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Systems analysis of stock buffering: development of a dynamic substance flow-stock model for the identification and estimation of future resource, waste streams and emissions

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Chapter 8 The Consequences of the Use of Platinum in New Technologies on its Availability and on Other Metals Cycles *

Abstract

Recently, fuel cell vehicles (FCV) are being developed to reduce the environmental impacts related to the conventional internal combustion engine vehicles. Although on the short term the newly proposed technology might serve the intended purpose. On the long term, there may be bottlenecks in the supply of specific metals required for the technology and new emissions may replace the old ones.

Fuel cell technology requires the use of platinum, which is cited as a possible bottleneck for a more widespread use of the new technologies. Moreover, an increase in platinum demand ultimately implies an increased production of the co-produced metals Cu and Ni. Consequently an increased supply may well have environmental consequences on Ni and Cu recycling system.

The chapter is aimed at

- Investigating the potential long-term impact of the increase use of platinum in fuel cell technology and other applications in terms of resource depletion
- Evaluating the long-term consequences of the increased demand of platinum on the cycles of other co-produced metals especially Ni and Cu

The analysis is carried out using a dynamic substance flow-stock model for platinum, nickel and copper.

The model consists of a set of differential equation describing the change of the magnitude of the substance stock in the system compartments (production, use and waste management of platinum applications, primary production of platinum in South Africa, Russia, USA, Canada and others and secondary production of platinum) over time and several model relations. The model is implemented in Matlab/SIMULINK environment.

The main driving force in the model is the global demand for platinum. The global demand for platinum is estimated based on the demand for its applications (fuel cell, catalytic converters, and the other applications) and platinum required for each application. In turn, the demand for platinum applications are modelled based on socio-economic variables such GDP, per capita GDP, population size, material price and the cost of these applications. Platinum required for each application is modelled as a function of cumulated production using the learning curve. In addition, several other factors are important in determining the main outcome such as the applications life span, the applications collection rates and the efficiency of the production processes (primary and secondary).

The main model outcomes are the amount of primary platinum required for FCVs and other applications and the consequences on platinum current reserve, platinum identified resources and the co-produced metals recycling and primary production from other ores.

The model shows that the demand for primary platinum will increase dramatically with the introduction of FCVs despite the possibility of the decrease of platinum loading of FC. This is mainly due to the increased demand for vehicles. Without changes in management, the current platinum reserve would be exhausted in three decades and the identified resources in roughly 60 years. The model also shows that the demand for the co-produced materials is increasing over time. The supply of these metals from Pt ores is, combined with only a part of their current secondary production, sufficient to meet the rising demand. Consequently the primary production of these metals from other ores than those of Pt ores will not be needed. Recycling of these metals is expected to decrease.

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8.1 Introduction

The increase in global population and the growth in consumption per head have led to an increase in materials and energy use. This has raised the concern about the exhaustion of limited resources and the environmental impact of resources during their life cycle.

Several new technologies for sustainable development in the field of energy production, nanotechnologies and ICT aim at reducing the environmental pressure by decreasing the use of (fossil) energy and materials. Some of these technologies require the use of specific metals. Among these are platinum and palladium that are required for car catalysts and fuel cells technologies, indium and germanium that are required for solar cell technologies, and bismuth and germanium, in the case of lead free electronic solder.

On the short term, each of the proposed technologies may serve the intended purpose of reducing environmental impact. Combined and on the long term, however, there may be bottlenecks in the supply of the required metals and new emissions may replace the old ones. The proposed technologies might reduce the environmental impacts related to the use of resources, however, on the long term, firms might start extracting low-grade ores to meet the demand for the required materials. This will lead to the use of more energy and will produce more waste. Another concern stems from the fact that platinum and palladium are mostly co-produced with other, more abundant metals such as copper and nickel. The link between the required metals and their "host" metals in nature may have negative impacts on the host metals cycles. An increase in the demand for Pt or Pd ultimately implies an increased production of these host metals. This may well have environmental consequences, the more so as lower prices will make extraction of the metals from wastes for recycling less attractive.

The assessment of the new technologies requires the inclusion of all above-mentioned environmental impacts in terms of long term availability of resources, emissions and waste generation, energy use, and co-produced metals.

This chapter treats a case in point to illustrate the importance of the abovementioned problems. The long term potential use of platinum in fuel cells is evaluated in terms of platinum resource availability and the co-produced metals supply and demand. The other aspects are mentioned briefly.

Platinum is a rare metal with a concentration of 5 part per billion (ppb) (British Geological Survey, 2005) in the earth crust. Platinum can be found in nature in three different types of ores; PGE dominants ores, Ni-Cu dominant ores and miscellaneous ores (Xiao and Laplante, 2004). Recently fuel cell vehicles are being developed to reduce the environmental impacts related to the conventional internal combustion engine vehicles. Fuel cell technology, one of the main items required for these vehicles, requires the use of platinum as an important element of the electrodes of the proton exchange membrane fuel cell (PEMFC). Pt is used to promote the rate of the electrochemical reactions required for H_2 to release electrons and become H_2 ions. In addition to the new proposed technologies, platinum is currently used in several applications due to its chemical and physical properties. It is used in catalytic converters to reduce the emissions of hydrocarbons, carbon monoxide, nitrogen oxide, and other atmospheric pollutants from vehicle exhausts. It is widely used in industrial applications (chemical, petrochemical, glass, and electrical and electronics) due to its relative inertness and its ability to catalyze specific chemical reactions. Moreover, platinum is used in dental alloys, spark plugs, sensors, turbine blade and biomedical applications. Moreover, it is proposed that Pt might be widely used to replace gold in electronic circuits (Gediga et al., 1998).

This chapter is aimed at

- Investigating the potential long-term impact of the worldwide increase use of platinum in fuel cell technology and other applications in terms of resources depletion
- Evaluating the long-term consequences of the worldwide increased demand of platinum on the cycles of other co-produced metals especially Ni and Cu

The analysis is carried out using a dynamic substance flow-stock model for platinum, nickel and copper, which is implemented in Matlab/SIMULINK environment (Math-Works, 2005).

The chapter is structured as follows. Section 2 outlines the general setup of the model. Section 3 contains the results of the model calculations and a discussion of the results. Section 4 is dedicated to the conclusions.

8.2 General setup of the model

The model described in this section is a dynamic substance flow-stock model. Figure 1 shows the modelled substances (platinum, nickel and copper), the main processes in their economic systems and their flows and stocks.

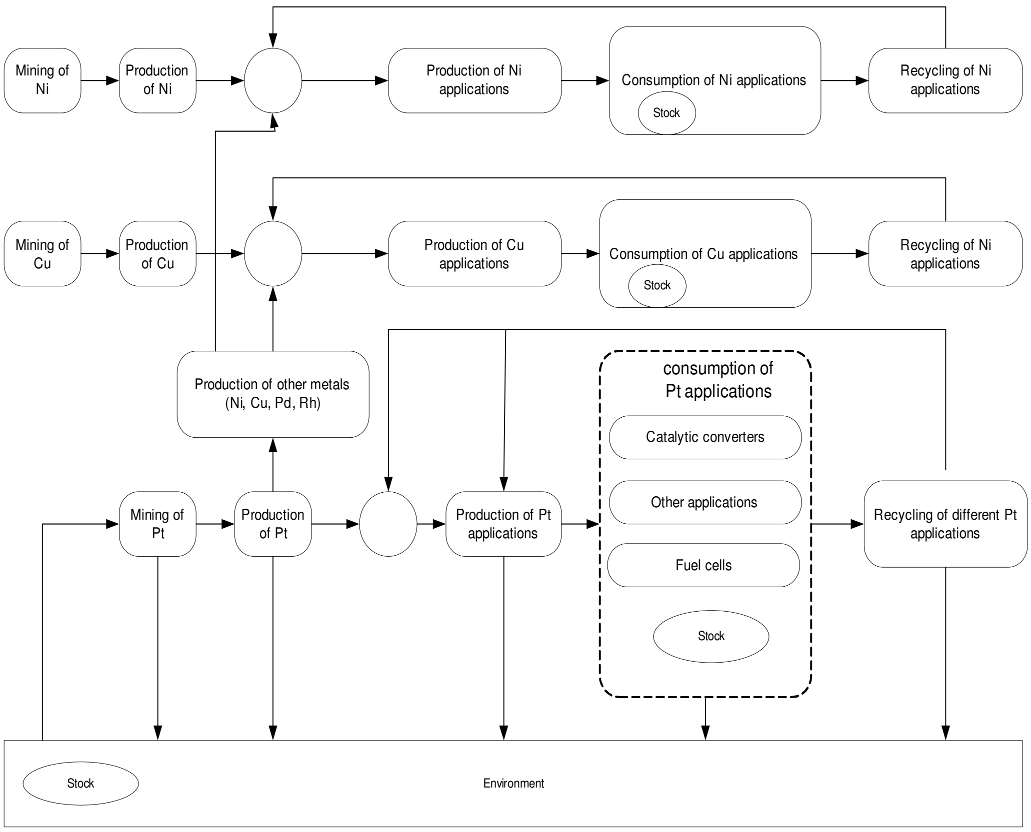

Fig. 1: The main processes in the economic system of Pt, Ni and Cu and their flows and stocks

The model includes the extraction of platinum, the production of platinum from primary resources and its main co-products, the production, consumption and waste management of platinum applications (fuel cell, catalytic converter, chemical industry, electrical and electronic industry, glass industry, investment, jewelery, petroleum industry and other applications) and the production of secondary platinum. The model also includes the production of co-produced metals (Ni and Cu) from primary resources, the consumption and waste management of Ni applications and Cu applications and the production of Ni and Cu from secondary resources.

