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Resource-Efficient Gigawatt Water Electrolysis in Germany—A Circular Economy Potential Analysis

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Abstract
Green hydrogen will play a key role in the future energy system. For the production of green hydrogen, an installation of alkaline (AWE) and proton exchange membrane water electrolysis (PEMWE) of several gigawatts per year is projected in the upcoming decades. The development of the hydrogen economy is associated with a great demand for scarce and expensive resources. To reduce resource demand and avoid supply bottlenecks, actions toward a circular economy are required. In the present study, three circular economy actions (repair, reuse, and recycling) are analyzed with regard to AWE and PEMWE installation taking Germany as an example. It is found that, so far, only recycling is a viable strategy for a circular economy. For further analysis, a model is developed to assess the impact of recycling on resource demand for AWE and PEMWE scale-up. Mass flows from end-of-life recycling are intergrated into the model, and their economic value is estimated. The results imply that closed-loop recycling can reduce the cumulated primary resource demand by up to 50% in the long run. However, recycling will first be relevant after 2040, while water electrolysis capacities installed before still depend on primary materials. The outlook on the economic value of the recycling materials indicates a volume of up to 2.15 B € per decade for PEMWE and 0.98 B € per decade for AWE recycling. To realize the potential, a recycling industry specialized for those technolgies considering the whole value chain covering dismantling, collection, and recycling must be introduced.

Keywords Proton exchange membrane water electrolysis · Alkaline water electrolysis · Hydrogen economy · Circular economy · 3 R's

Abbreviations

AWE	Alkaline water electrolysis
PEMWE	Proton exchange membrane water electrolysis
EOL	End-of-life

Highlights
•Study on AWE and PEMWE circular economy actions: repair, reuse and recycling.
•Providing a technology-specific material demand model for alkaline and PEM water electrolysis.
•Assessing closed-loop recycling as a strategy to reduce AWE and PEMWE resource demand in the long run.
•Scenario analysis of large-scale water electrolysis future market development and outlook on the economic volume of recycling streams.

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HTEL	High-temperature electrolysis
CCM	Catalyst-coated membrane
PTL	Porous transport layer
HTH	Hydrothermal treatment
HMT	Hydrometallurgical treatment
PMT	Pyro-hydrometallurgical treatment
TD	Transient dissolution

List of Symbols

$C(k)$	Annual gross installed capacity $C(k)$, GWa^{-1}
$C_{exp}(k)$	Water electrolysis expansion rate, GWa^{-1}
$C_{rep}(k)$	Annual repowering rate, GWa^{-1}
k	Year
$\dot{m}_{gd,\alpha}(k)$	Annual gross material demand for material α, ta^{-1}
$\dot{m}_{nd,\alpha}(k)$	Annual net primary material demand after recycling, ta^{-1}
$\dot{m}_{rec,\alpha}(k)$	Annual material availability from recycling , ta^{-1}
$m_{sd,\alpha}(k)$	Specific material demand for material α in year k, $g(kW)^{-1}$
R_α	Material specific recycling rate, %
α	Material index
$T(k)$	Water electrolysis system lifetime, a

Introduction

In this paper, the potential of a circular economy for alkaline (AWE) and proton exchange membrane water electrolysis (PEMWE) technologies in Germany is analyzed. For AWE and PEMWE as the most market-mature technologies to produce green hydrogen, an increasing annual expansion of up to several gigawatts in installed capacities in Germany is expected for the next decades [1].

However, research is addressing potential barriers that might hamper the expansion of water electrolysis capacities. Many of these barriers arise from the demand for materials that are essential for the construction and functionality of water electrolysis systems but are associated with high costs and restricted supply or accessibility [2, 3]. There are two strategies to ensure that the material demand for the projected water electrolysis capacity expansion is covered: firstly, to reduce the specific material demand for AWE and PEMWE and secondly, to establish a circular economy with high material recycling rates [2–4].

Furthermore, several life cycle assessments analyze the environmental impact of recycling water electrolyzers at their end-of-life (EOL). They indicate that establishing a circular economy in water electrolysis mainly based on efficient recycling is reducing such environmental impacts [5–7]. Therefore, it is necessary to further analyze the potential for a circular economy in water electrolysis.

There already exist investigations on material demand for different water electrolysis technologies as well as on the role of efficient recycling of water electrolyzers at their EOL to reduce primary resource demand. Often, the focus is on noble metals, since its demand represents a potential bottleneck hampering the market ramp-up of water electrolysis capacities.

An analysis of global platinum demand for the green transition until 2050 identifies potential bottlenecks in platinum supply. To address such potential future supply risks, long-term strategies to mitigate bottlenecks in platinum supply are identified. Those strategies are the improvement of EOL collection and recycling rates as well as spreading the use of best practices and technologies in recycling. Further, a shift in the platinum recycling landscape from automotive catalyst scrap, as solely applied today, to more diverse scrap, e.g., from EOL fuel cells and water electrolyzers, is expected [4].

Iridium is another noble metal that could hamper water electrolysis market ramp-up. Minke et al. (2021) show that the expected iridium demand for the realization of PEMWE on a multi-GW scale in Germany until 2050 is a potential bottleneck due to limited mine production. The analysis is based on a model in which the technical prospects for the optimization of PEMWE specific iridium demand and PEMWE installation rates are taken into account for the next 50 years. The results show the necessity of a substantial reduction of iridium loading in PEMWE cells and the development of a recycling infrastructure for iridium in PEMWE cells with recycling rates of at least 90% [3].

Further, Kiemel et al. (2021) published an analysis of critical materials with potential future supply constraints for water electrolysis installations in Germany and the potential of a closed-loop recycling of water electrolyzers at their EOL to ensure the material supply for new water electrolysis installations. It is concluded that even though conventional recycling pathways for platinum and iridium already exist, secondary material from water electrolyzers at their EOL will not reduce the dependence on primary resources significantly within the period from 2020 until 2050 [2].

Additional research on the recycling of different waste streams for the use in water electrolysis further underlines that developing a recycling infrastructure for technologies such as AWE and PEMWE is important for several reasons. Those are to take advantage of abundant sources of materials, relieve the stress of mining scarce elements, present an opportunity to develop cost-effective-catalysts for green hydrogen production, and ensure the sustainability of the green energy sector [8].

All these investigations set a focus on recycling but no other circular economy actions to handle water electrolyzers at their EOL such as repair or reuse are discussed. Further, the investigated literature considers materials mainly used in PEMWE and high temperature electrolysis (HTEL) that are scarce noble metals and critical in terms of supply risk. However, no detailed investigations for AWE material demand on an annual base or the potentials of EOL AWE recycling on primary resource demand are conducted, even though specific material demand per installed capacity of AWE is much higher than for PEMWE due to lower current densities. Furthermore, AWE is the most mature water electrolysis technology. In terms of market penetration, AWE is on the same level as PEMWE and is expected to have higher market penetration in the upcoming years due to its higher technology maturity [1, 9].

Moreover, the analysis conducted by Minke et al. (2021) and Kiemel et al. (2021) are based on progressive trajectories in the water electrolysis market development between 2020 and 2050 [2, 3]. Ambitious water electrolysis installation rates are based on the assumption that no hydrogen is imported and all of the hydrogen demand in Germany is covered by water electrolysis built in Germany [1]. However, the installed water electrolysis capacities in Germany between 2020 and 2023 as well as announced water electrolysis projects for the next 2 years are below the progressive projections used in Minke and Kiemel [10]. Furthermore, current political actions indicate a significant import of hydrogen into Germany leading to reduced water electrolysis installation rates in Germany [11–14].

Even though recycling of water electrolyzers at their EOL is considered important for the reason of reducing resource supply risks and for ecological reasons, the economic perspective of water electrolysis recycling is not considered in research so far. To encourage research and stakeholders from the recycling industry, an estimation of the economic volume of water electrolysis recycling mass flows is made in this paper.

To reinforce previous research, fill up weak spots, and add further perspective on circular economy potentials in water electrolysis, this work aims to answer the following four research questions.

(i) What are reasonable circular economy actions to handle water electrolyzers at their EOL?
(ii) What is the resource demand for main materials used for AWE and PEMWE when expecting installation of multi GW scale water electrolysis in Germany in the next decades?
(iii) To what extent and when can a closed-loop recycling approach of water electrolyzers at their EOL help to flatten primary resource demand for new water electrolysis installations in Germany?
(iv) How big is the economic potential of recycled materials from water electrolyzers at their EOL and thus the economic potential for the development of a water electrolysis recycling industry?

To answer the second and third question, the focus is not only on the noble metals platinum and iridium used in PEMWE but also on titanium as well as the main metals used in AWE, which are steel and nickel [15, 16]. Furthermore, the water electrolysis installation rates in Germany between 2020 and 2050 considered in this paper are less ambitious compared to the examined literature, and the market ramp-up phase is postponed [1].

The structure of the paper is based on the research questions. First, a qualitative description of the potential and the applicability of three circular economy actions already established in other technologies, repair, reuse, and recycling, is given. Thereafter, to answer questions (ii)–(vi), a calculation model and the corresponding input data for the analysis and quantification of the potentials of closed-loop recycling of EOL water electrolysis are introduced. Then, the economic potential of the water electrolysis recycling industry is estimated. Finally, in the last two chapters, the results of the paper are presented, discussed, and summarized.

Considerations on Circular Economy Actions to Handle End-of-Life Water Electrolyzers

In this chapter, research question (i), discussing reasonable and applicable circular economy actions to handle EOL of water electrolysis, is answered. Therefore, based on the waste hierarchy concept, three common circular economy actions to prevent materials and products from being disposed, incinerated, or landfilled are analyzed in terms of their applicability to water electrolysis. The discussed actions (3 R's) are reuse, repair and recycling [17]. The info box in Fig. 1 provides a brief ovierview, before detailed considerations are given in subsequent sections.

