

Sufficiency, sustainability, and circularity of critical materials for clean hydrogen

CLIMATE-SMART MINING FACILITY

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Hydrogen Council



Climate Smart Mining

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This report was developed jointly with the Hydrogen Council. It was supported by the Climate-Smart Mining Initiative and the Energy Sector Management Assistance Program (ESMAP) of the World Bank Group.

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Foreword

Effective global decarbonization will require an array of solutions across a portfolio of low-carbon resources. One such solution is developing clean hydrogen. This unique fuel has the potential to minimize climate change impacts, helping decarbonize hard-to-abate sectors such as heavy industry and global transport, while also promoting energy security, sustainable growth, and job creation.

Our estimates suggest that hydrogen needs to grow seven-fold to support the global energy transition, eventually accounting for 10 percent of total energy consumption by 2050. A scaleup of this magnitude will increase demand for materials, such as aluminum, copper, iridium, nickel, platinum, vanadium and zinc to support hydrogen technologies—renewable electricity technologies and the electrolyzers for renewable hydrogen, carbon storage for low-carbon hydrogen, or fuel cells using hydrogen to power transport.

An analysis of the impact of this material intensity is vital to deploying hydrogen sustainably, at scale. First, it can help identify bottlenecks in the supply of a critical material that could create challenges for the entire hydrogen sector or a specific technological component. Second, it highlights the need to consider the wider environmental challenges—impacts on greenhouse gas emissions or stresses to water supply—that may arise from mining and processing the materials. And last, while the material footprint of the hydrogen economy is low, it's worth assessing whether materials needed for hydrogen may be competing with large-scale demand from other—and fast-growing—sectors of the low-carbon transition, such as wind, solar, and battery technologies.

This report, a joint product of the World Bank and the Hydrogen Council, examines these three critical areas. Using new data on the material intensities of key technologies, the report estimates the amount of critical minerals needed to scale clean hydrogen. In addition, it shows how incorporating sustainable practices and policies for mining and processing materials can help minimize environmental impacts. Key among these approaches is the use of recycled materials, innovations in design in order to reduce material intensities, and adoption of policies from the Climate-Smart Mining (CSM) Framework to reduce impacts to greenhouse gas emissions and water footprint.

This research should be seen as the starting point of analysis in this area, with a need to increase the scope and depth to give a more complete picture of the material impacts of hydrogen along its value chain, including crucial aspects such as transportation, storage, and distribution.

Ultimately, governments and the private sector need to be proactive and work together to ensure that the supply of key materials across the energy transition can be successfully deployed without impeding the global supply of clean hydrogen, and that these materials can be supplied with the lowest environmental and social footprint possible.

Acknowledgments

This report was developed by the Climate-Smart Mining Team of the World Bank's Energy and Extractive Global Practice jointly with the Hydrogen Council, with support from the Energy Sector Management Assistance Program (ESMAP). The team was led by Susana Moreira. The primary author and research team was Tim Laing (University of Brighton) assisted by Celia Pannetier, with vital modelling input on carbon capture and sequestration from Brendan Beck and initial research by Benjamin Sprecher. Yann Doignon, Nilar Chit Tun and Joanna Sampson provided communications support and Mark Lindop graphic design expertise. Maria Luisa Meer provided organizational support.

The team is grateful for the input and contributions received from the following individuals: Damian Brett, Sean Christopher Nelson, Simran Kalyan Borade and Ton Bastein.

Data for the modelling was gratefully received from the Hydrogen Council who led a clean-room process collecting data from all their members. We are immensely grateful for the participation of all involved in the process, led by Daryl Wilson and Steven Libbrecht, with support of consultants at Ludwig-Bölkow-Systemtechnik GmbH (LBST). All members of the Hydrogen Council who contributed data are also appreciatively acknowledged.

The report's model was built on previous publications of the World Bank, *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* and *The Growing Role of Minerals and Metals for a Low Carbon Future* and has benefited from insight, feedback, and data from several other esteemed colleagues through its whole evolution. Our sincerest thanks go to all of them.

Lastly, the team greatly appreciates the input and guidance from Demetrios Papathanasiou and Gabriela Elizondo Águila.

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Abbreviations

- | | |
|--------------|--|
| AEL | Alkaline electrolyzers |
| CCS | Carbon Capture and Sequestration |
| CSM | Climate-Smart Mining |
| EL | Electrolyzers |
| GHG | Greenhouse Gas emissions |
| HDV | Heavy Duty Vehicle |
| LDV | Light Duty Vehicle |
| LOHC | Liquid Organic Hydrogen Carrier |
| PEMEL | Polymer Electrolyte Membrane electrolyzers |
| PEMFC | Proton-exchange membrane fuel cells |
| PGM | Platinum Group Metals |



Executive summary

Hydrogen is to play a relevant role in decarbonization, meriting an impact check

Clean hydrogen¹ has the potential to be a crucial tool to help decarbonize hard-to-abate sectors such as heavy industry and heavy-duty transport. The Hydrogen Council projects that the demand for hydrogen could rise seven-fold by 2050, with two-thirds of production in 2050 via renewable electricity and electrolyzers, with the remaining third methane reforming with carbon capture and sequestration (CCS) (Hydrogen Council, 2021a). Similarly, the IEA projects an increase in hydrogen production of over 135% between 2020 and 2030 to meet a net-zero trajectory (IEA, 2021c). IRENA envisages that clean hydrogen could account for 12% of final energy consumption by 2050 under a 1.5 degree scenario (IRENA, 2022), while BNEF estimated an even higher role of up to 24% (BNEF, 2020). A scale-up of this magnitude requires major deployment of the equipment to produce, transport, store, distribute and consume hydrogen. Key questions that arise in the feasibility, and potential impacts of this deployment include whether there are supply constraints in the availability of crucial materials, for either the deployment of hydrogen in general, or particular production or consumption technologies specifically; what the wider demand context may look like for key materials – and whether there are materials for which hydrogen may be competing with large scale increases in demand from other parts of the low-carbon transition; and what the wider environmental impacts, such as greenhouse gas emissions (GHG), and water footprint, may be from the mining and processing of the materials required for the widespread deployment of hydrogen.

Taking the materiality of hydrogen technologies into focus

This report examines these three questions: first modelling the potential material demand from key components of the production of clean hydrogen (electrolyzers and the renewable technologies needed to power them, and methane reformers and carbon capture and sequestration technologies) and the fuel cells used in the consumption of hydrogen up to 2050; then examining this demand in the context of wider demand from the low-carbon transition, and the supply and sourcing of these materials; and,

then examining the potential emissions and water footprint of the sourcing of these materials along with the production of hydrogen. The report utilizes new data on the bill of materials needed for the construction of technologies for both renewable and low-carbon hydrogen production, along with fuel-cells for hydrogen consumption, obtained from companies via a clean-room process conducted by the Hydrogen Council. This data is combined with the latest scenarios for hydrogen deployment from the Hydrogen Council to produce new estimates for key materials required for the hydrogen sector.

