Platinum demand and potential bottlenecks in the global green transition: A dynamic material flow analysis

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ABSTRACT

Platinum, as a key catalytic material, is important for the global green transition due both to its current main use in autocatalysts and its increasing use in emerging and renewable energy technologies such as fuel cells and electrolysers. In this study, we developed a dynamic material flow analysis model to characterize the global platinum cycle between 1975 and 2016 and to develop scenarios for future global platinum demand to 2050. Our results show that the autocatalyst and jewellery uses represent the most primary platinum use and possess the highest platinum stocks in use by 2016; however, when closed loop recycling is considered, the gross platinum demand from the glass industry would be the largest. Many socioeconomic (e.g., population and car ownership) and technological (e.g., engine and energy technologies) factors will affect the future demand for platinum in a global green transition. Our analysis concludes that, only in high demand scenarios and when fuel cell market penetration is high compared to the expected, the aggregate demand to 2050 will exceed the 2016 global platinum reserves. Improving the end-of-life collection and recycling rates would be important to address potential

future supply risks due to geopolitical reasons. These demand scenarios and further mapping of the global platinum value chain can help inform government and industry policies on transportation and energy transition, platinum supply risk mitigation, and recycling capacity planning and technology development.

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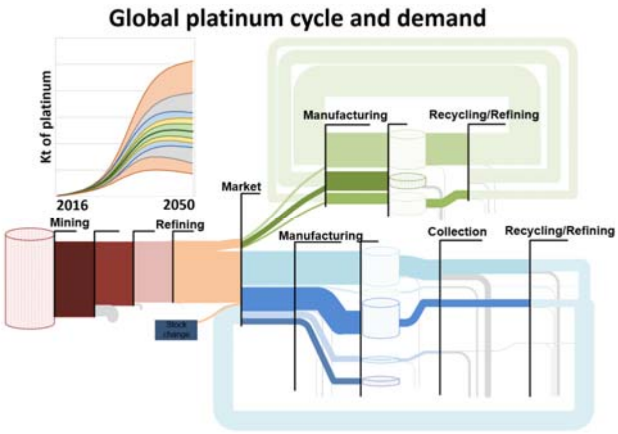


1. INTRODUCTION

The post-Paris Agreement era continues to face a daunting and urgent dual challenge of satisfying growing societal demand (e.g., transportation) and significantly curbing greenhouse gas (GHG) emissions. The emerging and renewable energy technologies, such as wind turbines, solar panels, and battery and fuel cell vehicles, are widely recognized as necessary for the global green transition in a climate-constrained world[1]. However, such a transition requires a large number of critical and precious metals, such as rare earth elements (REEs), lithium[2], cobalt[3], and platinum group metals (PGMs)[4] amongst others. This consequently raises questions of resource availability issues for large scale implementation of these technologies[5] due to the highly concentrated geographical distribution[6] of these critical materials, lack of effective substitutes[4], and political instability in some producing countries[7]. Therefore, an understanding of future demand and potential supply bottlenecks for these critical materials will be important for government and industry decision making on sustainable transportation and energy transition, supply risk mitigation, and technology development in the long term.

Platinum is an example of a critical[8], yet unevenly distributed (91.3 % of reserves in South Africa[9]) metal, for the global green transition. Platinum is used widely in a variety of industrial, chemical, medical, and environmental applications that are indispensable for our sustainable societal transition. The transportation sector, in particular, as one of the key intervention but difficult sectors to develop climate-friendly technologies due to the fuel energy density it requires, relies significantly on platinum. At present, the majority of internal combustion engine (ICE) vehicles need platinum-based autocatalysts to convert the harmful chemicals released from the engine exhaust into less detrimental products such as carbon dioxide, molecular nitrogen, and water vapour. In the future, sustainable and renewable fuels, in parallel with efficient battery technologies, will be key[10] for a low carbon transportation transition (especially for long-haul and heavy-duty vehicles, ships, and aviation where batteries cannot cover the required range), and production of these fuels often requires platinum as a catalyst. For example, polymer electrolyte membrane electrolysers (PEMEL) for hydrogen and further electrofuel (mixtures of hydrogen from electrolysis and carbon from sustainable sources such as biogas or the air to form a gas or liquid fuel) production and proton-exchange membrane fuel cells (PEMFC) currently depend significantly on platinum as a catalytic material[6,11].

Several governments have already announced plans to ban ICE vehicles[12], indicating a significant societal commitment towards gradually phasing them out over the coming decades. Meanwhile, it is expected that the demand for fuel cell vehicles and other new applications for platinum (e.g., in electrolysers) will increase in a green transition. It is, therefore, important to understand the implications of such a transition for platinum demand, recycling opportunities and challenges, and related supply risk and environmental impact mitigation.

Earlier studies have characterized the platinum cycle and demand-supply balance at different scales and from various points of view. Most of these studies focused on the characterization of the historical and/or current platinum cycle and especially its end use in different sectors, at the country (e.g., Germany[13] and Japan[6]), regional (e.g., EU[14]), or global[4] scale. These studies are based mainly on a material flow analysis (MFA) approach, but other methods such as input-output analysis[15] and system dynamics[16] were used as well. They provided an overview of the platinum flow and efficiency throughout our economy. A few studies have further modeled the future demand of platinum in major end use sectors based on scenarios and compared the availability of PGM reserves with the automotive sector's demand[17,18] or the increasing demand of fuel cells in the future[17,18,20,21,22]. However, there are still two major knowledge gaps that need to be addressed.

- Most studies did not consider the varying end of life (EoL) management and recycling routes (e.g., open or closed loop recycling) of different platinum end-use products in detail (except very few static or country-level studies[13,4]), which would have a significant impact on the platinum cycle[13] and future primary platinum demand.
- The future platinum cycle and demand scenarios developed in the literature often do not consider in details the temporal dynamics of market transformation and technology penetration for all end use sectors. In particular, the assumptions on fuel cell penetration and technology efficiency (platinum intensity) are often outdated[21,22], and the increasing demand of electrolysers towards global renewable energy transition has seldom been considered in previous studies.

The main reason that previous studies excluded electrolysis is that the only commercial type of alkaline electrolysis does not use platinum. However, a shift towards polymer electrolyte membrane (PEM) electrolysis is expected[11] (for example, it is better suited for flexible operation time), and it is, therefore, necessary to include electrolysers in future scenarios. Electrolysers will be of high importance in a future energy system reliant on hydrogen, the source of which in a renewable system is limited to electrolysers and biomass. Hydrogen use is not limited to fuel cells, if the hydrogen is mixed with CO_2 from biogas, cement kilns, or the air to form methane.

Methane can, find use in gas motors to back up the electricity grid, or as feedstock in a gas to liquid plant and then as a fuel in transportation in the engines that we have today.

Robust platinum demand scenarios would help understand the quantity, quality, and dynamics of scrap availability, and thus opportunities and barriers for recycling[23] (e.g., investment in recycling infrastructure and technologies[24] based on a different framework condition of platinum cycle in the future) and consequent environmental implications[25,14]. For example, Alonso et al. analyzed declining ore grades and the environmental implications of mining PGMs[17] based on mass flow scenarios. These scenario results, together with consideration of the geopolitical conditions[4] and opportunities for future additional primary production, will help identify supply risk mitigation strategies and plan future recycling capacities.

