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Unlocking the resources of end-of-life ICEVs: Contributing platinum for green hydrogen production under the IEA-NZE scenario

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ABSTRACT

Proton exchange membrane (PEM) water electrolyzers are a promising technology for high-purity, efficient green hydrogen production, with expanding installations. This has increased demand for materials like platinum (Pt) used in PEM manufacturing. Conversely, Pt, which currently serves primarily as catalysts for internal combustion engine vehicles (ICEVs), would become available as ICEVs are phased out. Here, we simulate the Pt requirements for rapid scale-up PEM electrolyzers and quantitatively compare these requirements with the availability of Pt from scraped autocatalysts under the IEA-NZE scenario. Our results show that demand for Pt in PEM electrolyzers is expected to increase by an order of magnitude by 2050, while ICEVs are expected to cumulatively scrap ~2500 tons of Pt. The Pt surplus from ICEVs would meet the increasing Pt demand for PEM eletrolyzers from 2030 onwards. These findings offer fresh insights into using the potential of urban mines to meet the energy transition challenges.

1. Introduction

Green hydrogen, generated via water electrolysis using renewable energy sources, has attracted significant attention as an energy carrier for grid balancing and inter-seasonal energy storage (Abdollahipour and Sayyaadi, 2022; Folgado et al., 2022; Mac Dowell et al., 2021; Samsatli and Samsatli, 2019). Additionally, it serves as a valuable industrial feedstock for applications like steel-making and oil refining (Devlin et al., 2023; Moradpoor et al., 2023). Discussions about the hydrogen economy, which relies on hydrogen as a primary energy carrier, have been ongoing for years (Kleijn and van der Voet, 2010; van der Spek et al., 2022). Market turmoil and the energy crisis have further increased the focus on energy security and other energy solutions, such as green hydrogen (Goldthau and Tagliapietra, 2022). For instance, the RepowerEU plan sets a target of installing 80GW electrolyzer capacity by 2030 (European Commission, 2022). The U.S. hydrogen roadmap also stated clean hydrogen could support ~10% economy-wide emission reduction in 2050 (DOE, 2023). The International Energy Agency's Net-zero Emission by 2050 (IEA-NZE) scenario, which is also in line with the Sustainable Development Goals 2030 agenda (UN, 2016), calls for a 2560-fold increase in water electrolyzer capacity over the next 30 years (IEA, 2021a).

Three water electrolysis approaches are being considered for the generation of green hydrogen: proton exchange (or polymer electrolyte) membranes (PEM) electrolyzers and alkaline electrolyzers (AEL) designed for low-temperature operation, and solid oxide electrolyzers (SOEL) suitable for high-temperature environments which are less developed and only being tested in small scale (Chi and Yu, 2018; Schmidt et al., 2017). PEM electrolyzers offer benefits such as compact size, greater operational flexibility, and higher pressure output compared to AEL (IEA, 2021b). AEL is presently the dominating technology, but according to IEA's Hydrogen Project Database (IEA, 2023a), PEM capacity has been steadily approaching that of AEL over the past five years. It is anticipated that the individual capacity of the PEM project will rise from megawatts to gigawatts by 2030 (FuelCellsWorks, 2023; ITM power, 2023; Parkinson, 2018). With the increasing capacity of electrolysis, PEM electrolyzers are driving the demand for Pt, which is used as bipolar plate coating and cathode catalyst materials (Kiemel and Smolinka, 2021; Ouimet et al., 2022). The ongoing upscaling of PEM technology increases demand for precious Pt applications but also creates supply challenges due to the need for rapid ramp-up (IRENA, 2020; Minke et al., 2021).

Pt-based catalysts, as the most substantial application for Pt, constitute over a third of the global Pt consumption (Johnson, 2023; Rasmussen et al., 2019). These catalysts are employed to transform harmful exhaust emissions in ICEVs (Hughes et al., 2021). The global

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energy and transportation landscape is changing rapidly (Crabtree, 2019; Greim et al., 2020). The electromobility transitions have already begun and will continue to be accompanied by a phase-out of ICEVs (IEA, 2023b; Liang et al., 2023). Consequently, the demand for catalysts containing Pt is expected to decrease, leading to the potential accumulation of significant quantities of Pt in the waste stage. The waste present in society contains vast reservoirs of materials that can be recycled and reused, known as 'urban mines' (Auld et al., 2018; Brunner, 2011). Conversely, if we could recycle and repurpose these discarded urban mines, it would not only result in primary material savings but also significantly reduce the extended lead times associated with mining (IEA, 2021b). According to the IEA-NZE scenario, the sales of passenger ICEVs will cease globally by 2035 (IEA, 2022). Considering the time interval between vehicle use and end-of-life, coupled with the current 99% share of ICEVs in the global vehicle fleet (IEA, 2021a), the generation of discarded Pt in automotive catalysts will continue until 2050 and beyond (Tong et al., 2022; Zhang et al., 2023).

