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Life Cycle Benefits of Using Nanotechnology To Stabilize Platinum-Group Metal Particles in Automotive Catalysts

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Due to advances in nanotechnology, the approach to catalytic design is transitioning from trial-and-error to planned design and control. Expected advances should enable the design and construction of catalysts to increase reaction speed, yield, and catalyst durability while also reducing active species loading levels. Nanofabrication techniques enabling precise control over the shape, size, and position of nanoscale platinum-group metal (PGM) particles in automotive catalysts should result in reduced PGM loading levels. These reductions would decrease energy consumption, improve environmental quality, and contribute to sustainable resource usage. We estimate the amount of PGM required to meet U.S. vehicle emissions standards through 2030 based on current catalyst technology. We then estimate the range of PGM that could be saved from potential nanotechnology advances. Finally, we employ economic input–output and process-based life cycle assessment models to estimate the direct and life cycle benefits from reducing PGM mining and refining.

Introduction

Nanotechnology is the manipulation of atoms, molecules, and materials with at least one dimension between 1 and 100 nm. Control at the nanoscale offers opportunities to use materials and energy more efficiently and reduce waste and pollution. Federal investment in nanoscale science, engineering, and technology has increased from $270 million in 2000 to nearly $1 billion requested for fiscal year 2005 (*1*). At the same time, recent studies provide preliminary evidence that some manufactured nanoparticles may be harmful to living organisms (*2–6*). Efforts have been initiated to develop a fundamental understanding of the behavior of nanomaterials in natural systems and their influence on biological systems. This understanding will improve the ability to project the direct environmental and health effects of nanomaterials. To obtain a complete picture, it is also necessary to consider life cycle implications of nanotechnology-based products. For example, we used life cycle assessment (LCA) to estimate the potential environmental implications from substituting a nanocomposite for steel in automobile body panels (*7*). Similar detailed analyses are needed to understand the specific implications of forthcoming nanotechnology-based products and processes.

Catalysts containing nanometer-dimensioned particles were one of the first nanotechnologies (*8*). Nanoscale platinum-group metal (PGM) particles are widely used in industrial and automotive catalysts. The PGM elements—iridium, osmium, palladium, platinum, rhodium, and ruthenium—have high corrosion resistance, are stable to oxidation at high temperatures, have exceptional catalytic properties, and are extremely rare. Complex extraction and refining processes are required for their use. While South Africa and Russia supply roughly 90% of global PGM, North America, Europe, and Japan consume roughly 80%. Automotive pollution control catalysts employ a combination of platinum (Pt), palladium (Pd), and rhodium (Rh) to oxidize carbon monoxide (CO) and hydrocarbons (HC) to carbon dioxide and water and to reduce oxides of nitrogen (NO_x) to N_2. There are currently no acceptable substitutes for PGM in this application, which accounts for roughly 50% of the global PGM (Pt, Pd, and Rh) demand. Furthermore, new emissions standards around the globe, including three new U.S. emission standard programs scheduled to be phased-in between 2004 and 2014 and an expected surge in vehicle demand in developing countries could increase this market 3-fold (*9*).

In automotive catalysts, CO, HC, and NO_x emissions are abated by oxidation and reduction reactions occurring on the surface of PGM particles. To increase the amount of PGM surface area exposed to vehicle exhaust, PGM particles are dispersed on high surface area particles such as aluminum oxide. This washcoat is then applied to a high surface area ceramic or metallic support. The resulting ratio of PGM surface atoms to total PGM atoms is termed metal dispersion. A General Motors' test on a commercial automotive catalyst found metal dispersion to be approximately 50% in the new catalyst, below 10% in 10 000 mi, and below 5% in 25 000 mi (*10*). This indicates that only 50% of PGM atoms in a new catalyst are exposed to a vehicle's exhaust with current technology; metal dispersion deteriorates rapidly during vehicle use, primarily due to particle sintering and agglomeration from exposure to high temperatures and vehicle vibration; and current emission standards are met with 5% of PGM participating in catalytic reactions during 80% of a vehicle's life. Assuming that PGM dispersion is correlated with required loading levels, manufactures could meet emissions standards with 5% of current PGM loading levels by overcoming current design, manufacturing, and system inefficiencies.

While conventional catalyst design relies on rational planning and lengthy trial-and-error testing, advances in nanotechnology are expected to offer increased understanding of and control over catalyst design and performance (*8*, *11*, *12*). The ability to control the size, shape, and placement of PGM particles would improve metal dispersion in new catalysts. Furthermore, the ability to securely anchor particles to the substrate would aid in maintaining high metal dispersion during vehicle use. As indicated above, such technological advances could reduce loading levels by as much as 95%.

