TOWARDS A GREEN FUTURE

PART 2: HOW WE CAN PREVENT MATERIAL SCARCITY AND TURN OUR GREEN HYDROGEN AMBITIONS INTO REALITY

innovation for life

TNO.NL

TOWARDS A GREEN FUTURE:

PART 2: HOW WE CAN PREVENT MATERIAL SCARCITY AND TURN OUR GREEN HYDROGEN AMBITIONS INTO REALITY

Green hydrogen technologies require further research to reduce dependence on critical materials as well as both national and EU-level policies to secure their availability.

In the previous paper we showed that meeting future European hydrogen demand (FCH Ambitious Scenario of 8100 PJ in 2050) using currently available technologies, such as Polymer Electrolyte Membrane (PEM) and Alkaline (AEL) electrolysis, could require more rare materials than we have available. More than the current global annual production of iridium (122%) and significant amounts of other Critical Raw Materials (CRMs) such as platinum (25% of current global annual production) are required, and this is on top of all other products that require these materials. The shortage of critical materials could slow down the energy transition and put reaching the EU Paris Climate Agreement goals at risk.

This paper will focus on solutions to this problem. We will look into nine potential mitigation strategies around electrolysis technology development. The strategies focus on various parts of the electrolyzer value chain:

- reducing CRM amounts or substituting CRMs with less critical materials at the design stage
- using stacks longer or with higher productivity
- applying various recycling techniques to recover CRMs at the end of equipment's life

We will discuss these strategies in detail and describe their potential impact on the future supply-demand imbalance. Next, we will outline what different stakeholders need to do in order to implement these strategies. Given that technological development could take decades, it is crucial that the topic of critical materials in the transition towards an emission-free energy system – and in the future hydrogen economy in Europe in particular – is addressed now. It is equally important that asset scale-up is done promptly and in a sustainable manner, and that the right policies are in place to ensure that such societally crucial materials are available.

HOW THE EU CAN BUILD A SUSTAINABLE HYDROGEN ECONOMY WITH LIMITED CRITICAL RAW MATERIAL SUPPLY: DEMAND-DRIVEN STRATEGIES ARE CRUCIAL

The European continent is facing the challenge of building a sustainable energy system. Obtaining the required CRMs in a sustainable way is certainly one of the issues, as the previous paper has shown. The CRM shortage can be alleviated through either increasing supply or reducing demand or doing both. Like in the previous paper, when exploring the impact of different solutions, we will only discuss the EU hydrogen economy's CRM demand. Energy transition goals of other countries and continents will surely aggravate this material availability problem and lead to much higher CRM demand.

Increasing virgin[1] materials **supply** to meet growing demand seems like a simple and logical solution. In practice, this would mean intensified extraction from existing mines around the world as well as increased exploration to find new reserves. Increasing supply through these means is challenging for three reasons. First of all, ramping up mining output takes time, because opening a new mine can take up to a decade[2]. Given that materials supply is so inelastic, any technology that scales up quickly and relies on specific materials faces supply issues or potential competition with other applications. Energy transition-related technologies are no exception[3].

Secondly, many of the essential materials required for sustainable energy technologies are by-products or "companions" (term coined by Thomas Graedel[4]) of mining for other materials. This means that supply of such companions will be less sensitive to changes in the market price and instead defined by the amount of the "host" metal mined every year. For example, materials such as iridium and cobalt are mainly obtained as by-products of mining for other metals: iridium is a by-product of platinum[5] and nickel[6] mining, and cobalt is a by-product of copper mining[7]. Only a small share of miners' total turnover can be attributed to iridium and cobalt production, which means that despite rising market demand for these materials it is unlikely that new mines will be opened[8].

Thirdly, societal pressure – from communities that live in the vicinity of the production site as well as end consumers concerned about environmental damage and human rights violations – can make it difficult to extend mining operations. For instance, several lithium mining projects in Spain are have faced strong public opposition grounded in environmental concerns[9]. In turn, delays or cancellations of new mining projects increase supply risks for battery producers that use lithium[10]. To avoid these issues in the future, proper management and governance for mining operations are required, as is transparency concerning the origin of raw materials. This would help ensure that mining is done sustainably and with the best interests of local communities in mind.

1 *Materials which were mined and have not been used / recycled yet.*

2 *Sveinson F. (2017, March 24). How to build a mine. Mining dot com. Retrieved from https://www.mining.com/web/how-to-build-a-mine/*

3 *World Bank (2020). Minerals for Climate Action*

4 *Graedel T. et al. (2015). Criticality of metals and metalloids. Proceedings of the National Academy of Sciences, 112 (14), 4257-4262*

5 *Iridium is present in the ore along with other Platinum Group Metals (see https://ipa-news.de/index/platinum-group-metals/the-six-metals/iridium.html)*

6 *Study on the EU's list of Critical Raw Materials (2020) https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf*
RussiaPalladium 40 %USABeryllium 88%BrazilNiobium 92% ChinaAntimony74

7 *Nazarewicz T. (2016, Aug-Sep). Cobalt: a critical commodity. Resource World Magazine. Retrieved from https://s1.q4cdn.com/337451660/files/doc_downloads/articles/160811-Resource-World-Cobalt-a-critical-commodity.pdf*

8 *Nassar, N. T., Graedel, T. E., & Harper, E. M. (2015). By-product metals are technologically essential but have problematic supply. Science advances, 1(3), e1400180*

9 *Macintosh E. (2018, February 13) Thousands take to streets to protest Spanish mining boom. META. Retrieved from https://meta.eeb.org/2018/02/13/public-outcry-over-spanish-mining-boom/*

10 *The majority of lithium globally currently comes from Chile and Australia (see USGS 2020 Data Sheet on lithium, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf). However, these locations, too, can experience disruption of production due to protests, see for example Reuters news on protests of indigenous communities in Chile (https://www.reuters.com/article/us-chile-protests-lithium-idUSKBN1X42B9)*

The looming supply-demand imbalance can also be addressed by **reducing demand** for virgin CRM in electrolyzers. In the case of green hydrogen, this can be achieved by advancing technology to produce more hydrogen while using fewer or different materials as well as through recycling technologies. Technology development should focus on the most critical materials and on those of which the largest quantities are required. To identify these materials, the composition of electrolyzers should be investigated in more detail, the same way as in the previous publication.

