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Aligning platinum recycling with hydrogen economy growth: a comparative LCA of hydrometallurgical and pyrometallurgical methods

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In the transition to renewable energy systems, the demand for proton exchange membrane fuel cells (PEMFC) is increasing, highlighting the need for sustainable platinum (Pt) recycling methods. This study combines future hydrogen demand projections with life cycle assessment (LCA) to compare the environmental impacts of hydrometallurgical and pyrometallurgical Pt recycling routes. Hydrometallurgical recycling was found to have a global warming potential (GWP) impact of 88.35 kg CO_2-eq per kg Pt, significantly lower than the 639 kg CO_2-eq per kg Pt associated with current pyrometallurgical methods. Utilising Integrated Assessment Models (IAM) and LCA methodologies, the research shows that introducing hydrometallurgical recycling by 2030–2035 could reduce cumulative GWP by 24–36%, subject to the rate of PEMFC market growth. Delaying implementation until 2040 still achieves a 19–22% reduction but misses the optimal window for environmental benefit. The study underscores the importance of developing efficient recycling processes to align with the projected growth in PEMFC demand, thereby reducing the GWP and enhancing sustainable material management. The study provides a forward-looking framework for policymakers and industry to prioritise low-carbon recycling technologies, supporting circular economy goals and reducing the environmental burden of critical material use in clean energy systems.

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1. This article uses life cycle assessment and material flow analysis to demonstrate that hydrometallurgical recycling of platinum in PEM fuel cells reduces global warming potential compared to conventional methods. It also highlights the importance of aligning the new recycling route with PEM fuel cell market growth to maximise development and optimisation while minimising the GWP associated with platinum circularity.
2. This study found a reduction from 639 kg CO_2-eq per kg of platinum for pyrometallurgical recycling to 88.35 kg CO_2-eq per kg of platinum for hydrometallurgical recycling. Over a 30-year period (2020–2050), hydrometallurgical recycling should be adopted by 2035 to maximize GWP reduction.
3. Going forward, further research should consider other impact categories as well as broaden the scope of the LCA to include the potential for recycling ionomer, as well as include other phases of the value chain.

1 Introduction

In the transition to renewable energy systems, the global demand for hydrogen fuel cells is expected to increase. Hydrogen, created with renewable energy, can help to reduce the impacts of difficult-to-decarbonise sectors such as transport or industrial heat sources.[1] While many fuel cell technologies exist, proton exchange membrane fuel cells (PEMFC) have the potential to be the most promising as, according to a review by Singla *et al.*, they have a fast start-up and shutdown time, which is required for vehicles as they need to respond to a power source on demand for acceleration.[2] They are also convenient for remote locations, have portable power, and are stackable, so they can scale easily to the energy demand required.[2] The catalyst required for this technology uses platinum (Pt) due to its high activity and selectivity even at low temperatures and its stability despite the corrosive acidic environment and high voltages present within the fuel cell.[3,4] However, a major criticism of PEMFC lies in its use of Pt due to its cost and environmental impact associated with it. Previously done cradle-to-gate Life Cycle Assessments (LCA) on membrane-electrode assemblies show that Pt is the largest contributor to global warming (GW) by an order of magnitude with PFSA as the second biggest contributor. This was based on the average market mix of Pt globally.[5]

The International Platinum Group Metals Association (IPA) has published a LCA that provides widely accepted industry

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average data for Pt from primary (~mining & refining) and secondary (~recycling & refining) sources.[6] Based on the 2022 values, the global warming potential (GWP) impact associated with the production of 1 g of Pt is 33.3 kg CO_2-eq for primary Pt and 0.639 kg CO_2-eq for secondary Pt. It is worth noting that the boundary conditions are slightly different for primary and secondary values because the transport to the recycling site is not included in the secondary number. The IPA LCA also reports values for primary energy demand, acidification potential, eutrophication potential, photochemical ozone creation potential, and blue water consumption, all of which show that secondary Pt has a lower impact than primary. While secondary Pt has a 98% lower GWP than primary Pt, the recycling & refining process uses pyrometallurgical techniques to recover the Pt, which accounts for about two-thirds of the GWP for secondary Pt. Additionally, relying solely on secondary Pt does not fully resolve issues of cost or supply, as platinum remains a scarce and valuable material used across multiple critical technologies. Therefore, improving material management through the development of dedicated, lower-impact recycling routes, such as hydrometallurgical processes tailored to PEM fuel cells, is essential to maximise environmental benefits and support a more circular and resilient hydrogen economy.[7]

The environmental impacts associated with the hydrometallurgical recycling of fuel cells have been considered previpously,[8,9] and it has been shown to have a lower GWP than the incumbent pyrometallurgical recycling route.[10] While promising, the hydrometallurgical process is still in development and is not readily available in the market, unlike the pyrometallurgical recycling process.

The market demand for fuel cells and, therefore, fuel cell recycling is currently still relatively low; however, this is expected to grow substantially in the future. While the 'current policy' scenario shows a modest increase in energy supplied from hydrogen, rising from 0.015 EJ per year in 2020 to 1.28 EJ per year by 2050, the majority (90%) of scenarios project a much higher range. These scenarios estimate hydrogen energy to be between 800 000 GJ per year and 40 EJ per year by 2050, with the highest projections reaching 150 EJ per year in 2050 and 317 EJ per year by 2100.[11] This potential for a very rapid and substantial increase in the fuel cell market means that in order to maximise benefit from this transition, it is critical not only to properly understand the difference in the environmental impact of the various recycling options but also to achieve the timely introduction of lower impact Pt recycling approaches (such as hydrometallurgical processing).

Without such recognition that the development of hydrometallurgical recycling needs to align with the fuel cell growth, there is a risk that the environmental burden associated with the recovery of Pt will be higher than necessary. In order to incentivise appropriate development goals and provide a strong case for improved recycling processes, quantification of the reduced environmental impacts and their timing is necessary. However, development takes time and resources, and allowing for optimisation during the development process can lead to further reduced impact and savings in cost. Additionally, building a recycling facility before there are significant quantities of scrap or end-of-life fuel cell material can cost unnecessary time, money, and materials. Therefore, a balance must be struck between the introduction of hydrometallurgical recycling soon enough to reduce the environmental burden of PEM fuel cell recycling and enough time allowed for successful development and optimisation of a recycling facility.