Modeling PGM Usage

Baseline Loading Levels. PGM loading levels vary considerably by manufacturer, vehicle type, model year, and motor vehicle destination. Current and projected PGM loading levels

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TABLE 1. Estimated Average PGM Loading Level per Vehicle for Compliant Vehicles Sold in the United States

vehicle category	baseline	new emissions standards				
	loading level (Pt:Pd:Rh g/vehicle)					
LDV		**2004**	**2006**	**2008**		
LDV	1.1:5.3:0.5	1.1:5.3:0.6	1.1:5.3:0.6	1.1:5.3:0.6		
LDT1	1.1:5.4:0.5	1.1:5.4:0.5	1.1:5.4:0.6	1.1:5.4:0.6		
LDT2	1.4:7.0:0.7	1.4:7.0:0.7	1.4:7.0:0.8	1.4:7.0:0.8		
LDT3	2.1:10.1:1.0	2.1:10.1:1.0	2.2:10.6:1.2	2.2:10.6:1.2		
LDT4/MDPV	2.2:10.5:1.0	2.2:10.5:1.0	2.2:10.5:1.0	2.3:11.2:1.3		
HDDE		**2007**	**2009**	**2011**		
light	2.4:2.4:0.0	27.3:2.4:1.6	22.4:2.4:1.3	18.4:2.4:1.0		
medium	3.2:3.2:0.0	36.4:3.2:2.1	29.8:3.2:1.7	24.5:3.2:1.4		
heavy	5.2:5.2:0.0	60.5:5.2:3.5	49.4:5.2:2.8	40.6:5.2:2.3		
bus	3.6:3.6:0.0	51.6:0.0:3.5	40.6:0.0:2.8	31.7:0.0:2.3		
HDGV		**2005**	**2008**			
complete, standard	0.0:9.2:0.9	0.0:17.5:1.7	0.0:22.8:1.6			
complete, large	0.0:11.1:1.1	0.0:21.1:2.1	0.0:28.0:2.0			
engine, standard	0.0:9.2:0.9	0.0:19.6:2.0	0.0:22.8:1.6			
engine, large	0.0:11.1:1.1	0.0:23.7:2.4	0.0:28.0:2.0			
Nonroad		**2008**	**2011**	**2012**	**2013**	**2014**
0 < hp < 25	0.0:0.0:0.0	0.1:0.0:0.0	0.1:0.0:0.0	0.1:0.0:0.0	0.1:0.0:0.0	0.1:0.0:0.0
25 ≤ hp < 50	0.0:0.0:0.0	2.9:0.0:0.0	2.9:0.0:0.0	2.9:0.0:0.0	2.4:0.0:0.0	2.4:0.0:0.0
50 ≤ hp < 75	0.0:0.0:0.0	4.6:0.0:0.0	4.6:0.0:0.0	4.6:0.0:0.0	3.8:0.0:0.0	3.8:0.0:0.0
75 ≤ hp < 100	0.0:0.0:0.0	0.0:0.0:0.0	0.0:0.0:0.0	16.1:0.0:1.0	16.1:0.0:1.0	13.0:0.0:0.8
100 ≤ hp < 175	0.0:0.0:0.0	0.0:0.0:0.0	0.0:0.0:0.0	20.4:0.0:1.3	20.4:0.0:1.3	16.5:0.0:1.0
175 ≤ hp < 300	0.0:0.0:0.0	0.0:0.0:0.0	32.3:0.0:2.1	32.3:0.0:2.1	26.1:0.0:1.6	26.1:0.0:1.6
300 ≤ hp < 600	0.0:0.0:0.0	0.0:0.0:0.0	44.6:0.0:2.8	44.6:0.0:2.8	36.1:0.0:2.3	36.1:0.0:2.3
600 ≤ hp ≤ 750	0.0:0.0:0.0	0.0:0.0:0.0	90.7:0.0:5.8	90.7:0.0:5.8	73.3:0.0:4.6	73.3:0.0:4.6
750 < hp	0.0:0.0:0.0	0.0:0.0:0.0	174:0.0:11.1	174:0.0:11.1	141:0.0:8.9	141:0.0:8.9

TABLE 2. Characteristics Used To Estimate Average PGM Loading Levels for Light-Duty Vehicles

engine type	catalyst vol[a] (L) LDV	catalyst vol[a] (L) LTD	vehicle sales[a] (%) LDV	LDT1	LDT2	LDT3	LDT4/MDPV
4-cylinder	1.8	2.3	53.0	65.9	2.3	0.0	0.0
6-cylinder	2.8	2.6	39.0	34.1	73.7	10.1	0.0
8-cylinder	4.0	4.7	8.0	0.0	24.0	89.9	87.0
8/10-cylinder	na	4.7	0.0	0.0	0.0	0.0	13.0

catalyst type	loading ratio	loading density (g/l)	vehicle sales (%)
Pt/Pd/Rh	1:14:1	3.3	30
Pt/Rh	5:1	1.6	30
Pd/Rh	14:1	3.6	30
Pd-only	na	3.7	10

[a] Ref *13*.

and catalyst technology are closely guarded by the industry. Therefore, we estimate average 2003 baseline loading levels for each motor vehicle class, as described below. These estimates are summarized in the second column of Table 1.

(i) For light-duty vehicles (LDV), the U.S. Environmental Protection Agency (EPA) estimated sales-weighted baseline catalyst volumes (*13*). However, PGM loading densities were not provided. We conducted a survey of the automotive catalyst literature, compiled an inventory of catalyst characteristics, and estimated average PGM loading ratios, loading densities, and sales percentages for the major catalyst types, summarized in Table 2. From these estimates and EPA sales-weighted catalyst volumes, we calculate baseline loading estimates.

(ii) For heavy-duty diesel engines (HDDE), the EPA estimated incremental costs required for transitioning from 1998 model year oxidation catalysts to advanced oxidation catalysts based on expected catalyst volumes, a PGM loading density of 1.4 g/L, and an even mix of Pt and Pd (*14*). However, the EPA projected that advanced catalysts would not be required to comply with 2004 standards. From the above information, we estimated PGM loading levels for advanced oxidation catalysts. We then back-calculated loading levels for 1998 model year catalysts by assuming that incremental PGM loading levels are proportional to incremental costs. We use the resulting estimates as a baseline for HDDEs.