Repair

In general, to be able to repair a product, its design must favor such actions. This also applies to the repair of water electrolysis. The components most prone to degradation

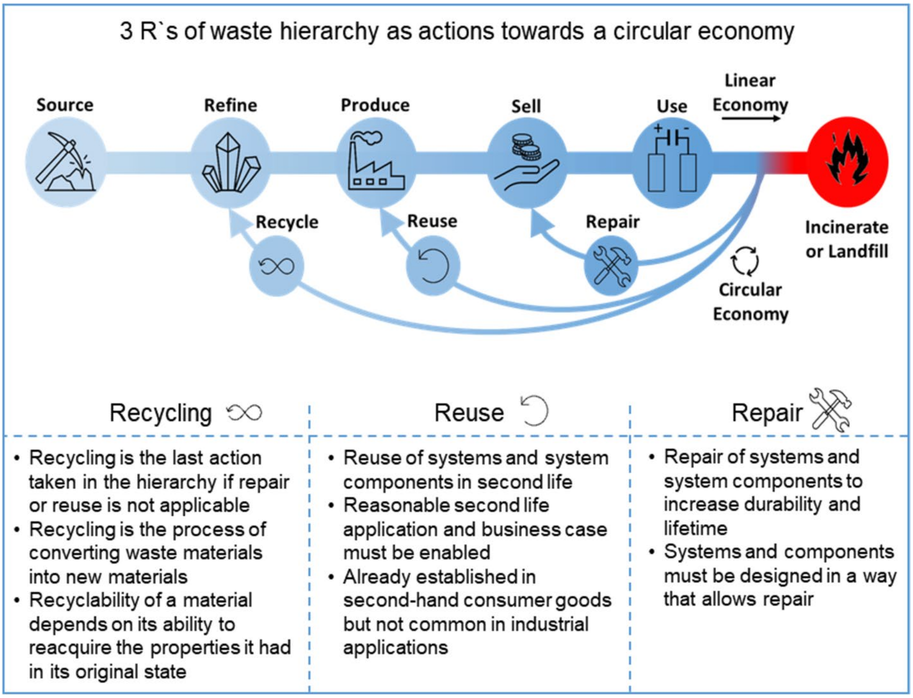

Fig. 1 Info box on 3 R's of waste hirarchy in circular economy based on [17–19]

and thereby limiting water electrolysis lifetime and efficiency are the electrodes in AWE, whereas in PEMWE, those are catalysts, membranes (catalyst-coated membrane, CCM), and the anodic porous transport layer (PTL) [20–22]. In water electrolyzers at their EOL, these components must be repaired or, if not possible, replaced. The replacement of degraded components is also referred to as refurbishment.

However, when developing and designing water electrolysis, repair actions are not the main focus even though repair actions might be favorable from a life cycle perspective. Instead, development of the design focuses on minimizing hydrogen costs and maximizing efficiency considering the complex electrochemistry which not necessarily goes in hand with enabling repair actions. Therefore, design for repair is not state of the art, and possibilities of repairing or replacing degraded components are limited due to compact and complex system design that the sensitive electrochemistry entails [23, 24].

Nevertheless, aiming toward a circular economy, the possibilities for repair actions in water electrolysis should be considered in further research, e.g., given a water electrolysis design favoring repair actions, replacement, or reactivation of degraded electrodes while other components are further used might be possible for AWE [25]. In the literature, it is stated that such repair actions for AWE can be conducted as part of a general overhaul after an operating period of 7 to 12 years [25]. However, some AWE are operating for 20 years without overhaul making repair measures unnecessary [25].

Compared to AWE, the design of PEMWE is less favorable regarding repair actions. In most PEMWE, the catalyst material is coated and pressed on the membrane to build the CCM. The PTLs are pressed on both sides of the CCM [24]. When the cell is opened, the layers stick together and cannot be separated without damaging the cell components. Only if the cell design favors repair actions, degraded CCM and the PTL can be substituted in an overhaul process [20]. This would require a modular design favoring such replacement of individual components or cells which is not state of the art.

Reuse

So far, water electrolyzers at their EOL are showing limited possibilities for reuse in a second life as similar or different applications. Only some water electrolyzer system components can be reused without previous refurbishment or recycling such as containers, housings, pumps, and other peripheric systems which are not in the scope of this work [5].

The lack of second-life applications for water electrolysis after 10–20 years of operation is due to technical and economical reasons. Water electrolysis components are degraded to a point where the electrochemical processes are hampered to the extent that the efficiency of further operation is reduced and energy consumption and safety risks are increased. Also, technology has meanwhile been improved so that water electrolyzers at their EOL no longer correspond to the state of the art [26].

Strategies for the reuse of degraded and inefficient but still technically functioning water electrolysis in economically weaker regions that offer the availability of cheap renewable energies allowing low operating costs might show some potential but are not addressed in this paper.

Recycling

Since reuse and repair are no reasonable options for treating water electrolyzers at their EOL so far, recycling is the only viable action to enable a circular flow of resources and reduce the use of primary materials for water electrolysis installations [5]. Metals are the main materials used in water electrolyzers and assumed to have excellent properties for recycling. For many metals, and corresponding industrial branches, recycling technologies, infrastructures, and regulations are already established [27]. Examples are steel recycling in the car industry and titanium recycling in the aviation industry [28, 29]. However, this is not the case for water electrolyzers at their EOL so far due to a lack of standadized system design, specified technologies, and regulations [5]. Further, some metals used in water electrolysis are present in small amounts and complex compounds [16, 30]. Last but not least, there is no notable amount of water electrolyzers at their EOL making a recycling industry necessary so far.

Today, there are no standardized or common recycling technologies specified to water electrolysis technologies [5]. However, existing recycling technologies based on hydrometallurgical, pyro-hydrometallurgical, and hydrothermal recovery treatments can be applied for the recycling of water electrolyzers at their EOL [2, 15, 31].

Further, there are innovative recycling technologies specified to water electrolysis such as electrochemical dissolution in the research and development phase [16, 31]. Also, in fuel cell technology, there already are various recycling technologies and routes, especially for PEM fuel cells [2]. Since the general material composition of PEMWE is quite similar to PEM fuel cells, respective fuel cell recycling processes can be utilized for water electrolysis recycling with minor adjustments [2].

However, not only innovative recycling processes but also efficient dismantling and collection is necessary to allow high recycling rates in the long term [2]. Strategies proposed in the literature to realize high collection rates are the establishment of recovery centers connected to the manufacturers considering extended producer responsibility and reverse logistics as well as introducing a regulatory framework. Also, a dual role of manufacturers as recovery centers and new business models such as product leasing are proposed to enable circular economy strategies within a well-developed hydrogen industry [31].

In conclusion, already existing and upcoming recycling infrastructure, conventional and new technologies as well as research efforts indicate that recycling is the most promising of the circular economy actions examined. Therefore, in this paper, the potential of recycling as a circular economy action is further analyzed in terms of its ability to reduce primary resource demand in water electrolysis industrialization in Germany. The analysis is based on a calculation model and scenario analysis that is described in the following.

Calculation Model to Analyze Closed-Loop Recycling Potential of Water Electrolyzers in Germany

In the following, the method to analyze and quantify the potential of a closed-loop recycling approach as a circular economy action for water electrolysis in Germany in the period between 2020 and 2070 is described. For the analysis, a calculation model is developed and implemented in Matlab to quantify material demand for water electrolysis installations and material availability from closed-loop recycling of water electrolyzers at their EOL. Further, the potential to cover material demand for water electrolysis installations by recycling material is analyzed.

The chapter is structured in three sections (see Fig. 2). The first section is covering the input data of the calculation model. In the second section, the process flow and formulas yielding the results of the calculation model are described. In the third section, scenarios are defined to analyze the effect of conservative and innovative assumptions for the input data.

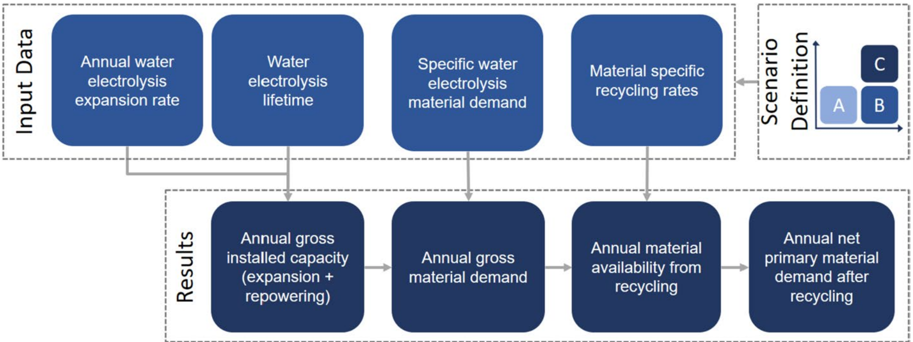

Fig. 2 Overview of calculation model inputs (annual electrolysis expansion rate, electrolysis lifetime, specific material demand, and recycling rates) and results (annual gross installed capacity including expansion rates and repowering rates, where repowering is the replacement of EOL capacities, annual gross material demand, material availability from recycling, and primary material demand after recycling)

Input Data

The input data for the calculation model is based on four separate datasets as shown in Fig. 2. Each dataset entails values for each year $k(0 \leq k \leq 50)$ in the considered period between 2020 and 2070.

(i) The first input dataset contains the projected water electrolysis expansion rate $C_{\text{exp}}(k)$ for each year k in $\text{GW}a^{-1}$.
(ii) The second input dataset contains the average water electrolysis system lifetime $T(k)$ for each year since the lifetime for PEMWE is assumed to increase between 2020 and 2035 which will be discussed later.
(iii) The specific material demand $m_{\text{sd},\alpha}(k)$ for each material α in g(kW)^{-1} to install one kW of nominal power of water electrolysis is found in the third input data set.
(iv) The material-specific recycling rate R_α in % is contained in the fourth dataset.

The input data is further discussed in the "Data" section (see Table 1) and is based on literature research.

