |
| **2015** | 2.74 | 2.19 | 0.04 | 0.05 | 4.27 | 14.13 |
| **2020** | 1.55 | 3.09 | 0.03 | 0.06 | 3.31 | 16.64 |
| **Min 2005-20** | 1.55 | 0.83 | 0.03 | 0.03 | 3.31 | 9.08 |
| **Average 2005-20** | 2.82 | 1.82 | 0.05 | 0.04 | 4.27 | 12.63 |
| **Max 2005-20** | 3.52 | 3.09 | 0.07 | 0.06 | 4.89 | 16.64 |
| **Cumul. 2005-20** | 45.2 | 29.08 | 0.77 | 0.68 | 68.29 | 202.05 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.06 | 0.06 | 0 | 0 | -0.07 | 0.07 |
| **2010** | -0.44 | 0.44 | -0.01 | 0.01 | -0.45 | 0.45 |
| **2015** | -1.05 | 1.05 | -0.02 | 0.02 | -1.07 | 1.07 |
| **2020** | -1.77 | 1.77 | -0.04 | 0.04 | -1.8 | 1.8 |
| **Min 2005-20** | -1.77 | 0.06 | -0.04 | 0 | -1.8 | 0.07 |
| **Average 2005-20** | -0.8 | 0.8 | -0.02 | 0.02 | -0.81 | 0.81 |
| **Max 2005-20** | -0.06 | 1.77 | 0 | 0.04 | -0.07 | 1.8 |
| **Cumul. 2005-20** | -12.72 | 12.72 | -0.31 | 0.31 | -13.03 | 13.03 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.02 | 108.33 | 96.82 | 109.04 | 98.5 | 100.71 |
| **2010** | 87.96 | 150 | 79.73 | 157.69 | 90.93 | 104.38 |
| **2015** | 72.32 | 191.67 | 62.84 | 205.77 | 79.9 | 108.23 |
| **2020** | 46.69 | 233.33 | 45.95 | 253.85 | 64.73 | 112.16 |
| **Min 2005-20** | 46.69 | 108.33 | 45.95 | 109.04 | 64.73 | 100.71 |
| **Average 2005-20** | 78.02 | 170.83 | 71.61 | 180.8 | 84.39 | 106.34 |
| **Max 2005-20** | 98.02 | 233.33 | 96.82 | 253.85 | 98.5 | 112.16 |
| **Cumul. 2005-20** | 78.03 | 177.81 | 71.61 | 180.8 | 83.98 | 106.89 |

Table E.3: PGM inputs in the R2 scenario

| ***PGM use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 60.95 | 8.56 | 11.52 | 22.88 | 96.75 | 121.12 |
| **2010** | 66.05 | 20.76 | 6.9 | 27.5 | 99.11 | 143.52 |
| **2015** | 55.1 | 39.16 | 2.31 | 32.09 | 85.71 | 174.04 |
| **2020** | 35.13 | 60.36 | 0.78 | 33.63 | 66.66 | 205.67 |
| **Min 2005-20** | 35.13 | 8.56 | 0.78 | 22.88 | 66.66 | 121.12 |
| **Average 2005-20** | 56.76 | 31.43 | 5.18 | 29.22 | 89.26 | 160.18 |
| **Max 2005-20** | 67.3 | 60.36 | 11.52 | 33.63 | 99.85 | 205.67 |
| **Cumul. 2005-20** | 908.22 | 502.94 | 82.88 | 467.59 | 1428.16 | 2562.86 |

| ***Difference wrt BAU*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.81 | 0.81 | -0.9 | 0.9 | -1.7 | 1.7 |
| **2010** | -7.99 | 7.99 | -5.51 | 5.51 | -13.5 | 13.5 |
| **2015** | -20.91 | 20.91 | -10.1 | 10.1 | -31.01 | 31.01 |
| **2020** | -37.73 | 37.73 | -11.64 | 11.64 | -49.37 | 49.37 |
| **Min 2005-20** | -37.73 | 0.81 | -11.64 | 0.9 | -49.37 | 1.7 |
| **Average 2005-20** | -15.97 | 15.97 | -7.24 | 7.24 | -23.2 | 23.2 |
| **Max 2005-20** | -0.81 | 37.73 | -0.9 | 11.64 | -1.7 | 49.37 |
| **Cumul. 2005-20** | -255.49 | 255.49 | -115.77 | 115.77 | -371.26 | 371.26 |

| ***Ratio wrt BAU*** | | | | | | |
|---|---|---|---|---|---|---|
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.69 | 110.42 | 92.79 | 104.07 | 98.27 | 101.43 |
| **2010** | 89.21 | 162.5 | 55.61 | 125.06 | 88.01 | 110.38 |
| **2015** | 72.49 | 214.58 | 18.62 | 145.95 | 73.43 | 121.68 |
| **2020** | 48.22 | 266.67 | 6.27 | 152.93 | 57.45 | 131.58 |
| **Min 2005-20** | 48.22 | 110.42 | 6.27 | 104.07 | 57.45 | 101.43 |
| **Average 2005-20** | 78.53 | 188.54 | 41.72 | 132.91 | 79.89 | 116.12 |
| **Max 2005-20** | 98.69 | 266.67 | 92.79 | 152.93 | 98.27 | 131.58 |
| **Cumul. 2005-20** | 78.05 | 203.25 | 41.72 | 132.91 | 79.37 | 116.94 |

| ***Platinum use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 37.74 | 3.98 | 2.98 | 0.76 | 57.43 | 60.49 |
| **2010** | 43.86 | 9.8 | 2.26 | 1.47 | 64.02 | 66.62 |
| **2015** | 38.83 | 21.17 | 1.51 | 2.23 | 59.56 | 77.92 |
| **2020** | 28.64 | 34.65 | 0.75 | 2.99 | 50.09 | 92.27 |
| **Min 2005-20** | 28.64 | 3.98 | 0.75 | 0.76 | 50.09 | 60.49 |
| **Average 2005-20** | 38.84 | 16.7 | 1.9 | 1.84 | 59.34 | 73.56 |
| **Max 2005-20** | 45.33 | 34.65 | 2.98 | 2.99 | 65.59 | 92.27 |
| **Cumul. 2005-20** | 621.51 | 267.26 | 30.33 | 29.43 | 949.49 | 1176.89 |

| ***Difference wrt BAU*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.38 | 0.38 | -0.2 | 0.2 | -0.57 | 0.57 |
| **2010** | -3.77 | 3.77 | -0.91 | 0.91 | -4.68 | 4.68 |
| **2015** | -11.31 | 11.31 | -1.67 | 1.67 | -12.98 | 12.98 |
| **2020** | -21.66 | 21.66 | -2.43 | 2.43 | -24.09 | 24.09 |
| **Min 2005-20** | -21.66 | 0.38 | -2.43 | 0.2 | -24.09 | 0.57 |
| **Average 2005-20** | -8.64 | 8.64 | -1.28 | 1.28 | -9.92 | 9.92 |
| **Max 2005-20** | -0.38 | 21.66 | -0.2 | 2.43 | -0.57 | 24.09 |
| **Cumul. 2005-20** | -138.25 | 138.25 | -20.46 | 20.46 | -158.71 | 158.71 |

| ***Ratio wrt BAU*** | | | | | | |
|---|---|---|---|---|---|---|
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 99.01 | 110.42 | 93.81 | 135.07 | 99.01 | 100.95 |
| **2010** | 92.09 | 162.5 | 71.32 | 262.5 | 93.19 | 107.55 |
| **2015** | 77.45 | 214.58 | 47.43 | 397.92 | 82.11 | 119.98 |
| **2020** | 56.94 | 266.67 | 23.53 | 533.33 | 67.53 | 135.33 |
| **Min 2005-20** | 56.94 | 110.42 | 23.53 | 135.07 | 67.53 | 100.95 |
| **Average 2005-20** | 82.6 | 188.54 | 59.72 | 328.27 | 86.28 | 115.12 |
| **Max 2005-20** | 99.01 | 266.67 | 93.81 | 533.33 | 99.01 | 135.33 |
| **Cumul. 2005-20** | 81.8 | 207.16 | 59.72 | 328.27 | 85.68 | 115.59 |

Continued on next page

**Table E.3 – continued from previous page**

| ***Palladium use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 20.08 | 3.73 | 8.48 | 22.1 | 35.03 | 51.31 |
| **2010** | 19.08 | 9.53 | 4.59 | 25.99 | 30.65 | 65.95 |
| **2015** | 13.79 | 15.53 | 0.76 | 29.81 | 22.15 | 81.73 |
| **2020** | 5.39 | 22.17 | 0 | 30.58 | 13.71 | 96.32 |
| **Min 2005-20** | 5.39 | 3.73 | 0 | 22.1 | 13.71 | 51.31 |
| **Average 2005-20** | 15.29 | 12.71 | 3.24 | 27.34 | 25.85 | 73.8 |
| **Max 2005-20** | 20.41 | 22.17 | 8.48 | 30.58 | 35.12 | 96.32 |
| **Cumul. 2005-20** | 244.69 | 203.42 | 51.77 | 437.48 | 413.56 | 1180.74 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.35 | 0.35 | -0.7 | 0.7 | -1.05 | 1.05 |
| **2010** | -3.67 | 3.67 | -4.59 | 4.59 | -8.25 | 8.25 |
| **2015** | -8.29 | 8.29 | -8.41 | 8.41 | -16.7 | 16.7 |
| **2020** | -13.86 | 13.86 | -9.17 | 9.17 | -23.03 | 23.03 |
| **Min 2005-20** | -13.86 | 0.35 | -9.17 | 0.7 | -23.03 | 1.05 |
| **Average 2005-20** | -6.33 | 6.33 | -5.94 | 5.94 | -12.27 | 12.27 |
| **Max 2005-20** | -0.35 | 13.86 | -0.7 | 9.17 | -1.05 | 23.03 |
| **Cumul. 2005-20** | -101.34 | 101.34 | -95 | 95 | -196.34 | 196.34 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.28 | 110.42 | 92.4 | 103.26 | 97.09 | 102.09 |
| **2010** | 83.88 | 162.5 | 50 | 121.43 | 78.78 | 114.3 |
| **2015** | 62.45 | 214.58 | 8.33 | 139.29 | 57.01 | 125.68 |
| **2020** | 28 | 266.67 | 0 | 142.86 | 37.31 | 131.43 |
| **Min 2005-20** | 28 | 110.42 | 0 | 103.26 | 37.31 | 102.09 |
| **Average 2005-20** | 70.09 | 188.54 | 35.27 | 127.74 | 67.85 | 118.86 |
| **Max 2005-20** | 98.28 | 266.67 | 92.4 | 142.86 | 97.09 | 131.43 |
| **Cumul. 2005-20** | 70.71 | 199.28 | 35.27 | 127.74 | 67.81 | 119.95 |

| ***Rhodium use*** | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 3.13 | 0.84 | 0.07 | 0.03 | 4.3 | 9.32 |
| **2010** | 3.11 | 1.43 | 0.05 | 0.04 | 4.45 | 10.95 |
| **2015** | 2.48 | 2.46 | 0.04 | 0.05 | 4.01 | 14.39 |
| **2020** | 1.11 | 3.54 | 0.03 | 0.06 | 2.87 | 17.08 |
| **Min 2005-20** | 1.11 | 0.84 | 0.03 | 0.03 | 2.87 | 9.11 |
| **Average 2005-20** | 2.63 | 2.02 | 0.05 | 0.04 | 4.07 | 12.83 |
| **Max 2005-20** | 3.39 | 3.54 | 0.07 | 0.06 | 4.76 | 17.08 |
| **Cumul. 2005-20** | 42.01 | 32.26 | 0.77 | 0.68 | 65.11 | 205.23 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.08 | 0.08 | 0 | 0 | -0.08 | 0.08 |
| **2010** | -0.55 | 0.55 | -0.01 | 0.01 | -0.56 | 0.56 |
| **2015** | -1.31 | 1.31 | -0.02 | 0.02 | -1.34 | 1.34 |
| **2020** | -2.21 | 2.21 | -0.04 | 0.04 | -2.25 | 2.25 |
| **Min 2005-20** | -2.21 | 0.08 | -0.04 | 0 | -2.25 | 0.08 |
| **Average 2005-20** | -0.99 | 0.99 | -0.02 | 0.02 | -1.01 | 1.01 |
| **Max 2005-20** | -0.08 | 2.21 | 0 | 0.04 | -0.08 | 2.25 |
| **Cumul. 2005-20** | -15.9 | 15.9 | -0.31 | 0.31 | -16.21 | 16.21 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 97.52 | 110.42 | 96.82 | 109.04 | 98.14 | 100.88 |
| **2010** | 84.95 | 162.5 | 79.73 | 157.69 | 88.73 | 105.44 |
| **2015** | 65.4 | 214.58 | 62.84 | 205.77 | 74.99 | 110.24 |
| **2020** | 33.37 | 266.67 | 45.95 | 253.85 | 56.09 | 115.14 |
| **Min 2005-20** | 33.37 | 110.42 | 45.95 | 109.04 | 56.09 | 100.88 |
| **Average 2005-20** | 72.53 | 188.54 | 71.61 | 180.8 | 80.57 | 107.88 |
| **Max 2005-20** | 97.52 | 266.67 | 96.82 | 253.85 | 98.14 | 115.14 |
| **Cumul. 2005-20** | 72.54 | 197.26 | 71.61 | 180.8 | 80.07 | 108.58 |