Three types of platinum ores are identified, PGE dominants ores, Ni-Cu dominant ores and miscellaneous ores depending on the geographical distribution. Platinum resources in these ores can be classified as current reserve and identified resources. Current reserve includes all platinum resources that are economic to extract at current market price using existing technology. Identified resources include economic, marginally economic and sub-economic resources.

The demand in the model is the global demand for Pt, Ni and Cu and the supply of platinum is covered by four sources (Republic of South Africa, Russia, USA and Canada, and Other countries (Zimbabwe, Finland, China, Columbia and Australia)).

The model consists of a set of differential equations (Eqs. 1-6) describing the change of the magnitude of the substance stock in the system's compartments over time.

The change of the magnitude of the substance stock in the use phase over time is given by Eq. 1. The inflow into the stock-in-use is determined by external factors and the outflow is determined by the inflow, the product life span, and the emissions during use. The change of the magnitude of the substance stock in the production processes of platinum applications over time is given by Eq. 2 and equal to zero. The inflow into the stock is determined by the outflow from the stock, which is determined by the inflow into the stock-in-use. The change of the magnitude of the substance stock in the collection processes of platinum applications over time is given by Eq. 3 and equal to zero. The outflow from the stock is determined by the inflow into the stock, which is determined by the outflow from the stock-in-use. The change of the magnitude of the substance stock in the recycling processes of platinum applications over time is given by Eq. 4 and equal to zero. The outflow from the stock is determined by the inflow into the stock, which is determined by the outflow from the collection processes. The change of the magnitude of the substance stock in the mining processes of platinum over time is given by Eq. 5. The outflow from the stock is determined by the required primary platinum in the market. The change of the magnitude of the substance stock in the platinum market over time is given by Eq. 6 and equal to zero. The required platinum from primary resources (required to solve Eq. 5) is determined by the outflows from the recycling processes (estimated from Eq. 4) and the inflow of platinum into the production processes of its applications (estimated from Eq. 2)

Moreover, the model consists of several model relations describing the inflow of substances into the stock-in-use as function of the socio-economic variables. Some of the variables in the model relations constitute exogenous variables (GDP and population) and others are endogenous variables (price).
The historical data of the exogenous variables GDP and population size are given in Ayres et. al. (Ayres et al., 2003). In the future, GDP and population size are modelled as a function of time based on the historical data and the IPCC B1 Scenario for the future development in these variables.
The model also includes the environmental flows and stocks of platinum and an analysis of the energy required for the production of platinum, however these issues will not be discussed in details here.

$$\frac{dS_{x,C,i}}{dt} = F^{in}{}_{x,C,i}(t) - F^{out}{}_{x,C,i}(t) \tag{1}$$

$$\frac{dS_{x,PP,i}(t)}{dt} = 0 = F^{in}_{x,PP,i}(t) - F^{out}_{x,PP,i}(t) \tag{2}$$

$$\frac{dS_{x,SC,i}(t)}{dt} = 0 = F^{in}_{x,SC,i}(t) - F^{out}_{x,SC,i}(t) \tag{3}$$

$$\frac{dS_{x,R,i}(t)}{dt} = 0 = F^{in}_{x,R,i}(t) - F^{out}_{x,R,i}(t) \tag{4}$$

$$\frac{dS_{x,\mathrm{Re}s}(t)}{dt} = F^{in}_{x,\mathrm{Re}s}(t) - F^{out}_{x,\mathrm{Re}s}(t) = F^{in}_{x,\mathrm{Re}s}(t) - F^{in}_{x,\mathrm{Pr}}(t) \tag{5}$$

$$\frac{dS_{x,m}(t)}{dt} = 0 = F^{out}_{x,R}(t) + F^{out}_{x,\mathrm{Pr}}(t) - F^{in}_{x,PP}(t) \tag{6}$$

where *x's* are the different metals (Pt, Ni, Cu), i is the metal application, *C* is the consumption of metal applications, *PP* is the production processes of metal applications, *SC* is the collection of the scrap of metal applications, *R* is the recycling of metal applications, *Res* is the identified resources of metals, *M* is the metals market, *S* is the stock, F^{in} is the inflow and F^{out} is the outflow.

8.2.1 Consuption of platinum applications

The change of the magnitude of the stock-in-use over time is the difference between the inflow and the outflow of platinum as given by the differential equation (Eq. 1).

Inflow of platinum into stock-in-use

The inflow of platinum into the stock-in-use is the amount of platinum used in catalytic converters, other applications and fuel cell and is modelled as given by Eq. 7. The relations between different factors determining the total inflow of platinum into the stock-in-use in the economic system are shown in figure 2.

$$F^{in}{}_{Pt,C}(t) = F^{in}{}_{Pt,FC}(t) + F^{in}{}_{Pt,CC}(t) + F^{in}{}_{Pt,Others}(t) \tag{7}$$

where $F^{in}{}_{Pt,C}$ is the inflow of platinum into the stock-in-use, $F^{in}{}_{Pt,Fc}$ is the inflow of platinum into the stock-in-use of fuel cells, $F^{in}{}_{Pt,CC}$ is the inflow of platinum into the stock-in-use of catalytic converters and $F^{in}{}_{Pt,others}$ is the inflow of platinum into the stock-in-use of other applications.

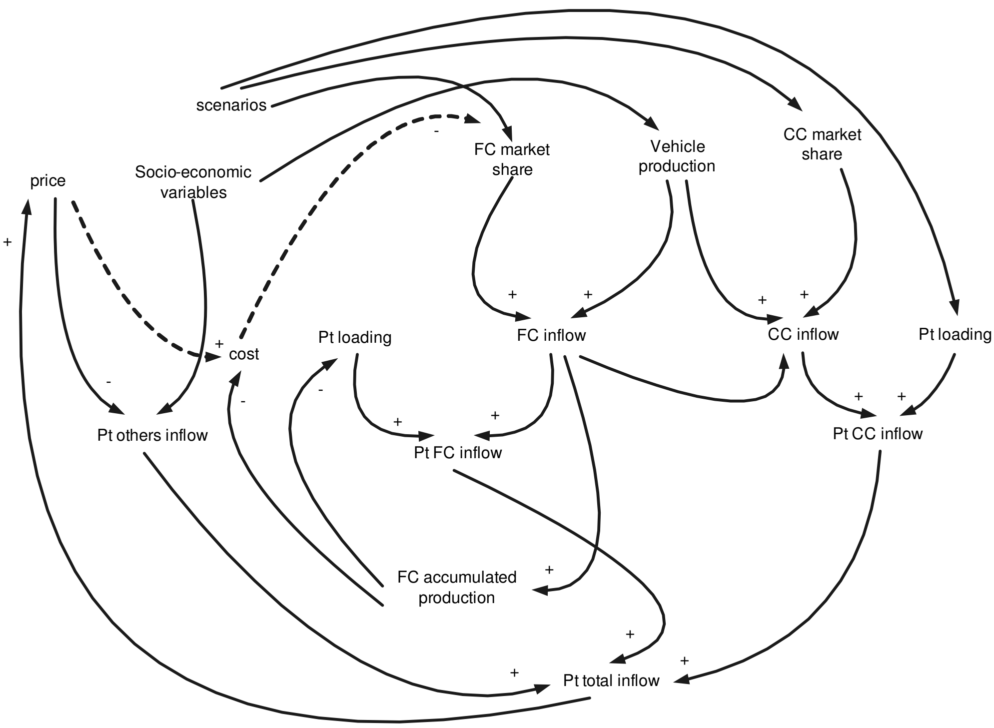

Fig. 2: Total inflow of platinum into the stock-in-use model relations

The inflow of platinum into the stock-in-use of fuel cell is modelled based on the demand for vehicles, the share of fuel cell in the vehicles market and the platinum content of fuel cell as given by Eq. 8 and 9.

$$F^{in}{}_{FC,V}(t) = F^{in}{}_{v}(t) \cdot \lambda_{FC}(t) \cdot \left(T_v \big/ T_{FC} \right) \tag{8}$$

$$F^{in}{}_{Pt,FC}(t) = F^{in}{}_{FC,V}(t) \cdot \alpha_{Pt,FC}(t) \tag{9}$$

where $F^{in}{}_{Fc,V}$ is the inflow of fuel cell in vehicles, $F^{in}{}_{v}$ is the inflow of vehicles, T_V is the life span of vehicles, T_{FC} is the life span of fuel cell, $F^{in}{}_{Pt,Fc}$ is the inflow of platinum into the stock-in-use of fuel cells, λ_{FC} is fuel cell market share and $\alpha_{Pt,FC}$ is the platinum content of fuel cell

The demand for vehicles is modelled based on socio-economic variables as given by Eq. 10.

$$F_V^{in}(t) = a + b \cdot GDP \tag{10}$$

Fuel cell market share (λ_{FC}) is modelled based on different scenario using the following formula.

$$\lambda_{FC}(t) = \frac{100 \cdot e^{0.1(t-t_1)}}{1 + e^{0.1(t-t_1)}} \quad (\%) \tag{11}$$

The platinum content of fuel cell is modelled based on the learning curve concept. The learning curve (Tsuchiya & Kobayashi, 2004) is adapted for the possible reduction in platinum loading as given by Eq. 12.

$$\alpha_{Pt,FC}(t) = A \cdot X^{-r}(t) \tag{12}$$

$\alpha_{Pt,FC}$ *(t)* is the platinum loading of fuel cell at time t, *A* constant, *X (t)* cumulated production at time t.
The progress ratio F = 2^{-r}

$$r = -\left[\ln F \big/ \ln 2\right] \tag{13}$$

Although, the progress ratio may increase overtime for some technologies (Junginger et al., 2003), in the model the progress ratio is assumed to be constant during the simulation time.
For the recycling to be possible, the amount of platinum should not be lower than 20 g/FC. Therefore, the minimum Pt content in FC is set to 20 g in the model.