The aim of this study is to address the abovementioned knowledge gaps using a dynamic MFA model, for the gross demand of platinum in a global green transition up to 2050. All end-use sectors have been considered (including fuel cells and electrolysers) in the future demand scenarios and the EoL management and recycling routes have been investigated in details. We have then discussed the implications of the consequent demand in terms of potential supply constraints and opportunities and challenges of recycling.

2. MATERIALS AND METHOD

2.1 System definition

The system definition of the global platinum cycle is shown in Figure 1. The major life cycle stages of the platinum cycle include: extraction and production; processing and manufacturing; use; and end of life management.

Platinum can be produced via either primary (Processes 1, 2, and 3) or secondary (Processes 20, 21, and 23) routes. After production, platinum in the form of powder and bars is used in different applications, after undergoing the stages of manufacturing of intermediate or final products (Processes 6-10) and then the use stage (Processes 11-19). The largest current market demand for platinum comes from autocatalysts (Process 16) and jewellery (Process 19). Large gross demand comes from the glass industry as well, where platinum is used to coat ovens and other equipment for glass production[26]. Two sectors with a potentially large demand for platinum in the future are electrolysers (Process 14) and fuel cells (Process 15; only fuel cell vehicles are considered, as we assume that stationary and portable fuel cell power will have a negligible role in future energy systems due to efficiency and cost). Electrolysers produce hydrogen powered by electricity, which in the most sustainable way is generated from renewable sources (e.g., wind power). A fuel cell is the reverse technology of an electrolyser, which consumes hydrogen to produce electricity and water. The investment sector (Process 5) refers to platinum demand in the financial sector and commodity market, through purchase of bars and coins, and is best considered as storage of platinum without loss.

The last phase is end of life management where the platinum is either returned to the market, for use in a manufacturing process, or lost to landfills or the environment (Processes 20-23). Two distinct platinum recycling routes were differentiated:

- In closed loop recycling, the platinum-containing product (and the embodied platinum) is owned by the industry through all life stages[27]. This means that, in general, the same amount of recycled platinum as was delivered to end of life management are returned to the manufacturing processes within the same sector, minus very small losses in refining. Currently platinum recycling from the glass, petroleum refining, chemical production, and electrolysers sectors are examples of closed loop recycling.
- In open loop recycling, the recycled platinum is sold on the global market, and may subsequently be used in any sectors that use platinum. Currently, the jewellery, electrical products, autocatalysts and fuel cells in transportation units, and all other applications are all recycled in open loops.

Losses of platinum occur throughout the entire life cycle starting from extraction and production. For losses in manufacturing and use, we assumed (based on literature[4,28,29]) that manufacturing losses are considered only for jewelry, electrical, and other products, because platinum in these sectors is handled in a hard solid form, and losses in the use stage (e.g., dissipation) are mainly found in the catalyst based products and the glass industry. The losses in end of life management vary depending on the end-use sector and the stage in the recycling chain. The largest losses in end of life management are in the open loop recycling end-use sectors where collection (e.g., of electrical products) and the existence of less professional operators (e.g., in autocatalyst preprocessing/decanning) can be a challenge. While losses in the final stage of the recycling chain, refining, are very low and already near thermodynamic limits.

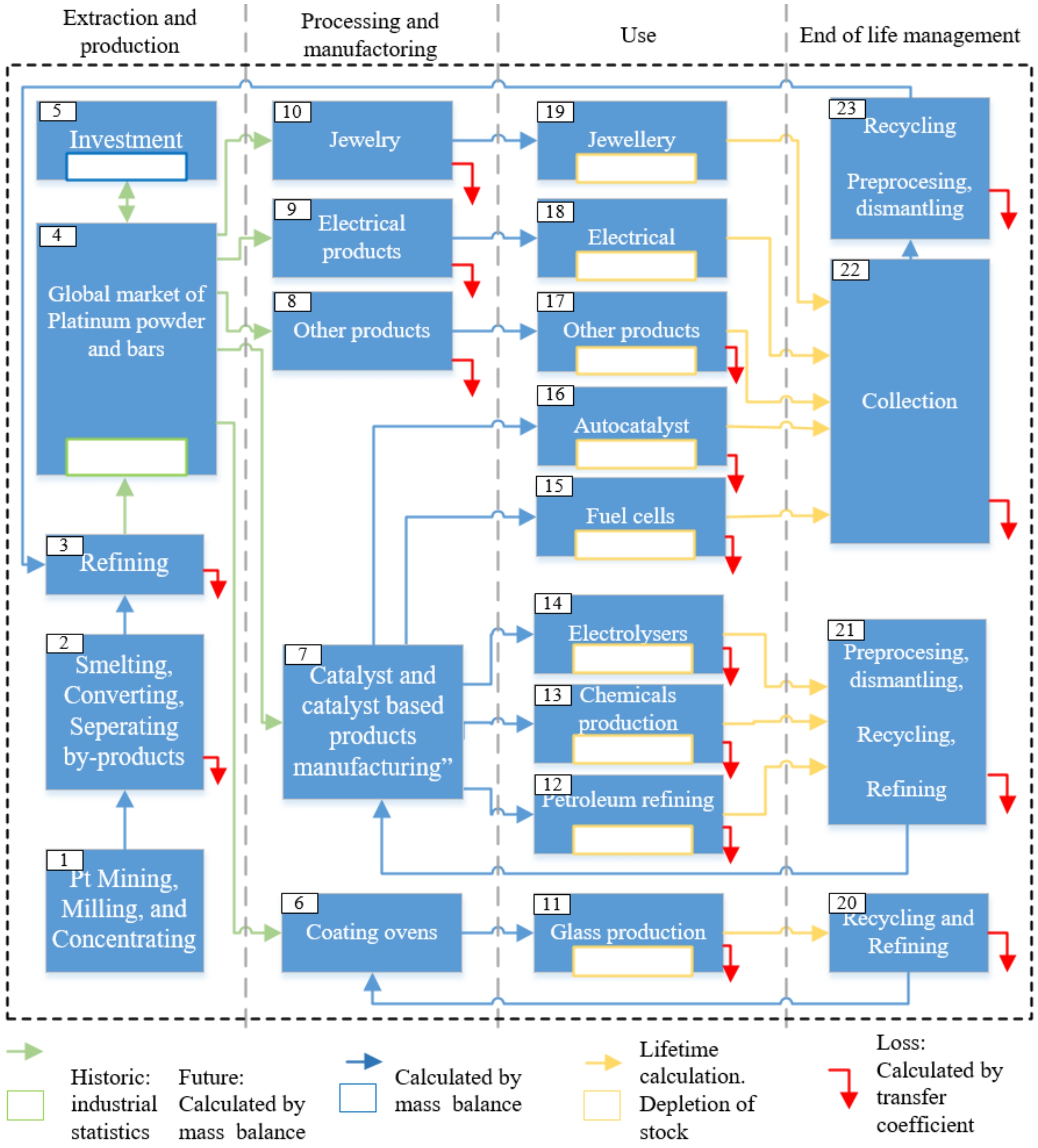


Figure 1. System definition of the global anthropogenic platinum cycle. Methods to derive different stocks and flows are visualized by colors of arrows and stock boxes, which is further detailed below and in the in the Supporting Information (SI). The processes are numbered (1-23)

so that it is easier to refer to flows using symbols; for example, F_{6-11} represents the flow from Process 6 (coating ovens) to Process 11 (glass production).