The existing literature has provided a solid foundation for Pt cycle analysis at the national, regional (Hao et al., 2019b; Saurat and Bringezu, 2009; Tong et al., 2022), and global levels (Nansai et al., 2014; Rasmussen et al., 2019; Xun et al., 2020). Research related to the Pt cycle provides detailed information on the flow of platinum in various applications. However, the increasing demand for Pt from PEM electrolyzers has not been given sufficient consideration. As one of the rarest elements on Earth, some research also tracks the demand for Pt in large-scale PEM electrolyzer deployment (Clapp et al., 2023; Kiemel and Smolinka, 2021; Ouimet et al., 2022). They highlight that an increase in demand for Pt in electrolyzers could further increase supply tension as the energy transition process accelerates. However, we have not found any studies that provide a solution to mitigate the Pt demand for PEM electrolyzers by using existing urban mines. Furthermore, none of them connects green hydrogen and automobility under IEA-NZE scenario in an assessment of Pt supply and demand.

To fill this gap, in this paper we make this connection by exploring the possibility of using Pt from end-of-life catalysts as a source to supply Pt for PEM electrolyzers under the IEA-NZE scenario. Our findings offer insights into reducing primary material dependence by recycling materials from existing urban mines. The paper is structured as follows: Section 2 presents the methodology and scenario setting for the prospective analysis of Pt demand, outflows, and stocks of both PEM electrolyzers and ICEVs. Section 3 contains our results, followed by the discussion and conclusion in Section 4, where we elaborate on the main findings and conclusions of this work.

2. Methodology

2.1. Material flow analysis

Our analysis relies on projected global electrolysis capacity from the IEA-NZE. Then we determine the potential yearly deployment of electrolyzers capacity by using an S-shaped logistic function (Odenweller et al., 2022) (Eq. (1)). As a well-established commercial technology, the PEM electrolyzers are projected to capture a 40% market share by 2050 (Clapp et al., 2023; IEA, 2022; Kiemel and Smolinka, 2021; Smolinka et al., 2018), scaled from Germany to worldwide (Eq. (2)).

$$S_{total\ (t)} = \frac{S_{max}}{\left(1 + e^{-k(t-t_0)}\right)} \tag{1}$$

$$S_{PEM(t)} = S_{total\ (t)} \times MS_{PEM(t)} \tag{2}$$

Where $S_{total\ (t)}$ and $S_{PEM(t)}$ represent the total installed capacity and the PEM electrolyzers capacity in year t, respectively. S_{max} is the saturation level (target capacity 2050) of global electrolyzers. k is the growth constant. $MS_{PEM(t)}$ represents the dynamic market penetration of PEM electrolyzers in year t.

A stock-driven dynamic material flow analysis (DMFA) (Müller, 2006; Pauliuk and Heeren, 2020) was applied to calculate the total annual newly installed capacity of PEM electrolyzers ($I_{PEM(t)}$) (Eq. (3)). Then, the prospective inflow of the materials $I_{mat\ (t,i)}$ is a conversion of the demand for capacity from Eq. (3) multiplied by the dynamic material intensity data ($MI_{(t,i)}$) in year t (Eq. (4)).

$$I_{PEM\ (t)} = S_{PEM(t)} - \sum_{n=t_0}^{t-1} I_{PEM}(n) \times Survival(t-n) \tag{3}$$

$$I_{mat\ (t,i)} = I_{PEM(t)} \times MI_{(t,i)} \tag{4}$$

Where *Survival (t)* refers to the complementary cumulative distribution function (cdf) of the lifetime distribution of the PEM

