

The impact of platinum group metal catalysts in fine chemical synthesis

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ABSTRACT

Catalysts based on Platinum Group Metals (PGMs: Pd, Pt, Rh, Ir, Ru) play a fundamental role in modern civilization, enabling modern life in most aspects from food to travel to medicines. However, concerns about the security of supply and the environmental impact of mining are driving a trend towards the replacement of PGM catalysts. In this paper we provide an analysis of the sustainable use of PGMs, which accounts for the current and future shift in PGM availability and the true extent of PGM recycling. The actual contribution of PGMs to the carbon footprint of a model catalytic process is described in a simplified LCA case study, showing how the footprint of the whole catalytic step, rather than the catalytic metal in isolation, must be considered. The use of PGM catalysts, especially when effectively recycled, can provide more environmental value than generally perceived.

KEYWORDS:

sustainability; platinum group metals; life cycle analysis; circularity; catalysis.

Introduction

In fine chemical synthesis, Platinum Group Metal (PGM) catalysts, both homogeneous and heterogeneous, are critical for the building of complex chemical structures via formation or cleavage of C-C, C-N and C-O bonds and chemo and stereoselective redox steps involving C=C, C=N and C=O bonds. The manufacturing of most small molecules pharmaceuticals intermediates in fact involves some metal-catalysed synthetic step.

Recently, suggestions have been made in the literature for the replacement of PGM catalysts with Earth-Abundant Metals (EAMs). The fundamental argument for the replacement of PGMs with EAMs is the greater natural abundance of the latter. PGMs are indeed rare (and included in the EU and US lists of critical minerals), but this does not translate into a scarcity of supply.

An additional concern is the greater environmental impact of mining PGMs

which leads to a higher Global Warming Potential (GWP)/carbon footprint of PGMs per kg of mined metal compared to base metals. In an initial assessment of the sustainability of a catalytic process, the impact of using a PGM catalyst appears high. However, this is often not the case when one considers the carbon footprint of the entire process. The most effective way to reduce the environmental impact of catalytic processes is to focus on optimizing catalytic performance (1). It is the conditions

enabled by the specific catalyst, rather than the catalyst itself that are crucial.

Future availability and sustainability of Platinum Group Metals

PGMs are effectively recycled through a global, mature network of collectors and refiners. PGM refining occurs in two distinct recycling loops:

- An **'open loop'** where the metal exchanges hands and is therefore visible in market data. The automotive market is a typical example.
- A **'closed loop'** where the end user owns the metal throughout the cycle of use and recycling, leading to very high recycling levels. Many industrial applications work on a closed loop model.

The impact of the closed loop recycling is challenging to quantify but critical to appreciate the role of circularity in the use of PGMs. Johnson Matthey has recently estimated the combined impact of open and closed loops, showing that every year approximately 57% of the total PGMs used worldwide in new products is recycled metal from secondary sources (Table 1) (2).

A technology shift from the internal combustion engine to electric power is happening in transportation. Large amounts of PGMs (especially Pd, Pt, Rh) have been stored year after year in the form of catalytic converters and most of this metal has yet to be released back into the annual PGM supply (Figure 1). Although a contribution from mining to the annual PGM supply is still required, this 'urban mine' stores PGMs in amounts significantly larger than any yearly industrial consumption. This has the potential to ensure access to PGMs for many years to come, stabilizing future prices and progressively reducing their overall environmental impact.

The Environmental impact of PGMs

The most accurate data on the environmental impact of both primary (mined) and secondary (recycled) PGMs are published by the International Platinum Association (IPA)(3). The data are collected directly from member companies covering 95 % and 60 % of primary and secondary global supply respectively and do not rely on secondary sources as do other commonly referenced literature.

	Pt	Pd	Rh	Ru	Ir	Total
Estimated gross demand (tons/year)	546	395	61	76	21	1100
Estimated total recycling (tons/year)	355	184	37	42	14	631
% of gross demand met by recycling	65%	47%	61%	55%	66%	57%

Table 1. Estimated contribution of recycling to PGM gross consumption (preliminary figures for 2024) (2).

