Critical materials for water electrolysers at the example of the energy transition in Germany

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Summary
The present work aims to identify critical materials in water electrolysers with potential future supply constraints. The expected rise in demand for green hydrogen as well as the respective implications on material availability are assessed by conducting a case study for Germany. Furthermore, the recycling of end-of-life (EoL) electrolysers is evaluated concerning its potential in ensuring the sustainable supply of the considered materials. As critical materials bear the risk of raising production costs of electrolysers substantially, this article examines the readiness of this technology for industrialisation from a material perspective. Except for titanium, the indicators for each assessed material are scored with a moderate to high (platinum) or mostly high (iridium, scandium and yttrium) supply risk. Hence, the availability of these materials bears the risk of hampering the scale-up of electrolysis capacity. Although conventional recycling pathways for platinum, iridium and titanium already exist, secondary material from EoL electrolysers will not reduce the dependence on primary resources significantly within the period under consideration—from 2020 until 2050. Notably, the materials identified as critical are used in PEM and high temperature electrolysis, whereas materials in alkaline electrolysis are not exposed to significant supply risks.

KEYWORDS
green hydrogen, material criticality, recycling, supply risk, water electrolysis

1 | INTRODUCTION

In comparison to the preindustrial era, the world’s climate experienced an average temperature rise of 0.85°C.1 The global temperature increase has significant consequences for vulnerable climate and ecological systems. Excessive anthropogenic emissions of greenhouse gases (GHG) are widely seen as the major trigger of such occurrences.2

In order to approach climate change, representatives of 195 countries met in Paris at the COP21 in 2015. The meeting resulted in the first global and legally binding climate protection agreement and the pledge to keep global warming considerably beneath an increase of 2°C compared to the preindustrial era.3 Hence, several countries pursue their own national climate action plans in order to reduce GHG emissions and thus contribute to the ratified goal.4 One of them is the German “Klimaschutzplan 2050” which intends to reduce the German GHG emissions by 85% until 2050 as against the level of 1990.5 As the power generation sector is one of
the main emitters of greenhouse gases (responsible for nearly 38% of the total German GHG emissions in 2016), a transformation towards sustainability is intended, among others through the integration of renewable energies. In total, about 85% of the emissions in Germany can be considered as energy related. The goals of German energy transition strategy are described in the “Renewable Energy Sources Act” (EEG), which sets the target share of renewables in the German energy supply in 2050 to 80%. However, generation profiles of renewable energy sources are highly fluctuating and depending on seasons (eg, solar), weather conditions (eg, wind, solar) and generally the rotation of the earth (tidal power plants). Thus, the integration of concepts for energy storage and sector coupling is required in order to facilitate the necessary flexibility of the electricity system. A promising element in the portfolio of energy storage systems, which lately experienced an increase in popularity are power-to-gas process chains. The respective gases can be stored and transported comparatively easy in conventional tanks and pipelines. By the use of fuel cells, the energy carrier hydrogen can be used for stationary power generation, combined heat and power applications and for propulsion of vehicles in the transport sector. Hydrogen from water electrolysis is potentially able to substitute fossil fuels in combustion processes in any sector while not emitting GHGs, and as such able to make energy from wind and solar available to end uses that are challenging or impossible to be powered by electricity directly (eg, long-haul road transport, shipping, aviation). Hence, hydrogen from water electrolysis is seen as an important cornerstone for achieving the objectives of the German climate policy. Conventional industrial processes for producing hydrogen are steam reforming, partial oxidation, autothermal reforming and hydrocarbon pyrolysis. Although being technically established, the mentioned processes use fossil energy sources as feedstock and thus emit large amounts of GHGs (except for pyrolysis). Water electrolysis offers a pathway to avoid such emissions. The electrochemical process requires water and electric energy as input parameters, and creates no emission of GHGs during the hydrogen production, depending on the source of electricity used. Operated with renewable energies, water electrolysis is a non-fossil fuel-based process and its product is thus considered as “green hydrogen.” Factors like high capital costs and high operational costs due to high electricity prices, especially in Germany, currently prevent the market penetration of the technology. Nevertheless, nearly all recently published studies see water electrolysis as an inevitable element for the transformation of the energy sector, making green electrons from wind and solar power available as molecules in other sectors. This expected increase in demand for electrolysers necessitates a detailed analysis if currently available technologies are able to fulfil the three pillars of sustainability (social-, environmental- and economic sustainability) sufficiently. The present work represents one important aspect of such a holistic analysis by evaluating the criticality of material use for electrolysis systems. One of the more recent electrolyser technologies, Proton Exchange Membrane Electrolysis (PEMEL) uses platinum group metals (PGM), while some rare-earth metals could potentially be used in High Temperature Electrolysis (HTEL), which is an approach to hydrogen generation with low TRL but potential use case specific benefits. Water electrolysis is widely seen at the beginning of its industrialisation. Hence, difficulties experienced with other innovative technologies in the past might be avoided by addressing potential barriers to the scale up of electrolyser supply at this early stage and before large production capacities for electrolyser components are set up. The restricted availability of some materials used in novel electrolyser technologies bears the risk of inhibiting the fulfilment of future demand (compare the use of cobalt in certain lithium-ion batteries). The identification of potential critical materials in water electrolysers shall indicate possible necessary improvements of available technologies (eg, the search for substitutes for specific materials) and/or promote alternative approaches for the production of green hydrogen. Criticality assessments are a useful and acknowledged methodology for identifying and evaluating potential risks along the supply chain of material provision. Such assessments are available for several materials of the periodic system in a general regard. Moreover, some publications focus on technology specific material criticality. While Helbig et al. assess the supply risk of lithium-ion battery materials, others assess several clean or sustainable energy technologies such as for example LEDs, PV systems, wind turbines, electric vehicles and more. Some of these studies also include material criticality assessments of fuel cells and water electrolysers. With the exception of Voglitsis et al., no differentiation between the available fuel cell-/electrolysis technologies is performed. While not incorporating hydrogen technologies in their own studies, Moss et al. recommend the conduction of criticality analysis for fuel cells and hydrogen technologies. Ferriz et al., who summarise the results of the European HyTechCycling Project, describe the material criticality of various fuel cell- and water electrolysis technologies. With reference to Deloitte Sustainability et al., an overall estimation of criticality on a three-stage scale is provided (same as by Stropnik et al., who focus on PEM Fuel Cells). Furthermore, the technological readiness of recycling pathways...
of PEM- and High Temperature Fuel Cells is described. The most detailed analysis of material criticality with specific focus on electrolyser is provided by Zauner and Reiter. The criticality of various materials of the three main electrolysis technologies (PEMEL, HTEL & AEL) is described and discussed qualitatively.

Yet, there is no analysis combining the potential future demands for electrolyses, the accompanied material use and the respective implications on material availability with a detailed criticality assessment of the respective materials. Consequently, the potential effect of electrolyser recycling on the material availability is not evaluated in literature either. The present work aims at identifying such critical materials for water electrolysis and assesses them concerning their future supply risk in reference to the fulfilment of the modelled demand of electrolyses in Germany until 2050. Furthermore, a brief overview of the potential implications of the implementation of a circular economy on the future supply of critical materials is generated.