Calculation Model and Results

The calculation is built up in four modeling steps producing the results on which the analysis of the closed-loop recycling approach is based (see Fig. 2). First, the calculation of the annual gross installed capacity $C(k)$ in GWa^{-1} for AWE and PEMWE. The water electrolysis annual gross installed capacity is calculated as

$$C(k) = C_{\text{exp}}(k) + C_{\text{rep}}(k)$$

Table 1 Data for scenario analysis: specific material demand and material recycling rates for AWE and PEMWE, today and future projection

Material	Specific material demand base year (2020) in g(kW)^{-1}		Specific material demand projected (2035) in g(kW)^{-1}		Recycling rates	
	Conservative	Innovative	Conservative	Innovative	Conservative	Innovative
AWE						
Nickel [30, 35–38]	2000.00	1503.13	793.65	200.00	0.57	0.90
Steel [30, 35, 36, 39, 40]	51,956.25	33,333.33	30,000.00	10,000.00	0.70	0.90
PEMWE						
Iridium [16, 24, 30, 35, 41]	2.50	0.70	0.40	0.05	0.40	0.90
Platinum [24, 30, 35, 42]	1.00	0.30	0.50	0.03	0.76	0.90
Titanium [1, 20, 30, 35, 43]	528.00	450.00	35.00	32.20	0.40	0.91

The capacity of water electrolysis systems entering their EOL must be repowered by new installations with $C_{rep}(k)$ being calculated through

$$C_{rep}(k) = \begin{cases} 0 & \text{for } k < T_0 \\ C_{exp}(k - T_k) & \text{for } k \geq T_0 \end{cases}$$

The repowered capacity $C_{rep}(k)$ in GWa^{-1} is added to the electrolysis expansion rate $C_{exp}(k)$ yielding the annual gross installed capacity. The annual repowering capacity $C_{rep}(k)$ is calculated by shifting each year's net expenasion rate $C_{exp}(k)$ by its corresponding lifetime $T(k)$ to calculate the EOL capacity that must be replaced for each year. Since in reality, not all water electrolysis installed in year k will have the same lifetime $T(k)$; the replacement rate is smoothed. Thereby strong fluctuations in the repowering capacities caused by the progressive lifetime $T(k)$ are avoided.

Second, the calculation of the annual gross material demand $\dot{m}_{gd,\alpha}(k)$ for material α in period k in ta^{-1}. The required annual gross material demand $\dot{m}_{gd,\alpha}(k)$ is calculated based on the annual gross installed nominal capacity $C(k)$ and the specific material demand $m_{sd,k}$.

$$\dot{m}_{gd,\alpha}(k) = C(k) \cdot m_{sd,\alpha}(k)$$

Third, the calculation of the annual material availability from recycling $\dot{m}_{rec,\alpha}(k)$ in period k in ta^{-1} is calculated by postponing the annual material gross demand $\dot{m}_{gd,\alpha}(k)$ by the lifetime $T(k)$ and multiplication with material-specific recycling rates R_α.

$$\dot{m}_{rec,\alpha}(k) = \begin{cases} 0 & \text{for } k < T_0 \\ \dot{m}_{gd,\alpha}\left(k - T_k\right) \cdot R_\alpha & \text{for } k \geq T_0 \end{cases}$$

Again, the annual material availability from recycling of water electrolyzers at their EOL $\dot{m}_{rec,\alpha}(k)$ is smoothed for the same reasons considering the progressive development of water electrolysis lifetime as well as uncertain time spans for the shutdown and dismantling of the plants.

Fourth, the calculation of annual net primary resource demand after recycling in period k in ta^{-1}. Therefore, annual gross material demand $\dot{m}_{gd,\alpha}(k)$ is offset with available recycling material $\dot{m}_{rec,\alpha}(k)$ yielding the net primary resource demand $\dot{m}_{nd,\alpha}(k)$ in ta^{-1}.

$$\dot{m}_{nd,\alpha}(k) = \dot{m}_{gd,\alpha}(k) - \dot{m}_{rec,\alpha}(k)$$

The resulting annual data on material demand and availability is further condensed for each material type by cumulating the annual demand for each decade.

Scenario Definition

To analyze the impact of a variation of the described input data and to account for the range of data in the literature which is described in the following chapter, a scenario analysis is conducted. There is a wide span of available data from different literature sources considering the four datasets taken into account in the analysis. That is due to the difficulty to assess technical data and future development of the water electrolysis technologies on an industrial scale. However, a variation of two datasets, the specific material demand and the recycling rates, is considered in this scenario analysis, while water electrolysis expansion rate and lifetime are the same across scenarios. Therefore, three scenarios are defined with conservative and innovative assumptions for the specific water electrolysis material demand $m_{sd,\alpha}(k)$ and the material specific recycling rates R_α (see Fig. 3).

Scenario A is based on a conservative specific material demand and conservative recycling rates. In scenario B, innovative recycling rates due to a more progressive technical development in the recycling industry are reflected. Development and technical progress in specific material demand is assumed as conservative. In scenario C, technical development leads to both innovative specific material demand and innovative recycling rates. A fourth scenario based on innovative specific material demand but still conservative recycling rates is not further investigated in this analysis due to two reasons. First, it is assumed that innovative approaches such as innovative material compounds or novel manufacturing processes leading to reduced specific material demand in electrolysis cannot be recovered with conventional recycling processes for technical or economic reasons. Second, it is assumed as unrealistic that technical progress will lead to a reduced specific material demand while recycling processes do not develop but remain inefficient. However, the results of such a scenario would fall within the range of the other investigated scenarios and would not significantly broaden the analysis, as the resulting recycling mass flows would be intermediate between scenarios B and C.

Data

The data processed for the analysis of the closed-loop recycling potential of AWE and PEMWE is described in the following. The chapter is subdivided into the three datasets used as input for the calculation model.

First, the annual water electrolysis expansion rates based on scenario S0-95 from IndWEDe study are discussed [1]. Thereafter, the data for specific material demand of

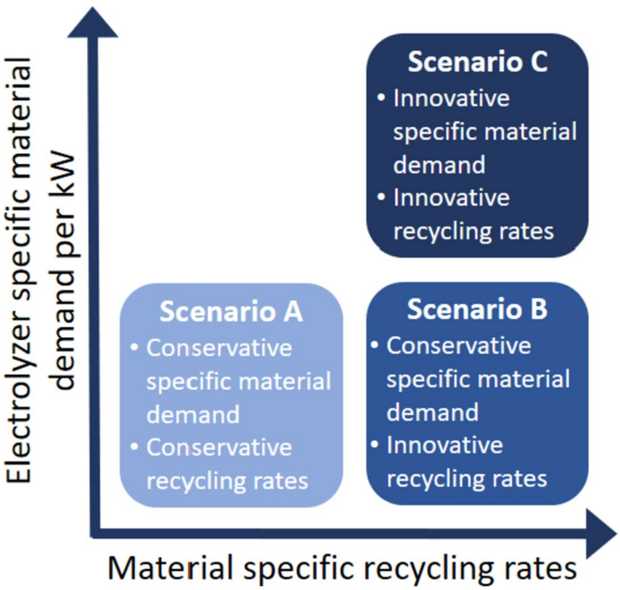

Fig. 3 Scenario definition for scenario analysis

water electrolysis capacity for the analyzed materials and the recycling rates of the analyzed materials are described. Finally, the material prices for the considered materials are described as input for the estimation of the economic potential of water electrolysis recycling.

Water Electrolysis Expansion Rate Between 2020 and 2050

The expansion rate of water electrolysis capacity is the net additional installed capacity. Between 2020 and 2023, it is based on actually realized water electrolysis projects during that period in Germany [10]. Data for water electrolysis expansion rate between 2024 and 2050 is based on IndWEDe study published by Fraunhofer ISE [1]. In the IndWEDe study, different scenarios for the industrialization and expansion of water electrolysis in Germany are analyzed between 2020 and 2050. The results are based on an energy system model called REMod-D. It simulates and generates the transformation of the energy system in Germany.

For the present analysis, the most conservative scenario S0-95 from the study is chosen. S0-95 is assumed to represent the most realistic forecast for water electrolysis expansion in Germany considering the following three reasons. First, when considering the actual water electrolysis expansion and realized projects in Germany until 2023 and comparing them to the scenarios presented in IndWEDe study, all scenarios for water electrolysis expansion overshoot the actual installations but scenario S0-95 is the closest by far [10]. Second, the announced water electrolysis projects in Germany in the next few years and also the government targets for the water electrolysis expansion are below the forecasts of all scenarios of IndWEDe study [10, 32]. Third, current political developments indicate that H2 imports will cover a considerable amount of German H2 demand at least in the middle term. However, scenario S0-95 is the only scenario in the IndWEDe study that considers H2 imports into Germany [1].

The annual expansion rate of water electrolysis capacity from S0-95 is shown in Fig. 4. It is subdivided into AWE, PEMWE, and high temperature electrolysis (HTEL). HTEL is also shown here for the sake of completeness, since HTEL is also considered in the IndWEDe study, but is not considered further in this paper.

The cumulated installed water electrolysis capacities are 7 GW in 2030 and 137 GW in 2050 as can be seen in Fig. 4 [1]. The expansion rate is rather low between 2020 and 2030 and between 2040 and 2045. It is first starting to incline drastically between 2030 and 2040 and, again, between 2045 and 2050. In the first decade, the expansion rate is dominated by the installations of AWE. In the second decade, PEMWE installation rate levels AWE. Thereafter, the share of PEMWE and HTEL in annual installations is dominant. The market shares of the overall capacity among AWE, PEMWE, and HTEL are defined in the IndWEDe study as 90%, 10%, and 0% in 2020; 55%, 40%, and 5% in 2030; and 40%, 40%, and 20% in 2050 [1]. In the present study, after 2050, until 2070, the annual expansion rate is assumed to be a constant rate of 1.5 GWa^{-1} for AWE and 2 GWa^{-1} for PEMWE as no further external forecasts are available for this period yet [3].