Furthermore, according to the normal lifetime distribution (Müller et al., 2014), an inflow-driven DMFA (Van der Voet et al., 2002) was applied to calculate the outflows ($O_{mat\ (t,i)}$) and stocks ($S_{mat\ (t,i)}$) of the materials based on Eqs. (5) and (6):

$$O_{mat\ (t,i)} = \int_{t_0}^{t} I_{mat\ (t',i)} \times \left(\frac{1}{\partial\sqrt{2\pi}} \times e^{-\frac{1}{2}\times\left(\frac{t'-\tau}{\partial}\right)^2}\right) \tag{5}$$

$$S_{mat\ (t,i)} - S_{mat\ (t-1,i)} = I_{mat\ (t,i)} - O_{mat\ (t,i)} \tag{6}$$

Where $\left(\frac{1}{\partial\sqrt{2\pi}} \times e^{-\frac{1}{2}\times\left(\frac{t-\tau}{\partial}\right)^2}\right)$ is the normal distribution; τ is the average lifetime of PEM electrolyzers,; ∂ is the standard deviation (30% of the mean lifetime); t' is the age of the PEM electrolyzers from produced to the year t.

2.2. Scenario setting and data source

For our calculations, we use the assumptions of the IEA-NZE scenario as published in May 2021 (IEA, 2022, 2021a). The IEA-NZE is the most ambitious energy transition scenario released by the IEA. It outlines a pathway for the global energy sector to achieve net-zero emissions by 2050 using a variety of clean energy technologies, such as green hydrogen, without relying on land use measures for offsets. Additionally, the IEA-NZE scenario assumes a higher share of hydrogen in final energy consumption compared to most other IPCC 1.5° scenarios (IEA, 2021a; IPCC, 2018). This scenario provides projections of the global installed capacity of electrolyzers on a decadal basis. Historical global electrolysis capacity derived from the International Renewable Energy Agency (IRENA) (IRENA, 2020) and IEA (IEA, 2023c). Dynamic material intensity data of PEM electrolyzers, based on the current state of the art and considering future technological innovations, are derived from the reports of Joint Research Centre (JRC) (Dolci and Weidner, 2021), IEA (2021b), IRENA (2020), and other existing research (Delpierre et al., 2021; Kiemel and Smolinka, 2021; Liang et al., 2022; Making and Possible, 2021; Minke et al., 2021; Stropnik et al., 2019; van der Star, 2022). Presently, the lifetime of PEM electrolyzers is around 10 years, but the expectation is that it can double in the period up to 2050 (Clapp et al., 2023; Delpierre et al., 2021; Dolci and Weidner, 2021; IRENA, 2020, 2022; Minke et al., 2021; Ouimet et al., 2022; Urban Europe, 2019). Therefore, we assumed PEM electrolyzers' lifetimes of 10 years (short lifetime), 20 years (long lifetime), and a gradual increase from 10 to 20 years (changing lifetime: the lifetime is projected to increase from 10 years in 2025 to 15 years in 2035, and ultimately to 20 years in 2050), respectively. The detailed data are shown in the **Table S1** of the Supporting Information (**SI**).

To calculate the amount of Pt used in autocatalysts, we begin by calculating the difference between the total stock of passenger cars and the electric vehicle fleet, as outlined in (Liang et al., 2023). Then similarly, we use the dynamic stock model (Eqs. (3) and (4)) to obtain the annual inflows, outflows, and stocks of platinum in autocatalysts. The average platinum content is determined using data from a wide range of sources (see Fig. S2).

3. Results

3.1. The stocks and flows of Pt in PEM electrolyzers

The anticipated increase in the capacity of PEM will result in a tenfold increase in global demand for Pt in the coming decades. Between 2020 and 2050, the cumulative demand for Pt by PEM electrolyzers is projected to reach 700 tons (Fig. 1(b)). The resulting annual demand for Pt metals would peak around 2035 and then gradually drop. However, in the 10-year lifetime scenario, demand for Pt continues to grow after a plateau period (upper limits of the shaded area).

The total outflow of Pt is negligible compared with the demand before the 2030s. Scrapping will increase significantly after 2040 due to the time interval between the peaks of inflow and outflow. The annual outflow accounts for more than half of the inflow in the same year since 2040, and is even comparable to the inflow around 2050. In terms of socio-economic metabolism, the total cumulative outflow of Pt over the period 2020–2050 is between 25 and 55% of the cumulative inflow over the same period, with shorter lifetimes resulting in faster metabolism rates.