Table E.4: PGM inputs in the R3 scenario

| | | | | | | |
|---|---|---|---|---|---|---|
| ***PGM use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 60.79 | 8.72 | 11.52 | 22.88 | 96.59 | 121.28 |
| **2010** | 64.45 | 22.36 | 6.9 | 27.5 | 97.51 | 145.12 |
| **2015** | 50.92 | 43.34 | 2.31 | 32.09 | 81.53 | 178.23 |
| **2020** | 27.59 | 67.91 | 0.78 | 33.63 | 59.12 | 213.21 |
| **Min 2005-20** | 27.59 | 8.72 | 0.78 | 22.88 | 59.12 | 121.28 |
| **Average 2005-20** | 53.57 | 34.63 | 5.18 | 29.22 | 86.07 | 163.37 |
| **Max 2005-20** | 65.29 | 67.91 | 11.52 | 33.63 | 98.98 | 213.21 |
| **Cumul. 2005-20** | 857.12 | 554.03 | 82.88 | 467.59 | 1377.06 | 2613.96 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.97 | 0.97 | -0.9 | 0.9 | -1.86 | 1.86 |
| **2010** | -9.58 | 9.58 | -5.51 | 5.51 | -15.09 | 15.09 |
| **2015** | -25.09 | 25.09 | -10.1 | 10.1 | -35.2 | 35.2 |
| **2020** | -45.27 | 45.27 | -11.64 | 11.64 | -56.91 | 56.91 |
| **Min 2005-20** | -45.27 | 0.97 | -11.64 | 0.9 | -56.91 | 1.86 |
| **Average 2005-20** | -19.16 | 19.16 | -7.24 | 7.24 | -26.4 | 26.4 |
| **Max 2005-20** | -0.97 | 45.27 | -0.9 | 11.64 | -1.86 | 56.91 |
| **Cumul. 2005-20** | -306.59 | 306.59 | -115.77 | 115.77 | -422.36 | 422.36 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.43 | 112.5 | 92.79 | 104.07 | 98.11 | 101.56 |
| **2010** | 87.06 | 175 | 55.61 | 125.06 | 86.6 | 111.61 |
| **2015** | 66.99 | 237.5 | 18.62 | 145.95 | 69.85 | 124.61 |
| **2020** | 37.86 | 300 | 6.27 | 152.93 | 50.95 | 136.41 |
| **Min 2005-20** | 37.86 | 112.5 | 6.27 | 104.07 | 50.95 | 101.56 |
| **Average 2005-20** | 74.24 | 206.25 | 41.72 | 132.91 | 77.13 | 118.33 |
| **Max 2005-20** | 98.43 | 300 | 92.79 | 152.93 | 98.11 | 136.41 |
| **Cumul. 2005-20** | 73.65 | 223.9 | 41.72 | 132.91 | 76.53 | 119.27 |
| ***Platinum use*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 37.67 | 4.06 | 2.98 | 0.76 | 57.35 | 60.57 |
| **2010** | 43.1 | 10.55 | 2.26 | 1.47 | 63.26 | 67.37 |
| **2015** | 36.57 | 23.43 | 1.51 | 2.23 | 57.3 | 80.19 |
| **2020** | 24.31 | 0 | 0.75 | 2.99 | 45.76 | 96.6 |
| **Min 2005-20** | 24.31 | 0 | 0.75 | 0.76 | 45.76 | 60.57 |
| **Average 2005-20** | 37.12 | 0 | 1.9 | 1.84 | 57.62 | 75.28 |
| **Max 2005-20** | 44.37 | 0 | 2.98 | 2.99 | 64.64 | 96.6 |
| **Cumul. 2005-20** | 593.86 | 0 | 30.33 | 29.43 | 921.84 | 1204.54 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.45 | 0 | -0.2 | 0.2 | -0.65 | 0.65 |
| **2010** | -4.52 | 0 | -0.91 | 0.91 | -5.43 | 5.43 |
| **2015** | -13.57 | 0 | -1.67 | 1.67 | -15.24 | 15.24 |
| **2020** | -25.99 | 0 | -2.43 | 2.43 | -28.42 | 28.42 |
| **Min 2005-20** | -25.99 | 0 | -2.43 | 0.2 | -28.42 | 0.65 |
| **Average 2005-20** | -10.37 | 0 | -1.28 | 1.28 | -11.65 | 11.65 |
| **Max 2005-20** | -0.45 | 0 | -0.2 | 2.43 | -0.65 | 28.42 |
| **Cumul. 2005-20** | -165.9 | 0 | -20.46 | 20.46 | -186.36 | 186.36 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 98.82 | 0 | 93.81 | 135.07 | 98.88 | 101.08 |
| **2010** | 90.51 | 0 | 71.32 | 262.5 | 92.09 | 108.77 |
| **2015** | 72.94 | 0 | 47.43 | 397.92 | 78.99 | 123.46 |
| **2020** | 48.32 | 0 | 23.53 | 533.33 | 61.69 | 141.68 |
| **Min 2005-20** | 48.32 | 0 | 23.53 | 135.07 | 61.69 | 101.08 |
| **Average 2005-20** | 79.12 | 0 | 59.72 | 328.27 | 83.89 | 117.75 |
| **Max 2005-20** | 98.82 | 0 | 93.81 | 533.33 | 98.88 | 141.68 |
| **Cumul. 2005-20** | 78.16 | 0 | 59.72 | 328.27 | 83.18 | 118.3 |

Continued on next page

**Table E.4 – continued from previous page**

| *Palladium use* | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 20.01 | 3.8 | 8.48 | 22.1 | 34.96 | 51.38 |
| **2010** | 18.34 | 10.27 | 4.59 | 25.99 | 29.91 | 66.68 |
| **2015** | 12.13 | 17.19 | 0.76 | 29.81 | 20.49 | 83.39 |
| **2020** | 2.62 | 24.95 | 0 | 30.58 | 10.93 | 99.09 |
| **Min 2005-20** | 2.62 | 3.8 | 0 | 22.1 | 10.93 | 51.38 |
| **Average 2005-20** | 14.03 | 13.98 | 3.24 | 27.34 | 24.58 | 75.06 |
| **Max 2005-20** | 20.23 | 24.95 | 8.48 | 30.58 | 34.96 | 99.09 |
| **Cumul. 2005-20** | 224.43 | 223.69 | 51.77 | 437.48 | 393.29 | 1201.01 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.42 | 0.42 | -0.7 | 0.7 | -1.12 | 1.12 |
| **2010** | -4.4 | 4.4 | -4.59 | 4.59 | -8.99 | 8.99 |
| **2015** | -9.95 | 9.95 | -8.41 | 8.41 | -18.36 | 18.36 |
| **2020** | -16.63 | 16.63 | -9.17 | 9.17 | -25.8 | 25.8 |
| **Min 2005-20** | -16.63 | 0.42 | -9.17 | 0.7 | -25.8 | 1.12 |
| **Average 2005-20** | -7.6 | 7.6 | -5.94 | 5.94 | -13.54 | 13.54 |
| **Max 2005-20** | -0.42 | 16.63 | -0.7 | 9.17 | -1.12 | 25.8 |
| **Cumul. 2005-20** | -121.61 | 121.61 | -95 | 95 | -216.61 | 216.61 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 97.93 | 112.5 | 92.4 | 103.26 | 96.9 | 102.23 |
| **2010** | 80.66 | 175 | 50 | 121.43 | 76.9 | 115.58 |
| **2015** | 54.94 | 237.5 | 8.33 | 139.29 | 52.74 | 128.23 |
| **2020** | 13.6 | 300 | 0 | 142.86 | 29.76 | 135.21 |
| **Min 2005-20** | 13.6 | 112.5 | 0 | 103.26 | 29.76 | 102.23 |
| **Average 2005-20** | 64.11 | 206.25 | 35.27 | 127.74 | 64.53 | 120.79 |
| **Max 2005-20** | 97.93 | 300 | 92.4 | 142.86 | 96.9 | 135.21 |
| **Cumul. 2005-20** | 64.86 | 219.14 | 35.27 | 127.74 | 64.48 | 122 |

| *Rhodium use* | | | | | | |
|---|---|---|---|---|---|---|
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 3.11 | 0.86 | 0.07 | 0.03 | 4.28 | 9.33 |
| **2010** | 3 | 1.54 | 0.05 | 0.04 | 4.34 | 11.06 |
| **2015** | 2.22 | 2.72 | 0.04 | 0.05 | 3.75 | 14.65 |
| **2020** | 0.66 | 3.98 | 0.03 | 0.06 | 2.43 | 17.52 |
| **Min 2005-20** | 0.66 | 0.86 | 0.03 | 0.03 | 2.43 | 9.15 |
| **Average 2005-20** | 2.43 | 2.21 | 0.05 | 0.04 | 3.87 | 13.03 |
| **Max 2005-20** | 3.25 | 3.98 | 0.07 | 0.06 | 4.62 | 17.52 |
| **Cumul. 2005-20** | 38.83 | 35.44 | 0.77 | 0.68 | 61.93 | 208.41 |
| ***Difference wrt BAU*** | | | | | | |
| (in tonnes) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | -0.1 | 0.1 | 0 | 0 | -0.1 | 0.1 |
| **2010** | -0.66 | 0.66 | -0.01 | 0.01 | -0.68 | 0.68 |
| **2015** | -1.57 | 1.57 | -0.02 | 0.02 | -1.6 | 1.6 |
| **2020** | -2.65 | 2.65 | -0.04 | 0.04 | -2.69 | 2.69 |
| **Min 2005-20** | -2.65 | 0.1 | -0.04 | 0 | -2.69 | 0.1 |
| **Average 2005-20** | -1.19 | 1.19 | -0.02 | 0.02 | -1.21 | 1.21 |
| **Max 2005-20** | -0.1 | 2.65 | 0 | 0.04 | -0.1 | 2.69 |
| **Cumul. 2005-20** | -19.08 | 19.08 | -0.31 | 0.31 | -19.39 | 19.39 |
| ***Ratio wrt BAU*** | | | | | | |
| (in %) | **Autocatalysts** | | **Electronics** | | **All sectors** | |
| | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* | *Primary input* | *Secondary input* |
| **2005** | 97.03 | 112.5 | 96.82 | 109.04 | 97.78 | 101.05 |
| **2010** | 81.94 | 175 | 79.73 | 157.69 | 86.53 | 106.5 |
| **2015** | 58.48 | 237.5 | 62.84 | 205.77 | 70.09 | 112.25 |
| **2020** | 20.04 | 300 | 45.95 | 253.85 | 47.45 | 118.12 |
| **Min 2005-20** | 20.04 | 112.5 | 45.95 | 109.04 | 47.45 | 101.05 |
| **Average 2005-20** | 67.04 | 206.25 | 71.61 | 180.8 | 76.76 | 109.43 |
| **Max 2005-20** | 97.03 | 300 | 96.82 | 253.85 | 97.78 | 118.12 |
| **Cumul. 2005-20** | 67.05 | 216.71 | 71.61 | 180.8 | 76.15 | 110.26 |

Table E.5: Environmental pressures in the BAU scenario

| $CO_{2eq}$ | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 2,779,360.84 | 577,411.59 | 3,356,772.43 |
| **2010** | 3,256,061.20 | 614,311.25 | 3,870,372.45 |
| **2015** | 3,424,442.64 | 669,727.66 | 4,094,170.30 |
| **2020** | 3,463,909.01 | 721,414.29 | 4,185,323.29 |
| **Min 2005-20** | 2,779,360.84 | 577,411.59 | 3,356,772.43 |
| **Average 2005-20** | 3,276,344.97 | 644,369.79 | 3,920,714.76 |
| **Max 2005-20** | 3,463,909.01 | 721,414.29 | 4,185,323.29 |
| **Cumul. 2005-20** | 52,421,519.60 | 10,309,916.62 | 62,731,436.22 |
| $SO_{2eq}$ | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 178,540.07 | 5,222.34 | 183,762.41 |
| **2010** | 205,142.85 | 5,556.07 | 210,698.92 |
| **2015** | 213,290.75 | 6,057.28 | 219,348.02 |
| **2020** | 212,691.21 | 6,524.75 | 219,215.96 |
| **Min 2005-20** | 178,540.07 | 5,222.34 | 183,762.41 |
| **Average 2005-20** | 205,201.44 | 5,827.93 | 211,029.37 |
| **Max 2005-20** | 213,769.77 | 6,524.75 | 219,910.32 |
| **Cumul. 2005-20** | 3,283,223.04 | 93,246.90 | 3,376,469.95 |
| $TMR_{eq}$ | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 46,765,381.12 | 1,830,761.29 | 48,596,142.40 |
| **2010** | 54,866,550.72 | 1,947,756.61 | 56,814,307.33 |
| **2015** | 57,753,123.27 | 2,123,461.83 | 59,876,585.11 |
| **2020** | 58,479,590.48 | 2,287,341.23 | 60,766,931.71 |
| **Min 2005-20** | 46,765,381.12 | 1,830,761.29 | 48,596,142.40 |
| **Average 2005-20** | 55,232,748.71 | 2,043,061.27 | 57,275,809.99 |
| **Max 2005-20** | 58,479,590.48 | 2,287,341.23 | 60,766,931.71 |
| **Cumul. 2005-20** | 883,723,979.42 | 32,688,980.36 | 916,412,959.77 |

Table E.6: Environmental pressures in the R1 scenario

| $CO_{2eq}$ | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 2,749,394.08 | 583,167.36 | 3,332,561.45 |
| **2010** | 3,023,891.88 | 658,872.09 | 3,682,763.97 |
| **2015** | 2,838,077.09 | 779,767.68 | 3,617,844.77 |
| **2020** | 2,445,041.22 | 908,889.62 | 3,353,930.85 |
| **Min 2005-20** | 2,445,041.22 | 583,167.36 | 3,332,561.45 |
| **Average 2005-20** | 2,831,973.93 | 727,511.13 | 3,559,485.05 |
| **Max 2005-20** | 3,103,328.19 | 908,889.62 | 3,783,044.14 |
| **Cumul. 2005-20** | 45,311,582.81 | 11,640,178.05 | 56,951,760.87 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -29,966.75 | 5,755.77 | -24,210.98 |
| **2010** | -232,169.32 | 44,560.84 | -187,608.47 |
| **2015** | -586,365.55 | 110,040.01 | -476,325.53 |
| **2020** | -1,018,867.78 | 187,475.34 | -831,392.44 |
| **Min 2005-20** | -1,018,867.78 | 5,755.77 | -831,392.44 |
| **Average 2005-20** | -444,371.05 | 83,141.34 | -361,229.71 |
| **Max 2005-20** | -29,966.75 | 187,475.34 | -24,210.98 |
| **Cumul. 2005-20** | -7,109,936.79 | 1,330,261.43 | -5,779,675.36 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.92 | 101.00 | 99.28 |
| **2010** | 92.87 | 107.25 | 95.15 |
| **2015** | 82.88 | 116.43 | 88.37 |
| **2020** | 70.59 | 125.99 | 80.14 |
| **Min 2005-20** | 70.59 | 101.00 | 80.14 |
| **Average 2005-20** | 86.92 | 112.33 | 91.13 |
| **Max 2005-20** | 98.92 | 125.99 | 99.28 |
| **Cumul. 2005-20** | 86.44 | 112.90 | 90.79 |

| $SO_{2eq}$ | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 175,910.97 | 5,274.39 | 181,185.36 |
| **2010** | 184,848.70 | 5,959.10 | 190,807.79 |
| **2015** | 166,751.04 | 7,052.52 | 173,803.56 |
| **2020** | 138,839.20 | 8,220.35 | 147,059.55 |
| **Min 2005-20** | 138,839.20 | 5,274.39 | 147,059.55 |
| **Average 2005-20** | 170,403.44 | 6,579.89 | 176,983.34 |
| **Max 2005-20** | 187,581.01 | 8,220.35 | 193,728.62 |
| **Cumul. 2005-20** | 2,726,455.11 | 105,278.31 | 2,831,733.41 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -2,629.10 | 52.06 | -2,577.04 |
| **2010** | -20,294.15 | 403.03 | -19,891.12 |
| **2015** | -46,539.70 | 995.24 | -45,544.46 |
| **2020** | -73,852.01 | 1,695.60 | -72,156.41 |
| **Min 2005-20** | -73,852.01 | 52.06 | -72,156.41 |
| **Average 2005-20** | -34,798.00 | 751.96 | -34,046.03 |
| **Max 2005-20** | -2,629.10 | 1,695.60 | -2,577.04 |
| **Cumul. 2005-20** | -556,767.94 | 12,031.40 | -544,736.53 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.53 | 101.00 | 98.60 |
| **2010** | 90.11 | 107.25 | 90.56 |
| **2015** | 78.18 | 116.43 | 79.24 |
| **2020** | 65.28 | 125.99 | 67.08 |
| **Min 2005-20** | 65.28 | 101.00 | 67.08 |
| **Average 2005-20** | 83.50 | 112.33 | 84.31 |
| **Max 2005-20** | 98.53 | 125.99 | 98.60 |
| **Cumul. 2005-20** | 83.04 | 112.90 | 83.87 |

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Table E.6 – continued from previous page

| *TMR*$_{eq}$ | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 46,275,219.33 | 1,849,010.73 | 48,124,230.06 |
| **2010** | 51,067,538.00 | 2,089,042.77 | 53,156,580.77 |
| **2015** | 48,064,180.11 | 2,472,358.52 | 50,536,538.64 |
| **2020** | 41,503,939.54 | 2,881,757.06 | 44,385,696.60 |
| **Min 2005-20** | 41,503,939.54 | 1,849,010.73 | 44,385,696.60 |
| **Average 2005-20** | 47,880,657.34 | 2,306,672.10 | 50,187,329.43 |
| **Max 2005-20** | 52,451,682.64 | 2,881,757.06 | 54,606,813.68 |
| **Cumul. 2005-20** | 766,090,517.37 | 36,906,753.53 | 802,997,270.90 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -490,161.78 | 18,249.44 | -471,912.34 |
| **2010** | -3,799,012.72 | 141,286.16 | -3,657,726.56 |
| **2015** | -9,688,943.16 | 348,896.69 | -9,340,046.47 |
| **2020** | -16,975,650.95 | 594,415.83 | -16,381,235.12 |
| **Min 2005-20** | -16,975,650.95 | 18,249.44 | -16,381,235.12 |
| **Average 2005-20** | -7,352,091.38 | 263,610.82 | -7,088,480.55 |
| **Max 2005-20** | -490,161.78 | 594,415.83 | -471,912.34 |
| **Cumul. 2005-20** | -117,633,462.05 | 4,217,773.18 | -113,415,688.87 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.95 | 101.00 | 99.03 |
| **2010** | 93.08 | 107.25 | 93.56 |
| **2015** | 83.22 | 116.43 | 84.40 |
| **2020** | 70.97 | 125.99 | 73.04 |
| **Min 2005-20** | 70.97 | 101.00 | 73.04 |
| **Average 2005-20** | 87.18 | 112.33 | 88.08 |
| **Max 2005-20** | 98.95 | 125.99 | 99.03 |
| **Cumul. 2005-20** | 86.69 | 112.90 | 87.62 |