(iii) For heavy-duty gasoline vehicles (HDGV), the EPA estimated the cost of PGM in current catalyst systems and estimated a 60% single underfloor and 40% dual underfloor catalyst system technology mix (*15*). We used this information to estimate baseline PGM loading levels for HDGVs.

(iv) Current nonroad diesel engines (such as agricultural, construction, industrial, and lawn and garden equipment) do not utilize exhaust aftertreatment devices and employ particulate filters on a limited basis. Therefore, we assumed no PGM usage in the baseline case.

While it is difficult to measure how well baseline loading estimates represent catalysts used in current vehicles, it is possible to verify aggregate PGM usage. Using our baseline loading estimates, 137 thousand kg of PGM would have been required for motor vehicles sold in the United States in 2003. In recent years, Johnson Matthey's estimates of North American PGM demand for automotive catalysts have been as high as 130 thousand kg (*16*). We expect PGM usage for vehicles sold in the United States to be higher than North American demand for several reasons. First, roughly 85% of vehicles produced in North America are sold in the United States (*17*, *18*). These vehicles incorporate more than 85% of North American PGM demand since emission standards in Mexico are not as stringent as those in the United States or Canada, where standards generally match those in the United States. Second, 16% of vehicles sold in the United States are manufactured outside of North America (*17*, *18*). The PGM in these vehicles would not be captured in the North American PGM demand estimate.

Increased Loading Levels for New Emissions Standards. Three new EPA programs setting more stringent emissions standards for passenger cars, light-duty trucks, medium-duty passenger vehicles, heavy-duty trucks, and nonroad diesels in conjunction with tighter gasoline sulfur standards are scheduled to be phased-in between 2004 and 2014. Manufacturers are expected to employ higher PGM levels in catalysts to meet the tighter standards (*13*, *19*, *20*). We use information from the EPA's Regulatory Impact Analyses (RIA) to estimate loading level estimates for compliant vehicles as described below. The average PGM loading level estimates for compliant vehicles are summarized in Table 1.

(i) The Tier 2 light-duty highway rule sets more stringent particulate matter (PM) standards and a corporate average NO_x standard of 0.7 g/mi. Manufacturers are expected to meet Tier 2 standards by refining and optimizing current emissions control technologies. The EPA estimated the incremental PGM loading level for each LDV class (*13*). We added these values to our baseline estimates.

(ii) The 2007 heavy-duty (2007HD) highway rule is the final phase of a comprehensive program for controlling heavy-duty vehicle emissions. To meet 2007HD diesel standards, manufacturers are expected to use integrated systems comprising NO_x adsorber catalysts, catalyzed diesel particulate filters, and diesel oxidation catalysts. The EPA estimated new technology costs and applied a 20% learning curve, including a 20% reduction in PGM use, at the beginning of the 2009 and 2011 model year (*19*). We estimated HDDE loading levels based on the EPA's cost, catalyst volume, PGM ratios, and content per volume estimates.

(iii) To meet 2007HD gasoline standards, manufacturers are expected to increase the use of dual underfloor and dual close-coupled catalyst configurations and increase PGM content. The EPA estimated PGM loading levels based on the expected technology mix (*19*). We use these loading level estimates for compliant HDGVs.

(iv) The EPA has proposed new standards for reducing emissions from mobile nonroad diesel engines. Manufacturers are expected to employ NO_x adsorbers, diesel oxidation catalysts, and catalyzed diesel particulate filters to meet the proposed standards. The EPA developed a set of equations based on engine displacement, number of cylinders, and future learning effects to estimate a unique technology package and cost for each of the over 7000 pieces of nonroad equipment in the 2000 model year Power Systems Research (PSR) database (*20*). Since the PSR database is proprietary, we employed the EPA's equations using sales-weighted data provided for nine horsepower categories to estimate future PGM loading levels (*21*).

PGM Savings from Nanotechnology. Exhaust catalyst performance is a complex function of many design parameters, location in the exhaust system, operating conditions, and exhaust composition. Nanotechnology research continues to improve understanding of the behavior and structure sensitivity of nanoscale particles in catalytic reactions. As this understanding matures, it will improve the ability to predict optimal atomic structure and arrangement of metal particles in supported catalysts. Precise fabrication techniques will then be required to produce highly efficient and stable catalysts. The level of atomic control achieved by future catalyst synthesis techniques and the level of stability once exposed to the operating environment are highly uncertain.

Rather than attempt to predict the structure and composition of future exhaust catalysts, we provide a first approximation of maximum possible reductions in PGM loading levels. We suggest, as an upper bound, that loading levels from current technology could be reduced by 95%, as discussed in the Introduction. This assumes an optimal atomic structure and arrangement resulting in complete dispersion and eliminating all sintering, agglomeration, and other deactivation during vehicle use. Current nanotechnology-based research has suggested similar potential loading level reductions. For example, Nishihata et al. (*22*) reported a method for uniformly placing palladium ions in a perovskite crystal structure. The Pd-perovskite-based catalysts retained palladium particle dispersion substantially better than a conventional Pd/alumina catalyst. Successful production of such catalysts could reduce PGM loading levels by 70−90% (*23*). Savings projected from this particular nanotechnology-based catalyst are lower than the 95% savings we use to show the maximum potential savings.