The inflow of platinum into the stock-in-use of catalytic converters is modelled based on the demand for vehicles as given by Eq. 10, fuel cell market share, catalytic converters market share and the platinum content of catalytic converters as given by Eq. 14, 15, 16 and 17.

$$F^{in}{}_{CC,V}(t) = \left[F^{in}{}_{v}(t) - \left(F^{in}{}_{FC,V}(t) \cdot \left(T_{FC} \big/ T_v\right)\right)\right] \cdot \lambda_{CC}(t) \cdot \left(T_v \big/ T_{CC}\right) \tag{14}$$

$$F^{in}{}_{Pt,CC}(t) = F^{in}{}_{CC,V}(t) \cdot \alpha_{Pt,CC}(t) \tag{15}$$

$$\lambda_{CC}(t) = 100 \cdot \left(1 - \left[\frac{1}{e^{(t-t0)/T_{CC}}}\right]\right) \% \tag{16}$$

$$\alpha_{Pt,CC}(t) = stepfunction \tag{17}$$

where λ_{CC} is catalytic converters market share and $\alpha_{Pt,CC}$ is the platinum content of catalytic converters

As given by Eq. 16, the market share of catalytic converters is increasing over time, however, the number of vehicles occupied by catalytic converters is decreasing over time due to the impact of the introduction of fuel cell as given by Eq. 14.

The model assumes that at the time the vehicles are completely occupied by fuel cell (100% market share of fuel cell), the number of vehicles occupied by catalytic converters will be zero.
The inflows of platinum into the stock-in-use of other applications (chemical industry, petrochemical industry, glass industry, electrical and electronics industry, jewllery, investment and others (dental alloys, spark plugs, sensors, turbine blade and biomedical applications)) are modelled based on socio-economic variables such as per capita GDP (GDP and Pop), price and time. The socio-economic variables GDP, per capita GDP, and population size constitute exogenous variables and the price is an endogenous variable.

$$\ln\left[F^{in}_{Pt,i}(t)\right] = \beta_0 + \sum_{i=1}^{n} \ln\left[\beta_i X_i(t)\right] + \varepsilon(t) \tag{18}$$

$$\ln\left[P(t)\right] = \ln\left[a\right] + b \cdot \ln\left[D(t)\right] \tag{19}$$

Outflow of platinum from stock-in-use

The outflow of platinum from the stock-in-use of its applications is the outflow due to the discarded platinum products and the outflow due to the emissions during use.

$$F^{out}_{Pt,i}(t) = F^{out}_{Pt,E,i}(t) + F^{out}_{Pt,D,i}(t) \tag{20}$$

The emissions of platinum during the use phase of platinum applications are estimated as a fraction of the stock as given by Eq. 21.

$$F^{out}_{Pt,E,i}(t) = C_{Pt,i} \cdot S_{Pt,i}(t) \tag{21}$$

where *C* is the emission factor and *S* is the stock-in-use

The discarded outflow is estimated as a delayed inflow, corrected for the leaching that has taken place during use, as given by Eq. 22 and 23:

$$F^{out}{}_{Pt,D,i}(t) = F^{in}{}_{Pt,C,i}\left(t - L_{U,i}\right) - \sum_{i=1}^{L_U} C_{Pt,i} \cdot F^{in}{}_{Pt,C,i}\left(t - L_{U,i}\right) \cdot \left(1 - C_{Pt,i}\right)^{i-1} \tag{22}$$

where $F^{out}_{Pt,D,i}(t)$ is the outflow of application i due to the delay mechanism at time t and $L_{U,i}$ being the average life span of the product in use.

$$F^{out}{}_{Pt,D,i}(t) = \sum_{j=0}^{\infty} W_j \cdot F^{in}{}_{Pt,C,i}(t - j) = \sum_{j=-\infty}^{t} W_{t-j} \cdot F^{in}{}_{Pt,C,i}(j) \tag{23}$$

where the lag weights w's are the probabilities of exiting the delay in any time period j and must sum to unity

$$\sum_{j=0}^{\infty} W_j = 1 \tag{24}$$

The total outflow at time t, F^{out} then is given by Eq. 25

$$F^{out}{}_{Pt,D}(t) = \sum_{i=1}^{n} F^{out}{}_{Pt,D,i} \tag{25}$$

where $F^{out}_{Pt,D}(t)$ is the total outflow due to the delay mechanism at time t

8.2.2 Production of platinum applications

The change of the magnitude of the stock in the production of different platinum applications over time is the difference between the inflow and the outflow as given by the differential equation (Eq. 2).

Inflow of platinum into production processes

The input of platinum into the production processes of different platinum applications is equal to the output of platinum from the production processes in the products and the emissions during the production processes as given by Eq. 26.

$$F^{in}{}_{Pt,PP,i}(t) = F^{out}{}_{Pt,PP,i}(t) = F^{out}{}_{Pt,PP,P,i}(t) + F^{out}{}_{Pt,PP,E,i}(t) \tag{26}$$

Outflow of platinum from production processes

The output of platinum in the products is equal to the input of platinum into the stock-in-use as given by Eq. 27 and the emissions are estimated as a fraction of the input (Eq. 28).

$$F^{out}{}_{Pt,PP,P,i}(t) = F^{in}{}_{Pt,C,i}(t) \tag{27}$$

$$F^{out}{}_{Pt,PP,E,i}(t) = \beta_i \cdot F^{in}{}_{Pt,PP,i}(t) \tag{28}$$

From Eqs. 27 and 28, the inflow of platinum into the production processes

$$F^{in}{}_{Pt,PP,i}(t) = F^{in}{}_{Pt,C,i}(t) + \beta_i \cdot F^{in}{}_{Pt,PP,i}(t) = F^{in}{}_{Pt,C,i}(t) \Big/ 1-\beta_i \tag{29}$$

8.2.3 Production of platinum

Secondary production

The discarded outflow of platinum is either collected for recycling or ended up in the landfill sites and incineration plants. The collected flow for recycling is estimated as given by Eq. 30 and the landfilled and incinerated flows are estimated as given by Eq. 31.

$$F^{in}_{Pt,SC,i}(t) = \delta_i \cdot F^{out}{}_{Pt,D,i}(t) \tag{30}$$

$$F^{in}_{Pt,inc,land,i}(t) = F^{out}{}_{Pt,D,i}(t) - F^{in}_{Pt,Sc,i}(t) \tag{31}$$

The change of the magnitude of the stock in the collectionof different platinum applications over time is the difference between the inflow and the outflow and equal to zero as given by the differential equation (Eq. 3). Therefore, the inflow into the collection processes is equal to the outflow as given by Eq. 32.

$$F^{in}_{Pt,SC,i}(t) = F^{out}_{Pt,SC,i}(t) \tag{32}$$

The change of the magnitude of the stock in the recycling processes of different platinum applications over time is the difference between the inflow and the outflow as given by the differential equation (Eq. 4). Therefore, the inflow into the collection processes is equal to the outflow as given by Eq. 33.

$$F_{Pt,R,i}^{in}(t) = F_{Pt,R,i}^{out}(t) \tag{33}$$

The inflow into the recycling processes is equal to the outflow from the collection processes

$$F_{Pt,R,i}^{in}(t) = F_{Pt,SC,i}^{out}(t) \tag{34}$$

The outflow from the recycling processes is the refined platinum and the losses during the recycling processes (Eq. 35).

$$F_{Pt,R,i}^{out}(t) = F_{Pt,R,ref,i}^{out}(t) + F_{Pt,R,losses,i}^{out}(t) \tag{35}$$

The losses during the recycling processes are estimated as a fraction of the inflow into the recycling processes (Eq. 36).

$$F_{Pt,R,losses,i}^{out}(t) = \delta \cdot F_{Pt,R,i}^{in}(t) \tag{36}$$

The outflow (refined platinum) from the recycling processes (dismantling, smelting and refining) is estimated as given by Eq. 37.

$$F_{Pt,R,ref,i}^{out}(t) = F_{Pt,R,i}^{in}(t) \cdot (1 - \delta) \tag{37}$$

Total refined secondary platinum

$$F_{Pt,R,ref}^{out}(t) = \sum_{i=1}^{n} F_{Pt,R,ref,i}^{out}(t) \tag{38}$$

Primary production

The required platinum from primary resources is estimated as the difference between the total demand for platinum and the possible supply of platinum from secondary resources as given by Eq. 39. The total extracted platinum from ores is estimated based on the required platinum from primary resources and the efficiency of the production processes (mining, concentration, smelting, base metal separation, and refining) of primary platinum efficiency as given by Eq. 40.

$$F^{out}{}_{Pt,pr}(t) = F_{pt,PP}^{in}(t) - F_{Pt,R,ref}^{out}(t) \tag{39}$$

$$F^{in}{}_{Pt,pr}(t) = F^{out}{}_{Pt,pr}(t) \cdot (1 + \kappa) \tag{40}$$

κ is the processes efficiency of primary platinum production

The losses during the production of primary platinum are estimated as give by Eq. 41.