2.2 Simulation of historical stocks and flows

We used a dynamic MFA approach[30] for quantifying the global historical platinum cycle from 1975 to 2016. In such an approach, the stock in use and waste flow generation are simulated by the historical apparent consumption of platinum by end-use sector and their corresponding lifetime (e.g., waste streams from use phase to end of life management, see Equation (1)). The other upstream and downstream flows are subsequently calculated by either transfer coefficients (e.g., all loss flows), statistics (e.g., all flows from the market to manufacturing), or the mass balance principle (e.g., all flows from manufacturing to use phase), as detailed in Figure 1 for an example of the glass production (Process 11) sector (the same applies for all other sectors; see details in Table S1 in the SI).

$$F_{11-20,n} = \sum_{i=n-2\mu}^{n} \left(F_{6-11,i\ to\ n} - F_{11-0,i\ to\ n}\right) * \left(\frac{1}{\sigma * \sqrt{2 * \pi}} * e^{-\left(\frac{1}{2}\right)*\left(\frac{X-\mu}{\sigma}\right)^2}\right) \qquad (1)$$

in which $F_{11-20,n}$ represents the waste flow generation, n is the year in focus, σ is the standard deviation, μ is the mean lifetime of the product, and X represents age of the cohort.

The primary source of platinum consumption data is the market purchase estimates by sector reported by Johnson Matthey[31]. These data are directly used for the open loop recycling sectors as their corresponding apparent consumption, whereas they are further adjusted by adding up simulated internal recycling flows as the apparent consumption of the closed loop recycling sectors.

We assumed the platinum stock in use before 1975 is negligible, due to data gaps. The impact of this assumption on current stocks and flows in 2016 is limited because the lifetime of many platinum end-use products is shorter than 20 years. The impact on jewellery (with a lifetime of 35 years or more) and close loop recycling sectors is higher (especially for jewellery stock estimation in the 1970s and 1980s) than that of the open loop recycling sectors, because the platinum input that occurred 40 years ago may still be recycled within closed loop sectors with high recycling rates.

The lifetimes for each end-use sector[13,4] and transfer coefficients of the manufacturing, collection, recycling, concentration, smelting, and refining processes [13,4,28,32,33,34,29] are based on literature and detailed in the SI.

2.3 Scenario setting and simulation of future stocks and flows

A prospective top-down, stock-driven approach is used to quantify the future global platinum cycle. In other words, we model the future demand of platinum by end-use sector and other flows (e.g., recycling, losses, production, and extraction) based on the services provided by their corresponding in-use stocks, which are assumed based on their historical patterns and the need of a global green transition. Sensitivity analysis was also conducted to evaluate the impact of key model parameters, in addition to the various scenarios developed.

The levels of detail for the future stock growth assumptions vary by sector, based on the relative importance of that sector in the total use and our understanding of influencing parameters. We have grouped them into three categories as shown in Figure 2 and explained below.

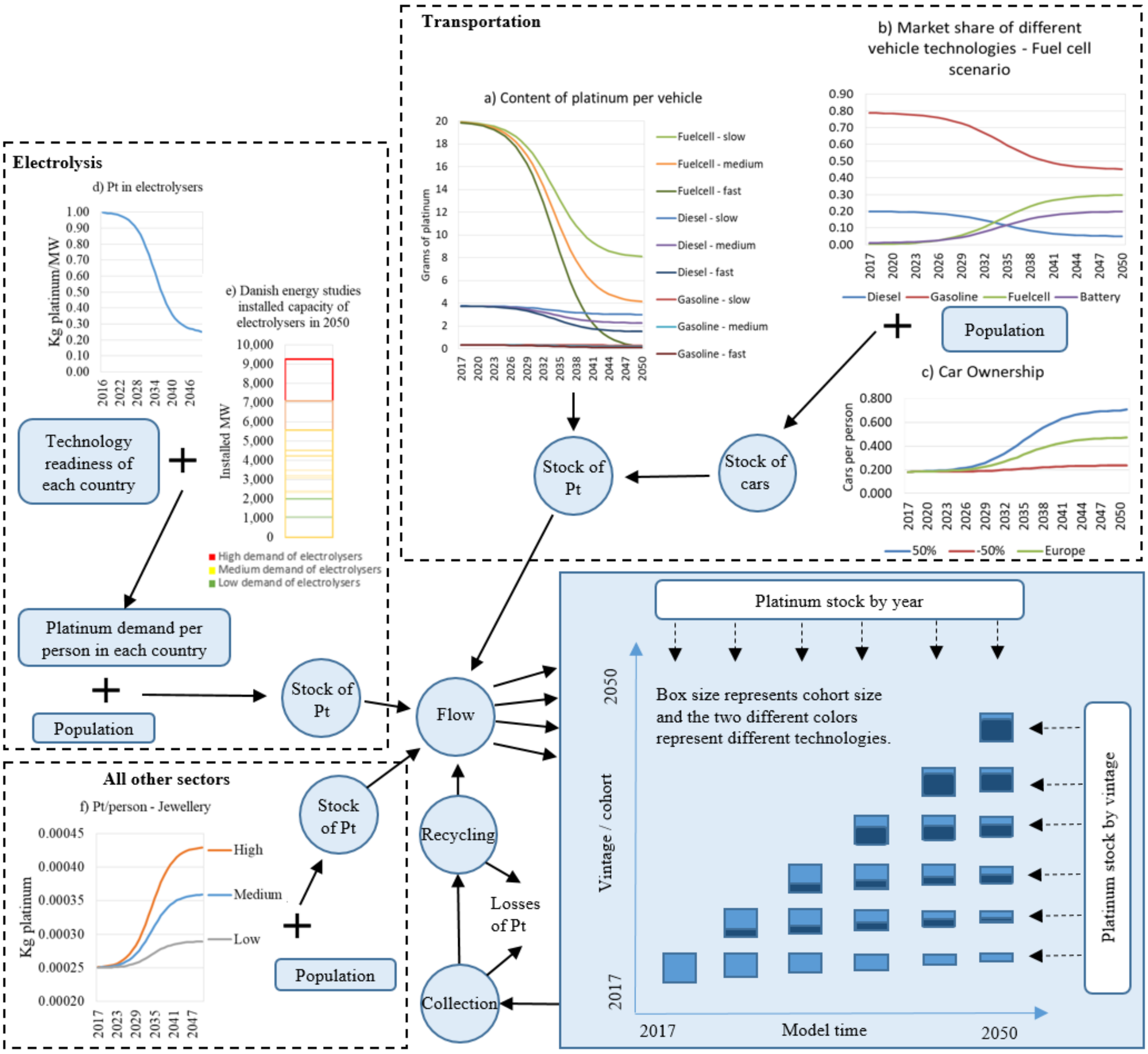


Figure 2. Conceptual model framework for the stock driven approach to quantify the future global platinum cycle, with details on stock estimations and assumptions made for the three different sectors (transportation, electrolysers, and all other sectors) and how they are used for quantification of recycling, collection, production, and losses. Individual graph legends: a) Platinum content over time in fuel cell, gasoline, and diesel cars with fast, medium, and slow technological development; b) Market shares of different car engines over time in the fuel cell scenario; c) The fast, medium, and slow development of global car

ownership; d) Platinum content in electrolysers over time; e) Estimated installed capacity of electrolysers by 2050 in the 16 Danish energy scenarios (details in the SI), with red, yellow, and green boxes representing our high, medium, and low scenarios; and f) Example of jewellery future platinum stock on an aggregated per capita level in high, medium and low scenarios.