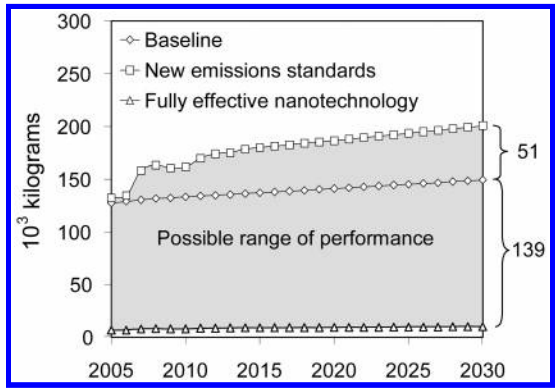

FIGURE 1. Estimated annual PGM requirement for vehicles sold in the United States (excluding California). Data points represent expected PGM demand for meeting current emissions standards using baseline loading levels, meeting new emissions standards with current technology, and meeting new emission standards with a fully effective deployment of nanotechnology.

PGM Required for U.S. Vehicle Fleet. We model U.S. PGM requirements using loading level estimates defined above and projected motor vehicle sales from the EPA's regulatory impact analyses (*13*, *19*, *20*). California sales are excluded since they are subject to separate regulations. Figure 1 shows estimated annual PGM requirements for each loading level scenario. We model all results through 2030 to parallel the time horizon of the EPA's Regulatory Impact Analyses of the emissions standards programs (*13*, *19*, *20*).

The "baseline" scenario shows expected annual PGM requirement for meeting current emissions standards using baseline loading estimates. PGM requirements increase with increased motor vehicle sales. The "new emissions standards" scenario shows expected annual PGM requirements for meeting new standards using current technology according to the scheduled phase-in of these programs (*13*, *19*, *20*). PGM requirements increase substantially through 2008 to meet tighter emissions standards, drop slightly between 2009 and 2011 due to learning effects for the diesel vehicle classes, and increase thereafter with increased motor vehicle sales. Compared to the baseline scenario, an additional 51 thousand kg of PGM would be required in 2030 to meet tighter emissions standards. The "fully effective nanotechnology" scenario applies a 95% reduction over loading levels used in the new emissions standards scenario. Compared to the baseline scenario, an annual PGM savings of 139 thousand kg would be realized in 2030 while still meeting tighter standards. Since this scenario includes reductions resulting from both nanotechnology and learning effects, we also estimated annual PGM requirements with learning effects removed. The resulting PGM requirement estimates were only slightly higher and are not considered in this analysis.

While the baseline and new emissions standards scenarios provide expected PGM usage for specified emissions standards and technology, the nanotechnology scenario provides the maximum possible performance improvement for a fully effective deployment of nanotechnology. Since catalyst technology will improve over time, the new standards scenario is viewed as a lower performance bound. Since a fully effective deployment is unlikely to be realized, the nanotechnology scenario is viewed as an upper performance bound. Hence, the new standards and nanotechnology scenarios show an inclusive range of possible performance for any given year, shown in Figure 1. Achieving and maintaining complete PGM dispersion in automotive catalysts, hence realizing the full 95% reduction is unlikely. As indicated by Nishihata et al. (*22*), a 70−90% reduction may be more realistic. Furthermore, advances in catalyst technology will occur incrementally rather than in a radical improvement and will likely result from both nanotechnology and other technologies. Since all environmental inventories presented hereafter assume a linear relationship with material usage, PGM requirements and environmental performance for PGM loading reductions less than 95% can be estimated by interpolating between the new emissions standards scenario (0% PGM reduction) and the fully effective nanotechnology scenario (95% PGM reduction).

Recycled PGM Usage. Environmental burdens from recycling PGM are different than those from producing virgin PGM. Retired automobiles are the primary source of secondary PGM for automotive catalysts. Secondary PGM availability depends on the number, type, and age of retired vehicles, PGM loss during vehicle use, and the percentage of PGM that can be recovered from retired catalysts. The economic viability of recycling available PGM, however, has been limited by the complexity involved in establishing a systematic method for collecting catalysts and the amount of labor required to recover PGM.

For the baseline and new standards scenarios, we estimate expected virgin and recycled PGM usage based on historical recycling practices. To estimate historical secondary PGM availability, we used reported 30-yr vehicle survival rates and annual vehicle miles traveled (VMT) estimates to model the number and type of vehicles retired each year and catalyst age at retirement (*15*, *24−26*); developed a general loss function to estimate material loss during vehicle use (Supporting Information, Section 10); and applied a 95% recovery efficiency for Pt and Pd and 80% for Rh (*27*). We estimate historical rates of recycling available secondary PGM by comparing modeled availability estimates from 1990 through 2003 to Johnson Matthey's recycled PGM usage estimates for North America (*16*). We estimate average secondary recycling rates of 54.2% for Pt, 60.8% for Pd, and 39.9% for Rh.

While recycling is influenced by many factors, such as market price, recovery capacity, and amount of PGM in catalysts, we estimate future recycled PGM usage by assuming constant rates of recycling available secondary PGM. We modeled secondary PGM availability for the baseline and new standard scenarios as defined above and applied the historical recycling rates through 2030. Nonroad vehicles have a longer life expectancy than light-duty and heavy-duty vehicles. We calculated and used 50-yr survival rates from average activity, life, and load data provided by the EPA for each nonroad vehicle class (*21*). Figure 2 shows expected annual virgin and recycled PGM usage. In 2005, recovered PGM is expected to meet 18% of total PGM requirements in the baseline scenario and 17% in the new standards scenario. This is comparable to Johnson Matthey's estimate that secondary PGM makes up approximately 16% of PGM used in current automotive catalysts (*16*). In 2030, these percentages increase to 50% and 45%, respectively. The increase in recycled to virgin PGM usage in our model is driven by increased secondary PGM availability. PGM loading levels have increased over the last three decades. As vehicles with higher loading levels are retired, more secondary PGM will become available. Recycling the same percentage of available secondary PGM will result in more recycled PGM. Figure 2 also shows the amount of available secondary PGM not expected to be recovered in each scenario.