As described earlier, the annual repowering rate is added to the annual water electrolysis expansion rate from IndWEDe, yielding the annual gross installed capacity. Therefore, further input data for the calculation model is the average water electrolyzer lifetime in years. Based on literature study, the average AWE lifetime is set to 20 a and is assumed as constant over the analyzed period for the reason that the technology is already developed [1, 24, 33]. For PEMWE, the lifetime is set to 10 a in 2020 and increases linearly to 20 a

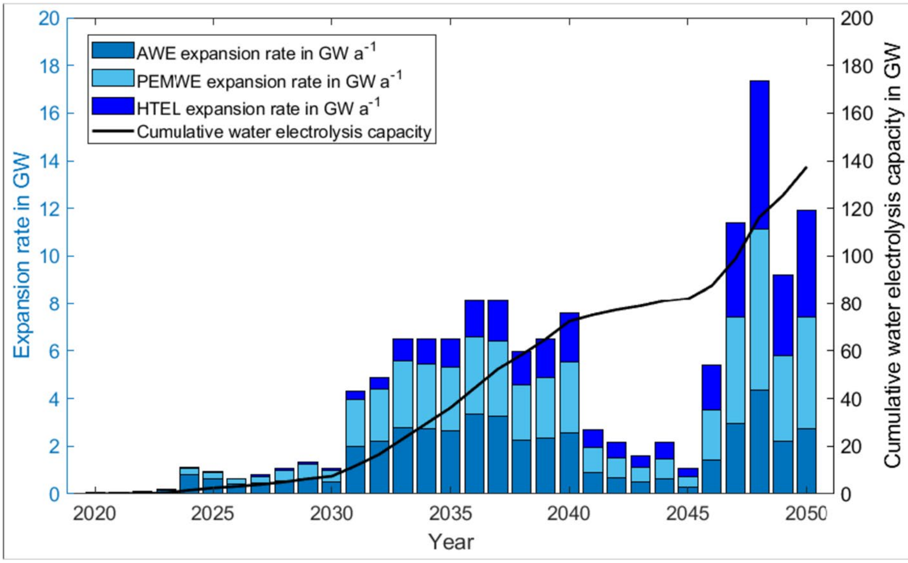

Fig. 4 Water electrolysis expansion in Germany: annual expansion rate and cumulative water electrolysis capacity in GW for AWE, PEMWE, and HTEL based on IndWEDe study scenario S0-95 [1]

in 2035 due to technical development leading to a reduction of degradation effects. After 2035, PEMWE lifetime is assumed as constant [1, 24, 34].

Specific Material Demand in Alkaline and PEM Water Electrolysis

For the analysis of closed-loop recycling, the three most essential materials in terms of quantity and quality for both AWE and PEMWE are taken into account. These are steel and nickel for AWE and iridium and platinum as well as titanium for PEMWE [15, 16]. The specific material demand per water electrolysis capacity in $g(kW)^{-1}$ is shown in Table 1. For the analysis, only data regarding material demand for the AWE and PEMWE stacks, including cells and framework but no peripheric and balance of plant systems are taken into account.

The specific material demand per installed water electrolysis capacity is decreasing over the considered period due to research and development efforts. This reduction in water electrolysis specific material demand is represented in the calculation model by a linear decrease between the base year 2020, representing the state of the art, and the projected specific material demand in the year 2035. After 2035, the specific material demand is considered constant since major progress of technical development of the considered technologies is assumed to be achieved until 2035 and further progressions cannot be reliably projected.

Noble metals such as iridium and platinum used in PEMWE allow high current densities [24]. Therefore, PEMWE systems are much more compact than AWE while having the same nominal power and hydrogen production rate [44]. This yields a lower overall material demand per kW for PEMWE compared to AWE [5]. However, iridium and platinum are much more expensive per kg than the materials used in AWE [24]. Also, the noble metals used in PEMWE are described as critical materials and are exposed to supply risk that could be a bottleneck for upscaling PEMWE and hamper the market ramp-up [3, 24].

Today, specific iridium demand for PEMWE is assumed to be between 0.7 $g(kW)^{-1}$ in the innovative scenario and 2.5 $g(kW)^{-1}$ in the conservative scenario. Until 2035, the specific iridium demand is assumed to decrease down to 0.05 $g(kW)^{-1}$ in the innovative scenario and 0.4 $g(kW)^{-1}$ in the conservative scenario [24, 35, 41]. Iridium is used as a catalyst material in PEMWE. The reduction in specific iridium demand is realized i.a. by replacement and substitution of iridium with other materials and alloys, by increasing catalyst surface area through improved catalyst manufacturing techniques, and by using thinner layers of coating material [24].

The specific platinum demand is decreasing from 1 $g(kW)^{-1}$ in the conservative and 0.3 $g(kW)^{-1}$ in the innovative scenario in the base year down to 0.5 $g(kW)^{-1}$ in the conservative and 0.03 $g(kW)^{-1}$ in the innovative scenario in 2035 [24, 35]. Platinum is used as a catalyst material and for PTLs in PEMWE: the decrease in platinum loading per capacity is i.a. due to an expected increase in catalyst surface area through improved catalyst manufacturing techniques and current densities [24].

Titanium is used in PEMWE bipolar plates and the PTL [24, 45, 46]. For the base year, the titanium demand is assumed to be between 450 and 528 $g(kW)^{-1}$. Titanium demand is assumed to decrease to between 32.2 and 35.0 $g(kW)^{-1}$ until 2035 [1, 20, 35]. The reduction is realized by replacing titanium with cheaper materials and increasing current densities [24].

In AWE, many parts such as electrodes, PTL, BPP, and parts of the frame are nickel and steel based [24, 47–49]. The nickel demand in AWE is between 1503 $g(kW)^{-1}$ in the innovative and 2f000 $g(kW)^{-1}$ in the conservative scenario in the base year and is assumed to decrease down to 200 and 794 $g(kW)^{-1}$ until 2035 [35–38].

Next to nickel, steel is also a material used in large quantities in AWE. The assumed specific steel demand for AWE for the base year is between 33,333 $g(kW)^{-1}$ in the innovative and 51,956 $g(kW)^{-1}$ in the conservative scenario. It is assumed to decrease down to 10,000 $g(kW)^{-1}$ in the innovative and 30,000 $g(kW)^{-1}$ in the conservative scenario until 2035 [35, 36, 39].

Recycling Rates

The recycling rates for each material for both the conservative and the innovative scenarios considered in the scenario analysis can be seen in Table 1 and are described in the following. In the present analysis, the recycling rate is seen as the quotient of recovered material from EOL water electrolysis by recycling to the mass of material bound in an EOL water electrolysis. It includes the entire recycling process chain starting at collection, continuing with dismantling and mechanical pre-treatment, and ending with chemical or metallurgical recycling [50]. The recycling rate is assumed as constant over the entire period under consideration within the scenarios (see Table 1). This is based on the assumption that the recycling technologies and infrastructures can be implemented within the next decade if appropriate incentives are provided and measures are taken. Therefore, innovative recycling rates of 90% and above could be reached within 15 to 20 years when first significant water electrolysis capacities enter their EOL.

The conservative scenario assumes today's sector-specific and industry-standard values for the recycling rates of the respective materials. Imperfect collection and recycling technology leads to higher material losses yielding lower EOL recycling rates and, finally, less recycling material available for new installations [50]. The innovative scenario, on the other hand, assumes high EOL recycling rates due to a well-developed recycling infrastructure enabling high collection rates and efficient recycling processes specified to EOL water electrolysis. Losses in collection and dismantling stage are minimized. All EOL water electrolysis systems are dismantled, collected, and transported to recovery centers where they are transferred to recycling processes [31, 50]. The recycling processes are aligned toward maximum material recovery rates. To realize that, establishing new and innovative recycling processes as industry standards might be necessary. Such infrastructures for water electrolysis collection and recycling are presented in detail in [31].

For the recycling of AWE materials, the recycling rates are assumed as follows. Nickel from water electrolysis stacks can be recycled by hydrothermal (HTH) and hydrometallurgical treatment (HMT) [31]. The recycling rate is assumed to be 57% in the conservative and 90% in the innovative scenario [30]. Steel is considered to have a 70% recycling rate in the conservative and a 90% recycling rate in the innovative scenario [30, 40]. Regarding PEM, the recycling rate of iridium is assumed as 40% in the conservative and 90% in the innovative scenario [16, 30]. Current recycling technologies can be based on HMT and pyro-hydrometallurgical treatment (PMT). Innovative recycling processes can be based on transient dissolution (TD) [16, 31]. For platinum, the recycling rate is assumed to be 76% in the conservative and 90% in the innovative scenario [30]. Current recycling technologies are HMT and PMT, and novel technologies are among others TD and selective electrochemical dissolution [31]. The recycling rate of titanium is assumed to be 40% in the conservative and 91% in the innovative scenario [30, 43].

Material Prices for Economic Considerations

The material prices considered for the estimation of the economic potential of water electrolysis recycling in Germany are based on data from online commodity platforms in January 2023. The exchange rate is 1 US$ = 0.92 € (23.01.2023). Current material prices and historic fluctuations in commodity prices are reflected in the 10-year lows and highs in

Table 2. It can be seen, that fluctuations in material prices are very strong. However, it is not possible to give a reliable and precise forecast of price developments based on historic data. Therefore, today's prices are taken into account for the economic estimation. This introduces significant uncertainty into the analysis. The scale of fluctuations in material prices, as illustrated in .

Table 2 Metal prices based on commodity exchange. [a]For titanium, only 5 years could be considered

Material	Price in € kg^{-1}			High/low fluctuation
	10 years low	10 years high	January 2023	
Nickel [51, 52]	6.16	44.29	26.36	86%
Steel [52]	0.60	1.43	0.73	58%
Iridium [53]	10,700.00	185,800.00	150,300.00	94%
Platinum [51]	19,260.00	41,730.00	34,100.79	54%
Titanium[a] [54]	3.40	19.30	7.14	82%

Table 2, underscores the inherent level of uncertainty within our analysis. However, it is important to note that the purpose of this analysis is limited to providing a broad overview and rough estimation of the scale of the economic potential of electrolyzer recycling. Delving into a more comprehensive examination of uncertainties, such as sensitivity analysis, falls beyond the scope of this study.

Today's platinum price is set as 34,100.79 € kg^{-1} [51] while the price for iridium is 150,300.00 € kg^{-1} [53]. The price fluctuation within 10 years is 54% for platinum and 94% for iridium. Titanium has a price of 7.14 € kg^{-1} with a fluctuation of 82% [54]. However, titanium prices only cover a period between 2017 and 2022 for the reason that no older data was available. Stainless steel price is assumed to be 0.73 € kg^{-1} [52] with a 10-year fluctuation of 58%, and the nickel price is assumed to be 26.36 € kg^{-1} with a 10-year fluctuation of 86% [51].