2.3.1 Transportation

The transportation sector is modelled in a detailed bottom-up approach. Autocatalyst currently represents the largest end use of platinum, and, together with fuel cells, the transportation sector is likely to remain the prominent use in the future. The factors included in the platinum stock ($f(x)$, x for a specific year) assumptions of the transportation sector are vehicle ownership per thousand persons (VO), from the International Organization of Motor Vehicle Manufacturers (2016) (OICA), population forecast (P) from the United Nations (2017), platinum intensity (PtI) in all type of vehicles, and market penetration (MP) of different types of vehicles, as shown in Equation (2):

$$f(x) = (VO_x * P_x) * \left(PtI_{diesel,x} * MP_{diesel,x}\right) + (VO_x * P_x) * \left(PtI_{gasoline,x} * MP_{gasoline,x}\right) + (VO_x * P_x) * \left(PtI_{fuel\ cell,x} * MP_{fuel\ cell,x}\right) \qquad (2)$$

The current platinum intensity in diesel and gasoline cars is calculated based on the PGM content of autocatalysts[37] and the platinum content of PGMs[38] (ending up as 3.75 grams and 0.32 grams, respectively, per diesel and gasoline car). The future platinum intensity in cars depends on future emissions regulation and price of PGMs, and varies from 1.5 to 3 grams and from 0.1 to 0.3 grams in 2050 in our scenarios per diesel and gasoline car, respectively. The platinum content in a single fuel cell is assumed to be 20 grams per car at present[39], which is representative of the lowest levels demonstrated today. Depending on which future scenario may prevail, this may vary from 0 to 8 grams in 2050 in our scenarios (see figure 2a).

We assume that the global average vehicle ownership would follow an S-curve and saturate at the current level of Europe (471 cars/1000 persons) by 2050 as the baseline scenario. A ± 50% difference is considered in the high (706 cars/1000 persons, close to the current level of USA) and low (235 cars /1000 persons) saturation level scenarios at 2050 (see figure 2c).

The market penetration of different vehicle engine types is key to platinum demand scenarios. We simulated the market penetration as an S-curve from 2016 to 2050 and have considered three scenarios for the year 2050 market share, inspired by the International Energy Agency[40,1,41,42], 16 Danish energy scenarios (detailed in the SI), and a study conducted by Precious Metal Watch[37].

i. A Reference (REF) scenario assuming that the car market share remains the same as of today (20% diesel, 79% gasoline, and 1% battery cars);
ii. A fuel cell scenario assumed a high share of 30% for fuel cell cars (the remaining: 5% diesel, 45% gasoline, and 20% battery cars); and
iii. A battery scenario with 80% of battery cars in the market (the remaining: 5% diesel and 15% gasoline cars). The fuel cell scenario is shown as an example in Figure 2b.

2.3.2 Electrolysers

Figure 2d shows the development of platinum intensity in electrolysers. The starting point in 2016 is set as 1 kg/MW installed capacity, which among others[43] is based on a real world project

“DuraPEM”[44]. The ending point in 2050 on 0.25 kg/MW is estimated based on an industry report[45] and two journal articles[46,47] on the future technology prospect.

The demand for electrolysers depends fundamentally on the future energy system. There are currently no global demand forecasts for the capacity of electrolysers. Denmark has undertaken however many detailed analysis of the paths towards a full sustainable energy transition, which takes into consideration the role of electrolysers, and is therefore chosen as the reference point for predicting the future global demand for electrolysers.

The installed capacity of electrolysers to 2050, as predicted by 16 different Danish energy system analyses, forms the basis (see Figure 2e and details in the SI) for our high, medium, and low scenarios (red, yellow, and green bars, respectively, in Figure 2e). We have extrapolated the Danish demand of platinum for electrolysers to all other countries and derived a global total, based on a factor of population (2016 to 2050, from the United Nations forecast)[36] and a scaling indicator of technology readiness index of a country (from the World Bank)[48]. This index consists of, for example, companies spending on R&D, the creativity of its scientific community, and personal computer and internet penetration rates. We assumed that the relationship between each country and Denmark’s technology index level stays the same from 2005 to 2050. Such an extrapolated global total was deemed a good proxy, given the data gaps. Also, the Danish electrolyser forecasts are based on energy scenarios that compare the need for electrolysis with the need for biomass input with a global limit. When compared with the scenario in the Hydrogen Roadmap Europe[49], which estimates an electrolyser installed capacity of about

800,000 MW (assuming a capacity factor of 50 % and an efficiency of 65 %), our extrapolated European total capacity falls in the same range (about a quarter higher).

2.3.3 All other sectors except transportation and electrolysers

The platinum use in all other sectors, including the chemical, glass, petroleum refining, investment, medical, electrical, and other sectors, is considered on an aggregated level as per capita stock of each sector. We assumed a medium 2050 saturation level for the global per capita stock of each sector based on their historical patterns (with ±30% as high and low scenarios) and modelled the stock growth from 2016 to 2050 as an S-curve. The global population forecast is based on the United Nations projections[36]. More details are provided in the SI.

2.4 Reserves and supply concentration

Global reserves of PGMs, defined as that part of the total resources in the Earth's crust that are economically and technically feasible to extract with prices and technology at the time of determination,[50] is estimated by United States Geological Survey (USGS) to be around 69,000 tonnes of PGMs equivalent in 2016. Nassar et al [51] have collected platinum content data for 21 PGM mines (detailed in Figure S1 in the SI), which varies from 37.1% to 57.6% with an average of 51.3% This equates to a global platinum reserve from 25,599 tonnes to 40,917 tonnes with an average of 35,379 tonnes in 2016, based on the assumption that those 21 mines are representative of the global platinum reserves in terms of PGMs ore grade.

