

DEEP DIVE ON CRITICAL RAW MATERIALS FOR **HYDROGEN TECHNOLOGIES** IN THE EU

Bolard, J., Nohl, M., Pavel, C.,
Istrate, R., Eynard, U.,
Blagoeva, D., Dolci, F., Kuzov, T.

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Contact information

Name: Julien BOLARD, Scientific Officer, Joint Research Centre

Address: European Commission Joint Research Centre, Westerduinweg 3, 1755 LE Petten, Netherlands

Email: Julien.bolard@ec.europa.eu

Tel.: +31 22456-5225

Joint Research Centre

<https://joint-research-centre.ec.europa.eu>

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Abstract

This report assesses the exposure of the European Union to critical raw material supply risk in the water electrolyser and fuel cell value chains. It maps the supply chain of five key materials (iridium, platinum, titanium, nickel and zirconium) from extraction through processing, component manufacturing and system assembly, and projects gross material demand to 2050 under two scenarios differing in the intensity of technological innovation. Projected demands are compared against current global production. Of the five materials assessed, only the two platinum group metals (iridium and platinum) are found likely to experience a supply bottleneck which could potentially limit the deployment of hydrogen technologies at the projected levels. EU iridium demand for PEM electrolyzers could exceed a third of global supply already by 2030 and global demand by 2050 could exceed 225 % of today's global supply. Global platinum demand, driven mainly by fuel cell electric vehicles, could reach almost 200 % of current mine production by 2050. EU demand for titanium remains below 1 % of global supply, and nickel and zirconium EU needs do not reach 1 % of global supply throughout. Criticality assessed at material level does not, however, capture the full picture, as single-supplier positions at the component stage are not visible in raw material statistics. Circularity measures are identified as the most effective mitigation available without changes to system design or operating conditions, although secondary supply becomes significant only after 2035.

Foreword

The clean energy transition is our only path towards a sustainable future.

To tackle the dual challenge of reducing dependency on fossil fuels – particularly those imported from Russia following its war of aggression against Ukraine – and addressing the climate crisis, the EU has set ambitious targets to accelerate economic decarbonisation and achieve net-zero emissions by 2050. However, **the clean energy transition is essentially a materials transition**. The focus is shifting from fossil fuels to the critical materials needed to manufacture clean energy technologies.

Meeting the EU's energy and climate targets means deploying the right technologies, in the right quantities, at the right speed. Falling short on any of these fronts risks undermining the clean energy transition, delaying decarbonisation, and derailing the EU's climate ambitions. To mitigate these risks, the EU has adopted the **Critical Raw Materials Act (CRMA)**, which aims to ensure a secure and sustainable supply of critical raw materials.

This marks a **paradigm shift in energy security**: ensuring not only the availability of energy itself but also the **materials critical to building the technologies** that will power the future. In this context and following the publications of three reports on wind power, solar photovoltaic, and batteries for energy storage and electro-mobility in 2025, the Joint Research Centre once again partnered with the Directorate-General for Energy and has analysed the materials supply chains of two other industries: hydrogen technologies and electricity grids.

These analyses build on the structure and results of the **2023 JRC Foresight study** (Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU), but they go deeper, to provide further insights for policy and a better understanding of the potential bottlenecks of the relevant supply chains, of our exposure to disruption risks and of the potential risk mitigation measures that can be adopted.

In particular, the five deep dives shed light on:

- the profiles of the materials needed for the relevant technologies, including their use in other sectors, their sourcing and supply risk, and the material intensities used for these technologies;
- the detailed supply chains, including examples of the main companies that could ramp up production to strengthen EU domestic supply, and any dependencies related to that supply;
- the EU materials demand projections for 2030 and 2050, updated according to recent EU and global policy developments;
- the impact on materials consumption of an “accelerated innovation” scenario;
- the challenges and benefits of circularity in these technologies and the opportunities for substitution with advanced materials and innovative designs;
- insights on the way some other economies – such as the People's Republic of China – are addressing similar challenges and the resilience of the relevant supply chains;
- the measures available for mitigating supply disruption risks.

It is hoped that these deep dives, which are the fruit of a valued collaboration between two directorates-general, and the scientific evidence and knowledge that they provide, can support policies to secure resilient supply chains and climate neutrality for the benefit of all.

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Authors

- Julien BOLARD, European Commission, Joint Research Centre (JRC), Petten, Netherlands.
- Markus NOHL, European Commission, Joint Research Centre (JRC), Petten, Netherlands.
- Claudiu PAVEL, European Commission, Joint Research Centre (JRC), Petten, Netherlands.
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- Umberto EYNARD, European Commission, Joint Research Centre (JRC), Ispra, Italy. Contributions: drafting for chapter 4.1 “Materials circularity-related measures”
- Darina BLAGOEVA, European Commission, Joint Research Centre (JRC), Petten, Netherlands.
- Francesco DOLCI, European Commission, Joint Research Centre (JRC), Petten, Netherlands.
- Teodor KUZOV, European Commission, Joint Research Centre (JRC), Petten, Netherlands.

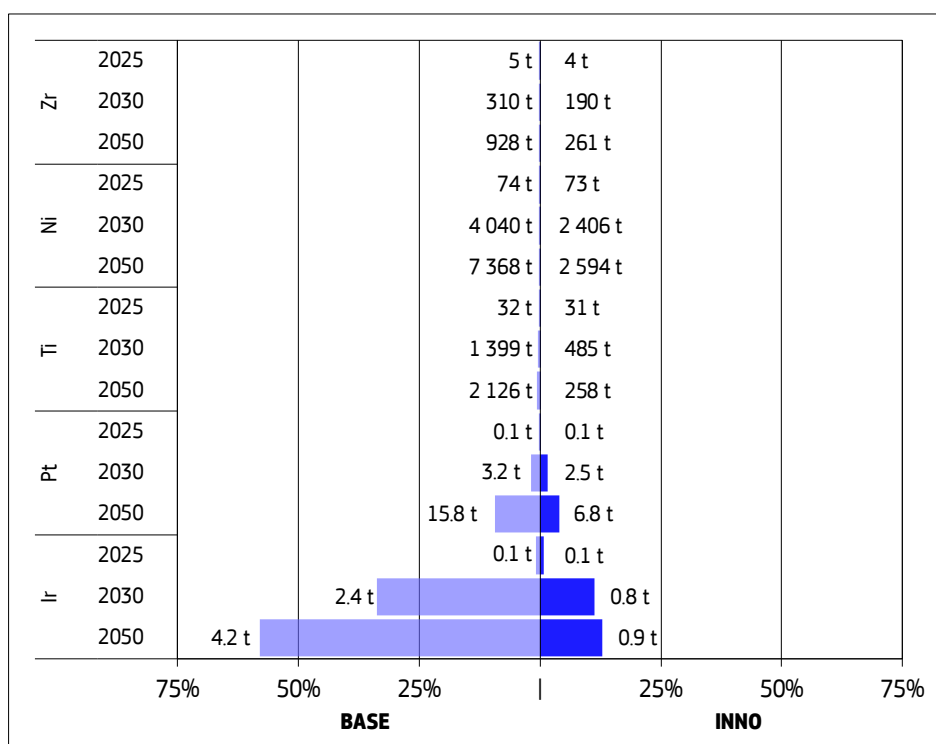
Executive summary

Renewable and low-carbon hydrogen technologies are no longer assessed solely against decarbonisation objectives. Following the Draghi report and the proposed Industrial Accelerator Act, they are also treated as instruments of energy security and industrial policy, and water electrolyzers and fuel cells are listed technologies under the Net Zero Industry Act. Both rely on materials whose production and processing are concentrated in a small number of third countries. This report, commissioned by DG ENER and forming part of the JRC Deep Dive series on materials security for clean technologies, examines whether such a concentrated supply could hinder the deployment of these technologies in the EU.

The analysis covers five materials — iridium, platinum, titanium, nickel and zirconium — selected either for their criticality in the 2023 JRC foresight assessment or for their dominant position in current designs. The scope of the material demand projections is deliberately restricted to sub-technologies whose designs are likely to remain stable over the next five to fifteen years: alkaline and PEM electrolyzers, and PEM fuel cells for mobility. Gross material demand is projected to 2050 from hydrogen production and vehicle stock targets provided by the POTEnCIA and POLES-JRC models, under a BASE scenario in which today's performance and material intensities are broadly stationary, and an INNO scenario in which technical performance improves rapidly and lower-TRL technologies gain market share. The two scenarios are best read as a plausible range within a single energy scenario rather than as alternative futures.

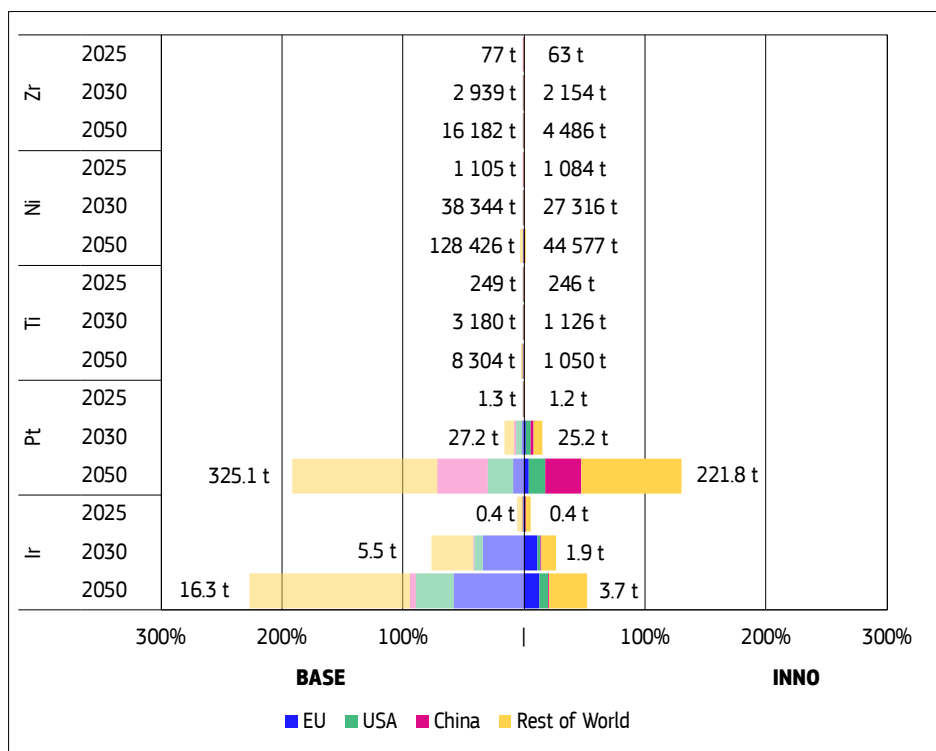
Two of the five materials might constrain the deployment of hydrogen technologies at the projected levels, and both are platinum-group metals. Iridium, of which 7 to 8 tonnes are produced annually and approximately 90 % is extracted and processed in South Africa, is the primary bottleneck for PEM electrolysis. It is recovered as a by-product of platinum, so its output responds to platinum demand rather than to its own, and no substitute is available at commercial scale. EU iridium demand for electrolyser deployment could exceed 33 % of current global supply by 2030 and half of it by 2050 in the BASE scenario. Global iridium demand exceeds 225 % of today's supply by 2050 in the BASE scenario and stays around 50 % of the supply in the INNO scenario. Platinum presents a comparable constraint at global rather than EU level: driven principally by fuel cell electric vehicle fleets, global demand could reach almost twice current mine production by 2050 in the BASE scenario, and more than 125 % in the INNO scenario. By contrast, EU demand for nickel and zirconium (used in alkaline electrolyzers), and titanium does not reach 1 % of 2025 global supply in either scenario or either horizon (see **Figure 1** and **Figure 2**).

Figure 1. Material demand projections of key raw materials for the European Union



Source: authors' analysis (2026). Note: the horizontal axis represents the calculated share of estimated annual demand each year against today's global supply of the raw materials as indicated in **Table 16**. Values on the left side of the graph represent the demand in the BASE scenario, while values on the right side of the graph represent the demand in the INNO scenario.

Figure 2. Material demand projections of key raw materials for all regions



Source: authors' analysis (2026). Note: same as above.

Criticality assessed at material level however does not draw the full picture, as some concentrated positions identified could lie further down the chain, at the processed material and component stages, which are not systematically tracked in trade statistics. For example, a single company in Belgium manufactures the zirconia-based diaphragm used in almost all European alkaline designs. Against projected 2030 deployment needs, EU manufacturing capacity assessed in 2025 covers 58 % of alkaline stack requirements, 40 % of PEM stack requirements, 36 % for alkaline electrodes and 9 % for porous transport layers and gas diffusion layers.

Circularity emerges as the most effective mitigation available without modifying system designs or operating conditions. Combining enhanced material efficiency, extended stack lifetimes and advanced recycling reduces cumulative EU material demand over 2020–2050 by 31–55 % in the BASE scenario and 29–48 % in the INNO scenario and brings forward and lowers the peak of annual demand. Secondary supply from electrolyser stacks becomes significant only after 2035, when capacity installed between 2025 and 2030 begins to reach end of life, and most demand over the period must still be met from primary sources (58–69 % for iridium, 56–72 % for platinum and 56–82 % for titanium). Peak iridium demand corresponds to 54–61 % of current global supply, and even under the most ambitious combination of levers the net primary requirement at peak still amounts to 36–41 % of current global production. No dedicated recycling capacity for hydrogen technologies yet exists in Europe, and hydrogen technology-specific recovery routes for iridium, platinum and titanium remain at low technology readiness. This is expected to change as the market keeps maturing.

Other mitigation options are more limited. Technological reallocation towards AEM designs, which permit the use of steel in place of titanium and might be able to operate without using PGMs, is constrained by a lack of EU manufacturing capacity at the required scale and by the continued reliance of commercial AEM systems on noble metal catalysts. Strategic stockpiling, addressed in the EU Stockpiling Strategy adopted in July 2025, requires particular care for iridium, where the illiquidity of the market means that large-scale purchasing could itself distort prices and constrain near-term deployment. Techno-economic designs or regulation affecting the capacity factor of electrolyzers might also have a strong influence on the supply risk, because materials demand scales with installed capacity rather than with hydrogen output. In addition, lower capacity factor reduces degradation rates and increases lifetime of assets, requiring less frequent system renewal but providing fewer resources available for recycling.

The report provides seven recommendations falling into three groups: (1) proposes to develop and increase the circularity potential of components to be ready when secondary supply becomes more available by 2035, (2) suggests diversifying the source of supply and to align foreign policy tools with CRMA objectives, (3) highlights the critical data gaps on processed materials and components and the lack of capacity to dynamically assess supply risks, as current tools mostly provide a static picture based on trade statistics.

1. Introduction

The recent years have witnessed a shift in the development of clean technologies beyond their sole potential for decarbonisation. Following the urgent recommendations of the Draghi report (European Commission, 2025f) and the Commission's proposed framework of the Industrial Accelerator Act (IAA) (COM(2026)100), climate decarbonisation objectives are now entangled in the imperative of strategic autonomy, energy security and industrial growth. The IAA introduces "Made in EU" and low-carbon requirements for public procurement, conditioning large non-EU investments on local job creation and content requirements. However the materials content of clean technologies are characterised by both a high economic importance and a significant supply risk due to concentrated global production and geopolitical vulnerabilities (European Commission. Joint Research Centre., 2023). The Critical Raw Materials Act (Regulation (EU) 2024/1252), together with the RESourceEU Action Plan (COM(2025) 945) are framing a response to those risks.

Renewable and low-carbon hydrogen technologies—particularly electrolyzers and fuel cells—play a central role in this dual ambition and respond both to the EU's decarbonisation strategy laid out in the European Green Deal as well as the call for strengthening the EU industrial capacity of the Clean Industrial Deal (European Commission, 2025a). These technologies depend heavily on several critical raw materials (CRMs) such as platinum group metals (PGMs), nickel, cobalt, or titanium.

This report builds on the assessment and conclusions of the abovementioned report analysing the materials demand of a set of strategic technologies (European Commission. Joint Research Centre., 2023). It complements this report by providing a more detailed analysis (deep dive) on the status of the supply chain of key hydrogen technologies: water electrolyzers and fuel cells. This report will follow the structure of the other deep dive reports published in 2025 (European Commission. Joint Research Centre., 2025a, 2025b, 2025c). It will start with a mapping of each step of the supply chain from raw materials to systems, provide projections of materials demands, and an assessment of the vulnerabilities of these supply chain. It will conclude with an overview of possible mitigation measures which the EU can implement to hedge against these risks.

1.1. Geopolitical context of the development of hydrogen technologies

As for other clean technologies, the development of the hydrogen sector expanded from being a key pillar of environmental policies to also become deeply entangled with industrial competitiveness and energy security imperatives. The Hydrogen Council¹ notes that the clean hydrogen sector channels now more than USD 110 billion in investment worldwide, indicating that the sector ambition is maintained and backed by public and private stakeholders (Hydrogen Council, 2025). These investments represent a USD 35 billion year-on-year increase and have been secured across more than 500 projects worldwide that had successfully passed final investment decision, entered construction, or commenced commercial operations. This supports the assessment that the hydrogen market has now entered a consolidation phase, where less viable projects have been cancelled and delayed (European Commission. Joint Research Centre, Bolard et al., 2025).

¹ The Hydrogen Council is a global alliance of around 140 energy, transport, and industrial companies launched in January 2017 at the World Economic Forum in Davos, with the objective of promoting and accelerating the development of the clean hydrogen economy.

This report focuses on water electrolyzers and fuel cells, which are the core technological focus of EU policies such as the Net Zero Industry Act, and the Industrial Accelerator Act (EU 2026/0068).

The United States of America has recently shifted its support on clean technologies in general, including for renewable and low-carbon hydrogen ambition, leaving the hydrogen market uncertain. The Executive Order on "Unleashing American Energy" (published in January 2025) paused the disbursement of funds allocated through the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA), creating immediate uncertainty for hydrogen projects (Jones Day, 2025). The "One Big Beautiful Bill Act" (OBBBA), passed into law in July 2025, significantly modifies energy tax provisions, including those related to hydrogen. The bill reduces the possibility for projects to apply for the clean hydrogen production tax credit (45V) of up to USD 3/kgH₂ if their construction date is planned for 2027 at the latest, 5 years earlier than initially provisioned in the IRA (Corbeau, 2025; Sam Bartlett, 2025). The new administration is prioritising "blue hydrogen" pathways supported by natural gas infrastructure, and placing less focus on environmental justice, community benefits, and long-term climate goals that were embedded in the original framework (Bruce White, 2025).

Although the regulatory framework shifted, flagship projects are still being deployed, with the 220-MW_{el} electrolysis facility in the ACES Delta hydrogen project in Utah approaching commissioning phase (Fuelcellworks, 2026). This shows that despite changes in the policy drivers, US projects are still being deployed. US electrolysis capacity was estimated between 600-700 MW_{el} at the end of 2025, approximately 15 % of global installed capacities. Recent estimates project the US-headquartered companies to own approximately 8.4 GW_{el}/annum electrolyser manufacturing capacities (European Commission. Joint Research Centre, Bolard et al., 2025).

China's 15th Five-Year Plan (2026–2030) marks a significant shift in China's strategy. The narrative moved from developing China's massive manufacturing capacity of traditional technologies to focus now on the development of "advanced industries" such as innovative materials, quantum computing, nuclear fusion, or hydrogen technologies (Embassy of the People's Republic of China in the Republic of Slovenia, 2026). New energies and hydrogen are among the sectors under focus of this new plan. They remain considered as key technology for long-term decarbonisation of hard-to-abate sectors, coupled with the integration of high shares of variable renewables, and supporting new export-oriented industries. This is aligned with the global paradigm that the development of clean technologies are now not only perceived as a means to reach climate objectives, but also necessary to guarantee the security of energy supply (GIZ et al., 2025; Gong et al., 2025; Li Shuo, 2026). As of early 2025, China implemented its first energy law which reclassifies hydrogen as energy carrier, transitioning its status from a hazardous chemical. This change indicates the government's intention to provide enhanced policy backing and a more defined position for hydrogen within China's energy sector transformation (Patel, 2025).

In this context, it is likely that China will maintain its leadership in the deployment and manufacturing of water electrolyzers and fuel cell technologies. Although it is difficult to track the exact magnitude of deployment of those emerging technologies, analysts suggest that by the end of 2025, China had deployed between 2 and 4.4 GW_e of electrolysis capacity, which represents between 50 % and 69 % of global installed capacities and hosted most of the estimated global electrolyser manufacturing capacities (34.7 GW_{el}/year, 55.1 %) (European Commission. Joint Research Centre, Bolard et al., 2025).

1.2. EU policy context

Renewable and low-carbon hydrogen is a fundamental pillar of the European Union's decarbonisation strategy, and the EU has put in place a comprehensive regulatory framework to promote and secure its domestic production (European Court of Auditors, 2024).

The EU established the Hydrogen Bank, a financial instrument which aims to bridge the cost gap between renewable and fossil hydrogen, stimulating demand and manufacturing with a total budget of approximately EUR 3 billion (European Commission, 2022, 2023a). The European Commission also developed market accelerating capacities with the Hydrogen Mechanism embedded in the EU Energy and Raw Materials Platform, which aims at facilitating the matching of hydrogen producers and off-takers in the EU (European Commission, 2025d, 2025e).

EU member states are also contributing to this industrial strategy under the scheme of the Important Projects of Common European Interest (IPCEI) framework. The IPCEI framework is a state-aid mechanism allowing MS to fund large-scale innovative projects deemed to be essential for Europe's interest. The IPCEI scheme complements other State aid rules such as the Climate, Energy and Environment Aid Guidelines, the General Block Exemption Regulation and the Framework for State aid for research and development and innovation. Although not considered as traditional R&D funding, IPCEI mechanism allows Member States to support innovative projects, while ensuring that potential competition distortions are limited. In total, the scheme allows more than EUR 18.9 billion of public funds to be directed towards the hydrogen market, mirroring approximately the same amount of private funding (Clean Hydrogen Partnership, 2025).

Renewable hydrogen falls under the purview of Renewable Fuels of Non-Biological Origin (RFNBOs), defined in the Renewable Energy Directive (EU) 2023/2413 whose share in the EU energy mix is set to increase following the implementation of the 2nd amendment of the Renewable Energy Directive. However, significant challenges persist. The implementation of renewable sub-targets for RFNBOs in transport and in the industrial sectors is heterogeneous across Member States, creating market uncertainty (European Commission. Joint Research Centre, Bolard et al., 2025).

As discussed above, hydrogen technologies are under the purview of the Clean Industrial Deal (CID). The CID builds on the Net Zero Industry Act, the Critical Raw Materials Act and the future Industrial Accelerator Act, and aims at leveraging the development of clean technologies to increase the growth of the EU industrial base, strengthen the EU's strategic autonomy and reduce exposure to the risk of disruption of raw materials and energy supply (European Commission, 2025a).

1.3. Hydrogen technologies considered in this assessment

Hydrogen technologies refer to a broad set of energy systems related to the production, storage, transportation and use of hydrogen. This report covers the supply chain of water electrolyzers and hydrogen fuel cells, as they are the two main hydrogen technologies listed in main EU policies such as the NZIA. Furthermore, it examines the sustainability and circularity implications of these hydrogen technologies. The objective is to pinpoint areas where targeted policy interventions can mitigate the EU's vulnerability to supply chain disruptions, ultimately ensuring the successful rollout of these technologies and helping the EU meet its targets.

1.3.1. Water electrolyzers

Water electrolysis is the most mature and scalable method for producing hydrogen using renewable electricity. The process relies on applying an electric current to split water (H₂O) into hydrogen (H₂)

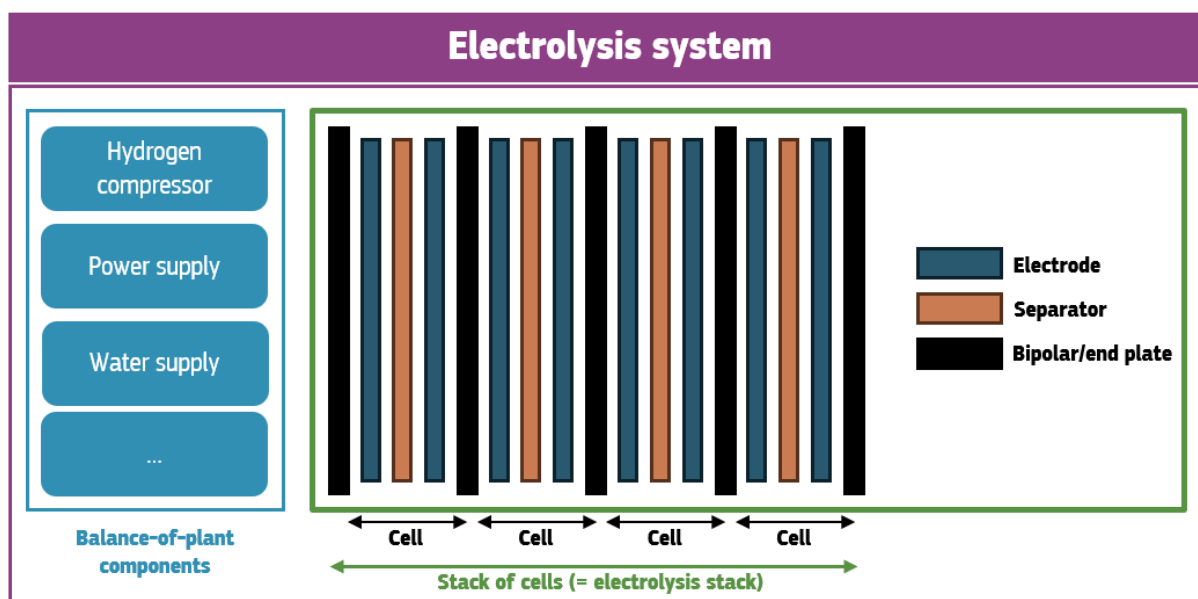
and oxygen (O₂) through an electrochemical reaction. The efficiency and performance of this process depend on the type of electrolyser technology used, with the two major types of electrolysers being alkaline electrolysers and proton exchange membrane (PEM) electrolysers. Two other emerging technologies also exist and are based on the use of membrane or ceramic electrolytes.

- Alkaline electrolysers are a well-established, cost-effective option for hydrogen production, offering long lifetimes and no reliance on expensive noble metal catalysts. However, they operate at relatively low current densities and have limited flexibility, making them less suited to variable renewable energy sources. Recent developments aim to improve their dynamic performance.
- Proton Exchange Membrane (PEM) electrolysers provide high efficiency and rapid response, making them ideal for integration with renewable energy. However, they remain expensive due to their platinum-group catalysts and face durability challenges that limit widespread adoption.
- Solid Oxide Electrolysers (SOEC) offer the highest efficiency when coupled with high-temperature heat, but their slow startup times and material constraints limit operational flexibility. Despite successful demonstrations—including a 2.6-MW_{el} project commissioned in Europe in 2025—they require further research and development to address durability and scalability issues.
- Anion Exchange Membrane (AEM) electrolysers combine the benefits of alkaline media with solid electrolytes, with some research showing promising capacities to use non-precious metal catalysts while producing high-purity hydrogen. Though still in the early stages of commercialisation, they are gaining traction, with 5-MW_{el} systems already deployed.

Figure 3 provides a simplified schematic of an electrolyser system. An electrolyser system consists of several essential components, essentially decomposed between the electrolyser stacks and balance-of-plant (BoP) components:

1. The electrolyser stack is the core reaction unit where the electrochemical process occurs, composed of multiple cells.
2. Power supply & control system regulates voltage and current to optimise the stack efficiency and prevent damage from voltage fluctuations.
3. Water management system ensures proper water circulation, purity, and temperature control to maintain optimal performance.
4. Gas separation & purification system prevents gas cross-contamination and ensures high-purity hydrogen output.
5. Thermal management system maintains the required operating temperatures (e.g., PEM electrolysers operate at 50 – 80°C (Ayers et al., 2019), while alkaline systems work at 30 – 80°C (Arsad et al., 2024)).
6. Auxiliary systems: includes compressors, dryers, and safety controls for efficient hydrogen storage and distribution.