Materiality of renewable power generation outweighs hydrogen technologies

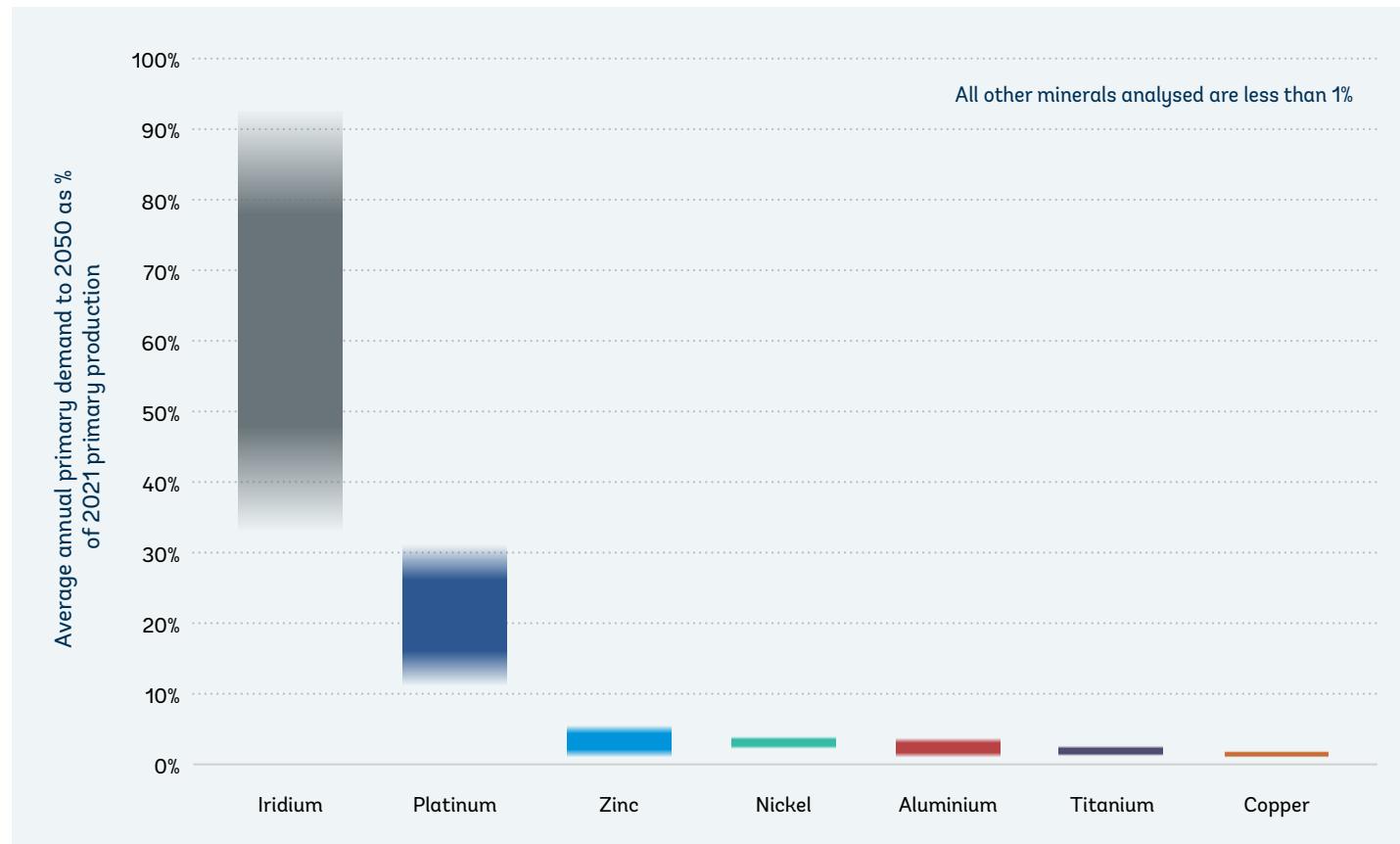
The results of the analysis highlight that the largest source of material demand from the parts of the hydrogen sector modelled are likely to come from the renewable electricity generating capacity needed for renewable hydrogen deployment. This basket of materials includes aluminum, copper, nickel, and zinc – though the actual scale and composition is highly dependent on the type (and sub-types) of renewable electricity used to power electrolyzers. Higher use of solar photovoltaics (PV) could increase the demand for aluminum, whilst more use of wind could increase the need for zinc, or even dysprosium and neodymium if wind turbines with permanent magnets are used. Beyond these materials there is a wide grouping of other materials that are needed in smaller absolute volumes but spread across the different types of hydrogen-related technologies from platinum and iridium to cerium and cobalt. Some are used in just a singular technology such as cerium for fuel-cells while others are used widely across the sector such as nickel and titanium.

Keeping an eye on competing materials

The scope of this mineral demand is generally relatively small compared to existing levels of production (Figure ES1). For example, the demand from the production of clean hydrogen for zinc in 2050 would account for 4% of current levels of zinc production. However, the demand from the production of clean hydrogen needs to be placed in the context of the wider low-carbon transition. Minerals required for different production paths for hydrogen such as graphite, needed in alkaline electrolyzers and

¹ This report follows the Hydrogen Council's terminology whereby 'clean hydrogen' includes hydrogen produced via electrolysis where the electricity is generated from renewables ('renewable hydrogen') and 'low-carbon hydrogen'. Low-carbon hydrogen refers to hydrogen that is produced via autothermal or steam methane reforming using natural gas with Carbon Capture Use and Sequestration (CCUS).

Figure ES1: Modelled average annual primary demand from clean hydrogen production and consumption to 2050 as a percentage of current primary production



cobalt, used in low-carbon hydrogen production, face potentially large, but highly uncertain increases in demand from the low-carbon transition as a whole, chiefly from their use in lithium-ion batteries. Thus, although demand from producing clean hydrogen itself represents just a small share of current mineral production, the sourcing of these materials may create challenges for the hydrogen sector as the scale of demand from elsewhere could imply that shortages or higher prices occur. Understanding the different demand contexts in which key materials for hydrogen sector, using tools such as the World Bank's Demand Risk Matrix is a vital action for governments and the private sector looking to secure the supply of materials for the deployment of clean hydrogen.

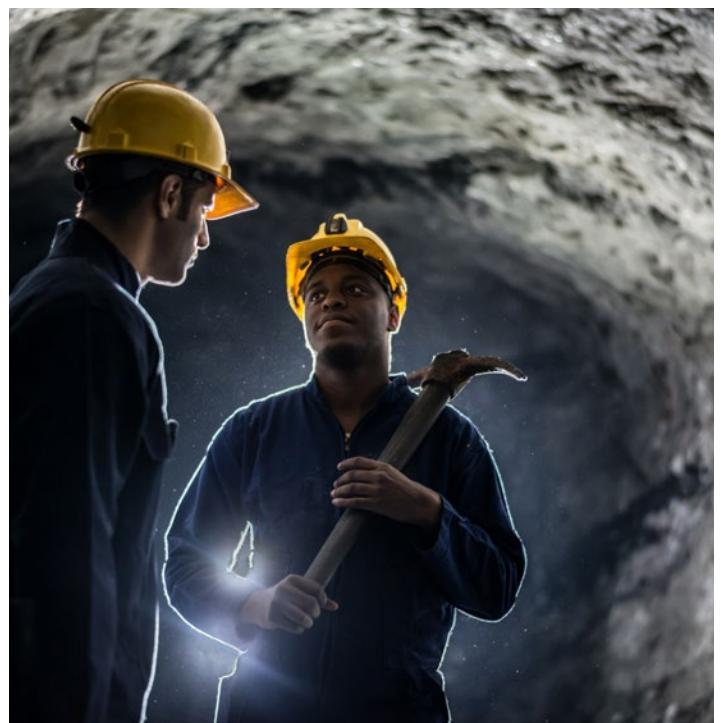
The overall scale of material demand for the production and consumption of clean hydrogen is unlikely to cause major challenges in the markets for most of the commodities involved. There are few challenges regarding the scale of identified

resources in the ground compared to demand for material from hydrogen deployment. There are, however, some materials for which production levels could be a key challenge but also in some cases an opportunity. Chief amongst these the platinum groups metals: platinum and iridium. Demand for primary platinum from the production of hydrogen could reach over a third of current production levels in the 2030s, before large-scale secondary material from within the hydrogen sector emerges to dampen this primary demand. This could create short-term challenges in meeting this demand for platinum. There is however significant uncertainty: a lot will depend on the ramp-up speed of the hydrogen demand against a context of declining demand from traditional sources such as catalytic converters in internal combustion vehicles and the potential release into the market of existing substantial above-ground stocks of platinum and of growing amounts of scrap platinum from converters and jewelry.

Despite potentially creating some challenges in the short-term, the emerging demand from the hydrogen sector could make up in the mid-term for the drop-off in demand from other sectors and support the platinum industry and the employment it offers, especially in southern Africa. More of a challenge is iridium, needed for polymer electrolyte membrane electrolyzers, with production heavily concentrated in southern Africa. Demand for primary iridium from the hydrogen sector could reach over 160% of current production in the 2040s, depending on the extent to which the intensity of iridium use in these electrolyzers reduces and higher rates of recycling are achieved. Scaling up supply may also be more challenging given its nature as a minor by-product of other materials predominantly platinum. It is highly unlikely that primary production could be divorced from platinum, and thus market signals from increasing demand for the material do not translate to increased capacity. Overcoming this challenge through increasing supply from above-ground stocks such as recovery from premium spark-plugs and tailings, encouraging recycling and designed-in circularity, and stimulating material substitution where possible, is an important task for policymakers and the private sector.

Assessing the environmental impacts of hydrogen technologies

Beyond these challenges understanding the material implications of the widespread deployment of clean hydrogen is important for helping to first understand, and then help to mitigate, the environmental impacts from sourcing the materials needed for clean hydrogen production and consumption. GHG emissions of the materials required for renewable hydrogen are likely to be higher than for low-carbon hydrogen. Emissions from materials for renewable hydrogen are predominantly accounted for by the need to build renewable technologies to power electrolyzers. Aluminum is likely to be a major component of this, assuming a large share of solar power in the mix. Increasing recycled content in these technologies, improving efficiency and lifetimes of technologies, reducing material intensities, and implementing the World Bank Group's Climate-Smart Mining (CSM) principles² in the mining sector more broadly can help to reduce the emissions associated with the materials needed for the hydrogen sector.