$$F^{losses}{}_{Pt,pr}(t) = \kappa \cdot F_{Pt,\mathrm{Pr}}^{in}(t) \tag{41}$$

8.2.4 Resources issues

The change of the magnitude of the stock of platinum resources over time is estimated in each country based on the required primary platinum and the possible increase of platinum resources as given by the differential equation (Eq. 5). The resources of platinum included in the model are the identified resources, which include the economic, marginally economic and sub-economic resources. The increase in the resources of platinum is assumed to be zero, therefore the change of the magnitude of the stock of platinum resources is estimated as given by 42.

$$\frac{dS_{Pt,\mathrm{Res},A}(t)}{dt} = -F^{out}_{Pt,\mathrm{Res},A}(t) = -F^{in}_{Pt,\mathrm{Pr},A}(t) \tag{42}$$

The supply of Pt from the main producing countries (Republic of South Africa, Russia, USA and Canada and other countries such as Finland, Zimbabwe, China, Columbia and Australia) is estimated based on an average value of the supply from these countries in the last 29 years and the total primary Pt required as given by Eq. 43.

$$F^{in}{}_{Pt,pr,A}(t) = \alpha_A \cdot F^{in}_{Pt,\mathrm{Pr}}(t) \tag{43}$$

A in Eqs. 42 and 43 refers to the producing countries and α_A is the supply from country A.

8.2.5 Co-production issues

Supply of co-produced metals as a result of Pt primary demand is estimated as given by Eq. 44.

$$S_{x,A}(t) = F^{in}{}_{Pt,pr,A}(t) \cdot \beta_{x,A} \tag{44}$$

$\beta_{x,A}$ is the concentration of specific co-produced material in the ore in specific country, x is the co-produced metals and A represents different countries

The total demand for different metal applications can either be estimated based on different scenarios or based on the socio-economic variables.
The total demand for metals ($F^{in}_{x,C,total}$) are estimated based on socio-economic variables using Eqs. 18 and 19. The total inflow is divided into several applications based on the life span. Each one of these applications is estimated as given by Eq. 45.

$$F^{in}_{x,C,i}(t) = \chi_i \cdot F^{in}_{x,C,total}(t) \tag{45}$$

i represents the different products categories based on the life span

The change of the magnitude of the stock of the metals in the metals market over time is estimated based on the demand for the metals and the supply of these metals from primary resources and secondary resources as given by the differential equation (Eq. 6). Based on Eq. 6, the demand for the metals is equal to the supply of these metals from primary resources (from Pt ores and other ores) and the supply from secondary resources as given by Eq. 46.

$$F^{in}_{x,C}(t) = F^{out}_{x,R}(t) + F^{out}_{x,\mathrm{Pr},Pt}(t) + F^{out}_{x,\mathrm{Pr},other}(t) \tag{46}$$

$$F^{out}_{x,\mathrm{Pr},Pt}(t) = \sum_{i=1}^{4} S_{x,A}(t) \tag{47}$$

The availability of the co-produced metals from secondary resources is estimated based on the discarded metals applications, the current collection rates and the efficiency of the recycling processes.
The discarded outflows of the metal applications are estimated based on their inflow and their life span as in a similar equation used for Pt applications (Eqs. 22-25).
The collected streams of co-produced metals applications are estimated based on the discarded outflow and the collection rate as given by Eq. 30.
The possibility of oversupply is checked by the estimates of the total demand for co-produced metals and the estimates of the supply of primary co-produced metals due to the demand for Pt. The required metals from other sources are estimated based on the difference between the total demand and the possible supply from Pt ores. The required amount of these metals from other sources (secondary sources and primary from other ores) is estimated as given by Eq. 48 and compared with the possible availability of metals from secondary resources.

$$F_{x,\mathrm{Pr},other}^{out}(t) + F_{x,R}^{out}(t) = F_{x,C}^{in}(t) - F_{x,\mathrm{Pr},Pt}^{out}(t) \tag{48}$$

8.3 Results and discussion

8.3.1 Platinum stock and demand

Inflow of platinum into stock-in-use

The total inflow of platinum into the stock-in-use is platinum inflow into the stock-in-use of its applications (fuel cell, catalytic converter and the other applications).
The inflow of platinum into the stock-in-use of fuel cell vehicles is estimated based on the demand for vehicles, market penetration of fuel cell vehicles and platinum required for each fuel cell. The demand for vehicles is modelled as a function of GDP, several scenarios are used for fuel cells market penetration and platinum required for each fuel cell is modelled based on the learning curve concept with initial loading of 60 g and a progress ratio of 0.97. Figure 3 shows the demand for platinum for fuel cell vehicles from 1975 through 2100 based on fuel cell vehicles market penetration scenarios. These scenarios are estimated as given by Eq. 11 to give values similar to those given by the UK department for transport (UK DFT, 2003) and listed in table 1.

Table 1: Scenarios used for fuel cell market penetration

Scenario	2005	2020	2030	2040	2050	2070	2090	2100
Sc1	1	4.7	12	27	50	88	98	100
Sc2	3.5	50	90	99	100	100	100	100
Sc3	0	5	26	70	94	100	100	100
Sc4	0	2.4	5	10	20	53	84	100
Sc5	0	0	0	0	0	0	0	0

The amount of platinum required for each fuel cell over time is estimated as a function of the cumulated production of fuel cells based on the learning curve concept. Figure 4 shows the demand for platinum from 1975 through 2100 based on different progress ratios.
Although the amount of platinum required for one fuel cell is decreasing overtime reaching almost 20 g in 2100, the demand for Pt is increasing due to the increase demand for fuel cell vehicles. As shown in figure 2, the progress ratio is an important factor in determining the platinum content of fuel cells and consequently the total demand for Pt.
The inflow of platinum into the stock-in-use of catalytic converters is determined by the demand for vehicles, the market share of fuel cells, the market share of catalytic converters and the amount of platinum required for each catalytic converter as given by Eq. 14 and Eq. 15. The demand for vehicles is modelled as a function of the GDP as given by Eq. 10, the market share of catalytic converters is estimated based on scenario using Eq. 16 and Pt required for each catalytic converter is modelled as a step function taking the

value of 2 g from 1970 through 2005, 3 g from 2006 through 2012 and from 2013 onwards taking a maximum value of 4 g.

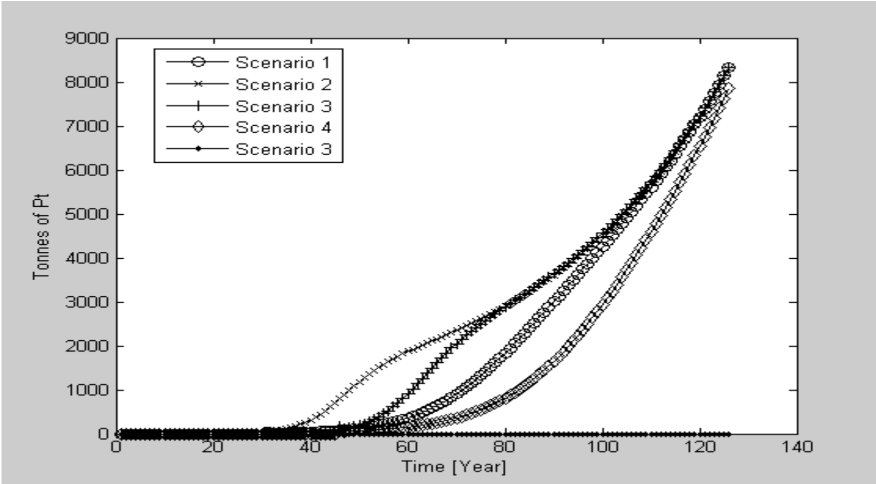

Fig. 3: worldwide platinum inflow into the stock-in-use of fuel cell vehicles under various scenarios regarding market penetration

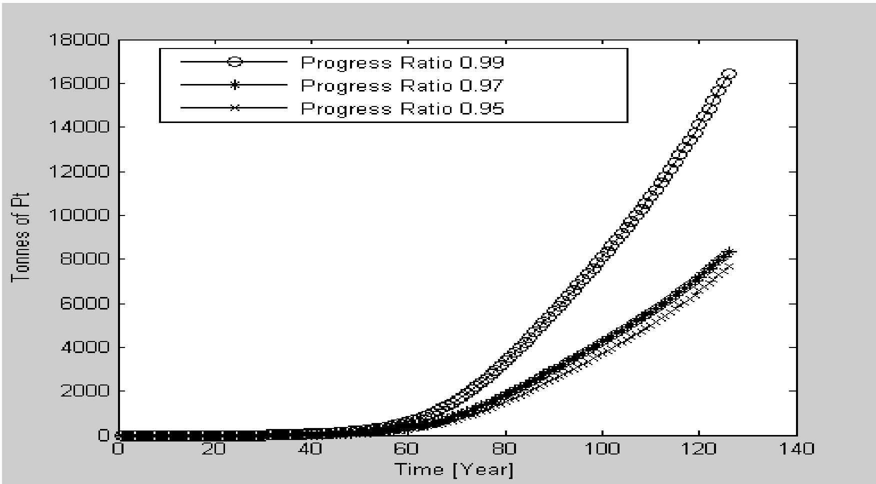

Fig. 4: worldwide platinum inflow into the stock-in-use of fuel cell vehicles under various assumption regarding progress ratios

The inflow of platinum into the stock-in-use of the other applications of platinum is modelled as a function of the GDP, platinum price and the time is used as a proxy of other determinants variables. Regression analysis is used to determine the relation between the explanatory variables and the inflow of platinum in each application. The model parameters and the goodness of the relations are shown in table 2. The analysis is carried out for the inflow from 1975 till 1990 (Johnson Mathey, 2005) . The inflows of these applications from 1975 through 2100 are shown in figure 5 and the total inflow of platinum into the stock-in-use of all applications from 1975 through 2100 is shown in figure 6.