TECHNICAL ASSUMPTIONS AND OVERALL METHOD

Same as in the previous publication, we will consider two commercially available green hydrogen production technologies: Polymer Electrolyte Membrane electrolysis (PEM) and Alkaline electrolysis (AEL). Solid Oxide Electrolysis (SOE) is another promising technology, but not yet commercially applied at this moment, so will be left out of scope. Zooming in on PEM and AEL technologies, the focus is on the CRM required for the electrolyzer stack: this is the "core part" of the electrolyzer where the splitting of water into hydrogen and oxygen occurs. Most of the critical materials are required in this part of the electrolyzer to enable the reaction. The CRMs[11] contained in the AEL and PEM stacks are the following:

PEM		AEL		
Iridium (Ir)	Platinum (Pt)	Cobalt (Co)	Platinum (Pt)	Nickel (Ni) [12]

Table 1

For the base case electrolyzer composition we use literature values obtained from Smolinka et al. (2015)[13]. Obtaining information on the stack composition and loadings used by industry players is challenging, since this is commercially sensitive information. Several AEL and PEM manufacturers were contacted during this research and these shared a broad indication of whether specific CRMs are indeed used. This information is reflected in the strategies' impact calculation. For example, if there was an indication that a specific material is not used by one or more players, this was regarded as a successful 100% substitution strategy.

As explored in the previous paper, green hydrogen production is likely to require a significant share of the annual CRM production, particularly iridium and platinum. To assess the quantity of critical materials that would be needed annually for the production of green hydrogen for the EU in 2050 (8100 PJ according to the FCH Ambitious Scenario[14]), assumptions on the type of electrolyzers and their technical specifications, lifetimes and critical material loadings were made.

Concerning the type of electrolyzers, it is likely that both PEM and AEL-type electrolyzers will be used in the future energy system because of their different advantages and disadvantages[15]. Therefore, it is assumed that 50% of the total green hydrogen production (4050 PJ) will use PEM-type electrolyzers and the other 50% AEL-type electrolyzers. The capacity of the electrolyzers (in MW power input) and the amount of critical materials (in g/m^2) in the electrolyzers were taken from literature, expert knowledge and verification with market parties.[16] All main technical assumptions and sources are depicted in Table 6 at the end of this paper.

---

11 Critical materials for the study are chosen based on the Study on the EU's list of Critical Raw Materials (2020), retrieved from https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf

12 Ni includes both Class 1 and Raney nickel. Even through nickel is not highlighted as a critical material by the EU, it was added to the overview in this paper, since it is present in various parts of an AEL stack. Moreover, the amount of Raney-nickel available depends on the capacity of production facilities, that might require extra time to be increased

13 Smolinka, T., Ojong, E. T., & Garche, J. (2015). Hydrogen Production from Renewable Energies—Electrolyzer Technologies. Electrochemical Energy Storage for Renewable Sources and Grid Balancing, 103–128

14 In the Ambitious FCH scenario predicted hydrogen demand is relatively high compared to other EU scenarios. The Ambitious scenario is used in this paper to assess the magnitude of the potential CRM problem or "test the limits". It is also assumed that all 8100 PJ are produced as green hydrogen, i.e. using PEM or AEL technologies, because this allows us to calculate how much CRM a fully sustainable hydrogen system would require using state-of-the-art technology

15 Yujing Guo et al. 2019 IOP Conf. Ser.: Earth Environ. Sci. 371 042022

16 For the exact amounts and assumptions, see Table 6 at the end. For more details and questions, please contact the authors

The scale-up towards 8100 PJ capacity was assumed to accelerate in the coming decade (2021-2030) and will then be evenly spread over the period from 2030 to 2050. When electrolyzers approach the end of their lifetime (we assume seven years for PEM and ten for AEL), CRMs are also needed to replace the stacks. Therefore, the overall CRM demand every year consists of the amount required for the new electrolyzer to scale up the overall capacity as well as the amount needed for stack replacement. When presenting the results, we focus on the replacement part to show how much of CRMs is required to keep the system running when it reaches its required capacity.

Let us have a look at an example: iridium in PEM systems, which is considered the main CRM bottleneck in electrolysis upscaling. To replace the stacks needed to produce 8100 PJ of green hydrogen in the EU alone every year (i.e. to “keep the system running”), the amount of iridium required would exceed the current global annual production of iridium by 22%. Table 2 shows similar percentages for all the critical materials selected above compared to the current global annual production of each of them. Next to iridium, green hydrogen production requires a significant share of the global annual production of platinum (25%). Nickel (both Class 1 and Raney nickel) and cobalt seem to put less pressure on the demand for these materials, because the annual global production of these metals is much larger. These numbers show the required material amounts for the production of green hydrogen for Europe only.

	CRM	Required for green hydrogen, 2050, ton	Current annual global production, ton	% of current global annual production	Global annual production – source
PEM	Iridium	7.4	6.1	122%	Average 2012-2016, EU Critical Material Factsheets, 2020
PEM	Platinum	48	190	25%	BGS, 2018
AEL	Raney-Ni	91	26,000	0.4%	BGS, 2018
AEL	Nickel (class 1)	22,753	1,150,000*	2%	US GS, 2018
AEL	Cobalt	70	168,000	0.1%	BGS, 2018

** Class 1 and Class 2 represent different purities. The total production (2.3 Mt) is assumed to be 50/50 Class 1/Class 2.*

***Table 2.** Amount of critical materials required for hydrogen production in the EU in 2050 as a share of global annual production in 2018*

As depicted in Table 2, the availability of the critical materials for electrolyzers could become a bottleneck in green hydrogen production upscaling. The supply of some materials, like iridium, might have to be expanded drastically to meet the demand. Other materials, like cobalt, do not directly put pressure on the global supply, since the amounts required for these technologies are relatively small, but their availability is uncertain, given supply chain risks[17] and high demand from other applications. Therefore, looking into strategies for reducing the amounts of all above-mentioned CRM could offer solutions that enable the timely scale-up of green hydrogen.

17 About 68% of all cobalt globally is mined in Congo (USGS factsheets, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cobalt.pdf).