² The World Bank's Climate-Smart Mining Initiative supports the sustainable extraction, processing and recycling of minerals and metals needed to secure supply for low-carbon technologies and other critical sectors by creating shared value, delivering social, economic and environmental benefits throughout their value chain in developing and emerging economies. More information including Climate-Smart Mining Framework is available at: <https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action>

At a macro-scale the overall water footprint of the hydrogen sector is likely to be small compared to other energy sectors, and renewable water resources as a whole – however there maybe challenges at a regional or water-shed level especially as it pertains to water quality, requiring careful assessment of the water impact of projects, and choice of water sourcing, including the use of desalination where relevant. The water footprint of the materials needed is small compared to the water needed to produce both renewable and low-carbon hydrogen and the fuel cells to power vehicles, though it is likely to rise over-time. Regionally the broader challenges of water availability for producing renewable and low-carbon hydrogen are likely to be largest in the Middle East, and to a lesser extent in Japan, South Korea, and China. Incentivizing increased water recycling and re-use; encouraging energy efficient desalination plants powered by renewable energy also equipped with adequate brine management systems where appropriate; investing in solutions that will allow the use of lower-quality water (e.g. salt water, waste water) across the hydrogen sector, along with improving water intensities within mining and processing, and increasing the use of secondary materials, will all help to mitigate this water footprint.

Looking forward

Clean hydrogen has a critical role to play in decarbonizing otherwise hard to abate sectors. The overall material footprint of the sector is unlikely to cause major stress to most material markets involved, indeed in some markets, such as platinum it may actually relieve stress that could occur with the decline in demand from current uses. However, the broader context of a potentially materially intensive low-carbon transition needs to be borne in mind, implying that materials crucial for different aspects of the hydrogen sector may be under significant strain from demand elsewhere. This means that reducing the material stress from clean hydrogen will be beneficial to both the deployment of the technology, while also reducing any negative impacts relating to GHG emissions and water from the sector. As detailed in Figure ES2, boosting recycling and re-use, reducing material intensity, encouraging material substitution, and encouraging designed-in circularity are all vital for improving security of supply and reducing material impacts – whilst there are virtuous circles available such as the deployment of clean hydrogen within the mining industry. Both governments and the private sector have crucial roles to play in this regard, from establishing the right policy frameworks, to implementing technology transfer, to innovating and investing in efficiency and new technologies.

Figure ES2: Key Recommendations

Climate mitigation	Climate resilience	Circular economy	Creating market opportunities
<ul style="list-style-type: none"> • Increase energy efficiency and renewables in extraction and processing • Policy and incentives for Forest-Smart Mining • Increase data on GHG and other environmental impacts of mining 	<ul style="list-style-type: none"> • Conduct hydrological analyses for renewable and low-carbon hydrogen projects 	<ul style="list-style-type: none"> • Overcome barriers to scaling up use of secondary materials • Increase recovery of climate-action materials from tailings and other above-ground sources • Provide assistance to reduce material intensity of hydrogen technologies • Encourage water efficiency (e.g. closed-loop, recycling, wastewater use) 	<ul style="list-style-type: none"> • Improve geological data for climate action materials • De-risk investments in climate action materials including new and replacement mines





1. The role of hydrogen in achieving low-carbon transition

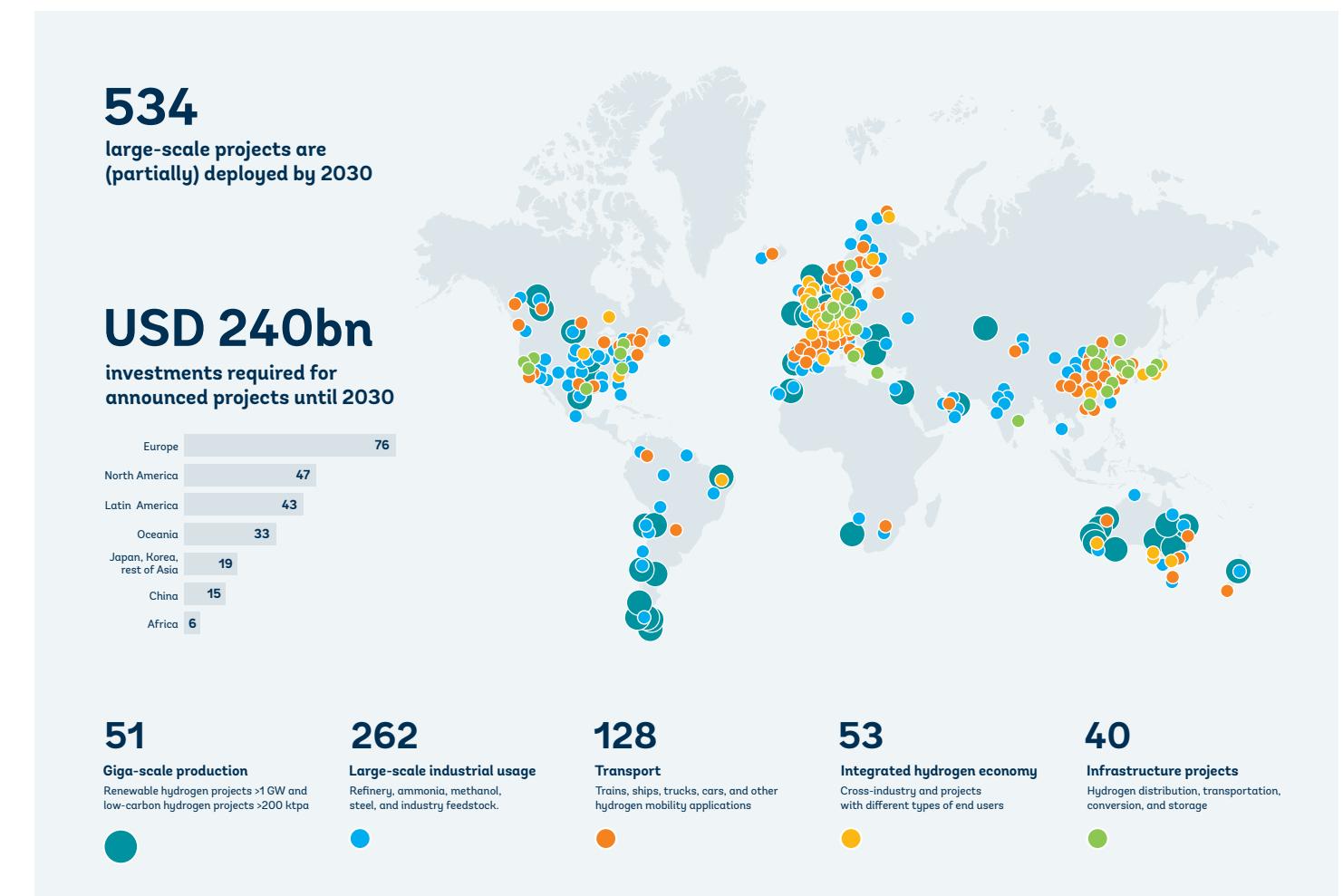
The race is on to reach net zero by 2050, and innovative ways of reducing emissions and decarbonizing some of the most polluting sectors and industries are gaining pace. The world is grappling with the challenge of holding global temperature rises to less than 2°C above pre-industrial levels. In this race, hydrogen is anticipated to play a key role and is ideally positioned to complement electricity in the energy transition and decarbonize hard-to-abate sectors such as heavy industry and heavy-duty transport.

Hydrogen is a gaseous chemical element that has the capacity to act as an energy carrier, and can be used as fuel to store, move and deliver energy. In its combustion it emits only water as a

3 EEX Week, McKinsey. Hydrogen session

by-product and is hence seen as key to decarbonizing otherwise greenhouse gas-emitting (GHG) sources of energy. According to McKinsey, it is estimated that as much as 25% of global emissions could be reduced using hydrogen by 2050.³ Hydrogen is projected to significantly help decarbonize hard-to-abate sectors such as iron and steel production, chemical industry, as well as heavy duty transport. With current industrial uses of hydrogen focusing on petroleum refining and ammonia production, the Hydrogen Council and McKinsey estimate use of hydrogen could avoid as much as 270 million tonnes of CO₂ a year, and 90 million tonnes of CO₂ in transport and mobility alone (Hydrogen Council & McKinsey & Company, 2021a).

Figure 1: Global hydrogen projects across the value chain (Source: Hydrogen Council. 2021a)



Looking beyond emissions reduction as a key characteristic of hydrogen production, it can also bring resilience to countries that are pursuing energy independence and diversification, thanks to the fact that it can be produced domestically from multiple feedstocks using diverse production pathways.

Already, governments, businesses and investors are building an enabling environment for accelerated hydrogen growth. Thirty countries have developed, or are in the process of developing, hydrogen plans central to their decarbonization strategies. In the private sector, more than US\$300 billion in hydrogen investments are earmarked through 2030 (Hydrogen Council & McKinsey & Company, 2021b),⁴ much of which is dedicated to the scale-up of its production. In parallel, over six hundred large-scale hydrogen project proposals, worth US\$240 billion have been put forward worldwide (Hydrogen Council & McKinsey & Company, 2022), an investment increase of 50% since November, 2021 – however only about 10% have reached final investment decisions (Figure 1).

Hydrogen production

Hydrogen can be produced using diverse technologies and feedstocks, which is part of its appeal. (Figure 2).