2 | BASICS

2.1 | Water electrolysis

Water electrolysis as an electrochemical process that splits water molecules in its constituents hydrogen and oxygen. In an alkaline water electrolyser, which is the most common type, the application of a DC voltage in a cell with a power circuit of two electrodes separated by and submerged in an electrolyte under the presence of water, leads to the evaporation of hydrogen and oxygen. Many of such electrolytic cells are connected and piled up to build the core of the respective electrochemical device (electrolyser), which is widely known as the electrolyser stack. The structure of an electrolytic cell with its individual components can be obtained from Smolinka et al. Electrolysers are thus used for converting electric into chemical energy (hydrogen), and storing that energy (hydrogen storage is not further investigated in this work). Currently there are three different technologies for water electrolysis on the market which mainly differ in their respective electrolyte, the charge carrier as well as the operating temperature range.

Alkaline electrolyser (AEL) are an established and reliable technology that has been used on a commercial large scale for more than a century. Alkaline electrolytic cells are comprised of an aqueous electrolyte (potassium hydroxide) in which the two electrodes are submerged. The electrodes are separated by a diaphragm, which historically was made of asbestos, while nowadays the most common structure are polyphenylene sulphide (PPS) multifilament fabrics. The electrodes are made of nickel or more often sponge-like Raney nickel, derived from an nickel-aluminium alloy. The water is reduced at the cathode into hydrogen and hydroxide anions. After passing the diaphragm, the emerging hydroxide anions recombine at the anode leading to the evaporation of oxygen. Alkaline electrolysis is characterised as a cost-effective technology with no necessity for noble metal catalysts. On the other hand, it is often low operating pressure and limited current density as well as a slow start capability are considerable disadvantages.

Proton exchange membrane electrolyser (PEMEL) have become commercially available in recent years at larger scale and are believed to increasingly compete with alkaline electrolysis for market share in the coming years. The cathode (typically platinum) and anode (typically iridium) are separated by an ion conducting polymer membrane. The fluoropolymer copolymer Nafion is the most widely known membrane material. The bipolar plates between the individual membrane electrode assemblies (MEA) are most commonly made of titanium, the same material that is also used for the porous transport layers on the anode side which are located between the catalyst coated membrane and the bipolar plates. On the cathode side, titanium or synthetic graphite or carbon composites can be used for the porous transport layers. In contrast to AEL, the hydrogen is produced at the cathode. Following the oxidation of water at the anode, the protons pass through the proton conducting membrane to the cathode where they are getting reduced to hydrogen. Advantages of PEMEL systems are a higher power density compared to alkaline electrolysis in addition to the ability of operating highly flexible and under differential pressure (high pressure of hydrogen side). However, noble metals and complex membrane materials increase the costs of the systems which today also have shorter lifetimes than AEL. Anion exchange membrane (AEM) electrolyser are proposed as a novel approach, combing some of the advantages of PEMEL, such as solid electrolyte, and AEL, such as absence of precious metal catalysts. Due to the early stage of development and in absence of industrial activity to commercialise megawatt scale AEM systems this technology was not included in the analysis in this work.

High temperature electrolysis (HTEL), often referred as Solid Oxide Electrolysis (SOEL), is another technology currently being commercialised, but less mature than AEL and PEMEL. The use of yttria stabilised zirconia as a solid electrolyte is most common and requires temperatures between 650°C and 850°C to become sufficiently conductive. In HTEL systems, water vapour is split at the cathode into oxygen ions and protons by the application of external power. The oxygen ions permeate the solid
ceramic electrolyte and release electrons at the anode, which results in pure oxygen gas. By circulating the electrons to the cathode, the hydrons at the cathode side are reduced and hydrogen gas is formed. As cathode material mostly nickel cermet is applied while the anode is often comprised of lanthanum strontium manganite. The interconnects between the individual cells are typically made of lanthanum chromite or yttrium chromite. Main disadvantage is the material degradation linked to the high operating temperatures and thermal cycling.

2.2 Material criticality analysis

Criticality analyses are multi-criterial assessments aiming at describing the potential risks accompanied with the use of specific materials by the evaluation of predefined indicators. As various stakeholders with individual interests are conducting research concerning material criticality and hence use different indicators as well as bases of valuation, the respective methodologies vary widely. These differences involve the selection of considered indicators as well as the strategies for aggregating the used indicators and deriving statements concerning decision support accordingly. Graedel et al. as well as Erdmann et al. provide an overview of several studies concerned with material criticality and their respective approaches. One of the most popular frameworks in assessing material criticality is described by Graedel et al. Various studies adopt the approach (or at least parts of it), which evaluates the “vulnerability” of the resource consuming system to an absence of the respective material as well as the “environmental impact” of resource extraction beside the most popular dimension of “supply risk.” Some authors go even further by incorporating social implications associated with the use of the evaluated material in their criticality assessment. Others neglect certain dimensions or only focus on the supply risk. The respective approach applied in the present work is described in Section 3.3. In order to carry out a criticality analysis, specific mass inventory data are required. For the present work, data from the German IndWEDe study is used (“Industrialization of Water Electrolysis in Germany: Opportunities and challenges for sustainable hydrogen for transport, electricity and heat”). The study assesses the scale-up potential of electrolyser production in Germany. The potential demand for electrolyser during the considered timespan until 2050 in Germany has been modelled with the simulation tool REMod-D (developed at the Fraunhofer Institute for Solar Energy Systems ISE). The model identifies technically and economically feasible transformation pathways of the German energy system under the constraint of meeting the CO₂ reduction targets defined by the German government. By using a scenario approach, the effect of various input parameters can be assessed. The result is a cost-optimised dimensioning of relevant power generators, converters and consumers while meeting the energy balance for every hour of every year during the period under consideration. REMod-D considers hydrogen in various applications and methods of its production. Beside the four sectors of transport, energy, heat and industry, the usage of hydrogen as a way to store energy is incorporated. This together enables the quantification of the future hydrogen demand in Germany. In turn, the necessary electrolysis capacity can be calculated respectively. A plausible distribution of the overall capacity among AEL, PEMEL and HTEL was defined based on expert workshops and interviews, taking into consideration that the respective market shares will be a result of competition on the market, rather than predictable by a model (2017: 90%, 10%, 0%; 2030: 55%, 40%, 5% and 2050: 40%, 40%, 20%).

3 METHODOLOGY

In order to assess the criticality of materials during the industrialisation of water electrolysis in Germany, initially potential critical materials were identified in expert workshops. In a further step, the required amounts of these materials are calculated by considering the potential demand for electrolysers in Germany until 2050 as well as the expected decrease in material use per kW of electrolysis capacity during the same time span. For the respective elements, a detailed criticality assessment as well as an evaluation of secondary material extraction and supply is conducted. The approach is visualised in Figure 1 and described in the following sections.