We have further applied the widely used Herfindahl–Hirschman Index (HHI) to determine the production concentration based on the percentages of production/refining per country in the world's total (x_i), as shown in Equation (3):

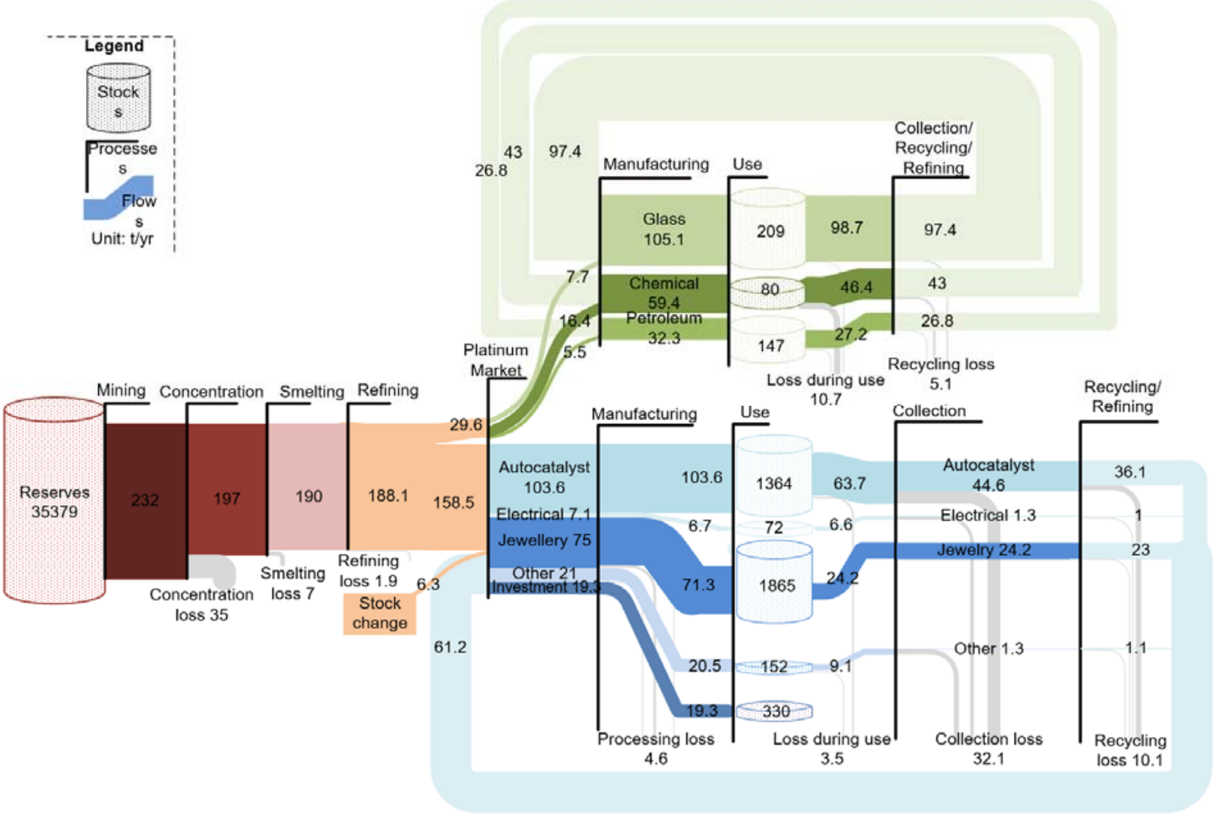
$$HHI = x_1^2 + x_2^2 + x_3^2 \dots . + x_n^2 \qquad (3)$$

Recycling is important for platinum supply. Therefore we have included recycling data[31] in the HHI calculation, which means open loop recycling flows that usually take place close to the demand, were subtracted.

3. RESULTS AND DISCUSSION

3.1 The historical and present global platinum cycle.

Figure 3 shows results of the global stocks and flows of platinum in 2016. It is shown that the autocatalyst sector uses the most primary platinum (103.6 tonnes), which is not surprising, because almost all new cars with combustion engines have an autocatalyst. However, when closed loop recycling is taken into account, the total secondary platinum supply exceeds the primary supply, and the glass industry would have the largest gross use of platinum (105.1 tonnes). It should be noted that these large closed loop recycling flows are usually not shown in the industry's market statistics (e.g., from Johnson Matthey), because such platinum flows are not counted as market transactions. However, considering their significant size and relatively short lifetime, it is important to understand these flows in order to better characterize future platinum demand and in particular their consequent economic and environmental implications (e.g., short lifetime and thus rapid circulation of platinum in closed loop recycling may result in more energy use for maintaining the same amount of platinum products in use).