After two decades of rapid accumulation of Pt stocks, there is a notable slowdown in stock growth after 2040. This slowdown benefits from technological innovations that have improved the efficient use of these materials.

3.2. Pt flows and stocks from ICEVs

The projected demand for Pt in autocatalysts, presently a major application (Tang et al., 2023), will decrease as ICEVs are phased out (Fig. 2(a)). The amount of Pt in waste streams increases each year (outflows) up to the mid-2030s. After that, the annual scrap generation goes down as the remaining stock of ICEVs dwindles. According to the NZE scenario setup, no more passenger ICEVs will be sold worldwide since 2035 (IEA, 2021a).

According to Fig. 2(b), the cumulative outflow of Pt from ICEV catalysts between 2020 and 2050 is as high as 2500 tons, which means that a large surplus of Pt will be generated in addition to the amount of Pt needed to meet the demand of new ICEVs production. These surplus Pt have the potential to alleviate the demand pressures in emerging Pt end-use sectors, such as PEM electrolyzers.

3.3. Surplus of Pt among ICEVs and PEM electrolyzers

As shown in Fig. 3, in 2030 and beyond, Pt outflows from the ICEVs will exceed inflows, creating a surplus represented by the positive blue bar. Furthermore, the surplus Pt from the ICEVs alone would be sufficient to meet the Pt requirements of the PEM electrolyzers after 2035. From the analysis, it appears that Pt surpluses from the ICEVs could contribute significantly to supplying the demand for Pt for PEM electrolyzers. Whether or not this potential contribution can be realised, depends on the actual recycling rate of Pt in autocatalysts. The current end-of-life recycling rate (Eol-RR) is around 50% (Graedel et al., 2011; Hao et al., 2019b). We compare and provide a baseline of the Eol-RR that needs to be achieved to supply the Pt required for PEM electrolyzers (Table 1). Between 2031 and 2040, if the ICEV industry achieves an Eol-RR of 80.9% for Pt scrap, it is possible to eliminate the need for primary Pt mining for the deployment of PEM electrolyzers. When Pt scrap from PEM electrolyzers is included, the required EoL-RR drops to 71.2%. After 2040, the Pt surplus from ICEVs decreases, but it is still possible to fully cover the Pt demand of the PEM electrolyzer in the same period with optimistic recycling rates. The current EoL-RR of Pt from autocatalysts would not be sufficient to supply the required amount of Pt for PEM electrolysers. However, from the technical perspective, studies of Pt recycling from automotive catalysts show that Pt recycling rates can be quite high: from 85% (Torrejos et al., 2021; Xia and Ghahreman, 2023), 90% (Hong et al., 2020), 95% (Maes et al., 2016), or even 100% (Limjuco and Burnea, 2022).

4. Discussion and conclusion

Our analysis shows that under the IEA-NZE scenario, emerging PEM electrolyzers will increase the demand for Pt, while at the same time, large stocks of Pt currently in ICEVs will become obsolete in the future. From a materials perspective, Pt from end-of-life ICEVs have the potential to meet the material demand for PEM electrolyzers.

4.1. Rising surplus of Pt from autocatalysts could meet the Pt demand for PEM electrolyzers

By quantifying the demand for PEM electrolyzers, we provide insights into a particular bottleneck related to the energy transition. We investigate a potential solution as well: using scrap from ICEV catalysts. Our results show that Pt demand for green hydrogen production during 2030–2050 could potentially be satisfied through the material recycling of scrap automotive catalysts (Table 1). This paper does not consider the