To effectively reduce the environmental impact of recycling Pt from PEM fuel cells, it is essential to compare the hydrometallurgical recycling route with the incumbent pyrometallurgical route through a comprehensive LCA. However, it is even more critical to integrate this data with market demand projections to understand the potential long-term risks and benefits of adopting a new recycling process and the risks associated with delaying its deployment. Specifically, it is useful to understand when a new recycling plant should be commissioned as this allows companies time to create robust technology that is optimised, construct any required facilities, and ensure a supply chain is in place. While LCA has been carried out for similar processes,[10] the link back to the material flow has not been assessed.

The research presented here examines these risks by quantifying the GWP associated with recycling scenarios for PEM fuel cells over the time period of 2020 to 2050. The objective is to identify the optimal timing and strategy for implementing low-impact recycling technologies that align with projected market growth. It does this by using a novel approach that integrates Material Flow Analysis (MFA) and LCA with projections from Integrated Assessment Models (IAM). By situating platinum recycling within a dynamic, forward-looking framework, this research moves beyond static LCA comparisons and provides a more realistic basis for decision-making. This study is the first to explicitly link the timing of technology deployment to hydrogen market growth, quantifying the environmental cost of delay and offering a risk-informed roadmap for aligning recycling innovation with PEM fuel cell end-of-life timelines. This study aims to support the earliest necessary introduction of a new technology while balancing the practicalities of that introduction. This approach supports the broader goals of the circular economy, sustainable material management practices, and climate mitigation in clean energy systems by aligning recycling innovation with the expansion of hydrogen technologies. By quantifying the environmental cost of delayed action, this study provides actionable insights for policymakers and industry to prioritise timely and low-carbon recycling solutions.

2 Materials & methods

2.1 IAM projections to platinum flows

To quantify the overall carbon footprint of recycling scenarios, it is first necessary to project the amount of Pt that will be recycled within the given time frame. This can be determined

Table 1 List of selected IAM IMPs adapted from Byers *et al.*[11] and IPCC[12]

Acronym	Climate category	Model	Scenario name in database
Cur-Pol	C7: limit warming to 4 °C (>50%)	GCAM 5.3	NGFS2_Current Policies (version: 2)
Mod-Act	C6: limit warming to 3 °C (>50%)	IMAGE 3.0	EN_INDCi2030_3000f (version: 1)
Ren	C1: limit warming to 1.5 °C (>50%) with no or limited overshoot	REMIND-MAgPIE 2.1–4.3	DeepElec_SSP2_ HighRE_Budg900 (version: 1)
LD	C1: limit warming to 1.5 °C (>50%) with no or limited overshoot	MESSAGEix-GLOBIOM_GEI 1.0	SSP2_openres_lc_50 (version: 1)
GS	C3: limit warming to 2 °C (>67%)	WITCH 5.0	CO_Bridge (version: 1)
SP	C1: limit warming to 1.5 °C (>50%) with no or limited overshoot	REMIND-MAgPIE 2.1–4.2	SusDev_SDP-PkBudg1000 (version: 1)

from the expected quantity of PEM fuel cells that will be in the market each year and, therefore, the amount of Pt going into and out of the market. This work uses the Illustrative Mitigation Pathways (IMP) from IAM as a basis to calculate the mass of Pt that will be required to meet potential PEMFC demands.[11] There are six selected scenarios shown in Table 1 that provide estimated energy supplied by hydrogen in exajoules (EJ) with a timeframe from 2000 or 2010 to 2100.[11]

The models presented in Table 1 are associated with climate categories from the IPCC that relate to temperature warming, ranging from limiting warming to 1.5 °C to 4 °C. These models come from different IAMs and encompass varying levels of climate policy, mitigation strategies, timing, and sustainable development. It is important to note that this selection is not representative of every model or scenario available but is a curated set that covers a broad range of potential outcomes while limiting the number of IMP used.[11]

The IAM projections provide values for the quantity of energy coming from hydrogen, but for this research, we aim to understand how much PEMFC may be on the market. The energy from hydrogen could be coming from other fuel cell technologies, but is also likely to be used in syngas, sustainable aviation fuel, or blended into the gas grid to reduce the impact of current technologies. It's important to note that the IAM projections refer specifically to energy supplied by hydrogen, not total hydrogen production, which includes non-energy uses such as ammonia synthesis and steelmaking. In order to use the projection values to predict Pt used in PEMFC, a factor of 30% is applied to the energy supplied per year to represent the quantity that is likely from fuel cells. This value is based on the predicted sectors for hydrogen from the International Energy Agency (IEA) roadmap,[13] which predicts that by 2050, 194 million tonnes (Mt) of the total 528 Mt of hydrogen-based fuels will be directly from hydrogen (including electricity from hydrogen and transport from hydrogen). Additionally, to account for the various types of fuel cell technology, this study assumes that approximately 80% of the energy from fuel cells is PEM. This assumes that PEMFC demand will be directly tied to the total energy from hydrogen being produced, which may be inaccurate, but is revisited in Section 3.1, where the results are compared with other projected fuel cell vehicle quantities. Initially, a smaller proportion of hydrogen will be used in PEMFC as the market is still developing, and hydrogen is being used to mitigate current technologies. Over time, however, a larger proportion will be used directly in electricity generation and transport.[13] Although a flat value is used in this study, which may not fully represent the actual scenario, the difference is likely negligible due to the initially small quantities involved.

To calculate the Pt demand to cover the energy supplied and convert from EJ to kW, several variables must be assumed, including the loading of Pt (g kW^{-1}) and the average running time of a fuel cell. The Pt loading is assumed based on industry estimates for the power density (kW m^{-2}), which is expected to increase, and the Pt loading per area (g m^{-2}), which is expected to decrease. Confident projections for these data in industry are only available until 2050, and therefore, the timeframe that is focused on for this research is 2020 to 2050.

Fuel cell properties are expected to vary depending on the use case (*e.g.* passenger vehicles, heavy-duty vehicles, large stationary power, *etc.*), so a weighted average has been used with the IAM values to determine the gross Pt needed to fulfil estimated demand.