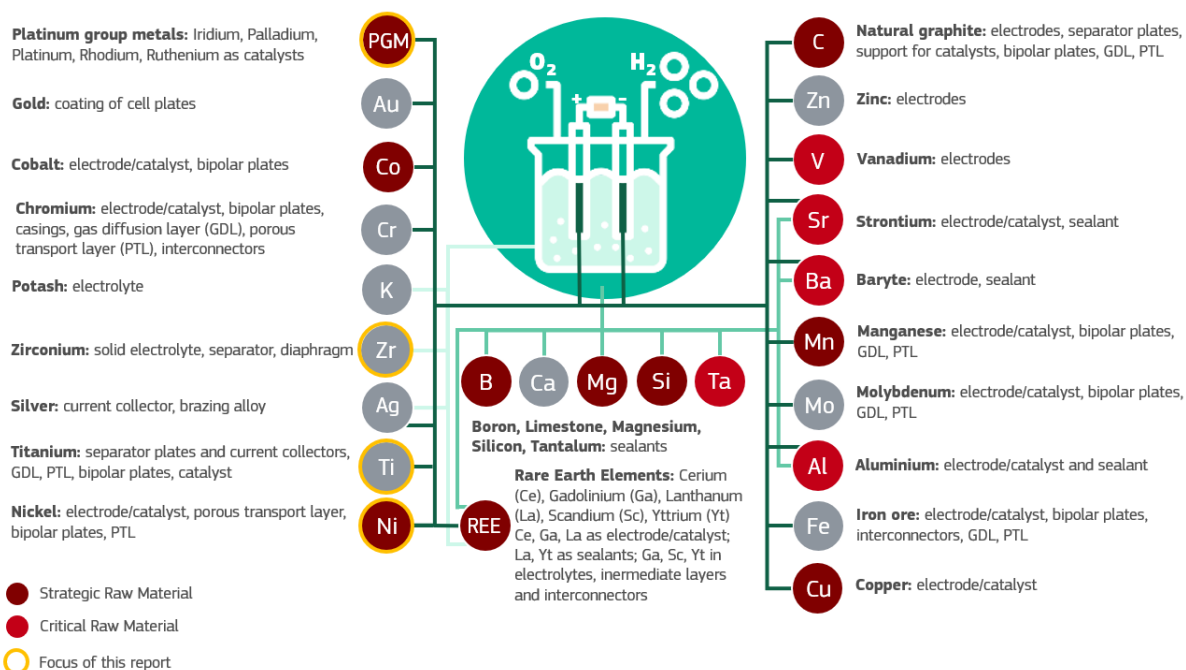
Figure 3. Simplified overview of an electrolyser system



Source: (European Commission. Joint Research Centre, Bolard et al., 2025)

Figure 4 provides a detailed overview of materials which may be found in both current state-of-art systems and emerging designs at a lower technological readiness level (TRL).

Figure 4. Overview of materials used in water electrolyzers.



Source: (European Commission. Joint Research Centre., 2023)

1.3.2. Fuel cells

Fuel cells are electrochemical devices that convert the chemical energy of a fuel, typically hydrogen, directly into electricity through reactions with oxygen. Unlike combustion-based systems, this

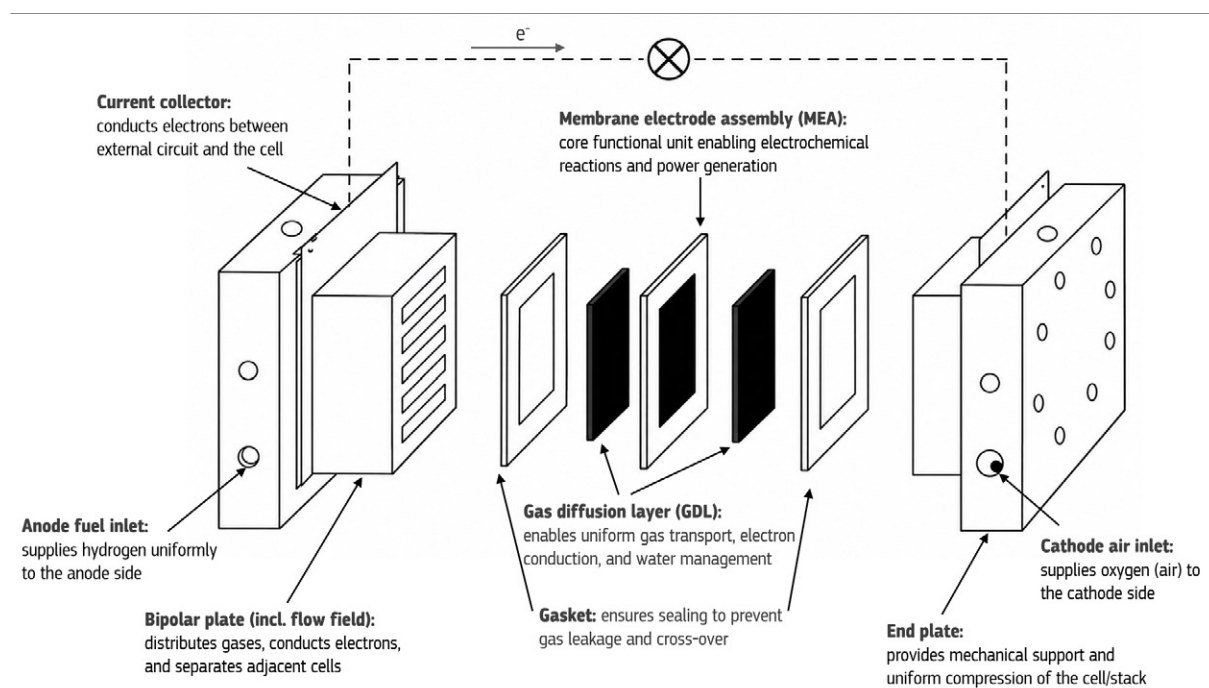
conversion occurs with higher efficiencies and significantly lower pollutant emissions. The main by-products are water and heat. Fuel cells are considered a key technology for the decarbonisation of energy systems, with applications across transport, distributed power generation and industrial energy supply.

Fuel cell technologies are classified according to the type of electrolyte used, which determines operating temperature, material requirements and system architecture. The main types include proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), phosphoric acid fuel cells (PAFC) and alkaline fuel cells (AFC).

Among these, **proton exchange membrane fuel cells (PEMFC)** are widely deployed in transport applications, including passenger cars, buses and heavy-duty vehicles. Their low operating temperature (typically 60–90 °C), fast start-up and high-power density make them well suited for dynamic and compact applications. PEMFC are assembled into stacks of repeating cells connected in series to achieve the required voltage and power output. These stacks are integrated with balance-of-plant components, including air supply, hydrogen management, humidification, thermal control and power electronics. System performance and durability depend on the interaction between materials, component design and operating conditions.

Figure 5 provides a simplified schematic of a PEMFC and the main components. The membrane electrode assembly (MEA) represents the core of the cell. It comprises a proton-conducting membrane and two catalyst layers (typically Pt-based), where hydrogen oxidation and oxygen reduction reactions occur. Gas diffusion layers (GDLs) distribute reactants, manage water and provide electrical conductivity. Bipolar plates (BPPs), incorporating flow-field channels, distribute gases, collect current and contribute to thermal and structural management. Gaskets ensure sealing, while end plates maintain compression and mechanical integrity.

Figure 5. Overview of main components of a PEMFC.



Source: JRC representation (2026)

Solid oxide fuel cells (SOFC) are characterised by high operating temperatures (typically 650–900 °C). They are primarily deployed in stationary applications such as distributed power generation, combined heat and power (CHP) systems and industrial energy supply. Their high efficiency and fuel flexibility make them well suited for continuous operation and integration with existing energy systems. SOFC systems rely on a ceramic-based architecture. SOFC stacks are integrated with balance-of-plant components, including fuel processing and thermal management systems. Their high operating temperature enables efficient heat recovery and, in some configurations, internal fuel reforming. However, it also introduces challenges related to material degradation, thermal cycling and system complexity.

Table 1 summarises the main technological and material differences between PEMFC and SOFC systems.

Table 1. Comparison of PEMFC and SOFC technologies.

Parameter	PEMFC	SOFC
Electrolyte	Polymer electrolyte membrane (typically perfluorosulfonic acid polymers – PFSA, e.g. Nafion)	Ceramic electrolyte (typically yttria-stabilised zirconia – YSZ)
Operating temperature	60–90 °C	650–900 °C
Ion conduction	Proton (H ⁺) conduction	Oxygen ion (O ²⁻) conduction
Typical anode material	Pt or Pt-based catalyst on carbon support	Nickel-based cermet (Ni-YSZ or nickel-gadolinium-doped ceria (Ni-GDC))
Typical cathode material	Pt or Pt-alloy catalyst	Perovskite oxides (e.g. LSM – lanthanum strontium manganite; LSCF – lanthanum strontium cobalt ferrite; LSC – lanthanum strontium cobaltite)
Fuel	Hydrogen	Hydrogen, natural gas, syngas, biogas
Start-up time	Fast (seconds to minutes)	Slow (tens of minutes to hours)
Electrical efficiency	~40–60 %	~50–65 %
Typical applications	Transport (cars, buses, trucks), portable systems, backup power systems	Stationary power generation, combined heat and power (CHP), distributed energy
Key advantages	High power density, rapid response, compact system design	High efficiency, fuel flexibility, suitable for continuous operation
Key challenges	Platinum dependence, membrane durability	High operating temperature, material degradation, thermal management
Materials relevance	Platinum group metals (PGMs), fluorinated polymers (PFSA), carbon-based materials	Nickel, zirconium, rare earth elements (e.g. lanthanum, yttrium), ceramic processing materials

Source: (Malik et al., 2021)

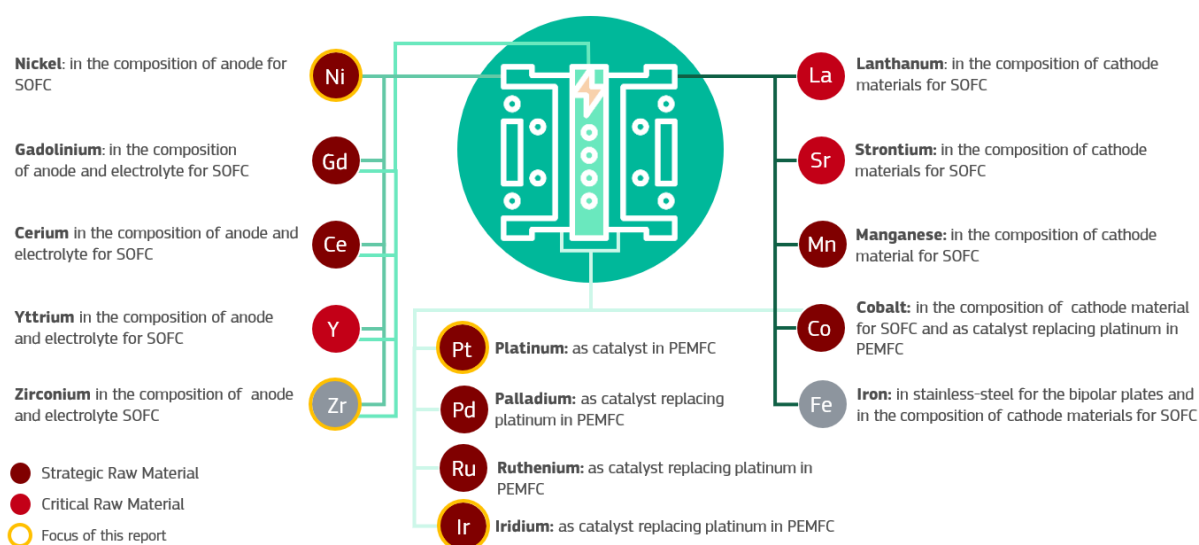
Fuel cells are deployed across multiple sectors. The main application segments include transport (75 %), stationary power generation (24 %) and portable systems (1 %) (European Commission. Joint Research Centre., 2023).

- The transport sector represents the largest and fastest-growing application area for fuel cells. Fuel cell electric vehicles (FCEVs) combine hydrogen storage, fuel cell stacks and electric drivetrains to deliver zero-emission mobility. Applications include passenger cars, buses, heavy-duty trucks, trains and maritime vessels (IEA, 2025).
- The stationary power sector is the second major segment. Fuel cells are used for distributed electricity generation, micro-combined heat and power (micro-CHP) in buildings, backup power for telecommunications and data centres, and off-grid supply. High-temperature systems such as SOFC are particularly suited to these applications due to their high efficiency and continuous operation capability (Clean Hydrogen Partnership, 2024).
- Fuel cells are also used in portable and specialised applications, including remote power systems, auxiliary power units and defence-related equipment. Although these applications represent a smaller share of deployment, they highlight the flexibility of fuel cell technologies across a wide range of use cases (IEA, 2025).

The supply chain of fuel cells consists of several steps such as raw materials extraction, processing into functional materials, component manufacturing, stack assembly and system integration. At the upstream stage, raw materials are transformed for instance into carbon-based materials, polymers, ceramics and metallic materials with specific functional properties. These processed materials are subsequently used to manufacture key components such as membranes, electrodes, gas diffusion layers and bipolar plates in PEMFC, and electrolytes, electrodes and interconnects in SOFC. Downstream, these components are assembled into stacks and integrated into complete systems.

Fuel cell performance depends on a relatively limited set of raw materials that enable electrochemical reactions, ionic and electronic transport, and structural stability (**Figure 6**).

Figure 6. Overview of raw materials used in fuel cells.



Source: (European Commission. Joint Research Centre., 2023)

- In PEMFC, platinum group metals (PGMs), in particular platinum (Pt), play a central role as catalysts for both the hydrogen oxidation and oxygen reduction reactions. Platinum is a key performance-enabling material, directly affecting efficiency, power density and durability. While partial substitution with palladium, ruthenium or iridium is possible in specific configurations, platinum remains difficult to replace without performance losses, making it a critical raw material from both a technological and supply perspective.
- In SOFC, the material base is different and much broader, relying more on ceramic and nickel-based systems. Nickel is used in cermet anodes (e.g. Ni-YSZ: nickel-yttria-stabilised zirconia; Ni-GDC: nickel-gadolinium-doped ceria), providing both catalytic activity and electronic conductivity. Zirconium and yttrium are combined in yttria-stabilised zirconia (YSZ) to ensure oxygen ion conduction in the electrolyte. Rare earth elements (such as lanthanum, cerium and gadolinium) and strontium are used in cathode and electrolyte materials to enhance electrochemical performance. Additional elements such as cobalt, manganese and iron further contribute to catalytic activity, electrical conductivity and structural properties. Iron is used notably in stainless steel components such as bipolar plates and in cathode materials for SOFC.

1.4. Final list of materials and components investigated in this report

On one hand, this report aims to conduct an in-depth analysis of supply chain challenges related to critical raw materials, processed materials, components, and stacks that may impede the planned deployment of electrolyzers and fuel cells in the EU. On the other hand, electrolyzers and fuel cells are subject to intense research efforts for the development of new and innovative materials or manufacturing processes, to reduce the use of expensive compounds, or improving performance. This results in a wide variety of systems and substances being investigated at lab-scale, as exhaustively listed in **Figure 4** and **Figure 6**. Providing a complete picture of the used materials in electrolyser and fuel cells technologies is therefore considered out of the scope of this report, which aims to provide trends and estimations of large-scale demands based on technology and designs prone to dominate the market in the near-term. The scope of investigation has then been reduced to focus on sub-technologies whose designs are likely to remain stable in the short- and medium-term (5-15 years) and likely to represent the major market share. Alkaline and PEM electrolyzers as well as PEM fuel cells fall into this category.

Among those technologies, we focused on either the materials with the highest criticality level as identified in (European Commission. Joint Research Centre., 2023) (iridium, platinum, nickel, titanium) or materials which seem to overly dominate the market share either as raw or processed materials (e.g. zirconium oxide). All materials (apart from zirconium) are listed under the European Commission fifth list of identified Critical and Strategic Raw Materials for EU economy.

Table 2 is giving an overview of the investigated raw materials, processed materials and their occurrence in respective components of the individual technology.

Table 2. Scope of materials and components investigated within this report.

	Raw materials [elements]	Processed Materials	Components	System
Alkaline electrolyser	Nickel, Zirconium	Ni-based materials (Ni foam, Ni mesh, Ni-plated steel, Raney Ni), Zirconium dioxide powder	Separator, bipolar + end plates, electrodes, catalysts, gaskets	Alkaline stack
PEM electrolyser	Platinum, Iridium, Titanium,	Titanium-based materials, PGM-based processed materials (IrO _x , Pt/C)	Membrane, electrodes, catalysts, bipolar + end plates, porous transport layers, gasket	PEM stack
PEM FC	Platinum	Pt-based catalysts (Pt/C)	Proton exchange membranes, membrane electrode assemblies, gas diffusion layers, bipolar plates	PEMFC stack

Source: authors' analysis (2026)

2. Supply chain mapping and risk analysis

2.1. Principal raw and processed materials

This chapter provides a detailed analysis of the main raw materials used for state-of-art designs of the hydrogen technologies under the scope of this report (electrolysers and fuel cells). Each material contains an assessment of the market status together with a raw materials factsheet elaborated mostly using data from the JRC-maintained Raw Materials Information System (RMIS) (European Commission. Joint Research Centre, 2024), and completed with data from other sources such as Eurostat when available.

2.1.1. Iridium

2.1.1.1. Material description and use in hydrogen technologies

Iridium, frequently utilised in its oxide form (IrO_2), is employed in PEM electrolysers due to its excellent catalytic properties, stability, and resilience to the acidic conditions inherent in PEM technology. Electrocatalysts play a crucial role in the electrolysis process by facilitating the overcoming of thermodynamic challenges involved in splitting water into hydrogen (H_2) and oxygen (O_2).

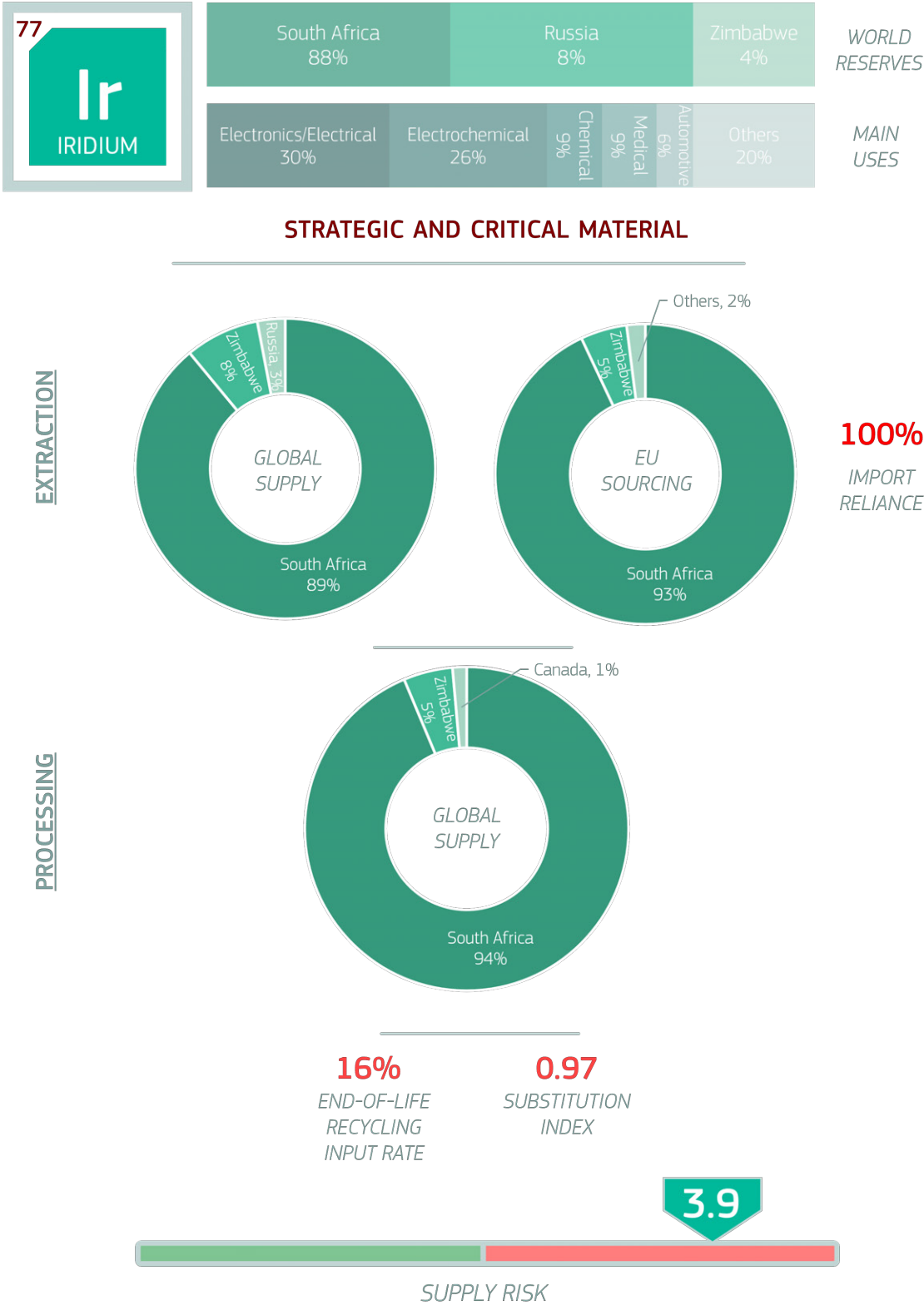
Iridium is considered the most critical material for PEM electrolyser production and is regarded as the primary bottleneck for the widespread deployment of this technology.

Another factor exacerbating the critical nature of iridium is the absence of proven alternative materials available at commercial scale that can ensure the same level of performance in electrolysers. Iridium is also used in combination with platinum and ruthenium, which are also PGM materials. Several alternative materials are investigated as potential substitutes for iridium, such as Ru-based materials, non-precious metal-based materials and carbon materials, but they are still far from commercialisation (Araújo et al., 2024).

2.1.1.2. Global market and trade

Iridium is one of the rarest materials on earth and is part of the platinum-group metals. The annual production of iridium ranges from 7 to 8 tonnes, with South Africa as the predominant supplier, accounting for approximately 90 % of global iridium extraction and processing (European Commission. Joint Research Centre, 2024; Johnson Matthey, 2025). This results in a highly concentrated supply chain. Iridium is also extracted as a by-product of platinum, meaning its annual production is closely linked to the demand for platinum, which serves as an additional complicating factor (Johnson Matthey, 2022).

Figure 7. Raw material factsheet: Iridium



2.1.2. Platinum

2.1.2.1. Material description and use in hydrogen technologies

Platinum is a key raw material for proton exchange membrane (PEM) technologies, including both fuel cells (PEMFCs) and electrolyzers (PEMELs). In PEM fuel cells, platinum is used as a catalyst in the membrane electrode assembly (MEA), enabling the hydrogen oxidation reaction at the anode and the oxygen reduction reaction at the cathode. In PEM electrolyzers, platinum is primarily used at the cathode to catalyse the hydrogen evolution reaction. Owing to its high catalytic activity, corrosion resistance and stability in acidic environments, platinum remains difficult to substitute without compromising performance and durability. Platinum in automotive PEMFCs is typically applied as carbon-supported nanoparticles within the catalyst layers. Total Pt loading has decreased substantially from early values above $\sim 0.8\text{--}1.0\text{ mgPt/cm}^2$ to around $\sim 0.2\text{--}0.3\text{ mgPt/cm}^2$ in current commercial systems (International Energy Agency, 2023). The Toyota Mirai is commonly used as a benchmark (0.31 mgPt/cm^2) (Andrade et al., 2024). In power-normalised terms, this corresponds to approximately $0.1\text{--}0.2\text{ gPt/kW}$, with technology targets approaching $\sim 0.125\text{ gPt/kW}$ ($\sim 10\text{ g Pt}$ per passenger vehicle) (U.S. Department of Energy, 2023).

2.1.2.2. Global market and trade

Platinum demand is currently dominated by established applications. Automotive catalytic converters represent the largest share ($\sim 35\text{--}45\%$), followed by jewellery ($\sim 25\text{--}30\%$) and industrial uses, including chemical, glass and electronics ($\sim 20\text{--}25\%$) (European Commission. Joint Research Centre, 2024). In comparison, hydrogen-related applications remain marginal (around $\sim 1\%$) but are expected to grow with the scale-up of fuel cell and electrolysis technologies.

Platinum is extracted from PGM-bearing ores, typically associated with nickel and copper deposits, and processed through complex multi-stage refining routes. According to RMIS and USGS data, global mine production is in the order of 170 tonnes per year, with South Africa accounting for around $70\text{--}75\%$ of global output. Other producers include Russia ($10\text{--}12\%$), Zimbabwe ($5\text{--}8\%$), and smaller contributions from Canada and the United States. The EU has a very limited role in primary platinum production, with output of around $1\text{--}2$ tonnes per year (less than 1% of global production), mainly from Finland (European Commission, Joint Research Centre (JRC), 2026).

Recycling is an important component of platinum supply. The metal can be recovered at high rates, and secondary supply already contributes a significant share of total supply. At present, most recycled platinum originates from automotive catalytic converters. Fuel cells and electrolyzers are expected to become additional secondary sources over time. The EU plays a significant role in platinum refining and recycling, with an estimated output of $40\text{--}50$ tonnes of refined platinum products annually². The Pt recycling capacity is primarily supported by EU-based industrial actors such as Umicore and Heraeus, complemented by companies including BASF, while additional European players such as Johnson Matthey (UK) contribute to refining, recycling and catalyst-related activities.

Platinum is classified as a critical and strategic raw material for the EU. In the 2023 criticality assessment, it shows a supply risk (SR) at the processing stage of 2.13 and an economic

² Estimation based on the global supply data and EU refining and recycling shares (USGS, 2024).

importance (EI) of 6.9. To reduce dependency, actions are required across the value chain. These include further reductions in platinum loading in PEM technologies, scaling up recycling and refining capacities, and improving the collection of platinum-containing waste streams. While exploration projects exist in Europe, their contribution to global supply is expected to remain limited. International partnerships therefore remain important to diversify supply sources and enhance supply chain resilience.

2.1.2.3. Platinum-related processed materials

Platinum used as a catalyst is usually processed and applied on a catalyst support, such as carbon black. Carbon black is the preferred catalyst (e.g. platinum) support material in PEM electrolyzers and fuel cells, offering a cost-effective way to reduce expenses linked to expensive platinum group metals (PGMs). The favourable properties that make carbon materials an excellent choice for catalyst supports include their high surface area stemming from a porous structure, excellent stability in acidic environments, superior electrical conductivity, and an advantageous balance between performance and affordability.

Carbon materials are used on both cathode and anode side, as well as in gas diffusion layer.

Carbon black is produced from petroleum-derived feedstocks, making its availability linked to the oil and gas sector. While current global production exceeds several million tonnes per year, any disruption (e.g., feedstock shortages, environmental regulations limiting fossil-fuel processing) could affect the price and reliability of supply for large-scale electrolysis projects.