Table E.7: Environmental pressures in the R2 scenario

| $CO_{2eq}$ | | | | $SO_{2eq}$ | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 2,745,144.80 | 583,939.23 | 3,329,084.03 | **2005** | 175,619.54 | 5,281.37 | 180,900.92 |
| **2010** | 2,983,369.47 | 666,277.32 | 3,649,646.79 | **2010** | 181,997.00 | 6,026.07 | 188,023.07 |
| **2015** | 2,723,605.55 | 800,430.21 | 3,524,035.76 | **2015** | 159,189.49 | 7,239.40 | 166,428.89 |
| **2020** | 2,231,523.43 | 947,231.97 | 3,178,755.40 | **2020** | 125,119.92 | 8,567.14 | 133,687.05 |
| **Min 2005-20** | 2,231,523.43 | 583,939.23 | 3,178,755.40 | **Min 2005-20** | 125,119.92 | 5,281.37 | 133,687.05 |
| **Average 2005-20** | 2,744,578.49 | 743,286.94 | 3,487,865.43 | **Average 2005-20** | 164,629.71 | 6,722.58 | 171,352.28 |
| **Max 2005-20** | 3,052,379.19 | 947,231.97 | 3,741,405.35 | **Max 2005-20** | 183,997.72 | 8,567.14 | 190,229.54 |
| **Cumul. 2005-20** | 43,913,255.84 | 11,892,590.97 | 55,805,846.81 | **Cumul. 2005-20** | 2,634,075.30 | 107,561.23 | 2,741,636.53 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -34,216.04 | 6,527.63 | -27,688.40 | **2005** | -2,920.53 | 59.04 | -2,861.49 |
| **2010** | -272,691.73 | 51,966.07 | -220,725.66 | **2010** | -23,145.85 | 470.00 | -22,675.85 |
| **2015** | -700,837.09 | 130,702.55 | -570,134.54 | **2015** | -54,101.26 | 1,182.12 | -52,919.13 |
| **2020** | -1,232,385.58 | 225,817.68 | -1,006,567.90 | **2020** | -87,571.29 | 2,042.38 | -85,528.91 |
| **Min 2005-20** | -1,232,385.58 | 6,527.63 | -1,006,567.90 | **Min 2005-20** | -87,571.29 | 59.04 | -85,528.91 |
| **Average 2005-20** | -531,766.48 | 98,917.15 | -432,849.34 | **Average 2005-20** | -40,571.73 | 894.65 | -39,677.09 |
| **Max 2005-20** | -34,216.04 | 225,817.68 | -27,688.40 | **Max 2005-20** | -2,920.53 | 2,042.38 | -2,861.49 |
| **Cumul. 2005-20** | -8,508,263.76 | 1,582,674.35 | -6,925,589.41 | **Cumul. 2005-20** | -649,147.74 | 14,314.32 | -634,833.42 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.77 | 101.13 | 99.18 | **2005** | 98.36 | 101.13 | 98.44 |
| **2010** | 91.63 | 108.46 | 94.30 | **2010** | 88.72 | 108.46 | 89.24 |
| **2015** | 79.53 | 119.52 | 86.07 | **2015** | 74.63 | 119.52 | 75.87 |
| **2020** | 64.42 | 131.30 | 75.95 | **2020** | 58.83 | 131.30 | 60.98 |
| **Min 2005-20** | 64.42 | 101.13 | 75.95 | **Min 2005-20** | 58.83 | 101.13 | 60.98 |
| **Average 2005-20** | 84.36 | 114.65 | 89.38 | **Average 2005-20** | 80.77 | 114.65 | 81.72 |
| **Max 2005-20** | 98.77 | 131.30 | 99.18 | **Max 2005-20** | 98.36 | 131.30 | 98.44 |
| **Cumul. 2005-20** | 83.77 | 115.35 | 88.96 | **Cumul. 2005-20** | 80.23 | 115.35 | 81.20 |

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Table E.7 – continued from previous page

| ***TMR$_{eq}$*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 46,204,082.40 | 1,851,458.03 | 48,055,540.44 |
| **2010** | 50,390,640.48 | 2,112,522.05 | 52,503,162.52 |
| **2015** | 46,142,179.70 | 2,537,871.88 | 48,680,051.58 |
| **2020** | 37,911,279.37 | 3,003,326.63 | 40,914,606.00 |
| **Min 2005-20** | 37,911,279.37 | 1,851,458.03 | 40,914,606.00 |
| **Average 2005-20** | 46,413,286.08 | 2,356,691.42 | 48,769,977.50 |
| **Max 2005-20** | 51,600,577.63 | 3,003,326.63 | 53,785,227.97 |
| **Cumul. 2005-20** | 742,612,577.30 | 37,707,062.71 | 780,319,640.01 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -561,298.71 | 20,696.75 | -540,601.97 |
| **2010** | -4,475,910.24 | 164,765.44 | -4,311,144.80 |
| **2015** | -11,610,943.57 | 414,410.05 | -11,196,533.53 |
| **2020** | -20,568,311.11 | 715,985.40 | -19,852,325.71 |
| **Min 2005-20** | -20,568,311.11 | 20,696.75 | -19,852,325.71 |
| **Average 2005-20** | -8,819,462.63 | 313,630.15 | -8,505,832.49 |
| **Max 2005-20** | -561,298.71 | 715,985.40 | -540,601.97 |
| **Cumul. 2005-20** | -141,111,402.11 | 5,018,082.35 | -136,093,319.76 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.80 | 101.13 | 98.89 |
| **2010** | 91.84 | 108.46 | 92.41 |
| **2015** | 79.90 | 119.52 | 81.30 |
| **2020** | 64.83 | 131.30 | 67.33 |
| **Min 2005-20** | 64.83 | 101.13 | 67.33 |
| **Average 2005-20** | 84.62 | 114.65 | 85.70 |
| **Max 2005-20** | 98.80 | 131.30 | 98.89 |
| **Cumul. 2005-20** | 84.03 | 115.35 | 85.15 |

Table E.8: Environmental pressures in the R3 scenario

| $CO_{2eq}$ | | | | $SO_{2eq}$ | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 2,740,895.51 | 584,711.09 | 3,325,606.61 | **2005** | 175,328.12 | 5,288.36 | 180,616.47 |
| **2010** | 2,942,847.05 | 673,682.55 | 3,616,529.60 | **2010** | 179,145.30 | 6,093.05 | 185,238.35 |
| **2015** | 2,609,134.01 | 821,092.75 | 3,430,226.76 | **2015** | 151,627.93 | 7,426.28 | 159,054.21 |
| **2020** | 2,018,005.63 | 985,574.31 | 3,003,579.94 | **2020** | 111,400.63 | 8,913.92 | 120,314.55 |
| **Min 2005-20** | 2,018,005.63 | 584,711.09 | 3,003,579.94 | **Min 2005-20** | 111,400.63 | 5,288.36 | 120,314.55 |
| **Average 2005-20** | 2,657,183.05 | 759,062.74 | 3,416,245.80 | **Average 2005-20** | 158,855.97 | 6,865.26 | 165,721.23 |
| **Max 2005-20** | 3,001,430.18 | 985,574.31 | 3,699,766.57 | **Max 2005-20** | 180,414.43 | 8,913.92 | 186,730.46 |
| **Cumul. 2005-20** | 42,514,928.87 | 12,145,003.89 | 54,659,932.75 | **Cumul. 2005-20** | 2,541,695.50 | 109,844.15 | 2,651,539.65 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -38,465.32 | 7,299.50 | -31,165.82 | **2005** | -3,211.95 | 66.02 | -3,145.93 |
| **2010** | -313,214.15 | 59,371.30 | -253,842.85 | **2010** | -25,997.55 | 536.98 | -25,460.57 |
| **2015** | -815,308.63 | 151,365.08 | -663,943.55 | **2015** | -61,662.81 | 1,369.00 | -60,293.81 |
| **2020** | -1,445,903.37 | 264,160.03 | -1,181,743.35 | **2020** | -101,290.57 | 2,389.17 | -98,901.41 |
| **Min 2005-20** | -1,445,903.37 | 7,299.50 | -1,181,743.35 | **Min 2005-20** | -101,290.57 | 66.02 | -98,901.41 |
| **Average 2005-20** | -619,161.92 | 114,692.95 | -504,468.97 | **Average 2005-20** | -46,345.47 | 1,037.33 | -45,308.14 |
| **Max 2005-20** | -38,465.32 | 264,160.03 | -31,165.82 | **Max 2005-20** | -3,211.95 | 2,389.17 | -3,145.93 |
| **Cumul. 2005-20** | -9,906,590.73 | 1,835,087.26 | -8,071,503.47 | **Cumul. 2005-20** | -741,527.55 | 16,597.24 | -724,930.30 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.62 | 101.26 | 99.07 | **2005** | 98.20 | 101.26 | 98.29 |
| **2010** | 90.38 | 109.66 | 93.44 | **2010** | 87.33 | 109.66 | 87.92 |
| **2015** | 76.19 | 122.60 | 83.78 | **2015** | 71.09 | 122.60 | 72.51 |
| **2020** | 58.26 | 136.62 | 71.76 | **2020** | 52.38 | 136.62 | 54.88 |
| **Min 2005-20** | 58.26 | 101.26 | 71.76 | **Min 2005-20** | 52.38 | 101.26 | 54.88 |
| **Average 2005-20** | 81.79 | 116.98 | 87.63 | **Average 2005-20** | 78.04 | 116.98 | 79.13 |
| **Max 2005-20** | 98.62 | 136.62 | 99.07 | **Max 2005-20** | 98.20 | 136.62 | 98.29 |
| **Cumul. 2005-20** | 81.10 | 117.80 | 87.13 | **Cumul. 2005-20** | 77.41 | 117.80 | 78.53 |

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Table E.8 – continued from previous page

| ***$TMR_{eq}$*** | | | |
|---|---|---|---|
| **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 46,132,945.48 | 1,853,905.34 | 47,986,850.81 |
| **2010** | 49,713,742.96 | 2,136,001.33 | 51,849,744.28 |
| **2015** | 44,220,179.29 | 2,603,385.24 | 46,823,564.52 |
| **2020** | 34,318,619.20 | 3,124,896.20 | 37,443,515.40 |
| **Min 2005-20** | 34,318,619.20 | 1,853,905.34 | 37,443,515.40 |
| **Average 2005-20** | 44,945,914.83 | 2,406,710.74 | 47,352,625.57 |
| **Max 2005-20** | 50,749,472.62 | 3,124,896.20 | 52,963,642.25 |
| **Cumul. 2005-20** | 719,134,637.24 | 38,507,371.88 | 757,642,009.13 |
| ***Differences wrt BAU*** | | | |
| **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -632,435.64 | 23,144.05 | -609,291.59 |
| **2010** | -5,152,807.76 | 188,244.71 | -4,964,563.04 |
| **2015** | -13,532,943.99 | 479,923.40 | -13,053,020.58 |
| **2020** | -24,160,971.28 | 837,554.97 | -23,323,416.31 |
| **Min 2005-20** | -24,160,971.28 | 23,144.05 | -23,323,416.31 |
| **Average 2005-20** | -10,286,833.89 | 363,649.47 | -9,923,184.42 |
| **Max 2005-20** | -632,435.64 | 837,554.97 | -609,291.59 |
| **Cumul. 2005-20** | -164,589,342.17 | 5,818,391.53 | -158,770,950.65 |
| ***Ratios wrt BAU*** | | | |
| **(in %)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 98.65 | 101.26 | 98.75 |
| **2010** | 90.61 | 109.66 | 91.26 |
| **2015** | 76.57 | 122.60 | 78.20 |
| **2020** | 58.68 | 136.62 | 61.62 |
| **Min 2005-20** | 58.68 | 101.26 | 61.62 |
| **Average 2005-20** | 82.07 | 116.98 | 83.32 |
| **Max 2005-20** | 98.65 | 136.62 | 98.75 |
| **Cumul. 2005-20** | 81.38 | 117.80 | 82.67 |

Table E.9: $SO_{2eq}$ emissions in the RU scenario

| ***$SO_{2eq}$*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 178,540.07 | 5,222.34 | 183,762.41 |
| **2010** | 98,700.50 | 5,556.07 | 104,256.57 |
| **2015** | 102,975.74 | 6,057.28 | 109,033.02 |
| **2020** | 103,162.65 | 6,524.75 | 109,687.40 |
| **Min 2005-20** | 98,700.50 | 5,222.34 | 104,256.57 |
| **Average 2005-20** | 129,799.10 | 5,827.93 | 135,627.04 |
| **Max 2005-20** | 200,000.53 | 6,524.75 | 205,498.48 |
| **Cumul. 2005-20** | 2,076,785.68 | 93,246.90 | 2,170,032.58 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.00 | 0.00 | 0.00 |
| **2010** | -106,442.35 | 0.00 | -106,442.35 |
| **2015** | -110,315.00 | 0.00 | -110,315.00 |
| **2020** | -109,528.55 | 0.00 | -109,528.55 |
| **Min 2005-20** | -110,504.85 | 0.00 | -110,504.85 |
| **Average 2005-20** | -75,402.34 | 0.00 | -75,402.34 |
| **Max 2005-20** | 0.00 | 0.00 | 0.00 |
| **Cumul. 2005-20** | -1,206,437.37 | 0.00 | -1,206,437.37 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.00 | 100.00 | 100.00 |
| **2010** | 48.11 | 100.00 | 49.48 |
| **2015** | 48.28 | 100.00 | 49.71 |
| **2020** | 48.50 | 100.00 | 50.04 |
| **Min 2005-20** | 48.11 | 100.00 | 49.48 |
| **Average 2005-20** | 64.46 | 100.00 | 65.44 |
| **Max 2005-20** | 100.00 | 100.00 | 100.00 |
| **Cumul. 2005-20** | 63.25 | 100.00 | 64.27 |

Table E.10: $SO_{2eq}$ emissions in the SA scenario

| ***$SO_{2eq}$*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 163,264.83 | 5,222.34 | 168,487.16 |
| **2010** | 187,203.65 | 5,556.07 | 192,759.72 |
| **2015** | 194,396.48 | 6,057.28 | 200,453.76 |
| **2020** | 193,546.24 | 6,524.75 | 200,071.00 |
| **Min 2005-20** | 163,264.83 | 5,222.34 | 168,487.16 |
| **Average 2005-20** | 187,136.92 | 5,827.93 | 192,964.85 |
| **Max 2005-20** | 194,795.18 | 6,524.75 | 200,935.72 |
| **Cumul. 2005-20** | 2,994,190.70 | 93,246.90 | 3,087,437.60 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -15,275.25 | 0.00 | -15,275.25 |
| **2010** | -17,939.20 | 0.00 | -17,939.20 |
| **2015** | -18,894.27 | 0.00 | -18,894.27 |
| **2020** | -19,144.96 | 0.00 | -19,144.96 |
| **Min 2005-20** | -19,144.96 | 0.00 | -19,144.96 |
| **Average 2005-20** | -18,064.52 | 0.00 | -18,064.52 |
| **Max 2005-20** | -15,275.25 | 0.00 | -15,275.25 |
| **Cumul. 2005-20** | -289,032.34 | 0.00 | -289,032.34 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 91.44 | 100.00 | 91.69 |
| **2010** | 91.26 | 100.00 | 91.49 |
| **2015** | 91.14 | 100.00 | 91.39 |
| **2020** | 91.00 | 100.00 | 91.27 |
| **Min 2005-20** | 91.00 | 100.00 | 91.27 |
| **Average 2005-20** | 91.20 | 100.00 | 91.45 |
| **Max 2005-20** | 91.44 | 100.00 | 91.69 |
| **Cumul. 2005-20** | 91.20 | 100.00 | 91.44 |