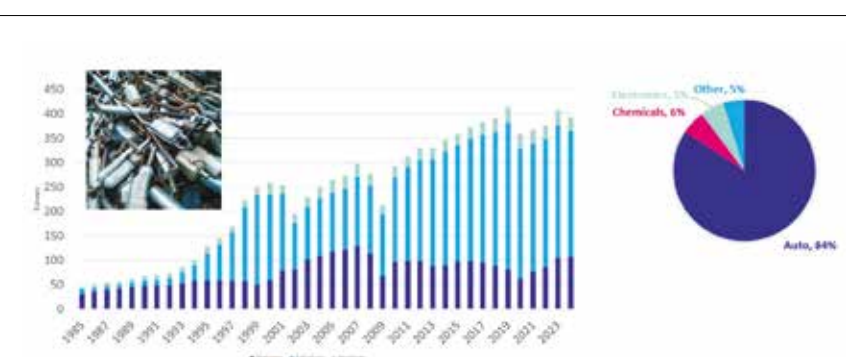


Figure 1. Global use of PGM on new vehicles annually since 1985. The pie chart is showing net demand for Pd in 2024 (net of closed loop)(2).

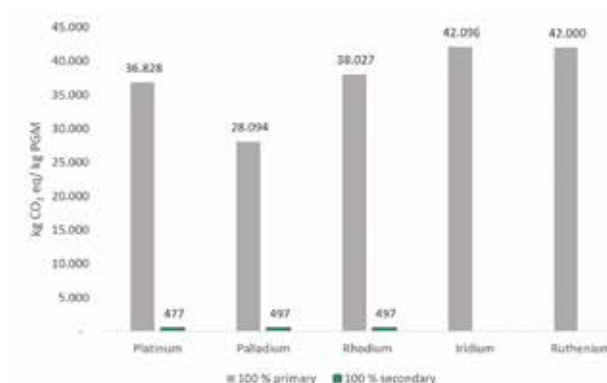
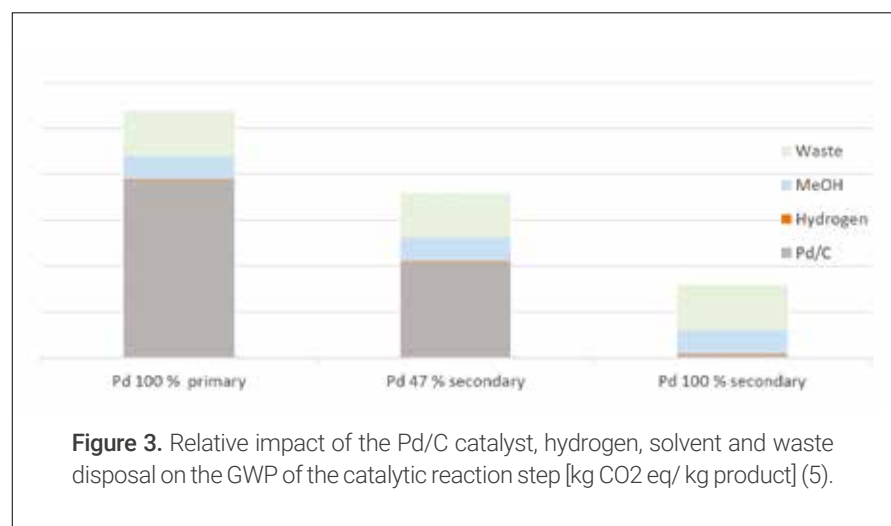
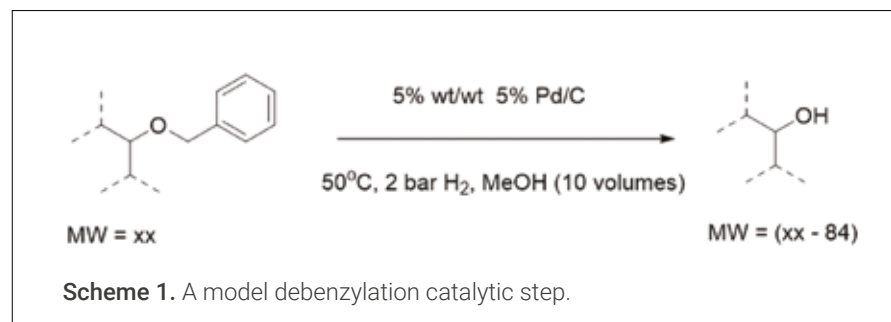


Figure 2. GWP of primary and secondary production of PGM metal (kg/CO₂ eq. / kg of metal) (3).