The gross Pt demand per year was calculated for each model using the equation:

$$\mathrm{Pt}_{\mathrm{gross}} = (\mathrm{Pt}_{\mathrm{avg\ loading}}/t_{\mathrm{running\ time}}) \cdot E_{\mathrm{energy\ supplied}} \quad (1)$$

The units used in this case were $\mathrm{Pt}_{\mathrm{gross}}$ (tonnes), $\mathrm{Pt}_{\mathrm{avg\ loading}}$ (tonnes per kW) $t_{\mathrm{running\ time}}$ (hours), and $E_{\mathrm{energy\ supplied}}$ (kWh).

The gross Pt demand can then be used to understand the net Pt required to produce enough PEMFC to cover the projected demands based on scrap rates. These rates are assumed to decrease exponentially and reach a minimum of 10%. The fuel cells are anticipated to remain in the market for an average of 13 years with a normal distribution based on industry data. This assumption is slightly more conservative than the 15 years used in the literature.[14] The lifespan curve is applied to the Pt that is going into the market at the start-of-life each year to determine the end-of-life Pt that would become available each year. A collection loss of 20% is assumed based on what is currently seen with petrol vehicles.[15] With these values, which are provided with more detail in Table SB2 in the SI, it is possible to determine the

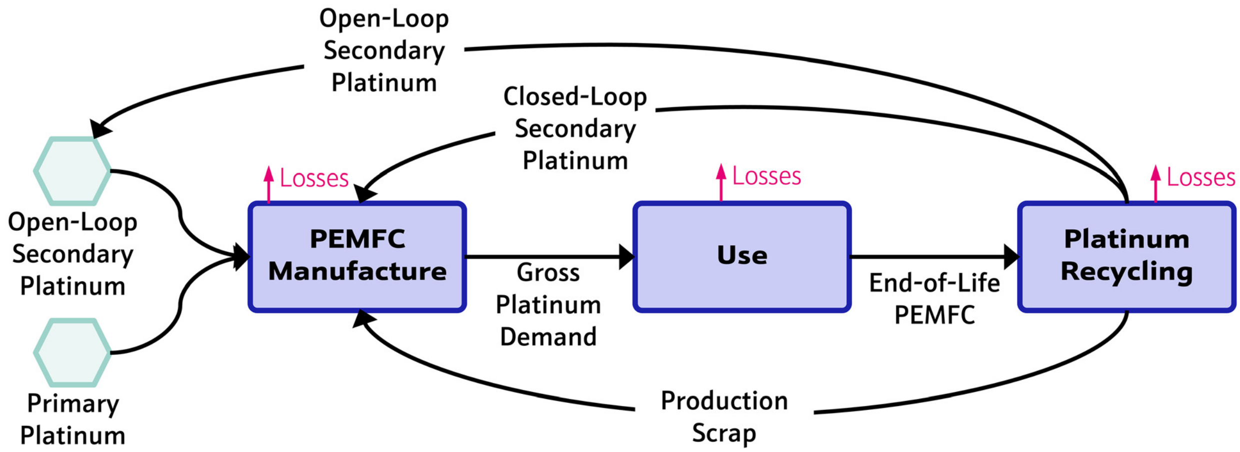

Fig. 1 Simplified stocks and flows of Platinum in PEMFC lifetime.

mass of Pt that is expected to be going to recycling each year based on the IAM demand scenario.

Overall, this process provides an estimate for the mass of Pt required per year in each of the flows represented in Fig. 1. In this case, Pt from outside of the system is considered a source or sink. The issue of Pt availability is outside of the scope of this work but has previously been considered.[16,17]

2.2 GWP of recycle routes

LCA is a comprehensive methodology (ISO14040-44) for systematically assessing environmental impacts of a whole cradle-to-cradle (from raw material acquisition through manufacturing, logistics and use to resource circulation) system.[18] As this study focuses on the recycle part, the system boundary starts from post-life raw material acquisition at the recycle gate, includes the recycling technologies and ends with the recovered refined resource (Pt) circulation into the value chain. In this study, the goal of the LCA work done was to provide a GWP value for the hydrometallurgical recycling of Pt to compare directly to the impacts associated with secondary Pt reported by the IPA in kg CO_2-eq per g Pt.

The life cycle inventory (LCI) was based on data available from a new proprietary recovery system. Due to data sensitivity, the variations around each value are presented (Table SA1 on the basis of 1 kg Pt recovery). The GWP was previously calculated for this process and estimated to be 13.6 kg CO_2-eq per kg Pt; however, the contribution of wastewater processing was not included in the greenhouse gas (GHG) emissions.[10] The final value may be sensitive to the emission factor used for wastewater treatment, which, based on a previous meta-analysis of wastewater treatment plants, can range between 0.055 and 5.3 kg CO_2-eq per m^3 of waste.[19] This could increase the impact by about 20% of the literature-reported value.[10] Additionally, there is no data for the treatment of potentially PFAS-containing waste caused by the perfluorinated ionomer material that is mixed with the catalyst, which could increase the value further. While this study uses a similar process, differences in inventory values and emission factors are chosen with ranges used in this study provided in Table SA1 of the SI. In order to directly compare with the IPA values,[6] the same system boundaries and the life cycle impact assessment method CML v4.8 of GWP100 were used. CML v4.8 was published in 2016 and therefore uses the superseded IPCC values for GWP100 from 2013 so it may vary slightly from the most recent IPCC 2021 GWP100 values.

The LCA of both recycling routes is assumed to be carried out after the collection and dismantling of the fuel cells into catalyst coated membranes (CCM), which would be the same in both scenarios. Therefore, the system boundaries have been set to include waste CCM at the point of being at a recycling facility and the recycling process to create refined Pt, which can be used directly in the manufacture of new PEMFC catalyst. The study does not include the ionomer recovery; however, this is something that should be considered going forward as it is a potential benefit of hydrometallurgical recycling when compared with pyrometallurgical recycling in which the ionomer is lost. The system boundaries are shown in Fig. 2 with further details in Table SA2 of the SI.