Results and Discussion

This chapter presents the results of the analysis assessing the potential of a closed-loop recycling approach for EOL water electrolysis. Firstly, results of the three modeling steps described in Fig. 2, (i) annual water electrolysis installations, (ii) annual gross material demand, and (iii) annual material availability from recycled water electrolysis at their EOL, are described in detail on the example of iridium in scenario A (see Fig. 5). Thereafter, the summarized results of all three scenarios for all analyzed materials for PEMWE and AWE are presented (see Figs. 6 and 7). Detailed illustrations of all results and scenarios are listed in the Appendix.

Introducing Results of Scenario A for Iridium

The detailed results of scenario A with conservative specific material demand and conservative recycling rates are introduced in Fig. 5, containing three sub-figures each showing the analyzed period between 2020 and 2070. In (a) the total annual PEMWE gross installed capacity in GW is shown as bars split in repowering and expansion rate. The cumulative installed PEMWE capacity is shown as a black line. The dark blue bars show that in the first decade until 2030, the annual PEMWE expansion rate is far below 1 GWa^{-1}. In the decade between 2030 and 2040, the market ramp-up phase kicks off with expansion rates of above 2 GWa^{-1} before decreasing again in 2041. After 2045 PEMWE expansion rate jumps up to above 6 GWa^{-1} while first significant PEMWE capacities enter the EOL and must be replaced, which is reflected in increased repowering rates. After 2050, a market maturation phase can be observed in which PEMWE repowering rates outrun expansion rates.

In (b), the total annual iridium demand for PEMWE installations is shown as dark blue, and the annually available iridium supply due to closed-loop recycling is shown as light blue bars. Further, the black line shows the total cumulative iridium demand. The dashed blue line shows the cumulative net iridium demand when iridium from closed-loop recycling is substituting primary iridium.

In (c), the total annual iridium demand and annual closed-loop recycling iridium supply from (b) is cumulated over each decade, which again are represented as dark and light blue bars. Also, (c) shows cumulative iridium demand with and without recycling again as black lines.

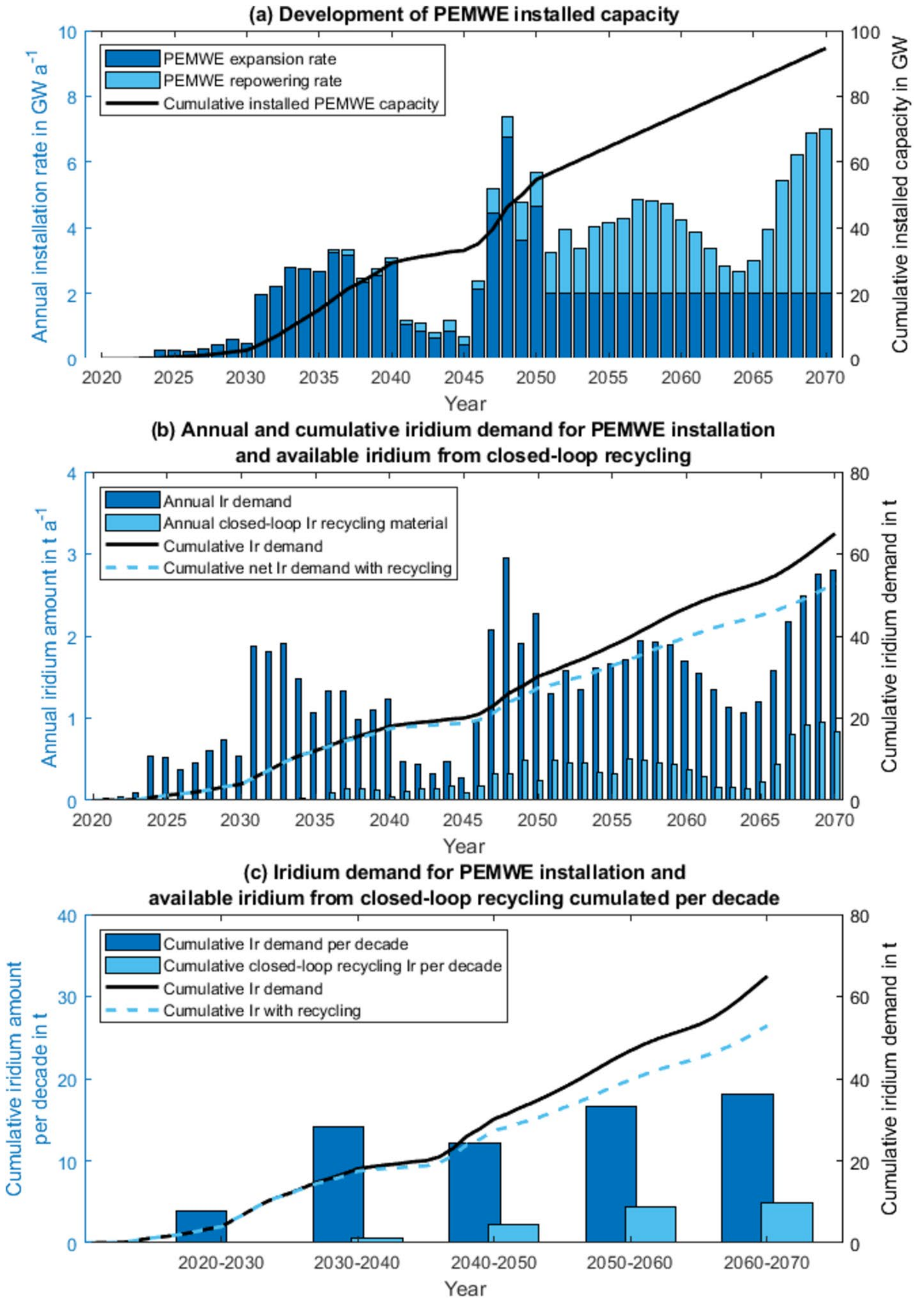

Fig. 5 Overview results iridium scenario A: **a** installation rates, **b** annual gross iridium demand and closed-loop recycling iridium availability, and **c** iridium demand and recycling availability per decade

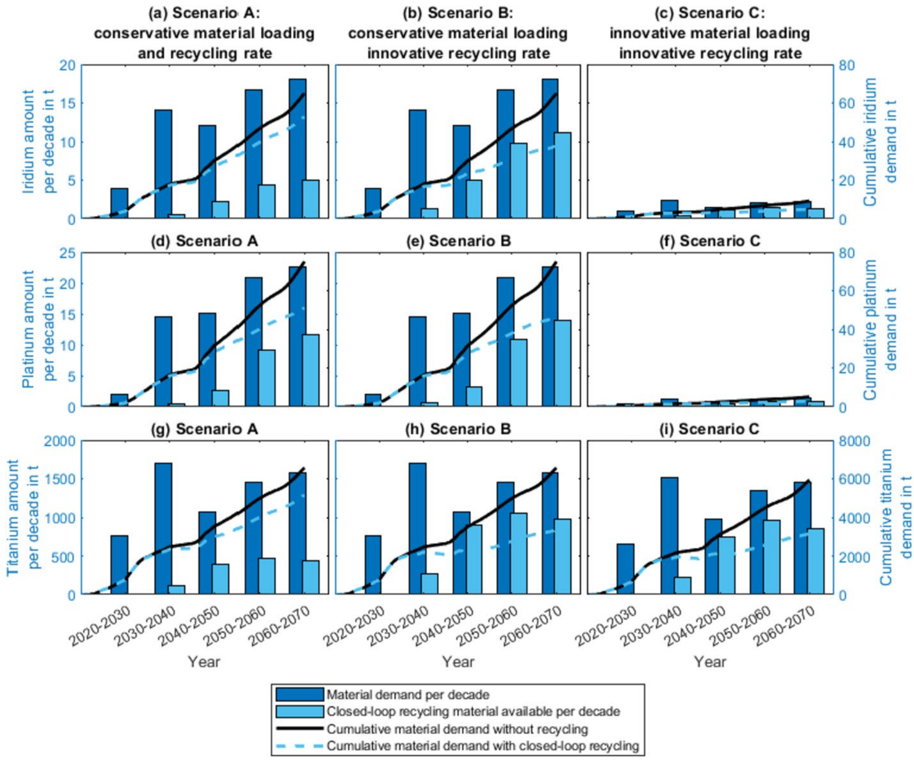

Fig. 6 Results of scenario analysis for PEMWE iridium, platinum and titanium demand, and recycling amount in tons per decade

It is observed that the iridium demand in the first decade between 2020 and 2030 is rather low due to low installation rates. Even though specific material demand is decreasing until 2035, total iridium demand is increasing in the decades between 2030 and 2070 due to significantly higher installation rates compared to the first decade. Due to conservative recycling rates in scenario A, the annual closed-loop recycling material supply is low compared to iridium demand. Not before 2040, closed-loop recycling leads to a slight downshift in cumulative iridium demand, pushing the cumulative net iridium demand until 2070 from 65 t down to 53 t.

Results of Scenario Analysis for PEMWE Closed-Loop Recycling

Figure 6 is showing the results of the scenario analysis for the closed-loop recycling potential of the materials iridium ((a)–(c)), platinum ((d)–(f)), and titanium ((g)–(i)) used in PEMWE. When looking at the results, two main effects become apparent that hold for all three metals.