3.1 Forecast of electrolysis capacity in Germany until 2050

Before analysing the criticality of specific materials, the required quantity of electrolysers for each of the three technologies (AEL; PEMEL, HTEL—compare Section 1) until 2050 is modelled by applying the simulation tool REMod-D, thus determining the future demand for materials for this application and relating it to current supply. The programme REMod-D is an analysis tool developed at Fraunhofer ISE to determine the cost-optimal transformation of the German energy system by 2050 and to achieve the defined reduction of greenhouse gas emissions. It is a bottom-up energy system model with dynamic, non-linear optimization of the expansion
corridor and takes into account the interaction of the energy sectors electricity, heat, mobility and industry on the transformation path until 2050. The optimization goal is the dimensioning of all generators, storage facilities, converters and consumers at minimum cost in such a way that the energy balance of the entire system is met at every hour from the starting point to the target year (here 2015 to 2050) while at the same time complying with the reduction targets for the German greenhouse gas emissions according to the national climate protection policy for every year. Each technology property can be represented in any level of detail and the technical and economic progress for any technology is considered by adjusted parameters (as efficiency, investment costs, life-time) for each year. The simulation tool is set up in Delphi/Python using a particle swarm optimization algorithm (PSO) as solver. The evolution of economic and technological key performance indicators (KPIs) of the three technologies is obtained from the average results of an expert consultation (eg, product lifetime in years is one KPI) among leading industrial and academic stakeholders. The precise technology shares in the future are not known. Picking a winner or discarding one or more of the technology options available today would be premature. Therefore, the ratio of capacity distribution in 2050 was set to 40% AEL, 40% PEMEL and 20% HTEL. But this assumption, which gives all three technologies significant market shares, allows to test the material constraints for each of them. The rational for giving HTEL a smaller market share in 2050 compared to the other two technologies lies in its lower technology readiness today, and in the characteristic that HTEL installations are preferably integrated with other processes to utilise by-product steam or heat, which overall tends to lower its applicability compared to AEL and PEMEL. The superordinate criterion is the fulfilment of the German plans for reducing GHG emissions. Detailed information about the parametrisation of the REMod-D-tool can be obtained from the referred study. Various studies forecast electrolysis capacity in Germany for the upcoming years. While the results vary widely throughout these evaluations, there is a consensus on the necessity of a significant expansion of electrolysis capacity in Germany. Discrepancies can mostly be ascribed to certain constraints, like the possibility of importing hydrogen, or hydrogen derived fuels from neighbouring and overseas countries. The option of imports is neglected in the present work, since the aim is to identify the overall quantity of materials necessary for fulfilling the German hydrogen demand, irrespective of where the corresponding electrolysis systems are stationed. Hence, the described forecast of electrolysis capacity in Germany corresponds to a maximum value scenario, including potential installations outside Germany, dedicated to fulfill German hydrogen demand.

Under the chosen constraints and conditions, REMod-D calculates a total installed electrolysis capacity of 213 GW in 2050 in the reference scenario S3. The rate of capacity addition is illustrated in Figure 3. While this work analyses the implications of the German
electrolyser demand on material supply, the identified supply issues will amplify when the potential global electrolyser demand is taken into account. A number of recent studies has developed global energy system scenarios that would enable meeting the already mentioned 2015 Paris Climate Agreement. The Paris-compliant scenarios found in literature provide a wide bandwidth of additional hydrogen demand in 2050, ranging from 5 million tonnes per year used exclusively in transport (IEA-ETP B2DS scenario) to a theoretical potential across all sectors of 1370 million tonnes per year (BNEF). The large variation among different studies is mainly a result of assumptions regarding the cost of hydrogen technologies and timing of policy actions to introduce them. Hydrogen produced by electrolysis using renewable electricity is seen as a key enabler to reach the Paris Climate Agreement in many studies, but depending on the assumptions taken, there are also other measures that can meet the target, for example removal of CO₂ from the air and underground storage. The majority of the studies reviewed modelled a global hydrogen demand of between 248 and 654 million tonnes of hydrogen per year to be reached between 2050 and 2100. Assuming that all this hydrogen was to be made by water electrolysis, and further assuming an electricity input of 55 kWh per kg of hydrogen and 4000 full load hours of electrolyser operation per year, this results in a range of 3400 to 9900 GW of electrolysis capacity needed globally to meet the Paris Agreement. This would be between 16 and 47 times more than what was modelled for Germany alone in this work. The global total energy supply (TES) in 2018 was 598 EJ, which is 46 times more than that of Germany’s primary energy supply (13 EJ). This underlines the reliability of the modelled electrolyser demand for Germany, which broadly corresponds with modelling done at the global scale, in studies that see string role for hydrogen compared to other options in reaching the Paris Climate Agreement.

3.2 Identification of potential critical materials in electrolysis and forecast of material use

In order to identify materials that might be critical concerning their future supply while taking the expected scale-up of demand for electrolyser into account, the three technologies were broken down into their key components. Then, the materials, the components are comprised of were identified based on desk research and expert consultations as part of the IndWEDe study. Five materials have been identified as most relevant and these are further analysed in the present work. In contrast to PEM and HTEL, AEL is an established technology and is seen as uncrirical concerning the use and supply of materials. In PEMEL electrodes and their coatings are assessed as potentially critical due to special requirements on materials, like for example corrosion resistance in oxidative atmospheres which today can only be accomplished by the use of platinum group elements. The five selected elements are described briefly in the following.

Platinum itself is used in PEM electrolyser cells as the preferred cathode material. The thin catalytic layers can be comprised either of pure or carbon-supported platinum. Furthermore platinum is sometimes used as a coating for bipolar plates and PTLs in order to reduce electric resistance of the surface. However, the coating of bipolar plates is neglected in further analysis, as its demand is difficult to quantify, due to various coating materials applied and currently investigated, as well as different manufacturers following different approaches. In the present work, it is thus assumed that bipolar plates without platinum coating will be established as the standard technology in the future.

Iridium as another representative of the platinum group elements is also used as the main catalyst material for the anode. As of yet, there are no materials with reasonable prospects for substituting iridium. This is due to the fact that the coating of PEM anodes should be capable of being highly resistant to corrosion while featuring sufficient electrochemical activity—properties only satisfied by iridium sufficiently.

Titanium is the base material for bipolar plates in most PEM electrolyser, as it features appropriate mechanical properties and a high corrosion resistance. Furthermore, titanium screens, foams or felts are used for porous transport layers (PTL) in PEMEL technology.

Scandium is used in some concepts of solid oxide fuel cells (SOFC) as a doping material of the zirconium dioxide electrolyte. Thus, it is a potential substitute of yttrium, which is currently the state of the art doping material of HTEL electrolytes. The present work analyses a scenario in which scandium is established as the preferred doping material in the future, although this development is not foreseeable today. Special attributes of both elements are a high mechanical strength and oxygen ion conductivity while being chemically stable.

As already mentioned, yttrium is used for the same application as scandium. Other material compositions are generally possible, however, the doping with yttrium and scandium are seen as the most promising approaches. Thereof, yttrium-stabilised zirconia is expected to stay prevalent in HT electrolyser. However, scandium is preferred in some solid oxide fuel cells available today, and a scenario in which it is also used widely in HTEL is conceivable.
After determining the scope of research by predefining potentially critical materials used in electrolyzers, the expected demand of these materials for electrolyser demand generated by Germany in the period from 2020 to 2050 is assessed (see Figure 2 for respective applied methodology).

The REMod-D tool modelled the demand of electrolysis extension rate based on an energy system optimisation (Figure 3), but does not optimise the build-up and utilisation of production machinery to produce these electrolyzers. In order to model a realistic expansion of production capacity for the considered EL-components, a linear optimisation was applied (Figure 4). Namely those components are the membrane electrode assemblies (anode + cathode + membrane), bipolar plates and PTLs for PEMEL, as well as the solid electrolyte for HTEL.63,66,69,70 The assessment of a realistic production capacity development is achieved by minimising over-and undercapacities of the machinery in operation for each year, while fulfilling the overall demand from 2020 to 2050. Furthermore, the removal of already installed machinery is inhibited in the model. As input parameters, exemplary machinery with respective production capacity were identified for each production step. For AEL, no critical materials were identified. Hence, this technology was not further considered in the assessment.

The total annual material demand to 2050 is derived by multiplying the modelled annual installation rate for electrolyzers with the specific material inputs per kilowatt of electrolysis capacity. Two scenarios are used for the development of the specific material use. The state of the art of specific material use is evaluated by literature research, partially in combination with own calculations, experiences and expert opinions.15 Scenario 1 is defined as conservative, supposing that the material use per kW remains constant at the current level until 2050. The progressive scenario 2 expects the material use to decrease exponentially until reaching a minimum specific amount in 2035. This amount is defined based on expert estimates.
regarding the possible material use reductions while maintaining performance requirements. In scenario 2, this minimum amount remains constant from 2035 until 2050.