Current situation and scenarios for growth

Hydrogen has traditionally been used for refining or desulphurisation of diesel fuel and ammonia production, which has tripled since 1975.⁵ In these industries hydrogen's role is as a feedstock, used to create other products. Future scenarios however utilise hydrogen's potential as an energy carrier, transporting low-carbon energy to where it is needed. It is projected that the industry is about to experience a tremendous shift in scaling-up and diversification of end-uses of hydrogen to meet demand as climate ambitions increase. Announced investment in hydrogen end-uses through 2030 equate to approximately US\$60 billion and include fuel-cell vehicles, methanol and ammonia synthesis plants and the use of hydrogen in steelmaking and power generation (Hydrogen Council & McKinsey & Company, 2022)

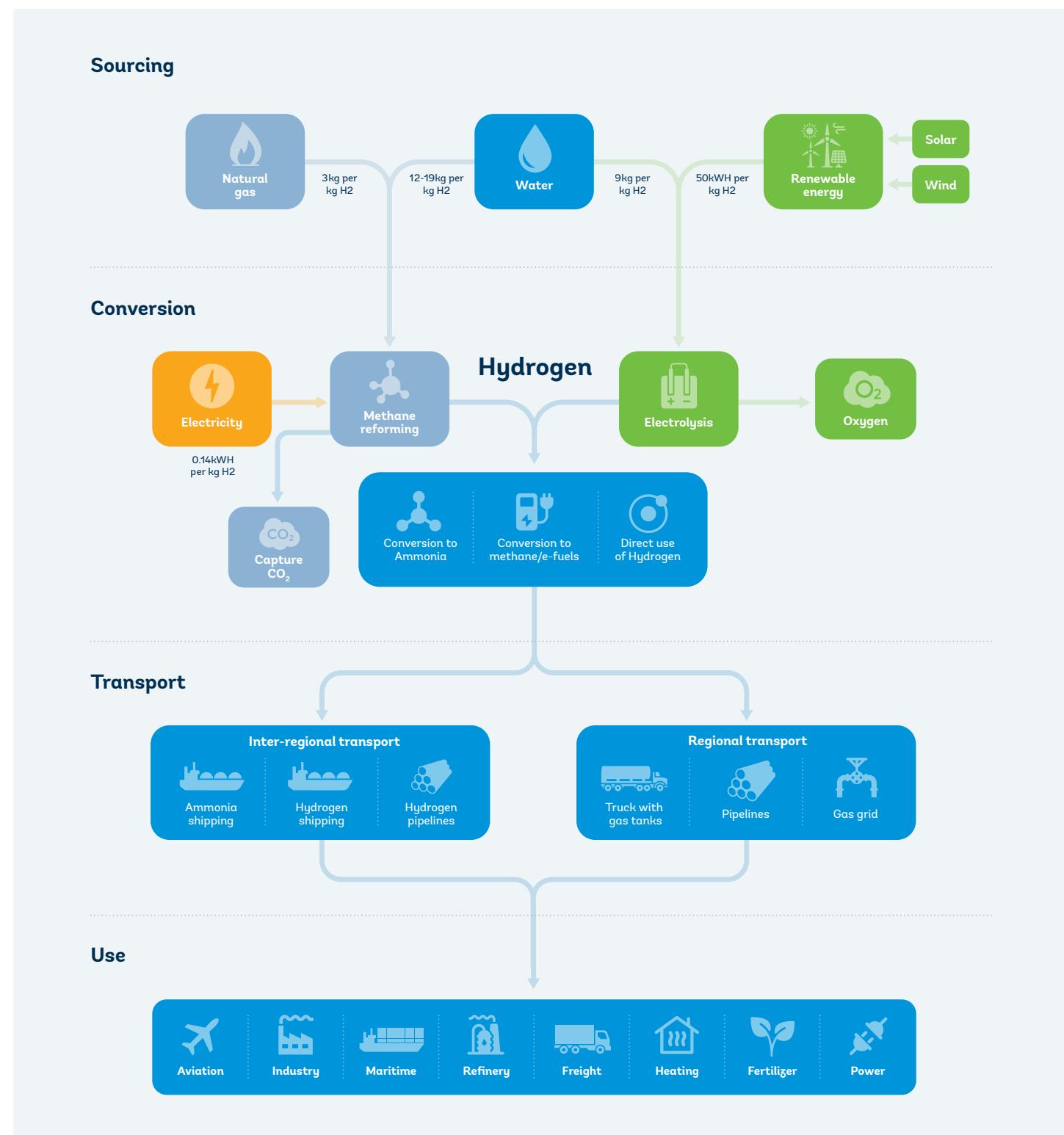
The Hydrogen Council and McKinsey estimate that for the world to reach its net-zero targets, hydrogen demand will be as high as 690 million tonnes per annum by 2050 – eleven times that of production in 2020.⁶ This equates to hydrogen accounting for 22% of global final energy demand, with projected uses for power generation, transportation, building heat, new industries (including steel and liquid biofuels), and existing industry uses (Hydrogen Council, 2021a). Estimates from other organisations show a similar scale of growth. The IEA, as part of their roadmap to Net-Zero project that use of hydrogen could increase by over 135% between 2020 and 2030 (IEA, 2021c). IRENA, for their 1.5 degree scenario estimate that hydrogen could contribute to 12% of total final energy consumption by 2050, playing key roles

in steel, chemicals, long-haul transport, shipping and aviation, along with helping to balance intermittent renewable generation (IRENA, 2022). The BNEF highlight that hydrogen's potential could be even greater in the presence of strong and comprehensive policy reaching up to 24% of final energy consumption in 2050 under a 1.5 degree scenario (BNEF, 2020). Announced project proposals equate to about 26 million tonnes of clean hydrogen production capacity by 2030 (Hydrogen Council & McKinsey & Company, 2022), about a third of what is needed to be on track for net-zero.

Deployment in the early stages is expected to be centred on Europe, Japan and the Republic of Korea, as well as China and North America (Hydrogen Council & McKinsey & Company, 2021a). Additionally, countries that have the advantage of abundant renewable power and/or carbon capture capacities will be well-placed to scale-up hydrogen production, including Argentina, Brazil, Chile, and Middle Eastern countries.⁷

The industry will need to pivot towards clean hydrogen if this transition is to be truly clean. Today, approximately 96% of hydrogen is produced from fossil fuels. As a result, hydrogen is responsible for roughly the equivalent of Germany's annual GHG emissions (IEA, 2021). For investments in clean hydrogen value chains to be scaled up, governments can scale up ambitions and take decisive action. More specifically, steps governments can take include developing strategies and roadmaps on hydrogen's

Figure 2: Production of hydrogen by different routes



⁴ 25% of these investments have funding committed to them, 75% are announced. As of 2021, \$80 billion are estimated to be committed until 2030.

⁵ Data from <https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-sustainable-development-scenario-2019-2070> IEA (2020)

⁶ EEX Week, McKinsey, Hydrogen session

⁷ Moreira, Susana, "Low-carbon hydrogen: State of Play", Workshop on Unlocking the Potential of Hydrogen in Mauritania, World Bank, May 2022.

role in energy systems; strengthening legal, regulatory, and institutional frameworks for hydrogen; support standards and drives towards certification; creating strong incentives to use hydrogen to displace fossil fuels where appropriate (and in the process help create new hydrogen demand); mobilizing investments in production assets and infrastructure; monitoring and enforcing measures to mitigate environmental and social impacts; supporting skilling up of the labour force; and providing innovation support.

Innovation alone does not guarantee the success of deployment

Access to renewable energy and CCS technology is one piece of the puzzle for ensuring a successful transition to a hydrogen economy. The electrolyzers needed for renewable hydrogen production have traditionally been costly and are still in early stages of production. However, increasing demand is driving costs down for this piece of technology, from \$2,400/kW in 2015, to between US\$650 – 1000 /kW in 2020, with some reports of costs as low as US\$300/kW in 2021 for Chinese AEL systems.⁸ The IEA place the present cost of a total electrolyzer system, including equipment and construction cost in the range of US\$1,400 – 1,770/kW – with AELs and the bottom of this range and PEM at the top (IEA, 2022).

Looking beyond production, hydrogen distribution and storage is a logistical question that needs to be addressed. Hydrogen can be transported in pure form either by pipelines and tube trailers in gaseous form, or by cryogenic tanks in liquefied form. The method of transport depends on distance and infrastructure availability of pipelines. At present, hydrogen pipelines cover more than 5,000km and are mostly located in Europe and the United States, for comparison, there are 3 million km of natural gas pipelines.⁹ Pipeline repurposing for hydrogen is possible and more cost effective than building new hydrogen pipelines,¹⁰ but long-term both will be required to accommodate for the high volumes of hydrogen demand (more details on the material requirements of pipelines are discussed in Section 3 below). For longer distances, hydrogen can be liquefied (LH_2), converted into ammonia (NH_3),

or bound to a liquid organic hydrogen carrier (LOHC). These options will also have material implications that warrant further analysis but are beyond the scope of this report. The cost-optimal solution depends on the targeted end-use, with deciding factors including the need for reconversion, and purity requirements. Ships carrying ammonia are likely to be more economic for intercontinental distances requiring high capacities. Shipping hydrogen as ammonia for end use as ammonia could also be economical at shorter distances.