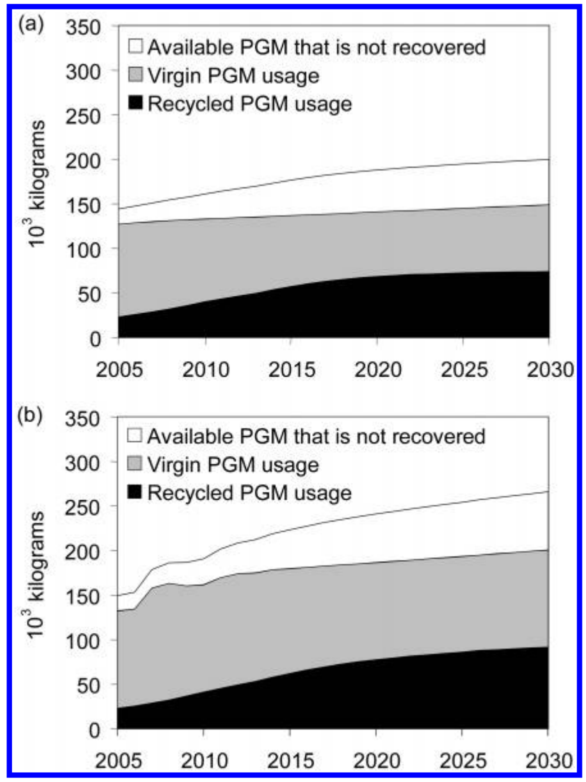

FIGURE 2. Modeled virgin and recycled PGM usage for vehicles sold in the United States for (a) meeting current emission standards with baseline loading levels and (b) meeting new emissions standards using current technology.

It is impractical to estimate expected recycled PGM usage in the nanotechnology scenario since it estimates maximum possible PGM savings rather than expected usage over time. Realistically, performance improvements would take a long time to be realized and would occur incrementally rather than in a radical performance leap. Furthermore, such low PGM content in catalysts may deem recovery impractical. We maintain an upper bound performance estimate by assuming complete virgin PGM usage in the nanotechnology scenario. Whether or not this is practical depends on when and to what extent performance improvements are realized.

Life Cycle Assessment Models

The industrial ecology of nanotechnology must include an analysis of environmental effects associated with the full life cycle of a commercialized product or process. This includes extraction of raw materials, production, use, and end-of-life. A number of life cycle assessment (LCA) models, each having unique strengths and limitations, have been developed to estimate resource consumption and environmental burdens associated with a product, process, or activity. Uncertainty in deterministic LCA models is caused by systematic modeling errors, input parameter estimation, and scenario framing (*28−31*). Multiple LCA models can be employed to help characterize the uncertainty. We employ input−output and process-based models to estimate the direct and life cycle effects from producing PGM for the U.S. vehicle fleet and discuss the limitations of each model.

EIO-LCA Model. The Economic Input−Output Life Cycle Assessment (EIO-LCA) model developed at Carnegie Mellon University uses public data sets to calculate the economic

TABLE 3. Expected Change in Life Cycle Effects from Changes in PGM Usage (EIO-LCA)

	meeting new standards with current technology		fully effective deployment of nanotechnology	
	2005	2030	2005	2030
Inputs				
energy used (TJ)	1020	12 700	−19 300	−22 100
fuels used (TJ)	910	11 300	−17 200	−19 600
electricity used (MkWh)	101	1 260	−1 910	−2 180
Outputs				
conventional pollutants (million kg)	2.66	33.2	−50.3	−57.5
greenhouse gases (million kg CO_2 equiv)	93.9	1 170	−1 770	−2 030
hazardous waste generated (RCRA, million kg)	28.2	351	−532	−608
toxic releases and transfers (million kg)	4.03	50.2	−76.1	−86.9

and environmental effects across the entire supply chain for purchases in any commodity sector of the U.S. economy (*32*−*34*). In particular, the model calculates the direct and life cycle implications for economic purchases, emissions of conventional pollutants and greenhouse gases, energy inputs, RCRA hazardous waste, and toxic releases. Here, we use the EIO-LCA model based on the U.S. Department of Commerce 1997 Industry Benchmark input−output model of the U.S. economy. Within this model, we use the "Primary nonferrous metals, except copper and aluminum" sector (sector 331419), which includes primary PGM refining.

For each year, we estimate economic activity associated with purchasing PGM for motor vehicles. We use the 1997 average market price for Pd (\$5.92/g) (*35*). To adjust for high price volatility, we use the average 1997 adjusted market price from 1992 through 2002 for Pt (\$13.85/g) and Rh (\$32.97/g) (*35*). We assume that recycled and virgin PGM prices are equal under current market conditions (*36*). This implies that aggregate implications of purchasing virgin and recycled PGM are the same. We input total PGM purchases for each scenario into the primary nonferrous metals sector to estimate expected energy use and environmental burden.