Results are the potential demand of platinum, iridium, titanium, scandium and yttrium for meeting Germany’s potential hydrogen demand from PEMEL and HTEL installations until 2050 in a conservative and progressive scenario.

3.3 Methodology used for material criticality determination

The present work does not conduct a material criticality analysis as introduced by Graedel et al. Similar to the majority of other studies concerned with material criticality, the present work only takes the most popular dimension of “supply risk” into account. This is due to the fact that the scope of this work is focused on only one specific application of the five considered materials (water electrolysis). Hence, there is no added value in including generally available values for the dimension of “vulnerability” as other studies consider different scopes. Furthermore, especially for iridium, scandium and yttrium, the non-transparent data availability reduces the selection of indicators.

The present criticality assessment involves no aggregation of values of individual indicators. Hence, no overall value for material criticality of the considered elements is calculated. A qualitative analysis of the individual quantitative results seems more helpful for evaluating the future supply risk of electrolysers, than reducing it to one single numeric indicator. This work is based on a literature research on a selection of relevant quantitative indicators for evaluating the supply risk of critical raw materials. Furthermore, a qualitative assessment of the respective quantitative results in view of material demand for electrolysers in Germany is carried out. The dimensions of “vulnerability” as well as “ecological risk” are neglected in the following analysis.

Table 1 summarises the incorporated indicators. As can be seen, this work includes six of the seven indicators that are applied most frequently in publications dealing with the supply risk of raw materials as analysed by Achzet et al. The depletion time is neglected, due to the unavailability of data on the geological reserves of scandium and iridium. The indicators country concentration and country risk are covered by the use of the Herfindahl-Hirschmann Index (HHI) in combination with the World-Governance Indicators (WGI). Thus, the combination (HHI-WGI) represents a weighted calculated average of the governmental conditions in countries that are mining the regarded raw material (measured in six dimensions: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption). The data for the HHI-WGI is obtained from Deloitte Sustainability et al., as they assess all of the considered materials. Deloitte Sustainability et al. aggregate the indicators considered in their work to a qualitative overall supply risk statement per element. A classification in a criticality scale is thus only available for the overall value, not for the individual indicators. As they are using indicators that are not of interest for this work (eg, the “substitution index,” as a complete substitution of the respective materials in electrolysers is not conceivable except for scandium), only a few individual indicators and not the overall criticality value are considered in this work. In order to connect the quantitative results of the HHI-WGI with a qualitative statement concerning the extent of criticality, the three-stage scale from the resource profiles published by the German Federal Institute for Geosciences and Natural Resources is utilised as a reference. At least for platinum, titanium and the group of rare earths the HHI as well as the WGI are categorised.

| Indicator | Frequency: Use in other studies (n = 15) | Unit | Source |
|-----------|------------------------------------------|------|--------|
| Country Concentration | 12 | HHI | 18,73-75,102 |
| Country Risk | 10 | HHI-WGI | |
| By-product dependency | 7 | [%] | 76 |
| Company concentration in mining operations | 5 | HHI | 77 |
| Demand growth | 5 | Qual. Assessment | 15,78 |
| Recycling | 3 | EoL-RIR [%]; EoL-RR [%] & Qual. Assessment | 18,79 & various (see Section 4.6) |
in a scale from low-moderate-high. For the combination of HHI-WGI, the two indicators are equally weighted. If the respective average is right between two characteristics, the HHI-WGI of the evaluated element is assessed with the higher criticality score.

The by-product dependency is evaluated by quoting the companionality indicator defined by Nassar et al. This indicator represents the share of the total produced raw material produced as a by-product of related host metals. By-production increases material criticality due to a dependency on market situations of other materials.

The company concentration in mining operations is depicted as well by the use of the HHI. Material production by few companies results in a high market power and thus the determination of supply and prices. Ericsson published respective values for platinum and titanium in 2012. It is assumed that the corporate landscape stayed more or less the same during the past few years, due to the strategic, long-term characteristic of the mining sector.

The demand growth is a qualitative assessment based on results of Marscheider-Weidemann et al. The potential effects of future technologies on the rise of material demands are assessed and discussed, in order to evaluate possible increases of the supply risk triggered by the demand side. In this context, a detailed outlook on the implications of the expected addition of electrolysis capacity by Germany (see Section 3.1) is presented.

The end-of-life recycling input rate (EoL-RIR) describes the share of the European supply of the respective materials that is sourced from recycled material. The values for this indicator are also obtained from Deloitte Sustainability et al. Furthermore, the global end-of-life functional recycling rates (EoL-RR) are analysed. Unlike the non-functional EoL-RR (collected materials are lost as a tramp element during the recycling process), this indicator describes the amount of recycled materials that can be reintroduced in production processes as pure metal or as an alloy. It is indicated in five ranges, starting from an EoL-RR of smaller than 1% and ending at the highest range of more than 50%.

### 3.4 Evaluation of the recyclability of materials in EoL electrolyser and consequent effects on future supply of critical materials

As recycling might be an important instrument for reducing supply risk, the present work focusses on this factor by taking two quantitative indicators (EoL-RIR & EoL-RR) into account. Furthermore, a qualitative discussion concerning the state of the art of recycling on a material as well as on a system level for fuel cells and, respectively, electrolyser is conducted based on a literature research. This shall provide a deeper understanding on how the recycling of electrolyser might have the potential to ease the critical supply situation described in Sections 4.1–4.3 for platinum, iridium, titanium, scandium and yttrium.

Additionally, a quantitative estimate about the amount of material returns from EoL electrolyser is generated on the basis of data described in Sections 3.1 and 3.2. The expected addition of installed capacity until 2050 by Germany is set against the expected lifespan of PEM and HT electrolysis systems. Structured interviews were conducted with industry representatives, in order to define the state of the art as well as the progression of the expected lifespan of electrolyser until 2050. While the lifespan of PEMEL systems is expected to increase from 20 to 27 years until 2050, the lifespan of HTEL systems is expected not to exceed 20 years. This can be attributed to material degradation due to high temperature operation in HTEL as well as to the earlier development stage in which HTEL is at the moment, resulting in higher uncertainties regarding future improvements. By taking the material input per kW of EL-capacity into account (conservative-/progressive scenario 1/scenario 2), the nominal material returns are calculated. In order to cover uncertainties in the reverse supply chain as well as losses during the recycling process, three more scenarios are defined which illustrate different recycling rates from EoL electrolyser (x, y & z). Table 2 lists the scenarios with the respective parameters.

Especially for PEM fuel cells, various concepts for recycling pathways exist (mostly pyrometallurgical recycling with hydrometallurgical processing of the resulting alloy). Since the general composition of a MEA for PEM fuel cells is similar to the one of PEM electrolyser, it is assumed that respective technologies can be utilised for electrolyser recycling with only minor adjustments. Unlike for the assessed PEMEL materials, there is currently no large-scale recycling circuit established for the recovery of the mentioned HTEL elements from EoL products in Japan. However, it is assumed that recycling processes for scandium and yttrium will be developed within the period under consideration. As it is unknown, when such recycling processes will be economically viable, the recovery rates used in the three evaluated scenarios are equal for platinum, iridium and titanium, while being significantly lower for scandium and yttrium.