Table E.11: $SO_{2eq}$ emissions in the R1-RU-SA scenario

| ***$SO_{2eq}$*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 160,792.70 | 5,274.39 | 166,067.09 |
| **2010** | 73,052.95 | 5,959.10 | 79,012.05 |
| **2015** | 66,236.26 | 7,052.52 | 73,288.78 |
| **2020** | 55,428.24 | 8,220.35 | 63,648.59 |
| **Min 2005-20** | 55,428.24 | 5,274.39 | 63,648.59 |
| **Average 2005-20** | 96,852.83 | 6,579.89 | 103,432.72 |
| **Max 2005-20** | 167,407.77 | 8,220.35 | 173,218.55 |
| **Cumul. 2005-20** | 1,549,645.26 | 105,278.31 | 1,654,923.57 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -17,747.37 | 52.06 | -17,695.31 |
| **2010** | -132,089.90 | 403.03 | -131,686.87 |
| **2015** | -147,054.48 | 995.24 | -146,059.24 |
| **2020** | -157,262.97 | 1,695.60 | -155,567.37 |
| **Min 2005-20** | -157,262.97 | 52.06 | -155,567.37 |
| **Average 2005-20** | -108,348.61 | 751.96 | -107,596.65 |
| **Max 2005-20** | -17,747.37 | 1,695.60 | -17,695.31 |
| **Cumul. 2005-20** | -1,733,577.78 | 12,031.40 | -1,721,546.38 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 90.06 | 101.00 | 90.37 |
| **2010** | 35.61 | 107.25 | 37.50 |
| **2015** | 31.05 | 116.43 | 33.41 |
| **2020** | 26.06 | 125.99 | 29.03 |
| **Min 2005-20** | 26.06 | 101.00 | 29.03 |
| **Average 2005-20** | 48.54 | 112.33 | 50.31 |
| **Max 2005-20** | 90.06 | 125.99 | 90.37 |
| **Cumul. 2005-20** | 47.20 | 112.90 | 49.01 |

## E.2 Autocatalysts

Table E.12: PGM inputs and $SO_{2eq}$ emissions in BAU scenario

| ***PGM use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 61.76 | 7.75 | 69.5 | **2005** | 113,030.07 | 335.09 | 113,365.16 |
| **2010** | 74.03 | 12.78 | 86.81 | **2010** | 136,129.70 | 535.81 | 136,665.51 |
| **2015** | 76.01 | 18.25 | 94.26 | **2015** | 140,282.09 | 815.48 | 141,097.57 |
| **2020** | 72.86 | 22.64 | 95.5 | **2020** | 135,118.43 | 1,040.35 | 136,158.78 |
| **Min 2005-20** | 61.76 | 7.75 | 69.5 | **Min 2005-20** | 113,030.07 | 335.09 | 113,365.16 |
| **Average 2005-20** | 72.73 | 15.47 | 88.2 | **Average 2005-20** | 134,031.53 | 680.48 | 134,712.01 |
| **Max 2005-20** | 77.33 | 22.64 | 95.5 | **Max 2005-20** | 142,512.15 | 1,040.35 | 143,089.56 |
| **Cumul. 2005-20** | 1163.71 | 247.44 | 1411.15 | **Cumul. 2005-20** | 2,144,504.45 | 10,887.64 | 2,155,392.09 |
| ***Differences*** | | | | ***Differences*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 12.28 | 5.03 | 17.3 | **2010 minus 2005** | 23,099.64 | 200.72 | 23,300.35 |
| **2015 minus 2005** | 14.25 | 10.5 | 24.75 | **2015 minus 2005** | 27,252.02 | 480.39 | 27,732.41 |
| **2020 minus 2005** | 11.11 | 14.89 | 25.99 | **2020 minus 2005** | 22,088.36 | 705.26 | 22,793.62 |
| ***Ratios*** | | | | ***Ratios*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 119.88 | 164.9 | 124.9 | **2010 over 2005** | 120.44 | 159.90 | 120.55 |
| **2015 over 2005** | 123.08 | 235.52 | 135.61 | **2015 over 2005** | 124.11 | 243.36 | 124.46 |
| **2020 over 2005** | 117.98 | 292.15 | 137.4 | **2020 over 2005** | 119.54 | 310.47 | 120.11 |

| ***Platinum use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Platinum*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 38.12 | 3.61 | 41.72 | **2005** | 74,057.52 | 223.29 | 74,280.81 |
| **2010** | 47.63 | 6.03 | 53.66 | **2010** | 92,534.05 | 373.24 | 92,907.30 |
| **2015** | 50.13 | 9.87 | 60 | **2015** | 97,406.51 | 610.84 | 98,017.35 |
| **2020** | 50.3 | 13 | 63.29 | **2020** | 97,719.30 | 804.48 | 98,523.78 |
| **Min 2005-20** | 38.12 | 3.61 | 41.72 | **Min 2005-20** | 74,057.52 | 223.29 | 74,280.81 |
| **Average 2005-20** | 47.48 | 8.06 | 55.55 | **Average 2005-20** | 92,258.55 | 499.18 | 92,757.73 |
| **Max 2005-20** | 50.3 | 13 | 63.29 | **Max 2005-20** | 97,719.30 | 804.48 | 98,523.78 |
| **Cumul. 2005-20** | 759.75 | 129.01 | 888.77 | **Cumul. 2005-20** | 1,476,136.87 | 7,986.89 | 1,484,123.76 |
| ***Differences*** | | | | ***Differences*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 9.51 | 2.42 | 11.93 | **2010 minus 2005** | 18,476.53 | 149.95 | 18,626.49 |
| **2015 minus 2005** | 12.02 | 6.26 | 18.28 | **2015 minus 2005** | 23,348.99 | 387.55 | 23,736.54 |
| **2020 minus 2005** | 12.18 | 9.39 | 21.57 | **2020 minus 2005** | 23,661.78 | 581.19 | 24,242.97 |
| ***Ratios*** | | | | ***Ratios*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 124.95 | 167.16 | 128.6 | **2010 over 2005** | 124.95 | 167.16 | 125.08 |
| **2015 over 2005** | 131.53 | 273.56 | 143.81 | **2015 over 2005** | 131.53 | 273.56 | 131.96 |
| **2020 over 2005** | 131.95 | 360.29 | 151.69 | **2020 over 2005** | 131.95 | 360.29 | 132.64 |

| ***Palladium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Palladium*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 20.43 | 3.38 | 23.81 | **2005** | 31,573.85 | 57.32 | 31,631.17 |
| **2010** | 22.74 | 5.87 | 28.61 | **2010** | 35,142.58 | 99.48 | 35,242.06 |
| **2015** | 22.08 | 7.24 | 29.32 | **2015** | 34,120.23 | 122.73 | 34,242.96 |
| **2020** | 19.25 | 8.32 | 27.57 | **2020** | 29,742.99 | 141.03 | 29,884.02 |
| **Min 2005-20** | 19.25 | 3.38 | 23.81 | **Min 2005-20** | 29,742.99 | 57.32 | 29,884.02 |
| **Average 2005-20** | 21.63 | 6.38 | 28.01 | **Average 2005-20** | 33,416.73 | 108.20 | 33,524.93 |
| **Max 2005-20** | 23.18 | 8.32 | 29.49 | **Max 2005-20** | 35,820.35 | 141.03 | 35,927.37 |
| **Cumul. 2005-20** | 346.04 | 102.08 | 448.11 | **Cumul. 2005-20** | 534,667.70 | 1,731.17 | 536,398.86 |
| ***Differences*** | | | | ***Differences*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 2.31 | 2.49 | 4.8 | **2010 minus 2005** | 3,568.73 | 42.16 | 3,610.89 |
| **2015 minus 2005** | 1.65 | 3.86 | 5.5 | **2015 minus 2005** | 2,546.39 | 65.41 | 2,611.79 |
| **2020 minus 2005** | -1.18 | 4.94 | 3.75 | **2020 minus 2005** | -1,830.86 | 83.71 | -1,747.15 |
| ***Ratios*** | | | | ***Ratios*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 111.3 | 173.56 | 120.14 | **2010 over 2005** | 111.30 | 173.56 | 111.42 |
| **2015 over 2005** | 108.06 | 214.11 | 123.12 | **2015 over 2005** | 108.06 | 214.11 | 108.26 |
| **2020 over 2005** | 94.2 | 246.04 | 115.75 | **2020 over 2005** | 94.20 | 246.04 | 94.48 |

Continued on next page

**Table E.12 – continued from previous page**

| ***Rhodium use in Autocatalysts*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 3.21 | 0.76 | 3.97 |
| **2010** | 3.66 | 0.88 | 4.54 |
| **2015** | 3.79 | 1.15 | 4.94 |
| **2020** | 3.32 | 1.33 | 4.64 |
| **Min 2005-20** | 3.21 | 0.76 | 3.97 |
| **Average 2005-20** | 3.62 | 1.02 | 4.64 |
| **Max 2005-20** | 4.05 | 1.33 | 4.97 |
| **Cumul. 2005-20** | 57.92 | 16.35 | 74.27 |
| ***Differences*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2010 minus 2005** | 0.46 | 0.12 | 0.58 |
| **2015 minus 2005** | 0.59 | 0.38 | 0.97 |
| **2020 minus 2005** | 0.11 | 0.56 | 0.68 |
| ***Ratios*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2010 over 2005** | 114.25 | 115.78 | 114.54 |
| **2015 over 2005** | 118.34 | 150.34 | 124.48 |
| **2020 over 2005** | 103.48 | 174.08 | 117.04 |

| ***$SO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 7,398.70 | 54.48 | 7,453.18 |
| **2010** | 8,453.07 | 63.08 | 8,516.15 |
| **2015** | 8,755.35 | 81.91 | 8,837.25 |
| **2020** | 7,656.15 | 94.84 | 7,750.98 |
| **Min 2005-20** | 7,398.70 | 54.48 | 7,453.18 |
| **Average 2005-20** | 8,356.24 | 73.10 | 8,429.34 |
| **Max 2005-20** | 9,355.76 | 94.84 | 9,421.15 |
| **Cumul. 2005-20** | 133,699.88 | 1,169.59 | 134,869.47 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 1,054.37 | 8.60 | 1,062.97 |
| **2015 minus 2005** | 1,356.64 | 27.43 | 1,384.07 |
| **2020 minus 2005** | 257.44 | 40.36 | 297.80 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 114.25 | 115.78 | 114.26 |
| **2015 over 2005** | 118.34 | 150.34 | 118.57 |
| **2020 over 2005** | 103.48 | 174.08 | 104.00 |

Table E.13: $CO_{2eq}$ emissions and TMR in BAU scenario

| ***$CO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 1,818,237.92 | 37,049.53 | 1,855,287.45 |
| **2010** | 2,235,673.55 | 59,241.83 | 2,294,915.38 |
| **2015** | 2,337,070.37 | 90,163.79 | 2,427,234.17 |
| **2020** | 2,300,735.50 | 115,027.03 | 2,415,762.53 |
| **Min 2005-20** | 1,818,237.92 | 37,049.53 | 1,855,287.45 |
| **Average 2005-20** | 2,219,986.33 | 75,237.52 | 2,295,223.85 |
| **Max 2005-20** | 2,355,749.65 | 115,027.03 | 2,432,624.47 |
| **Cumul. 2005-20** | 35,519,781.23 | 1,203,800.34 | 36,723,581.57 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 417,435.63 | 22,192.30 | 439,627.93 |
| **2015 minus 2005** | 518,832.45 | 53,114.26 | 571,946.71 |
| **2020 minus 2005** | 482,497.58 | 77,977.50 | 560,475.08 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 122.96 | 159.90 | 123.70 |
| **2015 over 2005** | 128.53 | 243.36 | 130.83 |
| **2020 over 2005** | 126.54 | 310.47 | 130.21 |
| ***$CO_{2eq}$ emissions due to Platinum*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 1,520,575.29 | 24,688.23 | 1,545,263.52 |
| **2,010.00** | 1,899,942.06 | 41,267.97 | 1,941,210.03 |
| **2,015.00** | 1,999,985.11 | 67,538.14 | 2,067,523.25 |
| **2,020.00** | 2,006,407.38 | 88,948.40 | 2,095,355.78 |
| **Min 2005-20** | 1,520,575.29 | 24,688.23 | 1,545,263.52 |
| **Average 2005-20** | 1,894,285.42 | 55,192.27 | 1,949,477.69 |
| **Max 2005-20** | 2,006,407.38 | 88,948.40 | 2,095,355.78 |
| **Cumul. 2005-20** | 30,308,566.78 | 883,076.27 | 31,191,643.05 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 379,366.77 | 16,579.74 | 395,946.51 |
| **2015 minus 2005** | 479,409.82 | 42,849.91 | 522,259.73 |
| **2020 minus 2005** | 485,832.09 | 64,260.17 | 550,092.26 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 124.95 | 167.16 | 125.62 |
| **2015 over 2005** | 131.53 | 273.56 | 133.80 |
| **2020 over 2005** | 131.95 | 360.29 | 135.60 |

| ***$TMR_{eq}$ due to PGM*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 30,669,201.40 | 117,470.54 | 30,786,671.94 |
| **2010** | 37,767,044.50 | 187,834.21 | 37,954,878.72 |
| **2015** | 39,520,309.11 | 285,876.46 | 39,806,185.58 |
| **2020** | 38,965,144.76 | 364,708.71 | 39,329,853.47 |
| **Min 2005-20** | 30,669,201.40 | 117,470.54 | 30,786,671.94 |
| **Average 2005-20** | 37,524,872.46 | 238,550.70 | 37,763,423.16 |
| **Max 2005-20** | 39,814,209.01 | 364,708.71 | 40,016,627.06 |
| **Cumul. 2005-20** | 600,397,959.37 | 3,816,811.24 | 604,214,770.61 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 7,097,843.10 | 70,363.67 | 7,168,206.78 |
| **2015 minus 2005** | 8,851,107.71 | 168,405.92 | 9,019,513.63 |
| **2020 minus 2005** | 8,295,943.36 | 247,238.17 | 8,543,181.53 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 123.14 | 159.90 | 123.28 |
| **2015 over 2005** | 128.86 | 243.36 | 129.30 |
| **2020 over 2005** | 127.05 | 310.47 | 127.75 |
| ***$TMR_{eq}$ due to Platinum*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 26,055,223.93 | 78,277.36 | 26,133,501.29 |
| **2,010.00** | 32,555,715.06 | 130,845.66 | 32,686,560.72 |
| **2,015.00** | 34,269,963.64 | 214,138.79 | 34,484,102.43 |
| **2,020.00** | 34,380,009.89 | 282,022.89 | 34,662,032.78 |
| **Min 2005-20** | 26,055,223.93 | 78,277.36 | 26,133,501.29 |
| **Average 2005-20** | 32,458,787.97 | 174,994.52 | 32,633,782.49 |
| **Max 2005-20** | 34,380,009.89 | 282,022.89 | 34,662,032.78 |
| **Cumul. 2005-20** | 519,340,607.55 | 2,799,912.34 | 522,140,519.89 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 6,500,491.13 | 52,568.30 | 6,553,059.43 |
| **2015 minus 2005** | 8,214,739.71 | 135,861.43 | 8,350,601.14 |
| **2020 minus 2005** | 8,324,785.97 | 203,745.53 | 8,528,531.50 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 124.95 | 167.16 | 125.08 |
| **2015 over 2005** | 131.53 | 273.56 | 131.95 |
| **2020 over 2005** | 131.95 | 360.29 | 132.63 |