Although the inflow of platinum into the stock-in-use of catalytic converters and some of the other applications is decreasing over time, the total demand for platinum is increasing due to the expected increase in demand for fuel cell vehicles and some of the other applications (jewellery and investment).

Table 2: Parameters used in modelling other applications inflows and the goodness of the relations

Application	**a**	**b**	**c**	**d**	R^2
Chemical industry	1475.4	1.861	-0.081	-201.4	0.8
Petrochemical industry	13881.0	28.61	-0.054	-1943.6	0.45
Glass industry	7071.8	16.17	0.029	-989.5	0.64
Electrical and electronics industry	2229.8	4.917	-0.205	-312.9	0.68
Jewllery	1573.2	5.359	-0.582	-227.2	0.57
Investment	2888.8	8.494	-0.502	-413.43	0.19
Others	1312.4	1.098	-0.01	-177.1	0.84

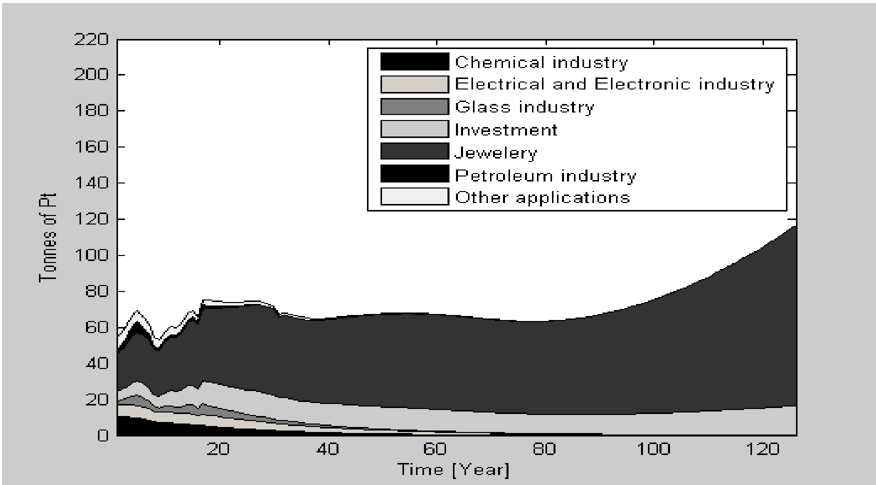

Fig. 5: The inflow of platinum into the stock-in-use of other applications

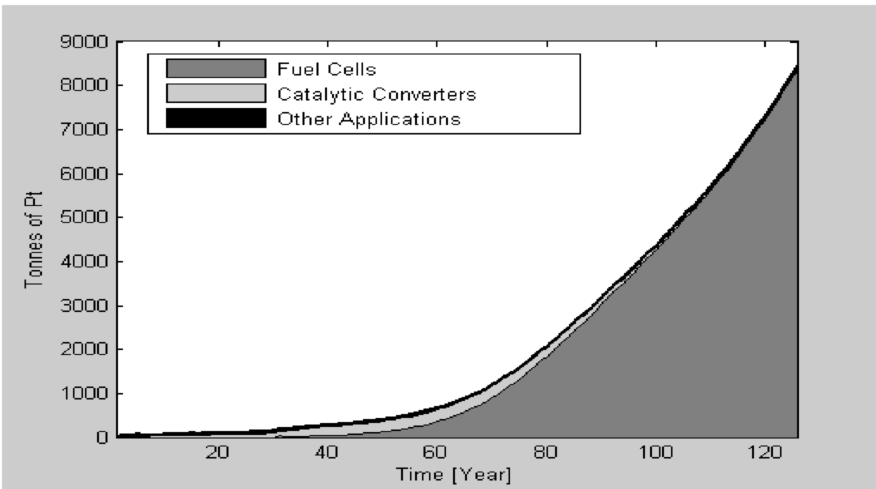

Fig. 6: Total inflow of platinum into the stock-in-use of other applications, catalytic converters and fuel cells

The price of platinum is estimated as a function of platinum demand based on Eq. 19. The parameters a and b of this equation are estimated using regression analysis and their values are 12.1 and 0.942 consecutively. The outcome of the model shows that the increased demand for platinum caused an increase in the price of platinum and consequently a decrease in the demand in some of the other applications.

Platinum stock-in-use

The stock of platinum related to fuel cells, catalytic converters, and the other applications in the economic system is modelled from 1975 through 2100 based on Eq. 1 and shown in figure 7.
The stock-in-use of platinum in fuel cells is increasing over time. For catalytic converters, the stock-in-use is decreasing overtime due to the substitution by fuel cells reaching zero in 2100. The stock of other applications is increasing overtime, although it contributes only little to the total stock of Pt in use. The increase in the stock is mainly due to the increased demand for fuel cell vehicles and the life span of the fuel cell.

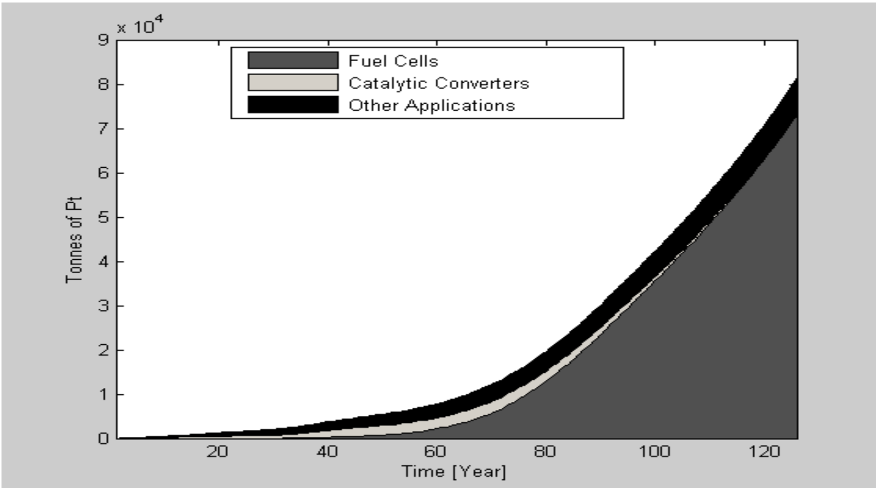

Fig. 7: Worldwide platinum in the stock-in-use of its applications

Platinum losses

The losses of platinum are due to the production of platinum from primary resources, the emissions of platinum during the production and consumption of catalytic converters and the waste management of platinum applications.

The emissions during use of platinum applications are estimated as a fraction of the stock in use as given by Eq. 21. The emission factor for catalytic converters (CC) is estimated using several parameters: the number of vehicles with CC, the average driving distance per vehicle, the emission per km, and the Pt loading. The emission factor is estimated for three countries, and the average is taken in the model. The parameters used in the estimates of the emission factor are listed in table 3a (Kummerer et al., 1999) and the emission factors for the three countries (Germany, Austria and The Netherlands) are listed in table 3b. The emission factors of the consumption of platinum applications and the production of catalytic converter are listed in table 3c. The losses of platinum in the production of platinum from secondary resources are estimated as given by Eq. 36 and the losses of platinum in the primary production are estimated as given by Eq. 41. The losses factors in platinum cycle are listed in table 4a (Hageluken, 2003) and table 4b (Rade et al., 2001). The losses of platinum from 1975 through 2100 are shown in figure 8.

Table 3a: Parameters used in the estimates of the emission factors of catalytic converters*

Parameters	D	A	NL
No of cars with CC	19200000	1607699	3307300
Driving distance (Km/car)	15000	14374	13580
Emissions (µg/Km)	0.65	0.5	0.5
Pt loading in CC (g/CC)	3	3	3

* Kümmerer et al., 1999

Table 3b: Emission factors in some EU countries

Country	Emission factor
D	0.00325
A	0.0024
NL	0.0023
Average	0.00264

Table 3c: Emission factors of the consumption of platinum applications

Application	Emissions
Catalytic converter	0.0023
Electrical and electronic industry	0
Petrochemical industry	0.015
Glass industry	0.01
Others	1.0
Production of catalytic converters	0.01

Table 4a: Losses during the recycling of platinum applications*

Application / processes	Losses %
Fuel cell	
Total recycling	10
Catalytic converter	
Dismantler	50
Collector	6
Decanner	3.2
Refiner	3.3
Chemical industry	
Refiner	6
Electrical and electronic industry	
Collection	50
Mechanical processes	20
Smelter	5
Refiner	1.05
Petroleum industry	
Refining	1.546
Refining	2.5
Glass industry	
Refining of spent GM equipments	1.01