On the one hand, the increased recycling rate (in scenario B higher than in A) shows an increased gap between the curves for the cumulative resource demand without and with closed-loop recycling. Hence, closed-loop recycling improves the availability of raw materials. An increasing part of the total resource demand (black graph) is covered by recycling

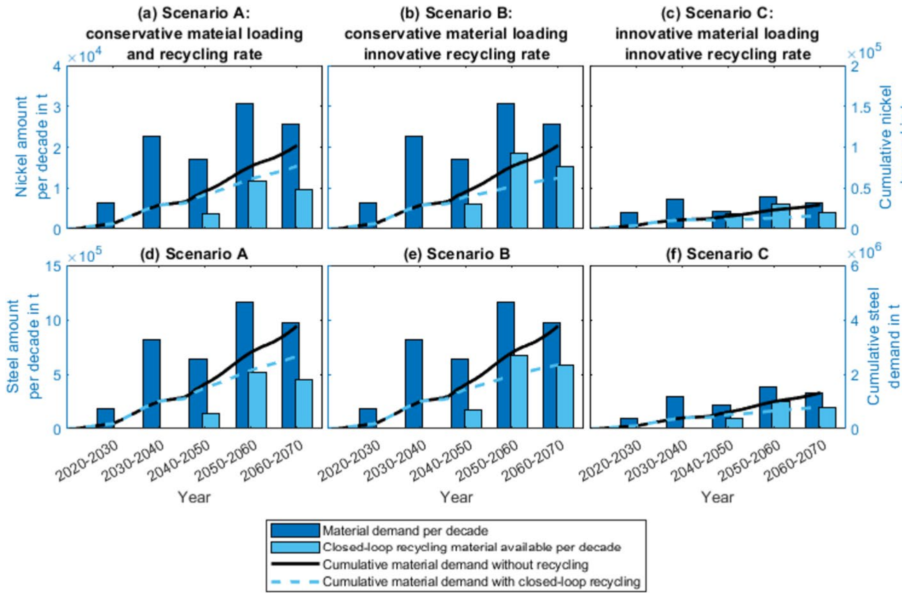

Fig. 7 Results of scenario analysis for AWE nickel and steel demand and recycling amount in tons per decade

material. The demand for primary raw materials is reduced to the level of the dashed blue line. In scenarios B and C, assuming an innovative recycling rate, in the decades after 2050, around half of the material demand can be covered by recycled material.

Secondly, however, it is also evident that a clear breakthrough in material demand is only achieved by increasing material efficiency (scenario C) since overall demand is reduced to a significantly lower level. This applies in particular to iridium and platinum and, to a limited extent, to titanium.

For iridium, in scenario A, the cumulative gross demand until 2050 is 30 t and 65 t in 2070. By a closed-loop recycling approach assuming conservative recycling rates, the cumulative iridium demand can be pushed down by 10% to 27 t in 2050 and by 18% to 53 t in 2070. In scenario B, assuming innovative recycling rates, the cumulative material demand is pushed down by 20% to 24 t in 2050 and by 42% to 38 t in 2070.

In scenario C, the innovative development of specific material demand in PEMWE is leading to a significant decrease in cumulative iridium demand. The impact of innovative specific iridium demand on cumulative iridium demand is much higher than innovative recycling rates. In 2070, the cumulative iridium demand in scenario C without recycling with 9 t is 86% lower and with closed-loop recycling with 5 t 92% lower than in scenario A.

For platinum, a similar trend as for iridium is observed. In scenario A, the cumulative platinum demand in 2070 is 75 t and pushed down by 32% to 51 t with conservative recycling rates. Assuming innovative recycling rates in scenario B, the cumulative platinum demand with recycling in 2070 is pushed down by 49% to 38 t. Assuming innovative development in specific platinum demand and innovative recycling rates in scenario C, the cumulative platinum demand with recycling in 2070 is pushed down by 96% to 3 t compared to scenario A.

For titanium, the cumulative demand in 2070 is 6573 t, which can be pushed down by 22% to 5162 t with conservative recycling rates in scenario A. Assuming innovative recycling rates in scenario B, the cumulative titanium demand with recycling in 2070 is pushed down by 49% to 3365 t. Further assuming innovative development in specific titanium demand and innovative recycling rates in scenario C, the cumulative titanium demand with recycling in 2070 is pushed down by 52% compared to scenario A to 3166 t. The reduction of specific material demand for titanium is much lower than for iridium and platinum. Therefore, only for titanium, the innovative recycling rates have a higher impact on the reduction of resource demand than the innovative specific material demand.

Results of Scenario Analysis for AWE Closed-Loop Recycling

The results of scenario analysis for the potential of closed-loop recycling of nickel and steel used in AWE (see Fig. 7) show qualitiavely the same as seen for the materials used in PEMWE. Comparing scenarios A and B, an increased recycling rate flattens the cumulative demand for primary resources significantly (c.f. dashed blue line). However, a stronger decrease in primary material demand is achieved through higher material efficiency in scenario C, through an innovative specific material demand.

In scenario A, the cumulative nickel demand until 2050 is 45,932 t, and 102,250 t in 2070. In cause of a closed-loop recycling approach assuming conservative recycling rates, the cumulative nickel demand can be pushed down by 8% to 42,068 t in 2050 and by 25% to 76,912 t in 2070. In scenario B, assuming innovative recycling rates, the cumulative nickel demand is pushed down by 13% to 39,832 t and 2050 and by 39% to 62,243 t in 2070. In scenario C, the innovative development of specific nickel demand in AWE is leading to a significant decrease in cumulative nickel demand. The impact of innovative specific nickel demand on cumulative nickel demand is much higher than innovative recycling rates. In 2070, the cumulative nickel demand in scenario C without recycling is 29,734 t, a decrease of 35%, and with closed-loop recycling even 84% lower (16,082 t) than in scenario A.

For steel, a similar trend as for nickel is observed; the cumulative demand in 2070 is 3,771,150 t and is pushed down by 29% to 2,660,670 t with conservative recycling rates in scenario A.

Assuming innovative recycling rates in scenario B, the cumulative steel demand with recycling in 2070 is pushed down by 38% to 2,343,400 t. Further assuming innovative development in specific steel demand and innovative recycling rates in scenario C, the cumulative steel demand with recycling in 2070 is 787,489 t (a decrease of 79%) compared to scenario A. Again, a strong reduction in specific material demand has a higher impact on the reduction of cumulative material demand than innovative recycling rates.

Outlook on Economic Potential of Water Electrolysis Recycling

Multiplying specific material prices (see . Table 2) with the recycling material for each decade from the scenario analysis yields the economic volume of the recycling material available from EOL water electrolysis recycling for each decade. As pointed out in the "Material prices for economic considerations" section, it is not possible to reliably forecast material prices over the coming decades. The underlying assumptions regarding material prices are accompanied by significant uncertainty. Given that, material prices from 2023 were used for the first estimate of the economic potential. The results show an outlook

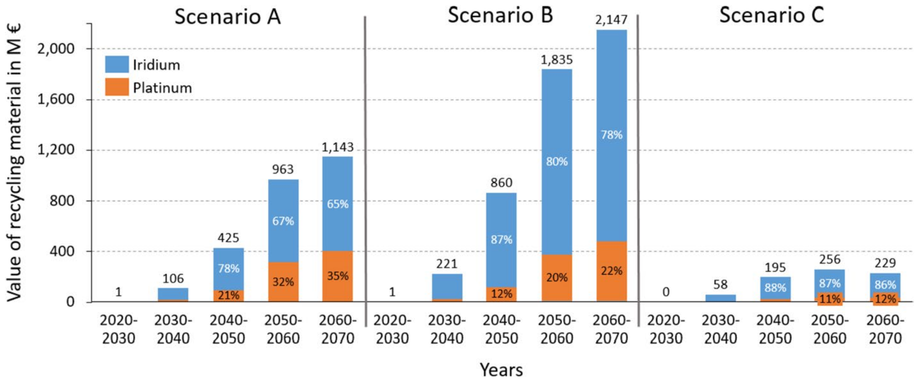

Fig. 8 Outlook on estimated economic volume of PEMWE recycling material in million € per decade

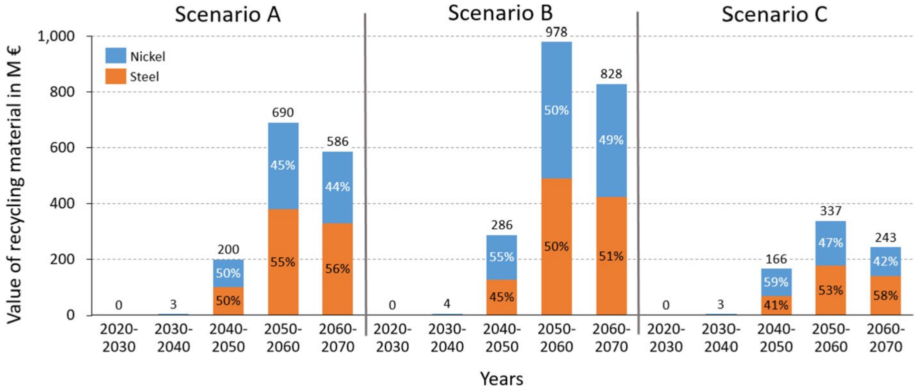

Fig. 9 Outlook on estimated economic volume of AWE recycling material in million € per decade

regarding the development of the economic volume of potential water electrolysis recycling materials which can be seen as a best guess for the turnover of a potential water electrolysis recycling industry.

The outlook on the estimated economic value of PEMWE recycling materials until 2070 is shown in Fig. 8 and for AWE recycling materials in Fig. 9. The results indicate that the economic volume strongly depends on the considered scenarios, hence the specific material demand and the recycling rate, as well as on the material prices.

The economic volume of PEMWE recycling material cumulated per decade peaks in the decade between 2060 and 2070. It is between 0.23 B€ in scenario C (low specific material demand, high recycling rates) and 2.15 B€ in scenario B (high specific material demand, high recycling rate). It can be seen that between 65% and 87% of the economic volume is attributed to iridium, while the remainder is mainly attributable to platinum. Titanium, even though it has the highest specific material demand per kW of installed PEMWE capacity, has a negligibly small proportion of the economic volume due to its comparably low price per kg. Therefore, the economic value titanium recycling massflows are not visible in Fig. 8. The decades yielding the highest economic volume of recycling material for AWE are between 2050 and 2070 with 0.34 B€ in scenario C and up to 0.98 B€ in scenario B. Steel and nickel are on an equal level with slight fluctuations.

Overall, the economic volume of recycling material from PEMWE exceeds AWE in scenarios A and B. However, due to the assumption of a higher reduction in specific material demand in PEMWE than in AWE, the economic volume of recycling material from AWE exceeds PEMWE in scenario C.