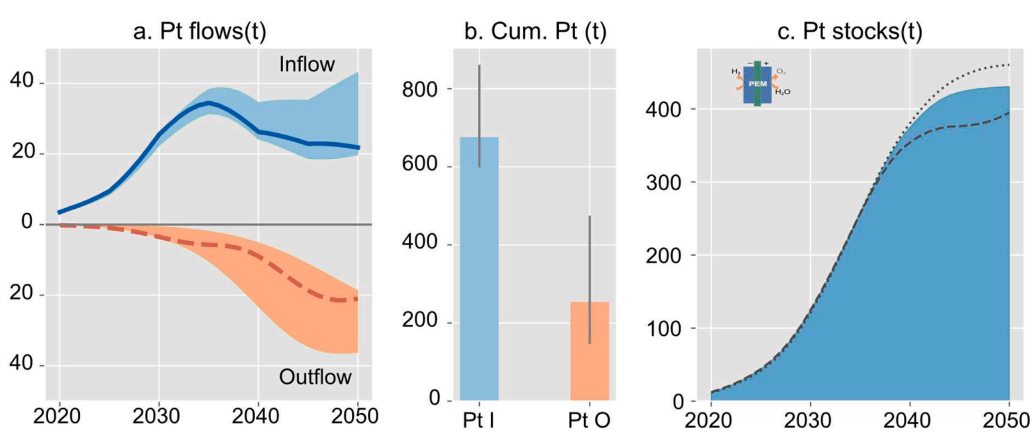

Fig. 1. Annual Pt demand (above the horizontal axis) and scrap generation (below the horizontal axis) (a), cumulative demand and scrap generation in the PEM electrolyzers (b), and the Pt stocks in PEM electrolyzers (c) from 2020 to 2050 under the NZE scenario. The shaded area in Fig. 1(a) illustrates the variation in flows with different lifetime assumptions: a shorter lifetime leads to higher material demand and more scrap, while a longer lifetime has the opposite effect. Similarly, the upper and lower gray lines in Fig. 1(b) represent the cumulative Pt demand under different lifetime assumptions, with longer lifetimes (lower value) and shorter lifetimes (upper value). The dotted and dashed lines in Fig. 1(c) represent the material stock under a 20 yrs and 10 yrs assumption, respectively.

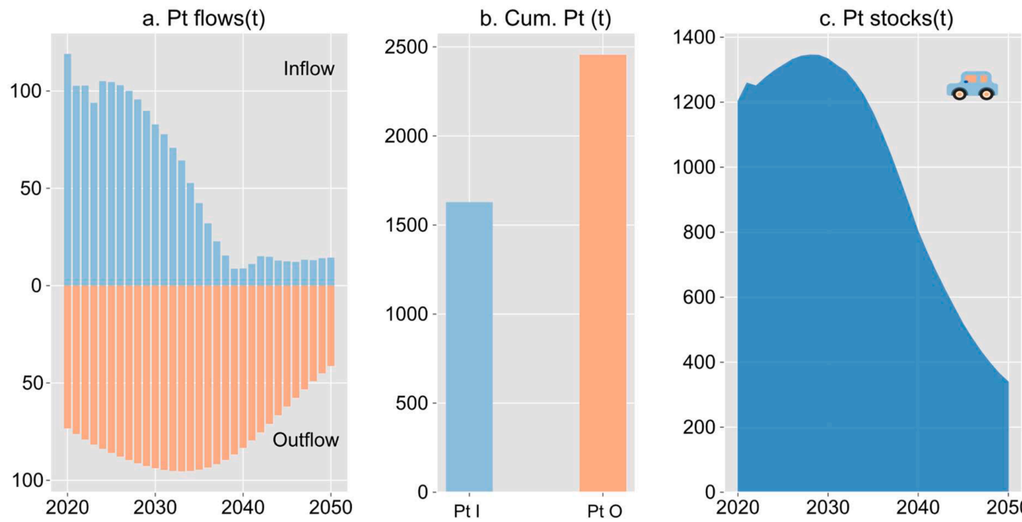

Fig. 2. Annual flows (a), cumulative demand and outflows (b), and stocks of Pt from ICEVs catalysts during the 2020–2050 period (unit: tonne) under the IEA-NZE scenario.

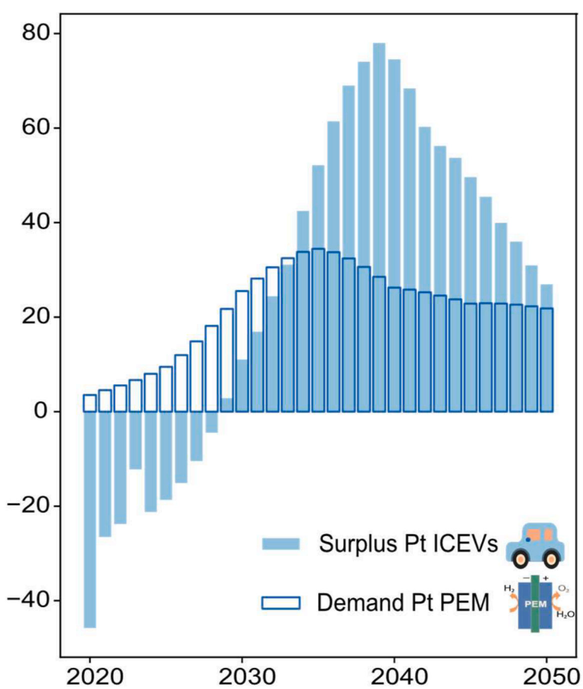

Fig. 3. The Pt surplus from ICEVs and the Pt demand of PEM electrolyzers.