* Hageluken C., 2003

Table 4b: Losses during primary platinum production*

Processes	**Losses %**
Mining	10
Concentrating	10
Smelting	2
Refining	1

* Rade et al., 2001

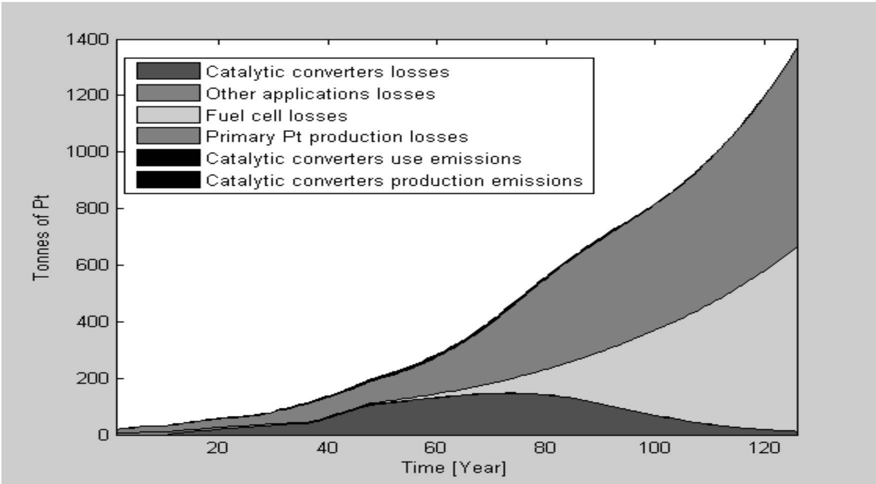

Fig. 8: Losses in platinum cycle

The emissions to the air due to the production and consumption of catalytic converter are small compared to the other losses, however, these emissions are expected to keep increasing till 2043 and decreasing afterwards. This trend is mainly due to the increase platinum content of catalytic converters and the declining market share of catalytic converters. These emissions amount to almost 503 tons in the period till the depletion of platinum resources.
The losses of platinum due to the production of platinum from primary resources constitute the largest source of the losses and are increasing overtime. These losses amount to almost 11337 tons in the period till the depletion of platinum resources. The losses of platinum due to the waste management of catalytic converters are the second largest source. These losses are expected to increasing till 2047 and decreasing afterwards. These losses amount to almost 7044 tons in the period till the depletion of platinum resources. The losses of platinum due to the waste management of fuel cell are the third largest source and also increasing overtime. These losses amount to almost 2358 tons in the period till the depletion of platinum resources. The losses of platinum due to the other applications are decreasing overtime. These losses amount to almost 315 tons in the period till the depletion of platinum resources. The total losses of platinum is 21559 tons which is almost 43% of the total platinum identified resources

8.3.2 Platinum resources and primary and secondary supply

Secondary supply

The possible supply of platinum from secondary resources is estimated based on the discarded platinum applications and the efficiency of the recycling processes. The discarded platinum applications are estimated based on the past inflow and the life span of these applications. The life span of platinum applications is listed in table 5 and the losses of platinum in the recycling processes are listed in table 4. The possible secondary supply of platinum from 1975 through 2100 is shown in figure 9.

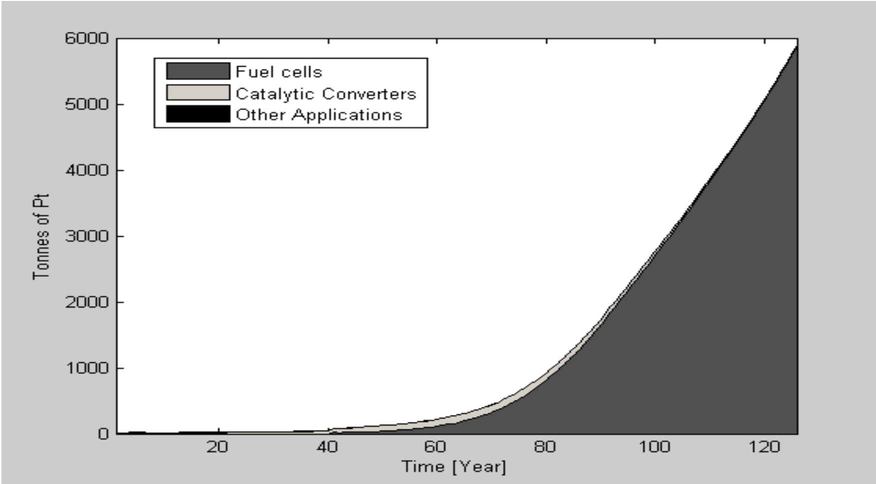

Fig. 9: The possible worldwide supply of platinum from secondary resources

Table 5: Life span of platinum applications

Application	**Life span (years)**
Fuel cell	10
Catalytic converter	10
Electrical and electronics	5

The production of platinum from secondary sources is increasing overtime, however it covers only part of the total demand for platinum. The demand for platinum is increasing at higher speed. The percentage of the total demand for platinum, which is covered by secondary sources, is increasing overtime reaching about 70% at the end of the simulation time and about 55% at the time that platinum resources are depleted. The losses of platinum during the waste management of its application amount to 20% of platinum identified resources. These losses are mainly from catalytic converters and fuel cells. For both, the efficiency of the waste management could be increased.

Primary supply

Primary platinum required is estimated as the different between the total demand for platinum and the possible supply from secondary resources. The total demand for platinum is shown in figure 6, the possible supply from secondary resources is shown in figure 9 and the required primary platinum is shown in figure 10.

The required platinum from primary sources is increasing overtime. This is mainly due to the increase in platinum demand at a higher speed than the increase supply of platinum from secondary sources.

Resources of platinum

At present, the required primary platinum is supplied mainly from South Africa and Russia. Small quantities are supplied from USA, Canada, and other countries. Platinum reserve (Blair, 2001) and identified resources (Vermaak, 1995) and the average supply of platinum of the last 29 years in the producing countries (Johnson Mathey, 2005) are listed in table 6. The total world identified resources of platinum as given by another reference is estimated as 47500 tons (Cawthorn, 1999)

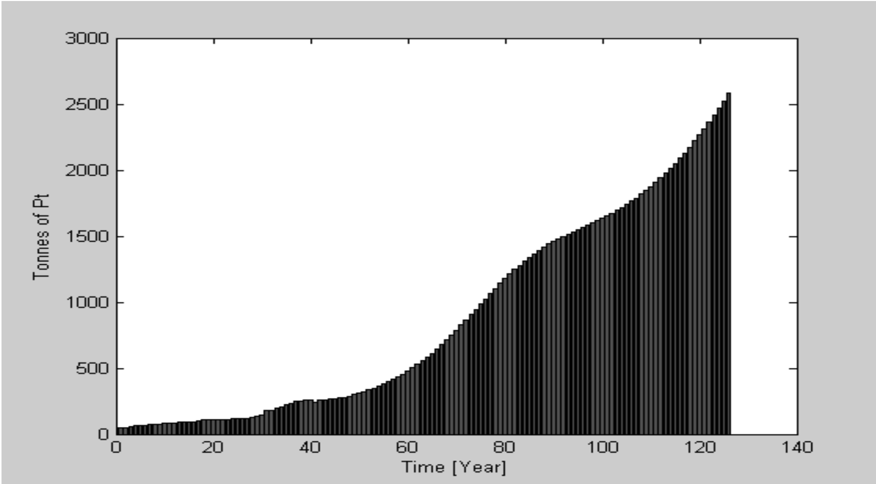

Fig. 10: Platinum required from primary resources

Table 6: Platinum resources and the share in the world supply from different sites

Site	Resources (t0) tones	Reserve (t0) tones[‡]	Supply (%)[†]
RSA	31408	9437	74.95
RUS	3585	1417	17.85
USA & Canada	2027	283	5.3
Other	12287	3939	1.9
Total	49307	14538	100

[*] Vermaak, 1995
[†] www. Platinum.mathey.com
[‡] Brad R. Blair, 2000

Due to the limited reserve and identified resources in the current supplying countries, in the future, the required primary platinum will be supplied mainly from other countries than those of today. The assumption in the model is that once the reserve or the identified resources of platinum is finished (i.e. the stock is reached zero) in a specific country, the model shifts the supply of platinum from this country to the other countries. Platinum current reserve and the identified resources of platinum in the producing countries are shown in figure 11 and 12.

As shown in figures 11 and 12, platinum current reserve will be depleted in three decades and the identified resources will be depleted in 2064. These estimates are based on the first scenario of fuel cell market penetration, progress ratio of 97%, fuel cell life span of 10 years and the losses in the waste management of fuel cell amount to 10 % of the total discarded outflow.

Although the platinum identified resources will be depleted in the world in 2064, a large amount of platinum will be accumulated in the economy by that time.
The model outcomes in terms of resources of platinum and co-produced Ni and Cu are sensitive to several parameters. These are the platinum content of fuel cell, platinum losses during the recycling processes of fuel cell and the fuel cell life span.