Generally, the lower recovery rates used in the scenarios y and z mainly represent losses occurring in the reverse supply chain. A popular example is the platinum
recycling from auto catalysts. Currently, only around 50% of the theoretical recycling potential is exploited in the EU, due to exports of EoL cars or inefficient processes in the reverse supply chain. Scenario \(x\) depicts the optimal scenario which assumes a complete recycling of the considered materials. Hence, the respective recycling rates are 100- (platinum), 100- (iridium), 100- (titanium), 100- (scandium) and 100- (yttrium) percent. This scenario is defined to show the maximum effect of material recycling although it is rated as highly unlikely. However, electrolysers are stationary systems with a long lifespan as well as high investment costs and thus are not expected to change proprietors multiple times during their lifespan. Therefore, in this scenario it is expected that recycling rates will be higher than for standard products with higher frequencies of replacements.

Scenario \(y\) represents a realistic pathway and assumes at least a 20% material loss in established recycling technologies. This scenario is the most likely, as it also expects a moderate improvement of recycling rates for scandium and yttrium within the next 30 years. The estimated total recycling rates are 80-, 80-, 80, 30-, 30%.

Scenario \(z\) is a conservative scenario assuming comparable low recycling rates for all materials as well as nearly no recycling for scandium and yttrium (50-, 50-, 50, 10-, 10%).

The result is a total of six scenarios, combining the scenarios for material input per kW of EL capacity and the scenarios of different material recycling rates. Generally, declining material inputs as well as material returns of less than 100% are seen as realistic. Thus, the combination of scenarios 2 and \(y\) is seen as the most plausible future development of material recycling from EoL electrolysers. Hence, \(2y\) is used as the reference scenario for detailed discussions.

The overall aim of this scenario analysis is to give an outlook on how the recycling of EoL electrolysers might reduce the demand for primary materials, while realising the modelled addition of electrolysis capacity in Germany until 2050. Different scenarios show a bandwidth of possible developments, due to the unforeseeable progress in electrolysis as well as recycling technology and potential problems in the organisation of the reverse supply chain for EoL electrolysers.

### 4 | RESULTS

The results of the introduced indicators for the five evaluated elements are depicted in Table 3. In general, it can be observed that titanium is scored with a low to moderate supply risk for every indicator, while the platinum group metals as well as the rare earth elements scandium and yttrium obtain values that indicate a moderate (platinum) to high (iridium, scandium and yttrium) supply risk.

Although using the same methodology, the scales of the country- and the company concentration are interpreted differently due to different sources of data and respective bases of assessment. The classification in the three-stage scale (compare Section 3.3) is based on the spectrum of the results of all assessed materials in the particular studies. Literature sources for the values of the individual indicators are stated in the following paragraphs.

The subsequent sections describe the supply risk for every assessed element in detail, while the recyclability of electrolysers and its implications for secondary material supply are depicted in the last section, aggregated for all elements.

#### 4.1 | Supply risk of platinum with regard to its application in PEM electrolysers

The HHI-WGI of platinum is scored with a high risk for future supply as the production of platinum is concentrated in very few countries which have a moderate risk concerning their governance.\(^{18,75}\) The main suppliers of platinum are South Africa (77%), Russia (13%), North America (4%) and Zimbabwe (4%).\(^{81}\) From the 22 elements assessed by Ericsson regarding their company
concentration, platinum comes in seventh place with niobium having the least suppliers and an HHI of 5.884. It is thus grouped to the elements with few suppliers and in turn with a high company concentration.77 Around 16.1% of the global platinum supply is mined as a by-product of other elements. Around 98% of this share are accompanied with nickel while the remaining 2% are a by-product of palladium mining. As the main supply originates from non by-production, the companionality of platinum is seen as moderate.76 While the EoL-RIR for the European Union accounts for only 11%, Graedel et al. assess platinum as uncritical concerning its recyclability by allocating it with their highest score.18,79 This implicates that the potential for platinum recycling is not yet exhausted within the European Union. Globally around 40 metric tonnes of platinum were recycled in 2016, the main share thereof from catalytic converters (around 35 metric tonnes).82

Total production of primary platinum accounted for 191 000 kg in 2016.83 The main consumers of platinum in 2018 were the automotive industry (~94 600 kg), the jewellery sector (~69 700 kg) as well as industrial applications (~48 200 kg).84

Current state of the art PEM electrolyser possess power densities of around 3 W/cm² at a platinum loading of around 1 mg/cm². According to expert opinions, future improvements in power density to 8 W/cm², while simultaneously decreasing the platinum loading to approximately 0.3 mg/cm² are conceivable.15 This results in a platinum demand of 0.333 g/kW in the conservative, and of 0.0375 g/kW in the progressive scenario in 2035. As depicted in Figure 5, the platinum demand for electrolyser in Germany in the conservative scenario is expected to account for 1300 kg in 2050. Whereas the demand in the progressive scenario reaches its peak in 2027 with 238 kg and levels off at around 150 kg in 2050 (Figure 6). With reference to the global platinum supply mentioned above, this seems not much. However, the total global platinum demand exceeds the supply from primary production already today.84 Furthermore, significant growth in demand is expected by the future market penetration of technologies such as fuel cells for automotive applications (increase from 0 kg in 2016 to approximately 93 000 kg in 2035).78 As this equals around 40% of the total supply of 2016 (primary & secondary production) the indicator “demand growth” is rated as critical (=high). Whether or not, technologies like fuel cells will replace existing demands for exhaust gas treatment in combustion engine vehicles, or whether these new demands will rather be additive, is yet to be seen.

### TABLE 3  Material Criticality (Supply Risk) for Platinum, Iridium, Titanium, Scandium & Yttrium [Colour table can be viewed at wileyonlinelibrary.com]

| Indicator | Platinum | Iridium | Titanium | Scandium | Yttrium |
|-----------|----------|---------|----------|----------|---------|
| Country Concentration (HHI) | 5.582 [high] | — [high] | 1.334 [low] | 7.896 [high] | 7.896 [high] |
| WGI | 0.09 [moderate] | — | 0.68 [low] | ~0.56 [high] | ~0.56 [high] |
| HHI-WGI (scaled) | 2.5 [high] | 3.4 [high] | 0.4 [low] | 3.0 [high] | 9.2 [high] |
| Companionality [%] | 16.1 [moderate] | 100 [high] | 0 [low] | 100 [high] | 29 [moderate] |
| Company concentration (HHI) | 1.883 [high] | — [high] | 1.064 [moderate] | — | — |
| Demand growth | [high] | [moderate] | [moderate] | [high] | [moderate] |
| EoL-RIR [%] | 11 [moderate] | 14 [moderate] | 19 [moderate] | 0 [low] | (31) [neglected] |
| EoL-RR [%] | >50 [high] | >25-50 [moderate] | >50 [high] | <1 [low] | <1 [low] |
| Production [kg/a] | 191 000 (2016) | 7100 (2016) | 170 000 000 (2016) | 10 000 (2013) | 9 200 000 (2013) |
| Demand conservative 2030 [kg] | ~1050 | ~2100 | ~1 310 000 | ~8000 | ~4000 |
| Demand conservative 2050 [kg] | ~1300 | ~2650 | ~1 640 000 | ~25 500 | ~13 000 |
| Demand progressive 2030 [kg] | ~180 | ~360 | ~207 000 | ~1500 | ~1000 |
| Demand progressive 2050 [kg] | ~150 | ~200 | ~130 000 | ~2900 | ~1500 |

### FIGURE 5  Platinum demand and returns, conservative scenario [kg/a] [Colour figure can be viewed at wileyonlinelibrary.com]
4.2 Supply risk of iridium with regard to its application in PEM electrolysers