Fig. 2 illustrates the system boundaries for platinum recovery *via* pyrometallurgical and hydrometallurgical routes. Our novel hydrometallurgical route offers a closed-loop, selective recovery of platinum directly from CCMs, significantly reducing material losses compared to pyrometallurgical methods, where precious ionomer materials are destroyed during high-temperature smelting. Ionomers can constitute a significant portion of a CCM, as the membrane itself is composed entirely of perfluorinated ionomer, and the catalyst layers also contain ionomer binders. Depending on the membrane thickness and the ionomer loading in the catalyst layers, their destruction in conventional processes represents a significant material loss. In the hydrometallurgical process, waste CCMs undergo mechanical processing, followed by leaching and purification steps that enable the recovery of both platinum and perfluorinated ionomers. These ionomers, which are currently incinerated in pyrometallurgy, are instead recovered, reducing emissions and aligning with the principle of designing safer pro-

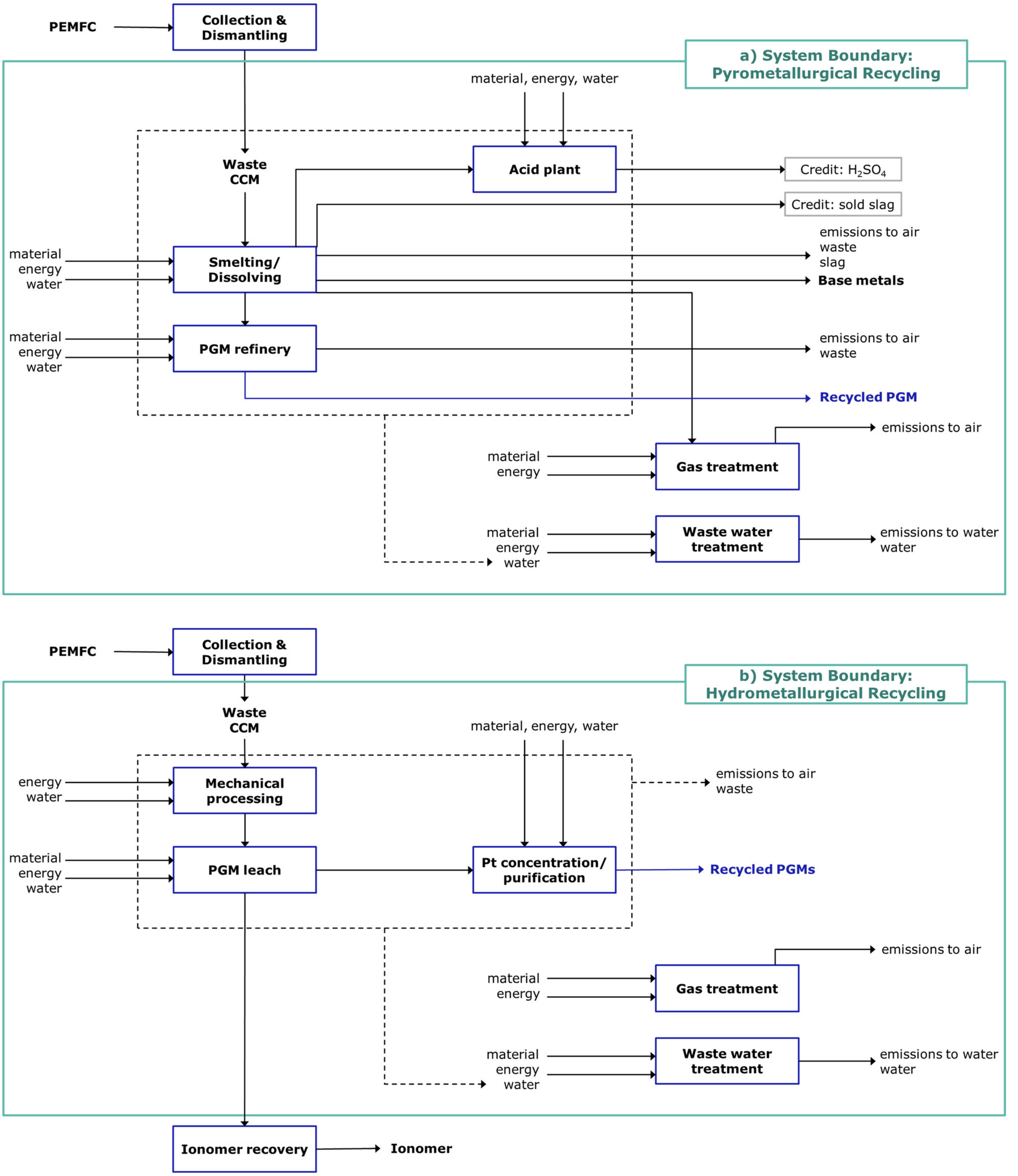

Fig. 2 System boundaries of secondary platinum from (a) current pyrometallurgical recycling route (adapted from International Platinum Group Metals Association[6]) and (b) potential future hydrometallurgical route.

cesses. This supports atom economy and waste minimisation. The novel process operates at temperatures approximately 90% lower than those used in pyrometallurgy, resulting in substantially lower energy consumption and carbon emissions, an important advance for energy-intensive critical material recovery. Moreover, the shift away from high-temperature smelting towards solution-based processing reduces operational hazards and allows for decentralised or modular deployment of recycling units, increasing resilience and safety across the value chain.

This study uses the cut-off method and background LCI data from Ecoinvent v3.9.1 in SimaPro v9.4. The foreground inventory industry data are from Johnson Matthey and follow the principles of ISO 14040 & 14044. Further assumptions are listed in Table SA3 of the SI.

2.3 Recycling strategies and platinum sources

This study considers two options for Pt recovery: a pyrometallurgical process and a hydrometallurgical process. In order to understand the impact of recycling options on GWP, it is assumed that the net Pt demand for fuel cells would be covered by secondary Pt, and all available end-of-life material would be recycled using the hydrometallurgical route to be used directly in the production of new PEM fuel cells, which is also referred to as closed loop recycling. This route has been demonstrated in the literature and is being marketed by Johnson Matthey.[7,20] The total GWP per year was calculated for each of the IAM scenarios described in Section 2.1. To then understand the impact of the delayed introduction of hydrometallurgical recycling, the same case was applied where the net Pt demand was completely filled by secondary Pt; however, the hydrometallurgical recycling was only considered for a portion of the time. This was done every 5 years, considering the introduction of hydrometallurgical recycling in 2025, then 2030, 2035, *etc.*, with the final scenario assuming that only pyrometallurgical recycling is in place from 2020 to 2050. The total GWP associated with the Pt used was then calculated, and a comparison was made between each 5-year period to see the increase in GWP associated with the use of pyrometallurgical recycling compared to hydrometallurgical recycling over the given time period.