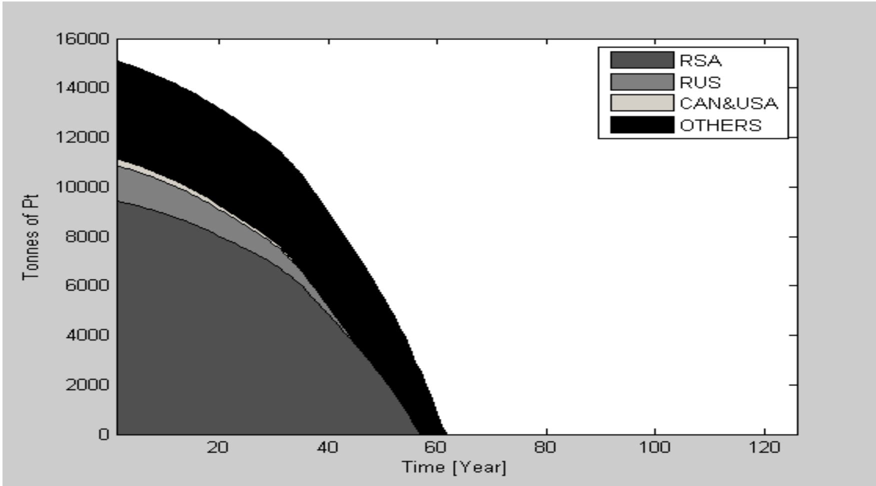

Fig. 11: Platinum current reserve in RSA, RUS, CAN, USA and Other Countries

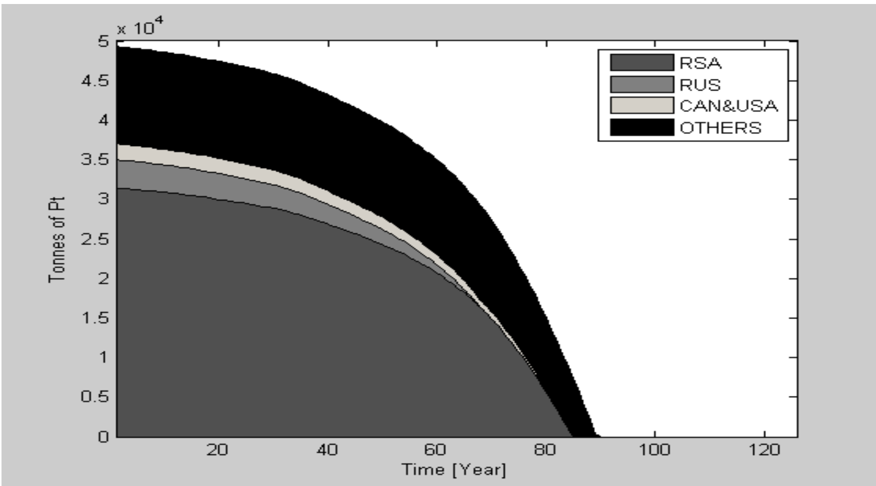

Fig. 12: Platinum identified resources in RSA, RUS, CAN, USA and Other Countries

Table 7 shows the consequences of changing certain parameter on the depletion time of platinum identified resources.

The figures in the table show that the most important factor in determining the future availability of platinum resources are the progress ratio and the life span of fuel cells. The progress ratio influences the platinum content of fuel cell, which could minimize the total demand for platinum. An increase in the progress ratio of 2 % will lead to an increase of 9 years in platinum availability.

The fuel cell life span is an important factor in determining the time required for Pt to be depleted. Longer life span will make platinum available for longer time.

Although the decrease in the losses of platinum during the waste management of fuel cell will lead to an increase in the secondary supply of platinum, this will cover only small part of an increasing demand. Consequently it will increase platinum availability for short time.

Although based on the assumption made platinum will be exhausted in about 60 years from now, there are several possibilities for increasing the time before platinum is depleted.

If the fuel cell system is introduced gradually as it is in the forth scenario and the efficiencies of fuel cell production and waste management are increased (i.e. high progress ratio (increase by 2%) and low losses (decrease by 5%)) combined with an increase in the efficiency of the waste management of catalytic

converters mainly in the Dismantling process (increase by 30%), this will increase the availability of platinum by 13 years.
Moreover, there are other places for improvement such as the losses during the primary production of platinum and the possibility of collecting platinum from soil (Ely et al., 2001).

Table 7: The impact of different parameters on the platinum world identified resources

Fixed Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Progress ratio 97% Life span 10 Recycling losses 10%	2064	2058	2058	2071	2088
	Progress ratio 97%	**Progress ratio 99%**	**Progress ratio 95%**		
Scenario 1 Life span 10 Recycling losses 10%	2064	2055	2067		
	Life span 10	**Life span 5**			
Scenario 1 Progress ratio 97% Recycling losses 10%	2064	2059			
	Recycling losses 10%	**Recycling losses 5%**	**Recycling losses 15%**		
Scenario 1 Progress ratio 97% Life span 10	2064	2065	2063		

8.3.3 Co-production of metals with platinum

The consequences of the introduction of fuel cells are not limited to the resource availability and other environmental impacts related to platinum cycle itself. It also has consequences in terms of the metals that are co-produced with platinum such as Ni and Cu.

The amount of metals co-produced with platinum is estimated based on Eq. 44 and the concentration of each metal in the ore in different producing countries as listed in table 8 (Athaus et al., 2003). The co-produced metals produced from platinum ores in Soth Africa is given in other sources as mining of 1 kg of Pt, yield 0.5 kg of Pd, 0.1 kg of Rh, 300 kg of Ni, and 200 kg of Cu (Pehnt, 2001).

Figure 13 shows the amounts of co-produced copper and nickel from 1975 through 2100 as a result of producing platinum from primary resources, considering the ore composition in the different producing countries.

The next step is comparing this supply with the worldwide demand for copper and nickel. The demand is estimated using different models for those metals. These models estimate the inflow of these metals into the stock-in-use of their applications, the outflow out of the stock through discarded products, and the amount of Cu and Ni available for recycling. The inflow into the stock, or in other words the demand, is modelled based on the socio-economic variables as given by Eqs. 18 and 19. The parameters in these equations are estimated using regression analysis. The analysis is carried out for the inflow from 1975 through 1990 The values of the parameters and strength of these relations are listed in table 9. The outflow of Cu and Ni with discarded products is estimated based on the past inflow and the life span of the metal applications.

Table 8: Metals concentration in different platinum ores

Metal	Merensky RSA	UG2 RSA	Norilsk RUS	Stillwater USA	Sudbury Canada
Nickel (Ni) (%)	0.28	0.16	3.0	< 0.1	1.4-1.5
Copper (Cu) (%)	0.17	0.03	4.0	< 0.1	1.1-1.3
Platinum (Pt) (ppm)	4.82	3.22	2.5	6.0	0.38
Palladium (Pd) (ppm)	2.04	3.24	7.3	20.0	0.39
Rhenium (Rh) (ppm)	0.24	0.54	0.2	0.21	0.03

[*] Athaus et al. 2003.

Table 9: Parameters used in modelling Nickel and Cupper inflows and the goodness of the relations

Metal	A	b	c	d	R^2
Nickel (Ni)	834.34	2.6334	-0.03194	-118.707	0.87
Copper (Cu)	1182.433	3.224	-0.0578	-166.58	0.93

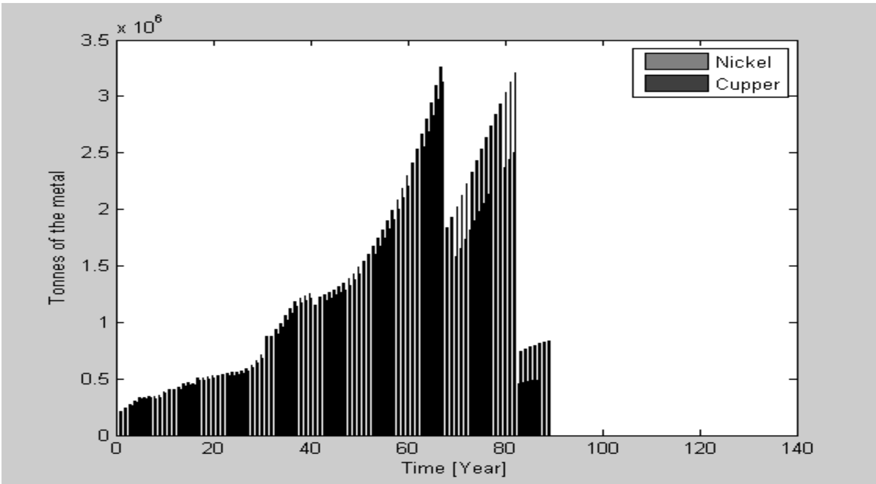

Fig. 13: Worldwide supply of Ni and Cu from Pt ores

The total demand for nickel and the total demand for cupper from 1975 through 2100 are shown in figure 14a and 14b.

The demand for Ni and Cu is compared by the supply of these metals from Pt ores, and the difference is estimated as the required metals from other sources (primary and secondary) from 2000 through 2100 as shown in figures 15a and 15b.