Neither information about the country concentration nor mining regions for the production of iridium were found in literature. However, as iridium is a platinum group metal and its production is completely coupled to platinum- (95%) and nickel mining (5%), it is expected that the country concentration equals the one of platinum or worse.76 This implication is approved by a very high HHI-WGI, which indicates that either the production sites are extremely rare or are located in countries assessed as critical concerning their government. However, in contrast to the HHI, implications for the WGI cannot be directly derived from platinum’s performance, which is why it is omitted in the supply risk assessment of iridium. The same as for the country-HHI also applies to the high scoring of iridium’s company concentration. Both EoL-RIR and EoL-RR are assessed as moderate. Main sources of recycled iridium in descending order are process catalysts from industrial applications and other applications like decoration, medical engineering, sensor technology and crucibles.85

Total mine production of iridium accounted for only 7100 kg in 2016.18 This is mainly due to its scarcity in earth’s crust (0.000003 ppm).86 As can be seen in Figure 7, the iridium demand for electrolysers in Germany in 2050 in the conservative scenario accounts for around 37% of the world’s iridium production in 2016 (constant material input of 0.667 g/kW15). If the necessary iridium input per kW of electrolysis capacity develops as expected and reaches its minimum of 0.05 g/kW in 2035, the long-term demand accounts for 200 kg of iridium in 2050. This still equals around 3% of the current world’s mining production to satisfy the PEMEL demand of only one country. The maximum demand in the progressive scenario is reached in 2027 (approximately 500 kg). Concerning the iridium demand growth in applications beyond electrolysis, no assessments were found in literature. The main applications for iridium in descending order are “other applications” (~2400 kg), electrical- (2350 kg), electrochemical- (1300 kg) and chemical applications (650 kg). Despite common fluctuations for precious metals, a general upward trend of iridium demand can be identified from around 5530 kg in 2012 to approximately 7030 kg in 2016.87 Thus, the indicator “demand growth” is rated moderate.

4.3 Supply risk of titanium with regard to its application in PEM electrolysers

The supply risk of titanium is assessed as uncritical. Huge reserves of the minerals ilmenite and rutile with a TiO2 content of around 830 000 000 tonnes and a current mining rate of approximately 6 600 000 tonnes per year do not suggest a resource depletion in the medium to long term.83 Although the company concentration is rated...
moderate, at least the country concentration is scored low. Furthermore, the mining sites are located in countries with uncritical governmental structures. This results in a low HHI-WGI score. As titanium is not produced as a by-product, the supply risk of titanium is further reduced by consulting the companionality indicator. With an EoL-RIR of 19% within the European Union, titanium ranks 21st of the 77 materials assessed by Deloitte et al. (with the element lead having the highest EoL-RIR of 75%). Same as for platinum, Graedel et al. allocate titanium to the group of materials with the highest possible EoL-RR of >50%. Globally, around 53,000 tonnes of titanium were recycled in 2016. Consequently, recycling has a high potential of further reducing the supply risk of titanium.

In order to deduce the material input per kW of PEM electrolysis capacity, a reference system with typical measurements of bipolar plates and porous transfer layers (PTLs) is defined. By assuming the substitution of bipolar plates comprised of pure titanium today by substrates coated with a thin layer of titanium (~0.01 cm) in the future, a progressive scenario is defined. Furthermore, by taking a potential reduction of thickness of PTLs from currently 0.1 to 0.03 cm into account (at a similar porosity of around 60% in both cases), the aggregated titanium use from 2035 on accounts for 32 g/kW in the progressive- and 414 g/kW in the conservative scenario. This results in a total titanium demand of 130 t/a in the progressive- and 1640 t/a in the conservative scenario in 2050 (compare Figures 9 and 10). The production rate of titanium varies widely throughout the past years, mainly due to oversupply and fluctuating demands. In 2016, around 170,000 tonnes of titanium sponge metal (pure titanium refined from titanium mineral concentrates) were refined worldwide (excluding U.S. production). Thus, the conservative demand equals around 1% of the global production.

This share of the total available feedstock is even further reduced by taking recycled titanium as a potential supply into account. With respect to the stated reserves, the additional demand for PEM electrolyzers in Germany is seen as not critical. However, increasing demands for other future technologies, like micro-electric capacitors, micro-energy harvesting, desalination plants and medical implants do have the potential of raising the future supply risk of titanium significantly. Marscheider-Weidemann et al. forecast an increase in demand from around 9000 tonnes in 2013 to approximately 41,200 tonnes in 2035 for these applications. Hence, the indicator “demand growth” is assessed with a moderate risk.

4.4 Supply risk of scandium with regard to its application in HT electrolyzers

As for most rare earth elements, the availability of data for scandium is comparably low. Hence, the HHI for the company concentration are not considered in the supply risk assessment of scandium.

Rare earth elements receive critical ratings for the country concentration of their production (HHI) as well as for the assessment of government performance in the respective countries (WGI). Accordingly, the scaled HHI-WGI of scandium is rated high as well. While scandium is exclusively mined as a by-product in China, Kazakhstan, Russia and Ukraine, currently around 95% of the global primary production is refined in China. In combination with low opportunities for recycling (compare Section 3.4), scandium is defined as highly critical concerning its supply risk.

The state of the art material input of scandium per kW of HT fuel cell capacity amounts to 23 g/kW. This equals around 35 g/kW of scandium oxide (S\textsubscript{2}O\textsubscript{3}).
Assuming an equality of structure, the different power densities of HT fuel cells (≈0.3-0.4 W/cm²) compared to HT electrolyser cells (≈1.2 W/cm²) result in a demand of scandium oxide of around 10 g/kW for electrolyser. Note that the stated power density for HT electrolyser cells are based on an expert survey. The authors assess this valuation as very progressive but achievable within the next years. As there were no expert opinions about potential future reductions of the necessary scandium demand, the progressive scenario assumes the same reduction rate as for platinum in PEMEL until 2035 (≈89%). This is a plausible pathway, given that the potential increases in current densities and thinner electrolyte layers (eg, by the use of anode supported cells) result in a decrease of the material use per kW. This leads to an average scandium oxide usage of 1.15 g/kW in 2035. The scandium oxide demand for HT electrolyser exceeds the global supply of around 10 000 kg in the conservative scenario in 2050 (compare Figure 11). Even by assuming the described material reduction of the progressive scenario, the scandium demand from Germany for HT electrolyser in 2050 accounts for around 29% of the world's primary production of 2013. Establishing recycling pathways for products containing scandium might mitigate this critical supply situation. Once more it needs to be stated that the use of scandium as a doping material of the zirconium dioxide electrolyte is currently not common. Currently, aluminium alloys are the main application of scandium. It is assumed that the demand for such alloys will be reduced especially in the aerospace industry within the next years, since advanced composite materials will be used more widely. However, the redundant supply this development creates is not expected to be sufficient to cover the demand for HT electrolyser and other future technologies, for example, HT fuel cells, for which an increase in annual demand of 7900 kg is estimated until 2035.