2.3.1 Sensitivity analysis. In Section 2.1, multiple assumptions are made in order to determine the quantity of Pt that is going into and being recycled from PEMFC. A sensitivity analysis was done on the assumptions where industry data was not available: the PEM market share and the running time of the fuel cell. These variables were each changed by ±25% to determine if they had an impact on the conclusions of the study.[18]

3 Results & discussion

3.1 Gross platinum demand

Based on the six IMP IAM scenarios, Fig. 3 and Table SB1 of the SI shows the projected demand for Pt in PEM fuel cells is expected to increase going forward, even with the lowest case where current policies remain until 2050. However, the range of expected Pt demand for PEMFC increases as time increases. By 2050, the range is between 25–850 tonnes of Pt. Due to the IAM scenarios being published in 2022, the models are from 2020. The Pt demand was calculated for the initial 2020 values, and at its highest of 60 tonnes, this falls outside of the actual use. Johnson Matthey report the total demand for Pt in 2020 to be 224.1 tonnes, with automotive demand being 28% of the demand, however, the majority of this will be autocatalysts.[21] The total Pt supply and demand over the last five years has been between 200–262 tonnes per year. In the results shown here, the values projected for 2050 have the potential to far exceed the demand that has been required in the past.

To understand how similar these values are to other estimates, the data is compared with various sources. The Hydrogen Council set out ambitions for ∼425 million road vehicles powered by hydrogen by 2050, with a 2030 milestone of 10–15 million cars and 500 000 trucks.[22] Based on the average Pt loading per vehicle (including light, medium, and heavy duty vehicles) decreasing from approximately 60 g per vehicle to 15 g per vehicle, this correlates most closely with the SusDev_SDP-PkBudg1000 scenario.

The U.S. Department of Energy estimates that the global manufactured capacity of PEMFC in 2050 will be approxi-

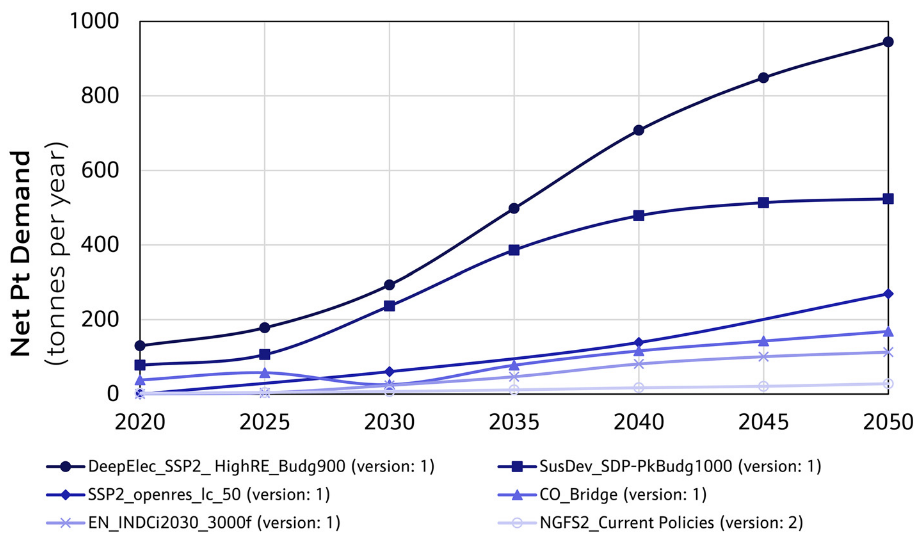

Fig. 3 Net platinum demand over six scenarios. Includes material that would be scraped during the manufacturing process.

mately 700 gigawatts.[23] In a complimentary report, they project that the global demand for Pt is between ~3–10 tonnes per year for PEMFC.[24] This estimate is very low compared to the Hydrogen Council vision and slightly lower than the result found in this paper from the NGFS2_Current Policies (version: 2) scenario which range from ~3–25 tonnes per year.

Similarly, the IEA reported that current global hydrogen targets see about 1.5 million fuel cell vehicles by 2030 and nearly 5 million by 2040,[25] which again aligns with the NGFS2_Current Policies (version: 2) scenario. Based on these three comparisons, it suggests that the NGFS2_Current Policies (version: 2) scenario is the most likely scenario or at least most closely aligned to current expectations. This pathway follows a warming limit of 4 °C, so there is potential for governments to increase intervention in future. Despite the uncertainty on which scenario is most likely, it is expected that it will be strongly related to potential changes in policy and legislation.

The values for projected platinum demand used in this research are calculated from existing data estimating total global energy demand from hydrogen.[11] The use of multiple demand scenarios addresses the uncertainties within these projections caused by different possible rates of future increases in demand for electric vehicles. For example, the NGFS2_Current Policies scenario reflects a continuation of current vehicle ownership and electric vehicle penetration trends, while higher demand scenarios imply greater PEMFC uptake. Using multiple demand scenarios should also capture population changes that may occur over the study timespan. To further address uncertainties, a comparison of the projections with existing reports for future vehicle usage has been undertaken.

These results highlight two key risks associated with the future demand of Pt for PEMFC; the first is that there will be an increase in demand going forward that the existing supply cannot meet, leading to an associated increase in the mining of new Pt. The majority of Pt is mined in South Africa, where 71% of energy is coal-based.[26] Mining companies, including Sibanye Stillwater, Anglo American Platinum, Implats, and Northam Platinum Holdings Limited, are investing in securing renewable energy to try to reduce reliance on coal either through directly funding renewables capacity or through power purchases and offtake agreements that allow other bodies to invest in renewables within South Africa.[27–30] The mining process may still require a large amount of energy, especially as the grade of ore decreases over time, making it important to mitigate reliance on primary metal. This can be mitigated through appropriate materials management, including reducing Pt loading and effective recycling. The second risk associated with the results is the range of projected platinum demand. This creates uncertainty for recyclers and miners, especially when investing in new capital equipment, whether that be for miners to reduce reliance on coal or recyclers investing in new processes such as the one presented in this study.