TECHNOLOGY AS MITIGATION STRATEGY

Technological innovation is an important driver that can reduce raw material demand per unit of energy. In order to reduce critical material demand for electrolyzers, three stages of the electrolysis equipment's lifespan can be discerned: design, operation and end of life.
Based on these, three different types of strategies are formulated (see also Figure 1):

- prevention: minimizing the use of CRM in the design of electrolyzers by either using thinner layers of CRM or (partially) substituting them with less critical materials
- extension: using stacks longer or with higher productivity
- recycling: applying various recycling techniques to extract CRM from decommissioned stacks and reuse them either in new stacks or other applications requiring similar CRM

Design phase	Operation phase	End of life phase
Prevention strategies: 1. Reduce amount of material 2. Substitute critical materials 3. Adjust technology mix	**Extension strategies:** 4. Increase productivity 5. Extend lifetime	**Recycling strategies:** 6. Hydrometallurgical treatment (HMT) 7. Transient dissolution (TD) 8. Selective electrochemical dissolution (SED) 9. Acid process (AP)

Figure 1. *CRM reduction strategies at each stage of electrolysis equipment life*

Direct reuse and repair could also play a role, but were dismissed as strategies within this study, since it is expected that the efficiency of electrolyzer components will grow significantly in the coming decades, making the use of older components less attractive economically.

R-LADDER OF CIRCULARITY STRATEGIES

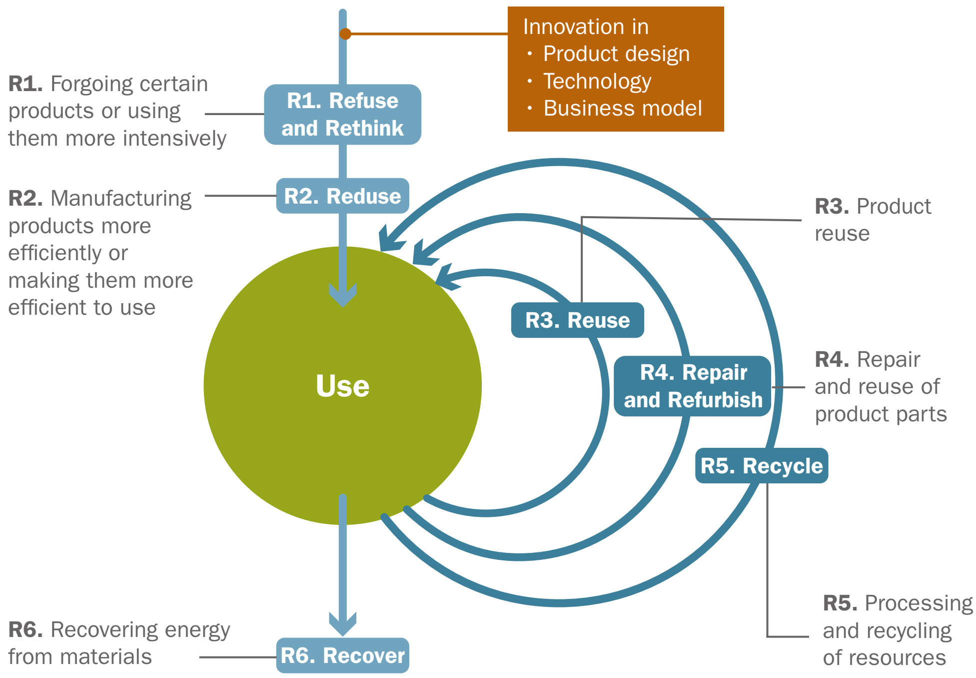


Figure 2 *R ladder as presented by PBL[18]. Prevention strategies correspond to "Reduce", Extension – to "Refuse and Rethink".*

18 *PBL Netherlands Environmental Assessment Agency (2019). Outline of the circular economy*

Specific strategies can be defined to demonstrate which exact steps reduce the CRM footprint of electrolysis. It is important to note that at this point we ignore the interdependencies between the strategies in order to isolate and quantify the impact of each individual strategy on the CRM demand. This is done to pinpoint the most promising strategies and to guide further technical research accordingly. In reality many of these are of course interrelated: for example, a thinner layer of material could lead to shorter lifetime of the stack or less profitable and more complex recycling processes. More in-depth technical research would be required to fully understand and quantify these interdependencies.
Each of the strategies is described in more detail below.

Prevention
Strategy 1: CRM amount reduction
Significant research efforts are aimed at reducing the amount of iridium per geometric cell area for PEM electrolysis, aiming towards an order of magnitude of 0.1 mg Ir/cm^2 compared to the current loadings in the order of 1.5-2 mg Ir/cm^2. The most common strategy is to increase the electrochemically active area by increasing iridium dispersion onto stable[19] and high surface area support materials[20] with favorable electronic / lattice interactions[21]. Iridium is applied to further enhance stability and intrinsic oxygen evolution reaction (OER), therefore allowing lower iridium loadings. Examples are the atomic layer deposition of iridium on doped tin oxides[22], resulting in loadings of 0.25 mg/cm^2. Remaining challenges include reaching lower levels of iridium loading around 0.1 mg/cm^2 with sufficient catalytic activity and stability. At the moment research is mostly done on lab scale and iridium substitution is regarded a long-term goal[23].
Apart from iridium, efforts to reduce platinum amounts in both AEL and PEM[24] are also ongoing. For AEL, several equipment manufacturers mentioned that they do not use platinum in their stacks, therefore reduction to zero is assumed to be possible in the strategies calculation. Finally, the use of Raney-nickel in AEL systems can be reduced, as is evident from the literature[25].

S2: CRM substitution
In some cases it is feasible to substitute Critical Raw Materials by different materials with similar properties. Table 3 shows the substitution options included in this study. The substitution of the most critical material – iridium – still presents a challenge due to its unique combination of high catalytic activity and stability for the oxygen evolution reaction in PEM systems.
For AEL, platinum or cobalt in the electro-catalyst enhance the electro-catalytic activity and stability for both hydrogen and oxygen evolution reactions. However, platinum and cobalt are not mandatory for the AEL functionality and can be omitted or substituted by high catalytic surface area Raney nickel catalysts. A substitute for the critical raw materials Raney nickel or Class 1 nickel has not been identified.