4.5 | Supply risk of yttrium with regard to its application in HT electrolyser

Yttrium as another rare earth element also lacks of a comprehensive data basis. Hence, the indicator of company concentration is neglected for yttrium. The country concentration of rare earth refining is high (compare Section 4.4). As the HHI-WGI achieves an extreme value of 9.2, it is to be expected that the production of yttrium is limited to even less countries (or takes place in countries with even worse assessments of the WGI) than the one of rare earths in general (compare Section 4.4). Nearly one third of the total production is a by-product of samarium-(13%), cerium- (9%), lanthanum- (5%), iron- (3%) as well as tin and titanium mining (<1%). Deloitte Sustainability et al. state an EOL-RIR of 31% for yttrium within the European Union. Indeed, there are notable efforts in establishing recycling pathways and technologies for rare earth elements. However, as they are mostly used in small amounts within the respective final product, their recycling is very complex and thus not common and lucrative on a large-scale yet. Although there exist several approaches in extracting yttrium from red phosphors of EuL fluorescent lamps as well as from laser crystals and synthetic garnets, the mentioned EOL-RIR of 31% seems disproportionately high. This impression is supported by the EOL-RR rating of less than 1% for yttrium by Graedel et al. as well as by the United States Geological Survey which assesses the amount of recycled yttrium as “insignificant.” Given these concerns, the findings of Deloitte et al. suggest that high recycling rates are neglected in this work.

Concerning the material use per kW of EL capacity, the same assumptions as for scandium are applied. Marscheider-Weidemann et al. indicate an yttrium usage of 14 g/kW capacity of HT fuel cells. This is equivalent to

FIGURE 11 | Scandium demand and returns, conservative scenario [kg/a] [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 12 | Scandium demand and returns, progressive scenario [kg/a] [Colour figure can be viewed at wileyonlinelibrary.com]
17.7 g of yttrium oxide (Y₂O₃). By taking the different power densities of fuel cells and electrolysers into account, a material use of 5.2 g/kW of HTEL capacity is supposed. We presume that the reduction rate in the progressive scenario the same as for scandium. Hence, from 2035 on, a material input of around 0.6 g/kW is assumed. This results in a demand for yttrium oxide of approximately 13 tonnes in the conservative- and 1.5 tonnes in the progressive scenario in 2050. Hence, the conservative demand is equivalent to 0.14% of the global production of 9200 tonnes in 2013.

The future supply can thus only be threatened by increasing demands deriving from other future technologies and consequently an aggravation of the competitive context for available reserves. Prominent future technologies with this potential are high temperature fuel cells (increase in demand of ~4.3 tonnes until 2035), autonomous driving technologies (~1004 tonnes), solid-state lasers (~28.7 tonnes) and high temperature superconductors (~0.9 tonnes). In total, the expected increase of demand for these four applications equates 11.3% of the mentioned global production. Once more, the demand growth is rated moderate.

4.6 | Recycling of electrolysers

As already stated, the recycling of PEM fuel cells is commercially established by using today’s small amounts of EoL fuel cells as additional feedstock in pyrometallurgical recycling processes. A comprehensive overview of the recycling of fuel cells is provided by Wittstock et al.⁹³ Common approaches are comprised of four steps, namely the collection, dismantling, disassembly and preprocessing as well as the actual material recovery.⁹³ While the titanium bipolar plates can be separated in the disassembly process and introduced in conventional melting processes, the extraction of the precious metal catalyst material is more complex, because it is incorporated in the membrane electrode assembly. Most recycling pathways apply incineration in order to separate the membrane from the catalyst materials.⁹³ By doing so, platinum recovery rates of more than 95% are achievable.⁹⁴ This process also enables the extraction of iridium. However, the incineration of Nafion, which is currently the main membrane material for electrolysers, results in the emission of hydrogen fluorides, which are harmful for human health and the environment. Possible approaches concerning this matter are leaching processes (Jha et al. provide a detailed overview) or the use of inorganic additives during the thermal treatment.⁹⁴,⁹⁵ Concerning the recovery of materials from PEM MEAs, hydrometallurgical processes (Pt, Ir & Ru) and pyrohydrometallurgical (Pt) processes are applicable. While the first requires mechanical pre-treatment and large volumes of solvents and potentially produces toxic wastewater, the latter is accompanied with safety- and environmental concerns.⁹⁶

In their overview on “existing EoL technologies applicable to FCH products,” the project group of HyTechCycling proposed hydrothermal treatment as an approach in recycling YSZ from Solid Oxide Fuel Cells (SOFC) by referring to Kojima et al.⁹⁶,⁹⁷

By taking the lifespan of electrolysers as well as the expected addition of electrolysis capacity until 2050 into account, the capability of electrolyser recycling to reduce the supply risk of the assessed materials or rather for supplying the demands of prospective electrolyser installations is evaluated. For doing so, the calculated demands of the individual materials is offset against the recovered materials from the potential recycling of EoL electrolysers in the six introduced scenarios (compare Section 3.4). The results illustrated in Figures 5–14 indicate that in most scenarios the demands for new systems...
cannot be covered by the recycling of electrolysers within the period under consideration until 2050. This is due to the long lifespan of electrolysers which hampers the contribution of recycling to a relaxation of the material supply situation for such systems in the near to medium term. For PEMEL, significant material returns (platinum, iridium and titanium) are estimated to occur from the beginning of the 2040s, while materials from HT electrolysers (scandium, yttrium and) are expected to return in meaningful quantities from around 2045, due to its later market introduction (compare Figure 4). Generally, the reduction of material input per kW (progressive scenarios) results for platinum, iridium and titanium in a fulfilment of demand by secondary material towards the end of the period under consideration (at least in the scenarios estimating the complete recirculation of the deployed materials). This is not to be expected in the conservative scenarios. Note that for PEM electrolysers experts expect the lifespan of future systems to increase approximately 1 year per every 5 years. In the described approach of forecasting material returns, this results in net returns of 0 tonnes every 5 years (compare Figures 5–14).

Since it is defined as the reference scenario, the following statements refer to scenario 2y, which assumes a progressive decline of material input while expecting a medium rate of material returns. Maximum returns of secondary platinum are expected around 2050 with a total amount of 730 kg. This equals around 92% of the total platinum demand for electrolysers in this year. From then on, the material backflows are decreasing. However, assuming the addition of electrolysis capacity staying the same in the years after the period under consideration, between 64% and 88% of the material demand of the following years until 2070 can be covered via recycling. The analysis of iridium expects that demands from 2040 can be covered with minor outliers. The titanium demand in 2040 is covered nearly twice by the recycling of EoL electrolysers. Although expecting major variations in material backflows during the following years, the titanium demand is, same as for iridium, fulfilled with minor outliers. Even in the progressive scenarios no fulfilment of demand for scandium and yttrium is to be expected. Since relevant capacity addition of HTEL systems can be observed starting in 2030 (compare Figure 4), the earliest installed systems are not defined by a significant larger material use per kW than the later ones (other than PEMEL). Hence, the EoL returns of those systems will not compensate the rising material demands due to increasing extension rates of HTEL systems. If the addition of electrolysis capacity stays at the level of 2050, recycling might contribute with 30% to the material demands of new HT systems in 2070.

5 | DISCUSSION

Generally, platinum is evaluated with a high supply risk. Although, the expected demands can be covered from primary production, electrolysis is in competition with many other technologies for platinum resources. Titanium is assessed as not critical. Expected demands can be covered by primary production—a depletion of reserves is not conceivable in the medium to long term. Other future technologies beside hydrogen production by water electrolysis (eg, fuel cells for automotive applications) might increase the supply risks of the respective materials significantly. Thus, either platinum and iridium are rated critical for water electrolysis or generally for sustainable energy or environmental technologies in other literature.16,89,98

While this work focused on Germany, the conclusions regarding material supply will only amplify if the potential global demand for water electrolysers is taken into account. In case all the projected future hydrogen demand (compare Section 3.1) will be supplied via water electrolysis and assuming the same market shares between AEL, PEMEL & HTEL as considered in ReMod-D, iridium supply is evaluated as highly critical. Its global demand from PEMEL electrolysis could be equivalent to ~470-1400% of the current global mining rate. In case HTEL technologies will use scandium as a doping material, the demand for scandium even exceeds these numbers by accounting for 1300-3800% of the current world’s production. The ratio of demand and supply for titanium and platinum, required for PEMEL is significantly lower. Furthermore, the geological availability of titanium and platinum presumably enables a long-term supply of these materials. Identified resources of titanium mineral concentrates (830 000 000 tonnes83) and platinum group metals (69 000 tonnes83) reveal the theoretical potential of capacity increase of mining operations. However, as already discussed, other future technologies and state of the art applications are in competition over available quantities on the market. Hence, with such significant growth in demand price increases can be expected.

