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Metal Coatings for Electrocatalytic Applications: Towards a Safe and Sustainable by Design Approach †

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Abstract

Several attempts have been made to replace the critical raw material platinum (Pt) with other metals, mainly focusing on its functional performance, while safety and sustainability criteria are often overlooked. Here, the substitution of Pt by nickel-based coatings is addressed for water electrolysis applications. Risk assessment and life cycle assessment are iteratively performed at the laboratory scale and after upscaling metal coating protocols. The challenges for the transition towards an integrated safe and sustainable by design (SSbD) approach are identified, and strategies are proposed to resolve them. Valuable insights emerge from the individual assessments (e.g., hotspots, trade-offs, and recommendations for sustainability and safety), as well as regarding the transition towards an integrated SSbD (e.g., dealing with data gaps and uncertainties).

Keywords: life cycle assessment (LCA); chemical risk assessment (CRA); safe and sustainable by design (SSbD); platinum-free cathode; water electrolysis (WE)

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1. Introduction

Platinum (Pt) and other platinum group metals (PGMs) have unique properties, such as high resistance to chemical attack, wear, and high temperatures, and outstanding catalytic and electrical properties, which make them indispensable for several key industrial applications, such as renewable energy, electric mobility, and digital technologies. However, due to their high price and scarcity, reliance on imports from sources outside Europe for their supply, and the lack of effective substitutes for PGMs in these strategic applications, they are categorized as critical raw materials by the European Commission [1,2]. To address this, several attempts have been made to decrease the loading or to fully replace Pt with more inexpensive and earth-abundant metals and their alloys, such as nickel (Ni), Iron (Fe), molybdenum (Mo), and cobalt (Co) [3]. Previous reports on Pt substitution primarily focused on experimental results regarding functional performance at the lab scale, while criteria related to risk, safety, and sustainability are often overlooked.

Here, the substitution of Pt coatings by Ni-based coatings is addressed as a possible cathode electrocatalyst for water electrolysis (WE) applications, using experimental protocols initially validated at the lab scale, and thereafter adapted to the pilot scale. Importantly, at early stages of the experimental protocol development for both scales, chemical risk assessment (CRA) and life cycle assessment (LCA) were applied to identify hotspots and develop recommendations. Thus, at each scale, criteria related to safety and sustainability

were considered, in addition to electrocatalytic performance, to finalize the experimental protocols and select the most promising ones for further development. Finally, the transition from individual CRA and LCA towards an integrated safe and sustainable by design (SSbD) methodology [4] was pursued by identifying similarities, differences, and challenges for this transition and proposing strategies to resolve them, thus facilitating the implementation of the SSbD methodology in metal coating development.

2. Materials and Methods

An adaptation of the simplified method developed by the French National Institute of Safety at Work [5] was employed for CRA, using the online platform Quarks Safety® V4.30.21. LCA was performed according to ISO standards 14040/44 [6,7] and the ILCD Handbook [8], using software SimaPro 9.5, database Ecoinvent 3.8, and the Environmental Footprint (EF) 3.0 method for impact assessment. Coating development at the lab scale was performed by researchers at the Universitat Autònoma de Barcelona and CIDETEC, and thereafter upscaled at the facilities of CIDETEC.

3. Results and Discussion

3.1. Effect of Upscaling on Safety and Sustainability

Metal coating is a multi-step process (Steps 1–7), including pre-treatment, post-treatment, and two hybrid deposition steps, employing Ni and two other elements (Ni-A in Step 4, Ni-B in Step 5). The comparative LCA of Steps 4 and 5 at the lab and pilot scale is shown in Figure 1a for selected impact categories, and the occupational risk priority results of all steps (numbered) and the corresponding chemicals used (indicated with letters) are shown in Figure 1b. Upscaling resulted in up to 80% decrease in LCA impacts (downward arrows in Figure 1a), for both steps in all 16 impact categories. On the other hand, upscaling had mostly negative impacts on safety. The risk priority of six fabrication tasks increased (upward arrows), while only three decreased (downward arrows), and four remained stable (indicated with lines in Figure 1b). Different hotspots were identified via LCA between scales, due to deposition protocol modifications. For example, at the lab scale, only the Ni source exceeded 15% of impacts in any category, whereas at the pilot scale, component A also had a significant contribution of up to 36%. Both hybrid deposition components (Ni-B) had significant contributions of up to 69% and 77%, respectively, to Step 5 impacts. While some overlap exists for hotspots between LCA and CRA, a different set of substances and processes were proposed for substitution or optimization via CRA at both scales, such as strong acids or bases used for deposition bath maintenance.