There are several options available for storing hydrogen in its gaseous and liquid state. Storing hydrogen in gaseous state is more cost effective than storage of hydrogen in liquid or solid state (ETC, 2021). In its gaseous state, options include salt or rock caverns, in depleted gas fields and pressurized containers, all with varying storage costs with salt caverns estimated as being cheapest by 2050. However, to date storage has been at relatively small scale. To meet the expected growth of the sector there are several challenges associated with these storage options that must be overcome. Ensuring a safe and affordable mechanism for hydrogen storage will require substantial investments, research, and improvements to regulatory frameworks including on safety. Hydrogen and its derivatives, including ammonia, have hazards that have been well studied and are well understood. There are effective safety control measures currently widely used throughout the existing production and supply chain for all of these products. In the case of ammonia, for example, industry has adopted the practices and processes that allow to transport millions of tons of ammonia safely every day across the globe in all types of conveyances, including through more than 100 ports. Going forward, equally strong regulatory and industry best practices will need to be adopted by countries and industries that have not yet handled these products and for the other uses for which these hydrogen products will be employed.

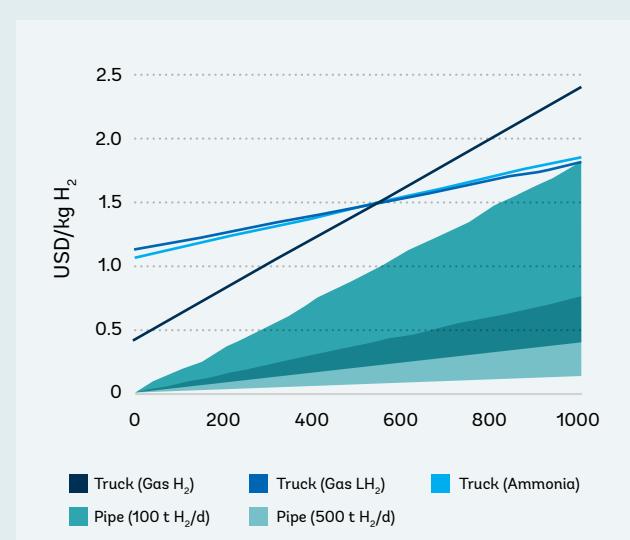
Material intensity of the hydrogen sector

The different components of the hydrogen sector require a range of materials for different technologies, from electrolyzers for renewable hydrogen, to CCS for low-carbon hydrogen, to the fuel-cells using hydrogen to power transportation and for the pipelines needed for distribution and storage. Understanding this material intensity is vital. It can help to understand where there may be bottlenecks in the supply of a critical material that could create challenges for either the hydrogen sector as a whole, or a technological component of the sector. It is also vital to help understand the wider environmental challenges (such as GHG emissions, or water use) that may arise as a result of mining and processing the materials. This report builds on previous work in the area such as Wieclawska & Gavrilova (2021a, 2021b) and IEA, (2021). The IEA (2022) highlighted the importance of materials such as nickel, steel and aluminum for AELs and platinum and iridium for PEMELs (IEA, 2022). This study extends this work by using a confidential data-set, provides estimates for the potential material requirements of some of the key components of the hydrogen supply chain including on the production side: the renewable energy capacity required to produce renewable hydrogen; the electrolyzers, steam methane reformers, autothermal reformers and CCS equipment needed to produce renewable and low-carbon hydrogen; and on the consumption side the fuel-cells to convert hydrogen into energy to power vehicles. Thus, the numbers presented should not be seen as comprehensive of all aspects of the hydrogen supply chain. Key aspects that could not be included due to a lack of data include the energy infrastructure needed to produce low-carbon hydrogen (including natural gas extraction), and crucially the infrastructure required to transport, store, and distribute hydrogen, whether this by via pipelines, tankers, or other options. The material requirements of these components may be considerable and would benefit from further analysis. Aspects of these sections are discussed in relevant sections in Section 3. Additional details on the scope of the study are available in the methodology section (Section 2), Section 3 provides estimates for the material requirements in the production and consumption sectors modelled. In Section 4 the report places these estimates in a wider demand context, before discussing the supply context and sourcing issues in Section 5. Section 6 examines the emissions and water intensity of the material requirements and Section 7 offers conclusions and recommendations.



Box 1: Transporting Hydrogen

The cheapest hydrogen transport option depends on the distance to market, the volume to be transported and the types of products needed by the customers. For short distances costs of transportation may be low (approximately 10%) but rise with distance to 30%. Pipelines are likely to be cheapest for short distances, with trucking an attractive option to bridge the gap until a full pipeline network is in place, or to deal with low/ fluctuating demand.



Source: IEA, 2021.

⁸ ibid; IRENA (2021) Making the breakthrough: Renewable hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi; <https://www.rechargenews.com/energy-transition/will-us-and-european-green-hydrogen-markets-soon-be-flooded-by-cheap-chinese-electrolyzers-2-1-1165966>

⁹ Moreira, Susana, "Low-carbon hydrogen: State of Play", Workshop on Unlocking the Potential of Hydrogen in Mauritania, World Bank, May 2022.

¹⁰ Department of Energy (2022) Hydrogen Pipelines, Available at: Hydrogen Pipelines | Department of Energy



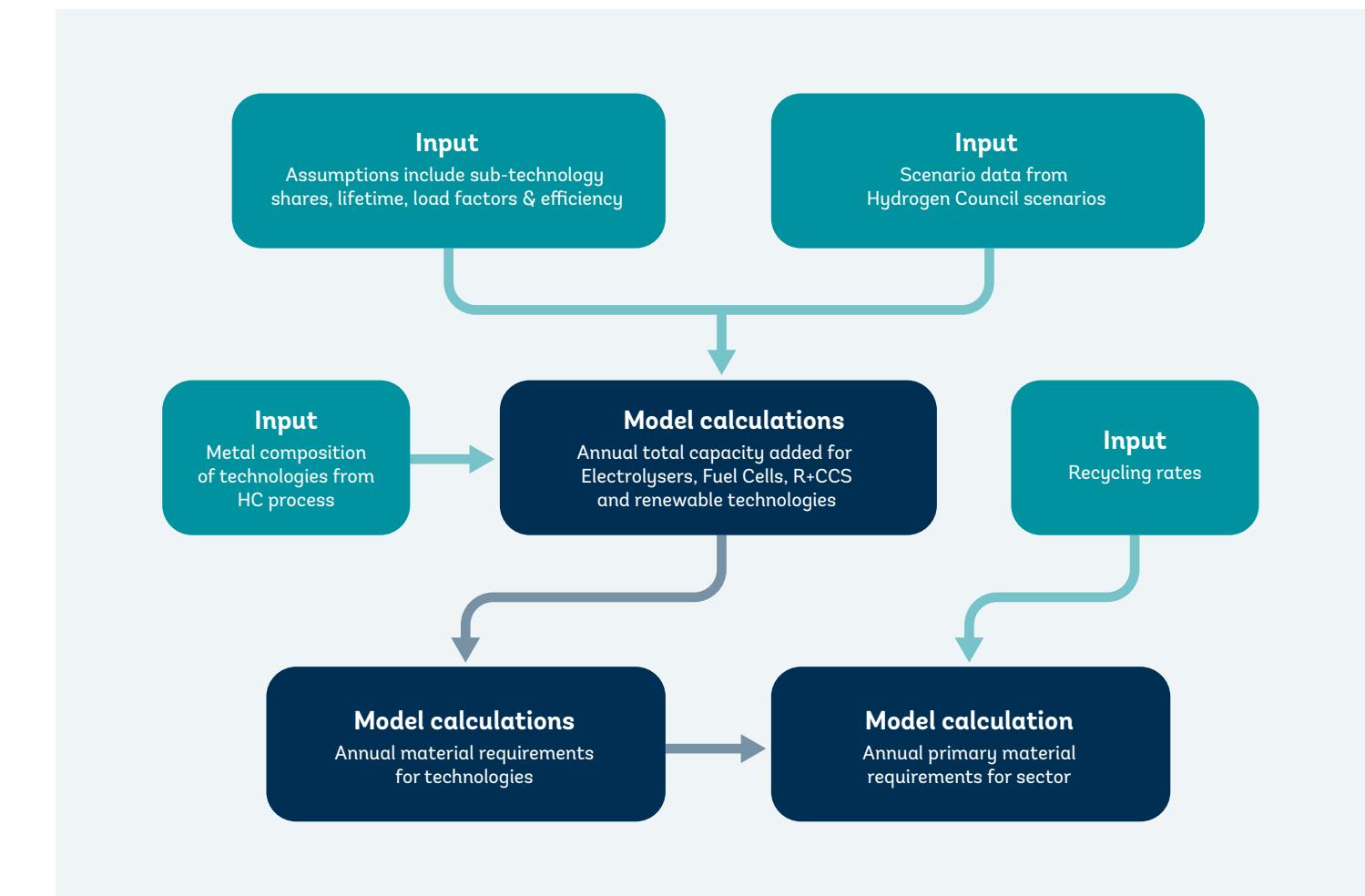
2. Methodology

The aim of the report is to provide estimates for the material requirements of the wide-scale production and use of clean hydrogen across the economy. The conceptual underpinning of the modelling follows the approach adopted in Hund et al (2017) and Hund et al (2020). The schematic of the modelling is provided in Figure 3:

The analysis examines some of the key aspects of the hydrogen production and consumption process. The scope of the analysis includes:

- Production of renewable hydrogen including the electrolyzers and renewable electricity generation capacity required
- Production of low-carbon hydrogen including reformers (steam methane and autothermal) and CCS infrastructure, but

Figure 3: Schematic of modelling approach



excluding the energy infrastructure (e.g., natural gas extraction, pipelines, etc.). The latter component was excluded due to the complexity of modelling the different options available for gas extraction, transportation, distribution and storage and a lack of available related data.