The project HyTechCycling, funded by the FCH2JU, aims at identifying feasible recycling technologies for fuel cells and electrolysers. Among others, the project group named critical materials used in electrolysis systems in the draft of their final report. Same as in the present work, the general material use in alkaline electrolysers is assessed as rather uncritical (based on the report on critical raw materials for the EU15). Nevertheless, “precious metals” used for the anode in some AEL concepts are scored with a “high” criticality. Furthermore, Raney nickel used in electrodes is evaluated as critical. Nickel is
also assessed as critical for high temperature fuel cells (SOFC), mainly due to its “economic importance” for the European Union. However, it has to be stated that other studies rate nickel as uncritical concerning its supply, which would also apply to Raney nickel, which is produced from an aluminium nickel alloy. Furthermore, the SOFC cathode, which is made of strontium-doped lanthanum chromate, is rated critical. As this work only considers electrolysis technologies, it has to be annotated that, unlike in SOFCs, the most common cathode material for HT (or SOECs) is a Ni-YSZ cermet. In accordance with the findings in this work, the electrolyte YSZ (HTEL) and the electrode materials platinum and iridium (PEMEL) are rated critical. The criticality of titanium used for bipolar plates is assessed as “medium.” Additionally, ruthenium, a potential substitute for iridium, is mentioned and assessed with a “high” criticality.

Further potential critical elements applied in water electrolyzers as named by Zauner and Reiter which were not under detailed examination in this work are: tungsten (AEL), ruthenium (certain AEL and PEMEL concepts), cobalt (AEL, PEMEL, HTEL), antimony (PEMEL), niobium (PEMEL), cerium (PEMEL, HTEL), gadolinium (HTEL), lanthanum (HTEL), samarium (HTEL), neodymium (HTEL), holmium (HTEL) and chromium (HTEL). Those elements are no main constituents of electrolysers or mostly substitutes for the evaluated ones. For electrolyser concepts that use some of these elements, further research is recommended.

McCullough and Nassar apply the criticality methodology published by the U.S. National Science and Technology Council in order to calculate material criticality of 78 minerals over the time period from 1996 to 2014. The overall criticality potential is calculated by taking the WGI, HHI, an indicator for measuring the annual growth rate of global production as well as one for assessing the market dynamics of the evaluated minerals, into account. Iridium and rare earth elements in general (and thus scandium and yttrium) surpass the defined threshold value of 0.3 for the criticality potential in 2014 and thus are rated critical. Platinum receives a medium (0.19) and titanium a low (0.15) rating. Yttrium faces a fluctuating and rare earth elements in general a constant increase of criticality potential within the period under consideration. While the criticality of titanium fluctuated slightly, that of platinum fluctuated strongly, finding its peak in 2006 (0.33). The criticality potential of iridium even decreased from 0.51 in 2007 to 0.31 in 2014. Although this work considers different indicators than McCullough and Nassar, further research on the future supply risk of iridium is recommended, since a decrease in criticality potential is not consistent with findings in the present work in Section 4.2. Beyond that, the long-term analysis of McCullough and Nassar as well as the present work obtained similar results.

Generally, the recycling of electrolysers bears the potential of lowering the supply risk of all assessed materials under consideration for PEMEL technology. However, significant returns of materials cannot be expected in the next 20 years. However, from around 2040, a large share of the demand for new systems could be covered by secondary materials recycled form EoL electrolysers. As there are no industrial scale recycling pathways established yet for scandium and yttrium, the supply of secondary materials is seen as critical. This effect is aggravated by fewer returns in HT than in PEM electrolysers within the period under consideration, as HT electrolysers are expected to reach relevant market penetrations much later than PEMEL.

6 CONCLUSION

This work aims at the identification of potential critical elements for water electrolysers and a respective evaluation of their future supply risk. This research focuses on the potential electrolysis capacity demand of Germany until 2050, not considering the location of the actual installed electrolysis systems (compare Section 3.1). After a preselection of potential critical materials (iridium, platinum, titanium, scandium and yttrium) in expert workshops, a detailed analysis is conducted. The applied methodology is partly based on academic literature, as this work considers common indicators used in other supply risk assessments. Nevertheless, several indicators (and dimensions of criticality assessments) are neglected, due to data unavailability or the specified scope of location and especially application. In addition, the recyclability of EoL electrolysers is analysed by a literature research. By combining the expected electrolysis installations with the respective expected lifetime and material input per kW for each technology (technological development represented in a progressive and a conservative scenario), the recycling potential for the future supply of the assessed materials is evaluated.

Out of the five assessed materials, only titanium (PEMEL) is rated with low to medium scores for the assessed supply risk indicators, as it is produced in stable countries in comparable large quantities. The emerging additional demand caused by the industrialisation of water electrolysis will presumably not exacerbate the supply situation substantially. On the contrary, meeting projected demands for scandium (HTEL) and iridium (PEMEL) in 2050 is rated extremely critical, if the material input per kW of electrolysis capacity stays constant.
during the period under consideration. The demand for scandium would even exceed the current supply in the conservative scenario (constant material input), but only if scandium becomes the primary doping material in HTELO technology, which is currently not expected. The demand for iridium accounts for 37% of the world's production. Especially for scandium, but also for platinum (PEMEL) the supply risk is even increased, due to predicted immense demands from other future technologies. Except for titanium, mining operations of the assessed materials are concentrated in very few countries, resulting in a strong dependency of consumers and market power of suppliers. This is even aggravated by critical political conditions in some of the respective countries, which bears the risk of sudden destabilisation of the supply situation. As the discussion revealed, those findings are mostly consistent with the state of the art reported in literature.

Although there are no large-scale recycling routes for scandium and yttrium established yet, it is expected that technological progress will enable a cost-effective recycling of these elements within the next 30 years. Recycling processes for potentially critical materials from PEM electrolyser already exist. However, as the scenario analysis indicates, recycling will not play a major role in relaxing the supply situation of critical materials for water electrolysis within the period under consideration (especially for scandium and yttrium). This is mainly due to the long lifespan of electrolyzers.

The present work illustrates the importance of tracking material use and criticality of innovative technologies like water electrolyzers. If water electrolysis will be as important as expected for the German “Energiewende,” the development of innovative approaches in reducing the material inputs per kW for the evaluated materials is inevitable. The calculations in the present work are based on projected material use for electrolysis demand generated by Germany alone. Even if the roll-out of electrolyzers turns out to be not as progressive as expected in Germany, the worldwide demand for respective materials is likely to increase substantially. Power to gas technologies are expected to play a major role, since the world is moving slowly towards wind power and photovoltaics as the main primary energy sources. This requires water electrolyzers to store at least some of the electrical energy in molecules. Hence, the development of strategies for reducing the material input or substituting several materials in electrolysis technologies is inevitable.

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