Primary and secondary PGMs on the world market are mixed (as well as undistinguishable) and the recycled content of the PGM used in a catalyst greatly affects its carbon footprint. Using the IPA data the appropriate GWP for any purchased PGM can be calculated if the ratio of secondary to primary content is known. The IPA data are plotted in Figure 2 and can be downloaded from the IPA web site (2025 report, data referring to 2022) (3).

Robust global average GWP numbers for secondary iridium and ruthenium cannot yet be reported.

It should be noted that the carbon footprint of primary PGMs is predicted to decrease significantly (by between 30 and 60%) in the next five years due to the decarbonisation of electricity generation in South Africa, the world's biggest supplier of PGMs (58% of total PGM supply in 2023)(4).



Carbon footprint of a model PGM-based catalytic process

It is often difficult to complete an accurate Life Cycle Assessment (LCA) of specific transformations in the fine chemical space since only the manufacturer will have all the data related to the footprint of the substrate. A useful alternative is to create a basic model for the carbon footprint contribution originating from the catalytic step. This may then be used to compare alternative synthetic routes that start from the same intermediate and lead to the same target product.

Johnson Matthey has a vast experience in the application of PGM catalysts. We propose an example based on a very common reaction: the debenzylization of a benzyl ether using a heterogeneous Pd/C catalyst, which is often part of a protective group synthetic strategy. This typical hydrogenolysis process may use 5% weight of a 5% Pd/C, in a solvent (often MeOH, or EtOH, AcOEt, THF), with a substrate concentration that could be 10% weight/weight, under low hydrogen pressure (i.e. 2 bar H₂) and moderate temperature (i.e. 40-50° C) (Scheme 1).

In addition to the the metal, the following factors contributing to the carbon footprint of the reaction were considered (see Supplementary Information for the methodology used):

Manufacture of the Pd/C catalyst

The carbon footprint of the catalyst is accurately modelled as it is manufactured on site at Johnson Matthey. Our data shows that, unless a very low metal loading is used, the manufacturing process of preparing Pd/C adds very little to the overall footprint of the catalyst and the footprint of the catalyst can be approximated with the footprint of the metal.

Impact of the reaction step

The contributions of hydrogen and methanol were included, although the impact of hydrogen was found to be negligible. The impact of energy was not modelled as energy requirements will be specific to the plant in use but, as the reaction takes place at moderate temperature and pressure, it is likely to have a low impact. It was assumed that the total mass of solvent used would be incinerated as hazardous waste with energy recovery.

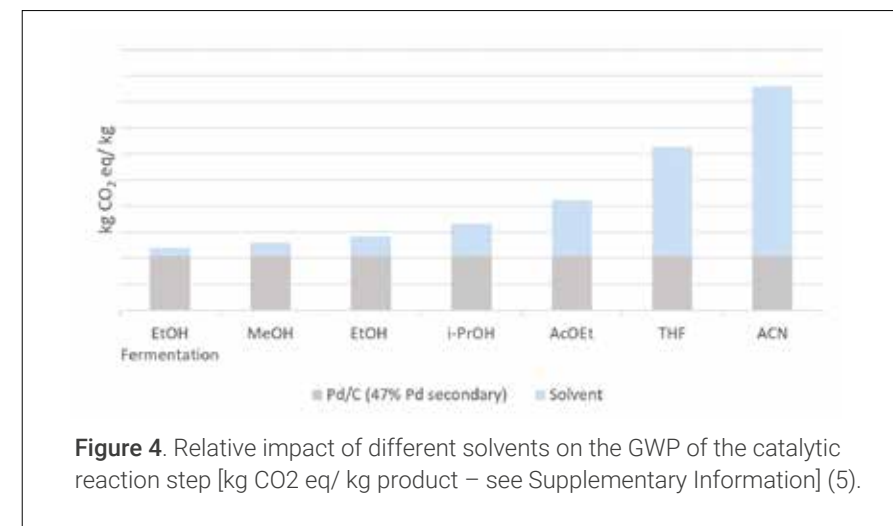
Two factors were found to have the greatest effect on the overall carbon footprint of the reaction, namely the origin of the Pd and the choice of solvent.