Continued on next page

**Table E.13 – continued from previous page**

| ***$CO_{2eq}$ emissions due to Palladium*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 147,570.32 | 6,337.66 | 153,907.98 |
| **2,010.00** | 164,249.91 | 10,999.50 | 175,249.41 |
| **2,015.00** | 159,471.65 | 13,569.53 | 173,041.18 |
| **2,020.00** | 139,013.22 | 15,592.90 | 154,606.12 |
| **Min 2005-20** | 139,013.22 | 6,337.66 | 153,907.98 |
| **Average 2005-20** | 156,183.61 | 11,962.99 | 168,146.60 |
| **Max 2005-20** | 167,417.69 | 15,592.90 | 179,249.98 |
| **Cumul. 2005-20** | 2,498,937.83 | 191,407.83 | 2,690,345.66 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 16,679.59 | 4,661.84 | 21,341.43 |
| **2015 minus 2005** | 11,901.34 | 7,231.87 | 19,133.20 |
| **2020 minus 2005** | -8,557.10 | 9,255.24 | 698.14 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 111.30 | 173.56 | 113.87 |
| **2015 over 2005** | 108.06 | 214.11 | 112.43 |
| **2020 over 2005** | 94.20 | 246.04 | 100.45 |

| ***$TMR_{eq}$ due to Palladium*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 2,041,226.18 | 20,094.41 | 2,061,320.59 |
| **2,010.00** | 2,271,942.05 | 34,875.41 | 2,306,817.46 |
| **2,015.00** | 2,205,848.17 | 43,024.02 | 2,248,872.19 |
| **2,020.00** | 1,922,862.42 | 49,439.39 | 1,972,301.81 |
| **Min 2005-20** | 1,922,862.42 | 20,094.41 | 1,972,301.81 |
| **Average 2005-20** | 2,160,367.24 | 37,930.27 | 2,198,297.51 |
| **Max 2005-20** | 2,315,759.57 | 49,439.39 | 2,353,275.44 |
| **Cumul. 2005-20** | 34,565,875.86 | 606,884.33 | 35,172,760.18 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 230,715.87 | 14,781.00 | 245,496.87 |
| **2015 minus 2005** | 164,621.99 | 22,929.61 | 187,551.60 |
| **2020 minus 2005** | -118,363.76 | 29,344.98 | -89,018.78 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 111.30 | 173.56 | 111.91 |
| **2015 over 2005** | 108.06 | 214.11 | 109.10 |
| **2020 over 2005** | 94.20 | 246.04 | 95.68 |

| ***$CO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 150,092.31 | 6,023.64 | 156,115.96 |
| **2,010.00** | 171,481.58 | 6,974.36 | 178,455.94 |
| **2,015.00** | 177,613.61 | 9,056.12 | 186,669.73 |
| **2,020.00** | 155,314.91 | 10,485.73 | 165,800.64 |
| **Min 2005-20** | 150,092.31 | 6,023.64 | 156,115.96 |
| **Average 2005-20** | 169,517.29 | 8,082.27 | 177,599.55 |
| **Max 2005-20** | 189,793.72 | 10,485.73 | 197,024.52 |
| **Cumul. 2005-20** | 2,712,276.62 | 129,316.24 | 2,841,592.86 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 21,389.27 | 950.72 | 22,339.98 |
| **2015 minus 2005** | 27,521.30 | 3,032.48 | 30,553.77 |
| **2020 minus 2005** | 5,222.59 | 4,462.09 | 9,684.68 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 114.25 | 115.78 | 114.31 |
| **2015 over 2005** | 118.34 | 150.34 | 119.57 |
| **2020 over 2005** | 103.48 | 174.08 | 106.20 |

| ***$TMR_{eq}$ due to Rhodium*** | | | |
|---|---|---|---|
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2,005.00** | 2,572,751.29 | 19,098.77 | 2,591,850.07 |
| **2,010.00** | 2,939,387.40 | 22,113.15 | 2,961,500.54 |
| **2,015.00** | 3,044,497.30 | 28,713.66 | 3,073,210.96 |
| **2,020.00** | 2,662,272.45 | 33,246.43 | 2,695,518.88 |
| **Min 2005-20** | 2,572,751.29 | 19,098.77 | 2,591,850.07 |
| **Average 2005-20** | 2,905,717.25 | 25,625.91 | 2,931,343.16 |
| **Max 2005-20** | 3,253,278.03 | 33,246.43 | 3,276,204.28 |
| **Cumul. 2005-20** | 46,491,475.96 | 410,014.57 | 46,901,490.54 |
| ***Differences*** | | | |
| (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 minus 2005** | 366,636.10 | 3,014.37 | 369,650.47 |
| **2015 minus 2005** | 471,746.01 | 9,614.88 | 481,360.89 |
| **2020 minus 2005** | 89,521.16 | 14,147.65 | 103,668.81 |
| ***Ratios*** | | | |
| (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2010 over 2005** | 114.25 | 115.78 | 114.26 |
| **2015 over 2005** | 118.34 | 150.34 | 118.57 |
| **2020 over 2005** | 103.48 | 174.08 | 104.00 |

Table E.14: PGM inputs and $SO_{2eq}$ emissions in HD scenario

| ***PGM use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 61.86 | 7.75 | 69.61 | **2005** | 113,434.92 | 335.09 | 113,770.01 |
| **2010** | 75.12 | 12.82 | 87.94 | **2010** | 139,725.83 | 540.18 | 140,266.00 |
| **2015** | 78.26 | 18.29 | 96.55 | **2015** | 147,449.60 | 836.35 | 148,285.95 |
| **2020** | 76.25 | 22.6 | 98.85 | **2020** | 145,626.60 | 1,085.07 | 146,711.67 |
| **Min 2005-20** | 61.86 | 7.75 | 69.61 | **Min 2005-20** | 113,434.92 | 335.09 | 113,770.01 |
| **Average 2005-20** | 74.44 | 15.48 | 89.92 | **Average 2005-20** | 139,453.93 | 696.63 | 140,150.56 |
| **Max 2005-20** | 78.69 | 22.6 | 98.85 | **Max 2005-20** | 147,794.63 | 1,085.07 | 148,690.08 |
| **Cumul. 2005-20** | 1191.02 | 247.76 | 1438.78 | **Cumul. 2005-20** | 2,231,262.85 | 11,146.16 | 2,242,409.00 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.1 | 0 | 0.1 | **2005** | 404.85 | 0 | 404.85 |
| **2010** | 1.08 | 0.05 | 1.13 | **2010** | 3596.12 | 4.37 | 3600.5 |
| **2015** | 2.25 | 0.04 | 2.29 | **2015** | 7167.51 | 20.87 | 7188.39 |
| **2020** | 3.39 | -0.04 | 3.35 | **2020** | 10508.17 | 44.72 | 10552.89 |
| **Min 2005-20** | 0.1 | 0 | 0.1 | **Min 2005-20** | 404.85 | 0 | 404.85 |
| **Average 2005-20** | 1.71 | 0.02 | 1.73 | **Average 2005-20** | 5422.4 | 16.16 | 5438.56 |
| **Max 2005-20** | 1.36 | -0.04 | 3.35 | **Max 2005-20** | 5282.48 | 44.72 | 5600.52 |
| **Cumul. 2005-20** | 27.31 | 0.32 | 27.63 | **Cumul. 2005-20** | 86758.4 | 258.52 | 87016.92 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.17 | 100 | 100.15 | **2005** | 100.36 | 100 | 100.36 |
| **2010** | 101.46 | 100.37 | 101.3 | **2010** | 102.64 | 100.82 | 102.63 |
| **2015** | 102.97 | 100.22 | 102.43 | **2015** | 105.11 | 102.56 | 105.09 |
| **2020** | 104.65 | 99.84 | 103.51 | **2020** | 107.78 | 104.3 | 107.75 |
| **Min 2005-20** | 100.17 | 100 | 100.15 | **Min 2005-20** | 100.36 | 100 | 100.36 |
| **Average 2005-20** | 102.35 | 100.13 | 101.96 | **Average 2005-20** | 104.05 | 102.37 | 104.04 |
| **Max 2005-20** | 101.76 | 99.84 | 103.51 | **Max 2005-20** | 103.71 | 104.3 | 103.91 |
| **Cumul. 2005-20** | 102.35 | 100.13 | 101.96 | **Cumul. 2005-20** | 104.05 | 102.37 | 104.04 |
| ***Platinum use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Platinum*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 38.93 | 3.61 | 42.54 | **2005** | 75,637.02 | 223.29 | 75,860.31 |
| **2010** | 53.81 | 6.11 | 59.92 | **2010** | 104,547.75 | 378.56 | 104,926.30 |
| **2015** | 62.08 | 10.4 | 72.48 | **2015** | 120,616.52 | 643.94 | 121,260.46 |
| **2020** | 67.31 | 14.22 | 81.54 | **2020** | 130,783.80 | 880.49 | 131,664.29 |
| **Min 2005-20** | 38.93 | 3.61 | 42.54 | **Min 2005-20** | 75,637.02 | 223.29 | 75,860.31 |
| **Average 2005-20** | 56.49 | 8.48 | 64.98 | **Average 2005-20** | 109,765.02 | 525.27 | 110,290.29 |
| **Max 2005-20** | 67.31 | 14.22 | 81.54 | **Max 2005-20** | 130,783.80 | 880.49 | 131,664.29 |
| **Cumul. 2005-20** | 903.92 | 135.76 | 1039.68 | **Cumul. 2005-20** | 1,756,240.31 | 8,404.31 | 1,764,644.63 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.81 | 0 | 0.81 | **2005** | 1579.5 | 0 | 1579.5 |
| **2010** | 6.18 | 0.09 | 6.27 | **2010** | 12013.7 | 5.31 | 12019.01 |
| **2015** | 11.95 | 0.53 | 12.48 | **2015** | 23210.01 | 33.1 | 23243.11 |
| **2020** | 17.02 | 1.23 | 18.25 | **2020** | 33064.5 | 76.01 | 33140.51 |
| **Min 2005-20** | 0.81 | 0 | 0.81 | **Min 2005-20** | 1579.5 | 0 | 1579.5 |
| **Average 2005-20** | 9.01 | 0.42 | 9.43 | **Average 2005-20** | 17506.47 | 26.09 | 17532.55 |
| **Max 2005-20** | 17.02 | 1.23 | 18.25 | **Max 2005-20** | 33064.5 | 76.01 | 33140.51 |
| **Cumul. 2005-20** | 144.17 | 6.74 | 150.91 | **Cumul. 2005-20** | 280103.44 | 417.43 | 280520.87 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 102.13 | 100 | 101.95 | **2005** | 102.13 | 100 | 102.13 |
| **2010** | 112.98 | 101.42 | 111.68 | **2010** | 112.98 | 101.42 | 112.94 |
| **2015** | 123.83 | 105.42 | 120.8 | **2015** | 123.83 | 105.42 | 123.71 |
| **2020** | 133.84 | 109.45 | 128.83 | **2020** | 133.84 | 109.45 | 133.64 |
| **Min 2005-20** | 102.13 | 100 | 101.95 | **Min 2005-20** | 102.13 | 100 | 102.13 |
| **Average 2005-20** | 118.98 | 105.23 | 116.98 | **Average 2005-20** | 118.98 | 105.23 | 118.9 |
| **Max 2005-20** | 133.84 | 109.45 | 128.83 | **Max 2005-20** | 133.84 | 109.45 | 133.64 |
| **Cumul. 2005-20** | 118.98 | 105.23 | 116.98 | **Cumul. 2005-20** | 118.98 | 105.23 | 118.9 |

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**Table E.14 – continued from previous page**

| ***Palladium use in Autocatalysts*** | | | | ***SO2eq emissions due to Palladium*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 19.83 | 3.38 | 23.21 | **2005** | 30,632.52 | 57.32 | 30,689.84 |
| **2010** | 18.35 | 5.83 | 24.18 | **2010** | 28,353.22 | 98.93 | 28,452.15 |
| **2015** | 13.79 | 6.81 | 20.6 | **2015** | 21,304.64 | 115.54 | 21,420.18 |
| **2020** | 7.59 | 7.23 | 14.82 | **2020** | 11,725.49 | 122.64 | 11,848.13 |
| **Min 2005-20** | 7.59 | 3.38 | 14.82 | **Min 2005-20** | 11,725.49 | 57.32 | 11,848.13 |
| **Average 2005-20** | 15.37 | 6.04 | 21.41 | **Average 2005-20** | 23,751.06 | 102.35 | 23,853.41 |
| **Max 2005-20** | 19.98 | 7.23 | 24.32 | **Max 2005-20** | 30,878.45 | 122.64 | 30,948.55 |
| **Cumul. 2005-20** | 245.95 | 96.56 | 342.51 | **Cumul. 2005-20** | 380,016.93 | 1,637.68 | 381,654.61 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -0.61 | 0 | -0.61 | **2005** | -941.32 | 0 | -941.32 |
| **2010** | -4.39 | -0.03 | -4.43 | **2010** | -6789.36 | -0.55 | -6789.91 |
| **2015** | -8.29 | -0.42 | -8.72 | **2015** | -12815.59 | -7.19 | -12822.78 |
| **2020** | -11.66 | -1.08 | -12.75 | **2020** | -18017.5 | -18.39 | -18035.89 |
| **Min 2005-20** | -11.66 | 0 | -8.99 | **Min 2005-20** | -18017.5 | 0 | -18035.89 |
| **Average 2005-20** | -6.26 | -0.34 | -6.6 | **Average 2005-20** | -9665.67 | -5.84 | -9671.52 |
| **Max 2005-20** | -3.2 | -1.08 | -5.18 | **Max 2005-20** | -4941.9 | -18.39 | -4978.81 |
| **Cumul. 2005-20** | -100.09 | -5.51 | -105.6 | **Cumul. 2005-20** | -154650.76 | -93.49 | -154744.25 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 97.02 | 100 | 97.44 | **2005** | 97.02 | 100 | 97.02 |
| **2010** | 80.68 | 99.45 | 84.53 | **2010** | 80.68 | 99.45 | 80.73 |
| **2015** | 62.44 | 94.14 | 70.26 | **2015** | 62.44 | 94.14 | 62.55 |
| **2020** | 39.42 | 86.96 | 53.76 | **2020** | 39.42 | 86.96 | 39.65 |
| **Min 2005-20** | 39.42 | 100 | 62.23 | **Min 2005-20** | 39.42 | 100 | 39.65 |
| **Average 2005-20** | 71.08 | 94.6 | 76.43 | **Average 2005-20** | 71.08 | 94.6 | 71.15 |
| **Max 2005-20** | 86.2 | 86.96 | 82.45 | **Max 2005-20** | 86.2 | 86.96 | 86.14 |
| **Cumul. 2005-20** | 71.08 | 94.6 | 76.43 | **Cumul. 2005-20** | 71.08 | 94.6 | 71.15 |

| ***Rhodium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 3.1 | 0.76 | 3.87 | **2005** | 7,165.37 | 54.48 | 7,219.85 |
| **2010** | 2.96 | 0.88 | 3.83 | **2010** | 6,824.86 | 62.69 | 6,887.55 |
| **2015** | 2.39 | 1.07 | 3.47 | **2015** | 5,528.44 | 76.87 | 5,605.31 |
| **2020** | 1.35 | 1.15 | 2.5 | **2020** | 3,117.31 | 81.94 | 3,199.25 |
| **Min 2005-20** | 1.35 | 0.76 | 2.5 | **Min 2005-20** | 3,117.31 | 54.48 | 3,199.25 |
| **Average 2005-20** | 2.57 | 0.96 | 3.54 | **Average 2005-20** | 5,937.85 | 69.01 | 6,006.86 |
| **Max 2005-20** | 3.16 | 1.15 | 4.06 | **Max 2005-20** | 7,294.36 | 81.94 | 7,358.94 |
| **Cumul. 2005-20** | 41.16 | 15.44 | 56.59 | **Cumul. 2005-20** | 95,005.60 | 1,104.16 | 96,109.77 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -0.1 | 0 | -0.1 | **2005** | -233.33 | 0 | -233.33 |
| **2010** | -0.71 | -0.01 | -0.71 | **2010** | -1628.21 | -0.39 | -1628.6 |
| **2015** | -1.4 | -0.07 | -1.47 | **2015** | -3226.91 | -5.04 | -3231.94 |
| **2020** | -1.97 | -0.18 | -2.15 | **2020** | -4538.83 | -12.9 | -4551.73 |
| **Min 2005-20** | -1.85 | 0 | -1.47 | **Min 2005-20** | -4281.39 | 0 | -4253.93 |
| **Average 2005-20** | -1.05 | -0.06 | -1.1 | **Average 2005-20** | -2418.39 | -4.09 | -2422.48 |
| **Max 2005-20** | -0.89 | -0.18 | -0.9 | **Max 2005-20** | -2061.39 | -12.9 | -2062.21 |
| **Cumul. 2005-20** | -16.76 | -0.91 | -17.68 | **Cumul. 2005-20** | -38694.28 | -65.42 | -38759.7 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 96.85 | 100 | 97.45 | **2005** | 96.85 | 100 | 96.87 |
| **2010** | 80.74 | 99.38 | 84.36 | **2010** | 80.74 | 99.38 | 80.88 |
| **2015** | 63.14 | 93.85 | 70.26 | **2015** | 63.14 | 93.85 | 63.43 |
| **2020** | 40.72 | 86.4 | 53.76 | **2020** | 40.72 | 86.4 | 41.28 |
| **Min 2005-20** | 42.13 | 100 | 62.92 | **Min 2005-20** | 42.13 | 100 | 42.92 |
| **Average 2005-20** | 71.06 | 94.41 | 76.2 | **Average 2005-20** | 71.06 | 94.41 | 71.26 |
| **Max 2005-20** | 77.97 | 86.4 | 81.79 | **Max 2005-20** | 77.97 | 86.4 | 78.11 |
| **Cumul. 2005-20** | 71.06 | 94.41 | 76.2 | **Cumul. 2005-20** | 71.06 | 94.41 | 71.26 |