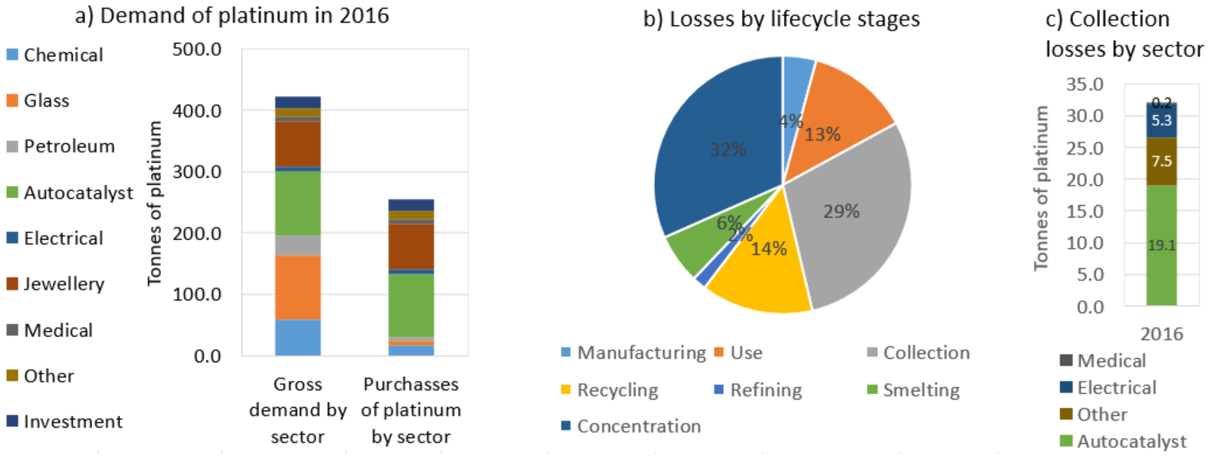


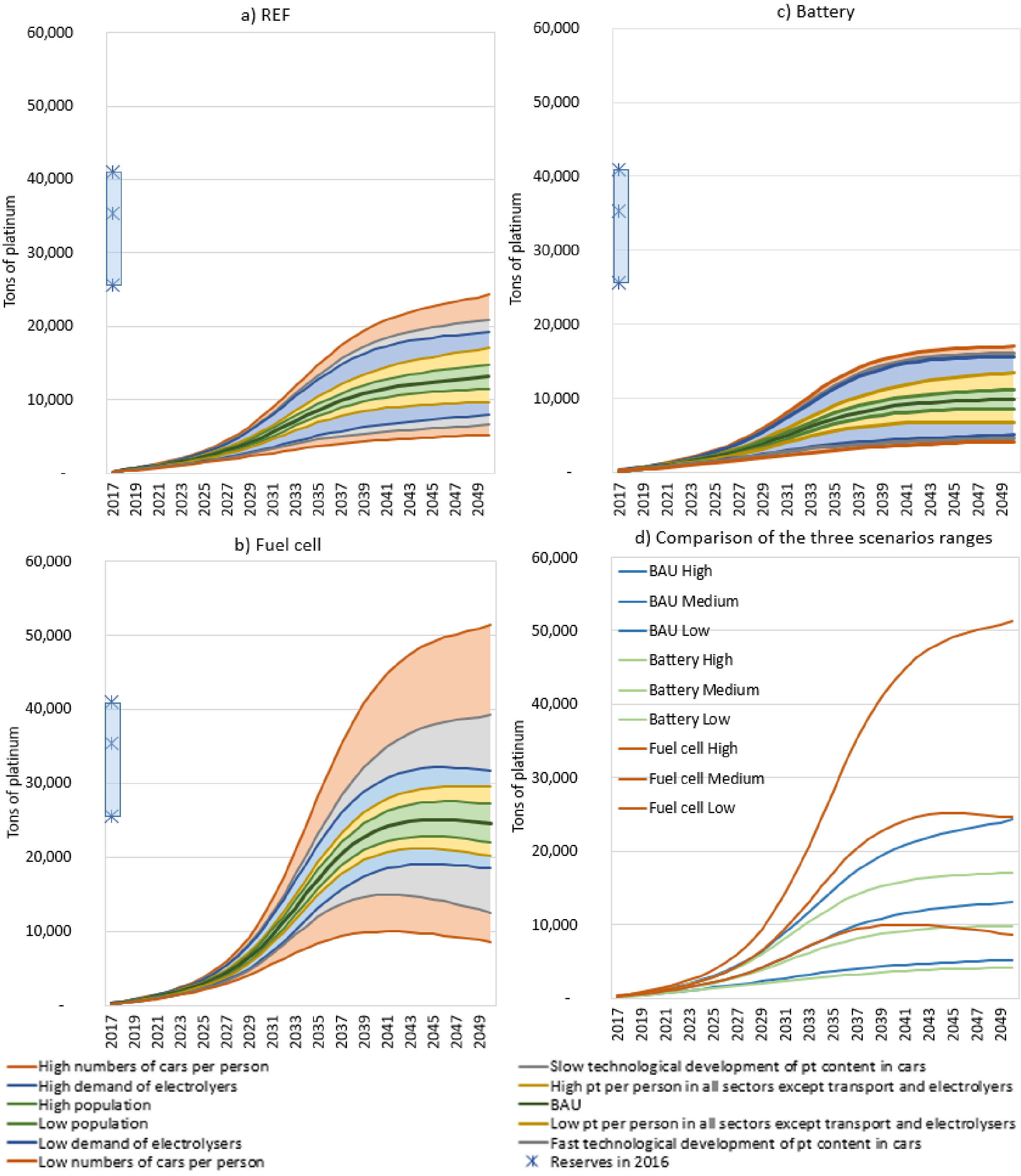
Figure 3. The global platinum cycle in 2016 in tonnes, with details of (a) market purchase and gross demand (including close loop recycling flows) for platinum by sector, and (b) losses of platinum by life cycle stage and (c) by end-use sector. The “stock change” is the balance difference of the market process.

Due to increasing levels of global car ownership, there are 1,364 tonnes of platinum accumulated in the current global car fleet in 2016. The jewellery sector, unexpectedly, was simulated to have the largest stock of platinum (1,865 tonnes) mainly because of their long lifetime (on average 35 years[4]). The investment and glass industry follow with the third (330 tonnes) and fourth (209 tonnes) largest platinum stock in use, though at a much lower level. All sectors, except the electrical product sector, show an increasing trend in per capita platinum stock since 2006. The declining trend in platinum per capita in the electrical product sector may be related to the general decline in the content of other precious metals in electrical products.[52]

The total loss of platinum in the whole life cycle added up to 111.9 tonnes in 2016, or around half of the global amount mined (231.5 tonnes). After ore processing to produce a Pt concentrate (32% of total loss), the second largest loss (29% of total) is found at the end of life collection, in which the transportation (autocatalysts) sector contributed the most. A comparison of our modelled results with historical data on the quantity of platinum recycled from autocatalysts (see SI Table S8 and S9 for details) showed that collection rate of 70% provided a good fit between the modelled and historical data. This collection rate reflects the fact that EoL cars may be exported to less developed countries, where proper or sufficient infrastructure and systems are not yet available[29] and that these flows are not easily tracked and recorded in market statistics. The manufacturing and use phases together contribute to the third largest loss (17% of total), which is in line with the results of an earlier study focusing on anthropogenic losses of platinum in 2010[53]. All losses occuring in EoL management are relatively small compared to the overall use of platinum, largely due to the high value of platinum, which incentivizes high recycling rates. Even with the relatively high collection and recycling rate the accumulative loss from 1975 to 2016 from collection and recycling in the autocatalysts sector adds up to more than 450 tonnes, which is the highest of all other sectors (around three times higher than the second largest sector, jewellery). Our results for the 2016 global platinum cycle in Figure 2 are generally in line with the 2010 global platinum cycle modelled by Nedal[4]. Both studies concluded that the closed loop recycling flows are almost as big as the primary use of platinum and that the autocatalyst and jewellery sectors have the largest in-use stocks of platinum. When compared with a study for the 2004 European PGM cycle[14], the relative relationships among flows and sectors (for the same year 2004) are also in good agreement. Another study[54] describing the European platinum cycle for the year 2012 simulates the European net addition to stock at 12 tonnes and platinum stock at 710 tonnes, giving a ratio of 1.7%. This is lower than our result (3%, with net addition to stock at 111 tones and total stock at 3,753 tonnes in 2012) for the global platinum cycle. Such a lower ratio on the global level is expected, because many developing countries are still building up stocks, whereas Europe already has mature stocks in many sectors. Moreover, the referenced study[54] showed that 20% of platinum input (from both primary and open loop recycling) comes from post-consumer functional recycling; whereas this percentage in our global model, without considering closed loop recycling, is 26%. We presumed this indicates the significant role of trade on a regional/country level.

3.2 Primary global demand of platinum and global platinum cycle by 2050.

Figure 4 presents how global aggregated values of primary demand for platinum are influenced by different key parameters, in the REF, fuel cell (the high demand scenario), and battery (the low demand scenario) scenarios. The thick green line in the middle of each scenario shows the starting point, where all parameters are set to medium. The first line above represents high population and the first line below represents low population, both with all other parameters set to medium. By changing one parameter after another, continuing upwards, we move towards the most aggressive case in all three scenarios and continuing downwards towards the least aggressive case, to show the potential range of future platinum demand.