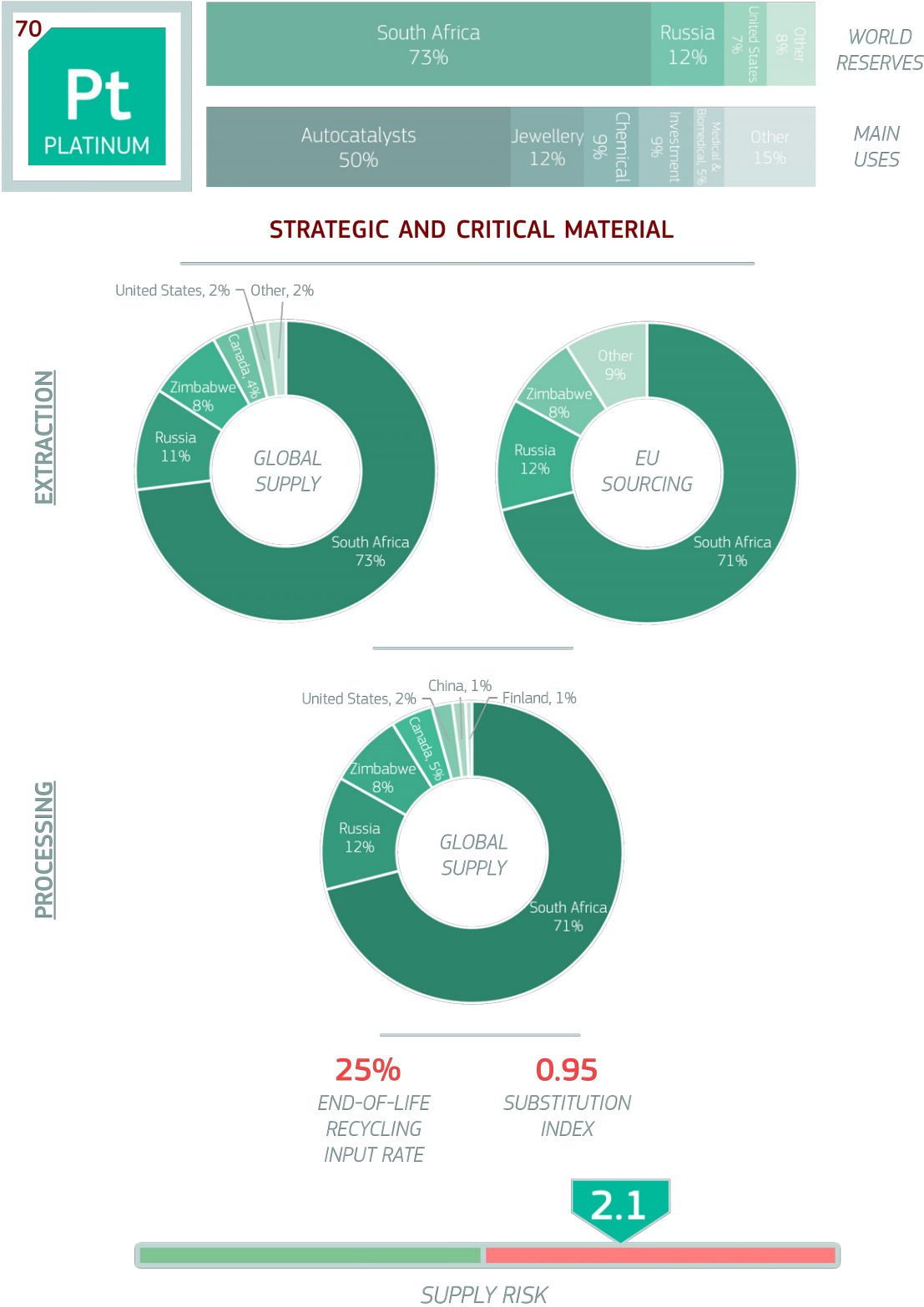
The global carbon black market was valued at approximately 14 million tonnes in 2024 and is expected to grow significantly in the coming years, mainly driven by the market for tyres, rubber goods, and plastics (Chemanalyst, 2026). The major players in carbon black production are Cabot Corporation (US-based), Birla Carbon (Aditya Birla Group) (with 19 manufacturing sites across 14 countries, including several in the EU), Orion Engineering Carbons S.A. (HQ in Luxembourg and factory in Germany), Tokai Carbon Co (Japan) and Jiangxi Black Cat Carbone Black Co (China).

Manufacturer specifications for commercial electrolyzers typically do not detail carbon black quantities; and such data on catalysts and components are often considered as proprietary³. Therefore, it is not possible to quantify the carbon materials used as catalysts support.

Research is ongoing on substitution of carbon black with graphene in the future (that can be produced from natural graphite) for the catalysts support (Zappia et al., 2023). Other potential substitutes include carbon nanotubes and metal-oxide (e.g., TiO_x, WO_x, and SnO_x) supports (Kadja et al., 2023). However, these are either more expensive or not yet proven at industrial scale.

³ Aggregated data are however available for some processed materials, such as HS code 280300 which covers carbon blacks and other forms of carbon n.e.c. Further assessment could make use of these data although it would require the allocation to hydrogen technologies more specifically.

Figure 8. Raw material factsheet: Platinum



STRATEGIC AND CRITICAL MATERIAL

EXTRACTION

GLOBAL SUPPLY

United States, 2%Other, 2%Canada, 4%Zimbabwe, 8%Russia, 11%South Africa, 73%

EU SOURCING

Other, 9%Zimbabwe, 8%Russia, 12%South Africa, 71%

PROCESSING

GLOBAL SUPPLY

United States, 2%China, 1%Finland, 1%Canada, 5%Zimbabwe, 8%Russia, 12%South Africa, 71%

25%END-OF-LIFE RECYCLING INPUT RATE

0.95SUBSTITUTION INDEX

2.1

SUPPLY RISK

Source: JRC elaboration based on (European Commission, 2023b) and (European Commission. Joint Research Centre, 2024)

2.1.3. Titanium

2.1.3.1. Material description and use in hydrogen technologies

Titanium comes from the mining of minerals such as rutile and ilmenite. Titanium ores are processed into titanium tetrachloride, which is then reduced into titanium sponge via the energy-intensive Kroll process. Producing one kilogram of titanium sponge through this route requires an estimated 257 MJ/kg (compared with the energy requirements of the production of aluminium (210 MJ/kg) or steel (20 MJ/kg)) (Buesa et al., 2025a; Xia et al., 2020).

Titanium metal is used in a wide variety of critical sectors, such as the defence industry, clean technologies, healthcare, or architectural applications (Buesa et al., 2025a). This emphasises that any disruption of titanium supply might create competition for sourcing.

Titanium ore used as a metal form is first transformed into titanium sponge, before being further melted into ingots (where alloying elements can be added), and wrought via mechanical working processes into semi-finished products (like bars or plates), before being used by manufacturers of components (Buesa et al., 2025a).

In hydrogen technologies, titanium is mostly found in bipolar plates / flow-field plates, current collectors and porous electrodes in PEM systems because it is mechanically strong, a good conductor and resists corrosion in the acidic environment. Wrought titanium can be used as substrate for bipolar plates, while sintered porous titanium can be used for PTL as its porous structure allows gases to move through (Badgett et al., 2024). It is not clear how much of the titanium used for hydrogen technologies has the same requirements as the one used in the aerospace industry.

Titanium sheet/mesh is commonly used as a substrate that is later coated with precious-metal catalyst (Pt/Ir) (Cheng et al., 2023). Coatings are essential to protect the titanium surface from corrosion and maintain low interfacial contact resistance (ICR), especially under harsh operating conditions.

The replacement of titanium for bipolar plates can be achieved with aluminium, stainless-steel or nickel, provided that the metallic plates are protected by a conductive coating that adheres firmly to the substrate and does not develop micro-pores or micro-cracks. Gold plating is the most widely used protective layer; a minimum thickness of 1 µm is required to achieve full surface coverage. Platinum and iridium plating, such as electrodeposited platinum on titanium, has also demonstrated lower cell resistance compared with bare titanium or carbon electrodes, highlighting the benefit of noble-metal coatings for regenerative fuel-cell applications (Kongstein et al., 2010).

2.1.3.2. Global market and trade

The titanium market is roughly divided in two major segments: more than 90 % of the global demand buys titanium in the powder form for the pigment market, where titanium can be used as whitening agents. The remaining 10 % groups unwrought titanium use in technological or industrial applications (Hu et al., 2022).

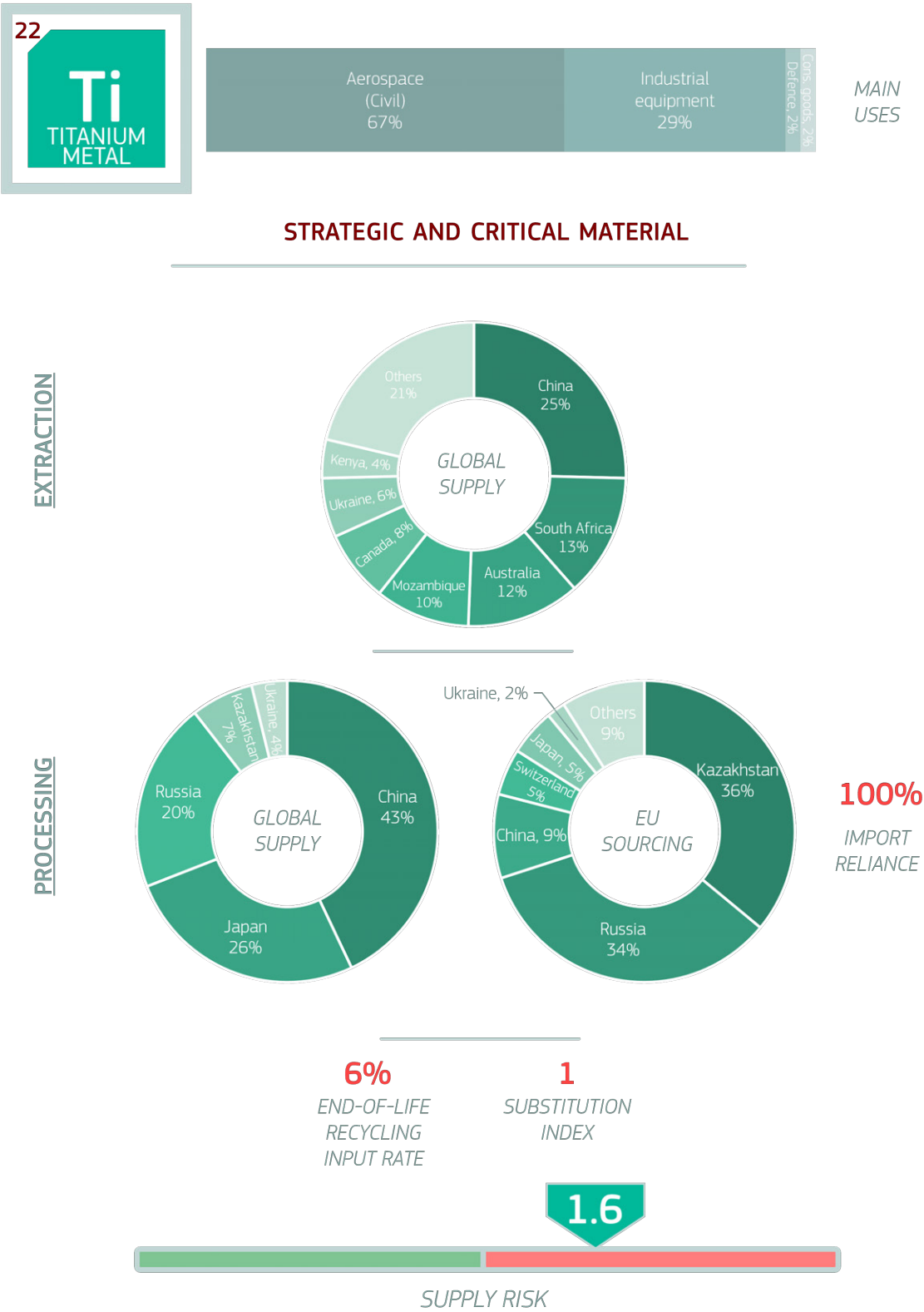
Global titanium sponge production output was estimated at 370 kt in 2025 (USGS, 2026a). The production of titanium sponge is heavily concentrated, with only five countries — China, Japan, Russia, Kazakhstan and Saudi Arabia — accounting for virtually all output. China has dramatically expanded its sponge production since 2018, growing its share from 37 % to approximately two thirds of global output by 2023; however, the majority of Chinese sponge is consumed domestically

and does not meet the quality standards required for aerospace-grade applications (Buesa et al., 2025a). High-quality sponge qualified for aviation and other critical uses remains largely produced and exported by manufacturers in Japan, Russia, and Kazakhstan. The EU does not have any production capacity of titanium sponge and is therefore 100 % reliant on imports at this stage of the supply chain.

China is the largest exporter of wrought titanium products. However, according to the SCREEN expert platform, Chinese producers are not certified by EU major players in the Aerospace industry (SCREEN project, 2024). EU companies usually import wrought titanium from the US manufacturers, with some titanium actually being supplied using scraps from EU manufacturers (Buesa et al., 2025a). Russia's VSMPO-AVISMA historically supplied a large share of high-grade wrought titanium for strategic industries (European Commission. Joint Research Centre., 2022). The loss of production capacity located in Ukraine following Russia's war of aggression against Ukraine was off-set by the opening of a new production facility in Yanbu, Saudi Arabia, which is co-owned between Saudi Arabia and Japanese company (Buesa et al., 2025a).

As of April 2026, titanium has so far been exempted from EU import bans applied to other metals, with analysts reporting this exemption as a means to reduce the risk of a shock on the global aerospace industry (Banks, 2025). Titanium imports from Russia to the EU has remained stable at around USD 213 million from January to November 2025, approximately 5 % lower than over the same period in 2024 (Eurometal, 2026). The European Union is preparing its 20th sanctions package against Russia however the list of metals included in the import bans has not been publicly revealed (European Commission, 2026b).

Figure 9. Raw material factsheet: Titanium metal



Source: JRC elaboration based on (European Commission, 2023b) and (European Commission. Joint Research Centre, 2024)

2.1.4. Nickel

2.1.4.1. Material description and use in hydrogen technologies

Nickel is the fifth most abundant element on Earth as a whole and occurs naturally in two primary mineral forms —sulfide and laterite ores—each influencing its extraction and processing methods. These ores are mined in approximately 25 countries and refined in about 26 nations as of 2024. The mineral form determines the extraction technique: sulfide ores (e.g., pentlandite) are typically processed through smelting (pyrometallurgy), while laterite ores (oxides/silicates like garnierite) require hydrometallurgical methods such as leaching.

Nickel is a metal traditionally used in alkaline electrolyzers, either in form of pure nickel, nickel-based alloyed or stainless steel. It is corrosion resistant in alkaline environments, has good catalytic activity and is less expensive than noble metals like PGMs.

Nickel sulfide usually yields an ore with a higher nickel content (0.15 – 8 %) and is referred to as “class 1” nickel, used for high technological applications (SCREEN project, 2023). Most of the lower ore quality found in laterite nodules has an ore grade of 0.2-2 %.

2.1.4.2. Global market and trade

The global nickel production was reported at approximately 3.9 million tonnes for 2025 (USGS, 2026a). Additionally, substantial quantities of secondary nickel are recovered through recycling, supplementing primary production (Schodde et al., 2025). Refining processes will output products like ferronickel, nickel oxide, nickel pig iron (NPI), and nickel sulphate (International Nickel Study Group, 2024).

Indonesia is the primary exporter of nickel products and was the primary exporter of nickel ore until 2020, before the Indonesian government imposed a ban on nickel ore exports and developed domestic refining capacities. China’s refining capacities slowed down in the following year because of this export ban and the reduced availability of nickel ore. However, the ban was concurrent with the increase of refining and processing capacity supported by the Indonesian government, attracting Foreign Direct Investment in Indonesia. China has significantly increased its national nickel strategic reserves in recent months, with estimates suggesting purchases of up to 100 000 tonnes since December 2024. According to the Financial Times, China’s imports of high-purity nickel soared to 77 654 tonnes in the first five months of 2025, more than double the volume from the same period in 2024, despite modest annual consumption growth of 5-10 % (Dempsey et al., 2025). This strategic accumulation coincides with a 40 % decline in nickel prices over the past two years, driven by expanded production in Indonesia and reduced demand for nickel-based electric vehicle batteries. Concurrently, withdrawals from London Metal Exchange (LME) warehouses also surged, with 78 798 tonnes of class-1 nickel withdrawn in the first six months of 2025, far exceeding the 17 544 tonnes moved in the same period in 2024.

At European level, large geological reserves are found in Finland and Greece, with EU importing most of its domestic demand from Finland and Canada. EU’s share of nickel imports from Russia fell sharply from Q1 2021—from 41 % to 15 % while increasing the share of its imports from the United States and Canada (Eurostat, 2025). As of Q2 2025, the primary extra-EU supplier of nickel was the United States (25 % of extra-EU imports), followed by Russia (15 %), Norway (12 %), Canada (12 %), the United Kingdom (11 %) (Eurostat, 2025).

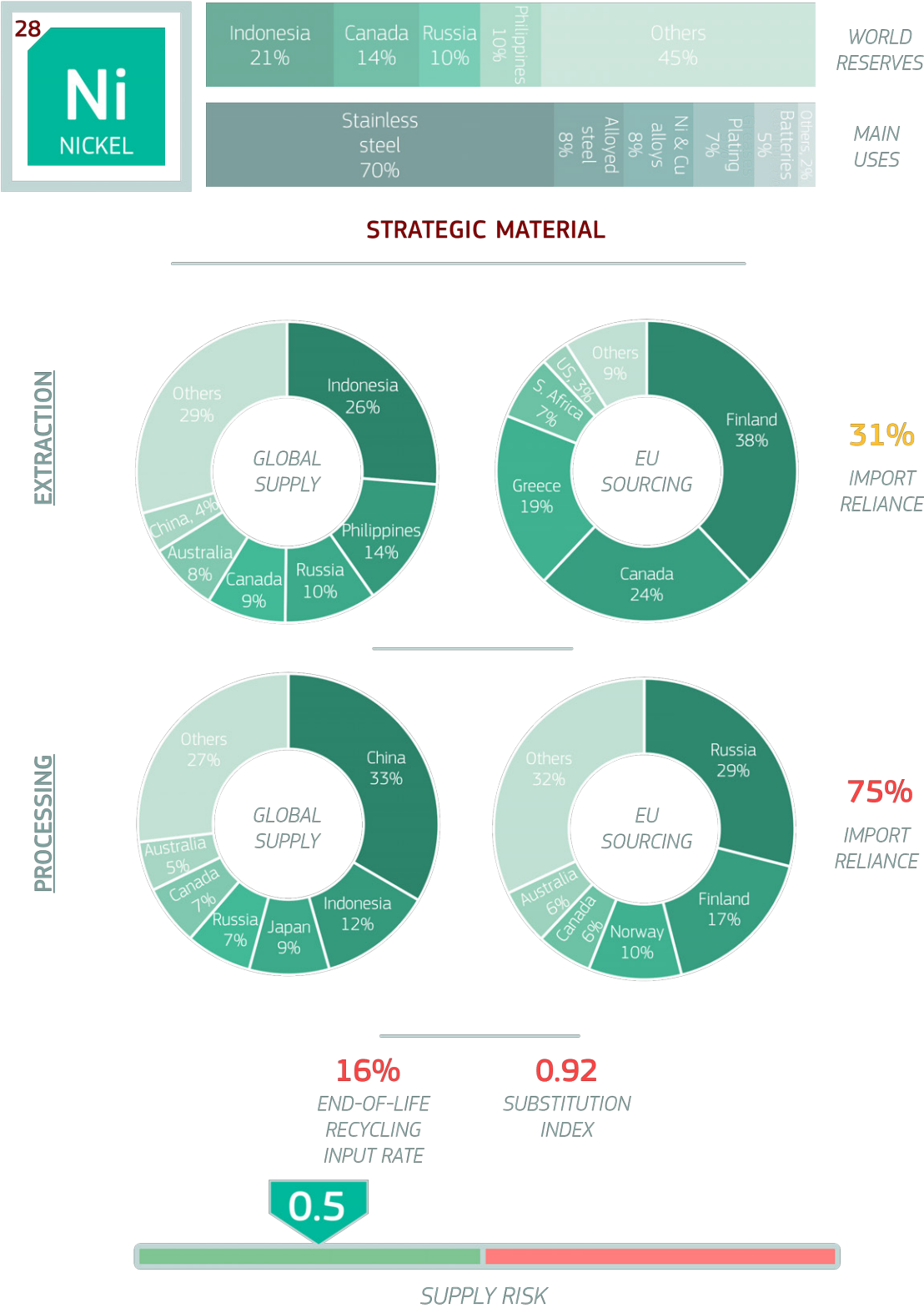
2.1.4.3. Nickel-based processed materials

Nickel-based processed materials are widely used across electrolyser technologies. They are found mostly in the bipolar plates, electrodes, or porous-transport layers in the form of:

1. Raney nickel is a porous metallic structure engineered to increase the surface of contact with hydrogen atoms. It was initially developed in the 1920s to facilitate catalytic reaction, as it increases the surface of contact available to reactants. It is usually coated on stainless steel substrate (Ciriminna et al., 2023).
2. Nickel foam is manufactured by electroplating nickel onto a polymer sponge, such as polyurethane, and subsequently burning away the polymer to leave a pure nickel skeleton. It is mostly used in design of modern cathodes (Aili et al., 2023; Nickel Green, 2024; 闫世凯 et al., 2010).
3. Nickel mesh is used as electrode substrate in more advanced alkaline zero-gap design (Wei et al., 2025).

Beyond those traditional materials, nickel-based catalysts are the focus of research and innovation efforts and are not limited to what is often perceived as traditional, less efficient systems. New and advanced manufacturing methods, such as methods to manufacture nano-structured, single-atom catalysts or new electrode shapes obtained via 3D-printing, are considered as one of the best leverage to reduce the cost of Ni-based alkaline electrolyser using Ni-based catalysts (Ciriminna et al., 2023).

Figure 10. Raw material factsheet: Nickel



Source: JRC elaboration based on (European Commission, 2023b) and (European Commission. Joint Research Centre, 2024)

2.1.5. Zirconium

2.1.5.1. Material description and use in hydrogen technologies

Although Zirconium (Zr) refers to a metal, it is typically used in the form of zirconia (or zirconium dioxide) nanoparticles (ZrO_2). These zirconia particles are used as an inorganic hydrophilic filler in advanced composite diaphragms (also called separators) (Henkensmeier et al., 2024).

A well-known commercial example is the Zirfon PERL diaphragm from the company AGFA (whose headquarters are based in Belgium). The material possesses a unique suite of engineering properties that make it highly valuable across various industries. A key differentiator from traditional, brittle technical ceramics is its high fracture toughness. This property is attributed to a "transformation toughening" mechanism, where applied localised stress induces a phase change that absorbs energy and effectively resists crack propagation. Furthermore, zirconia has low thermal conductivity, making it an effective thermal barrier material, and it is highly chemically inert, resisting most acids, alkalis, and corrosive environments.

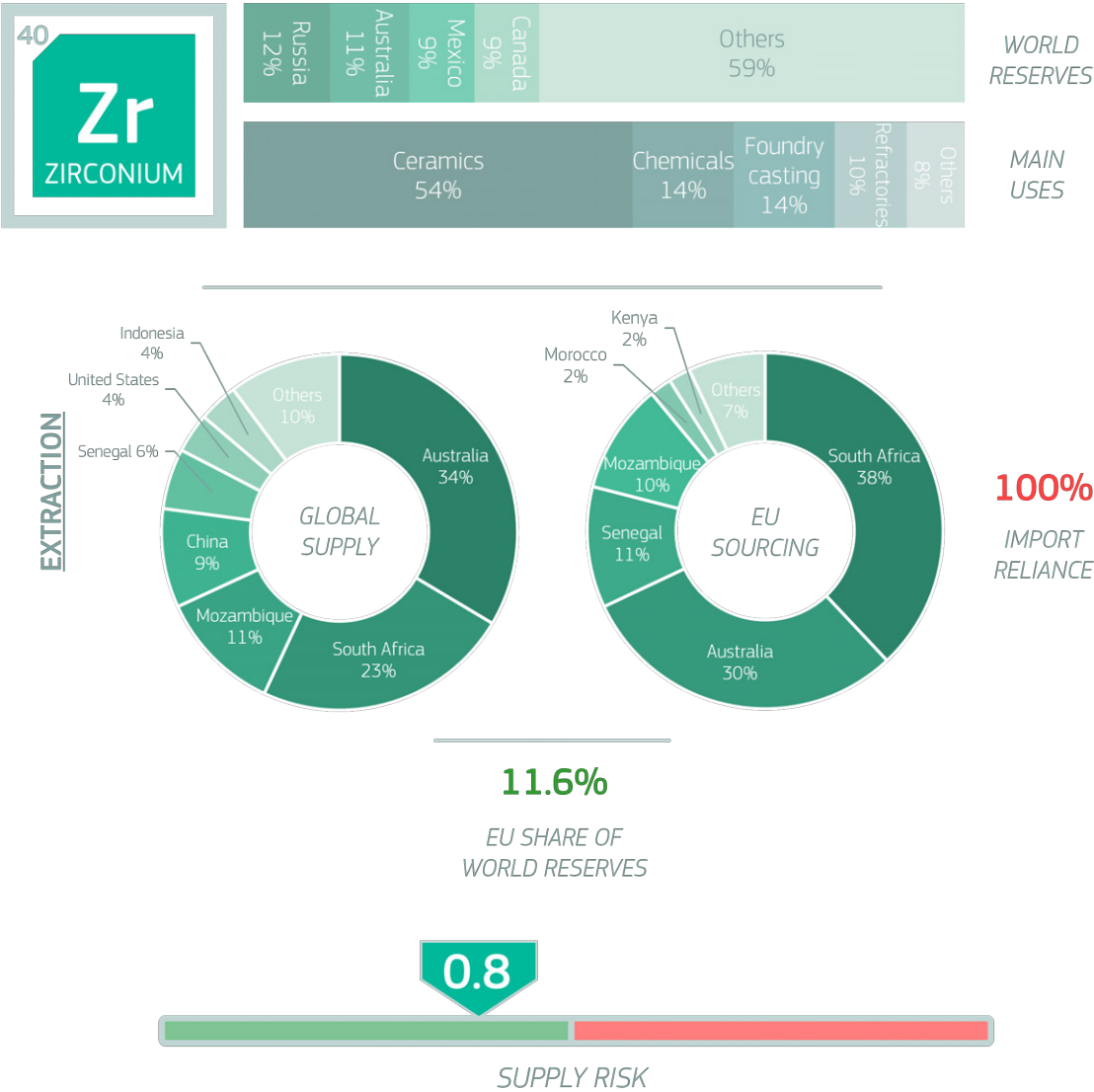
A Zirfon diaphragm contains 85 wt.% zirconium dioxide coated on a polyphenylene sulfide mesh (Agfa, 2025; Eikeng et al., 2024) (Aili et al., 2023; Brauns et al., 2021). The zirconia has essential properties like high chemical stability in concentrated, hot potassium hydroxide (KOH) and improves the separator's wettability, which is crucial for high ionic conductivity.

The criticality of zirconium materials is not clear and varies across clean technologies. Although not listed as a critical raw materials, some sources report Zr as of concern when considering the deployment of large-scale systems (Eikeng et al., 2024),

2.1.5.2. Global market and trade

Manufacturers specialising in high-purity zirconia powders and finished advanced ceramic components include leading technical material companies worldwide. The Saint-Gobain ZirPro division, for example, is a world-leading manufacturer of zirconium oxide powders (Saint-Gobain ZirPro, 2025). Tosoh Corporation is a Japanese-headquartered supplier of high-purity zirconia powders for industrial use (Tosoh Corporation, 2025). Other prominent manufacturers with strong positions in the advanced ceramics market include Kyocera Corporation, CoorsTek (a major North American producer of technical ceramics), Morgan Advanced Materials, CeramTec GmbH (a leader in medical-grade zirconia), and Imerys, a producer of fused zirconia powders for industrial and refractory applications globally.

Figure 11. Raw material factsheet: Zirconium



Source: JRC elaboration based on (European Commission, 2023b) and (European Commission. Joint Research Centre, 2024)

2.2. Components and systems manufacturing capacities

A systemic review of all materials used for all available designs is considered out of the scope of this work and a detailed list of components is presented in **Figure 3** and **Figure 5**. Data on manufacturing at component level is very difficult to compile with enough reliability. In the context of this exercise, a review of known manufacturers and the country of their headquarters was conducted and summarised in **Table 3**. Asia (mostly composed of China, Japan and South Korea) holds the greatest number of companies identified, dominating all categories except bipolar plates, interconnectors and sealing materials. The EU has a well-established presence of manufacturers across all components and technologies when accounted for in number of companies. This analysis however does not assess the distribution of manufacturing capacities of the factories (see **Table 4** for a rough assessment of manufacturing capacities of EU companies).

Table 3. Count of identified OEMs by component categories with headquarters' region

Components / regions	Bipolar plates	Electrode / MEA / PTL / GDL	Frame / Gaskets / Sealing materials	Interconnectors (SOEC)	Materials / Catalyst powders / Chemical precursors	Membranes / Separators	Total
Asia	12	39	11	1	13	15	85
EU27	24	27	15	8	5	10	76
Europe (not-EU27)	7	13	5		9		27
North America	9	23	12		11	13	54
RoW		1	1				2
Total	52	103	44	9	38	38	244

Note: all technologies (ALK, PEM, SOEC, AEM, PEMFC) are considered in this assessment. Grand total accounts for distinct count of companies, which might be counted several times in different columns if they produce different types of components. This table does not account for the manufacturing capacity of companies. More data on the manufacturing capacities of EU OEMs was also consolidated in the context of the CETO exercise and included in this chapter. Some companies are producing several components and are therefore accounted for multiple times in the table.