Given the outlook on the potential economic volume of water electrolysis recycling materials, further research regarding the techno-economic assessment of water electrolysis recycling processes is needed since secondary recycling materials compete with primary virgin materials, which can in many cases meet product specifications at a lower price. The costs of water electrolysis recycling processes and recycled materials should be addressed as it is already i.a. for lithium-ion battery recycling in Thompson et al. [55]. Different recycling processes and technologies in terms of i.a. recovery rate, recycling material costs, and gross profit must be investigated and compared. On that base, it can be assessed if economic incentives for water electrolysis recycling must be introduced to support the establishment of a recycling industry in water electrolysis to develop a circular economy. Such economic incentives that could help to address this situation are discussed in [56].

Conclusions

In this paper, the potential of three circular economy actions for EOL AWE and PEMWE in Germany was analyzed. The focus was on the closed-loop recycling approach as the most promising strategy to reduce the total primary resource demand in the industrialization of water electrolysis in Germany. To summarize the results from the analysis, the four research questions raised in the introduction are answered as follows.

(i) What are reasonable circular economy actions to handle EOL water electrolysis? So far, only recycling is showing potential as a reasonable circular economy action for water electrolysis. Reuse and repair are not yet applied as EOL water electrolysis systems show low efficiency and complex system design which is not aligned to repair. However, since these are very efficient actions in terms of closing the cycle, R&D would be desirable here.

(ii) How is resource demand for main materials used for AWE and PEMWE when expecting installation of multi GW scale water electrolysis in Germany in the next decades? Resource demand heavily depends on the specific material demand per kW installed capacity. Innovative specific material demand has a huge impact on gross material demand. For PEMWE the total cumulated gross material demand until 2070 is between 9 t and 65 t for iridium, between 5 t and 75 t for platinum, and between 5,944 t and 6,573 t for titanium. For AWE the total cumulated gross material demand for nickel until 2070 is between 29,733 t and 102,248 t and for steel between 1,320,620 t and 3,771,100 t.

(iii) To what extent and when can a closed-loop recycling approach for EOL water electrolysis help to flatten primary resource demand for new water electrolysis installations in Germany? Depending on the recycling rates taken into account, closed-loop recycling can reduce total primary resource demand for iridium by between 19 and 46%, for platinum between 33 and 43%, and for titanium between 21 and 49% until 2070. For AWE closed-loop recycling can reduce primary resource demand for nickel by between 25 and 46% and for steel between 29 and 40%. Hence, maximizing the recycling rates for each material to enable a closed-loop recycling approach can reduce the total primary material demand by up to 50% and in some decades even more. However, the first significant amounts of recycling materials are available after 2040 to reduce primary material demand. Further, in total, technical development minimizing specific material demand has a higher impact on primary resource demand than efficient recycling.

(iv) How big is the economic potential of recycled materials from EOL water electrolysis and thus the economic potential for the development of a water electrolysis recycling industry? Depending on the considered scenario, the economic potential of the recycling mass flows from PEMWE is up to 2.15 B€ per decade and up to 0.98 B€ for AWE. In PEMWE the main economic volume is in iridium recycling, followed by platinum recycling, and a neglectable economic volume in titanium recycling mass flows. In AWE, the shares are more equally split between nickel and steel. Nevertheless, it is essential to acknowledge that these results carry a high degree of uncertainty due to the underlying assumptions. The objective of the economic analysis is to provide an approximate estimation of the economic magnitude in the context of electrolyzer recycling.

In conclusion, the main findings of this paper are that the potentials of both reducing specific material demand and introducing a recycling infrastructure maximizing recycling rates should be exhausted before first significant amounts of water electrolysis enter their EOL and water electrolysis installation rates are skyrocketing, which in this analysis is the case in 2030. By a combination of both actions, the total resource demand of water electrolysis in Germany would be reduced tremendously and thus alleviate bottlenecks and barriers in the supply of materials and resource dependency in the long run.

To realize such potential, the development of a regulatory framework allowing and ensuring high recycling rates and reliable dismantling and collection of EOL water electrolysis are necessary. Such regulatory framework on EU level specified to hydrogen technologies is already discussed [57]. A comparable regulatory framework is already proposed for batteries in the context of the EU Circular Economy Action Plan which could be used as a blueprint for a water electrolysis regulatory framework [58].

Appendix

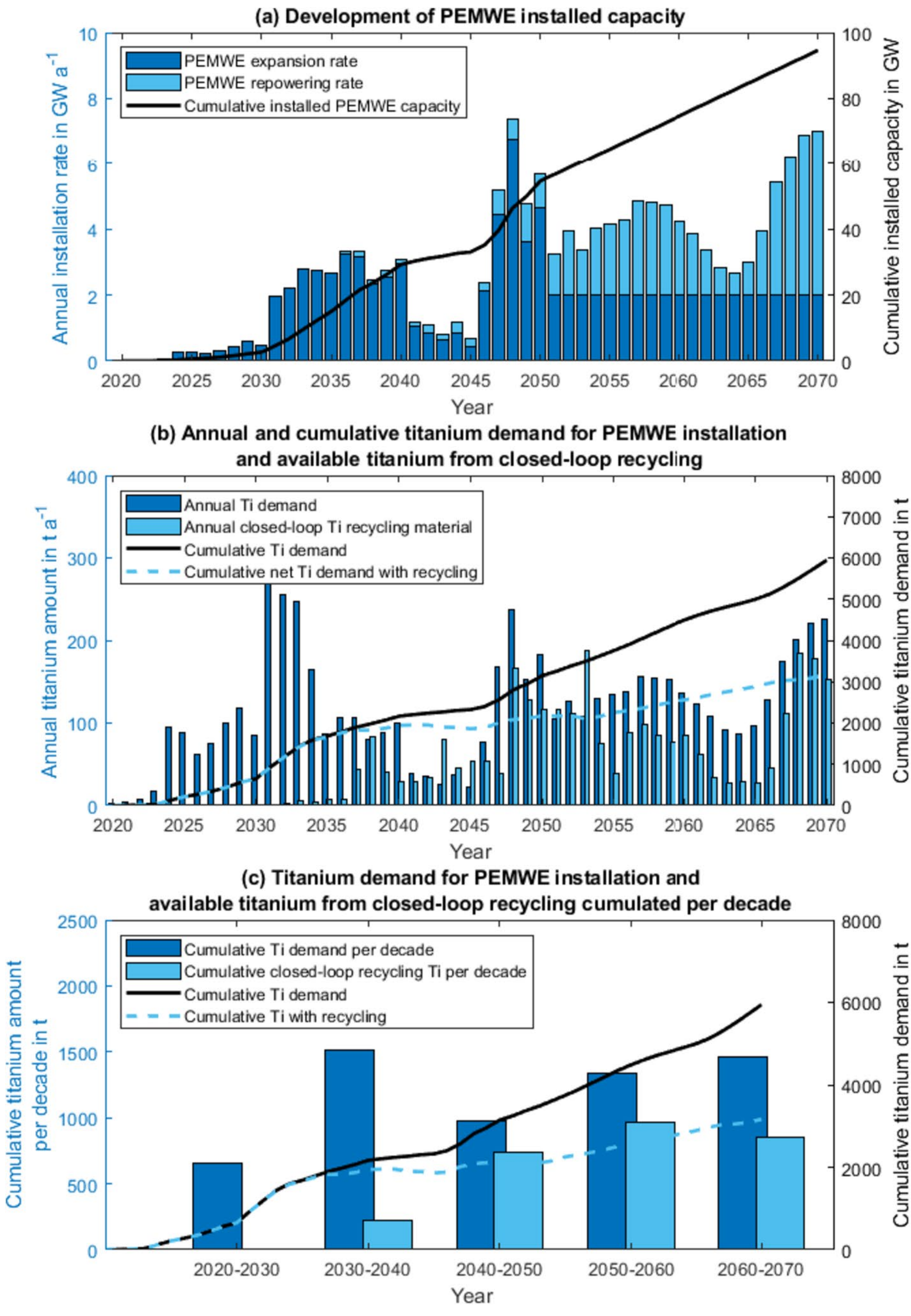

Fig. 10 Overview results titanium scenario C: **a** installation rates, **b** annual gross titanium demand and closed-loop recycling titanium availability, and **c** titanium demand and recycling availability per decade