- Consumption of hydrogen using fuel cells for transportation, both for light and heavy-duty vehicles.

Excluded from the scope was other components of the hydrogen supply chain, which could have considerable material consequences, including transportation, storage, and distribution of hydrogen. These parts were excluded due to a lack of available data on the scope of their deployment and their material intensity.

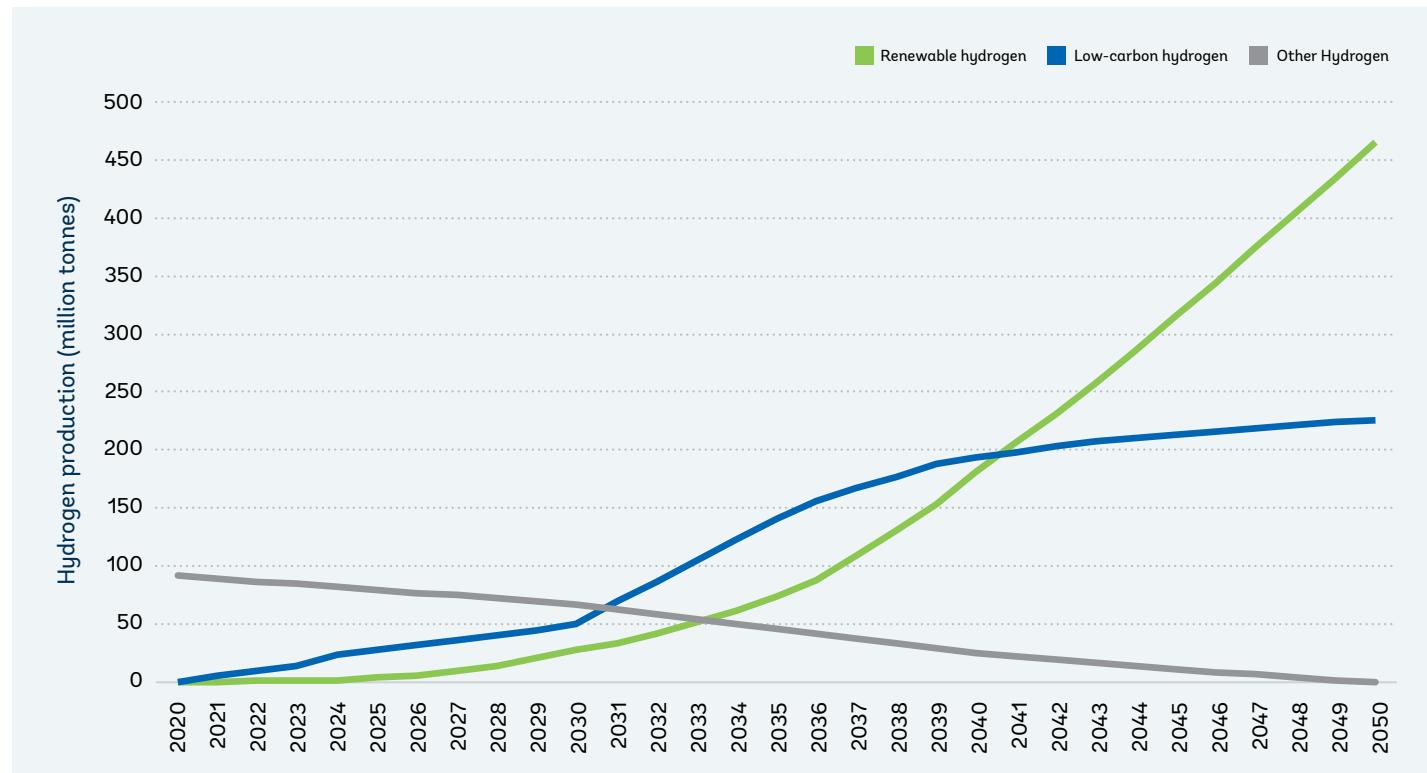
Four types of inputs are required in the modelling framework:

1. Scenarios of the future annual production and consumption of hydrogen in different sectors up to 2050.

These are provided by the Hydrogen Council from their 2021 study (Hydrogen Council, 2021a). The scenarios breakdown production between renewable, low-carbon, and other hydrogen (Figure 4). Consumption is also broken down across a wide range of categories – the split between production pathways is drawn from these scenarios, with an assumed split between electrolyzer types given in Appendix 1. The only end-uses of hydrogen that were modelled are fuel cells for use in transportation due to the lack of available data on the material content of other end-uses. For this purpose, two categories of fuel cell use in transportation were produced – light-duty vehicles (LDV) such as passenger cars, and heavy-duty vehicles (HDV) such as buses and trucks. The share of the total vehicle market that is accounted for by these vehicles is implicit in the Hydrogen Council scenarios (Hydrogen Council,



Figure 4: Projected annual hydrogen production by production pathway (Source: Hydrogen Council, 2021a)



2. Material composition of technologies

The material content of technologies involved in the production and consumption of hydrogen such as electrolyzers, steam methane reformers and autothermal reformers, CCS and fuel cells were obtained from companies in the sector via a clean-room process facilitated by the Hydrogen Council. A bill of materials was available for:

- Alkaline electrolyzers (AEL)
- Polymer Electrolyte Membrane electrolyzers (PEMEL)
- Proton-exchange membrane fuel cells (PEMFC)
- (for HDVs and LDVs)
- Reformers with CCS (R+CCS)

This data is proprietary and is thus not explicitly included in this report. Material content for fuel cells, electrolyzers and R+CCS was available for the materials shown in Table 1.

For most of the technologies estimated material content was available for present and 2050 time periods.¹¹ An assumed linear trend was made between these two data-points to give an estimated annual material content for the relevant technologies.

In addition to the material content for hydrogen producing and consuming technologies the material for the renewable energy technologies needed to power the electrolyzers for renewable hydrogen are also included. Given the diversity of renewable power options available and the different renewable resources available across geographies calculating the exact mix of renewable technologies that will be used to power the production of renewable hydrogen is beyond the scope of this report. A simplifying assumption of a mix between 50% wind turbines and 50% solar PV panels powering electrolyzers was made. Within these technologies a range of sub-technology options are also available. For example, wind could be onshore or offshore, direct-drive or geared. To simplify these options, it is assumed that the wind turbines powering electrolyzers are onshore, geared, and the solar panels are crystalline silicon. These are the most common types in the market for both technologies today, although future changes in technology are likely. Therefore, the material implications for the renewable technology component should

be seen as indicative of scale rather than of demand for any individual material.

Assumed material content for the wind and solar PV technologies was the same as was used for Hund et al (2020) – drawn from an array of wider literature sources and is assumed constant over time. Material content was included for the following materials:

- Aluminum (Solar PV)
- Copper (Solar PV, Wind)
- Nickel (Solar PV, Wind)
- Zinc (Solar PV, Wind)

Table 1: Material content and technology coverage

Material	Technologies		
Cerium	PEMFC		
Chromium	R+CCS		
Cobalt	R+CCS		
Copper	AEL	PEMEL	R+CCS
Graphite	AEL		
Iridium	PEMEL		
Manganese	R+CCS		
Molybdenum	R+CCS		
Nickel	AEL	R+CCS	
Niobium	R+CCS		
Platinum	PEMEL	PEMFC	
Titanium	PEMEL	R+CCS	
Tungsten	R+CCS		
Vanadium	R+CCS		

¹¹ Forecasting technology roadmaps on a 2050 timescale is challenging and therefore estimates for 2050 may be conservative. Intensive research and development as well as technology improvements could lead to greater reductions in material loading.

3. Additional technology and sub-technology assumptions

A basket of other assumptions was made in the modelling process. These include:

- Share of different electrolyzer and fuel-cell sub-technologies
- Capacity factors of renewable technologies
- Lifetime of renewable technologies
- Lifetime of electrolyzer, steam methane reforming and CCS technologies
- Lifetime of fuel-cell technologies
- Fuel-cell conversion efficiencies
- Fuel-cell running time per day

Values for these variables were drawn from the clean-room process where available (e.g. the stack size per vehicle), or from relevant literature such as NOW (2018), IRENA (2020) & Wieclawska & Gavrilova (2021b). Details are given in Appendix 1.