Source: authors' analysis from diverse public websites, commercial reports (2026).

Within the context of the NZIA benchmark analysis, the JRC tracked the EU production capacity with regards to projected demand, see **Table 4** below and related reports (European Commission. Joint Research Centre, Bolard et al., 2025; Hydrogen Europe, 2025a; IEA, 2025). These figures generally represent conservative estimates because, for many primarily used components (PUCs), other factories have been identified but lack manufacturing capacity data from our providers. Although these numbers are employed for calculating the NZIA benchmarks, they remain susceptible to significant changes as the industry continues to consolidate.

According to the CETO methodology developed for estimating the NZIA benchmark, EU manufacturing capacities are calculated against the annual deployment need capacities derived from the NZIA (Regulation (EU) 2024/1735) and the JRC POTEnCIA model projections (European Commission. Joint Research Centre, Bolard et al., 2025). As described in the cited report published in 2025, POTEnCIA projects a total electrolysis deployed capacity of 86.1 GW_{el} by 2030⁴, of which 32.4 GW_{el} is alkaline stacks and 53.7 GW_{el} is PEM (SOEC and AEM technologies are not considered in the *POTEnCIA CETO 2025 Scenario* and, thus, are not considered for calculating the benchmark). The annual deployment capacities are then derived based on a linear extrapolation over a five-year period of 2025-2030. All component deployment needs are expressed in final product deployment capacities (GW_{el}/annum).

⁴ This deployment level is based on POTEnCIA internal technical parameters which differ from the ones used in this analysis, therefore explaining the gap in deployment level from the same target of hydrogen production.

Table 4. EU manufacturing benchmark for 2030

Final products	Component	Production Capacity Units	EU Manufacturing Capacity	EU annual Deployment needs 2030	2030 EU Manufacturing Capacity Benchmark [%]	Notes
ALK	Stacks	GW _{el} /annum	3.8	6.5	58 %	
ALK	Separators	GW _{el} /annum equivalent	20	6.5	308 %	Conservative estimates as two manufacturing sites have been identified but only one with manufacturing capacities.
ALK	Electrodes	GW _{el} /annum equivalent	2.35	6.5	36 %	Conservative estimates as four manufacturing sites have been identified but only two with manufacturing capacities.
PEMEL	Stacks	GW _{el} /annum	4.25	10.7	40 %	
PEMEL	PTL/GDL	GW _{el} /annum equivalent	1	10.7	9 %	

Note: for components other than stack, the production capacity is given equivalent to the final electrolysis capacity. It should be recalled that the 2030 benchmark exercise relies on highly uncertain assumptions. These results should be considered as rough estimations of potential bottlenecks, but further monitoring and refinement of the data and models will improve the accuracy of this assessment in subsequent years.

Source: (European Commission. Joint Research Centre, Bolard et al., 2025)

The manufacturing of electrolyzers and fuel cells consists in the final assembly of cells into one stack and can also include the integration of the stack with the auxiliary components as listed in **Figure 3**. In the CETO report published in 2025⁵, JRC analysis concludes that the EU companies are well positioned both in the EU and global market, although they face increasingly fierce competition from global competitors (European Commission. Joint Research Centre, Weidner et al., 2025; European Commission. Joint Research Centre, Bolard et al., 2025). When it comes to electrolyzers, EU's global share has seen a relative decline, due to the faster pace of announcements elsewhere, and other factors affecting the overall cost competitiveness of hydrogen. European-made

⁵ This analysis will be updated in the forthcoming 2026 of the Clean Energy Technology Observatory report on water electrolysis and hydrogen in the European Union.

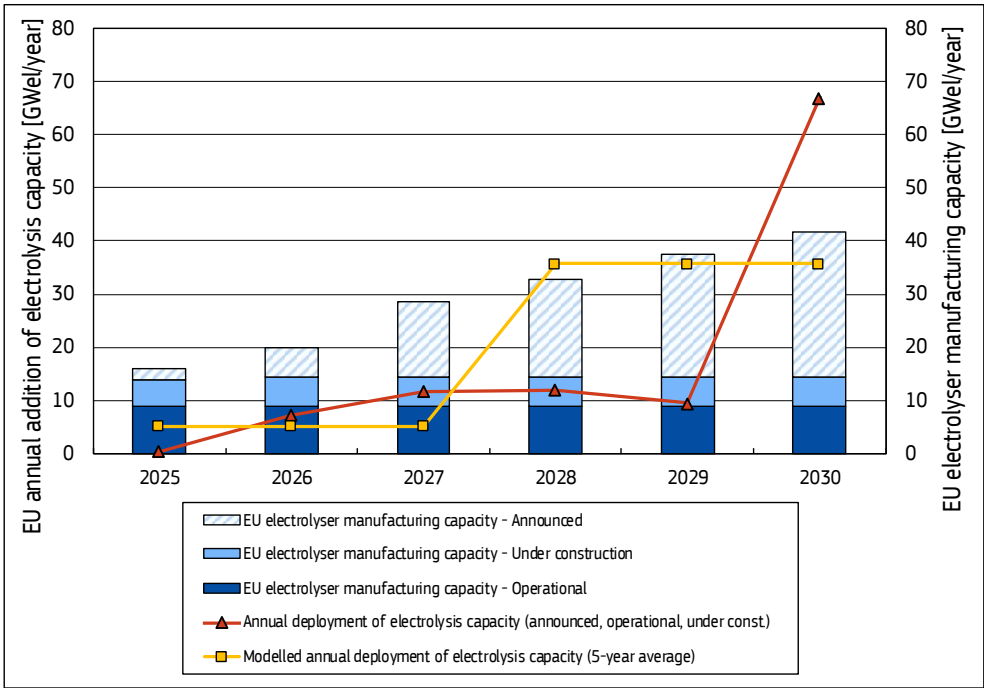
electrolysers often carry a higher price tag than Chinese alternatives, attributed to higher labour and energy costs.

At the end of 2025, conservative estimates based on publicly confirmed data indicate an EU operational manufacturing capacity of water electrolysers of approximately 8.9 GW_{el}/year. Most of EU’s manufacturing capacity is dedicated to PEM electrolysis, with approximately 4.2 GW_{el}/year, followed by alkaline (3.8 GW_{el}/year), SOEC (0.9 GW_{el}/year), and AEM (0.03 GW_{el}/year). In addition to this operational capacity, 5.4 GW_{el}/year of capacity were planned to be commissioned by the end of 2025. Manufacturing capacity could reach approximately 41.7 GW_{el}/year by 2030 considering all announcements from companies. These estimates represent the process of assembling cells to produce electrolyser stacks but does not necessarily consider the manufacturing of all BoP components. Most importantly, these estimates are based on announced nameplate capacities and do not represent the actual production of factories.

All factories within the EU are accounted for, independently of the headquarter location of the owning company. This is a conservative estimate compared to other analyses, particularly those from Hydrogen Europe, which predict an operational manufacturing capacity of around 12 GW_{el}/year (EU27, EFTA, UK) (Hydrogen Europe, 2025b). The discrepancy can be attributed to assumptions regarding the actual starting dates and whether the full scale of announced capacities, such as Siemens Energy’s projected 3 GW_{el}/year (Siemens Energy, 2023), is accurately accounted for.

Figure 12 illustrates the EU’s manufacturing capacity relative to the projected annual increase of water electrolysers based on estimates from the IEA. This highlights the disparity in utilisation rates, ranging from a low-capacity factor of 5 % (if all EU projects deploy EU-made electrolysers) to a potential shortage in manufacturing capacity, should all announced projects become operational by 2030 under optimistic projections and if they deploy only EU-made electrolysers.

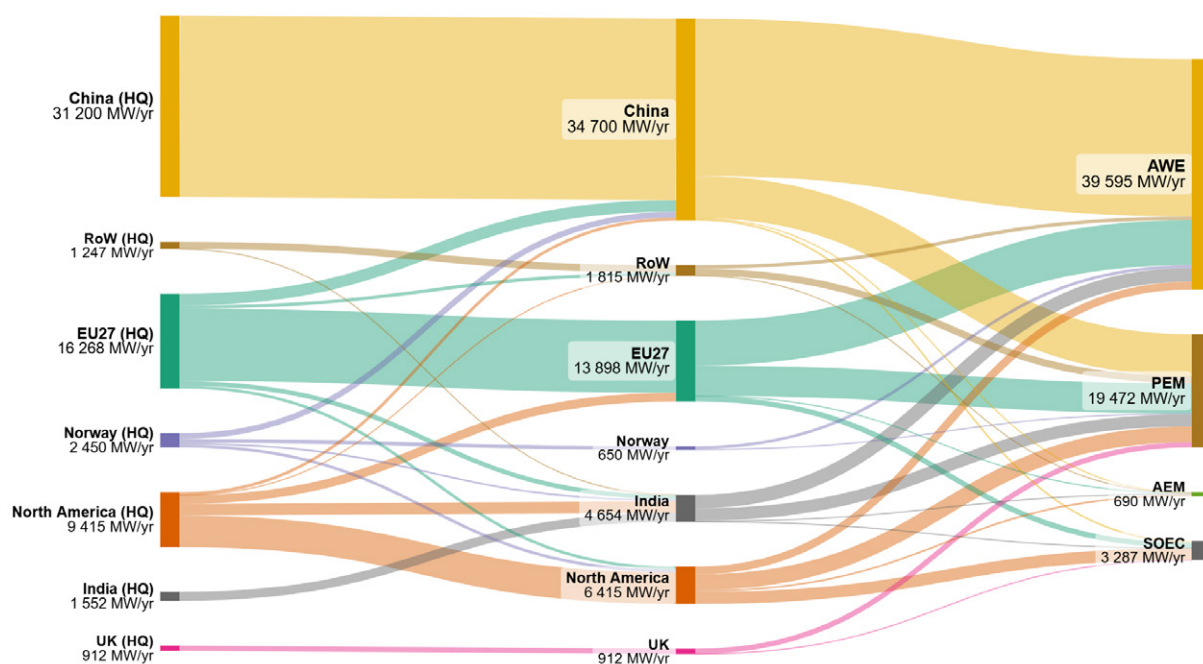
Figure 12. Manufacturing capacity versus annual added electrolysis capacity in the European Union



Source: Joint Research Centre analysis based on manufacturing capacity data from Rystad Energy, Enerdata, manufacturer websites. Modelled capacity based on POTEnCIA CETO 2025 Scenario as a 5-year average centred around 2025 and 2030. Annual added capacity based on IEA data. (2025)

Global electrolyser manufacturing capacity in operation or under construction by the end of 2025 is estimated to reach approximately 63 GW_{el}/year (European Commission. Joint Research Centre, Bolard et al., 2025)**Error! Reference source not found.** Most of the capacity (34.7 GW_{el}/year, 55.1 %) belongs to factories located in China. The EU capacity (in operation and under construction) represents approximately a quarter (13.9 GW_{el}/year, 22.1 %) of the global capacity. **Figure 13** below shows the relationship between the location of manufacturer headquarter and factories as of November 2025. It seems that all Chinese companies deploy manufacturing capacity in China, while approximately 2 GW_{el}/year of capacity from European companies are actually located in China.

Figure 13. Headquarters (left) versus factory locations (middle) and technology breakdown (right) of electrolyser manufacturers in 2025.



Note: manufacturing capacities are expressed in MW_{el}/year and include factories with status labelled as “Under construction” and “Operational”. Sankey produced with sankeymatic.com

Source: JRC analysis based on data from Rystad Energy and Enerdata (European Commission. Joint Research Centre, Bolard et al., 2025)

Figure 14 provides a selection of identified companies’ locations in the EU at member state level. This indicates that besides the production of raw materials, most of the processing steps of the value chain are covered in Europe (including EU member states, EEA countries and neighbouring countries).

Data on fuel cells manufacturing are scarce. However, the EU manufacturing capacities of fuel cell was estimated at approximately 1 GW_{el}/annum in 2025 (European Commission. Joint Research Centre, Weidner et al., 2025).

3. Materials demand analysis

An assessment of future materials demand for renewable and low-carbon hydrogen technologies (electrolysers and fuel cells) has been performed. This chapter describes the methodology, parameters, assumptions, and results of this modelling exercise. The materials gross demand is then compared against the global production of each material to understand the criticality of supply at material level.

3.1. Scenarios description

This sub-chapter presents the choice of scenarios, modelling assumptions and parameters. In line with previous reports, this work opted for the consideration of two scenarios discriminated by the intensity of innovation in hydrogen technologies compared to a benchmark set to today's market structure. The two scenarios are the following:

- The **BASE** scenario considers that the performance of current systems (electrolysers and fuel cells), sub-technology market share, as well as today's reported materials intensity are stationary or, in the case of materials intensity, slowly decreasing following the most conservative estimates.
- On the other hand, the **INNO** scenario considers intense technological improvement and the emergence of sub-technologies currently in low TRL in the case of electrolysers. The performances of systems are improving faster, and the materials intensities follow the most optimistic projections.

3.1.1. Targets of hydrogen production and vehicle stocks

The projections of electrolyser and fuel cells systems deployment are derived from targets provided by external energy scenarios. Those targets include the required annual hydrogen production produced by electrolysis, and the stock of fuel cells vehicles in circulation. Both **BASE** and **INNO** scenarios use the same targets, as an analysis of the sensitivity of material demands following different energy scenarios is out of scope of this report. As described above, only the degree of innovation and its effect on the criticality of materials supply for hydrogen technologies is considered in this chapter.

3.1.1.1. Hydrogen production targets

Hydrogen production targets are extracted from two JRC in-house energy system scenarios:

1. The annual hydrogen production targets (in million tonnes of hydrogen per year) are provided by POLES-JRC for the United States, China, and Global region (European Commission. Joint Research Centre., 2018);
2. The annual hydrogen production target for the EU regions are provided by the POTEnCIA model (Mantzos et al., 2017).

The two scenarios are then reconciled for the exercise, as indicated below in **Table 5**.

Table 5. Electrolytic hydrogen production target in million tonnes.

Model	Scenario	Region	Unit	2025	2030	2040	2050
POLES-JRC	GECO2025 1.5C	Global	MtH2	1.76	20.75	116.49	273.38
POLES-JRC	GECO2025 1.5C	US	MtH2	0.04	2.69	13.90	30.21
POLES-JRC	GECO2025 1.5C	CN	MtH2	0.55	0.59	17.08	38.05
POTEnCIA	CETO2025	EU	MtH2	0.12	4.22	21.28	36.43

Note: the numbers are projections of energy models and does not represent actual deployment data. For an estimation of electrolyser deployment projects in EU based on announced project pipelines, see (European Commission. Joint Research Centre, Bolard et al., 2025)

Source: POLES-JRC GECO 2025 scenario (European Commission. Joint Research Centre et al., 2026) and POTEnCIA CETO-2025 scenario (European Commission. Joint Research Centre, Neuwahl et al., 2025).

3.1.1.2. Targets for operational FCEV fleet

Similarly, the new operational FCEV stock levels are provided by the same models and scenarios. PEM fuel cell deployment projections for transport applications until 2050 (in million vehicles in operation) have been extracted from two JRC scenarios similarly to the targets on electrolytic hydrogen production capacity:

- POLES-JRC 2025 scenarios for global, the United States of America and China regions
- POTEnCIA 2025 model for the EU region.

Table 6. Stock targets of operational fuel cells vehicles.

Model	Scenario	Region	Unit	2025	2030	2040	2050
POLES-JRC	GECO2025 1.5C	Global	Million vehicles	0.29	7.26	101.2	299.79
POLES-JRC	GECO2025 1.5C	US	Million vehicles	0.08	2.49	25.68	39.90
POLES-JRC	GECO2025 1.5C	CN	Million vehicles	0.02	1.32	25.85	71.32
POTEnCIA	CETO2025	EU	Million vehicles	0.016	0.269	3.591	9.168

Note: these stock targets are derived from 2025 scenarios. Preliminary results from future projections to be published in the 2026 CETO editions show a significant shift of the market share towards heavy-duty vehicles, while the overall stock of vehicles diminishes. The consolidated results were, however, not available for use in the current analysis.

Source: POLES-JRC GECO 2025 scenario (European Commission. Joint Research Centre et al., 2026) and POTEnCIA CETO-2025 scenario (European Commission. Joint Research Centre, Neuwahl et al., 2025).

3.1.2. Sub-technology market share

3.1.2.1. Electrolyser technologies

The deployment curves of water electrolyzers (expressed in installed gigawatts of input electrical power) are derived from the annual electrolytic hydrogen production targets set in the energy scenarios by region and decomposed by market share of electrolysis sub-technology. This decomposition follows market shares per region presented in **Table 7** below and then extrapolated differently for each scenario. In the EU, PEM systems are dominating the market (expressed in the nominal power input), while alkaline systems are favoured in China and the rest of the world. Forecasting future market shares of sub-technologies is a difficult exercise, as there is no observed trend when it comes to prioritising one design over the other in each industrial setting. Further research will be needed on this front.

- In the **BASE** scenario, the market shares are set as constant to 2030 values. The market remains dominated by historically established technologies and the proportions calculated in the 2030 benchmark regional market shares remain stationary until 2050.
- On the other hand, the **INNO** scenario is calibrated to the benchmark market share for 2030 and then considers the emergence of lower TRL technologies like SOEC and AEM over the years until 2050 across all regions. The extent to which lower TRL technologies (SOEC and AEM) are gaining market share is arbitrarily set to reach 15 % for each technology⁶. The share of AEM technology increases at a slower pace than SOEC systems. This is to acknowledge that AEM technology is still lower TRL than SOEC when it comes to industrial deployment but is expected to catch up in industrial setting by 2050 when both technologies will be deployed equally.

Table 7. 2030 Market share benchmark per sub-technology for each region

Region	AEM	Alkaline	PEM	SOEC
CN	0.08%	95.01%	4.90%	0.00%
EU	0.24%	34.22%	64.69%	0.85%
US	0.00%	60.67%	39.27%	0.06%
Global	0.17%	72.73%	26.03%	1.07%

Note: These market shares are calculated based on hydrogen projects disclosing information about the type of electrolyzers currently in operation or planned for installation as of 2025.

Source: Joint Research Centre calibration based on data collected by Rystad Energy (Rystad Energy, 2025)

The resulting extrapolation of capacities, considering the technical performance of systems are presented in **Figure 16** and **Figure 17** in the results section.

⁶ These assumptions are based on expert judgement for the purpose of this study and are not calibrated to actual projects announcements or any modelling projections.

3.1.2.2. Fuel cell technologies

Only PEM fuel cells (PEMFC) are considered in this analysis. PEMFCs currently dominate fuel cell deployment across transport, resulting in larger scale manufacturing capacity, more extensive global supply chains and significantly larger dependence on raw materials such as platinum and fluorinated polymers.

This analysis considers 3 market segments using PEMFC: passenger cars, light-commercial vehicles and heavy-duty vehicles. The energy scenarios are used to calculate the deployment curve of each market segment.

The fuel cell systems differ substantially across these main transport segments due to different operational and performance requirements. For example, the passenger car PEMFC systems prioritise compactness, high power density and low platinum loading under strong cost constraints, while LCV systems require increased durability and operational flexibility for commercial fleet use. HDV PEMFC systems are characterised by significantly higher power demand, long operational lifetimes, robust thermal management and comparatively higher platinum loadings, reflecting the requirements of continuous heavy-duty operation in trucks and buses.

The absolute number of vehicle stocks and associated market share for the EU and at global level are described in the following **Table 8** and **Table 9**.

Table 8. EU fuel cells vehicle stocks [millions of vehicles]

EU FC stock data (POTEnCIA CETO 2025)	2025	2030	2040	2050
Passenger cars	0.014	0.180	2.212	5.667
LCV (Light commercial vehicles)	0.000	0.029	0.710	2.154
HDV (Heavy duty vehicles) - trucks and buses	0.002	0.060	0.669	1.346
TOTAL	0.016	0.270	3.591	9.168

Source: JRC POTEnCIA model – CETO 2025 scenarios (2025)

Table 9. Global fuel cells vehicle stocks [millions of vehicles]

Global FC stock (GECO2025 1.5C Scenario)	2025	2030	2040	2050
Passenger cars	0.22	6.09	83.74	241.82
LCV (Light commercial vehicles)	0.02	0.60	7.51	24.72
HDV (Heavy duty vehicles) - trucks and buses	0.05	0.57	9.96	33.25
TOTAL	0.29	7.26	101.20	299.79

Source: POLES-JRC model – GECO 2025, 1.5 scenario (2025)

3.1.3. Technical performance of each sub-technology

3.1.3.1. Electrolysers

Each sub-technology is characterised by different set of technical parameters with 2 objectives:

1. The model needs to translate the hydrogen production target per sub-technology into installed electrolysis capacity
2. The model needs to compute the decommissioned capacity due to degradation.

This exercise considers 3 technical parameters to model the technical performance of electrolysers:

1. The electrolyser stack energy consumption
2. The electrolyser stack lifetime
3. The electrolyser system capacity factor

The electrolyser stack **energy consumption (kWh/kg)** represents the amount of electrical power required to produce one kilogram of hydrogen. The values considered for this analysis are listed in **Table 11** and **Table 12** for each technology and scenario. The values are based on the Clean Hydrogen Joint Undertaking Strategic Research and Innovation agenda (Clean Hydrogen Joint Undertaking, 2022) with different trajectories for both scenarios:

- The **BASE** scenario considers that current state-of-art values of the SRIA are stationary from today until 2050.
- The **INNO** scenario sets the 2020 state-of-art values reported in the SRIA until 2025 and considers that the most ambitious targets set to be reached by 2030 in the SRIA are met by 2050. This accounts for the slower-than-expected development of the sector.

The electrolyser stack **lifetime (hours)** corresponds to the number of hours before the operator decides to decommission the system⁷.

To evaluate lifetime values, data on electrolysers collected by Rystad Energy directly from OEM data specifications was used (Rystad Energy, 2025). The dataset contains information about 485 systems, among which 219 alkaline, and 207 PEM⁸. The dataset contains standard, technical

⁷ This lifetime does not represent the duration after which the system cannot operate anymore, but an economic tipping point after which the cost of operation grows larger than the cost of replacing the system. It is therefore up to the project developers to conciliate the loss of efficiency, thus increasing the required electricity necessary to produce a given volume of hydrogen, against the price of decommissioning and replacing the electrolyser stack. Since OEMs are shipping electrolysers globally, the weighted average was processed homogeneously considering all OEMs without distinguishing per region of manufacturing.

⁸ These specifications are based on manufacturers claims and to the best of our knowledge, have not yet been confirmed in industrial operational settings. Most of the systems -especially in the range beyond 10-20 MWs, have been installed quite recently and have not experienced enough operational time to reach their end-of-life, except in the case of malfunction. There are numerous efforts on Accelerated Stress Test looking at how much these systems degrade. Most OEMs provide information expressed in number of total hours the system can be operational, or lifetime. This parameter is however a very strong simplifying assumption. In real settings, system will not just stop working after a given number of hours but will slowly degrade according to technical or environmental conditions. (for further information, see (European Commission. Joint Research Centre., 2024)).

information about the models, nominal power capacity, lifetime (in hours), water consumption energy consumption, and efficiency at stack or system level (see (Bolard et al., 2024) for more information about how to compare these values). The weighted average of lifetime values, shown in **Table 10**, is calculated then rounded to provide a baseline.

- In the **BASE** scenario, the weighted average values provided in **Table 10** are considered stationary over the years.
- In the **INNO** scenario, the lifetime will increase from today's weighted average and converges toward the weighted 75th percentile of the values which will be reached by 2050. This represents that the industry -as a whole- pushes innovation homogeneously and converges towards the higher end of performance of all designs due to innovation diffusion.

Table 10. Weighted average of electrolyser systems' lifetime as reported by OEM

Count of models per lifetime value				
Lifetime (hours)	AEM	ALK	PEM	SOEC
8000	0	5	0	0
10000	0	0	1	0
30000	1	0	0	0
35000	0	0	5	0
43800	0	0	0	1
50000	1	0	0	0
70000	0	0	1	0
80000	1	21	12	0
90000	0	1	0	0
100000	0	9	0	0
160000	0	2	0	0
200000	0	3	0	0
Calculations				
Count of unique systems	36	219	207	22
Count of unique systems with information on lifetime	3	41	19	1
Weighted average of reported lifetime per sub-technology	53333	88537	63947	43800
Weighted 75th percentile of reported lifetime per sub-technology	80000	100000	80000	-

Note: For the SOEC technology, we completed the data with modelled values from the literature, considering the results obtained from Beyrami and colleagues who modelled the long-term performance of solid-oxide cells and concluded that a potential performance of 50 000 hours at a current density of 0.6 A/cm² (Beyrami et al., 2025).

Source: publicly available systems specifications collected by Rystad Energy (Rystad Energy, 2025)

The system **capacity factor** represents the share of hours the electrolyser is being operated at its nominal capacity (full-load hours). This is a simplifying assumption because electrolyser systems, as many other electrical systems are usually not operated steadily at their nominal power, but can also fluctuate according to the consumption or production profile required by the system they are integrated with. For example, an electrolyser system deployed in a chemical plant would likely be operated at a given and steady power rate, while electrolyser deployment for grid balancing services or powered by renewable electricity sources would operate under a varying profile.

In both **BASE** and **INNO** scenario, this capacity factor is set to 70 % stationary over the years. This means that all electrolyzers are considered to operate during approximately 6136 hours each year at their nominal capacity. The reason behind is that this parameter does not only depend on the design of the system itself, but rather on the economics of each project or the source of the electricity. These aspects are defined by assumption at the energy-system level and are considered therefore outside of the scope of this chapter. They can also be impacted by regulations such as (RFNBO).

Table 11 and **Table 12** summarise the chosen parametrisation used for the modelling of the materials demand projections for the **BASE** and **INNO** scenario.

Table 11. Parametrisation of electrolyser technologies in the BASE scenario

Technology	Parameter	2025	2050
Alkaline electrolysis	Energy consumption (kWh/kg)	50	50
	Lifetime (h)	89000	89000
PEM electrolysis	Energy consumption (kWh/kg)	55	55
	Lifetime (h)	64000	64000
SOEC electrolysis	Electrical energy consumption (kWh/kg)	40	40
	Lifetime (h)	43800	43800
AEM electrolysis	Energy consumption (kWh/kg)	55	55
	Lifetime (h)	53333	53333

Source: Joint Research Centre own elaboration based on SRIA and Rystad Energy (2026)

Table 12. Parametrisation of electrolyser technologies in the INNO scenario

Technology	Parameter	2025	2050
Alkaline electrolysis	Energy consumption (kWh/kg)	50	48
	Lifetime (h)	89000	100000
PEM electrolysis	Energy consumption (kWh/kg)	55	48
	Lifetime (h)	64000	80000
SOEC electrolysis	Electrical energy consumption (kWh/kg)	40	37
	Lifetime (h)	43800	50000
AEM electrolysis	Energy consumption (kWh/kg)	55	48
	Lifetime (h)	53333	80000

Source: Joint Research Centre own elaboration based on SRIA and Rystad Energy (2026)

3.1.3.2. Fuel cell deployment trends

In the case of fuel cells for mobility applications, the deployed capacity is estimated on average by the size of each fuel cell per market segments (passenger cars, light-commercial vehicles, heavy-duty vehicles), the utilisation rate of each vehicle segments, as well as the durability of each fuel cell systems.

Similarly to electrolyzers, the lifetime of the fuel cells expresses the number of hours the fuel cell can be operated before it becomes economically viable to replace it. It is converted into years of utilisation based on the lifetime of the fuel cell and divided by the utilisation rate of the vehicles each year.

Nominal power of each fuel cell design differs according to each application, with heavy-duty vehicles requiring systems of higher power for example. **Table 13** below presents the selected technical parameter for the estimation of the deployment trajectories.