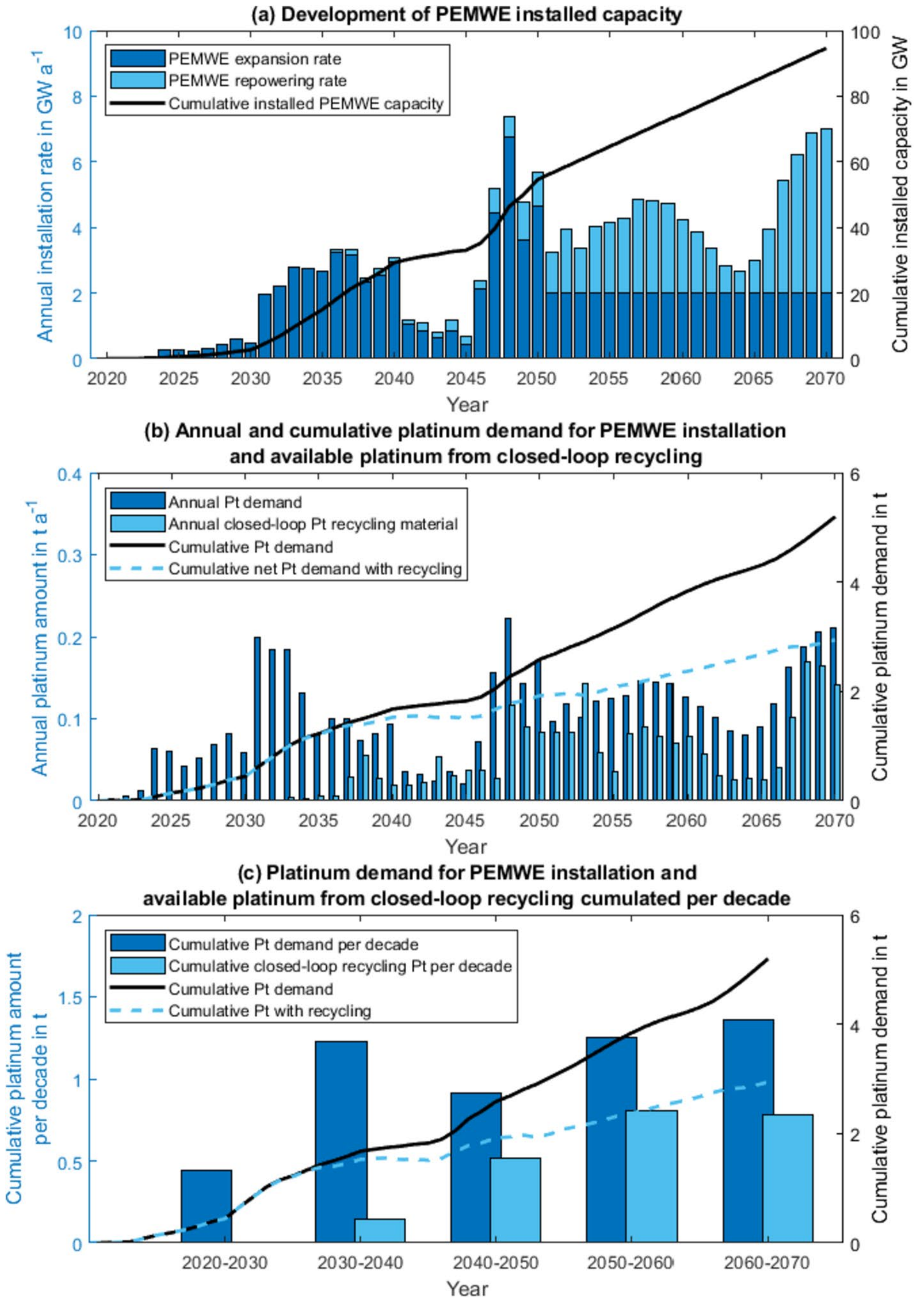

Fig. 11 Overview results platinum scenario C: **a** installation rates, **b** annual gross platinum demand and closed-loop recycling platinum availability, and **c** platinum demand and recycling availability per decade

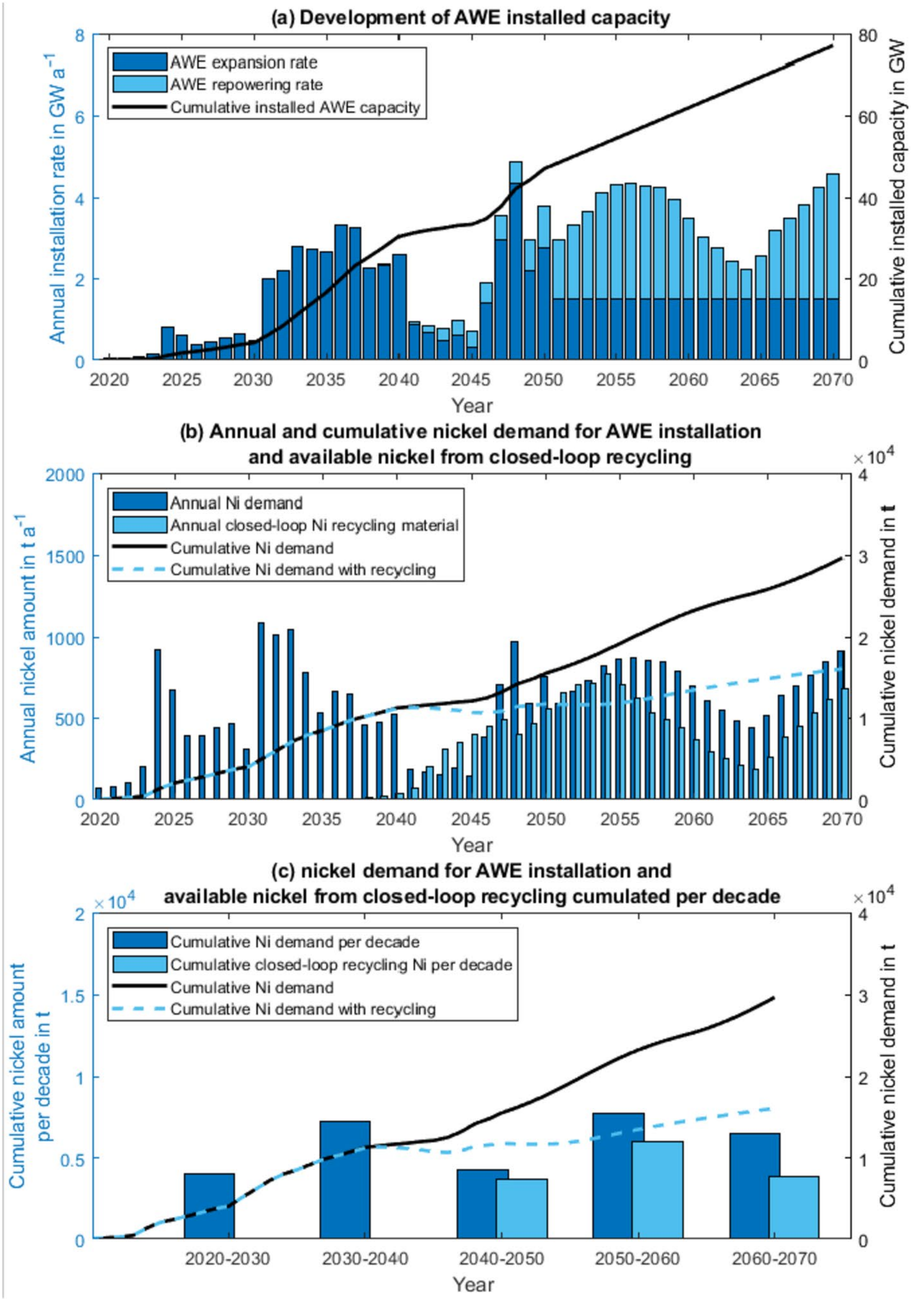

Fig. 12 Overview results nickel scenario C: **a** installation rates, **b** annual gross nickel demand and closed-loop recycling nickel availability, and **c** nickel demand and recycling availability per decade

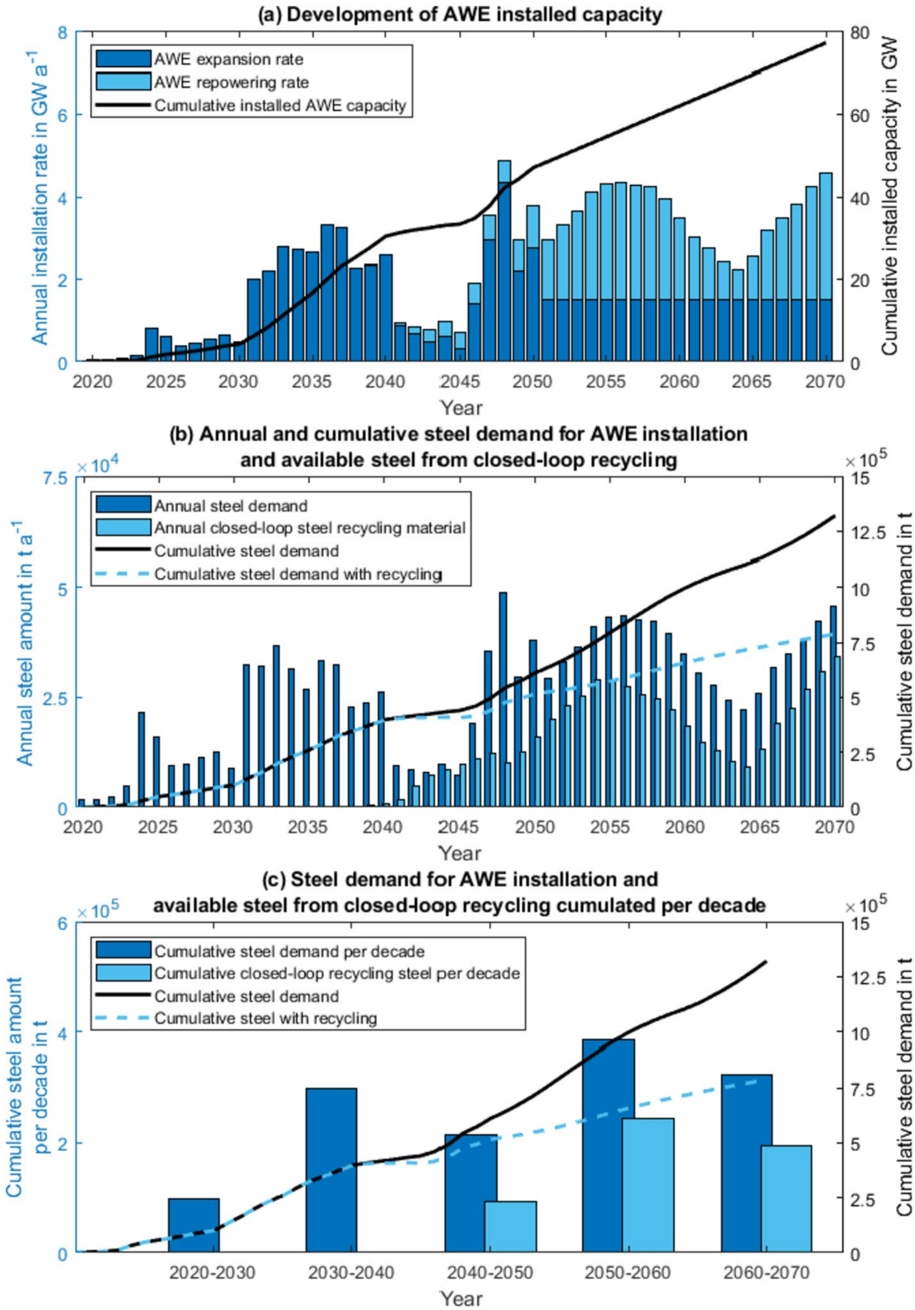

Fig. 13 Overview results steel scenario C: **a** installation rates, **b** annual gross steel demand and closed-loop recycling steel availability, and **c** steel demand and recycling availability per decade

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Declarations

Competing Interests The authors declare no competing interests.

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