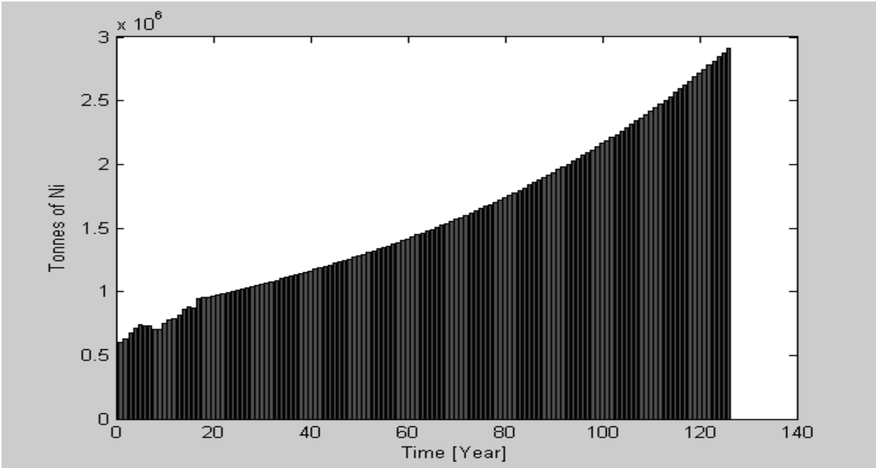

Fig. 14a: Worldwide inflow of Ni into the stock-in-use

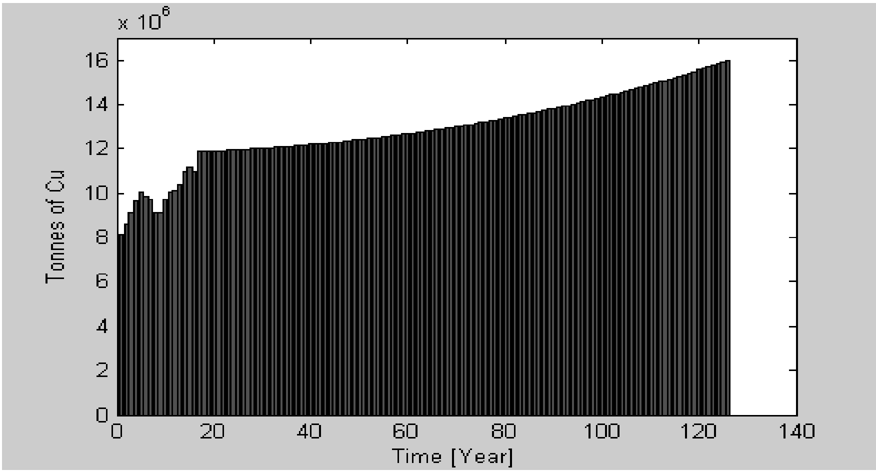

Fig. 14b: Worldwide inflow of Cu into the stock-in-use

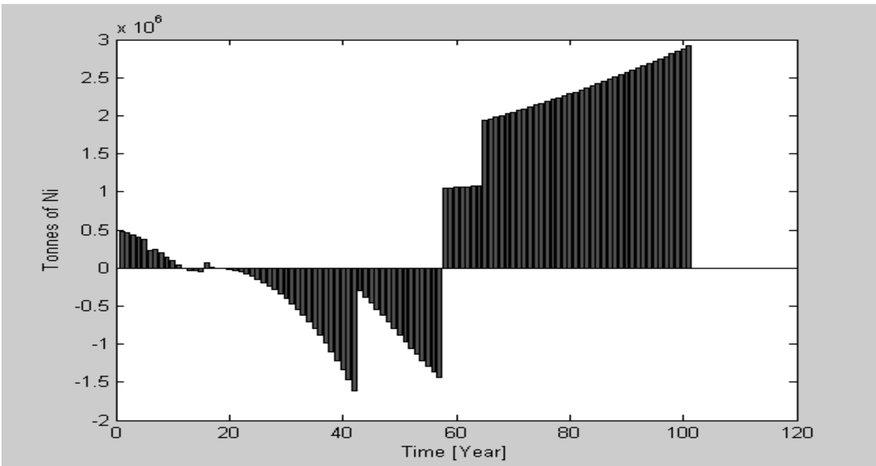

Fig. 15a: Ni required from other sources than those of Pt ores

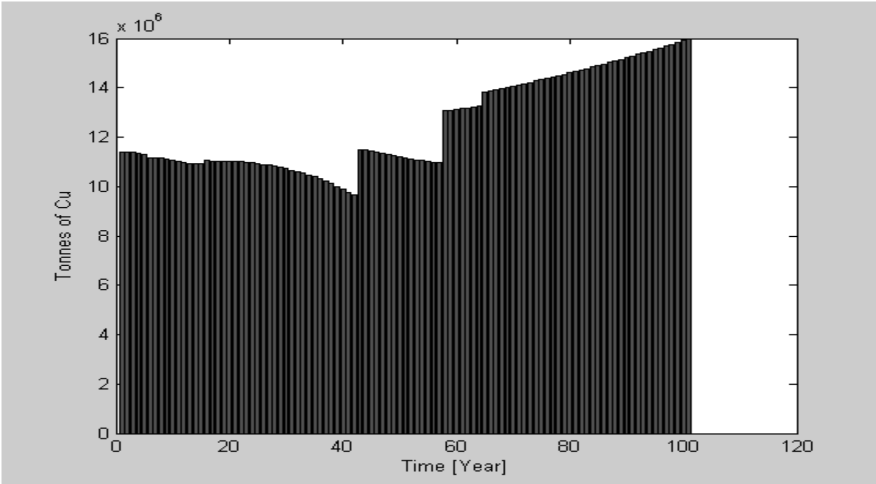

Fig. 15b: Cu required from other sources than those of Pt ores

From these figures, we can see that for nickel, the supply from Pt ores is already quite high compared to the demand, at least until the moment the Pt ores are depleted. For copper, the demand is much higher, therefore the supply from Pt ores only covers a fraction. This implies that for Ni, the production from other sources including secondary sources will hardly be needed. This can have important consequences for both the mining and the recycling sector. The possible supply from secondary resources from 2000 through 2100, shown in figure 16, will not be needed until the moment the supply from Pt ores starts to decline.

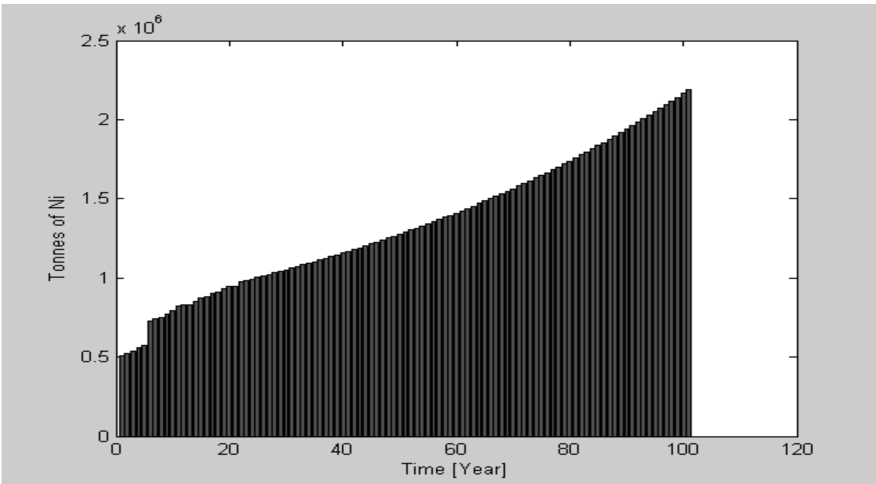

Fig. 16: Worldwide secondary supply of Ni

The required Ni from other sources (primary and secondary) is compared with the possible supply from secondary resources. The results show that there is no need for Ni from primary resources for sometime after the Pt ores are depleted (i.e. secondary supply is enough to cover the demand). This means that if the primary production of Ni will continue after the pt ores are depleted, the recycling of Ni will decline.

8.4 Conclusion

This chapter investigates the potential long-term impact of the increase use of platinum in fuel cell technology and other applications on platinum resources and evaluates the long-term consequences of the increased demand of platinum on the cycles of other co-produced metals especially Ni and Cu.

The model used in the analysis is a dynamic substance flow-stock model for platinum, nickel and copper and implemented in Matlab/SIMULINK environment.

The model estimates the development in platinum resources based on the global demand for platinum, the possible supply of platinum from secondary resources and the availability of platinum as identified resources in different producing countries.

The model estimates the development of the demand for the metals over time based on the development in the socio-economic factors. It estimates the possible supply of the metals from secondary resources based on the past inflow, the metal applications life span and the recycling efficiency. Moreover, it estimates the losses in the metals cycles.

The model shows that platinum resources will be depleted before the end of the century, however, there are a few factors may make platinum resources available for longer time.

The model shows that the most important parameters on the demand side are the efficiency of fuel cell production (indicated by the progress ratio) and the speed of fuel cell market penetration. An increase in the progress ratio of 2 % will lead to an increase of 9 years in platinum availability. This implies it is important to focus on technology development in this area.

The model also shows that the main platinum losses are due to the waste management of fuel cell and catalytic converters and the production of platinum from primary sources and constitute about 43% of the identified platinum resources at the time platinum resources are depleted.

On the supply side, the most important parameters are the efficiency of the waste management of fuel cell, the efficiency of the waste management of catalytic converters and efficiency of the production of platinum from primary sources. Another important factor is the life span of the fuel cell. The longer the life span, the longer platinum would be available.

The model shows that if the fuel cell system is introduced gradually (scenario 4) and the efficiencies of fuel cell production and waste management are increased (progress ratio increased by 2% and the losses decreased by 5%) combined with an increase in the efficiency of the waste management of catalytic converters (dismantling process efficiency increased by 30%), this will lead to an increase in the availability of platinum by 13 years.

Although the parameters in the model are affecting the availability of platinum, this effect is limited. This is mainly due to the growing demand for platinum, which is mainly driven, by the demand for vehicles and fuel cells that are increasing as long as the GDP is increasing.

Moreover, there are other places for improvement such as the losses during the primary production of platinum and the possibility of collecting platinum from soil.

The model also shows that the metals co-produced with platinum will be affected by the increased production of platinum. An increase in platinum production will lead to an increase in the production of co-produced metals. For the copper cycle, this will not have major consequences. Copper demand is very high compared to the supply from this specific source. For nickel, this is different: the supply of the metals from Pt ores exceeds its demand. This will have profound consequences for both mining and recycling of nickel.

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