Table 13. Technical parameter of fuel cell systems for BASE and INNO scenarios

Market segment	Parameter	Unit	2025	2050
Passenger Cars	Lifetime	h	4000	4000
LCV	Lifetime	h	4000	4000
HDV	Lifetime	h	15000	15000
Passenger Cars	Nominal power per vehicle	kW/unit	110	110
LCV	Nominal power per vehicle	kW/unit	50	50
HDV	Nominal power per vehicle	kW/unit	250	250
Passenger Cars	Utilisation rate	%	5	5
LCV	Utilisation rate	%	10	10
HDV	Utilisation rate	%	25	25

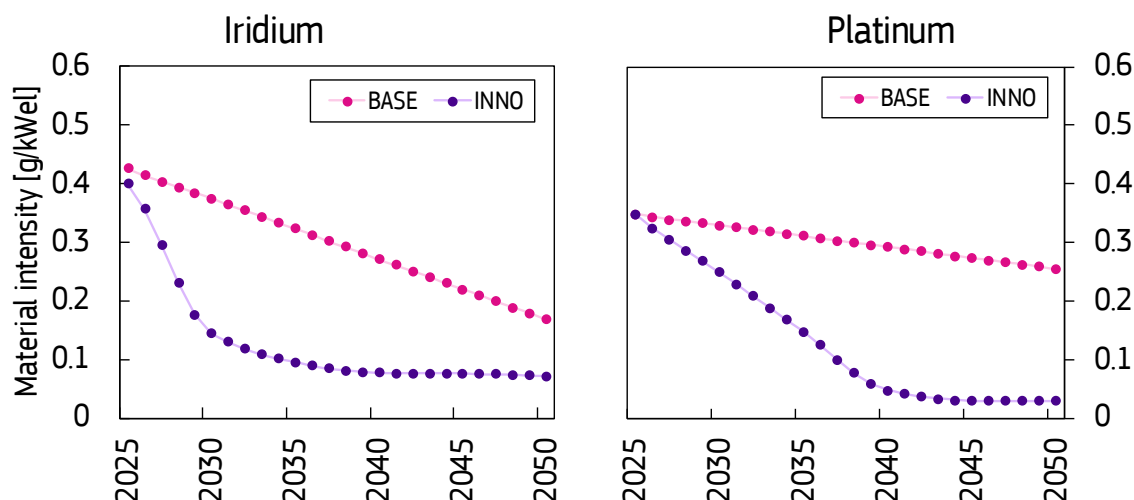
Source: (Clean Hydrogen Joint Undertaking, 2022; FCH2JU, 2018)

3.1.4. Materials intensity of hydrogen technologies

The material intensity represents the mass of materials required to build per unit of power input (kg/MWe or tonnes/MWe), either for electrolyser or fuel cells systems. This parameter is required to estimate the demand of materials given a deployment trajectory expressed in MWe. Actual numbers from industrial designs are difficult to retrieve, as manufacturers do not usually share this proprietary information. Moreover, designs are still maturing across all technologies, although alkaline and PEM electrolyzers appear to be more stable compared to SOEC and AEM designs. The values used for this report are collected from the literature and scarce industry reports. They provide realistic ranges but are expected to vary significantly across regions and manufacturers.

The detailed description and associated sources of the material intensities used for the calculations of the total materials demand (Chapter 3) and circularity assessment (Chapter 4.1) are provided in Annex 1. **Figure 15** below shows the trajectories for the iridium and platinum intensities of PEM electrolyzers to illustrate the differences between the BASE and INNO scenarios.

Figure 15. Parametrised material intensities for iridium and platinum of PEM electrolyzers in BASE and INNO scenarios.



Source: authors' analysis based on references reported in Annex 1 (2026)

The material intensities of AEM electrolyzers systems are not considered in this assessment. For AEM, the long-term ambition of technology development for AEM electrolysis excludes the use of CRMs (Clean Hydrogen Joint Undertaking, 2022) and this analysis considers as a first-order approximation that the development of AEM systems will not significantly increase the material security risks at scale.

Since the fuel cell assessment focuses specifically on mobility applications, only platinum is accounted for in the material demands of FC systems.

3.2. Results

3.2.1. Resulting deployment of electrolyser and fuel cell capacities

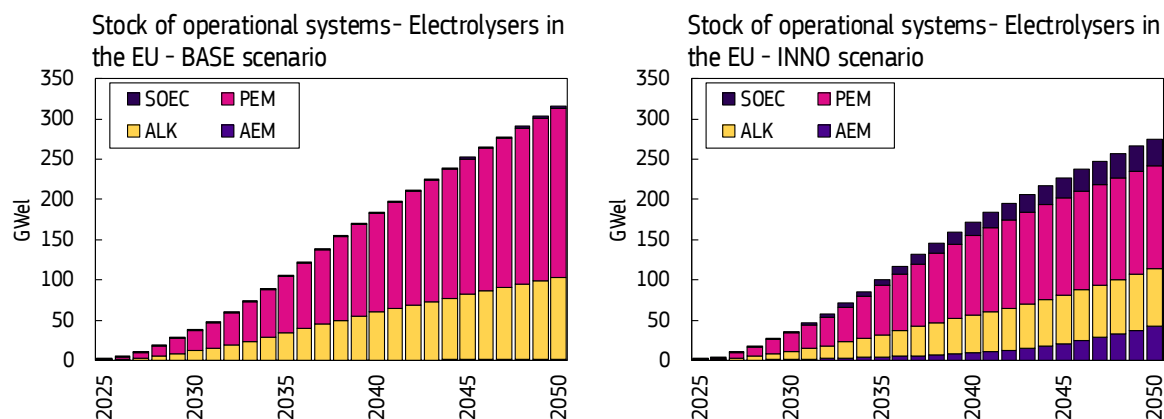
The deployment projections are calculated based on the required capacity needed to reach the electrolytic hydrogen production targets considering the market share and technical parameters for the EU, US, CN and at global level.

In the case of electrolytic hydrogen and as derived from the benchmark values (**Table 7**), PEM electrolyzers are the dominant technology in the EU. The EU total projected installed capacity reaches 36 GW_{el} in 2030 and 315 GW_{el} by 2050 in the BASE scenario (**Figure 16**) and reaches 35.7 GWe and 275 GWe by 2030 and 2050 respectively in the INNO scenario (**Figure 17**). At global level, the capacity required to reach the 2030 and 2050 target are 173 GWe and 2 281 GWe respectively for the BASE scenario, and 170 GWe and 2 066 GWe for the INNO scenario⁹. The gap

⁹ Again, those trajectories are calculated to reach the hydrogen production targets of the considered 2025 scenarios and cannot be considered as forecasts based on the announced project pipelines (which is significantly lower). In the context of this report analysis, those rather optimistic projections therefore represent a worst-case scenario when it comes to material needs and related risk of material supply.

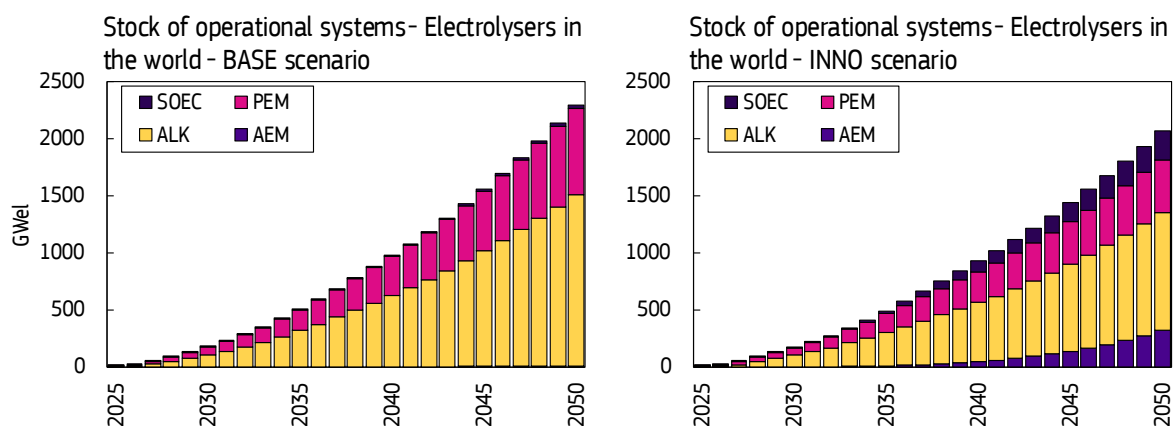
between deployment trajectories is explained by the differences in energy efficiency between scenarios as less capacity (expressed in input nominal power) is required to produce the same amount of hydrogen when using more efficient systems¹⁰.

Figure 16. Projected stocks of operational electrolyser systems (expressed in capacity) in the EU and decomposed by sub-technology in the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026)

Figure 17. Projected stocks of operational electrolyser systems (expressed in capacity) in the world decomposed by sub-technology in the BASE (left) and INNO (right) scenarios.



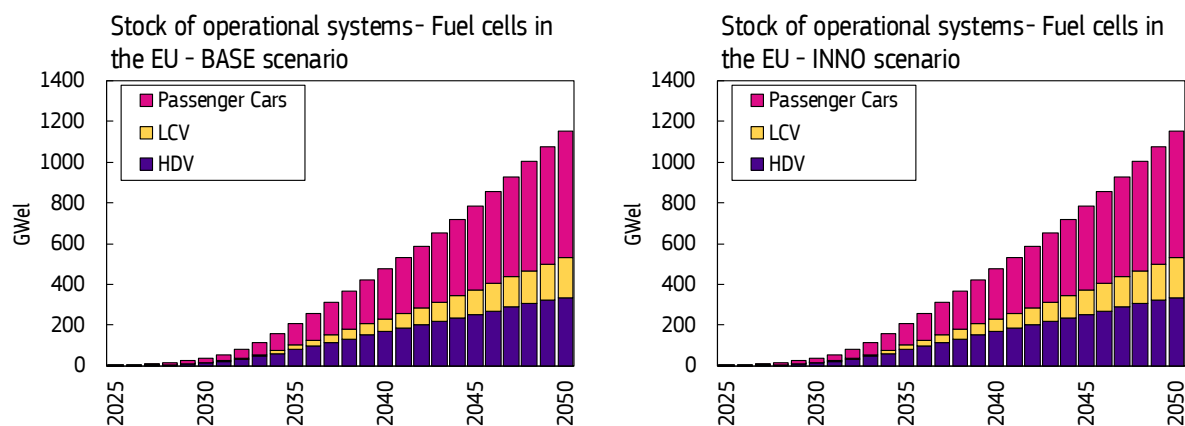
Source: authors' analysis (2026)

Similarly, the projected fuel cells capacities by technology type are calculated to reach the stock targets from the selected energy models, considering the power density range of fuel cells by market segment (**Figure 18** and **Figure 19**). The projected deployed capacities of fuel cells in scenarios are the same because both scenarios assume the same technical performances and only differ in the material intensities. In the EU, more than 36 GWeI and more than 1000 GWeI of fuel cell capacity is in operation by 2030 and 2050 respectively. At global level, more than 860 GWeI and

¹⁰ Further explanations and considerations related to power input and hydrogen output are given in (Bolard et al., 2024)

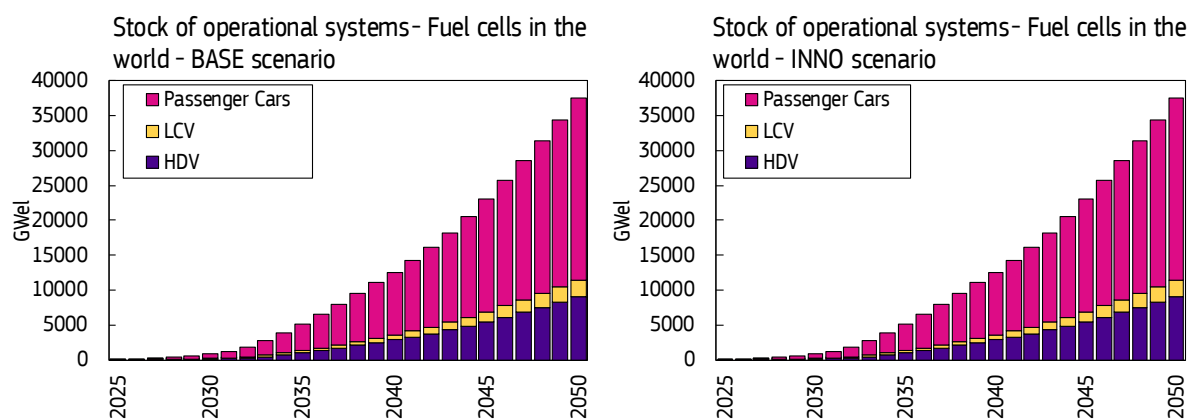
37 500 GW_{el} of capacity compose the operational stocks by 2030 and 2050 respectively¹¹. In both scenarios, passenger cars are the dominating segment for fuel cells applications in both the EU and the world.

Figure 18. Projected stocks of operational fuel cell vehicles (expressed in capacity) in the EU and decomposed by market segment in the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026). Note: both scenarios are shown for exhaustiveness but as abovementioned, they use the same set of technical parameters and therefore represent the same deployed capacity projections.

Figure 19. Projected stocks of operational fuel cell vehicles (expressed in capacity) in the world and decomposed by market segment in the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026). Note: both scenarios are shown for exhaustiveness but as abovementioned, they use the same set of technical parameters and therefore represent the same deployed capacity projections.

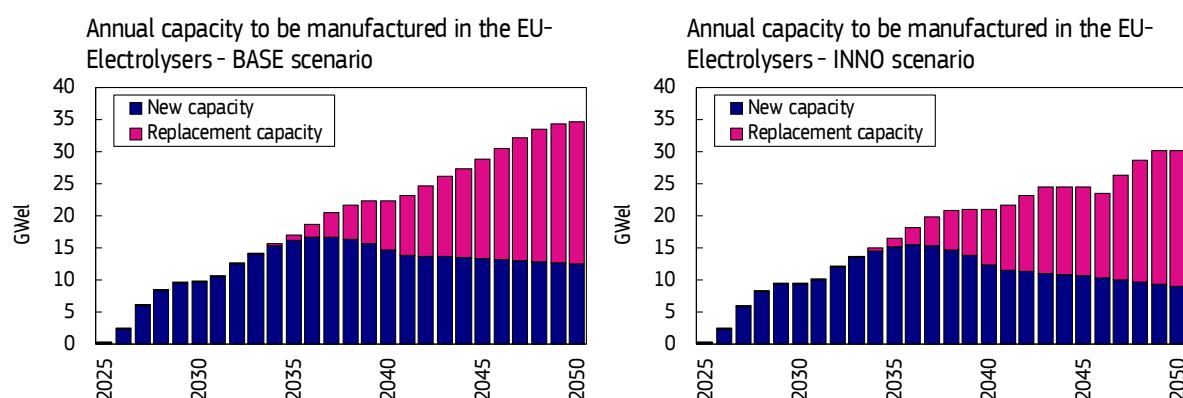
¹¹ The deployment level of fuel cell systems for both BASE and INNO scenarios are identical since they follow the same energy scenarios and technical performances.

3.2.2. Resulting annual manufactured capacities

To estimate the quantities of materials required to build the required stock capacities, it is necessary to calculate the annual flow of new systems to be built each year. This annual capacity is composed of both the additional capacity to be installed to increase the total stock, and the capacity required to replace the decommissioned systems after they reach their end-of-life. The model calculates those capacities automatically considering that not all systems installed in a given year degrade the same way and are decommissioned at the same time, as described in greater details in Annex 2.

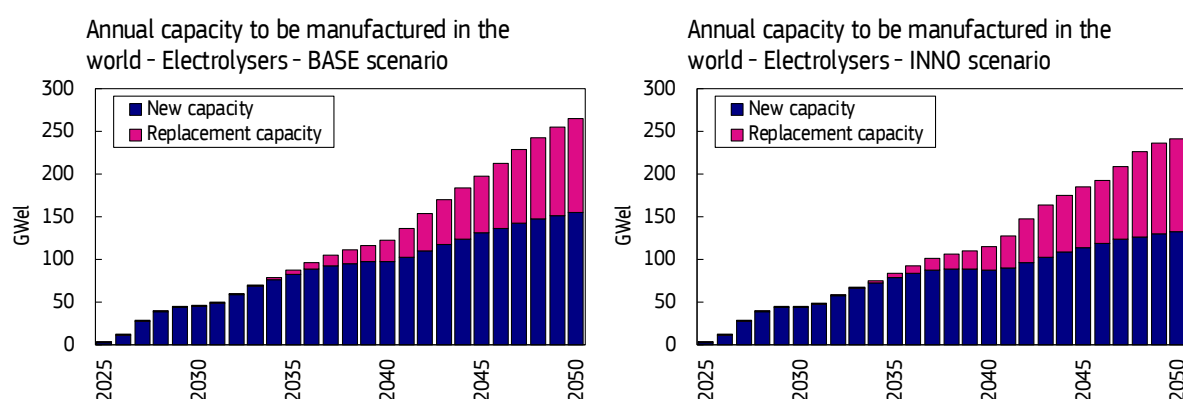
As shown in **Figure 20**, the EU needs to manufacture approximately 10 GW_{el} of electrolyser systems every year by 2030, increasing to approximately 35 GW_{el} by 2050. In the world, approximately 50 GW_{el} of capacity needs to be manufactured from 2030 onwards, up to 233 – 257 GW_{el} capacity by 2050 for the **INNO** and **BASE** scenarios as shown in **Figure 21**.

Figure 20. Annual total electrolysis capacity to be manufactured decomposed by additional and replaced capacity due to decommissioning in the EU [GW_{el}] in the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026)

Figure 21. Annual total electrolysis capacity to be manufactured decomposed by additional and replaced capacity due to decommissioning in the world [GW_{el}] in the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026)

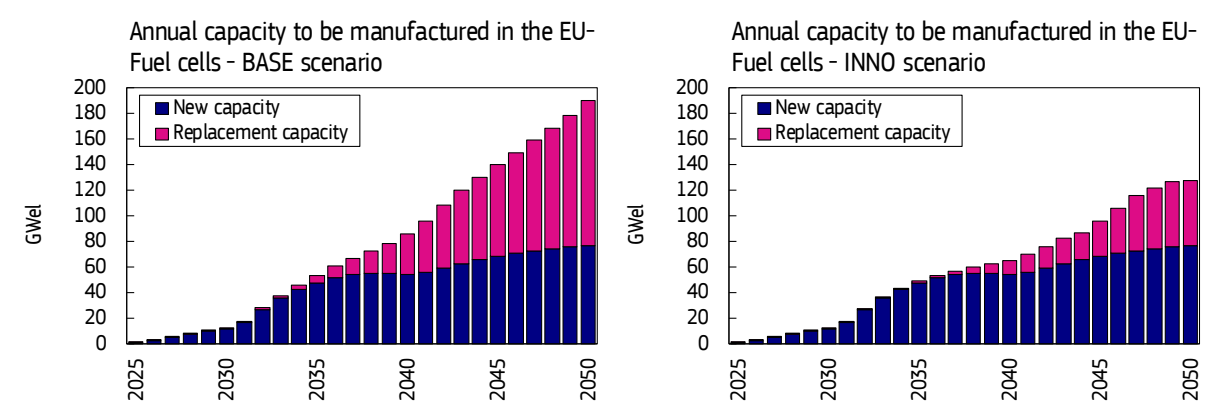
Across all regions, the share of new systems required to replace decommissioned electrolysers is noticeable only from 2030 onwards, as systems deployed in the early 2020s start to reach their

end-of-life. It is worth noting that this replacement capacity will be the primary source of recycled materials in a closed-loop recycling design. The evaluation of primary and secondary supply of materials is assessed in the chapter 4.1.1 which focuses on the role of circularity/recycling measures as a main lever for the security of supply of materials.

The annual manufacturing of fuel cells follow the same trend. As shown in **Figure 22**, approximately 11.2 - 11.4 GW_{el} of FC systems need to be manufactured annually by 2030 in the EU, increasing to 189.4 GW_{el} for the **BASE** scenario and 127.5 GW_{el} for the **INNO** scenario by 2050. In the world, the model projects approximately 259 GW_{el} by 2030 and 6 007 GW_{el} by 2050 for the **BASE** scenario, while the **INNO** scenario projects needs of annual manufactured capacities of 255 GW_{el} by 2030 and 4 404 GW_{el} by 2050, as shown in **Figure 23**.

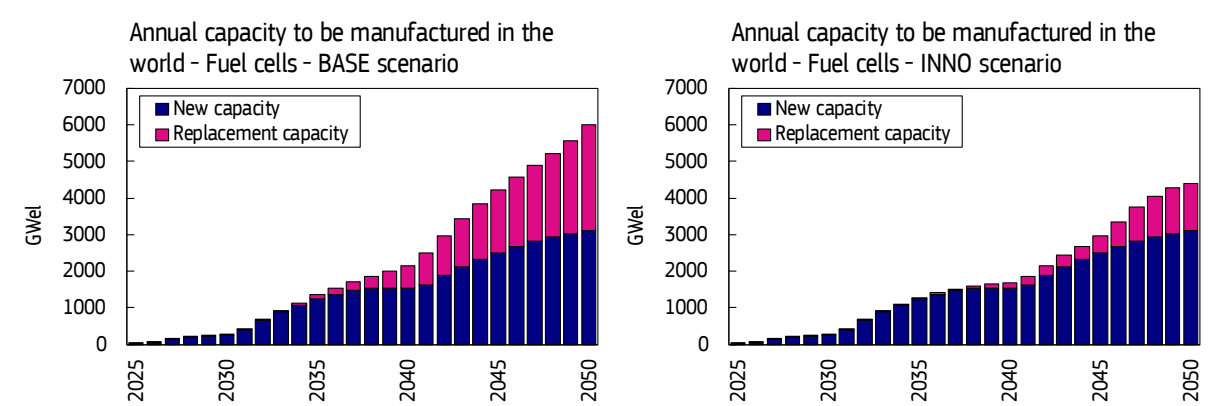
Similarly to electrolyzers, the availability of secondary materials in a closed-loop recycling architecture will increase together with the volume of decommissioned systems, as calculated in those projections.

Figure 22. Annual total fuel cells capacity to be manufactured decomposed by additional and replaced capacity due to decommissioning in the EU [GWel] for the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026)

Figure 23. Annual total fuel cells capacity to be manufactured decomposed by additional and replaced capacity due to decommissioning in the world [GWe] for the BASE (left) and INNO (right) scenarios.



Source: authors' analysis (2026)

3.2.3. Resulting gross materials demand

The annual manufacturing needs calculated in the previous section allows now to evaluate how much material is required each year. This chapter only focuses on the gross material demand and does not distinguish between its source of supply. As stated above, materials can be newly mined (primary) or sourced from decommissioned systems (secondary materials in closed-loop architecture) or sourced from other streams of secondary materials (open-loop architecture). These aspects as well as the role of circularity measures in reducing the needs of primary materials are tackled in greater details in chapter **4.1**, which uses another model for dynamic material flow analysis.

As already stated in chapter 3.1.4, the considerable uncertainty embedded in the scenario definitions and the material intensities requires us to consider the **BASE** and **INNO** scenarios as a realistic range in one, common energy scenario. The gross material demands of selected materials for both scenarios are presented in **Table 14** and **Table 15** for the EU and world respectively.

Table 14. Annual material demand for both scenarios at EU level (tonnes/year)

	2025		2030		2050	
Material	BASE	INNO	BASE	INNO	BASE	INNO
Iridium	0.1	0.1	2.4	0.8	4.2	0.9
Nickel	74.2	72.8	4040.1	2406.0	7368.4	2594.0
Platinum	0.1	0.1	3.2	2.5	15.8	6.8
Titanium	31.6	31.2	1399.0	485.2	2125.5	258.0
Zirconium	5.2	4.2	309.7	189.7	928.4	261.1

Source: authors' analysis (2026)

Table 15. Annual material demand for both scenarios at global level (tonnes/year)

	2025		2030		2050	
Material	BASE	INNO	BASE	INNO	BASE	INNO
Iridium	0.4	0.4	5.5	1.9	16.3	3.7
Nickel	1104.5	1083.7	38344.0	27316.3	128425.7	44577.4
Platinum	1.3	1.2	27.2	25.2	325.1	221.8
Titanium	248.9	246.0	3179.8	1125.5	8304.3	1049.6
Zirconium	77.1	62.7	2939.4	2154.2	16181.7	4486.2

Source: authors' analysis (2026)

For a better assessment of the criticality of supply of the selected materials, those demands are expressed comparatively to their respective estimated global supply indicated in **Table 16**. This global supply is the total production made available to all sectors and does not solely represent the supply of materials for hydrogen technologies only.

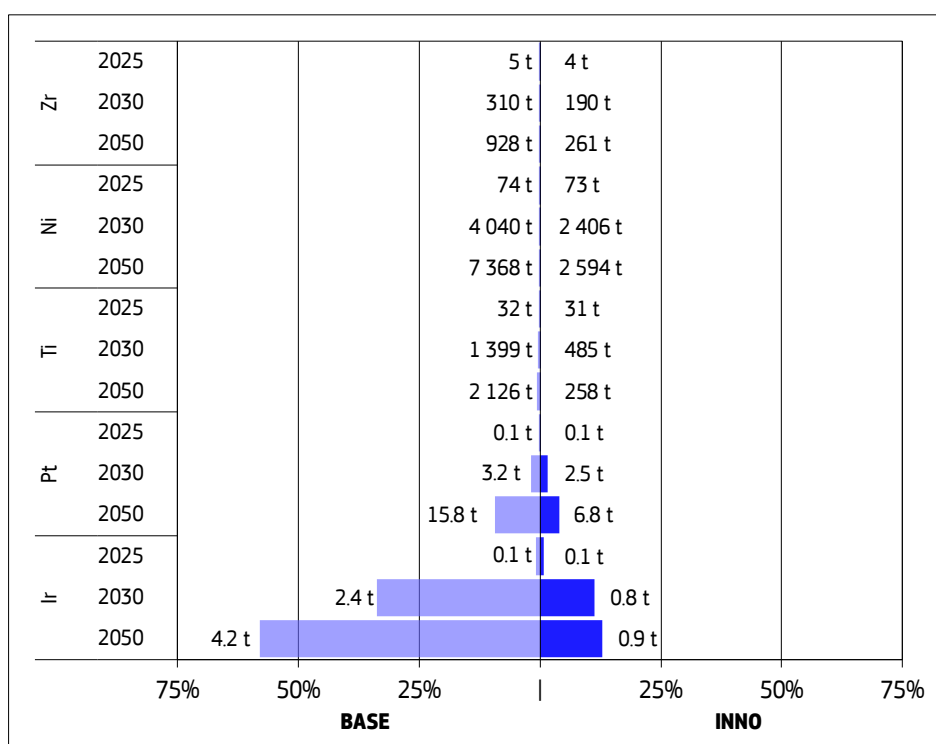
Table 16. Reference values for the calculation of share of EU and global material demands for hydrogen technologies.

Material	Global production or refining capacity [t/year]	Parameter	Reference year	Source
Iridium	7.92	Global primary Iridium produced	2022	(Joint Research Centre, 2026a)
Platinum	170	World mine production (estimated)	2025	(USGS, 2026a)
Titanium	370 000	World titanium sponge production	2025	(USGS, 2026a)
Nickel	3 900 000	World mine production (estimated) (Class 1 + Class 2)	2025	(USGS, 2026a)
Zirconium	1 386 000	Global primary Zirconium produced	2022	(Joint Research Centre, 2026b)

Source: indicated in the table.