3.1.1 Sensitivity analysis. The sensitivity analysis presented in Fig. 4 explores the impact of varying two key assumptions, the share of energy from hydrogen that can be attributed to PEM fuel cells and the fuel cell running time, by ±25%. These adjustments result in a broader range of projected platinum demand across all scenarios, but the overall trends remain consistent with the original analysis. In all cases, demand increases over time, and the differences between scenarios are consistent with the baseline analysis. The sensitivity analysis reinforces the reliability of the model's conclusions and proves its robustness. Regardless of uncertainties in market penetration or operational assumptions, the need for timely

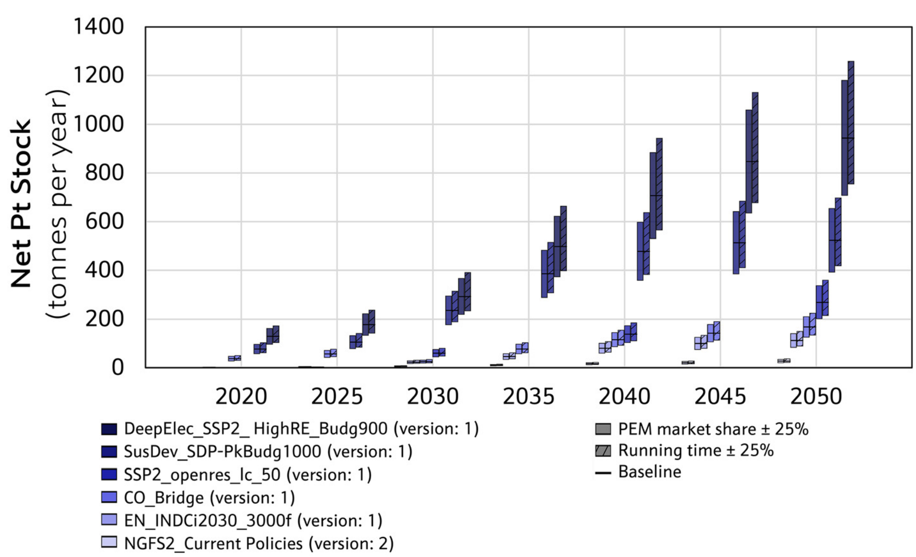

Fig. 4 Net platinum demand over six scenarios represented by a range for each scenario. The range shows the impact of ±25% to the assumed quantity of energy from hydrogen that will come from PEM fuel cells represented by a solid colour and the impact of ±25% of the running hours of the fuel cell over its lifetime represented by hatched colours.

implementation of low-impact recycling technologies remains critical. The analysis highlights that although the absolute output values may vary, the strategic insights derived from the scenario comparisons, particularly the benefits of early adoption of hydrometallurgical recycling, are not sensitive to these variations. Based upon this the remaining results are only presented using the baseline model assumptions.

The sensitivity analysis in Fig. 4 shows that the range of results is dependent on the chosen IAM scenario. The higher the projection for energy use from hydrogen, the greater the range of results from the sensitivity analysis.

3.2 Platinum recovery

When the baseline projections are taken forward to incorporate end-of-life, the Pt flows can be shown over time. As discussed in Section 3.1, most scenarios have a clear increase in demand over the next 10 years. Fig. 5 and Table SB1 in the SI show the quantity of Pt that is expected to be recycled back into the system for each year. This includes both production scrap and end-of-life material, where, in all scenarios, the majority of Pt being recovered in the first 5 to 10 years is production scrap. As efficiency and yields improve over time, there is a clear drop in the quantitative Pt being recycled. This is due to the slowdown of production scrap while still having limited end-of-life material available due to the lifetime of a PEMFC. During this growth stage, there will be reliance on other open sources of Pt from either pyrometallurgical secondary materials from other uses or primary material.

As time continues, the gap between Pt demand and Pt available from recycling will become smaller as the growth curves level out. In this study, the projection is to 2050, where there is expected to still be growth within this technology. For the steady state, it should be assumed that all production scrap could be readily recycled, and the amount of Pt at the end of life would become equal to that is going in. This would also rely on the amount of Pt being thrifted and the loadings remaining relatively constant in future cars, meaning what is going into the system 13 years earlier would be equal to that coming out. It would also rely on a more significant portion of the end-of-life vehicles going back to recycling. In 2019, it was estimated that the automotive market saw approximately 30% of losses in catalytic converters during its use and collection phase.[16] Due to the value of the stack, inability to run the vehicle without a fuel cell, and potential future legislation on recovery, there's potential for that value to decrease for fuel cell vehicles.

The speed of growth of the technology directly relates to how much closed-loop recycled Pt is for later use. For example, in 2050, the SusDev_SDP-PkBudg1000 (version: 1) scenario has a much greater proportion of the Pt being sourced from fuel cell recycling due to earlier market penetration. Another interesting aspect is that earlier market adoption saw a significant amount of production scrap in earlier years, for example, the 2020 and 2025 values for the CO_Bridge (version: 1) scenario.

Fig. 5 also shows the potential need for recycling processes specific to fuel cells to be available. In earlier years, the majority of the material required for recycling was production scrap. As the market grows, more end-of-life materials will be leaving the market. With the exception of the SSP2 scenario, all showed an initial requirement for recycling of the scrap material and then an increase from 2035 in requirements for end-of-life recycling.

These trends are helpful to understand future material management and to identify where Pt group metal (PGM) sourcing may be more difficult as the technology grows and is sensitive to the rate of growth. Due to the lower impact associated with secondary Pt, the goal should be to maximise the recovery of the metal and use secondary Pt where possible without transferring the burden to other industries. This analysis assumes an 80% recycling rate of Pt from PEMFCs in align-