Table E.15: PGM inputs and $SO_{2eq}$ emissions in DPd scenario

| ***PGM use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 61.89 | 7.62 | 69.5 | **2005** | 113,277.71 | 328.00 | 113,605.71 |
| **2010** | 74.24 | 12.57 | 86.81 | **2010** | 131,879.68 | 517.20 | 132,396.88 |
| **2015** | 76.23 | 18.03 | 94.26 | **2015** | 135,872.97 | 750.88 | 136,623.84 |
| **2020** | 73.02 | 22.47 | 95.5 | **2020** | 130,644.10 | 931.82 | 131,575.91 |
| **Min 2005-20** | 61.89 | 7.62 | 69.5 | **Min 2005-20** | 113,277.71 | 328.00 | 113,605.71 |
| **Average 2005-20** | 72.93 | 15.27 | 88.2 | **Average 2005-20** | 130,047.52 | 634.44 | 130,681.96 |
| **Max 2005-20** | 77.55 | 22.47 | 95.5 | **Max 2005-20** | 138,091.55 | 931.82 | 138,643.05 |
| **Cumul. 2005-20** | 1166.8 | 244.35 | 1411.15 | **Cumul. 2005-20** | 2,080,760.28 | 10,151.10 | 2,090,911.38 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.13 | -0.13 | 0 | **2005** | 247.64 | -7.09 | 240.55 |
| **2010** | 0.21 | -0.21 | 0 | **2010** | -4250.02 | -18.61 | -4268.63 |
| **2015** | 0.22 | -0.22 | 0 | **2015** | -4409.12 | -64.6 | -4473.72 |
| **2020** | 0.16 | -0.16 | 0 | **2020** | -4474.33 | -108.53 | -4582.87 |
| **Min 2005-20** | 0.13 | -0.13 | 0 | **Min 2005-20** | 247.64 | -7.09 | 240.55 |
| **Average 2005-20** | 0.19 | -0.19 | 0 | **Average 2005-20** | -3984.01 | -46.03 | -4030.04 |
| **Max 2005-20** | 0.22 | -0.16 | 0 | **Max 2005-20** | -4420.6 | -108.53 | -4446.51 |
| **Cumul. 2005-20** | 3.1 | -3.1 | 0 | **Cumul. 2005-20** | -63744.17 | -736.54 | -64480.71 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.21 | 98.29 | 100 | **2005** | 100.22 | 97.89 | 100.21 |
| **2010** | 100.28 | 98.38 | 100 | **2010** | 96.88 | 96.53 | 96.88 |
| **2015** | 100.29 | 98.78 | 100 | **2015** | 96.86 | 92.08 | 96.83 |
| **2020** | 100.22 | 99.28 | 100 | **2020** | 96.69 | 89.57 | 96.63 |
| **Min 2005-20** | 100.21 | 98.29 | 100 | **Min 2005-20** | 100.22 | 97.89 | 100.21 |
| **Average 2005-20** | 100.27 | 98.75 | 100 | **Average 2005-20** | 97.03 | 93.24 | 97.01 |
| **Max 2005-20** | 100.28 | 99.28 | 100 | **Max 2005-20** | 96.9 | 89.57 | 96.89 |
| **Cumul. 2005-20** | 100.27 | 98.75 | 100 | **Cumul. 2005-20** | 97.03 | 93.24 | 97.01 |
| ***Platinum use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Platinum*** | | | |
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 38.22 | 3.5 | 41.72 | **2005** | 74,266.65 | 216.63 | 74,483.27 |
| **2010** | 36.14 | 5.69 | 41.83 | **2010** | 70,218.09 | 352.44 | 70,570.53 |
| **2015** | 38.18 | 8.51 | 46.7 | **2015** | 74,184.27 | 527.09 | 74,711.36 |
| **2020** | 38.42 | 10.64 | 49.06 | **2020** | 74,639.30 | 658.80 | 75,298.09 |
| **Min 2005-20** | 31.25 | 3.5 | 34.78 | **Min 2005-20** | 60,706.80 | 216.63 | 60,925.46 |
| **Average 2005-20** | 36.72 | 7.11 | 43.83 | **Average 2005-20** | 71,339.09 | 440.30 | 71,779.39 |
| **Max 2005-20** | 38.42 | 10.64 | 49.06 | **Max 2005-20** | 74,639.30 | 658.80 | 75,298.09 |
| **Cumul. 2005-20** | 587.48 | 113.8 | 701.28 | **Cumul. 2005-20** | 1,141,425.48 | 7,044.77 | 1,148,470.25 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.11 | -0.11 | 0 | **2005** | 209.13 | -6.66 | 202.46 |
| **2010** | -11.49 | -0.34 | -11.82 | **2010** | -22315.96 | -20.81 | -22336.77 |
| **2015** | -11.95 | -1.35 | -13.31 | **2015** | -23222.25 | -83.75 | -23306 |
| **2020** | -11.88 | -2.35 | -14.23 | **2020** | -23080 | -145.69 | -23225.69 |
| **Min 2005-20** | -6.87 | -0.11 | -6.95 | **Min 2005-20** | -13350.72 | -6.66 | -13355.35 |
| **Average 2005-20** | -10.77 | -0.95 | -11.72 | **Average 2005-20** | -20919.46 | -58.88 | -20978.34 |
| **Max 2005-20** | -11.88 | -2.35 | -14.23 | **Max 2005-20** | -23080 | -145.69 | -23225.69 |
| **Cumul. 2005-20** | -172.27 | -15.22 | -187.49 | **Cumul. 2005-20** | -334711.39 | -942.12 | -335653.5 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.28 | 97.02 | 100 | **2005** | 100.28 | 97.02 | 100.27 |
| **2010** | 75.88 | 94.43 | 77.97 | **2010** | 75.88 | 94.43 | 75.96 |
| **2015** | 76.16 | 86.29 | 77.83 | **2015** | 76.16 | 86.29 | 76.22 |
| **2020** | 76.38 | 81.89 | 77.51 | **2020** | 76.38 | 81.89 | 76.43 |
| **Min 2005-20** | 81.97 | 97.02 | 83.35 | **Min 2005-20** | 81.97 | 97.02 | 82.02 |
| **Average 2005-20** | 77.33 | 88.2 | 78.9 | **Average 2005-20** | 77.33 | 88.2 | 77.38 |
| **Max 2005-20** | 76.38 | 81.89 | 77.51 | **Max 2005-20** | 76.38 | 81.89 | 76.43 |
| **Cumul. 2005-20** | 77.33 | 88.2 | 78.9 | **Cumul. 2005-20** | 77.33 | 88.2 | 77.38 |

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**Table E.15 – continued from previous page**

| ***Palladium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Palladium*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 20.46 | 3.35 | 23.81 | **2005** | 31,612.36 | 56.90 | 31,669.26 |
| **2010** | 34.44 | 6 | 40.43 | **2010** | 53,208.52 | 101.68 | 53,310.20 |
| **2015** | 34.26 | 8.37 | 42.62 | **2015** | 52,933.36 | 141.88 | 53,075.24 |
| **2020** | 31.29 | 10.51 | 41.8 | **2020** | 48,348.66 | 178.18 | 48,526.84 |
| **Min 2005-20** | 20.46 | 3.35 | 23.81 | **Min 2005-20** | 31,612.36 | 56.90 | 31,669.26 |
| **Average 2005-20** | 32.59 | 7.14 | 39.73 | **Average 2005-20** | 50,352.18 | 121.05 | 50,473.23 |
| **Max 2005-20** | 35.36 | 10.51 | 42.79 | **Max 2005-20** | 54,634.15 | 178.18 | 54,745.86 |
| **Cumul. 2005-20** | 521.4 | 114.2 | 635.6 | **Cumul. 2005-20** | 805,634.92 | 1,936.74 | 807,571.66 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.02 | -0.02 | 0 | **2005** | 38.51 | -0.42 | 38.09 |
| **2010** | 11.69 | 0.13 | 11.82 | **2010** | 18065.94 | 2.2 | 18068.14 |
| **2015** | 12.18 | 1.13 | 13.31 | **2015** | 18813.12 | 19.15 | 18832.28 |
| **2020** | 12.04 | 2.19 | 14.23 | **2020** | 18605.67 | 37.16 | 18642.82 |
| **Min 2005-20** | 1.21 | -0.02 | 0 | **Min 2005-20** | 1869.37 | -0.42 | 1785.24 |
| **Average 2005-20** | 10.96 | 0.76 | 11.72 | **Average 2005-20** | 16935.45 | 12.85 | 16948.3 |
| **Max 2005-20** | 12.18 | 2.19 | 13.29 | **Max 2005-20** | 18813.8 | 37.16 | 18818.49 |
| **Cumul. 2005-20** | 175.37 | 12.12 | 187.49 | **Cumul. 2005-20** | 270967.22 | 205.58 | 271172.8 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.12 | 99.26 | 100 | **2005** | 100.12 | 99.26 | 100.12 |
| **2010** | 151.41 | 102.21 | 141.32 | **2010** | 151.41 | 102.21 | 151.27 |
| **2015** | 155.14 | 115.61 | 145.38 | **2015** | 155.14 | 115.61 | 155 |
| **2020** | 162.55 | 126.35 | 151.63 | **2020** | 162.55 | 126.35 | 162.38 |
| **Min 2005-20** | 106.29 | 99.26 | 100 | **Min 2005-20** | 106.29 | 99.26 | 105.97 |
| **Average 2005-20** | 150.68 | 111.88 | 141.84 | **Average 2005-20** | 150.68 | 111.88 | 150.55 |
| **Max 2005-20** | 152.52 | 126.35 | 145.07 | **Max 2005-20** | 152.52 | 126.35 | 152.38 |
| **Cumul. 2005-20** | 150.68 | 111.88 | 141.84 | **Cumul. 2005-20** | 150.68 | 111.88 | 150.55 |

| ***Rhodium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 3.21 | 0.76 | 3.97 | **2005** | 7,398.70 | 54.48 | 7,453.18 |
| **2010** | 3.66 | 0.88 | 4.54 | **2010** | 8,453.07 | 63.08 | 8,516.15 |
| **2015** | 3.79 | 1.15 | 4.94 | **2015** | 8,755.35 | 81.91 | 8,837.25 |
| **2020** | 3.32 | 1.33 | 4.64 | **2020** | 7,656.15 | 94.84 | 7,750.98 |
| **Min 2005-20** | 3.21 | 0.76 | 3.97 | **Min 2005-20** | 7,398.70 | 54.48 | 7,453.18 |
| **Average 2005-20** | 3.62 | 1.02 | 4.64 | **Average 2005-20** | 8,356.24 | 73.10 | 8,429.34 |
| **Max 2005-20** | 4.05 | 1.33 | 4.97 | **Max 2005-20** | 9,355.76 | 94.84 | 9,421.15 |
| **Cumul. 2005-20** | 57.92 | 16.35 | 74.27 | **Cumul. 2005-20** | 133,699.88 | 1,169.59 | 134,869.47 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0 | 0 | 0 | **2005** | 0 | 0 | 0 |
| **2010** | 0 | 0 | 0 | **2010** | 0 | 0 | 0 |
| **2015** | 0 | 0 | 0 | **2015** | 0 | 0 | 0 |
| **2020** | 0 | 0 | 0 | **2020** | 0 | 0 | 0 |
| **Min 2005-20** | 0 | 0 | 0 | **Min 2005-20** | 0 | 0 | 0 |
| **Average 2005-20** | 0 | 0 | 0 | **Average 2005-20** | 0 | 0 | 0 |
| **Max 2005-20** | 0 | 0 | 0 | **Max 2005-20** | 0 | 0 | 0 |
| **Cumul. 2005-20** | 0 | 0 | 0 | **Cumul. 2005-20** | 0 | 0 | 0 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100 | 100 | 100 | **2005** | 100 | 100 | 100 |
| **2010** | 100 | 100 | 100 | **2010** | 100 | 100 | 100 |
| **2015** | 100 | 100 | 100 | **2015** | 100 | 100 | 100 |
| **2020** | 100 | 100 | 100 | **2020** | 100 | 100 | 100 |
| **Min 2005-20** | 100 | 100 | 100 | **Min 2005-20** | 100 | 100 | 100 |
| **Average 2005-20** | 100 | 100 | 100 | **Average 2005-20** | 100 | 100 | 100 |
| **Max 2005-20** | 100 | 100 | 100 | **Max 2005-20** | 100 | 100 | 100 |
| **Cumul. 2005-20** | 100 | 100 | 100 | **Cumul. 2005-20** | 100 | 100 | 100 |