GaBi Software. The GaBi software system developed by the University of Stuttgart in cooperation with PE Product Engineering GmbH is a process-based, ISO/SETAC-style LCA model (*37*−*39*). A noble metal extension database for the current version, GaBi 4, includes life cycle inventories for producing virgin Pt, Pd, and Rh. These "cradle to gate" inventories estimate total required inputs and resulting environmental burdens from mining through obtaining pure metal. The data sets were compiled based on input from industry, technical and patent literature, and other sources (*40*).

GaBi's noble metal database does not provide inventories for recycled PGM. However, Amatayaku's recent life cycle assessment of catalytic converters complied data for several environmental effects associated with producing both virgin and recycled PGM (*41*). Amatayaku obtained process information from a primary producer of PGM in South Africa and used economic information to allocate environmental effects to Pt, Pd, and Rh. The most complete inventory was compiled for energy use, indicating that 93% less energy is required to produce recycled PGM (93.8% less for Pt, 83.1% less for Pd, and 94.1% less for Rh.) Due to a lack of data for other inputs or environmental burdens, we apply the energy-specific comparison across the GaBi inventory to estimate effects from using recycled PGM.

Sources of Uncertainty in LCA Models. There are several important limitations associated with using the EIO-LCA and GaBi models for estimating life cycle environmental effects in this study:

(i) There is more value in ore than PGM. Some of the inputs and outputs, such as those associated with magnetic separation, are related only to the production of PGM. However, others, such as upstream mining and benification, are used primarily to produce other nonferrous metals such as copper, lead, zinc, and nickel. EIO-LCA derives allocation based on price and thus makes no material flow allocations. GaBi performs an allocation to split the efforts/burdens on the main products and coproducts (PGMs).

(ii) EIO-LCA does not distinguish between different grades or types of materials produced in the same sector. For example, the actual supply chain implications associated with refining virgin PGM may be substantially different than refining an equal value of secondary PGM or silver. However, all three are included in sector 331419.

(iii) While EIO-LCA is specific to economic transactions made in the United States, less than 5% of the world's PGM production occurs in the United States (*42*). Using the model implicitly assumes that implications associated with mining and refining operations in other countries are the same as those in the United States.

(iv) Process-based LCA models, such as GaBi, do not capture all supply chain effects and thus tend to underestimate production effects.

(v) Both models assume a linear relationship between environmental effects and amount of PGM purchased or produced.

(vi) The inventories generated from both models are based on current technology.

Summary of Inputs and Environmental Burdens

We input expected PGM requirements for each scenario into both LCA models to estimate annual life cycle effects associated with mining and refining virgin PGM and recovering and refining secondary PGM for vehicles sold in the United States. We assume effects occur in the same year vehicles are sold. We estimate expected changes in each effect from meeting new standards with current technology and with a fully effective deployment of nanotechnology by calculating the difference between each of these scenarios and the baseline scenario. Table 3 summarizes expected changes for 2005 and 2030 using the EIO-LCA model. Table 4 summarizes expected changes using the GaBi model. A negative result indicates a reduced environmental effect. For example, producing additional PGM to meet new emissions standards with current technology would require an additional 12 700 TJ (EIO-LCA) or 13 700 TJ (GaBi) of energy in 2030. However, a fully effective deployment of nanotechnology would enable manufacturers to meet new standards using less PGM, saving 22 100 TJ (EIO-LCA) or 19 300 TJ (GaBi) of energy in 2030.

Expected reductions from a fully effective deployment of nanotechnology are lower in 2030 than in 2005 using GaBi. This occurs because our baseline scenario employs a higher percentage of recycled PGM usage as more becomes available

TABLE 4. Expected Change in Life Cycle Effects from Changes in PGM Usage (GaBi)

	meeting new standards with current technology		fully effective deployment of nanotechnology	
	2005	2030	2005	2030
Inputs				
energy resources (TJ)	1270	13 700	−22 800	−19 300
non-renewable energy resources (TJ)	1250	13 600	−22 600	−19 100
renewable energy resources (TJ)	12	129	−215	−182
inert rock (million kg)	131	1 420	−2 370	−2 000
precious metal ore (million kg)	447	4 870	−8 100	−6 830
water (billion kg)	12.3	134	−222	−187
Outputs				
group NMVOC to air (thousand kg)	13.7	149	−247	−209
heavy metals to air (kg)	630	6 800	−11 400	−9 600
inorganic emissions to air (million kg)	284	3 070	−5 120	−4 320
organic emissions to air (VOC) (thousand kg)	194	2 100	−3 500	−2 950
particles to air (thousand kg)	135	1 460	−2 430	−2 050
heavy metals to water (thousand kg)	1.09	11.9	−19.8	−16.7
hydrocarbons to water (kg)	456	4 970	−8 270	−6 980
particles to water (thousand kg)	24.9	270	−450	−380
consumer waste (thousand kg)	7.53	82	−136	−115
hazardous waste (thousand kg)	24.8	270	−449	−379
radioactive waste (thousand kg)	35.9	389	−647	−546
overburden (million kg)	132	1 430	−2 390	−2 010
tailings (million kg)	442	4 820	−8 010	−6 760