19 *Benck JD, Pinaud BA, Gorlin Y, Jaramillo TF (2014) Substrate Selection for Fundamental Studies of Electrocatalysts and Photoelectrodes: Inert Potential Windows in Acidic, Neutral, and Basic Electrolyte. PLoS ONE 9(10): e107942*

20 *Karimi F., Peppley B.A. (2017). Metal Carbide and Oxide Supports for Iridium-Based Oxygen Evolution Reaction Electrocatalysts for Polymer-Electrolyte-Membrane Water Electrolysis. Electrochim. Acta. 246, 654-670*

21 *Oh H.S., et al. (2016). Electrochemical Catalyst–Support Effects and Their Stabilizing Role for IrOx Nanoparticle Catalysts during the Oxygen Evolution Reaction. Am. Chem. Soc. 138 12552–12563*

22 *Ledendecker, M., Geiger, S., Hengge, K. et al. Towards maximized utilization of iridium for the acidic oxygen evolution reaction. Nano Res. 12, 2275–2280 (2019)*

23 *P. Shirvanian, F. van Berkel (2020). Novel components in Proton Exchange Membrane (PEM) Water Electrolyzers (PEMWE): Status, challenges and future needs. A mini review. Electrochemistry Communications, 114*

24 *Maximilian Bernt et al (2018) J. Electrochem. Soc. 165 F305.*

25 *Santos, D. & Sequeira, César & Figueiredo, José. (2012). Hydrogen production by alkaline water electrolysis. Química Nova. 36. 1176-1193*

Technology	Base case CRM	Substitute	Source	In scope?
PEM	Ir	-		No – no substitute identified
PEM	Pt	Mo-sulfide	See reference[26]	Yes – full substitution of Pt by Mo-sulfide assumed. Amount of Mo not included in the analysis as it is considered less critical compared to other materials
AEL	Pt	Raney-Ni	AEL equipment manufacturers	Yes – full substitution
AEL	Co	Raney-Ni	AEL equipment manufacturers	Yes – full substitution
AEL	Ni (Class 1)	-		No – no substitute identified
AEL	Raney-Ni	-		No – no substitute identified

Table 3. *Substitution possibilities for certain CRM in AEL and PEM stacks*

S3: Mix of technologies
Instead of developing only one technology (AEL or PEM), both can be implemented on a large scale to balance the demand for CRMs. From a CRM perspective, AEL is a better choice: platinum is the only bottleneck, and it seems that the main electrolysis equipment producers are already able to substitute platinum with other materials (information obtained from AEL equipment manufacturers). However, AEL offers less operational flexibility and is much less compact compared to PEM[27], which makes it less attractive for certain applications like hydrogen production offshore. That is why at the moment PEM seems more suitable for remote small-scale applications, whereas AEL is more interesting for local large-scale ones. So even though a mix of technologies can help reduce reliance on certain CRMs, the choice of technology will be primarily dictated by the end-user's needs.

Extension
S4: Higher productivity
One straightforward way of reducing materials usage is to increase stack productivity per m^2 of membrane (i.e. the current density). This would effectively yield more hydrogen from the same stack area. It remains to be studied how an increased current density might affect the overall lifetime of electrolyzers before this strategy can be applied on the large scale. Changes to the design might also be required to ensure sustained higher productivity. It is also worth mentioning that one of the AEL equipment suppliers stated that productivity increase and the subsequent upscaling of AEL is only interesting if platinum group metals are no longer used, since they are likely to become the bottleneck. In their view, this is the only feasible way for AEL electrolyzers to reach GW scale, and increasing productivity should go hand in hand with the substitution strategy. To reflect this viewpoint zero use of platinum is assumed in calculations for a higher productivity strategy.

S5: Lifetime extension
Increasing the maximum effective number of stack operating hours will improve material utilization and decrease overall demand for CRMs. However, reliable lifetime estimates can only come with experience of operating electrolyzers at relevant scale. For instance, at the moment, the lifetime of an MW-scale PEM electrolyzer stack is estimated to be around 40.000-50.000 hours[28] (and PEM manufacturers indicate longer expected stack lifetimes). However, there are no MW-scale electrolyzer stacks in the world that have actually achieved such a high number of operating hours. The first MW-scale stacks were installed in 2015-2016, but they have not been operated continuously. Nevertheless, this is a viable strategy for reducing CRM demand for electrolysis and will be considered in this study. See Table 6 at the end for details on calculation assumptions.

26 *Tachmajal C., Ampurdanes J., Urakawa A. (2014). MoS2-based materials as alternative cathode catalyst for PEM electrolysis. International Journal of Hydrogen Energy, 39, pp 20837-20843*

27 *Sun et al. (2018). Earth-Abundant Electrocatalysts in Proton Exchange Membrane Electrolyzers. 10.20944/preprints201811.0077.v1*

28 *IRENA (2018). Hydrogen from Renewable Power*

Recycling

Recycling is an important strategy that can drastically reduce reliance on the virgin CRM. Several recycling technologies are currently being envisaged as potential recycling technologies for recovering CRM from electrolyzer stacks. However, it is important to know that the recycling technologies for electrolyzer stacks have not yet reached a mature state and have only been demonstrated on a lab scale. For all reported recovery technologies, the scale-up to larger volumes of materials requires further research, especially given the scale-up of electrolyzers envisaged for the coming decades. It still needs to be researched which recovery technology works best for electrolyzers, given the different advantages and disadvantages of technologies as shown in the following brief overview.

In this study we will use data reported on potential recycling technologies for electrolyzer stacks. Similar to the electrolyzer composition, obtaining information from industrial players on viable recycling processes and their recovery rates has been proven difficult.

S6: Hydrometallurgical treatment (HMT)

Hydrometallurgy is considered a state-of-the-art process for Platinum Group Metals (PGMs) recovery. The hydrometallurgical pathway involves the dissolution of target elements from solid matrices through caustic or acid attacks. This process consists of the following general steps: (i) leaching, (ii) solution concentration, purification and precipitation, and (iii) metal recovery/refining[29]. Platinum recovery rates of >95% have been demonstrated[30]. The hydrometallurgical process exhibits promising material recovery efficiencies and low energy consumption. The main drawback of this method is the use of large volumes of solvents and the environmental issues related to the generation of toxic wastewater. Another critical aspect that needs to be addressed is the potential to dissolve the highly stable iridium (oxide).

A related recovery technology is the pyro-hydrometallurgical treatment, which involves a calcination step for the gas diffusion layers, the electrodes and the membrane in order to facilitate the dissolution of critical raw materials in the Hydrometallurgical treatment process.

S7: Transient dissolution (TD)

The transient dissolution treatment is typically used for the dissolution of PGMs, such as platinum, iridium and ruthenium. The dissolution process of the PGM is performed by applying a cyclic change in the oxidation state of the platinum surface[31]. The short-lived in the oxidation state of the noble metal surface is established by switching oxidizing and reducing agents which facilitates the complete dissolution of the noble metal. The advantage is that it can result in high recovery under relatively mild operating conditions. The main criticism in regard to this technology is the use of hazardous reactants, which could form an issue with respect to increasingly strict environmental regulations. Although the technology has been demonstrated in lab-scale batch-wise reactors, the application of this technology for the recovery of CRMs from electrolyzer stacks on a larger scale remains a challenge.