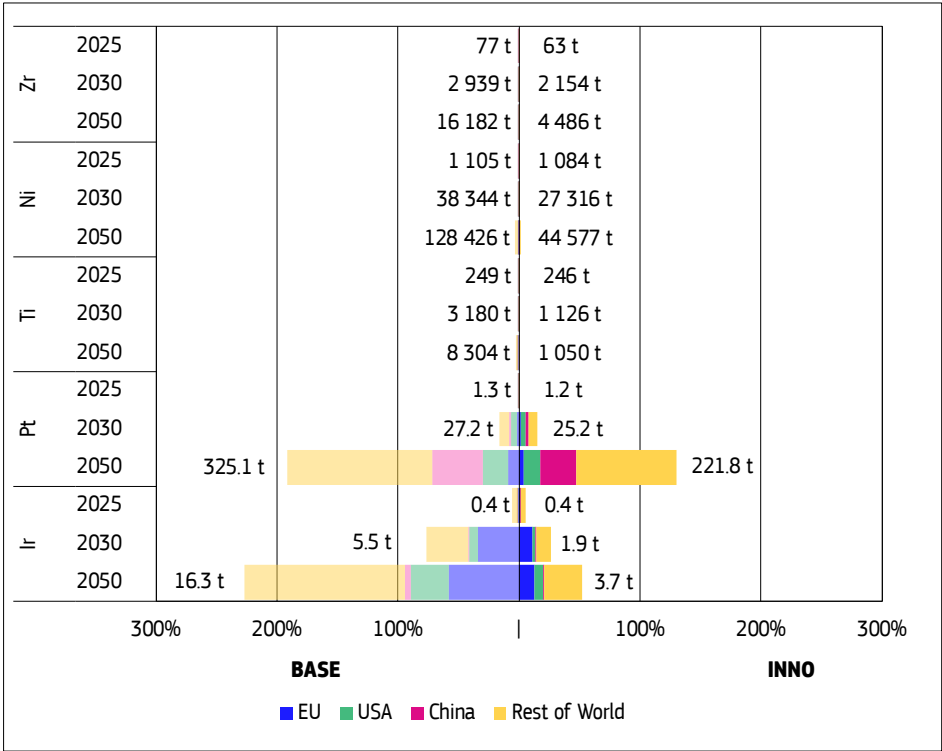
Figure 24 indicates the comparative needs of material for the deployment of hydrogen technologies in the EU, while **Figure 25** shows the same calculations for the world region.

Figure 24. Material demand projections of key raw materials for the European Union



Source: authors' analysis (2026). Note: the horizontal axis represents the calculated share of estimated annual demand each year against today's global supply of the raw materials as indicated in **Table 16**. Values on the left side of the graph represent the demand in the BASE scenario, while values in the right side of the graph represent the demand in the INNO scenario.

Figure 25. Material demand projections of key raw materials for all regions



Source: authors' analysis (2026). Note: *ibid*.

The evaluation of material demands against the estimated global supply shows that of the 5 key materials considered (nickel, zirconium, titanium, iridium, platinum), two PGMs (iridium and platinum) are likely to experience constraints on the supply in projected deployment level.

In the most conservative scenario (BASE), the EU iridium demand for PEM electrolyser deployment represents more than 33 % of today's global supply by 2030 and exceeds 50 % by 2050. At global level, the pressure on iridium is also strong with an estimated global demand of more than 225 % of today's global supply by 2050 in the BASE scenario. The INNO scenario maintains however the EU demand below 25 % by 2050 and the global demand around 50 % of the total supply (see exact shares in **Table 17**).

At global level, platinum holds a risk of supply bottleneck, driven by the significant FCEV deployment projected across all regions, with a demand of almost 200 % of today's global supply of platinum by 2050 in the BASE scenario, and more than 125 % in the INNO scenario. Although the share of EU demand compared to the global supply seems less alarming due to a smaller projection of FCEV deployment in the EU, it would still likely experience competition for accessing platinum resources from other regions (see exact shares **Table 17**).

Table 17. Relative share of material demands over the global production or refining capacity in the reference year.

Scenario	BASE				INNO			
Material	Iridium		Platinum		Iridium		Platinum	
Year	2030	2050	2030	2050	2030	2050	2030	2050
EU	34%	58%	2%	9%	11%	13%	1%	4%
World	77%	227%	16%	191%	26%	52%	15%	130%

Source: authors' analysis (2026)

The supply of titanium sponge does not seem to represent a risk in this assessment, with projected EU demands of not even 1 % of supply and global needs reaching 2 % of the global supply by 2050 in the BASE scenario. However, it is not clear how much of capacity reaches aerospace-grade quality, which might be required for some electrolyser components.

Current alkaline designs do not have the same exposure to the criticality of supply when it comes to nickel or zirconium, with EU demand for 2030 and 2050 projected to not even reach 1 % of 2025 global supply. However, this analysis does not distinguish between Class 1 and Class 2 nickel as no data on material needs from OEM was available for the analysis. This would require however further investigation.

However, this criticality addressed at the level of material supply should be considered carefully. Bottlenecks at processed materials and component supply might be experienced on the supply chain of both alkaline and PEM electrolysers. As an example, as seen in the **Chapter 2** for alkaline technologies, only one company (Agfa) located in Belgium manufactures the Zirfon-based diaphragm used in almost all European designs. Similarly, the abundance of sponge titanium does not capture any potential technical bottleneck when it comes to the transformation into semi-finished or finished products like bipolar plates for PEM electrolysers.

4. Mitigation measures

4.1. Potential of implementing circularity and resource efficiency strategies for materials in hydrogen technologies

Circularity is an important pillar of the Clean Industrial Deal, which aims to reduce waste and extend the life of materials by promoting recycling, reuse, and sustainable production. Maximising the EU's limited resources and reducing overdependencies on third-country suppliers for raw materials is crucial for a competitive and resilient market (European Commission, 2025b).

In parallel, the Critical Raw Materials Act (Regulation (EU) 2024/1252) provides the broader framework for securing the EU's access to strategic and critical materials, while also accelerating permits for recycling projects. The forthcoming Circular Economy Act announced in the Clean Industrial deal (European Commission, 2025b) aims at stimulating demand for secondary materials and improving the efficient use and reuse of resources such as critical raw materials, contributing to reduce global dependencies and stronger EU industrial capacity.

Electrolysers and fuel cells rely on critical and strategic raw materials such as platinum and iridium, whose supply is highly concentrated and exposed to disruption risks. In this context, this section analyses the circularity and resource efficiency measures such as material efficiency, recovery, recycling and the use of secondary raw materials that can strengthen supply resilience.

These measures are increasingly important because the scale-up of hydrogen technologies like electrolysers is expected to generate growing volumes of materials containing platinum group metals, for which recycling loops in the EU are still not yet fully established. Recycling potential will only be available in a time-horizon compatible with the lifetime of the electrolysers being deployed (European Commission. Joint Research Centre, Bolard et al., 2025). Recycling infrastructure for the collection, dismantling and processing of the relevant products, components and materials needs to be put in place in time to reach the highest possible benefit from recycling and circularity.

The findings of the analysis presented in this chapter require further consolidation and substantiation, particularly for the uncertainties related to projections.

4.1.1. Circularity strategies

This chapter presents strategies for materials in hydrogen technologies, focusing on levers consistent with the circular economy, notably recycling, material recovery, and lifetime extension, while also incorporating selected resource efficiency measures where these directly support circular outcomes. Resource efficiency aims to reduce material use per unit of output and can also enable circularity by lowering waste generation and preserving material value. **Table 17** summarises strategies and levers to increase the circularity and resource efficiency of electrolyser and fuel cell stacks.

Reduce, reuse, and recycling of stacks were identified by stakeholders across the value chain as the most promising strategies (Axt et al., 2025). Higher strategies in the hierarchy, such as refuse and rethinking, were deemed unsuitable, as the deployment of hydrogen technologies must expand substantially to meet climate, industrial competitiveness, and energy security targets. Refurbishing and remanufacturing effectively involve recycling when applied at the stack level. Repair also shows limited potential for stacks since possibilities for repairing degraded electrodes, catalysts, or membranes are limited due to compact and complex system design, while design for repair is not

yet state-of-the-art (Gramc et al., 2025). Replacement or reactivation of degraded electrodes might be possible for alkaline electrolyzers, whereas the design of PEM stacks is less favourable for repair as the catalyst material is coated (be it on the membrane or on the GDL) (Matz et al., 2024).

Moreover, it has been highlighted that PEM technology is difficult to repair due to the corrosive environment, making recycling preferable over repair (Axt et al., 2025). Finally, given the lifetime of the stack, repair and reuse of components might not be viable due to changes in technology composition and performance (Matz et al., 2024). Energy recovery, including incineration treatments, was also discarded because it does not address the recovery of key raw materials.

Table 18. Summary of strategies and levers to increase circularity and resource efficiency of hydrogen technologies.

Strategy	Lever	Impact
Reduce (consume less through efficient manufacturing or use)	Substitute material	A material is substituted with another that can deliver similar functionality
	Material efficiency	Amount of material per unit of capacity (material intensity) decreases over time due to technological improvements
	Extend lifetime	Technologies remain longer in use due to improved design and operating conditions that lead to improved durability
	Reduce manufacturing losses	Improved manufacturing processes and maximised internal reutilisation of new scrap
	Increase recycled content	Decrease in the consumption of primary raw materials while increasing the incorporation of recycled materials
	Technology shift	Prioritise technologies with lower or no requirements for some key raw materials
Reuse (reuse of functioning discarded products by another use)	Reuse stack sub-components after reconditioning	Reusing stack sub-components at their EoL after minimal reconditioning
Recycling (processing to obtain the same or lower quality materials)	Increase EoL collection rates	Share of decommissioned capacity diverted to recycling increases with higher collection rates
	Increase efficiency of stack disassembly and materials sorting	Reduce EoL losses and increase the amount of material effectively diverted to recycling
	Advanced recycling technologies	The amount of recovered secondary materials and their quality increase with more advanced recycling technologies

Source: authors' analysis (2026)

This section focuses specifically on the circularity of the five key raw materials contained in electrolyser technologies, aligned with the scope of this report. Therefore, technology shift is outside

the scope of this analysis and is further addressed in section **4.2** as well as the material substitution as it is considered a specific mitigation measure according to the criticality assessment methodology ((European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., 2017)). The reuse of stack sub-components after reconditioning was also discarded since this lever is not relevant for the selected raw materials (electrode catalysts have a low reuse potential due to degradation). Notably, components made of stainless steel show the highest potential for reuse if not yet excessively degraded (Gramm et al., 2025; Bargiacchi, 2022), yet stainless steel is not within the scope of this report.

4.1.1.1. Increase material efficiency

Material efficiency strategies aim to reduce material use while maintaining the same technology performance, efficiency, and durability. A review of the existing literature on projected material intensity for electrolyzers suggests substantial potential for large reductions in the future (**Table A1**).

Significant research has focused on reducing the amount of platinum and iridium per geometric cell active area without compromising performance or durability (Salonen et al., 2021). PGM requirement depends primarily on catalyst loading. Opportunities for better utilisation of platinum are large, including particle optimisation, higher mass activity, better manufacturing of catalyst-coated membranes (e.g., better dispersion of platinum on the membrane, better formation of the catalyst layer, and optimisation of the catalyst ink recipe), or partial substitution with alloying material (Bargiacchi, 2022). Literature projections suggest declines in the platinum intensity of PEM electrolyzers from current levels of 0.30–1.0 kg/MW to 0.03–0.59 kg/MW in the medium term (**Table A1**).

Similarly, iridium loading can be reduced by maximising iridium utilisation, with literature projections indicating a potential decline from current levels of 0.34–2.5 kg/MW to 0.04–0.40 kg/MW in the near term (**Table A1**). While very low iridium intensities can be achieved under short term testing, such levels may not be sustained over the operational lifetime of a MEA due to catalyst degradation. Therefore, the upper bound of projected ranges appears to represent a more realistic target (Clapp et al., 2023).

Titanium use in PEM electrolyzers can also be reduced by decreasing the thickness of bipolar plates and PTL (Bargiacchi, 2022). The literature suggests that titanium bipolar plates thickness could decrease tenfold, from 3 mm to 0.3 mm, enabled by a shift in manufacturing process from milling or etching thick base material toward forging thin sheet metal (Bareiß et al., 2019). Similarly, PTL thickness could be substantially reduced from current values of around 0.1 cm to 0.03 cm (Kiemel et al., 2021). Such reduction in component thickness would translate into a substantial decrease in titanium intensity, from current levels of 165–528 kg/MW to as low as 35 kg/MW in the near term (see **Table A1**).

The substantial amount of nickel used in alkaline electrolyzers can be reduced by using thinner mesh wire or nickel-based alloys in the electrodes that require lower nickel content. While the extent of potential reductions achievable remains uncertain, the literature suggests a wide range of current nickel intensities ranging from 200 to 2 885 kg/MW, which could potentially decrease to 200–794 kg/MW in the near term (**Table A1**). In addition to nickel, current commercial zirconium-based diaphragms for alkaline electrolyzers, such as Zirfon, contain about 54–100 kg of zirconium per MW (**Table A1**). Projections of future reductions in zirconium loading remain scarce, although some studies in the literature have assumed a decline of 50 % by 2035 (Eikeng et al., 2024).

Finally, since SOEC are relatively less mature, data availability on their current material intensities is rather scarce, and future projections almost inexistent. Reported nickel intensities vary widely across the literature, ranging from 46 kg/MW in (Bargiacchi, 2022) to 150–200 kg/MW in (Price, 2023) and as high as 541 kg/MW in (Baek et al., 2025). This wide range reflects significant potential for future reductions by moving towards the lower end of the intensity range. Zirconium dioxide is used in both the solid electrolyte (YSZ) and the fuel-side electrode (Ni-YSZ), with reported intensities ranging from 21 to 27 kg/MW ((Baek et al., 2025); (Campos-Carriedo et al., 2024)).

4.1.1.2. Extend stack lifetime

Electrolysers stack lifetimes vary by technology, with current average values of around 4 years for SOEC, 8 years for PEM electrolysers, and 9 years for alkaline electrolysers (**Table A2**). These lifetimes depend on operating conditions (e.g. the capacity factor or the electrical power input profile) and are considerably shorter than those of BoP components, which can operate for up to 20 years (Barei et al., 2019). Other key components, such as compressors and hydrogen storage infrastructure, can last for 10 and 25 years, respectively (Terlouw et al., 2022). As a result, multiple stack replacements are generally required over the operational lifespan of an electrolyser system. However, advances in cell design, materials, and operating conditions could substantially extend stack lifetimes, as reflected in the existing literature (**Table A2**). Longer lifetimes would reduce the frequency of stack replacements, thereby reducing raw materials demand and delay the point at which technologies reach their EoL and materials become available for recycling. Literature projections suggest substantial but highly variable achievable extended lifetimes, with alkaline electrolyser stacks potentially reaching 14–20 years, PEM electrolyser stacks 10–20 years, and SOEC stacks 7–11 years (**Table A2**). However, these projections remain highly uncertain, as relatively few electrolyser systems (particularly PEM) have operated long enough under commercial conditions to reach their EoL and validate long-term durability assumptions.

4.1.1.3. Reduce manufacturing losses

Reduction of losses in the manufacturing of the stack and its sub-components (i.e., catalysts, bipolar plates, etc.) through improved manufacturing processes and maximised internal reutilisation of scrap would contribute to reducing the demand for raw materials. PGM catalysts manufacturing generally involve mixing a PGM precursor with the carbon support, followed by separation, drying, and reduction (U.S. Department of Energy, 2022). Catalyst layers are then deposited on each side of the PFSA membrane, with the most common deposition methods being spray coating and screen printing, while emerging methods include slot-die coating (Badgett et al., 2024). The dried catalyst coated membrane is then cut into small individual pieces that are used in the MEA. Techno-economic analyses performed by the National Laboratory of the Rockies (NLR) reported process yields of 85–90 % for ultrasonic spray coating and up to 95 % for slot die coating (Badgett et al., 2024; Mayyas et al., 2019). Thus, the process can result in 5–15 % of the input material as scrap. However, the internal recovery of scrap is generally high, achieving about 95 % recovery (Duke et al., 2026) with some sources indicating that the platinum scrap rate is reduced to less than 1 % (Battelle Memorial Institute, 2016).

Titanium-based PTLs for use in PEM electrolysers are typically produced by placing in a sintering furnace a mixture of titanium powder with adhesive powder and lubricants followed by physical vapor deposition (PVD) coating. Process yields reported by NLR range from 90 % for the sintering furnace to 90 % for the PVD coating (Badgett et al., 2024; Mayyas et al., 2019). Moreover, scrap material is assumed to be lost, but recovery is acknowledged as a potential venue to reduce costs

and fresh raw material demand. Recycling of new titanium scrap achieves efficiencies of 90–95 % (see section **4.1.1.6** below). Metal bipolar plates manufacturing involves creating channels on both sides of the sheet using stamping die, followed by PVD coating. Stamping die process yield is about 90–95 %, while PVD coating reaches 90–99.9 % (Badgett et al., 2024; Mayyas et al., 2019). Further steps of stack assembly yield depend on the type of process, ranging from 90 % for manual assembly to 95 % for semiautomated and 98 % for fully automated (Badgett et al., 2024).

Since losses in stack assembly affect several materials, overall process yields are estimated at 77–93 % for platinum and iridium and 73–93 % for titanium (by combining the yields of individual steps). This wide range suggests potential for improving process yields in the future through improved manufacturing processes such as new coating techniques (i.e., slot-die coating), more precise material cutting, reduced off-cuts, improved defect detection technologies, and fully automated stack assembly lines (Bargiacchi, 2022; Duke et al., 2026). Material losses in the manufacturing of SOEC were estimated at 20 % within the eGHOST project (Bargiacchi, 2022), but estimates indicate that material losses can be reduced to 5–10 % (Campos-Carriedo et al., 2024).

4.1.1.4. Increase EoL collection rates

EoL collection is an important source of inefficiency across many sectors due to components that do not enter the formal EU recycling system, often being exported outside the EU. For example, the current relatively low global platinum EoL recycling rate of 25–50 % is largely due to inefficiencies in car catalysts and electronics recycling and the export of EoL vehicles and electronics to countries lacking recycling infrastructure and regulation (Hao et al., 2019; Xun et al., 2020). Current EoL vehicle collection in the EU is limited by missing vehicles and exports (both legal and illegal) outside the region, with about 30–40 % of EoL missing vehicles (European Commission. Directorate General for Environment. et al., 2023) or exported vehicles outside the EU (10 %) (Baars et al., 2020). Strategies to increase EoL vehicle collection rate include product-service business models, in which fuel cell ownership remains with the manufacturer. For example, Ballard operates a model where customers return fuel cell stack to Ballard for replacement (Ballard, 2024). Similarly, Bosch employs a model agreement ensuring the company is guaranteed an option to repurchase stacks for mobile applications for recycling. Regulation (EU) 2026/1738 adopted in July 2026 on “circularity requirements for vehicle design and on management of end-of-life vehicles” also ensures requirements to improve the collection of EoL vehicles.

In the particular case of electrolyzers and fuel cells used in stationary applications, these are stationary systems with a long lifespan and high investment costs and thus are not expected to change proprietor multiple times during their lifespan (Axt et al., 2025; Kiemel et al., 2021). Under these conditions, stack collection rates of 100 % can be assumed realistic (Axt et al., 2025). However, export for recycling outside the EU is still an important risk for some of the components. Titanium PTL and bipolar plates from PEM deserve particular attention, as currently a high share of the global titanium metal scrap is shipped to the US for recycling. Notably, the EU is a net exporter of old titanium scrap, mainly to the US and UK (Buesa et al., 2025a).

4.1.1.5. Increase efficiency of stack disassembly and material sorting

Following collection, the next step in the recycling chain is dismantling the stack into its components. For PEM electrolyzers, the MEA is separated and undergoes recycling processes. Titanium bipolar plates can be separated and introduced in conventional melting processes (Kiemel et al., 2021). For SOEC electrolyzers, it involves separating the layers from the frame and separating the cell from the frame. Dismantling can be done manually or automatised, and usually

material recovery is 100 % (Kaiser et al., 2025). As an alternative to disassembly, stack components can be mechanically shredded into particles. However, this involves high energy consumption and therefore disassembly is considered as preferable (Kaiser et al., 2025).

4.1.1.6. Advanced recycling technologies

Advanced recycling technologies could contribute not only to increasing recycling efficiencies but also to expanding the range of recoverable materials and increasing their quality, thereby enabling closed-loop recycling. **Table 18** summarises key mature and emerging recycling technologies for the recovery of raw materials from electrolyser technologies.

Table 19. Mature and emerging recycling technologies for electrolyser technologies.

Component	Recycling technology	Recovered element	Recycling efficiency	Quality	Phase
Alkaline electrolyser					
Electrode/mesh	Pyrometallurgy	Nickel	85–95 %	Closed-loop	TRL9
	Hydrometallurgy + post-processing	Nickel	85–99 %	Closed-loop	TRL9
Diaphragm	Hydrometallurgy	Zirconium	90 %	Closed-loop	Early stage
PEM electrolyser					
MEA	Pyrometallurgy	Platinum Iridium	≥ 96 % ≥ 96 %	Closed-loop	TRL9
	Hydrometallurgy	Platinum Iridium	72–98 % 72–98 %	Closed-loop	TRL9
	Electrochemical dissolution	Platinum Iridium	46–95 % 46–95 %	Open-loop	Early stage
	Acid dissolution	Platinum Iridium PFSA	≥ 73 % ≥ 73 % ca. 100 %	Open-loop Open-loop	Early stage
	Solvent dissolution	PFSA	63–99 %	Closed-loop	Early stage
PTL and bipolar plates	Vacuum arc remelting (VAR)	Titanium	90–95 %	Open-loop	TRL9
	VAR + Electron beam remelting (EBR) or plasma arc remelting (PAR)	Titanium	90–95 %	Closed-loop	TRL9
	Molten salt electrolysis	Titanium	n.a.	Closed-loop	Early stage
SOEC/SOFC					
Fuel-side electrode and electrolyte	Hydrothermal + hydrometallurgy	Nickel Yttrium	90 % 90 %	Closed-loop Closed-loop	TRL5
Air-side electrode (LSC)	Hydrometallurgy	Lanthanum Cobalt Strontium	100 % 87 % 60 %	Closed-loop Closed-loop Open-loop	TRL5

Source: authors' analysis (2026)

Both pyrometallurgical and hydrometallurgical routes for recovering platinum from PEM electrolyser stacks are based on mature technologies that are already applied at industrial scale for the extraction of PGMs from spent automotive catalytic converters (Uekert et al., 2024). Closed-loop recycling of platinum at high efficiencies (≥96 % and ≥73 % for the pyrometallurgical and hydrometallurgical routes, respectively) is possible (Uekert et al., 2024), though adoption rates will depend on the future prices of platinum and the platinum content in hydrogen technologies (Rasmussen et al., 2019). Emerging recycling technologies for PEM stacks include electrochemical

dissolution, acid dissolution, or solvent dissolution. These technologies are still in early stages of development, and uncertainty regarding their recycling efficiency and product quality persists. For example, current electrochemical dissolution technologies achieve lower recycling efficiency and purity of the recovered platinum, potentially resulting in open-loop applications (Uekert et al., 2024). Acid dissolution can also recover the PFSA, but again the quality of the recovered products can be compromised. In contrast, solvent dissolution focuses on separating PFSA from the other MEA components, potentially resulting in high-quality recovered PFSA suitable for closed-loop recycling.

Most recycling technologies are studied for platinum recovery from PEMFC, raising uncertainty about their applicability to PEM electrolyser stacks' MEAs as well as the recovery of iridium. Since the general material composition of PEM electrolyser stacks is quite similar to PEMFC, in principle fuel cell recycling processes can be utilised for electrolyser recycling (Kiemel et al., 2021; Matz et al., 2024). However, electrolyser and fuel cells operate under different conditions and degradation mechanisms, resulting in different EoL states. Consequently, some modifications to PEMFC-specific recycling processes are likely to be required (Nti et al., 2026). Moreover, assumptions have been made that recovery of iridium from PEM electrolyser stacks achieves the same recycling efficiencies (Minke et al., 2021; Xun et al., 2025). However, iridium recovery may involve challenges to dissolve the highly stable iridium oxide (TNO et al., 2021).

Titanium from PEM electrolyser PTL and bipolar plates can be processed through conventional melting alongside titanium sponge for ingot production (Buesa et al., 2025a; Takeda et al., 2019). The most applied melting process is the vacuum arc remelting. However, remelting old titanium scrap containing impurities is not suitable to produce high-grade ingots required for high-end applications such as PEM electrolyser stacks (Buesa et al., 2025a). To increase the grade of the recycled titanium, the oxygen concentration in the scrap must be reduced. Pre-processing with technologies such as electron beam melting and plasma arc melting is needed before the vacuum arc remelting furnace. This combination reaches recycling efficiencies of 90–95 % (Buesa et al., 2025a; Takeda et al., 2019). Alternative technologies such as molten salt electrolysis are also studied, which can deliver a high purity product (99.94 %) suitable for closed-loop recycling (Jiao et al., 2020). However, recycling is mainly applied to new scrap, while old scrap from the aviation industry is often downcycled to ferro-titanium (Hoff et al., 2025).

Nickel from electrodes and mesh in alkaline electrolyser can be recycled with high efficiencies through well-established pyrometallurgical or hydrometallurgical processes or a combination of both. The hydrometallurgical route is in general more suitable due to higher efficiency and purity (Xun et al., 2025). For example, leaching with sulfuric acid followed by precipitation to nickel carbonate with 100 % purity (Lee et al., 2010; Valente et al., 2018). The recovered nickel carbonate requires further processing to be converted into metallic nickel that can be used in the nickel-aluminium alloy for subsequent Raney nickel production. Lab-scale experiments demonstrated up to 99 % nickel and 39 % aluminium recovery efficiencies (Lee et al., 2010), although depending on process conditions these efficiencies can range from 90 % to 99 % for nickel. Several patents have been published presenting innovative methods based on acid leaching and precipitation for recovering nickel from spent catalysts with high purity. Additional inefficiencies may arise at industrial scale, such as losses through fines or dust during mechanical pre-treatment (washing and size reduction) or losses during the subsequent stages required to produce metallic nickel. Therefore, the recovery efficiency could range from 85 % to 99 % under a very optimistic scenario.

Both pyrometallurgical and hydrometallurgical processes have been studied for the recovery of zirconium from the diaphragm (Zirfon) of alkaline electrolyser (Xun et al., 2025), although other sources have also assumed the incineration of the diaphragm due to the lack of established

recycling pathways (Hoppe et al., 2025). Studied hydrometallurgical routes include hydrochloric acid leaching, which can recover zirconium salts with high purity. Although these salts can be converted into zirconium powders via calcination and reduction with an efficiency of 90 %, it remains uncertain whether the quality is high enough to be used in a closed-loop recycling. However, this route remains in early stages of development. Overall, global zirconium EoL recycling rates remain very low at 7 % in 2020, and the associated recycling industry is just emerging, with first zirconium recycling plants established in China (the largest consumer of zirconium) not before 2012.

Due to their relatively lower TRL, recycling processes for SOE/SOFC are much less advanced than for the other technologies (Kaiser et al., 2025). However, the Best4Hy project has developed a novel hydrothermal and hydrometallurgical treatment process that can recover the electrodes with high efficiency and purity (Mori et al., 2025). The process performance at TRL5 indicates 90 % recycling efficiency for the YSZ electrolyte and nickel oxide and enough quality for closed-loop recycling.

4.1.2. Potential for secondary raw materials supply from electrolyser stacks

4.1.2.1. Material flow analysis of EU electrolyser deployment scenarios

This section analyses the future potential for secondary raw materials supply from the recycling of electrolyser stacks in the EU. A dynamic material flow analysis (dMFA) has been conducted for the key raw materials (titanium, platinum, iridium, nickel, and zirconium) under the BASE and INNO scenarios described in chapter 3. The two exercises use independently parametrised models. Electrolyser capacity deployment in the EU and the technology mix (including alkaline, PEM, and SOEC electrolysers) were taken from the BASE and INNO scenarios. Material circularity levers were modelled to reflect three scenarios: Reference (REF), Recycling (REC), and Resource efficiency and recycling (RES+REC) (**Table 19**).