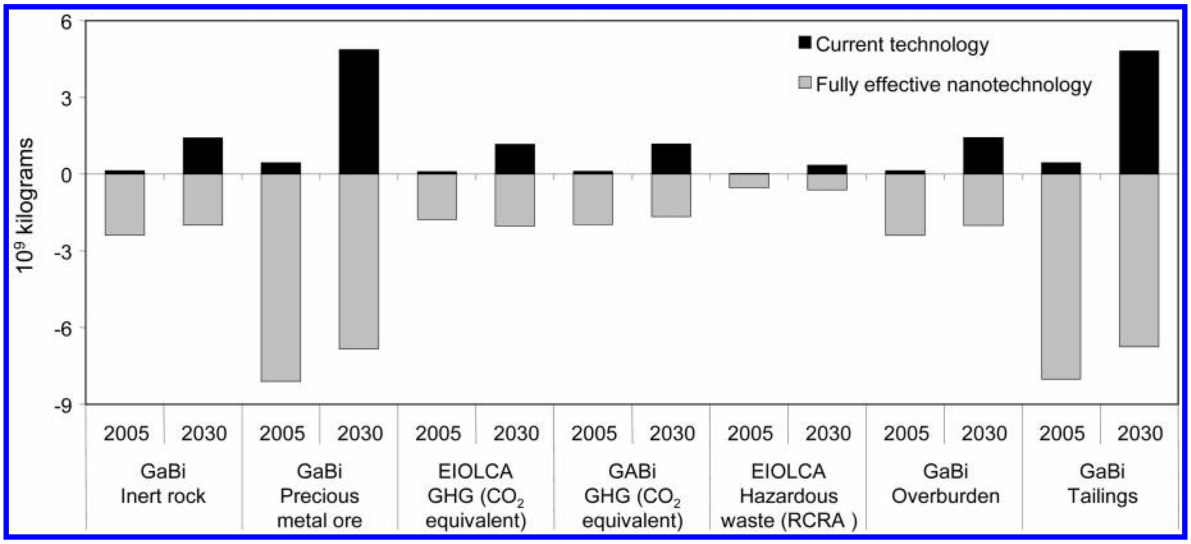

FIGURE 3. Change in life cycle effects from changes in PGM production. Black columns show the maximum expected increase over the baseline scenario from producing more PGM to meet new standards with current technology and gray columns show the maximum expected reduction over the baseline scenario from producing less PGM while still meeting new standards with a fully effective deployment of nanotechnology.

in retired vehicles. Our adjustment to GaBi's noble metal inventory results in much lower effects for producing recycled PGM. Thus, with a higher percentage of recycled PGM usage, total effects decrease even though total PGM requirements increase. In contrast, EIO-LCA results increase linearly with total PGM usage since we used the same market price for virgin and recovered PGM.

Figure 3 illustrates the range of change in life cycle effects from changes in PGM usage for 2005 and 2030. Black columns show the difference in effects between the new standards and baseline scenarios, representing the maximum possible increase in effects from producing more PGM to meet new emissions standards with current technology. Gray columns show the difference in effects between the nanotechnology and baseline scenarios, representing the maximum possible reduction in effects from using less PGM to meet new standards with a fully effective deployment of nanotechnology.

Expected changes in greenhouse gas (GHG) releases are presented from both models. The EIO-LCA model estimates the releases of four greenhouse gases (CO_2, CH_4, N_2O, and CFCs) and converts them into a global warming potential (GWP) based on equivalent releases of CO_2. We converted releases of these gases from GaBi into equivalent releases of CO_2 using weighting factors set by the Intergovernmental Panel on Climate Change (*43*). On average, the maximum increase in GHG releases using GaBi are 20% higher than EIO-LCA estimates, and the maximum reductions are 9% lower. CO_2 releases make up 75% of the GHG releases in the EIO-LCA model and 95% in the GaBi model.

Cost-Effectiveness of New Emissions Standards. The EPA evaluated the cost-effectiveness of each program by comparing expected incremental emission control technology cost and gasoline desulfurization cost to changes in social welfare from expected emissions reductions (*13, 19, 20*). While incremental PGM costs were included in the EPA's analyses,

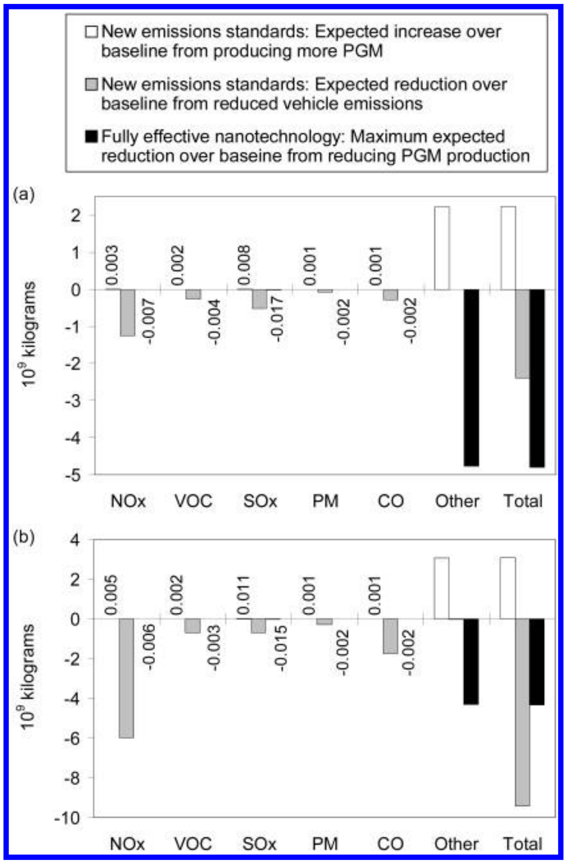

FIGURE 4. Comparison of expected vehicle emissions reductions from meeting new standards in (a) 2010 and (b) 2030 to the expected increase in releases from producing more PGM to meet new standards with current technology and the expected reduction in releases from producing less PGM while still meeting new standards with a fully effective deployment of nanotechnology.

life cycle implications associated with extracting, refining, and recycling PGM were not considered.