Table E.16: PGM inputs and $SO_{2eq}$ emissions in HD-DPd-A1 scenario

| ***PGM use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 61.99 | 7.62 | 69.61 | **2005** | 113,682.56 | 328.00 | 114,010.56 |
| **2010** | 75.32 | 12.62 | 87.94 | **2010** | 158,763.89 | 512.72 | 159,276.61 |
| **2015** | 78.49 | 18.07 | 96.55 | **2015** | 162,305.30 | 744.87 | 163,050.16 |
| **2020** | 76.41 | 22.44 | 98.85 | **2020** | 154,520.10 | 930.51 | 155,450.61 |
| **Min 2005-20** | 61.99 | 7.62 | 69.61 | **Min 2005-20** | 113,682.56 | 328.00 | 114,010.56 |
| **Average 2005-20** | 74.63 | 15.29 | 89.92 | **Average 2005-20** | 154,397.55 | 629.94 | 155,027.49 |
| **Max 2005-20** | 78.91 | 22.44 | 98.85 | **Max 2005-20** | 165,489.14 | 930.51 | 166,038.84 |
| **Cumul. 2005-20** | 1194.12 | 244.66 | 1438.78 | **Cumul. 2005-20** | 2,470,360.73 | 10,079.12 | 2,480,439.84 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.24 | -0.13 | 0.1 | **2005** | 652.49 | -7.09 | 645.4 |
| **2010** | 1.29 | -0.16 | 1.13 | **2010** | 22634.19 | -23.09 | 22611.1 |
| **2015** | 2.48 | -0.18 | 2.29 | **2015** | 22023.21 | -70.61 | 21952.6 |
| **2020** | 3.55 | -0.2 | 3.35 | **2020** | 19401.67 | -109.83 | 19291.83 |
| **Min 2005-20** | 0.24 | -0.13 | 0.1 | **Min 2005-20** | 652.49 | -7.09 | 645.4 |
| **Average 2005-20** | 1.9 | -0.17 | 1.73 | **Average 2005-20** | 20366.02 | -50.53 | 20315.48 |
| **Max 2005-20** | 1.58 | -0.2 | 3.35 | **Max 2005-20** | 22976.99 | -109.83 | 22949.28 |
| **Cumul. 2005-20** | 30.41 | -2.78 | 27.63 | **Cumul. 2005-20** | 325856.28 | -808.52 | 325047.76 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 100.38 | 98.29 | 100.15 | **2005** | 100.58 | 97.89 | 100.57 |
| **2010** | 101.74 | 98.76 | 101.3 | **2010** | 116.63 | 95.69 | 116.54 |
| **2015** | 103.26 | 99 | 102.43 | **2015** | 115.7 | 91.34 | 115.56 |
| **2020** | 104.88 | 99.12 | 103.51 | **2020** | 114.36 | 89.44 | 114.17 |
| **Min 2005-20** | 100.38 | 98.29 | 100.15 | **Min 2005-20** | 100.58 | 97.89 | 100.57 |
| **Average 2005-20** | 102.61 | 98.88 | 101.96 | **Average 2005-20** | 115.19 | 92.57 | 115.08 |
| **Max 2005-20** | 102.04 | 99.12 | 103.51 | **Max 2005-20** | 116.12 | 89.44 | 116.04 |
| **Cumul. 2005-20** | 102.61 | 98.88 | 101.96 | **Cumul. 2005-20** | 115.19 | 92.57 | 115.08 |

| ***Platinum use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Platinum*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 39.04 | 3.5 | 42.54 | **2005** | 75,846.15 | 216.63 | 76,062.77 |
| **2010** | 40.52 | 5.76 | 46.28 | **2010** | 71,560.28 | 302.44 | 71,862.71 |
| **2015** | 46.64 | 8.89 | 55.54 | **2015** | 82,371.23 | 467.02 | 82,838.25 |
| **2020** | 50.48 | 11.5 | 61.98 | **2020** | 89,151.79 | 603.87 | 89,755.65 |
| **Min 2005-20** | 32.54 | 3.5 | 36.07 | **Min 2005-20** | 57,456.58 | 185.49 | 57,642.07 |
| **Average 2005-20** | 43.12 | 7.41 | 50.53 | **Average 2005-20** | 76,572.91 | 391.25 | 76,964.16 |
| **Max 2005-20** | 50.48 | 11.5 | 61.98 | **Max 2005-20** | 89,151.79 | 603.87 | 89,755.65 |
| **Cumul. 2005-20** | 689.85 | 118.58 | 808.43 | **Cumul. 2005-20** | 1,225,166.64 | 6,259.95 | 1,231,426.59 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 0.92 | -0.11 | 0.81 | **2005** | 1788.63 | -6.66 | 1781.96 |
| **2010** | -7.1 | -0.27 | -7.37 | **2010** | -20973.78 | -70.81 | -21044.58 |
| **2015** | -3.49 | -0.97 | -4.46 | **2015** | -15035.28 | -143.82 | -15179.1 |
| **2020** | 0.19 | -1.5 | -1.31 | **2020** | -8567.51 | -200.62 | -8768.13 |
| **Min 2005-20** | -5.58 | -0.11 | -5.66 | **Min 2005-20** | -16600.94 | -37.8 | -16638.74 |
| **Average 2005-20** | -4.37 | -0.65 | -5.02 | **Average 2005-20** | -15685.64 | -107.93 | -15793.57 |
| **Max 2005-20** | 0.19 | -1.5 | -1.31 | **Max 2005-20** | -8567.51 | -200.62 | -8768.13 |
| **Cumul. 2005-20** | -69.9 | -10.44 | -80.34 | **Cumul. 2005-20** | -250970.24 | -1726.93 | -252697.17 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 102.42 | 97.02 | 101.95 | **2005** | 102.42 | 97.02 | 102.4 |
| **2010** | 85.08 | 95.52 | 86.26 | **2010** | 77.33 | 81.03 | 77.35 |
| **2015** | 93.04 | 90.13 | 92.56 | **2015** | 84.56 | 76.46 | 84.51 |
| **2020** | 100.37 | 88.49 | 97.93 | **2020** | 91.23 | 75.06 | 91.1 |
| **Min 2005-20** | 85.36 | 97.02 | 86.44 | **Min 2005-20** | 77.58 | 83.07 | 77.6 |
| **Average 2005-20** | 90.8 | 91.91 | 90.96 | **Average 2005-20** | 83 | 78.38 | 82.97 |
| **Max 2005-20** | 100.37 | 88.49 | 97.93 | **Max 2005-20** | 91.23 | 75.06 | 91.1 |
| **Cumul. 2005-20** | 90.8 | 91.91 | 90.96 | **Cumul. 2005-20** | 83 | 78.38 | 82.97 |

Continued on next page

**Table E.16 – continued from previous page**

| ***Palladium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Palladium*** | | | |
|---|---|---|---|---|---|---|---|
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 19.85 | 3.35 | 23.21 | **2005** | 30,671.04 | 56.90 | 30,727.93 |
| **2010** | 31.84 | 5.98 | 37.83 | **2010** | 81,031.10 | 157.10 | 81,188.21 |
| **2015** | 29.45 | 8.1 | 37.55 | **2015** | 74,934.06 | 212.64 | 75,146.70 |
| **2020** | 24.58 | 9.79 | 34.37 | **2020** | 62,548.96 | 257.14 | 62,806.10 |
| **Min 2005-20** | 19.85 | 3.35 | 23.21 | **Min 2005-20** | 30,671.04 | 56.90 | 30,727.93 |
| **Average 2005-20** | 28.94 | 6.92 | 35.86 | **Average 2005-20** | 72,411.54 | 179.64 | 72,591.18 |
| **Max 2005-20** | 32.26 | 9.79 | 38.82 | **Max 2005-20** | 82,097.91 | 257.14 | 82,270.01 |
| **Cumul. 2005-20** | 463.11 | 110.65 | 573.76 | **Cumul. 2005-20** | 1,158,584.61 | 2,874.23 | 1,161,458.84 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -0.58 | -0.02 | -0.61 | **2005** | -902.81 | -0.42 | -903.24 |
| **2010** | 9.1 | 0.12 | 9.22 | **2010** | 45888.53 | 57.62 | 45946.14 |
| **2015** | 7.37 | 0.86 | 8.23 | **2015** | 40813.83 | 89.91 | 40903.74 |
| **2020** | 5.33 | 1.48 | 6.81 | **2020** | 32805.97 | 116.11 | 32922.09 |
| **Min 2005-20** | 0.6 | -0.02 | -0.61 | **Min 2005-20** | 928.05 | -0.42 | 843.92 |
| **Average 2005-20** | 7.32 | 0.54 | 7.85 | **Average 2005-20** | 38994.81 | 71.44 | 39066.25 |
| **Max 2005-20** | 9.08 | 1.48 | 9.32 | **Max 2005-20** | 46277.56 | 116.11 | 46342.64 |
| **Cumul. 2005-20** | 117.07 | 8.57 | 125.65 | **Cumul. 2005-20** | 623916.91 | 1143.06 | 625059.98 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 97.14 | 99.26 | 97.44 | **2005** | 97.14 | 99.26 | 97.14 |
| **2010** | 140.01 | 102 | 132.22 | **2010** | 230.58 | 157.92 | 230.37 |
| **2015** | 133.36 | 111.9 | 128.06 | **2015** | 219.62 | 173.26 | 219.45 |
| **2020** | 127.7 | 117.77 | 124.7 | **2020** | 210.3 | 182.33 | 210.17 |
| **Min 2005-20** | 103.12 | 99.26 | 97.44 | **Min 2005-20** | 103.12 | 99.26 | 102.82 |
| **Average 2005-20** | 133.83 | 108.4 | 128.04 | **Average 2005-20** | 216.69 | 166.03 | 216.53 |
| **Max 2005-20** | 139.17 | 117.77 | 131.62 | **Max 2005-20** | 229.19 | 182.33 | 228.99 |
| **Cumul. 2005-20** | 133.83 | 108.4 | 128.04 | **Cumul. 2005-20** | 216.69 | 166.03 | 216.53 |

| ***Rhodium use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 3.1 | 0.76 | 3.87 | **2005** | 7,165.37 | 54.48 | 7,219.85 |
| **2010** | 2.96 | 0.88 | 3.83 | **2010** | 6,172.51 | 53.18 | 6,225.69 |
| **2015** | 2.39 | 1.07 | 3.47 | **2015** | 5,000.01 | 65.21 | 5,065.22 |
| **2020** | 1.35 | 1.15 | 2.5 | **2020** | 2,819.35 | 69.51 | 2,888.86 |
| **Min 2005-20** | 1.35 | 0.76 | 2.5 | **Min 2005-20** | 2,819.35 | 46.41 | 2,888.86 |
| **Average 2005-20** | 2.57 | 0.96 | 3.54 | **Average 2005-20** | 5,413.09 | 59.06 | 5,472.15 |
| **Max 2005-20** | 3.16 | 1.15 | 4.06 | **Max 2005-20** | 7,165.37 | 69.51 | 7,219.85 |
| **Cumul. 2005-20** | 41.16 | 15.44 | 56.59 | **Cumul. 2005-20** | 86,609.48 | 944.93 | 87,554.41 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | -0.1 | 0 | -0.1 | **2005** | -233.33 | 0 | -233.33 |
| **2010** | -0.71 | -0.01 | -0.71 | **2010** | -2280.56 | -9.9 | -2290.46 |
| **2015** | -1.4 | -0.07 | -1.47 | **2015** | -3755.34 | -16.7 | -3772.04 |
| **2020** | -1.97 | -0.18 | -2.15 | **2020** | -4836.8 | -25.33 | -4862.13 |
| **Min 2005-20** | -1.85 | 0 | -1.47 | **Min 2005-20** | -4579.35 | -8.07 | -4564.32 |
| **Average 2005-20** | -1.05 | -0.06 | -1.1 | **Average 2005-20** | -2943.15 | -14.04 | -2957.19 |
| **Max 2005-20** | -0.89 | -0.18 | -0.9 | **Max 2005-20** | -2190.38 | -25.33 | -2201.3 |
| **Cumul. 2005-20** | -16.76 | -0.91 | -17.68 | **Cumul. 2005-20** | -47090.4 | -224.66 | -47315.06 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 96.85 | 100 | 97.45 | **2005** | 96.85 | 100 | 96.87 |
| **2010** | 80.74 | 99.38 | 84.36 | **2010** | 73.02 | 84.31 | 73.1 |
| **2015** | 63.14 | 93.85 | 70.26 | **2015** | 57.11 | 79.61 | 57.32 |
| **2020** | 40.72 | 86.4 | 53.76 | **2020** | 36.82 | 73.29 | 37.27 |
| **Min 2005-20** | 42.13 | 100 | 62.92 | **Min 2005-20** | 38.11 | 85.19 | 38.76 |
| **Average 2005-20** | 71.06 | 94.41 | 76.2 | **Average 2005-20** | 64.78 | 80.79 | 64.92 |
| **Max 2005-20** | 77.97 | 86.4 | 81.79 | **Max 2005-20** | 76.59 | 73.29 | 76.63 |
| **Cumul. 2005-20** | 71.06 | 94.41 | 76.2 | **Cumul. 2005-20** | 64.78 | 80.79 | 64.92 |

Table E.17: PGM inputs and $SO_{2eq}$ emissions in HD-DPd-A1-R1 scenario

| ***PGM use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to PGM*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 61.36 | 8.25 | 69.61 | **2005** | 112,537.49 | 355.34 | 112,892.82 |
| **2010** | 69.01 | 18.93 | 87.94 | **2010** | 145,151.65 | 769.08 | 145,920.72 |
| **2015** | 61.93 | 34.63 | 96.55 | **2015** | 126,963.67 | 1,427.66 | 128,391.33 |
| **2020** | 46.5 | 52.35 | 98.85 | **2020** | 91,400.18 | 2,171.20 | 93,571.38 |
| **Min 2005-20** | 46.5 | 8.25 | 69.61 | **Min 2005-20** | 91,400.18 | 355.34 | 93,571.38 |
| **Average 2005-20** | 61.99 | 27.94 | 89.92 | **Average 2005-20** | 127,471.40 | 1,151.76 | 128,623.16 |
| **Max 2005-20** | 70.97 | 52.35 | 98.85 | **Max 2005-20** | 148,328.48 | 2,171.20 | 149,198.84 |
| **Cumul. 2005-20** | 991.8 | 446.98 | 1438.78 | **Cumul. 2005-20** | 2,039,542.42 | 18,428.19 | 2,057,970.61 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | -0.4 | 0.5 | 0.1 | **2005** | -492.58 | 20.25 | -472.33 |
| **2010** | -5.02 | 6.15 | 1.13 | **2010** | 9021.94 | 233.27 | 9255.21 |
| **2015** | -14.08 | 16.38 | 2.29 | **2015** | -13318.42 | 612.18 | -12706.24 |
| **2020** | -26.36 | 29.72 | 3.35 | **2020** | -43718.25 | 1130.85 | -42587.4 |
| **Min 2005-20** | -15.26 | 0.5 | 0.1 | **Min 2005-20** | -21629.89 | 20.25 | -19793.78 |
| **Average 2005-20** | -10.74 | 12.47 | 1.73 | **Average 2005-20** | -6560.13 | 471.28 | -6088.84 |
| **Max 2005-20** | -6.36 | 29.72 | 3.35 | **Max 2005-20** | 5816.33 | 1130.85 | 6109.28 |
| **Cumul. 2005-20** | -171.91 | 199.54 | 27.63 | **Cumul. 2005-20** | -104962.03 | 7540.55 | -97421.48 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 99.35 | 106.48 | 100.15 | **2005** | 99.56 | 106.04 | 99.58 |
| **2010** | 93.22 | 148.14 | 101.3 | **2010** | 106.63 | 143.54 | 106.77 |
| **2015** | 81.47 | 189.74 | 102.43 | **2015** | 90.51 | 175.07 | 90.99 |
| **2020** | 63.82 | 231.28 | 103.51 | **2020** | 67.64 | 208.7 | 68.72 |
| **Min 2005-20** | 75.29 | 106.48 | 100.15 | **Min 2005-20** | 80.86 | 106.04 | 82.54 |
| **Average 2005-20** | 85.23 | 180.64 | 101.96 | **Average 2005-20** | 95.11 | 169.26 | 95.48 |
| **Max 2005-20** | 91.78 | 231.28 | 103.51 | **Max 2005-20** | 104.08 | 208.7 | 104.27 |
| **Cumul. 2005-20** | 85.23 | 180.64 | 101.96 | **Cumul. 2005-20** | 95.11 | 169.26 | 95.48 |