4. Material recycling rates

Recycling rates, both end-of-life and recycled content, were drawn from Graedel et al (2011) or from the clean room process for materials such as platinum, iridium and cerium for which estimates for the recovery rate from within the hydrogen sector were provided.

The major assumptions made were that material from within the hydrogen industry (e.g., from spent electrolyzers and fuel-cells) could be made available at end-of-life rates. However, material from outside the hydrogen industry was available at recycled content rates, i.e., the prevailing mix between primary and secondary material. Recycling rates were assumed to be constant up to 2050.

5. GHG emissions and water footprint estimations

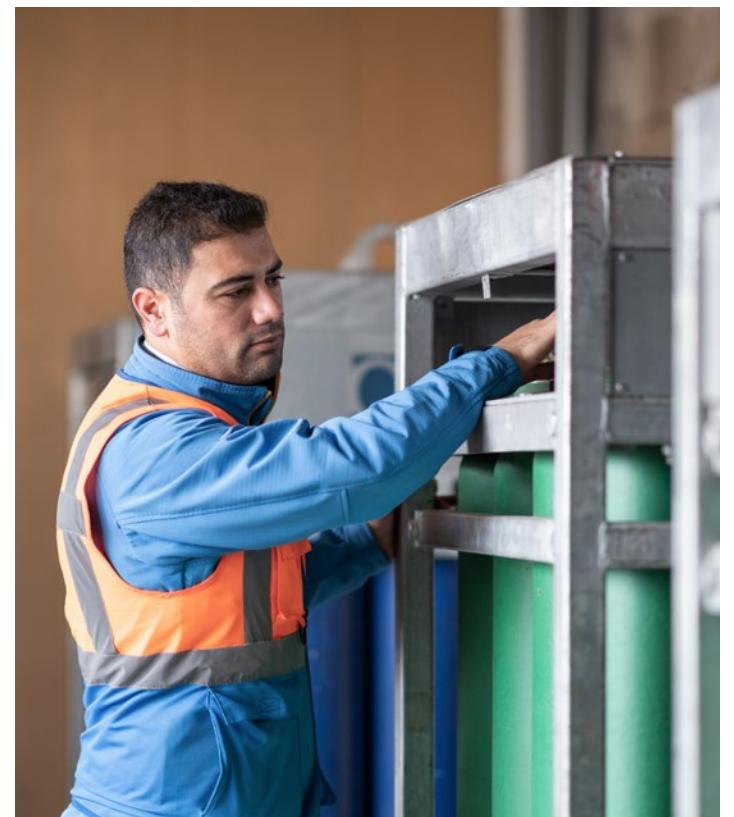
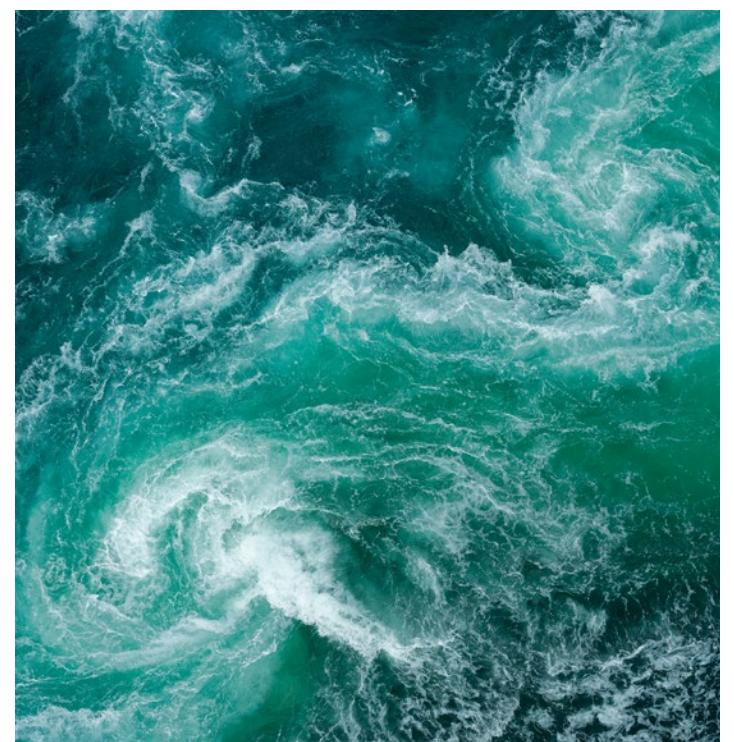
Estimates for the GHG emissions footprint from the materials and operations of renewable and low-carbon hydrogen production were produced. Material content for the production pathways were drawn from the modelling described above, with emissions intensities for the mining and processing of primary and secondary material drawn from Nuss and Ecklemann (2015) and assumed constant up to 2050. This is a strong assumption as a multitude of factors may shift the emissions intensity of mining and processing in either direction. Increasing the use of low-carbon energy sources such as renewables, or indeed clean hydrogen, in mining and processing is likely to reduce the intensity of production. On the other hand, declining ore grades, for example in copper, may increase the energy and therefore emissions intensity of production, assuming the energy source remains unchanged and renewable energy technologies not utilized.

For the computation of the water footprint of the materials input and production of clean hydrogen, data on the water intensity of different clean hydrogen production pathways from the Hydrogen Council (2021b) was used. These were combined into representative averages for renewable, low-carbon, and other hydrogen production, and then combined with regional estimates of hydrogen production from Hydrogen Council (2021a). Data on availability of renewable water resources was drawn from the FAO's Aquastat database.¹²

This section does not include emissions nor water footprint calculations for the consumption of hydrogen via fuel-cells. This process does not have a direct emissions or water footprint, and although there will be an indirect impact from the materials footprint, this is likely to be smaller than the manufacturing impact that is beyond the scope of this report.

Sensitivity

Given the uncertainty regarding a range of key parameters a number of scenarios were analyzed using the model described above. These scenarios are described in Appendix 2 and involved varying key parameters based on either values from the literature or mathematical spreads around the base case assumed parameter. Results presented below are drawn from this group of scenarios unless otherwise stated.





3. Total material requirements of the hydrogen sector

The aim of the report is to present the potential material requirements from delivering the proposed deployment of the hydrogen sector as envisaged in the scenarios developed by the Hydrogen Council. As described above the model covers elements through the electricity generation infrastructure for renewable hydrogen production, through the technologies required to produce clean hydrogen along different pathways to selected end-uses of the energy carrier such as fuel cells used in LDVs and HDVs. The material requirements are examined in three stages: production, consumption and distribution and storage.

Production

Two pathways of clean hydrogen are included in the analysis: renewable hydrogen production via renewable electricity and electrolyzers; and low-carbon hydrogen production via reformers (such as steam methane and autothermal reformers) and CCS. Included in the scope of the analysis is the renewable electricity generation needed to power the renewable hydrogen. Key materials in the renewable pathway include aluminum, copper, zinc and nickel for the wind turbines and solar PV panels, platinum, iridium, titanium and copper for PEMEL electrolyzers, and copper, nickel and graphite for AEL electrolyzers. For low-carbon hydrogen key materials include manganese, copper, zinc, nickel, titanium, niobium, chromium, tungsten, molybdenum, cobalt and vanadium.

Box 2: Producing clean hydrogen: Renewable

Production relies on the process of electrolysis where electricity is used to split water into hydrogen and oxygen. The reaction takes place in a piece of equipment called an electrolyzer. These can either be appliance sized units – for small-scale decentralized production, or large-scale centralized production facilities. The source of electricity is what makes the process ‘renewable’ – if electricity comes from renewable sources there is no direct emissions from this process. Electrolyzers, like fuel-cells, have an anode, cathode and an electrolyte, and come in different types. Polymer Electrolyte Membrane electrolyzers (PEMEL) have a solid-specialty plastic material as the electrolyte. Water reacts at the anode (which contain iridium and titanium) to form oxygen and hydrogen ions, which move across to the cathode (where platinum is used). Here the ions combine with electrons to form the hydrogen gas required. Alkaline electrolyzers use a similar process but the electrolyte is a liquid alkaline solution and there is no requirement for catalysts such as iridium and platinum. The technology is more established but PEMELs can ramp up and down more quickly and are more suited to coping with the intermittency of renewable power.