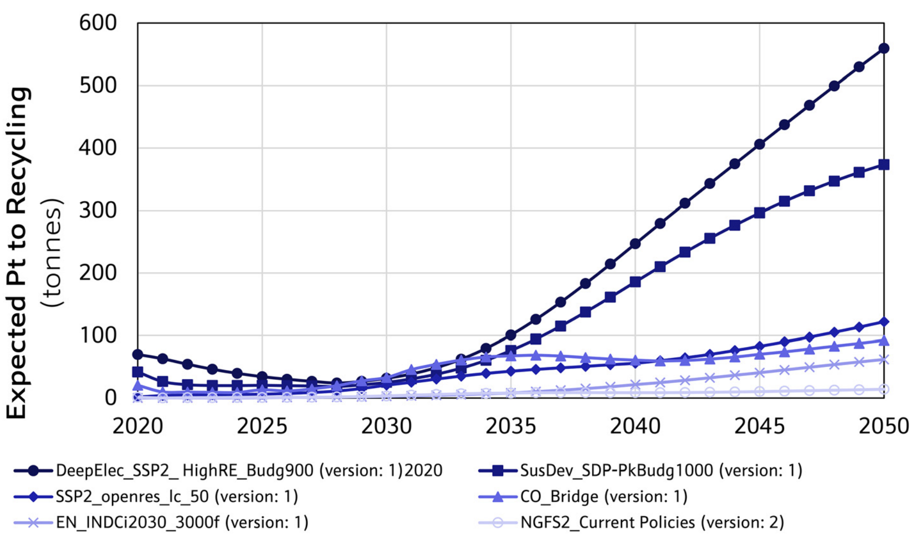

Fig. 5 Net platinum to recycling over six scenarios. Includes material that would be scraped during the manufacturing process.

ment with current recovery rates observed specifically for automotive catalysts.[16] In 2016, approximately 60% of open-loop platinum at end-of-life was successfully recycled, with the majority of losses occurring during the collection phase.[16] Therefore, the recycling rate of Pt from PEMFCs is above the average across the entire market.

3.3 GWP of recovery methods

The GWP of the hydrometallurgical recycling in this study was found to be 88.35 kg CO_2-eq per kg of Pt recovered in the form of 30% chloroplatinic acid (CPA). This is an order of magnitude higher than previously reported values of 13.6 kg CO_2-eq per kg of Pt.[10] The differences in found values can be attributed to the difference in quantities of materials and energy input into the system as well as the emission factors that are chosen. When calculating the GWP of the inventory supplied by Uekert, Wikoff and Badgett[10] with the chosen emission factors in this study, the result is 105.0 kg CO_2-eq per kg of Pt. This highlights the inherent limitation of LCA as the emission factors were not listed in the original study and it is therefore difficult to compare final values between studies without a certain level of transparency. Despite the differences in the values, 88.35 kg CO_2-eq per kg of Pt is used in this study as it is a reasonable number given the uncertainty in the literature values. Additionally, as it is larger than the originally reported value, it allows for more conservative projections in GWP reductions. The value calculated for hydrometallurgical recycling was then compared with the value from the IPA for pyrometallurgical recycling (639 kg CO_2-eq per kg of Pt (ref. 6)). For context the IPA has reported the GWP of primary production to be 33 300 kg CO_2-eq per kg of Pt.[6]

Based on these values, it is understood that as the demand for Pt in fuel cells increases, the quantity of end-of-life & scrap Pt increases, and the net GWP impact increases. The net GWP impact would, therefore, be higher if the industry standard for fuel cells remains pyrometallurgical recycling than if there is a shift to hydrometallurgical recycling. Because this process is not yet running at scale, the question of timing should be addressed. Due to the slow-to-start ramp-up of material and the delay in getting end-of-life fuel cells back to be recycled, the driver to improve the recycling process may be delayed.

Fig. 6 represents the net increase in GWP of the recycling of Pt in fuel cells for each 5-year delay in the introduction of hydrometallurgical recycling for each of the demand scenarios.

All scenarios follow a similar trend, with the introduction of hydrometallurgical recycling having a small effect on the total GWP until about 2035. This shows that it is critical to introduce the new recycling process by 2035 to avoid unnecessary contribution to GWP. If hydrometallurgical recycling is not introduced until 2040, there would still be a 19% to 22% reduction in GW compared to not introducing it at all. Moving this deadline to 2030 brings the savings up to 24% to 36% of overall GWP. This shows a massive improvement in its short 10-year time span. If the introduction is in 2025, the savings are between 24% and 38%. The difference between the 2030 and 2025 scenarios is minimal, which allows for additional time to develop the process and supply chain without contributing unnecessarily to global warming. Changing assumed values doesn't change the overall trend of the results in this case.

While these scenarios assume that the GWP impact per gram of Pt would remain the same for the two routes, there is a lot of potential for optimisation within both routes. As the introduction of the new recycling process is delayed, the average GWP impact per gram of Pt increases in all scenarios. These values are based on an ideal scenario where once hydrometallurgical recycling is deployed, all PEMFC requiring re-

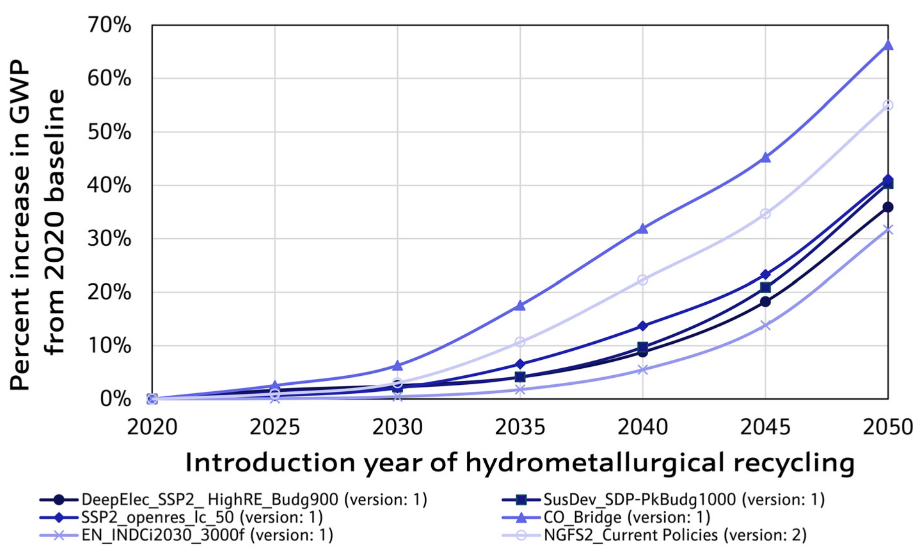

Fig. 6 Percent increase in total GWP impact for each year delay in the introduction of hydrometallurgical recycling route. Where 2020 represents hydrometallurgical recycling being available for the entire time period, 2050 represents no use of hydrometallurgical recycling during the given period, and 100% of platinum is recycled *via* pyrometallurgical routes.

cycling would go through a hydrometallurgical route; this still gives an indicator of the potential GWP savings.