Table 20. Definition of circularity levers under the three scenarios. The underlying data for each scenario is provided in **Annex 1**

Circularity lever	Reference (REF)	Recycling (REC)	Resource efficiency and recycling (RES+REC)
Material efficiency	Gradual reduction in material intensities following conservative projections	Same as Reference	Aggressive reduction in material intensities following the most ambitious projections
Extend stack lifetime	Gradual reduction following conservative projections	Same as Reference	Aggressive reduction following the most ambitious projections
Reduce manufacturing losses – process yield	Constant process yields at 80–85%	Same as Reference	Process yields increase by 2035 to 90–95%
Reduce manufacturing losses – internal scrap recovery	Internal recovery of manufacturing scrap is 90% for nickel in alkaline electrolysers, 95% for PGMs in PEM, and 0% for titanium in PEM and SOEC	Internal recovery of manufacturing scrap increases by 2030 to 95% for nickel in alkaline electrolysers, 99% for PGMs in PEM, and 90% for titanium in PEM	Same as Recycling
Increase EoL collection rate	100% collection rate (electrolyser stacks)	Same as Reference	Same as Reference

Circularity lever	Reference (REF)	Recycling (REC)	Resource efficiency and recycling (RES+REC)
Increase efficiency of stack disassembly and material sorting	100% efficiency (automatized disassembly and sorting)	Same as Reference	Same as Reference
Advanced recycling technologies	Mature recycling technologies. Recycling efficiencies remain constant: 85% for nickel, 84% for platinum and iridium, 48% for titanium, and 0% for zirconium	Gradual adoption of advanced recycling technology. Ambitious recycling efficiencies of 95–98% are achieved by 2050 (including for titanium and zirconium)	Same as Recycling

Source: authors' analysis (2026)

The total **annual demand** for all five raw materials is consistently lower in the INNO scenario than in the BASE scenario (**Figure 26**). This difference is driven by the more diversified electrolyser technology mix assumed in the INNO scenario: 31 % alkaline, 55 % PEM, and 14 % SOEC capacity by 2050, compared with 32 % alkaline, 67 % PEM, and 1 % SOEC in the BASE scenario. Cumulatively over 2020–2050, the INNO scenario reduces demand for titanium, platinum, iridium, and nickel by 16–30 % relative to the BASE (Figure 27). For comparison, implementing the most ambitious circularity levers within the BASE scenario (i.e., moving from REF to RES+REC) reduces cumulative demand for these materials by 31–51 %. These results point to the substantial reduction potential of technology shift. Yet, it should be noted that this analysis does not quantify the demand for key raw materials used in SOEC electrolyzers (e.g., yttrium).

The REC scenario has a limited effect on total annual material demand relative to the REF scenario. This is because material demand is primarily determined by electrolyser capacity deployment, technology mix, material intensities, and stack lifetimes, all of which are assumed to be the same in the two scenarios. Nevertheless, cumulative titanium demand decreases by 13 % as a result of increased closed-loop recycling of manufacturing scrap (Figure 27). While increasing manufacturing efficiency also reduces demand for the other materials, the additional savings are modest because internal scrap recovery is already relatively high in the REF scenario. In contrast, the REF scenario assumes that no titanium manufacturing scrap is recycled in a closed-loop; increasing the closed-loop recycling rate of this scrap to 90 % after 2030 substantially reduces the need for primary titanium production.

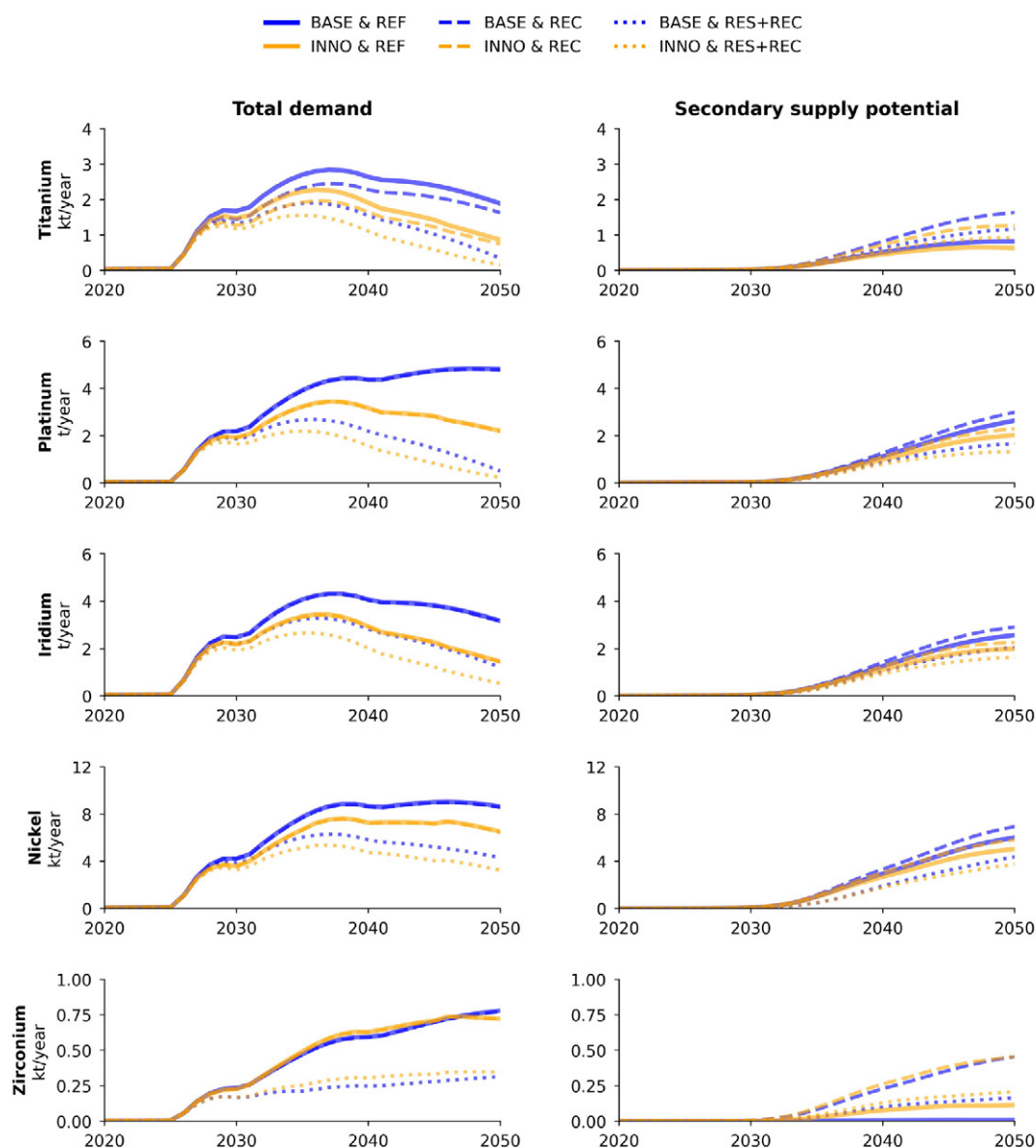
The RES+REC scenario substantially reduces total material demand after 2030, reflecting more ambitious improvements in material intensities and extended stack lifetimes. Across all materials, transitioning from the REF to the RES+REC scenario reduces cumulative material demand by 31–55 % in the BASE and by 29–48 % in the INNO. Moreover, the RES+REC scenario considerably advances the timing of peak annual demand and reduces its magnitude (Figure 26). For example, in the BASE & REF and BASE & REC scenarios, demand for platinum and iridium peaks at 4.8 and 4.3 t/year by 2048 and 2037, respectively. The RES+REC scenario advances the peak demand to as early as 2036 and reduces its magnitude to 2.7 t platinum/year and 3.3 t iridium/year. In the INNO scenario, due to the lower share of PEM electrolyzers after 2030, the peak of platinum and iridium demand is achieved by 2035–2037 under all three scenarios.

The **secondary supply potential**, considering only closed-loop recycling in electrolyzers, becomes significant only after 2035, when electrolyser stack capacity deployed between 2025 and 2030 start reaching their EoL. Differences in secondary supply potentials between the REF and REC scenarios are relatively small for platinum, iridium, and nickel. This is because the REF already

assumes high recycling efficiencies, leaving limited potential for further improvement. In the REC scenario, recycling efficiencies increase from 85 % to 98 % for nickel and from 84 % to 95 % for platinum and iridium between 2025 and 2050. The situation differs for titanium and zirconium, as their closed-loop recycling remains more uncertain. For titanium, the REF scenario assumes that only 50 % of EoL scrap undergoes advanced pre-processing technologies to produce high-grade titanium suitable for high-end applications, while the remaining 50 % is treated via conventional remelting and downgraded to lower-value applications. Increasing the share of high-grade recycling to 100 % by 2050 in the REC scenario leads to about 74 % increase in secondary titanium supply relative to the REF. For zirconium, recycling technologies are still in early stages, and the REF scenario assumes no effective recycling. In the REC scenario, introducing recycling efficiencies of up to 95 % for zirconium from alkaline electrolyzers and 90 % for zirconium from SOEC electrolyzers significantly increases the potential for secondary supply.

Secondary supply potential is consistently higher in the REC scenario than in the RES+REC scenario. In this RES+REC scenario, lower volume of stacks reaches EoL due to extended lifetimes, while the material content per stack also declines over time due to the material efficiency. Thus, the RES+REC scenario reduces both total material demand and the available secondary supply potential.

Figure 26. Total annual demand and secondary supply potential of key raw materials for electrolyser deployment in the EU over 2020–2050 in the BASE and INNO scenarios combined with three alternative lever scenarios (REF, REC, and RES+REC).

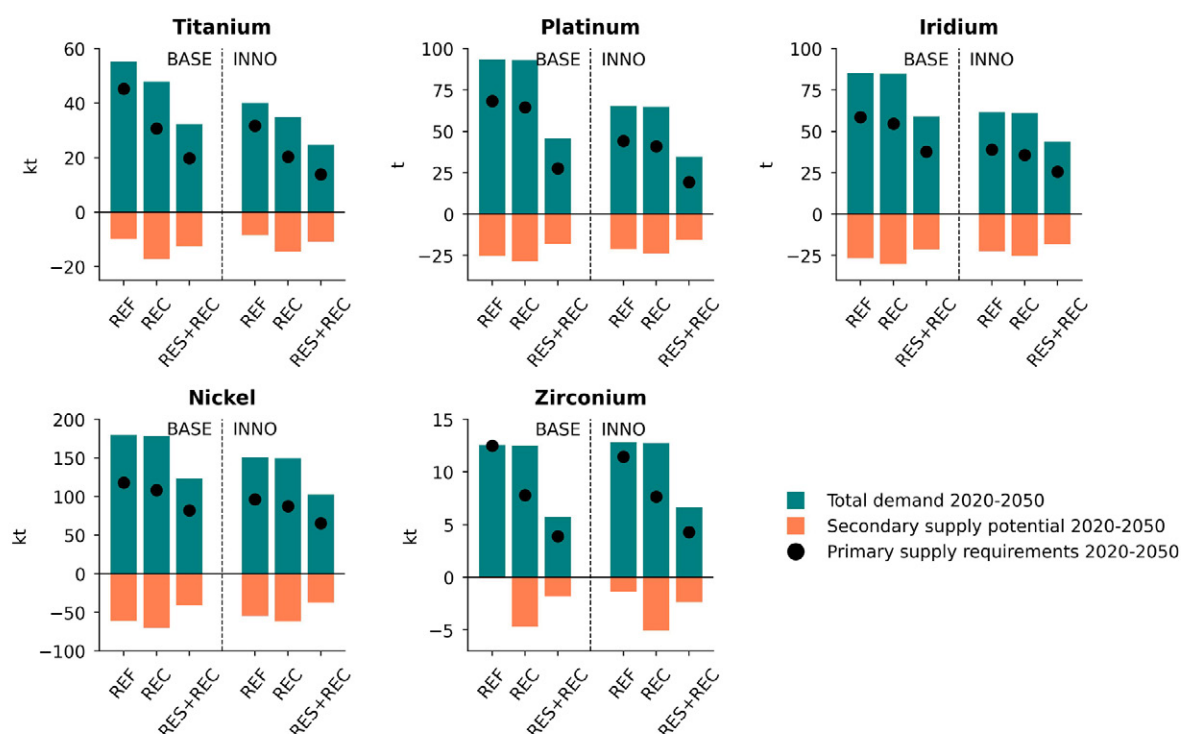


Source: authors' analysis (2026). Platinum numbers differ from the materials demand projections of chapter 3 which also considers the platinum demand for PEMFC, excluded here.

Figure 27 shows the **cumulative demand** for each raw material over 2020–2050, representing the total amount needed in the period. It also illustrates the **cumulative secondary supply potential**, defined as the amount of material that can be recovered and returned to use in a closed-loop system. The gap between cumulative demand and cumulative secondary supply potential represents net primary supply requirement; that is, the quantity that must still be provided from primary sources to meet overall demand. The cumulative results indicate that most of the material demand over 2020–2050 must still be met through primary supply, ranging from 56–82 % for titanium, 56–72 % for platinum, 58–69 % for iridium, 58–66 % for nickel, and 60–99 % for zirconium. Although the REC scenarios achieve the highest secondary supply potential, the RES+REC scenarios result in the lowest primary supply requirements because resource efficiency

measures reduce cumulative material demand. Future analyses are needed to consider the effect of other sectors and technologies using the same raw materials on demand and secondary supply balance.

Figure 27. Cumulative demand (positive values), secondary supply potential (negative values), and net primary supply requirements (difference between cumulative demand and secondary supply) of key raw materials for electrolyzers deployment in the EU over 2020–2050 in the BASE and INNO scenarios combined with three alternative circularity lever scenarios (REF, REC, and RES+REC).



Source: authors' analysis (2026)

4.1.2.2. Levers for increasing electrolyser circularity and reducing the demand of raw materials

The peak demand for key raw materials associated with electrolyzers deployment in the EU could be reached between 2035 and 2047, depending on assumptions regarding deployment levels, technology mix, material intensities, and stack lifetimes assumptions. The magnitude of these peaks is critical, as it determines the risk of future supply constraints. For all materials except iridium, peak demand remains relatively small compared with current global mine production (e.g., 4.8 t/year for platinum vs 170 t/year of current annual mine output). In contrast, peak iridium demand of 4.3 t/year in the BASE & REF scenario corresponds to 54–61 % of current global supply. Even under the RES+REC scenario, which combines rapid reductions in material intensity, extended stack lifetime, and high recycling rates, net primary iridium requirements at peak demand still amount to 36–41 % of current global production.

The recycling industry for hydrogen technologies is still at an early stage, as these systems have not yet reached EoL in significant volumes. As a result, there is currently no dedicated recycling capacity in Europe specifically for hydrogen technologies. Nevertheless, several European companies and research projects have developed patented technologies and deployed lab- and

pilot-scale plants, with most initiatives focusing on recovering high-value materials from PEM technologies. Current efforts primarily target PGMs, while a smaller number of projects also seek to recover polymer components such as Nafion/PFSA ionomers (BEST4Hy and LYDIA projects). Proposed technologies rely on combinations of mechanical pre-treatment and hydrometallurgical or chemical processing, with the technology readiness levels (TRL) ranging from 3 to 7. Beyond research projects, several companies, including Johnson Matthey (UK), Robert Bosch (Germany), and MONOLITHOS Catalysts & Recycling Ltd. (Greece), have developed patented recycling processes and/or pilot scale facilities. Certain components can potentially be integrated into existing recycling streams from other industries. For example, titanium recycling in the aviation sector. The EU melting capacity for ingot production was 11.7 kt per year in 2020, while the capacity to convert ingots into wrought titanium products was 12.5 kt per year in 2022 (Buesa et al., 2025a).

The secondary supply potential is strongly influenced by future trajectories of material intensities and stack lifetimes, as these levers reduce the volume of stacks reaching EoL and the amount of material available for recovery. Declining material intensities may also affect the economic viability of recycling infrastructure, as lower material content reduces the value of recovered materials and, consequently, the revenues generated from recycling. In addition to improving EoL recycling, reducing manufacturing losses through higher process yields and increased closed-loop recycling of manufacturing scrap should be a priority. Although manufacturing performance is already high for PGMs, for other materials such as titanium open-loop recycling of manufacturing scrap is still common, representing an opportunity to further reduce primary material demand.

Further scientific studies and more robust modelling would be needed to better assess the range of possible scenarios, test the sensitivity of the results to different assumptions, and provide a more reliable basis for future policy considerations.

4.2. Technological reallocation or materials substitution

As discussed above, among the various hydrogen technologies, PEM electrolyzers and fuel cells exhibit the highest exposure to CRMs (and PGMs in particular).

Although promises of technology development might reduce these dependencies, other sub-technologies relying on CRM-free designs might take a role, such as a traditional alkaline or emerging AEM electrolyser designs. AEM systems operate in an alkaline environment, permitting the use of steel instead of titanium (Enapter, 2026), of non-CRM catalysts (HYScale, 2026) while utilising a membrane architecture similar to PEM to enable compact, high-pressure operation.

However, current data indicates limitations regarding the immediate scale-up of this alternative. EU manufacturing capacity for AEM systems currently stands at 300 MW_{el}, despite ongoing research efforts (European Commission. Joint Research Centre, Bolard et al., 2025). Additionally, AEM stacks operating entirely without PGMs are still at a lower technology readiness level, as current commercial AEM systems still rely on noble metal catalysts (Pt seems likely to remain in current AEM designs) (Enapter, 2023; Hyter, 2026). Future regulations could introduce sub-technology criteria to prioritise the deployment of designs with lower CRM requirements. Implementing such criteria, however, would contrast with a technology-neutral regulatory approach.

There are significant R&D efforts for fuel cells and electrolyzers focusing on mitigating supply risks by substituting or drastically reducing Platinum Group Metals (PGMs) in PEM technologies (European Commission. Joint Research Centre., 2025e). Platinum substitution strategies can rely on the use of abundant transition metals, such as molybdenum and tungsten-based materials for electrolyser cathodes, or Metal-Nitrogen-Carbon (M-N-C) catalysts for fuel cells (Asset et al., 2020), though

these currently exhibit lower stability. To address the scarcity of iridium in anodes, advanced manufacturing techniques like Atomic Layer Deposition (ALD) and electrospinning of nanofibres are being developed to reduce loading to 0.1 mg/cm² or less (Frijters et al., 2023).

4.3. Strategic stockpiling of CRM

Stockpiling has received increasing attention in the recent years, including from the EU. In July 2025, the European Union released its Stockpiling Strategy as a core component of the broader Preparedness Union¹². This strategy lays down a whole-of-government integrated approach designed to secure access to essential goods across the EU. It covers a wide range of critical items, including emergency response supplies, medical countermeasures, energy equipment, and critical raw materials.

However, stockpiling should be carefully considered in the case of hydrogen technologies, where the criticality of supply seems to be limited to a specific subset of materials (mostly iridium and platinum to a certain extent due to global competition), with uneven diversity of suppliers. Implementing large-scale stockpiling of iridium for example, which is an illiquid market, could also hold significant market distortion consequences and affect the shorter-term capacity of deploying PEM electrolyzers, as warned by industry associations (Hydrogen Europe et al., 2023).

Such a strategy could be implemented at European level and leverage European Commission tools for energy or materials demand aggregation (e.g. the EU Energy and Raw Materials platform (European Commission, 2026a)) to increase bargaining power and secure long-term offtake agreements.

Stockpiling can also materialise as a standard stock management practice from the private sector where companies regularly adjust their exposure to the risk of supply while optimising their storage and production costs (IEA, 2026). Overall, companies can also be involved in storing larger amounts of materials or components to protect their operational continuity. In reality, this management seems to be nonetheless limited to medium- to large-scale companies with a steady input of standardised raw materials, as investigated in the Netherlands (Patrahau et al., 2025). Countries like NL are investigating the possibility to contract stockpiling to the private sector under public mandate under a co-finance scheme. The NL also explores the possibility to build offtake agreements with recyclers.

As described in sub-chapter **4.6**, the development of new modelling methods can also be useful to assess the impact of stockpiling on production cost. Some investigation has already been performed using game theory framework to assess the dynamic effect of CRMA policies coupled with stockpiling strategy on the price of platinum for clean technologies (Sesini et al., 2025).

¹² https://commission.europa.eu/topics/preparedness_en

4.4. Considerations on the influence of the capacity factor of electrolyzers on the materials demand

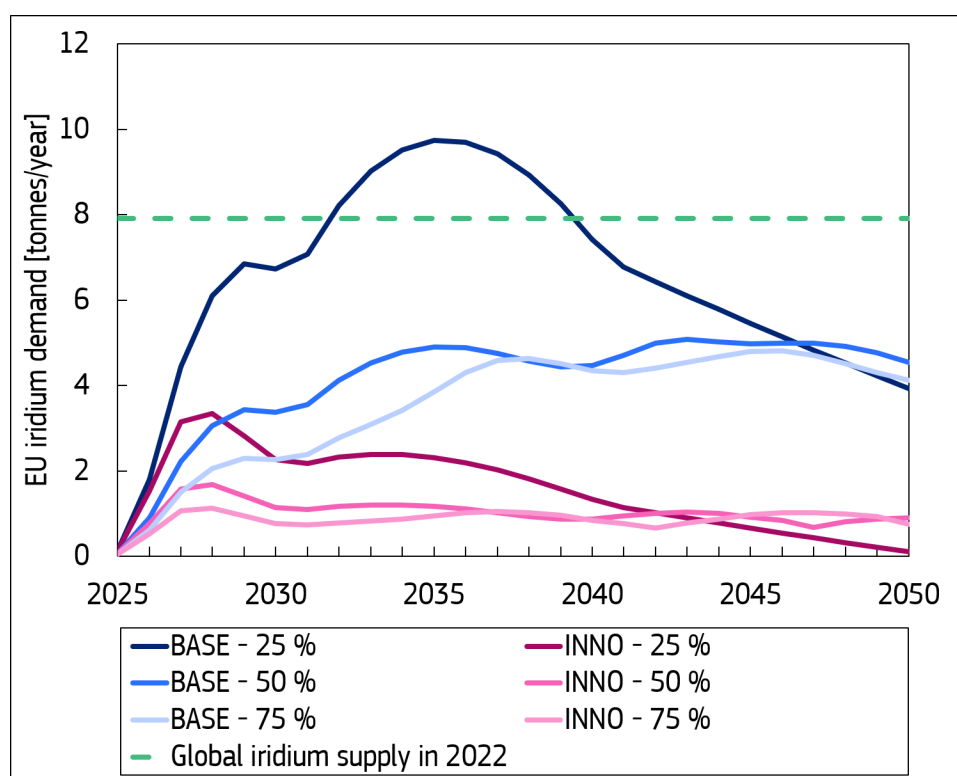
The materials demand for electrolyser deployment scales with installed capacity rather than with hydrogen output, so at the same technical performance, the capacity factor is the parameter that links the two.

On one hand, for a given annual production target, a lower capacity factor requires proportionally more installed GW_{el} , and therefore proportionally more iridium, platinum, titanium, nickel and zirconium. The capacity factor is set partly by techno-economic design choices or can partly be influenced by regulation, such as temporal correlation requirements.

On the other hand, an electrolyser being operated a smaller amount of time per year would degrade more slowly, leading to a higher lifetime and requiring to be replaced later in time. However, this also provides fewer available resources for recycling and secondary supply.

Figure 28 shows how the capacity factor influences the iridium demand in the EU. All other parameters are set to the same BASE and INNO scenarios from **chapter 3**, only the capacity factor is changed from 25 % to 50 % and 75 %. Similarly to the previous investigation, iridium demand in all BASE scenarios is overall higher than in the INNO scenarios. One exception is that the EU iridium demand in the INNO - 25 % scenario exceeds the BASE - 50 % and the BASE - 75 % demands until 2027 and 2029 respectively. The BASE - 25 % scenario exceeds the 2022 global iridium supply by 2035, showing that a capacity factory which is too low associated with today's technical performances might have consequences on the security of supply of iridium for electrolyzers.

Figure 28. Influence on different capacity factors [25 % / 50 % / 75%] in both BASE and INNO scenarios on the EU iridium demand.



Source: authors' analysis (2026)

4.5. Bill-of-materials reporting in publicly funded projects as the basis for an early warning system

Hydrogen technologies are currently experiencing a high intensity of research into new designs for both electrolyzers and fuel cells (European Commission. Joint Research Centre, Bolard et al., 2025).

The material demand projections presented in chapter 3 rest on material intensities collected from the literature, from scarce industry reports and from modelled systems, since manufacturers do not generally disclose this information. Data at component level are difficult to compile with sufficient reliability to support a manufacturing capacity assessment.

This uncertainty cannot be resolved through statistical channels in the near term. As set out in Subchapter 4.6, the institutional databases on which the Commission's dependency assessments rely (e.g. Eurostat, COMEXT, PRODCOM and TARIC) are designed for established products and do not yet resolve the trade flows relevant to electrolyser and fuel cell components, which is why the creation of new CN codes has been initiated. New codes will improve visibility over trade, but they will not reveal how much of a designated material a given system design contains, nor how many qualified vendors exist for the components in which that material is embedded.

At the same time, a substantial share of the hydrogen technologies deployed in the EU is supported by public money at some point in its development or installation: the IPCEI framework alone provided more than EUR 18.9 billion of public funds towards the hydrogen market, the Hydrogen Bank has a budget of approximately EUR 3 billion (from the Innovation Fund), and further support is provided through the Clean Hydrogen Partnership at the research and innovation stage and through the Innovation Fund at the demonstration and deployment stage. Where public funds are committed, the reporting of a bill of materials could be made a standard and consistent condition of support applied uniformly across instruments.

4.6. Development of new simulation-based criticality methodologies to assess the criticality of materials for hydrogen technologies

The hydrogen economy is a nascent industrial endeavour, and its supply chain is not mature yet with strong potential for new technologies, designs or materials to disrupt the dynamics of supply. Contrary to other established clean technologies, the scarcity of statistically meaningful data and the lack of standardised designs prevent a proper and reliable mapping of the entire supply chain (European Commission. Joint Research Centre, Weidner et al., 2025; European Commission. Joint Research Centre, Bolard et al., 2025). The European Commission's methodology used to calculate the EU dependency on third countries for the deployment clean technologies relies on institutional databases (e.g. EUROSTAT, COMEXT, PRODCOM, TARIC) particularly suited for tracking production capacities and trade of established technologies. However, these reporting channels fall short when required to track trade flows of new products or materials, thus leading the Commission to initiate the creation of new CN codes (European Commission, 2025c). Considering this, hydrogen technologies can significantly benefit from frameworks able to cope with uncertainty and partial observability.

The field of supply chain analysis offers sophisticated methods for understanding supply chain resilience and criticality (Ivanov, 2021). At materials and components level, some methodologies classified as "static" are described by the ORIENTING report (Charter et al., 2021). These include methodologies such as the European Commission's Critical Raw Material methodology (European Commission, 2023b) that evaluates the criticality of materials based on the current location of

producers and the substitutability of materials. However, the ORIENTING report concludes that such methodologies would benefit from the implementation of dynamic features.

The development of simulation-based capacities would allow for the exploration of criticality in a dynamic, forward-looking fashion by considering the whole behaviour of production networks calibrated to real-world data. This could include the use of latest AI-based technology to simulate more complex and unpredictable supply chains calibrated to real-world data (agent-based modelling, graph-based analysis, swarm-AI-based simulation, Digital Twins of supply chains).

Such features are available in methods belonging to the field of network analysis, system dynamics, ABM, discrete-event simulation or more recent digital twins methodologies which are used for modelling shock propagation and identifying vulnerabilities within a given supply chain structure (European Commission. Joint Research Centre., 2025d; Ghadge et al., 2022; Riddle et al., 2021; Ivanov, 2018). ABMs have also been used specifically to assess the criticality of the supply of raw materials (Knoeri et al., 2013), or rare-earths elements (Riddle et al., 2021). Zammori and colleagues provide a more detailed overview of the use of ABM for supply chains (Zammori et al., 2024).

Some other works took a sector-specific approach, in the likes of an exploratory assessment conducted by the European Commission DG GROW for the wind industry (European Commission, 2024). More limited assessments were carried out for water electrolyzers, where scholars studied the supply risk of materials of different electrolyser technologies (alkaline, PEM, SOEC) under capacity deployment scenarios in Germany (Kiemel et al., 2021), or compared the results of two material criticality analyses of AEM electrolyser technologies (Schropp et al., 2024). Interestingly, a recent literature review summarised the efforts done on the resilience of the hydrogen supply chain. It illustrated that besides their high capital requirements, the supply of electrolyzers was not considered in the risk assessment framework summarised by the authors (Kong et al., 2025).

One study at the intersection of techno-economic assessment and supply chain resilience for water electrolyzers stood out. Roeder and colleagues investigated the sensitivity of the levelised cost of hydrogen (LCOH) to long-term evolution of technology-specific parameters (e.g. degradation) and operational constraints (e.g. capacity factor) of alkaline, PEM, SOEC technologies (Roeder et al., 2024).

5. Conclusion and policy recommendations

5.1. Conclusion

Among the 5 key materials considered (nickel, zirconium, titanium, iridium, platinum), two raw materials (iridium and platinum) belonging to platinum-group metals are found likely to experience a supply bottleneck, which could potentially limit the deployment of hydrogen technologies at the projected levels under the chosen assumptions of operating conditions and designs.