Figure 4 shows the expected change in air pollutant releases from changes in PGM production using GaBi and during vehicle use from the EPA's Regulatory Impact Analyses (*13*, *19*, *20*). In cases where columns are not visible, values are provided. For the pollutants targeted by the EPA's emissions standards (NO_x, VOC, SO_x, CO, and PM), expected emissions reductions during vehicle use (gray columns) are several orders of magnitude larger than additional releases from producing more PGM to meet new standards using current technology (white columns). However, other air pollutants are released while producing PGM. In 2010, total expected emissions reductions during vehicle use are only 7% larger than additional releases of all air pollutants expected from producing more PGM. Releases from PGM production occur early in a vehicles life while vehicle emissions are reduced over the full life of the vehicle. Hence, the difference between emissions reduction from vehicle use and additional releases from producing more PGM will increase as more vehicles are equipped to meet tighter standards. By 2030, expected emissions reductions from vehicle use are more than three times larger than additional releases of all air pollutants from producing more PGM.

Figure 4 also shows expected reductions in air pollutant releases from PGM savings associated with a fully effective deployment of nanotechnology (black columns). At this upper bound performance level, maximum annual reductions form PGM savings are double expected emission reductions from vehicle use in 2010 and roughly half expected reductions from vehicle use in 2030.

It is evident that the health and environmental savings from abating emissions during vehicle use will far outweigh the costs associated with releases of the same pollutants during PGM production. It is not evident whether these savings will outweigh the costs associated with all air pollutant releases from PGM production. Furthermore, PGM production requires large amounts of energy, water, and ore; results in the releases of many pollutants to all media; and generates large amounts of tailings and overburden. While new standards will reduce emissions in the United States, environmental impact from increased PGM production would increase primarily in South Africa and Russia. Hence a complete analysis cannot be made on one environmental effect in one geographical region. It is clear that nanotechnology that reduces PGM in catalysts by up to 95% would make a large contribution to lowering the environmental burden associated with mining, smelting, and refining PGM. If the benefits of also lowering vehicle emissions are retained, the nanotechnology would make a large life cycle environmental contribution.

Discussion

Construction of catalysts was one of the earliest uses of nanotechnology, long before the field was recognized or the term coined. Understanding catalysis and enabling planned design and controlled synthesis requires knowledge and control at the nanoscale. Automotive exhaust catalysts are a particularly interesting application of nanotechnology since the required PGM is extremely expensive and no viable substitutes are yet available. Furthermore, increasing global PGM demand and emerging technologies such as fuel cells may drive up short-term PGM prices, precluding some applications (*36*). Empirical evidence indicates that up to 95% of the PGM currently used in automotive catalysts could be removed without harming performance by overcoming current catalyst system inefficiencies. This would require optimizing and controlling the shape, size, and location of PGM particles.

We modeled PGM requirements for complying with tighter U.S. emissions standards through 2030 assuming driving habits and vehicle selection do not change. Current levels of uncertainty concerning future catalyst design and synthesis lead to constructing lower and upper performance bounds. We used current technology and fully effective nanotechnology scenarios to show an inclusive range of possible performance. We then employed economic input−output and process-based LCA to estimate the relative change in life cycle environmental effects from changes in PGM usage. Current nanotechnology-based research proposes numerous distinct methods for synthesizing catalysts in the future. As more information about these methods becomes available, the life cycle effects from synthesizing the catalyst and assembling the catalyst system can be assessed. In addition, a more robust model would consider PGM supply and demand effects, characterize expected performance improvements over time, and consider factors that may influence vehicle usage, such as high crude oil prices or improved hybrid vehicle technology.

Three striking results can be gleaned from this analysis. First, results using EIO-LCA and GaBi models are comparable, hence providing reasonable first approximations of life cycle effects from producing PGM. While the sources of uncertainty listed above cause variation between results from the LCA models, a more detailed investigation would be required to explain variation in any particular effect.

Second, for regulations aimed at reducing environmental burden, life cycle assessment can be used to estimate life cycle costs and benefits associated with employing technologies to comply with standards. In the emissions abatement programs considered here, vehicle emissions reductions outweigh increased releases of the same pollutants during PGM production. However, a more detailed analysis is required to evaluate life cycle costs associated with all effects from producing PGM as well as other emission control components. The availability of better technology predictions and the use of life cycle-based benefit−cost analysis could provide the ability to design emissions programs and phase-in schedules that optimize environmental benefits.

Finally, this type of analysis can be used to identify opportunities for entrepreneurship and areas for government technology investment. Dramatic resource and environmental burden savings could be realized from reducing PGM in automotive catalysts while holding performance constant. The small amounts of PGM in ore mean that substantial quantities of rock must be mined, crushed, and processed in order to produce the few grams in an automotive exhaust catalyst. The resulting high price of PGM and environmental damage provide a powerful incentive to reduce the amount of PGM in catalysts. Furthermore, similar design and synthesis processes are used to construct catalysts used in other applications, resulting in inefficient material usage. The life cycle environmental benefits associated with advancing catalyst technology to overcome current design and synthesis inefficiencies are far-reaching.

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Supporting Information Available

Additional information about data sources, methods for estimating PGM availability from retired vehicles, and life cycle results. This material is available free of charge via the Internet at http://pubs.acs.org.

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