S8: Selective electrochemical dissolution (SED)

This method is based on electrochemical dissolution at different voltage and pH windows of both carbon support and catalyst materials from so-called catalyst coated membranes (CCM), which are in particular used in PEM electrolyzer stacks[32]. The difference with TD technology is that a direct voltage is applied to the CCM instead of a variation of the applied voltage through the use of oxidizing and reducing reagents. The first stage of SED technology consists of an electrochemical cleaning of the CCM. The system is then purged with oxygen while the voltage and pH windows are changed, resulting in the dissolution of the noble metal catalyst.

SED technology could potentially be extended to the recovery of materials for different electrolyzer technologies due the flexibility in applied voltage and pH window.

29 *Duclos L. et al. (2016). Process development and optimization for platinum recovery from PEM fuel cell catalyst. Hydrometallurgy 160 79-89*

30 *Jha, M. K., Lee, J. C., Kim, M. S., Jeong, J., Kim, B. S., & Kumar, V. (2013). Hydrometallurgical recovery/recycling of platinum by the leaching of spent catalysts: A review. Hydrometallurgy 133 22-32*

31 *Hodnik, N., Baldizzone, C., Polymeros, G. et al. Platinum recycling going green via induced surface potential alteration enabling fast and efficient dissolution. Nat Commun 7, 13164 (2016)*

32 *Latsuzbaia R., Negro E., Koper G.J.M. (2015). Environmentally friendly carbon-preserving recovery of noble metals from supported fuel cell catalysts. ChemSusChem vol.8, 11, pp 1926-1934*

The advantages of the SED technology are the high recovery efficiency and the option to recover more stack components. A point of criticism is the energy required for the recovery process. Although the technology has been demonstrated on a lab scale, the application of this technology for recovery of CRMs from electrolyzer stacks on a larger scale remains a challenge.

S9: Acid process (AP)

This method enables efficient recovery of both PGM and the ionomer from catalyst-coated membrane or a membrane electrode assembly by using strong acids to oxidize the carbon support followed by separation steps (filtration and centrifugation). The method was demonstrated on a lab scale for PEM fuel cell catalyst coated membranes by Xu et al.[33] One of the main features of this process is the possibility to regenerate the membrane for new stacks with an appropriate electrochemical performance in combination with a high PGM recovery efficiency. The main disadvantages of this technology are the harsh pH conditions, the relatively complex chain, and long duration of the process. As with other recycling technologies, the application of AP technology for the recovery of CRMs and membranes from electrolyzer stacks on a larger scale remains a challenge.

A summary of these mitigation strategies is given in Table 4.

Type	Strategy	Short description	Materials affected	
			PEM	AEL
Prevention	S1: Reduction	Reduction of the amount of CRM used (reduction of kgs)	Ir, Pt	Pt, Ni (Raney)
	S2: Substitution	Replacement of CRM by other materials	Pt	Pt, Co
	S3: Technology mix	Balance between AEL, PEM and (later on) SOEC	Ir, Pt	Pt, Co, Ni (both Class 1 and Raney)
Extension	S4: Higher productivity	Higher productivity of the electrolyzer stack (less stack area required)	Ir, Pt	Pt, Co, Ni (both Class 1 and Raney)
	S5: Extended lifetime	Extended lifetime of the stack (longer expected stack lifetime)	Ir, Pt	Pt, Co, Ni (both Class 1 and Raney)
Recycling	S6: Hydrometallurgical treatment (HMT)	See detailed description above	Pt, Ir (no recovery rates for Ir – Ir recycling out of scope)	Ni (Raney)
	S7: Transient dissolution (TD)	See detailed description above	Pt, Ir (no recovery rates for Ir – Ir recycling out of scope)	n/a
	S8: Selective electrochemical dissolution (SED)	See detailed description above	Pt	n/a
	S9: Acid process (AP)	See detailed description above	Pt	n/a

Table 4. *Strategies with description and which CRM they are applied to.*

33 *Xu F, Mu S, Pan M. (2010). Recycling of membrane electrode assembly of PEMFC by acid processing. International Journal of Hydrogen Energy vol.35, 7, pp 2976-2979*

To calculate the potential impact of each strategy, the following parameters were defined based on literature sources, TNO's own research, and input from several equipment manufacturers:

- for prevention strategies:
  - S1: Reduced material loadings
  - S2: Potential CRM substitutes where relevant
  - S3: Technology mix AEL/PEM as assumed to be 50/50. See more information on the Technology Mix strategy below
- for extension strategies:
  - S4: Potential increase in current density
  - S5: Stack lifetime extension
- for recycling strategies:
  - S6–9: Material recovery rates for each strategy; then strategies with highest recovery rates were selected (Hydrometallurgical treatment for Raney nickel and Transient dissolution for platinum in AEL stacks)

The base case values and target values for each strategy (along with the sources) are depicted in Table 6 at the end of this paper. Using these parameters, the amount of CRM required to produce 8100PJ of green hydrogen was calculated separately for each of the strategies. To give an idea about the scale, these numbers were divided by the current global annual production of each CRM.

Each of these strategies helps reduce the CRM footprint to a varying extent. The table below shows the percentage of the current global supply of different CRM that will be required to realize the ambitious EU hydrogen 2050 scenario of 8100 PJ when each of the strategies are applied. In other words: the higher the percentage, the bigger the challenge for each specific critical material after applying a given strategy. Strategy 3 Technology Mix (share of PEM vs. AEL capacity) is not explicitly mentioned because it acts as one of the basic assumptions for these calculations and adjusting the mix affects all the CRM in the base case proportionally.
For example, for platinum, ~96% of the total amount is used in AEL technology. That means that the demand for platinum will change significantly if fewer AEL electrolyzers are used. Similarly, iridium is only used in PEM, so the overall amount of iridium can be reduced if more AEL electrolyzers are deployed. In recycling, Hydrometallurgical Treatment and Transient Dissolution were selected, as they give the highest recovery rates (100% for Raney nickel in AEL and 98.6% for platinum in PEM respectively).