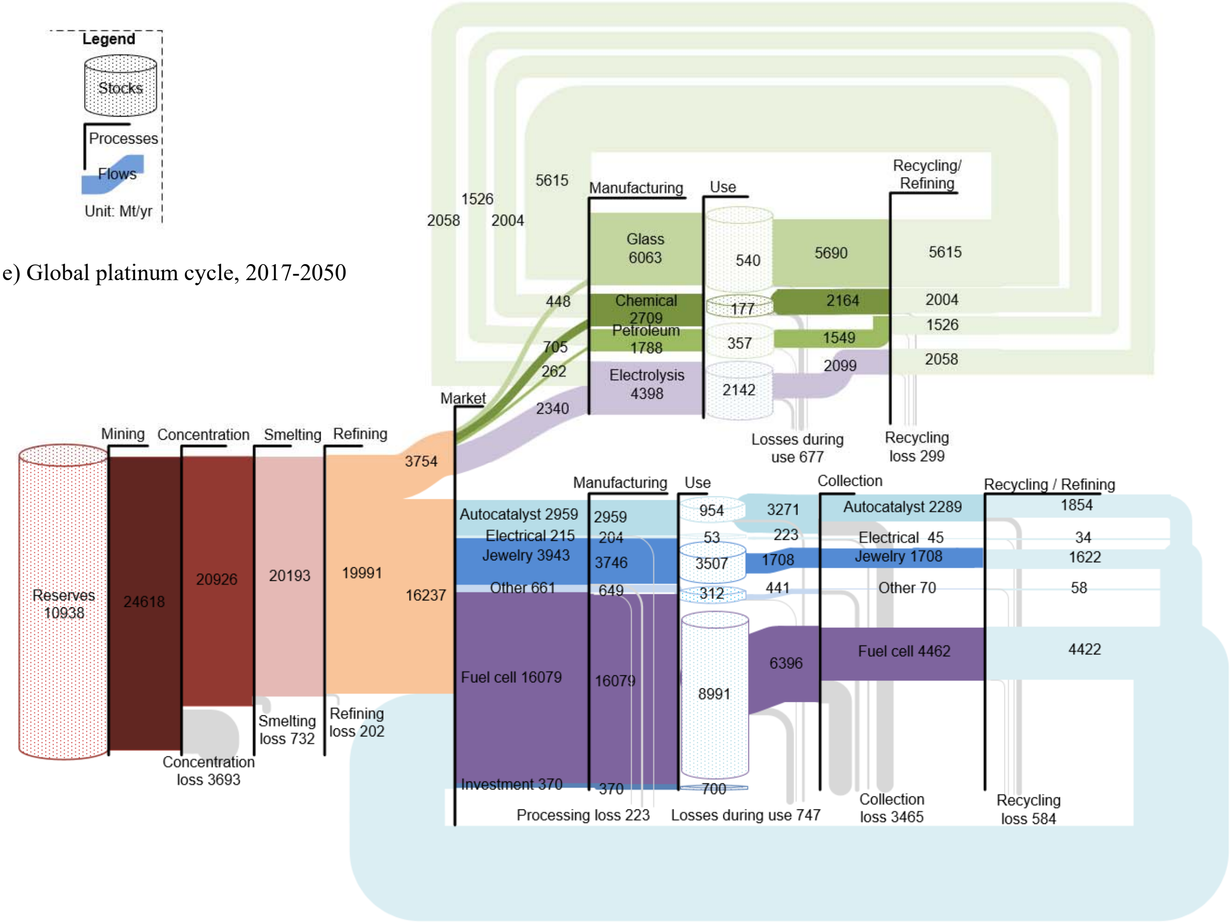


Figure 4. Accumulative global primary demand for platinum by 2050, with absolute sensitivities when changing one parameter after another in the three scenarios a) REF, b) fuel cell, and c) battery, d) a comparison of all three scenarios with the same Y-axis, and e) the global platinum cycle with accumulated flows from 2017 to 2050 and stocks in 2050 in the case of middle fuel cell scenario. In a), b), and c) the thick green line in the middle represents the aggregated demand, with all parameters set to medium. The first line above shows the result when the parameter population is set to high; the second line above shows the result when the two parameters, population (the parameter that was changed in the first line) and per capita stock of platinum in other sectors than transportation and electrolysers, are set to high; and so forth. This allows us to see the combined effect of changing several parameters. The three

(high, average and low) estimated global reserves of platinum in 2016 (see definition in section 2.4 and discussion in section 3.3.1) are only in the high demand fuel cell scenarios exceeded by the demand.

The total aggregated demand for platinum from 2016 to 2050 varies between 5 kt (the least aggressive battery scenario) to 51.4 kt (the most aggressive fuel cell scenario). The medium cases in the three scenarios are 9.8 kt for the battery scenario, 13.1 kt for the REF scenario, and 24.6 kt for the fuel cell scenario. The main demand in the medium REF scenario is found in autocatalysts, followed closely by electrolysers which together account for above 63% of the primary demand. In the medium battery scenario, this percentage falls to 52% due to a lower demand for autocatalyst. The main demand in the medium fuel cell scenario is not surprisingly fuel cells, which represents 58% of the primary demand (more than three time as much as electrolysers).

It can be seen that population change affects all sectors in all the three scenarios (since it is the first parameter we set to change in different scenarios), but to what extent the other parameters affect the demand of platinum in different sectors varies in different scenarios. For example, the impact of changing car ownership and platinum intensity in cars (due to engine technology improvements) is larger in the fuel cell scenarios than in the battery scenarios, because fuel cells in 2016 have a much higher platinum intensity than gasoline, diesel, and battery cars. It should be noted that, if we change the order of parameter change in the scenarios in Figure 4, the aggregated effects on platinum demand would still be the same but the contribution of each parameter may be different.

The impact of two parameters, demand for electrolysers and per capita platinum stock in other sectors than transportation and electrolysers, is the same in all the three scenarios. However, there is a difference between changing the demand of electrolysers from medium to low than from medium to high, since the parameter population is changed before the demand of electrolysers. The percentage of demand increase is larger than that of demand decrease, because of the population factor used in electrolysers demand calculation.

Figure 3 shows that the current stock of platinum is 1364 tonnes in autocatalysts (the only considerable use in the transportation sector in 2016) and this stock changes to between 300 and 6427 tonnes in our scenarios with global car ownership rising to the European 2016 levels in 2050 and the gradual change of engine technologies. For example, in the REF scenario in which 99% of the cars still run on gasoline and diesel, the stock of platinum in the transportation sector will change to 800-6500 tonnes (due to technological development, population, and car ownership increase). Such an increase is even more marked (2500-24400 tonnes) in all versions of fuel cell scenarios, because the platinum demand increase due to increasing fuel cell penetration will make up for, and eventually exceed, the decrease as a result of the phase-out of gasoline and diesel engines. It can also be seen in Figure 4b that several of the scenarios has a declining demand in the years close to 2050, which relates mainly to technological development that decreases platinum content in fuel cells.

However, the introduction of electric cars may result in a major decrease of platinum demand. In all versions of the battery scenarios (with 80% of electric cars), the platinum stock in the transportation sector will decrease, with the lowest reaching around half (700 tonnes) of the current level. This renders more secondary resources available from autocatalysts recycling for use in electrolysers, whose demand in high (4000 tonnes), medium (2100 tonnes), and low (750 tonnes) scenarios is higher than the decrease in platinum used in combustion engine cars. It is worth mentioning that, while the battery scenarios may not cause supply shortages for platinum, they may do so for other metals, such as cobalt and lithium. [55]

Figure 4(e) shows, an example of the medium fuel cell scenario, an overview of the future global platinum cycle with accumulated flows from 2017 to 2050 and stocks in 2050. When compared to the current situation (Figure 3), the most notable changes are the large inflows into electrolysis and fuel cells and their large stocks-in-use built up in the next decades. The stock of autocatalyst and electrical products will decrease, as the accumulated outflows are larger than the accumulated inflows. The autocatalyst sector has dropped from the largest consumption of primary platinum in 2016 to only the fourth after fuel cells, electrolysers, and jewellery in 2050. The largest loss occurs in concentration just as in 2016, but the collection of fuel cells is now the sector with the second largest loss (see Figure S12 in the SI).