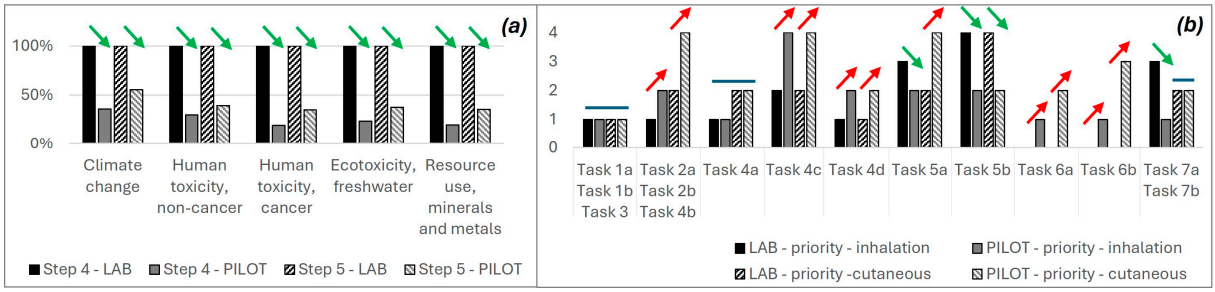


Figure 1. (**a**) Comparative LCA impacts of the hybrid deposition baths employed in Step 4 and Step 5 at the lab and pilot scale, per 1 m^2 coated surface; (**b**) comparative CRA influences for electrode fabrication (Steps 1–7) at the lab and pilot scale.

3.2. From Individual Assessments to SSbD—Challenges and Lessons Learnt

Several differences exist in the scope of CRA and LCA, resulting in different hotspots and recommendations. Highly hazardous chemicals at frequent exposure may be a CRA hotspot while resulting in negligible LCA impacts, depending on the processes and emissions during their upstream production. Moreover, materials and processes with significant LCA impacts, such as waste treatment or electricity use, are not part of CRA. This may result in different and even conflicting results, regarding, for example, the use of gloves or ventilation, which is mandated from the perspective of CRA but may result in significant impacts for LCA.

Several strategies were identified to bridge the gap between CRA and LCA and between individual assessments and SSbD. These included the use of a combined questionnaires for data collection, the selection of common tools for the prediction of emission factors/exposure/(eco)toxicity (e.g., the USEtox model used in the EF method during LCA), the homogenization of data sources and assumptions to fill in data gaps (e.g., to model upstream processes), and common models/tools to predict upscaled market trends at a European or global scale. An interdisciplinary approach will benefit CRA, LCA, and the transition towards SSbD, e.g., by using prospective LCA methods for developing scenarios in CRA, or by utilizing in silico CRA models to model novel materials in LCA.

4. Conclusions

Synthesis of Pt-free coatings as catalysts for WE was examined with CRA and LCA at the lab and pilot scale, leading to the identification of different hotspots and recommendations, due to the different scopes between CRA and LCA. The differences between the two assessments in the field of metal coating development were considered, and strategies were proposed to help integrate CRA and LCA and transition towards SSbD.

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References

1. Bossi, T.; Gediga, J. The environmental profile of platinum group metals. *Johns. Matthey Technol. Rev.* **2017**, *61*, 111–121. [CrossRef]
2. Lewicka, E.; Guzik, K.; Galos, K. On the possibilities of critical raw materials production from the EU's primary sources. *Resources* **2021**, *10*, 50. [CrossRef]

3. Salonen, L.M.; Petrovykh, D.Y.; Kolen'ko, Y.V. Sustainable catalysts for water electrolysis: Selected strategies for reduction and replacement of platinum-group metals. *Mater Today Sustain.* **2021**, *11*, 100060. [CrossRef]
4. Caldeira, C.; Farcal, R.; Garmendia Aguirre, I.; Mancini, L.; Tosches, D.; Amelio, A.; Rasmussen, K.; Rauscher, H.; Riego Sintes, J.; Sala, S. *Safe and Sustainable by Design Chemicals and Materials—Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials*; Publications Office of the European Union: Luxembourg, 2022; Volume 5, p. 45.
5. Vincent, R.; Bonthoux, F.; Mallet, G.; Iparraguirre, J.F.; Rio, S. Méthodologie d'évaluation simplifiée du risque chimique: Un outil d'aide à la décision. *Hygiène Et Sécurité Au Travail.* **2005**, *200*, 39–62.
6. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
7. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
8. Wolf, M.; Chomkhamsri, K.; Brandao, M.; Pant, R.; Ardente, F.; Pennington, D.; Manfredi, S.; De Camillis, C.; Goralczyk, M. *International Reference Life Cycle Data System (ILCD) Handbook—General Guide for Life Cycle Assessment—Detailed Guidance*; EUR 24708 EN; JRC48157; Publications Office of the European Union: Luxembourg, 2010.

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