% of CRM global annual supply used as a result of each strategy

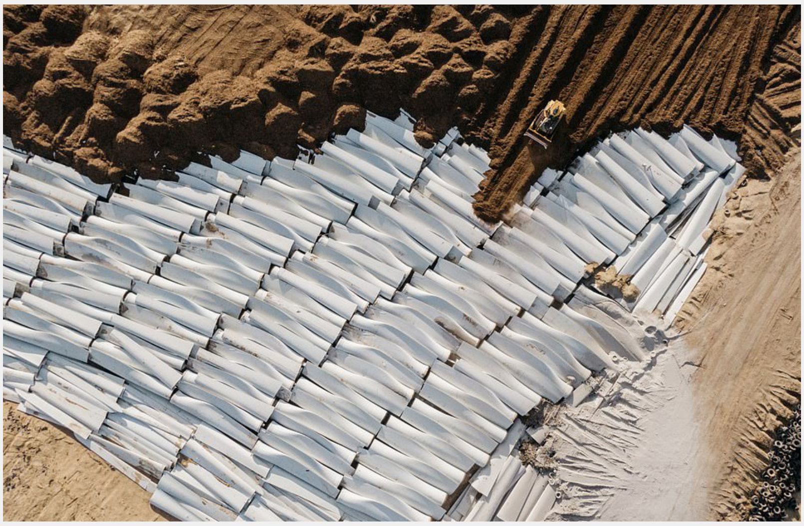
	CRM	base case	S1: reduction	S2: substitution	S4: higher productivity*	S5: extended lifetime	S6–S9: recycling
PEM	Iridium	122%	6%	122%	81%	91%	122%
PEM	Platinum	25%	0.1%	0%	1%	21%	24%
AEL	Raney-Ni	0.4%	0%	0.8%	0.1%	0.3%	0.0%
AEL	Nickel (class 1)	2%	2%	2%	0.6%	2%	2%
AEL	Cobalt	0.1%	0.1%	0%	0%	0%	0.1%

Table 5. *Effect of each strategy on CRM amounts required for upscaling*

**with higher productivity no PGM use is assumed, see strategies description*

Results
As can be seen from Table 5, the reduction strategy seems to be the most effective, as it decreases the demand for CRMs to single percentage points of global annual production. **Substitution** so far seems to not be able to remove the most critical material from the PEM stack: iridium. The advantages of **Higher Productivity** and **Extended Lifetime** are that they reduce the relative amount of all materials in the stack per unit of hydrogen produced and that it should be possible to combine these with other strategies.

Can recycling alone prevent the shortage of critical raw materials?
Electrolyzer stacks recycling cannot solve the CRM availability issue on its own, since the CRM demand for various applications is still growing. Moreover, there will always be a time lag between the moment when materials are needed and when they become available through recycling. For example, in order to scale up electrolysis, a lot of iridium will be required in the coming decades that will need to come from either mining or recycling other products. As PEM stacks will start to be replaced roughly seven years after installation, the iridium contained in them becomes available only at that moment.
Scaling up recycling technologies themselves should go hand in hand with the upscaling of the renewable energy infrastructure to ensure that the new infrastructure is sustainable and does not create large amounts of waste. Unfortunately, recycling does not always have a positive business case: for instance, glass fiber-reinforced plastics in the blades of wind turbines are difficult to reuse or recycle, which is why they are currently being buried in landfills or incinerated, which upon upscaling of wind energy could have a significant environmental impact[34].



Source: https://www.wind-watch.org/news/2020/05/07/not-so-green-energy-hundreds-of-non-recyclable-fiberglass-wind-turbine-blades-are-pictured-piling-up-in-landfill/

Lastly, the impact of **Recycling** on critical materials’ supply and demand is hard to assess. Fuel cells and hydrogen technologies are currently being developed and literature indicates that at least some of them are still on a low TRL (for example, see novel techniques in Valente et al. (2019)[35]). Furthermore, even though the recycling techniques described by Valente et al. can be applied to recover various CRMs from the stack, the recovery rates are difficult to find. In this research, only the recovery rates of platinum in PEM (extrapolated from recycling techniques for fuel cells) were obtained from literature[36] and the possibility of full recovery of Raney nickel from AEL stacks was indicated by several electrolyzer manufacturers.

34 *Larsen K., Recycling wind turbine blades (2009). Renew Energy Focus, 9 (7), 70-73*

35 *Valente A., Iribarren D., Dufour J. (2019). End of life of fuel cells and hydrogen products: From technologies to strategies. International Journal of Hydrogen Energy. 38, 20965-20977*

36 *Hodnik, N., Baldizzone, C., Polymeros, G. et al. (2016). Platinum recycling going green via induced surface potential alteration enabling fast and efficient dissolution. Nat Commun 7, 13164*

NO STRATEGY IS A SILVER BULLET

Strategies such as Reduction and Technology Mix seem the most impactful based on the results in Table 5, but in reality they cannot solve the CRM issue alone. At the moment, all technical strategies require years of research before they can be implemented, and will need to be followed by infrastructure and process upscaling. Technology mix is the most mature strategy in this respect, since both AEL and PEM technologies are already commercially available and are being upscaled. However, technology selection is often driven by technical and economic considerations and can therefore not ensure that only technologies with the least critical materials will be used. As a result, further research on all the proposed strategies should continue to offer feasible solutions to the CRM issue in the nearest future.

Most of the strategies described here are still in the early stages of technological development. For example, iridium reduction is still being researched on a lab scale to ensure stability and performance are not compromised. If and when the tests are successful, it will take time to change the design of electrolyzer stacks to reduce the demand for CRMs and demonstrate that performance indeed stays at the desired level when electrolyzers operate on GW scale.
The assumption behind the numbers in Table 5 is that strategies are applied independently and that stack performance is same as in the base case. Moreover, CRM reduction in new electrolyzer stacks will likely progress with experience of researchers and electrolyzer manufacturers, following a learning curve. This means that reduction could be relatively small at the beginning and accelerate later on when the technology matures. This would translate into more pressures on CRM markets on the short term, when electrolysis upscaling drives CRM demand up, while supply does not have sufficient time to expand.