Table 1
End-of-life recycling rates of Pt from catalysts required to meet the demand of Pt for electrolyzers.

Time	Baseline Eol-RR (Surplus ICEV)	Baseline Eol-RR (Surplus ICEV+ PEM scrap)
2031-2040	80.9%	71.2%
2041-2050	85.5%	54.9%

selection of different recycling methods or the technical details of Pt recycling. It is also unclear whether the losses that occur during the collection process are taken into account. Besides the Pt recycling from ICEV catalyst, according to the U.S. Hydrogen Strategy and Roadmap, the target recycling rate of Pt used in hydrogen production is even higher at 95% (2025) and 99% (2030–2035).

4.2. Other platinum group metals used for autocatalysts and PEM electrolyzers

We explored the contribution of Pt from end-of-life automotive catalysts to PEM Pt demand. Typically autocatalysts species also contain a small fraction of other platinum group metals such as rhodium and palladium, which are very low in content and interchangeable with Pt and have not been taken into account due to the lack of reliable content data. For PEM electrolyzers, in addition to the need for Pt, the risk of shortages of the other scarce platinum group element iridium (which is used as an anode material for PEM) has been widely discussed (Clapp et al., 2023; Minke et al., 2021; Rozain et al., 2016), but this is not a solution that can be found in end-of-life automotive catalysts.

4.3. Saving and recycling help balance the Pt supply and demand

The analysis in this paper has taken into account the increased material efficiency of technology innovations, with the Pt intensity of PEM in 2050 being only 30% of current levels (**SI, Fig. S5**). This is the main reason why the growth in installed capacity of PEM is two orders of magnitude greater than the growth in material demand, and without effective material efficiency improvements, the demand for Pt in PEM will increase dramatically. Emphasizing efficiency (less use) for this valuable element will support hydrogen's critical role in our journey to net-zero emissions.

Leveraging secondary materials through recycling not only mitigates the environmental impact often associated with primary mining (Hagelüken and Goldmann, 2022), but also reduces lead time (IEA, 2021b) and ultimately reshapes the Pt supply landscape. In addition, the supply of primary Pt is concentrated in South Africa (Nansai et al., 2014), while most of the Pt mines in autocatalysts are concentrated in developed countries with high car ownership (Pauliuk et al., 2021). By establishing a well-developed recycling industry, the secondary Pt supply chain will be more diversified, reducing potential supply risks.

4.4. Limitations and outlook

This paper does not address the PGMs used in heavy-duty trucks, as their number is minimal compared to passenger cars and the electrification of heavy-duty vehicles is slow (Hao et al., 2019a; IEA, 2023b). The supply and demand for Pt in other socio-economic sectors (e.g., jewellery and investment) have also not been considered (Sun et al., 2022). Expanding the scope of research in future studies will provide a clearer picture of the socio-economic metabolism of Pt. Some studies suggest that fuel cell vehicles rely on Pt, which would potentially offset the Pt surplus (Hao et al., 2019b; Tong et al., 2022; Zhang et al., 2023). However, this paper does not address this issue given the cost advantage of batteries for electric vehicles over performance enhancements such as range and the high uncertainty surrounding the development of fuel cell vehicles (IEA, 2023d, 2021a; Pivovar, 2019). Besides, different recycling technologies have their own advantages and disadvantages, which can also lead to differences in recycling rates (Tang et al., 2022). Several studies have also mentioned that high pressure and high temperature environments during vehicle operation may sometimes cause very small (microgram) Pt losses (Helmers, 2000; Xun et al., 2020), which are not considered here.

Bringing the recycling industry in line with the size of the waste market. Our results demonstrate the potential of using autocatalyst scrap as a source of Pt to supply emerging technology PEM electrolyzers. Future research should focus on how the recycling industry could meet the growing demand for Pt from this urban mine.

CRediT authorship contribution statement

Yanan Liang: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **René Kleijn:** Conceptualization, Supervision, Writing – review & editing. **Ester van der Voet:** Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107481.

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