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An analysis of future platinum resources, emissions and waste streams using a system dynamic model of its intentional and non-intentional flows and stocks

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ABSTRACT

Platinum is increasingly used intentionally and non-intentionally in several applications. This has raised the concern about its future resources, emissions and losses during its life cycle. On the one hand, increasing platinum emissions might affect human health. On the other hand, the accumulated platinum in mineral waste, soil, landfill sites and construction materials as a result of the emissions, losses and the utilization of secondary materials can be seen as potential resources for platinum. This paper is aimed at (1) analyzing the long term impacts of the use of platinum intentionally and non-intentionally on its future demand and supply, release to the environment and accumulation in mineral waste, soil, landfill sites and construction materials and (2) quantifying the amount of platinum in secondary materials that would be available for platinum future supply. The analysis is carried out on a global level using a system dynamic model of platinum intentional and non-intentional flows and stocks. The analysis is based on four scenarios for the introduction of fuel cell vehicles (FCVs). The results show that platinum demand is increasing overtime in all scenarios at different rates and its identified resources are expected to deplete before the end of the century with or without the introduction of FCVs. The release of platinum to the environment and the accumulation in soil are expected to decrease when conventional ICE vehicles is replaced by FCVs. The amount of platinum accumulated in mineral waste, soil, landfill sites and construction materials by the time platinum is depleted are more than double its identified resources and would be potential resources for platinum that are available in different parts of the world. The methodology presented in this paper can be used in the assessment of other technologies and other metals.

Introduction

Metals have been used intentionally in several applications due to their chemical and physical properties. Metals have been also used non-intentionally due to their natural occurrence in mixed primary resources (fossil fuels, other metals ores and phosphate ores) and consequently in secondary material generated through their uses and due to the utilization of secondary materials generated from the processing of their intentional applications waste flows (Elshkaki et al., 2009). Although secondary materials generated from coal-fired power plants, incineration plants, sewage treatment plants and metallurgical industry (fly ash, bottom ash and slag) are used in several applications in the area of construction industry, material recovery and agriculture, the availability of metals non-intentionally may limit their use (Ram and Masto, 2010; Sanchez et al., 2009). On the other hand, the increase generation of secondary material can be seen as a possible solution for the expected shortage in the availability of some metals. Secondary materials contain several metals such as Lead (Pb), Zinc (Zn), Copper (Cu), Germanium (Ge), Gallium (Ga), Nickel (Ni), Platinum (Pt), Vanadium (V) and Indium (In). Some of these metals are considered critical metals (European Commission, 2010) and bottlenecks for strategic energy technologies (Moss et al., 2011). The concentration of some metals in secondary materials is more than their concentration in their mineral resources, which make them potential secondary sources or substitutes for mining ores for these metals (Jung and Osako, 2009; Reijnders, 2005). Several studies reported the possibility of the recovery of metals such as Zn, Pb, Ga, V, Ni and others from fly ash generated from the incineration plants and coal fired power plants (Fang and Gesser, 1996; Izumikawa, 1996; Murase et al., 1998; Nagib and Inoue, 2000; Okada et al., 2007). In 2008, 30% of the global production of Ge originated from leaching fly ash generated from coal fired power plants (Bleiwas, 2010).

The environmental and economic consequences of the non-intentional use of metals have been studied using several

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methodologies such as Substance Flow Analysis (SFA), Life Cycle Assessment (LCA) and the Leaching Test (Kosson et al., 1996; Mroueh et al., 2001; Nunes et al., 1996; Van der Voet et al., 1994). Although, the leaching test can contribute to the study of pollution aspects of the utilization of secondary materials (Gao et al., 2008; Kosson et al., 2002), it is argued by Roth and Eklund (2003) that the leaching tests have to be complemented by the broader system boundary used in SFA and LCA to evaluate the resource and pollution aspects. Moreover, it is argued by Iyer and Scott (2001), that to evaluate the applicability of secondary materials in the current utilization options and the possible new options in the future, a long-term analysis is required.

This paper is aimed at (1) analyzing the long term impacts of the increasing use of platinum intentionally and non-intentionally on its future demand and supply, release to the environment and accumulation in mineral waste, soil, landfill sites and construction materials using a system dynamic model for platinum intentional and non-intentional flows and stocks and (2) quantifying the amount of platinum in secondary materials that would be available for platinum future supply.