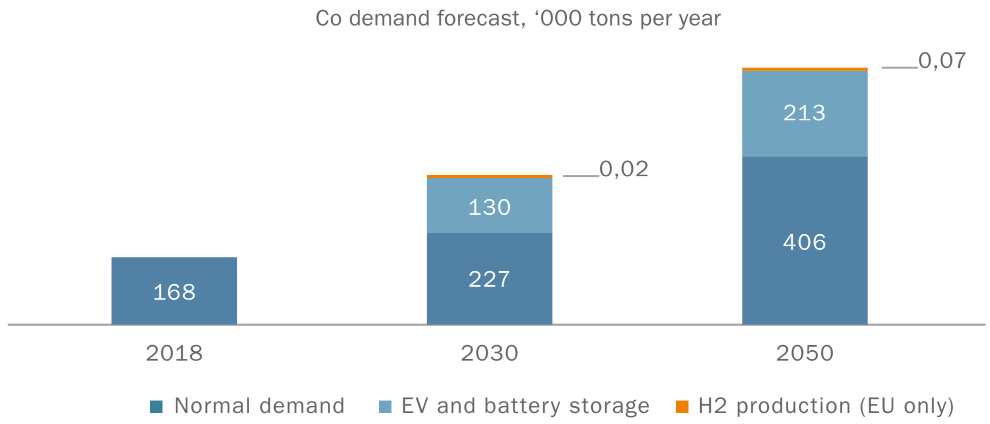
After the technologies are developed, the next step and the next challenge will be to build the required recycling infrastructure and to establish the required processes and guidelines, mainly for recycling strategies. As HyTechCycling research has shown, Fuel Cells and Hydrogen equipment recycling is not economically feasible at the moment because of the higher logistics and recycling costs[37]. Even though recycling creates value from a societal perspective by reducing the environmental hazards and ensuring that CRMs are available for both sustainable energy assets and consumer goods in the long-run, it is unlikely that upscaling will take place as long as the business case for the equipment manufacturers and recyclers is negative.
For instance, while electrolysis is being upscaled and the volumes of stacks to be recycled are relatively small, the business case for recycling will likely remain negative. This could lead to recycling infrastructure upscaling being delayed, which, in turn, worsens the shortage of CRM and environmental damage. Here the involvement of the government is key to ensure that recycling does upscale together with the waste streams. WEEE (Waste Electrical and Electronic Equipment) Directive introduced in 2003 is a good example of such involvement: it was introduced when electronic streams were certain to continue growing, but recycling rates were lagging behind, thus creating issues with hazardous substances in landfills and materials being wasted[38].

GOVERNANCE AND OVERSIGHT OVER CRM ARE CRUCIAL FOR THE SUCCESS OF THE ENERGY TRANSITION

Green hydrogen production is only one example of an energy transition technology requiring CRMs. For example, materials such as cobalt are likely to be required in large amounts for batteries, including those in EVs. In addition, non-energy related applications will require larger amounts due to the overall population growth and increase in standard of living. As a result, the demand for cobalt is expected to grow almost 4 times by 2050 compared to the current demand (see graph below). Hydrogen production will be only a very small part of it, but it will compete for cobalt with other sustainable energy assets as well as non-energy related products. This clearly demonstrates that success of the energy transition can be jeopardized by the limited availability of materials. Coordination between climate research, technology institutes, trade bodies and mining agencies is therefore necessary.

37 *HyThechCycling (2019). D6.2 Roadmap for recycling and dismantling strategies and technologies within FCH technologies*

38 *European Commission (n.d.). Waste Electrical & Electronic Equipment (WEEE). Retrieved from https://ec.europa.eu/environment/waste/weee/index_en.htm*



Source: BGS 2018, TNO analysis

Figure 3 *Global annual demand forecast for cobalt for 2030 and 2050*

Upscaling of sustainable energy assets is an unprecedented endeavor, monitored at a global level by organizations such as IPCC and IEA. Climate goals are translated into national and international policies that create incentives for the business to scale up sustainable energy assets. Materials availability, which is crucial for building these assets, however, lacks such a mechanism. At the moment, only a few countries have ongoing efforts to analyze the problem at a national level: this work is usually carried out by geological surveys such as the ones in Germany, the UK, the US and Japan. Policies safeguarding materials for applications that are deemed to be of overarching societal relevance are not established, with only partial exceptions in the US, where the Defense Agency holds strategic stocks for materials deemed essential to national security.

A supra-national level is slowly emerging in the EU: the creation of a European Raw Material Alliance (ERMA) was announced in September 2020[39], but policies addressing the failures of the free market cannot be expected from such initiatives in the short term. Although markets can balance supply and demand to avoid major disruptions, they cannot mitigate price and availability risks as well as ensure that materials are being mined sustainably.

The classic example of critical materials' price risk was the armed conflict in Zaire (Democratic Republic of Congo) in 1978 that led to cobalt prices soaring by 450% within a few months[40]. Leader et al. (2019)[41] have found that if similar events were to happen today, they could significantly increase the cost of some sustainable energy technologies and render them economically unfeasible. This demonstrates that price volatility risks can affect the speed of the energy transition if they are not anticipated and mitigation strategies are not in place.

Availability or supply risks seem to be already materializing in the modern times. In 2019, Tesla revealed that they expect "long-term supply challenges" with materials such nickel, lithium and copper that are crucial for Electric Vehicles (EVs)[42]. Jaguar Land Rover and Audi already had to temporarily halt production of their EVs earlier in 2020 and reduced their production targets for the year when faced with issues in the battery supply chain[43]. These examples show how disruption in supply chains of key components and their key ingredients can have an impact on the future energy infrastructure. Europe cannot afford such disruptions if it wants to stay on track to reach the Climate Agreement goals. Therefore, proper governance and oversight should help avoid market shocks from structural mismatches.

39 About us – European Raw Material Alliance. Retrieved from https://erma.eu/about-us/

40 Shedd, K.B. & McCullough, E.A. & Bleiwas, D.I.. (2017). Global trends affecting the supply security of cobalt. Mining Engineering. 69. 37-42

41 Leader, A., Gaustad, G. & Babbitt, C. The effect of critical material prices on the competitiveness of clean energy technologies. Mater Renew Sustain Energy 8, 8 (2019)

42 Scheyder E. (2019, May 2). Exclusive: Tesla expects global shortage of electric vehicle battery minerals – sources. Reuters. Retrieved from https://www.reuters.com/article/us-usa-lithium-electric-tesla-exclusive-idUSKCN1S81QS

43 Cohen A. (2020, March 25). Manufacturers are struggling to supply electric vehicles with batteries. Forbes Retrieved from https://www.forbes.com/sites/arielcohen/2020/03/25/manufacturers-are-struggling-to-supply-electric-vehicles-with-batteries/?sh=199755341ff3

TIME FOR ACTION

A couple of actions can help solve the looming problem of CRMs not being available for the energy transition. That is, if we act now.