| ***Platinum use in Autocatalysts*** | | | | ***$SO_{2eq}$ emissions due to Platinum*** | | | |
|---|---|---|---|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* | **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 38.75 | 3.79 | 42.54 | **2005** | 75,279.59 | 234.68 | 75,514.26 |
| **2010** | 37.64 | 8.64 | 46.28 | **2010** | 66,475.20 | 453.65 | 66,928.85 |
| **2015** | 38.49 | 17.04 | 55.54 | **2015** | 67,975.23 | 895.12 | 68,870.36 |
| **2020** | 35.15 | 26.83 | 61.98 | **2020** | 62,076.54 | 1,409.02 | 63,485.56 |
| **Min 2005-20** | 31.95 | 3.79 | 36.07 | **Min 2005-20** | 56,416.98 | 216.41 | 56,633.39 |
| **Average 2005-20** | 36.85 | 13.68 | 50.53 | **Average 2005-20** | 65,502.76 | 720.52 | 66,223.28 |
| **Max 2005-20** | 39.9 | 26.83 | 61.98 | **Max 2005-20** | 75,279.59 | 1,409.02 | 75,514.26 |
| **Cumul. 2005-20** | 589.58 | 218.84 | 808.43 | **Cumul. 2005-20** | 1,048,044.19 | 11,528.36 | 1,059,572.55 |
| ***Differences wrt BAU*** | | | | ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* | (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 0.63 | 0.18 | 0.81 | **2005** | 1222.07 | 11.39 | 1233.46 |
| **2010** | -9.98 | 2.61 | -7.37 | **2010** | -26058.86 | 80.41 | -25978.44 |
| **2015** | -11.64 | 7.18 | -4.46 | **2015** | -29431.28 | 284.28 | -29147 |
| **2020** | -15.14 | 13.84 | -1.31 | **2020** | -35642.75 | 604.54 | -35038.22 |
| **Min 2005-20** | -6.17 | 0.18 | -5.66 | **Min 2005-20** | -17640.54 | -6.88 | -17647.42 |
| **Average 2005-20** | -10.64 | 5.61 | -5.02 | **Average 2005-20** | -26755.79 | 221.34 | -26534.45 |
| **Max 2005-20** | -10.4 | 13.84 | -1.31 | **Max 2005-20** | -22439.71 | 604.54 | -23009.52 |
| **Cumul. 2005-20** | -170.17 | 89.83 | -80.34 | **Cumul. 2005-20** | -428092.68 | 3541.48 | -424551.21 |
| ***Ratios wrt BAU*** | | | | ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* | (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 101.65 | 105.1 | 101.95 | **2005** | 101.65 | 105.1 | 101.66 |
| **2010** | 79.04 | 143.28 | 86.26 | **2010** | 71.84 | 121.54 | 72.04 |
| **2015** | 76.78 | 172.74 | 92.56 | **2015** | 69.79 | 146.54 | 70.26 |
| **2020** | 69.89 | 206.47 | 97.93 | **2020** | 63.53 | 175.15 | 64.44 |
| **Min 2005-20** | 83.81 | 105.1 | 86.44 | **Min 2005-20** | 76.18 | 96.92 | 76.24 |
| **Average 2005-20** | 77.6 | 169.63 | 90.96 | **Average 2005-20** | 71 | 144.34 | 71.39 |
| **Max 2005-20** | 79.33 | 206.47 | 97.93 | **Max 2005-20** | 77.04 | 175.15 | 76.65 |
| **Cumul. 2005-20** | 77.6 | 169.63 | 90.96 | **Cumul. 2005-20** | 71 | 144.34 | 71.39 |

Continued on next page

**Table E.17 – continued from previous page**

| ***Palladium use in Autocatalysts*** | | | |
|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 19.57 | 3.63 | 23.21 |
| **2010** | 28.85 | 8.97 | 37.83 |
| **2015** | 22.03 | 15.52 | 37.55 |
| **2020** | 11.52 | 22.85 | 34.37 |
| **Min 2005-20** | 11.52 | 3.63 | 23.21 |
| **Average 2005-20** | 23.3 | 12.56 | 35.86 |
| **Max 2005-20** | 29.65 | 22.85 | 38.82 |
| **Cumul. 2005-20** | 372.77 | 200.99 | 573.76 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | -0.86 | 0.25 | -0.61 |
| **2010** | 6.11 | 3.11 | 9.22 |
| **2015** | -0.06 | 8.28 | 8.23 |
| **2020** | -7.73 | 14.53 | 6.81 |
| **Min 2005-20** | -7.73 | 0.25 | -0.61 |
| **Average 2005-20** | 1.67 | 6.18 | 7.85 |
| **Max 2005-20** | 6.47 | 14.53 | 9.32 |
| **Cumul. 2005-20** | 26.73 | 98.92 | 125.65 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 95.77 | 107.53 | 97.44 |
| **2010** | 126.86 | 152.99 | 132.22 |
| **2015** | 99.74 | 214.48 | 128.06 |
| **2020** | 59.87 | 274.79 | 124.7 |
| **Min 2005-20** | 59.87 | 107.53 | 97.44 |
| **Average 2005-20** | 107.72 | 196.9 | 128.04 |
| **Max 2005-20** | 127.9 | 274.79 | 131.62 |
| **Cumul. 2005-20** | 107.72 | 196.9 | 128.04 |

| ***$SO_{2eq}$ emissions due to Palladium*** | | | |
|---|---|---|---|
| **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 30,239.05 | 61.64 | 30,300.69 |
| **2010** | 73,418.86 | 235.65 | 73,654.52 |
| **2015** | 56,045.27 | 407.55 | 56,452.82 |
| **2020** | 29,323.64 | 600.00 | 29,923.63 |
| **Min 2005-20** | 29,323.64 | 61.64 | 29,923.63 |
| **Average 2005-20** | 58,060.97 | 327.74 | 58,388.71 |
| **Max 2005-20** | 75,449.73 | 600.00 | 75,597.58 |
| **Cumul. 2005-20** | 928,975.53 | 5,243.88 | 934,219.40 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | -1334.79 | 4.32 | -1330.47 |
| **2010** | 38276.28 | 136.17 | 38412.46 |
| **2015** | 21925.04 | 284.82 | 22209.86 |
| **2020** | -419.35 | 458.97 | 39.62 |
| **Min 2005-20** | -419.35 | 4.32 | 39.62 |
| **Average 2005-20** | 24644.24 | 219.54 | 24863.78 |
| **Max 2005-20** | 39629.38 | 458.97 | 39670.22 |
| **Cumul. 2005-20** | 394307.83 | 3512.71 | 397820.54 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 95.77 | 107.53 | 95.79 |
| **2010** | 208.92 | 236.88 | 209 |
| **2015** | 164.26 | 332.08 | 164.86 |
| **2020** | 98.59 | 425.44 | 100.13 |
| **Min 2005-20** | 98.59 | 107.53 | 100.13 |
| **Average 2005-20** | 173.75 | 302.91 | 174.17 |
| **Max 2005-20** | 210.63 | 425.44 | 210.42 |
| **Cumul. 2005-20** | 173.75 | 302.91 | 174.17 |

| ***Rhodium use in Autocatalysts*** | | | |
|---|---|---|---|
| **(in tonnes)** | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 3.04 | 0.83 | 3.87 |
| **2010** | 2.52 | 1.31 | 3.83 |
| **2015** | 1.41 | 2.06 | 3.47 |
| **2020** | 0 | 2.67 | 2.5 |
| **Min 2005-20** | 0 | 0.83 | 2.5 |
| **Average 2005-20** | 1.85 | 1.7 | 3.54 |
| **Max 2005-20** | 3.04 | 2.67 | 4.06 |
| **Cumul. 2005-20** | 29.63 | 27.15 | 56.59 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | -0.16 | 0.06 | -0.1 |
| **2010** | -1.14 | 0.43 | -0.71 |
| **2015** | -2.38 | 0.91 | -1.47 |
| **2020** | -3.32 | 1.35 | -2.15 |
| **Min 2005-20** | -3.21 | 0.06 | -1.47 |
| **Average 2005-20** | -1.77 | 0.67 | -1.1 |
| **Max 2005-20** | -1.01 | 1.35 | -0.9 |
| **Cumul. 2005-20** | -28.29 | 10.79 | -17.68 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 94.87 | 108.33 | 97.45 |
| **2010** | 68.77 | 149.07 | 84.36 |
| **2015** | 37.17 | 179.88 | 70.26 |
| **2020** | 0 | 201.6 | 53.76 |
| **Min 2005-20** | 0 | 108.33 | 62.92 |
| **Average 2005-20** | 51.15 | 166 | 76.2 |
| **Max 2005-20** | 75.02 | 201.6 | 81.79 |
| **Cumul. 2005-20** | 51.15 | 166 | 76.2 |

| ***$SO_{2eq}$ emissions due to Rhodium*** | | | |
|---|---|---|---|
| **(in tonnes)** | *Primary prod.* | *Secondary prod.* | *Total prod.* |
| **2005** | 7,018.85 | 59.02 | 7,077.87 |
| **2010** | 5,257.59 | 79.77 | 5,337.35 |
| **2015** | 2,943.17 | 124.98 | 3,068.15 |
| **2020** | 0.00 | 162.18 | 162.18 |
| **Min 2005-20** | 0.00 | 54.15 | 162.18 |
| **Average 2005-20** | 3,907.67 | 103.50 | 4,011.17 |
| **Max 2005-20** | 7,018.85 | 162.18 | 7,077.87 |
| **Cumul. 2005-20** | 62,522.70 | 1,655.96 | 64,178.66 |
| ***Differences wrt BAU*** | | | |
| (in tonnes) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | -379.86 | 4.54 | -375.32 |
| **2010** | -3195.49 | 16.69 | -3178.8 |
| **2015** | -5812.18 | 43.08 | -5769.1 |
| **2020** | -7656.15 | 67.35 | -7588.8 |
| **Min 2005-20** | -7398.7 | -0.33 | -7291 |
| **Average 2005-20** | -4448.57 | 30.4 | -4418.18 |
| **Max 2005-20** | -2336.91 | 67.35 | -2343.29 |
| **Cumul. 2005-20** | -71177.18 | 486.37 | -70690.81 |
| ***Ratios wrt BAU*** | | | |
| (in %) | *Primary input* | *Secondary input* | *Total input* |
| **2005** | 94.87 | 108.33 | 94.96 |
| **2010** | 62.2 | 126.46 | 62.67 |
| **2015** | 33.62 | 152.59 | 34.72 |
| **2020** | 0 | 171.01 | 2.09 |
| **Min 2005-20** | 0 | 99.39 | 2.18 |
| **Average 2005-20** | 46.76 | 141.58 | 47.59 |
| **Max 2005-20** | 75.02 | 171.01 | 75.13 |
| **Cumul. 2005-20** | 46.76 | 141.58 | 47.59 |

# E.3 Fuel Cell Vehicles

Table E.9: Platinum primary input and associated environmental pressures in the HR 75-100 kW, HR 75 kW and HR 75-50 kW scenarios

| **Scenario HR 75-100 kW** | **Yearly Figures (in tons)** Min | Avg | Max | **Cumulative 2010-2030 (in tons)** |
|---|---|---|---|---|
| ***Platinum primary inputs*** | | | | |
| **Best Case** | 105.31 | 202.11 | 1895.6 | 80.3 |
| **Avg Case** | 1.27 | 56.6 | 112.84 | 1018.82 |
| **Worst Case** | 2.02 | 131.15 | 278.07 | 2360.72 |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | |
| **Best Case** | 1,457.20 | 33,787.48 | 58,465.60 | 608,174.63 |
| **Avg Case** | 2,476.26 | 110,186.56 | 220,417.93 | 1,983,358.12 |
| **Worst Case** | 3,918.16 | 255,247.27 | 542,744.33 | 4,594,450.89 |
| ***$CO_{2eq}$q emissions associated with Pt production*** | | | | |
| **Best Case** | 29,919.70 | 701,626.68 | 1,240,471.80 | 12,629,280.19 |
| **Avg Case** | 50,843.52 | 2,281,782.02 | 4,632,502.71 | 41,072,076.44 |
| **Worst Case** | 80,448.98 | 5,279,661.19 | 11,367,058.28 | 95,033,901.43 |
| ***$TMR_{eq}$ associated with Pt production*** | | | | |
| **Best Case** | 512,677.37 | 11,884,366.09 | 20,554,969.73 | 213,918,589.58 |
| **Avg Case** | 871,209.36 | 38,759,202.49 | 77,509,293.40 | 697,665,644.76 |
| **Worst Case** | 1,378,502.12 | 89,787,954.44 | 190,868,925.92 | 1,616,183,179.84 |

| **Scenario HR 75 kW** | **Yearly Figures (in tons)** Min | Avg | Max | **Cumulative 2010-2030 (in tons)** | **Cumul. 75 kW / 75-100 kW** |
|---|---|---|---|---|---|
| ***Platinum primary inputs*** | | | | | |
| **Best Case** | 0.75 | 14.02 | 21.52 | 252.43 | 80.85 |
| **Avg Case** | 1.27 | 45.55 | 81.59 | 819.85 | 80.47 |
| **Worst Case** | 2.02 | 105.31 | 202.11 | 1895.6 | 80.3 |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 1,457.20 | 27,329.22 | 42,053.95 | 491,926.00 | 80.89 |
| **Avg Case** | 2,476.26 | 88,695.93 | 159,572.18 | 1,596,526.75 | 80.5 |
| **Worst Case** | 3,918.16 | 205,014.94 | 394,950.23 | 3,690,268.92 | 80.32 |
| ***$CO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 29,919.70 | 568,549.60 | 892,203.47 | 10,233,892.89 | 81.03 |
| **Avg Case** | 50,843.52 | 1,839,322.79 | 3,372,602.05 | 33,107,810.14 | 80.61 |
| **Worst Case** | 80,448.98 | 4,245,813.93 | 8,312,565.29 | 76,424,650.74 | 80.42 |
| ***$TMR_{eq}$ associated with Pt production*** | | | | | |
| **Best Case** | 512,677.37 | 9,612,368.35 | 14,787,320.01 | 173,022,630.25 | 83.26 |
| **Avg Case** | 871,209.36 | 31,198,720.05 | 56,106,705.51 | 561,576,960.85 | 82.86 |
| **Worst Case** | 1,378,502.12 | 72,115,906.15 | 138,878,681.42 | 1,298,086,310.76 | 82.68 |

| Scenario HR 75-50 kW | Yearly Figures (in tons) | | | Cumulative 2010-2030 (in tons) | Cumul. 75-50 kW / 75-100 kW |
|---|---|---|---|---|---|
| | Min | Avg | Max | | |
| ***Platinum primary inputs*** | | | | | |
| **Best Case** | 0.75 | 10.7 | 15.96 | 192.64 | 61.7 |
| **Avg Case** | 1.27 | 34.49 | 54.06 | 620.87 | 60.94 |
| **Worst Case** | 2.02 | 79.47 | 129.65 | 1430.48 | 60.6 |
| ***$SO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 1,457.20 | 20,870.96 | 31,044.04 | 375,677.36 | 61.77 |
| **Avg Case** | 2,476.26 | 67,205.30 | 105,386.90 | 1,209,695.37 | 60.99 |
| **Worst Case** | 3,918.16 | 154,782.61 | 253,057.79 | 2,786,086.96 | 60.64 |
| ***$CO_{2eq}$ emissions associated with Pt production*** | | | | | |
| **Best Case** | 29,919.70 | 435,472.53 | 640,542.43 | 7,838,505.58 | 62.07 |
| **Avg Case** | 50,843.52 | 1,396,863.55 | 2,199,371.91 | 25,143,543.83 | 61.22 |
| **Worst Case** | 80,448.98 | 3,211,966.67 | 5,307,372.24 | 57,815,400.04 | 60.84 |
| ***$TMR_{eq}$ associated with Pt production*** | | | | | |
| **Best Case** | 512,677.37 | 7,340,370.61 | 10,920,895.80 | 132,126,670.91 | 63.58 |
| **Avg Case** | 871,209.36 | 23,638,237.61 | 37,066,344.79 | 425,488,276.93 | 62.78 |
| **Worst Case** | 1,378,502.12 | 54,443,857.87 | 88,993,825.89 | 979,989,441.68 | 62.42 |

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