The source of the Pd in the Pd/C catalyst
PGMs that enter the yearly supply from secondary sources have a carbon footprint that is up to 97% lower than metal sourced directly from mining. The ratio of secondary to primary content thus has an enormous impact on the carbon footprint of the Pd/C catalyst used in the reaction outlined in Scheme 1. For the catalytic step, we considered three cases of Pd/C made from 1) fully primary metal, 2) 47% recycled metal 3) fully secondary metal. The choice of 47% recycled Pd was made as it is the proportion of Pd gross demand that we estimate is being met by recycling in 2024 (Table 1)(2).

The relative impact of the source of Pd in the 5% Pd/C catalyst, the solvent, hydrogen, and disposal of waste on the overall carbon footprint of the catalytic reaction step is illustrated in Figure 3. In the scenario of fully secondary metal, the contribution of both the solvent and waste disposal largely prevails over the contribution of the metal. The impact of waste and solvent would decrease if the solvent was distilled and recovered rather than incinerated, however this is not always possible, especially in a pharmaceutical process. It should also be noted that in a large scale industrial application the catalyst could either be recycled in several reaction cycles (usually with addition of some 5-10% fresh catalyst) and, almost certainly, it would be refined, possibly as part of a closed loop where the metal is topped up with few % of fresh metal after each refining cycle. This means that, in a large scale application, the metal contribution would progressively approach the best case scenario of (almost) fully secondary metal, pushing the metal contribution well below the solvent contribution.

The choice of solvent

Alcoholic solvents are common in the transformation under study (Scheme 1), as well as some aprotic solvents. MeOH is tabulated as having a relatively small carbon footprint and it has been considered the solvent of choice in our first scenario.



The relative contributions of the solvent and the catalyst to the reaction change when different solvents are used as illustrated in Figure 4. Moving from MeOH to non-protic solvents such as AcOEt or THF automatically brings the solvent to be the main contributor regardless of the source of the metal. Even with a 47% secondary Pd catalyst (a likely scenario if the Pd is sourced from the open market; Table 1) the impact of the solvent will be equal or greater than that of the Pd catalyst (note waste disposal is not included here). The effect will be even more visible when larger volumes of solvent are used for downstream isolation or purification or the catalyst is recycled. This figure also shows the downside of the commonly used metric Process Mass Intensity in which only the mass of solvent but not its environmental impact is considered.

Conclusion

Even a simplified model like the one outlined in this paper shows that, in estimating the carbon footprint of the catalytic step (additional to the carbon footprint of the substrate), the choice of reaction conditions overrides any concern about the carbon footprint of the metal per se. Productivity and choice of solvent become the main contributors as soon as the process is optimised for low catalyst loadings and/or any form of metal recycling is put in place, making the choice of a EAM vs a PGM-based catalyst a lot less impactful than generally perceived. When a full LCA approach is taken, similar conclusions have been reached comparing Pd and Ni-catalysed homogeneous coupling processes: it is the 'big

picture' of the whole process that matters (6). As we have recently highlighted (7), planning for PGM metal recycling should be an integral component of process development. Based on the most recent IPA figures on PGMs' environmental impact (3), an effective recycling loop has an enormous positive impact on both cost and environmental footprint: PGM-based catalysts are an example of circular economy that underpins security of supply as well as economic and environmental sustainability.

Supplementary information

The LCA was conducted in conformity to the ISO 14040 (2006) standards but has not been independently reviewed. The functional unit was 1 kg of product and the system boundaries were cradle-to-gate. Life cycle inventory data was sourced from ecovint v 3.10(5) and the model was created in Sima Pro software edition 9.6.(8). The GWP was calculated using using IPCC 2021 GWP 100 method. Absolute GWP values sourced from ecovint database cannot be disclosed.

Author

Sarah Facchetti obtained her degree and PhD in Organic Chemistry at the University of Pisa with Prof. Anna Iuliano. She worked in the research groups of Prof. Carmen Claver and Prof. Walter Baratta before joining Johnson Matthey in 2013. She currently is Senior Technical Product Specialist for ChemoCatalysis in the Life Science Technology business at Johnson Matthey.

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