Awareness and Analysis

At the moment, awareness about the link between materials and our climate goals is slowly developing. However, the materials perspective is not yet embedded in the current plans for a sustainable energy assets scale-up. It is crucial to realize that the energy transition and materials supply are interconnected and the former is not possible without the latter. Awareness is the first step, then a thorough analysis of our knowledge gaps. For example, literature on materials needed for electrolyzers is still very limited and it is only recently that organizations like the World Bank and the JRC have started looking into the CRM demands of energy transition technologies. Finally, the forecasting of CRM supply and demand should follow. **Awareness and analysis will create the urgency to put the CRM issue on (political) agendas.**

Regular review and action institutionalized

CRM availability is a societal problem which cannot be neglected. It is a complex problem that encompasses worldwide supply chains and comes with serious geopolitical risks and implications. Therefore, after the main risks for businesses or vulnerabilities for the EU products' supply chains are identified, action should be taken on national and EU level to help balance supply and demand. **Given the complexity of the CRM topic and its relevance for a wide range of products, ad-hoc actions are not enough; forward-looking analysis and risk management should be institutionalized as formal processes performed by governments on an ongoing basis.** Other countries already have such examples: the Defense Logistics Agency in the US monitors the markets of several materials identified as "strategic" for the defense sector and takes action whenever they see signals of potential supply chain disruptions[44]. For example, they builddomestic stockpiles of materials when supply is likely to become insufficient, for example if producers close some mines and reduce production.

The EU and its members had already acknowledged the potential security of supply issue in 2010[45], but an actionable strategy safeguarding essential supplies for energy technologies and other products has never been created. In September 2020 EU actions to secure the sustainable supply of raw materials were announced, one of which was the creation of a European "Critical Materials Alliance"[46]. Putting critical materials on the agenda this way is very much needed.

Example: forward-looking analysis and government action

When the forecasted supply of some CRMs will not be able to match the forecasted demand from all applications, a different approach to the materials market might become necessary. **To ensure that available CRMs end up in applications which bring the most societal and environmental benefits, the allocation of CRM to final applications might need to be regulated.** In order to assess which CRM applications might be at risk, we propose to perform analysis of a "merit order" to identify the applications with the highest willingness to pay for a given CRM as well as those that are likely to become the "losers". If a lot of sustainable energy assets do not make the cut, a revision of the free CRMs markets could be due.

44 *Defense Logistics Agency (n.d.). Strategic materials. Retrieved from: https://www.dla.mil/HQ/Acquisition/StrategicMaterials.aspx*

45 *Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials (June 2010)*

46 *https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1542 and https://www.crmalliance.eu/*

Concentrated R&D efforts
As discussed in this paper, R&D can help reduce demands for CRMs significantly. Typically this research takes time: for example, replacement of iridium in PEM electrolyzers has been ongoing for a decade, yet the TRL of these techniques is still low. Nonetheless, recent history has proven that humanity can achieve remarkable results in a very short time when we put our attention and resources to it: normally it takes years to develop a vaccine, but in the case of COVID-19, it was done within nine months. **A breakthrough in balancing CRM demand and supply will be needed the coming decades and it needs our utmost attention and resources.**

Main assumptions behind our research:
- Base case electrolyzer composition is based on Smolinka et al (2015).
- Operating hours of AEL and PEM are not linked to the amount and production profile of renewable energy. In practice this will be one of the important factors defining the scale of hydrogen production.
- Strategies are independent, more research is needed to study their interaction: for example, how thinner layer of material affects productivity.
- For comparability, the effect of all strategies was calculated assuming 50/50 PEM/AEL technology mix.
- All EU hydrogen demand (8100 PJ) is assumed to be met with green hydrogen only in order to test the limits of green hydrogen production. In lower scenarios the amount of CRM required will be reduced proportionally to the green hydrogen amount.

Technology	Criteria	Units	Base case	Target	Reference
Reduction					
PEM	Ir use in stack	[g/m^2]	10	0,5	Bernt, M., Siebel, A., & Gasteiger, H. A. (2018). Analysis of Voltage Losses in PEM Water Electrolyzers with Low Platinum Group Metal Loadings. Journal of The Electrochemical Society, 165(5), F305–F314
PEM	Pt use in stack	[g/m^2]	3	0.25	Maximilian Bernt et al 2018 J. Electrochem. Soc. 165 F305
AEL	Pt use in stack	[g/m^2]	13	0	Info from an AEL equipment supplier
AEL	Raney-Ni use in stack	[g/m^2]	26	0	Santos, D. & Sequeira, César & Figueiredo, José. (2012). Hydrogen production by alkaline water electrolysis. Química Nova. 36. 1176-1193.
Substitution					
AEL	Pt use in cathode	[g/m^2]	13	0	Info from an AEL equipment supplier
AEL	Co use in Anode	[g/m^2]	20	0	Info from an AEL equipment supplier
Lifetime extension					
PEM	Lifetime	[hours]	60.000	80.000	info from a PEM equipment supplier
AEL	Lifetime	[hours]	85.000	100.000	info from an AEL equipment supplier
Productivity increase					
PEM	Cell voltage	[V]	1.8	1.7	Info from a PEM equipment supplier
PEM	Current density	[A/cm^2]	2	3	Info from a PEM equipment supplier
AEL	Cell voltage	[V]	1.9	1.7	Info from an AEL equipment supplier
AEL	Current density	[A/cm^2]	0.3	1.0	Info from an AEL equipment supplier, no PGM use is critical for upscaling, so assumed 0 Pt use
Recycling					
PEM	Pt recycling	[%]	0%	99%	Hodnik, N., Baldizzone, C., Polymeros, G. et al. Platinum recycling going green via induced surface potential alteration enabling fast and efficient dissolution. Nat Commun 7, 13164 (2016).
AEL	Raney-Ni recycling	[%]	0%	100%	Info from 2 AEL equipment suppliers

Table 6. *Assumptions and sources for strategies' impact calculation*

ACKNOWLEDGEMENTS
We thank our colleagues Frans van Berkel, Octavian Partenie, Elmer Rietveld, Robin White, Ton Bastein and Willem ter Horst for their support and contributions to this paper and underlying research.

The research presented in this article was initiated within the VoltaChem Shared Innovation Program, in which the community identified limited availability of critical raw materials as one of the potential hurdles for large scale implementation of Power-2-X technologies.

AUTHORS

Anastasia Gavrilova
anastasia.gavrilova@tno.nl
Consultant at TNO

Sara Wieclawska
sara.wieclawska@tno.nl
Consultant at TNO

innovation
for life

21-12158 april 2021

TNO.NL