The sensitivity analysis results with each key model parameter changed one at a time are shown for a case of the medium fuel cell scenario in Figures S14 and S15. The sensitivity analysis investigates the importance of each parameter on the accumulative primary demand. Figure S14 shows that lifetime has by far the largest influence on the accumulative demand (a ± 10% change leads to above 900 tonnes in the change of primary platinum demand). Extraction loss rate follows with the second largest impact, while other parameters such as manufacturing loss, use phase loss, collection efficiency, and recycling loss have a very small effect on the final primary demand, because these loss rates are already low at present. For those key parameters included in the scenarios in Figure 4 (Figure S15), cars ownership and technological development in transportation are found to have much larger impact on accumulative primary platinum demand than other parameters such as population, per capita platinum stock in other sectors, and demand of electrolysers in 2050.

3.3 Discussion on potential bottleneck of platinum supply and mitigation strategies.

3.3.1 Geological availability. When the global demand of platinum in different scenarios (see Figure 4) is compared with the 2016 estimation of reserves, it can be concluded that, except in the most aggressive fuel cell scenarios, the future platinum supply will not face geological constraints. Even if the lowest estimate on platinum reserves at 25,599 tonnes was used for comparison, it is only the demand of the 5 highest fuel cell scenarios (out of 11 fuel cell scenarios) that ends above the 2016 estimated reserves.

This comparison does not capture the dynamic nature of reserves, which vary in response to changes in many factors, e.g. economic (e.g., an increase in willingness to pay more for platinum makes other extraction methods and/or sources economically viable), technological (e.g., which facilitates new discoveries or mining at greater depths), and regulatory (e.g., the rezoning of land that makes mining possible or impossible).

The prediction of how reserves will change in the future is out of the scope of this study. Nevertheless, we may consider how the future reserves might evolve based on the evolution of historical reserves. One way would be to consider the historical relationship between annual reserves change and production in the past two decades, is 0.75:1 from 1997 to 2016, meaning that for every 4 tonnes of platinum is mined, the reserves increase by 3 tonnes of platinum. Another way is to forecast is the future development of reserves follows the historical average development on 138 tonnes reserve growth per year. In the second case, the global platinum reserves will increase by 4700 tonnes by 2050 to 41000 tonnes (with the average PGMs ore grade). This kind of evaluation of the dynamic nature of reserves is required for the long term. In the short to medium term, however, capacity and co-production rates should be used as indicators instead.

3.3.2 Geopolitical risks and supply constraints. Rather than geological availability, geopolitical risks and price fluctuation are more likely to cause future constraints of global platinum supply, especially in the short and medium term. Since South Africa hosts more than 90% of the presently known reserves, the geopolitical risk to supply constraints is considered high. If calculated based on the percentages of production/refining per country (without recycling), the HHI value of platinum is already above 5000, much higher than the criticality threshold of 2500[56]. Supply shortages and consequent price peaks due to geopolitical risks have already been seen with cobalt, palladium, and rare earth metals in recent decades[57]. Platinum has also faced similar threats in recent years, most notably with the striking of 70,000 South African platinum workers in 2014-2015, which cut off ~40% of global platinum production.

There are additional factors which may add to the potential supply bottleneck, such as declining ore grade (e.g., the mines in South Africa have experienced declining ore grade throughout their lifetime[17]) and considerable share of co-production. About 18% of the platinum currently mined is mined as co-production[4], e.g. palladium and platinum are mined as co-products of nickel in Russia.

3.3.3 Mitigation strategies and opportunities and challenges for substitution and recycling.

The consequence of a shortage in production of platinum may be temporarily mitigated by depletion of stocks at the mines and in the investment sector. Long-term mitigation strategies include exploration for new deposits to diversify the supply base, better use of the resource potential of mine waste, improved co-production rates, better collection in the open loop recycling sectors, spreading the use of best available practices and technologies in recycling, substitution, and demand management.

The most likely substitutes for platinum in many applications are metals with similar properties to platinum, in particular the other five platinum group metals (ruthenium, rhodium, palladium, osmium, and iridium), nickel, cobalt, and gold. However, all other PGMs are already used in almost all platinum containing end uses[58], making any further substitution hard[4]. For example, iridium can substitute platinum in electrolysis, but iridium is also a very limited resource[59]; and the same is for palladium use in autocatalyst. Moreover, these other five PGMs are often mined as co-products of platinum, which in the event of a geopolitical supply disruption makes these metals insufficient as substitutes for platinum[4]. Using metals outside the PGM group is possible, but there are usually either negative technical or economic trade-offs[4]. Substitution can also happen on the component level (e.g., Polymer Electrolyte Membrane electrolysis is replaced by platinum free Solid Oxide Electrolysis Cells or Alkaline ones) and product level (e.g., fuel cell cars are replaced by battery cars), which deserves closer investigation in the future.

Recycling is also an important strategy for addressing supply constraints in the long run, as it generally occurs where the products are used and technologies are available (not limited to geological distribution). For example, when recycling is included, the current HHI index of platinum is very close to 2500, making it borderline critical[60]. As platinum demand and stocks continue to increase in the following decades, platinum scrap is expected to become more available, as shown in our scenarios, indicating increasing opportunities for recycling, especially in industrialized countries such as Europe and the U.S. Another advantage of recycling is the environmental benefit, since the emission intensity from recycling platinum is substantially lower than that from primary production.

However, several challenges are foreseen for platinum recycling in the global green transition. First, the leakages of EoL products to countries with less robust recycling infrastructure and technologies (e.g., in terms of export of second hand vehicles) could reduce the overall availability for recycling[14]. Second, the material specification and design of products is becoming more complex in the electrical and automotive sectors, which may challenge the current recycling infrastructure. Third, the high price of platinum has already incentivised the optimization of recycling and manufacturing streams, which indicates that further improvements in recycling are not easily achieved even if the price rises. Last but not least, the future platinum scrap supply may change significantly in the future, which may require significant adaptations to the recycling chain. For example, if the use of fuel cells and electrolysers increases as seen in some scenarios here, the recycling landscape will shift from one that is mainly dominated by autocatalyst scrap today, to one that is more diverse due to the addition of fuel cell and electrolyser scrap. The technological development that lowers the platinum content in fuel cells could make recycling in a few scenarios less attractive in the far future.

3.3.4 Future work. Our global scenario results indicate that there is enough platinum to supply future global demand, but the high HHI value also suggests potential supply bottlenecks at a regional or national level. A multi-regional trade-linked platinum cycle can help explore these aspects by using more specific demand assumptions by sector by region/country and by more explicit consideration of the role of international trade of raw, intermediate, final, and EoL products in the value chain. This will be addressed in our future work.

ASSOCIATED CONTENT

Supporting Information

Detailed description of the system definition, analytical solutions to the system, and data sources. The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX...

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The manuscript was produced with contributions from all authors. All authors have given approval to the final version of the manuscript.

Notes

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