Iridium represents the material with the highest chance of experiencing supply bottleneck across all regions. In the EU in the BASE scenario, iridium might experience a demand of more than 25 % of global supply already by 2030, even exceeding 50 % of global supply by 2050. It remains lower than 25 % by 2050 in the INNO scenario. Global iridium demand will exceed 200 % of today's supply by 2050 in the BASE scenario and stays around 50 % of the supply in the INNO scenario.

Even though the EU demand of platinum will remain low against supply (approx. 10 % of global supply by 2050 for the BASE scenario), the estimated global needs will reach almost 200 % in the BASE scenario and slightly more than 125 % in the INNO scenario, mostly driven by the deployment of FCEV.

Current alkaline designs do not have the same exposure to the criticality of supply when it comes to nickel or zirconium, with EU demand for 2030 and 2050 projected to not even reach 1 % of 2025 global supply.

However, this criticality addressed at the level of material supply does not provide the full picture. Severe bottlenecks at processed materials and component supply might be experienced in the supply chain of both alkaline and PEM electrolyzers. For example, in the case of alkaline technologies, only one company located in Belgium manufactures the product used in almost all European designs. The lack of data on actual flows of processed materials and components, as well as the manufacturing capacities of companies hinders the capacity to assess the associated supply risks.

New designs of alkaline-based technologies (AEM) or ceramic-based materials (SOEC) could alleviate these risks of supply. In the case of SOEC however, other materials might be required in current designs and were not studied in this report as market-preferred designs are not considered settled enough.

In all scenarios investigated, the development of circularity measures represents the most effective solution to palliate the criticality of PGMs without modifications to the designs of systems or their operating conditions. Circularity strategies have the potential to boost secondary raw materials supply in the future. Achieving this outcome, however, would require very high recycling rates and the recovery of materials of sufficient quality to enable closed-loop use. EoL collection rates for electrolyser stacks were assumed to be close to 100 %, given that electrolyzers are stationary systems with long lifetimes and high capital costs. For some materials, such as nickel and platinum, current recycling technologies are also assumed to achieve high recycling efficiencies (85–90 %), resulting in significant closed-loop recycling potential. In contrast, uncertainty remains for other materials, such as iridium, titanium, and zirconium due to relatively limited knowledge and data on their recycling. Targeted R&D and pilot projects are therefore essential to improve understanding and demonstrate scalable recycling solutions for these materials.

Further analysis should be carried out to extend the scope to other hydrogen technologies and to consider how demand and supply are affected by other sectors using the same raw materials, including open-loop recycling scenarios.

5.2. Policy recommendations

This chapter provides recommendations falling solely within the scope of hedging EU needs against critical raw material supply risk in the hydrogen value chain. Recommendations addressing hydrogen cost, demand creation, or infrastructure deployment fall outside our scope, as do measures whose primary rationale is industrial competitiveness rather than supply security. These recommendations are based on the outcomes of this report's analysis, including the modelling exercises. These recommendations should therefore be considered carefully and within the modelling scope, especially considering the significant underlying uncertainties and the sensitivity of the results to the assumptions taken.

5.2.1. Build recycling capacity

1. Supporting the development of dedicated recovery capacity for iridium, platinum, and titanium from end-of-life stacks, including refining routes capable of handling coated composite structures could be necessary to hedge against the risk of materials supply disruptions in the hydrogen sector.
2. Similarly, establishing collection obligations early, since recovery rates are determined by collection far more than by process yield might help in mitigating supply chain risks. Near-term targets could prioritise ensuring full EoL collection of electrolyser stacks and high recycling rates for materials with proven efficiencies, while adopting adaptive targets for materials with greater uncertainty, to be revised as recycling technologies mature.

5.2.2. Diversify sources of supply and use public procurement as a supply risk instrument

3. Aligning foreign policy initiatives like the Global Gateway strategy to match explicitly with CRMA objectives, so that partnership selection, project finance, and offtake support can be directed at reducing dependency.
4. Generalising non-price award criteria in public procurement frameworks reflecting supply chain resilience can support the diversification of supply, increase the traceability of designated materials and components, and enable the recyclability of the delivered system.

5.2.3. Close the data gap and enhance EU monitoring capacities

Data on processed materials and semi-finished components is the principal blind spot of the quantified analysis. Furthermore, current assessment of criticality is mostly based on trade statistics and does not consider dynamic effects on supply chain such as inter-regional or inter-clean technology competition for the same resources, as well as the propagation of shocks within supply chains.

5. Extending monitoring beyond raw material extraction to the processing and component stages, with priority on PGMs-based catalytic materials, processed titanium alloys and mill products would improve the accuracy of the mapping of supply of processed materials.

6. Establishing a framework for designing critical components similarly to critical materials based on explicit criteria such as supply concentration, qualification lead time, absence of qualified alternatives, criticality to system function, and switching cost would increase the scope of monitoring and assess criticality across the whole supply chain.
7. Improve the monitoring of supply chain risks by developing dynamic modelling capacity for production networks, capable of representing lead times, qualification delays, stock and flow dynamics, and feedback between price, substitution, and investment, instead of a static material intensity multiplied by deployment scenarios.

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List of abbreviations and definitions

Abbreviations	Definitions
ABM	Agent-based modelling
AEM	Anion exchange membrane
AFC	Alkaline fuel cell
AI	Artificial intelligence
ALD	Atomic layer deposition
ALK	Alkaline
BASE	Baseline scenario
BoP	Balance of plant
BPP	Bipolar plate
CETO	Clean Energy Technology Observatory
CHP	Combined heat and power
CID	Clean Industrial Deal
CN	Combined Nomenclature
COM	Communication from the European Commission
COMEXT	Eurostat reference database for international trade in goods
CRM	Critical raw material
CRMA	Critical Raw Materials Act
DG ENER	Directorate-General for Energy
DG GROW	Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
dMFA	Dynamic material flow analysis
EBR	Electron beam remelting
EI	Economic importance
EoL	End of life
EU	European Union
EU27	European Union (27 Member States)
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCH2JU	Fuel Cells and Hydrogen 2 Joint Undertaking
FLH	Full-load hours
GDC	Gadolinium-doped ceria
GDL	Gas diffusion layer
GECO	Global Energy and Climate Outlook

Abbreviations	Definitions
HDV	Heavy-duty vehicle
IAA	Industrial Accelerator Act
ICR	Interfacial contact resistance
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
INNO	Innovation scenario
IPCEI	Important Project of Common European Interest
IRA	Inflation Reduction Act
JRC	Joint Research Centre
KOH	Potassium hydroxide
LCOH	Levelised cost of hydrogen
LCV	Light-commercial vehicle
LME	London Metal Exchange
LSC	Lanthanum strontium cobaltite
LSCF	Lanthanum strontium cobalt ferrite
LSM	Lanthanum strontium manganite
M-N-C	Metal-nitrogen-carbon (catalyst)
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
MFA	Material flow analysis
micro-CHP	Micro combined heat and power
MS	Member State
NPI	Nickel pig iron
NREL	National Renewable Energy Laboratory
NZIA	Net-Zero Industry Act
OBBBA	One Big Beautiful Bill Act
OEM	Original equipment manufacturer
PAFC	Phosphoric acid fuel cell
PAR	Plasma arc remelting
PCHIP	Piecewise cubic Hermite interpolating polynomial
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PFSA	Perfluorosulfonic acid
PGM	Platinum group metal

Abbreviations	Definitions
POLES-JRC	Prospective Outlook on Long-term Energy Systems
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
PRODCOM	Eurostat statistics on the production of manufactured goods
PTL	Porous transport layer
PUC	Primarily Used Component
PVD	Physical vapour deposition
R&D	Research and development
REC	Recycling scenario
RED	Renewable Energy Directive
REF	Reference scenario
RES+REC	Resource efficiency and recycling scenario
RFNBO	Renewable fuel of non-biological origin
RMIS	Raw Materials Information System
RoW	Rest of world
SCREEN	Solutions for Critical Raw Materials - a European Expert Network
SOEC	Solid oxide electrolyser cell
SOFC	Solid oxide fuel cell
SR	Supply risk
SRIA	Strategic Research and Innovation Agenda
TARIC	Integrated Tariff of the European Union
TRL	Technology readiness level
USGS	United States Geological Survey
VAR	Vacuum arc remelting
YSZ	Yttria-stabilised zirconia

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Annexes

Annex 1. Materials circularity and resource efficiency data

Projections of material intensity and lifetime for electrolyser stacks

Table A1. Material intensity (kg/MW) of alkaline, PEM, and SOE electrolysers, both for current conditions and projected future developments based on available literature.

Technology	Material (sources)	≤2025	2030	2035	2040	2045	2050
Alkaline electrolyser	Nickel (1-5)	200 – 2,149	n.a.	200–794	200–794	200–794	200–2,000
	Zirconium(2,3,6)	54–100	n.a.	50	n.a.	n.a.	50
PEM electrolyser	Titanium (1,2,4,7-12)	165–528	68–103	32–35	19–40	32–35	11–35
	Platinum (1,4,5,8,9,11-15)	0.10–1.02	0.25–0.83	0.03–0.59	0.03–0.50	0.03–0.50	0.01–0.50
	Iridium (1,2,4,5,7,8,9,11,15, 16)	0.14–2.50	0.05–0.30	0.044–0.40	0.042–0.40	0.042–0.40	0.01–0.40
SOEC	Nickel (5,6,17,18)	46–541	n.a.	n.a.	n.a.	n.a.	n.a.
	Zirconium(5,6,18)	40	n.a.	n.a.	n.a.	n.a.	n.a.

Note: The ranges reflect values as reported in the literature for each year, and the resulting trend may not be consistent. Numbers in the “Material” column indicate the data sources, listed in the “Annex 1 references” section.

Table A2. Lifetime (years) of alkaline, PEM, and SOEC electrolyzers, both for current conditions and projected future developments based on available literature.

Technology (sources)	≤2025	2030	2035	2040	2045	2050
Alkaline electrolyser (8, 19-26)	7–10	7–11	n.a.	n.a.	n.a.	10–20
PEM electrolyser (4,8,11,13,19- 27)	3–10	7–10	15–20	9–20	n.a.	10–20
SOEC (8,19,21- 26,28)	1–10	4–9	n.a.	n.a.	n.a.	7–11

Note: The ranges reflect values as reported in the literature for each year, and the resulting trend may not be consistent. Numbers in the “Technology” column indicate the data sources, listed in the “Annex 1 references” section.

Data for the dynamic material flow analysis

Table A3 presents the data used to calibrate the dMFA used for estimating future raw materials demand and the secondary supply potential from electrolyser stacks recycling for the three scenarios (REF, REC, and RES+REC).

The evolution of material intensities under each scenario is based on literature projections summarised in Table A1 and taken as:

- For alkaline electrolyser stacks, the projected **nickel** intensity is derived from ref. [4]. Accordingly, an average nickel intensity of 1,752 kg/MW is assumed for 2020, decreasing linearly to 794 kg/MW by 2050 in the REF and REC scenarios and 497 kg/MW in the RES+REC scenarios. These values correspond to the conservative and optimistic targets reported in ref. [4], with the RES+REC scenario representing a more aggressive reduction in material intensity. The **nickel** intensity in SOEC is assumed to be 175 kg/MW based on the average value from ref. [5]. In the REC+RES scenario, this value is assumed to decrease to the lower bound of 150 kg/MW by 2050.
- For **zirconium** in alkaline electrolyzers, an average of 71 kg/MW (100 kg/MW for the MFA done in the Chapter 3 – Materials demand due to different extrapolation algorithms) is adopted for 2020 based on the literature. This value is assumed to remain constant throughout the time horizon in the REF and REC scenarios, whereas in the RES+REC scenario it declines by 50% by 2035 and remains constant afterwards, following the assumption in ref. [6]. The **zirconium** intensity in SOEC is assumed to be 40 kg/MW (refs. [6] and [18]) and is kept constant throughout the modelling period.
- The **titanium** intensity in PEM electrolyzers decreases from 414 kg/MW in 2020 (ref. [4]) (310 – 364 kg/MW for the MFA done in the chapter 3 – Materials demand due to different extrapolation algorithms) to 86 kg/MW by 2050 in the REF and REC scenarios and to 20 kg/MW in the RES+REC scenario. These values correspond to the conservative and average projections from ref. [10], respectively.
- The **platinum** intensity in PEM electrolyzers declines from 0.65 kg/MW by 2020 (refs. [4] and [13]) and 1 kg/MW by 2010 for the MFA done in chapter 3 – Materials demand due to different extrapolation algorithms) to 0.25 kg/MW by 2050 in the REF and REC scenarios, representing the average projection from the literature (Table A1), and to 0.03 kg/MW in the RES+REC scenario, corresponding to the advanced technology scenario described in ref. [8].
- Similarly, the **iridium** intensity in PEM electrolyzers decreases from 0.70 kg/MW by 2020 to 0.17 kg/MW by 2050 in the REF and REC scenarios, based on the scenarios presented in ref. [8], and to 0.07 kg/MW in the RES+REC, based on projections from ref. [16].

Stack lifetime extension was also modelled based on the literature projections from Table A2. A baseline lifetime of 9 years was assumed for alkaline and PEM electrolyzers and 4 years for SOE in 2020. In the REF and REC scenarios, these lifetimes increase to 15 years for alkaline and PEM and 9 years for SOE by 2050, representing the average projections reported in the literature (Table A2). The RES+REC scenario assumes a more aggressive lifetime extension, reaching 20 years by 2050 for alkaline and PEM and 11 years for SOEC. These values correspond to the most ambitious lifetime projections reported in the literature (Table A2).

Manufacturing losses were modelled using two parameters: i) process yield, representing the fraction of input material incorporated into the final product, and ii) manufacturing scrap recovery,

representing the share of rejected material that is recycled back into the manufacturing system. A baseline process yield of 80–85% was assumed based on the techno-economic data presented in Section 4.1.1.3. In the REF and REC scenarios, process yields remain constant throughout the modelling period, whereas in the RES+REC scenario they increase to 90–95% to reflect improvements in manufacturing methods. Manufacturing scrap recovery was assumed to be high for alkaline electrolyzers (90%) as well as for platinum and iridium from PEM electrolyzers (95%). In contrast, titanium from PEM electrolyzers and nickel and zirconium from SOEC were assumed to be either lost during processing or recovered through open-loop recycling, corresponding to an effective recovery rate of 0% into the manufacturing process. The REC scenario assumes substantial improvements in manufacturing scrap recovery, reaching 95% for alkaline electrolyzers, 99% for platinum and iridium from PEM, and 90% for titanium from PEM as early as 2035.

EoL collection rates, stack disassembly efficiency, and sorting efficiency were all assumed to reach 100% under every scenario. The rationale for these assumptions is provided in Sections 4.1.1.4 and 4.1.1.5, respectively. In contrast, recycling efficiencies were assumed to vary over time and across scenarios based on the literature summarised in Table 18–19. In the REF scenario, recycling efficiencies remain constant throughout the modelling period, with values reflecting the lower bound from the literature: 85% for nickel from alkaline electrolyzers, 48% for titanium from PEM electrolyzers, and 84% for platinum and iridium from PEM electrolyzers. Zirconium from alkaline electrolyzers, as well as nickel and zirconium from SOEC, are assumed to be recovered in this scenario. The REC scenario assumes substantial increase in recycling efficiencies over time, reaching 98% for nickel from alkaline electrolyzers and 95% for titanium, platinum, and iridium from PEM electrolyzers by 2050. Moreover, zirconium from alkaline electrolyzers and nickel and zirconium from SOEC are progressively recovered, achieving 90–95% recycling efficiencies by 2050.

Table A3. Data used in the dMFA model for the three scenarios (REF, REC, and RES+REC). The values for the period 2020–2050 every five years are shown in brackets.

MFA model parameter	Technology	Material	REF	REC	RES+REC
Circularity lever: Material efficiency					
Material intensity (kg/MW)	Alkaline electrolyser	Nickel	[1,752; 1,432; 1,305; 1,177; 1,049; 921; 794]	Same as Baseline	[1,752; 1,405; 1,224; 1,042; 860; 679; 497]
		Zirconium	71 (constant)	Same as Baseline	[71; 68; 51; 35; 35; 35; 35]
	PEM electrolyser	Titanium	[414; 249; 216; 183; 151; 118; 86]	Same as Baseline	[414; 246; 201; 155; 110; 65; 20]
		Platinum	[0.65; 0.35; 0.33; 0.31; 0.29; 0.27; 0.25]	Same as Baseline	[0.65; 0.35; 0.29; 0.22; 0.16; 0.09; 0.03]
		Iridium	[0.70; 0.43; 0.37; 0.32; 0.27; 0.22; 0.17]	Same as Baseline	[0.70; 0.40; 0.33; 0.27; 0.20; 0.14; 0.07]

	SOEC	Nickel	175 (constant)	Same as Baseline	[175; 173; 169; 164; 159; 155; 150]
		Zirconium	40 (constant)	Same as Baseline	40 (constant)
Circularity lever: Extend stack lifetime					
Stack lifetime (years)	Alkaline electrolyser	–	[9; 9; 9; 10; 11; 12; 15]	Same as Baseline	[9; 11; 12; 14; 15; 17; 20]
	PEM electrolyser	–	[9; 9; 11; 12; 14; 15; 15]	Same as Baseline	[9; 10; 12; 14; 16; 19; 20]
	SOEC	–	[4; 4; 5; 5; 6; 8; 9]	Same as Baseline	[4; 5; 6; 7; 9; 11; 11]
Circularity lever: Reduce manufacturing losses					
Process yield (%)	Alkaline electrolyser	Nickel & zirconium	85% (constant)	Same as Baseline	[85%; 85%; 88%; 90%; 90%; 90%; 90%; 90%]
	PEM electrolyser	Platinum & iridium	85% (constant)	Same as Baseline	[85%; 86%; 89%; 93%; 93%; 93%; 93%; 93%]
		Titanium	83% (constant)	Same as Baseline	[83%; 84%; 88%; 93%; 93%; 93%; 93%; 93%]
	SOEC	Nickel & zirconium	80% (constant)	Same as Baseline	[80%; 81%; 88%; 95%; 95%; 95%; 95%; 95%]
Manufacturing scrap recovery rate (%)	Alkaline electrolyser	Nickel & zirconium	90% (constant)	[90%; 91%; 95%; 95%; 95%; 95%; 95%; 95%]	Same as Recycling
	PEM electrolyser	Platinum & iridium	95% (constant)	[95%; 96%; 99%; 99%; 99%; 99%; 99%; 99%]	Same as Recycling
		Titanium	0% (constant)	[0%; 15%; 90%; 90%; 90%; 90%; 90%; 90%]	Same as Recycling
	SOEC	Nickel & zirconium	0% (constant)	Same as Baseline	Same as Baseline
Circularity lever: Increase EoL collection rates					
EoL collection rate (%)	All	All	100%	100%	100%
Circularity lever: Increase efficiency of stack disassembly and material sorting					

Stack disassembly efficiency (%)	All	All	100%	100%	100%
Material sorting (%)	All	All	100%	100%	100%
Circularity level: Advanced recycling technologies					
Recycling efficiency(%)	Alkaline electrolyser	Nickel	85% (constant)	[85%; 85%; 88%; 95%; 96%; 97%; 98%]	Same as Recycling
		Zirconium	0% (constant)	[0%; 0%; 85%; 88%; 93%; 94%; 95%]	Same as Recycling
	PEM electrolyser	Titanium	48% (constant)	[48%; 48%; 57%; 67%; 76%; 86%; 95%]	Same as Recycling
		Platinum	84% (constant)	[84%; 84%; 88%; 92%; 95%; 95%; 95%]	Same as Recycling
		Iridium	84% (constant)	[84%; 84%; 88%; 92%; 95%; 95%; 95%]	Same as Recycling
	SOEC	Nickel	0% (constant)	[0%; 0%; 0%; 85%; 89%; 89%; 90%]	Same as Recycling
		Zirconium	0% (constant)	[0%; 0%; 0%; 85%; 89%; 89%; 90%]	Same as Recycling

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Annex 2. Model used for the calculations of the materials demand in chapter 3.

This annex describes the model used for the calculation of the materials demand of chapter 3. This model is not used for the calculation of circularity potential used in chapter 4.1.

Calculations and model description

The model is initially calibrated using energy scenarios projections and real world data using the JRC Big Data Analytic Platform (Soille et al., 2018). This allows to fix a set of years (2025, 2030, 2040, 2050). The model then performs an extrapolation of the year in-between using a PCHIP algorithm to keep the monotonic growth of technologies and avoid overshooting the calibration points. The model advances year by year and evaluates the total electrolysis capacity required to reach stock targets either for hydrogen production or fleet deployment following equations below. The target to electrolyser stock conversion is performed using equation (1) below.

$$Cap(year)_{sub-tech} = Tot_{H_2}(year) \times m(year)_{sub-tech} \times \frac{\eta(year)_{sub-tech}}{cf_{sub-tech}(year) \times 8766} \quad (1)$$

Where:

— $Tot_{H_2}(year)$: represents the total hydrogen production target

And for each sub-technology each year:

— $Cap(year)_{sub-tech}$: represents the targets installed capacity

— $m(year)_{sub-tech}$: represents the market share

— $\eta(year)_{sub-tech}$: represents the energy consumption

— $cf_{sub-tech}(year)$: represent the share of full-load hours

For FCEV, since the target is a stock itself (total number of vehicles in operation), there is no need for intermediate calculations.

To accurately model replacement rates and recycling, the model tracks capacity in 'cohorts' or 'vintages'. When a batch of electrolyzers is built in a specific year, it is stamped with the technological standards of that year and assigned a lifespan. The model then checks the retirement of systems following a batched Gaussian distribution curve centered of the parametrised lifetime. To do so, the system lifetime (in hours) is converted to years of operation following equation below. This considers that systems do not age in the same way as some systems will be decommissioned earlier or later than others.

When a batch of electrolyzers reaches the end of its operational life, it is considered retired. This retirement triggers two simultaneous events: a new electrolyser must be built to replace it, and the old electrolyser is sent to the scrap heap to be recycled. The model then computes the total quantity of system to be manufactured each year to increase the total system stock and replace systems being decommissioned in a given year.

To calculate the **Total Gross demand** for materials, the model multiplies the newly built capacity (both for electrolyser capacity expansion and replacements) by the material intensity of the current year.

Similarly to what has been performed in previous Deep Dive reports (European Commission. Joint Research Centre., 2025a, 2025b, 2025c), this assessment builds on the comparative analysis of two different scenarios with a different set of those 4 key parameters:

1. The technology deployment level.
2. The market share of sub-technology
3. The technical performance of each sub-technology
4. The materials intensity of each material for each sub-technology to assess the effect that innovation in materials, recycling, and policies innovation will have on the gross materials demands of the considered technologies.

The model's outputs are computed based on several techno-economic parameters such as:

1. The energy consumption of the electrolyser to produce one kilogram of hydrogen (kWh/kgH₂). It determines the total MW_e of capacity required.
2. the Capacity Factor (%) which indicates the proportion of the year the electrolyser is actively running. Combined with energy consumption, it translates hydrogen volumes into MW capacity.
3. The Lifetime (operating hours), which is the durability of the electrolyser stack before it degrades enough so the customer decides to decommission it and replace it. It dictates exactly when a vintage cohort retires, triggering replacement demand and recycling supply.
4. The Material Intensity (kg/MW), which indicates the amount of material required to manufacture one Megawatt of capacity. It scales the physical MW_e infrastructure into raw tonnage of materials.
5. The Collection Rate & Recycling Efficiency (%), indicates the real-world effectiveness of the circular economy ecosystem. It defines what percentage of the material in a retiring electrolyser is successfully recovered for reuse.

To accommodate different futures, the model uses 'pathways' to adjust these variables over time depending on the analysed scenario.

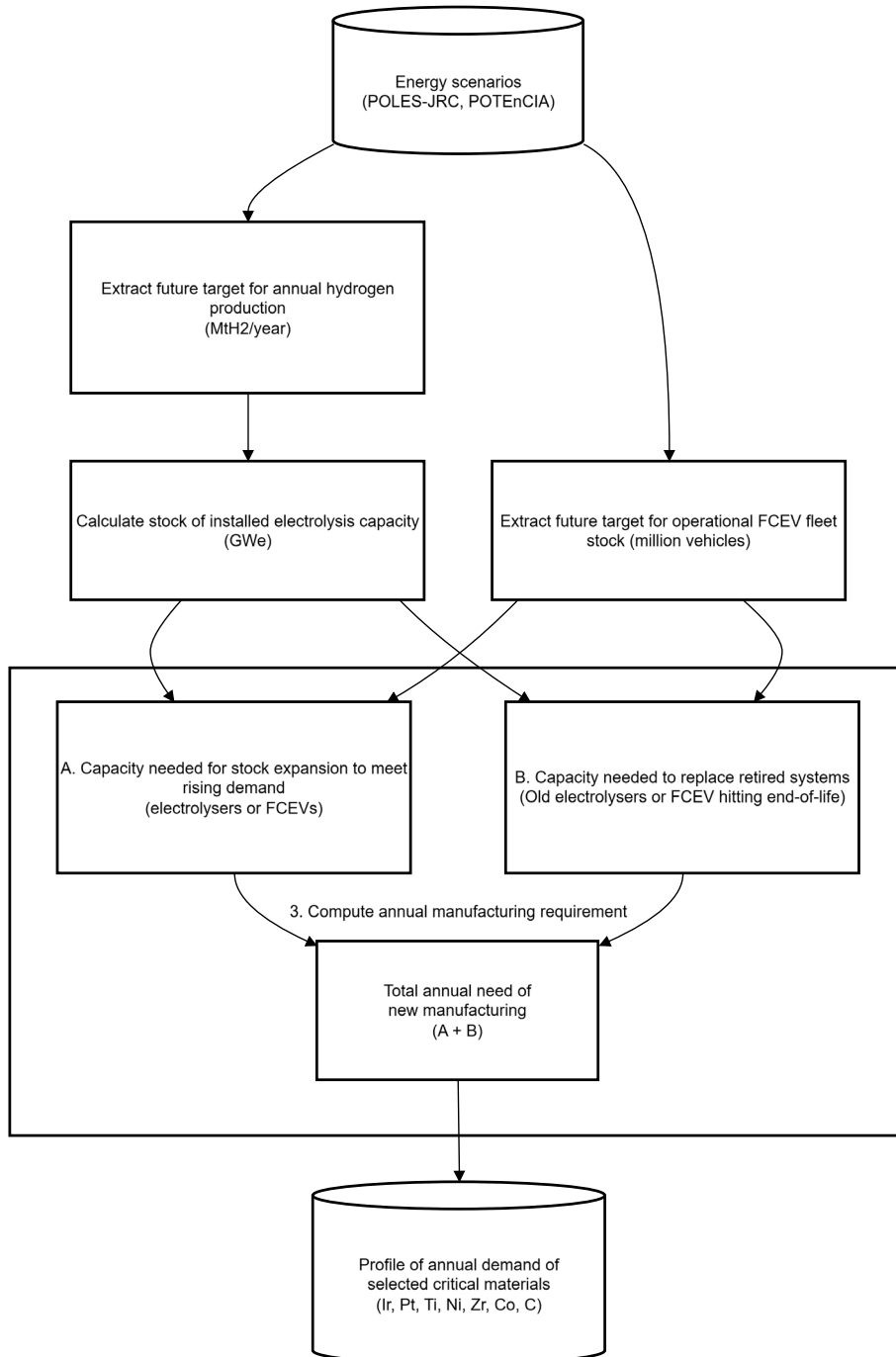
Limitations of the model

The model has several boundaries that must be considered when interpreting the results, such as:

1. The sub-technology market shares are set externally as inputs. The model does not consider any economic factor, such as price elasticity or economic feedback. The model only encodes the physical deployment required to meet the hydrogen targets regardless of cost. For example, if an extreme shortage of iridium were to drive prices up exponentially, the model will not automatically slow down PEM deployment or switch to Alkaline technologies.
2. The model assumes that when capacity is needed, it is built immediately. It does not account for manufacturing bottlenecks, permitting delays, or geopolitical disruptions in the supply chain.
3. The model assumes that 100% of the hydrogen demand projected by the GECO scenarios are produced via electrolysis without considering imports.

4. The model treats the EU as a single, frictionless pool of resources. It does not map the geographic mismatch between where electrolyzers are deployed, where they are recycled, and where the primary metals are mined.

Figure 29. Description of the modelling steps from scenario extraction to materials demand primary calculations.



Source: Joint Research Centre (2026)

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