Both from an industry and legislative perspective, it is recommended that the new recycling should target between 2030 and 2035, but the actual scale of GW savings does depend on the growth of the fuel cell market. For example, in the DeepElec_SSP2_ HighRE_Budg900 (version: 1) scenario, the 3% difference between 2030 and 2035 is approximately 111 tCO_2-eq over the 30-year span. On the other end of the spectrum, the NGFS2_Current Policies (version: 2) scenario difference between the 2020 and 2050 values is 71%, which is approximately 126 tCO_2-eq. While these are the two extreme cases, it shows that timing becomes even more pertinent if the market is to develop significantly.

Policymakers should seriously consider how fuel cell materials are managed, and better recycling practices should be promoted in a timely manner. Based on these findings, this should be encouraged no later than 2035. While it's likely that this estimate can be updated as time progresses and there is a better understanding of the fuel cell market, the introduction of a new recycling process requires foreplaning and development, making it helpful to have an initial target date.

4 Conclusions

As the transition to renewable energy systems accelerates, the demand for proton exchange membrane fuel cells is expected to rise in all scenarios. This research highlights the environmental importance of adopting hydrometallurgical recycling over the current standard pyrometallurgical processes for Pt recovery in PEMFC. While prior LCAs have reported GWP values for hydrometallurgical Pt recovery (*e.g.*, 13.6 kg CO_2-eq per kg Pt (ref. 10)), our study accounts for previously excluded emissions from wastewater treatment and PFAS handling, yielding a more practical, robust and realistic estimate of 88.35 kg CO_2-eq per kg Pt. Unlike previous studies that have limited their scope to static comparisons of GWP across existing recycling technologies, our work integrates dynamic projections of hydrogen market growth using Integrated Assessment Models[11] with LCA of Pt recycling routes. Crucially, this research is the first to quantify the environmental cost of delay in deploying a lower-impact hydrometallurgical route. We show that introducing hydrometallurgical recycling between 2030–2035 could reduce cumulative GWP by 24–36%, while delaying until 2040 results in diminished gains (19–22%) and misses a critical window for action. This temporal dimension, which connects emerging recycling technology to the fast-evolving hydrogen economy, is both novel and urgent, offering actionable intelligence for policymakers and industry stakeholders. We also address the practical challenges of aligning recycling infrastructure with PEM fuel cell end-of-life timelines and scrap availability. The study presents a risk-informed roadmap for optimised materials management, tailored to six IAM pathways, offering unprecedented granularity and foresight.

While there are significant assumptions made in this study due to the nature of forward projections, the exact values may vary but the overall conclusions do not change across different scenarios. There are, however, several limitations and potential for further work to be done. Firstly, this study focuses on the GWP benefits for Pt recovery, but hydrometallurgical recycling offers additional benefits. This includes the potential to recover the ionomer rather than incinerating it. Not only would this help eliminate possible safety concerns, but it would also prevent the manufacturing of fresh ionomer. This should be considered in future when looking at the cumulative benefits of the recycling process. Additionally, having a closed-loop process for both the Pt and ionomer would help mitigate the environmental contamination of PFAS from the ionomer. In addition to potential climate change benefits, there may be operational advantages such as faster processing times, which enable handling higher volumes of material more efficiently. From an economic perspective, faster processing times can also help with the cost of recycling. Recyclers' revenue is impacted if, during the processing time, there is a significant decrease in price. This means reducing processing time can also decrease the risk of price volatility in the PGM market affecting recyclers. In addition to this, while costing has not been considered at this point the advantages that contribute to reduced environmental impact such as reducing loss of material as seen with the ionomer, reducing temperature and therefore energy consumption and opportunity for decentralised or modular deployment of recycling units can also contribute to decreased cost. A closed loop model including the above points should be considered by changing the functional unit or using allocation in future along with a full techno-economic assessment when doing further comparators.

In addition to including the ionomer, in future it would be worth considering both PEM fuel cells and electrolysers which would also open the work to look at the iridium that's used in electrolysers. There is potential for this to take a cradle-to-cradle view of the system and incorporate all other aspects of the system such as the impact of PGM loading on the lifetime of the vehicle for example. Including other LCA impact categories would also help to provide a more rounded view of the system.

It would be useful in future to include prospective aspects of LCA that incorporate the optimisation of the new recycling route over time, as well as use the IAM energy system projections to show the reduction in impact associated with the renewable energy transition on both recycle routes. For the purposes of simplicity and to limit the variables in the scenarios, this has not yet been considered. Another potential limitation is the assumed values, such as loadings, lifetime, losses & yields, and PEM market penetration, could be varied to understand further sensitivities. Additionally, the impact of lowering Pt loadings on the carbon footprint of both recycle routes is outside of the scope of this research.

It is also important to understand the context of using PGMs as the footprint associated with the mining process is large. However, it plays a critical role in various industries, including renewable energy systems. The high GWP of mining means further emphasis should be placed on efficient recycling methods to maximise the utility of extracted materials. Although the cut-off method used in LCA does not account for the recyclability of a material, PGMs are able to be recovered at very high yields, making them ideal for a circular economy as long as there is effective material management in place to reduce losses of material throughout the use and collection phases.

This studies focus was on change in the recycling process for PEMFC, however it is suggested that this method could be used to determine the carbon cost of time for any technology comparison with an incumbent process.

In this study, it's shown that proactive planning and investment in hydrometallurgical recycling are crucial to achieving sustainable Pt use in PEMFC, thereby supporting the broader goal of reducing the carbon footprint of our energy systems. Policymakers and industry stakeholders must prioritise the advancement of hydrometallurgical recycling methods to mitigate the environmental impact of Pt extraction and recycling, with a recommended target introduction between 2030 and 2035.

Author contributions

JL: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing. RW: supervision, writing – review and editing. JS: supervision, writing – review and editing. RM: supervision, writing – review and editing, funding acquisition.

Conflicts of 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

This study was carried out using publicly available data from AR6 Scenario Explorer and Database hosted by IIASA at data.ece.iiasa.ac.at/ar6/. Additional data supporting this article have been included as part of the SI. Supplementary information includes the life cycle inventory and chosen emission factors, details on system boundaries, a list of assumptions for the LCA and MFA, and full MFA results. Supplementary information is available. See DOI: https://doi.org/10.1039/d5gc02447a.

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