General background of platinum

Platinum enters the economic system intentionally through several technologies. It is used in catalytic converters, industrial applications, dental alloys, spark plugs, sensors, turbine blade, medical and biomedical applications and fuel cells. Detailed description of the intentional platinum flows and stocks can be found in Elshkaki and Van der Voet (2006). In addition to its intentional use, platinum enters the economic system non-intentionally through coal used in electricity generation. Several studies have reported the availability of platinum in coal (Kjolholt et al., 2003; Sternbeck and Otlund, 1999). Kemp (1902) reported the results of the analysis of two samples of the ash of Australian coals made by Messrs Thirkell & CO of London who found platinum content per tons of coal is 633 g which makes coal the richest platinum ore yet analyzed. Platinum finds its way into the environment through several routes. The emitted platinum is accumulating in soil since the introduction of catalytic converter. In the future, the accumulated platinum in soil is expected to increase due to the increase use of catalytic converters and the increase of their platinum content (Schafer et al., 1999; Mock and Schmid, 2009). In addition, the emitted platinum to sewage system will end up mainly in sewage sludge, which is either used in soil or landfilled and incinerated. Moreover, the losses of platinum during its production and recycling processes will end up either in landfill sites or in the incineration plants and consequently in the incineration residues (fly ash and bottom ash). Platinum entered the economic system through coal will end up in fly ash and bottom ash and consequently in soil, landfill sites or construction materials. On the one hand, platinum emissions might affect human health (Bencs et al., 2011). The deposited platinum on soil from the emissions during the use of catalytic converter can be transferred to more mobile species through complexation with organic matter, can reach the water bodies and taken up by plants growing on contaminated soil (Ek et al., 2004; Ely et al., 2001). It is reported that a substantial amount of the emitted platinum is bioavailable and was found in the blood, urine and faces and all-important organs (liver, spleen, kidney, adrenals, stomach and femur) (Artelt et al., 1999). On the other hand the accumulated platinum in mineral waste, soil, landfill sites, and construction materials as a result of the emissions, losses and the utilization of secondary materials (fly ash, bottom ash and sewage sludge) can be seen as a potential resource for platinum production.

General description of the model

The model described here is a system dynamic model for platinum intentional and non-intentional flows and stocks. The model is implemented in MATLAB and SIMULINK (Math-Works, 2005) and includes platinum production from primary and secondary resources, platinum intentional and non-intentional applications use and waste management and platinum flows and stocks in the environment. Fig. 1a shows the production of platinum from primary resources, the fabrication and manufacturing of platinum containing products (Fuel Cells (FC), Catalytic Converters (CC), and Other Applications (OA) (chemical, petrochemical, glass, electrical and electronics, jewelry, investment, and others)), the use and waste management of these products and the emissions and losses in platinum cycle. The emissions of platinum refer to the emissions during the production and use of CC and the use of OA. The losses of platinum refer to the losses during the primary production (mining, concentration, smelting, base metal separation, and refining) and the waste management of all platinum applications. Fig. 1b shows platinum non-intentional and environmental flows and stocks. The demand in the model is the global demand for platinum. The primary supply of platinum is covered by four sources; Republic of South Africa (RSA), Russia (RUS), United States and Canada (USA and CAN), and Other Countries. Secondary supply of platinum is the global supply. For the production of platinum from secondary resources, the European data are used.

Platinum demand

The inflow of platinum into the stock-in-use is the amount of platinum used in CC, FC and OA. The inflow of platinum into the stock-in-use of FC is modeled based on the demand for vehicles, the share of Fuel Cell Vehicles (FCVs) and platinum content of FC. The demand for vehicles is modeled based on socio-economic variables. In the model, FCVs is introduced in 2005. FCVs market share is modeled based on four scenarios using a formula which produces a market share of 50%, 20%, 13% and 0% by the year 2050 and reaching 100%, 90%, 50% and 0% by the year 2100 in the four scenario (Fig. 2). Platinum content of FC is modeled based on the learning curve concept. The learning curve (Tsuchiya and Kobayashi, 2004) is adapted for the possible reduction in platinum loading. The initial platinum content is set to 60 g, based on TIAX LLC (2003), decreasing as the cumulated production increasing reaching 20 g as a minimum value that makes recycling possible. The progress ratio is set to 97%. The inflow of platinum into the stock-in-use of CC is modeled based on the demand for vehicles, FCVs market share, CC market share and the platinum content of CC. The CC of ICE vehicles contains between 2 g and 4 g of platinum (Sun et al., 2011). In the model, the initial platinum content of CC is set to 2 g, increasing overtime to reach 4 g and stabilizing thereafter. The inflows of platinum into the stock-in-use of OA are modeled based on socio-economic variables, metal price and time. The socio-economic variables GDP, per capita GDP, and population size constitute exogenous variables and the price is an endogenous variable. For detailed description of the estimates of the demand for platinum see Elshkaki and Van der Voet (2006).

Platinum supply from secondary and primary resources

The supply of platinum from secondary resources is estimated as the difference between the amount of platinum in the discarded outflow from the stock-in-use and the losses in the waste management phase. The discarded outflow is estimated as a delayed inflow, corrected for the emissions that have taken place during use (Elshkaki et al., 2004). The emissions of platinum during the use phase of its applications are estimated as a fraction of the stock