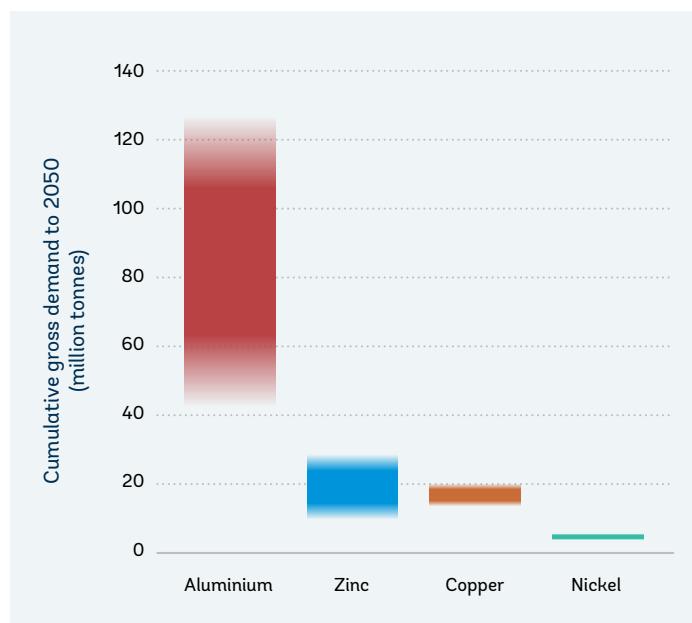
Box 3: Producing clean hydrogen: Low-carbon

This is mainly produced via the process or ‘reforming’ natural gas, most commonly using steam methane or autothermal reformers. In steam methane reforming, natural gas is combined with very hot steam, in the presence of a catalyst (such as nickel), creating hydrogen and carbon monoxide in an endothermic reaction. Water is then added which converts the carbon monoxide to carbon dioxide and creates more hydrogen. Autothermal reformers follow a similar process but use oxygen and carbon dioxide or steam in an exothermic reaction to produce hydrogen gas and carbon monoxide. What is crucial to either process is adding carbon capture and sequestration (CCS) with high capture rates to minimize the emission of CO₂. A variety of materials such as copper and steel are needed in this process to capture the CO₂ from the air flue and for the pipelines to transport CO₂ to the site where it will be stored or used.

Largest demand from the energy infrastructure required

The greatest demand for materials, by volume, up to 2050 comes from the materials needed to construct the renewable energy infrastructure needed to power electrolyzers that are projected to produce 67% of the total hydrogen production in 2050. The exact make-up of the renewable energy technologies that will provide the renewable electricity required is inherently uncertain. It will vary depending on the global deployment of renewables, and also from location to location depending on where hydrogen electrolyzers are deployed. As discussed above an illustrative scenario of 50% wind (onshore geared) and 50% solar PV (crystalline silicon) is used to highlight the material implications. The scale of the demand for the materials needed for these technologies is shown in Figure 5. To put these numbers in context, total annual aluminum production in 2021 was 68 million tonnes – with gross material demand in 2050 (i.e. total demand for materials, before recycled material has been accounted for) at just 6% of this level. Nickel demand relative to production in 2050 is slightly higher at 8% and copper slightly lower at 4%. The comparison with production is examined further in Section 5.

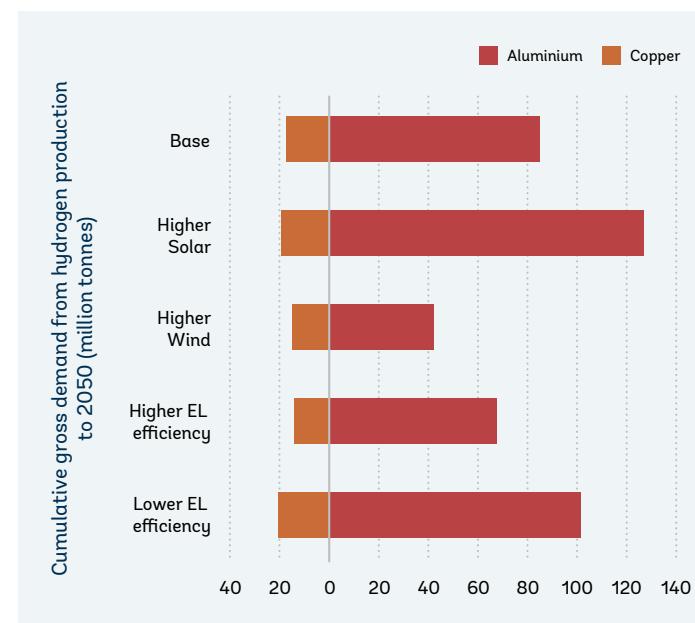
Figure 5: Cumulative gross demand up to 2050 for Al, Zn, Cu and Ni from the hydrogen sector



It should be noted that these estimates are highly dependent on the type of technologies, and sub-technologies assumed to provide renewable electricity to electrolyzers to produce renewable hydrogen. For example, should a greater role for permanent magnet-excited wind turbines be assumed then demand for materials such as neodymium or dysprosium would increase. On the other hand, should the mix of renewables be less solar-intensive, or utilize different types of solar technologies, then the overall demand for materials such as aluminum from clean hydrogen would be less.

An example of the sensitivity of these results to not only the assumptions regarding renewable electricity mix, but also the assumed efficiency of the electrolyzers that will affect how much renewable infrastructure is needed to produce a given amount of hydrogen, can be seen in Figure 6. This shows that the demand for aluminum and copper can vary significantly from the base scenario, just by varying aspects such as the extent of solar PV in the assumed renewable electricity mix, the efficiency of the electrolyzers and the capacity factors of the solar panels. These illustrative scenarios are outlined in Appendix 2.

Figure 6: Cumulative gross demand for Al and Cu from hydrogen to 2050 under various scenarios¹³



Hydrogen will demand a wide variety of minerals for production and consumption technologies but in relatively small volumes

Beyond the materials needed for the electricity generating technology several other materials are needed across the electrolyzers, fuel cells, reformers and CCS facilities needed to supply clean hydrogen. By volume, the largest of these materials are manganese (needed for low-carbon hydrogen), titanium (needed in PEMELs and for low-carbon hydrogen) and graphite (used in AELs) (Figure 7a). Although the volume of these materials may appear to be absolutely large, this does not directly translate into criticality, given the discussion on the supply context in Section 5. Beyond these materials, there is a larger basket that is needed in smaller absolute volumes. These include niobium, chromium, platinum, tungsten, molybdenum, vanadium, iridium and cobalt (Figure 7a).

Many of these minerals are only predominantly required in one component of the hydrogen sector. For example, manganese is required for low-carbon hydrogen, along with niobium and chromium, whilst graphite is needed for electrolyzers. The demand for these materials that are only needed in a singular hydrogen technology, can be considered as especially uncertain, as they will depend on both the scale of deployment of hydrogen generally, but also the scale of the particular technology used to produce or consume hydrogen.

The estimates are highly sensitive to assumed parameters – critical aspects include the shares of PEMELs in electrolyzer deployment, the efficiency of these electrolyzers and their utilization rates. Figure 7b shows the range of estimates for gross (i.e. before any recycled material has been taken into account) cumulative demand for iridium and platinum for hydrogen production up to 2050 for scenarios relating to the share of PEMELs in deployed electrolyzers. Higher shares for PEMELs in electrolyzer deployment increase the gross cumulative demand for iridium and platinum, whilst lower shares reduces this demand.

A critical assumption is the material loading assumed for these key materials. Within the dataset there is a considerable reduction in the amount of iridium required, with an 80% reduction in the iridium required per electrolyzer by 2050. However, there is considerable investment in the industry in research and development to reduce the amount of iridium and platinum

Figure 7a: Cumulative gross demand up to 2050 for Mn, Ti, Graphite, Nb and Cr, W, Mo, V and Co from hydrogen production in base scenario¹⁴

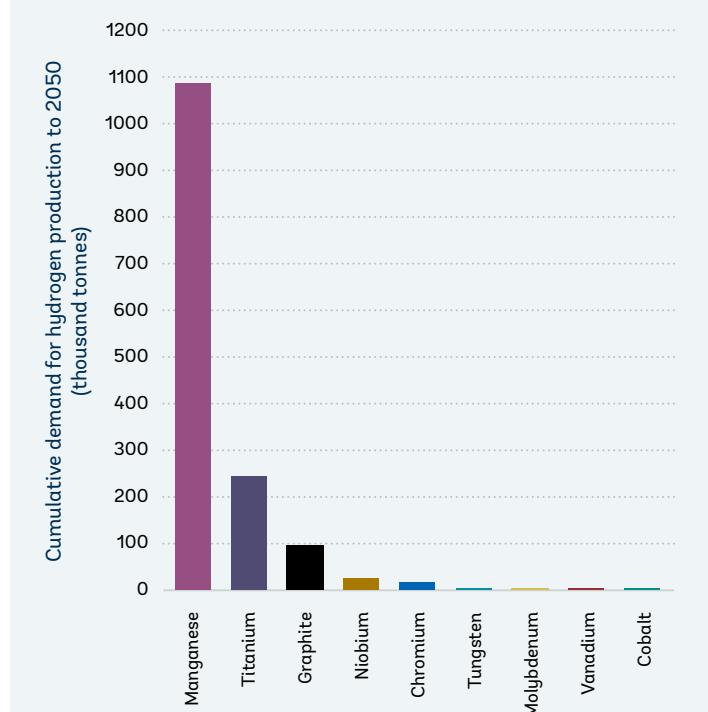
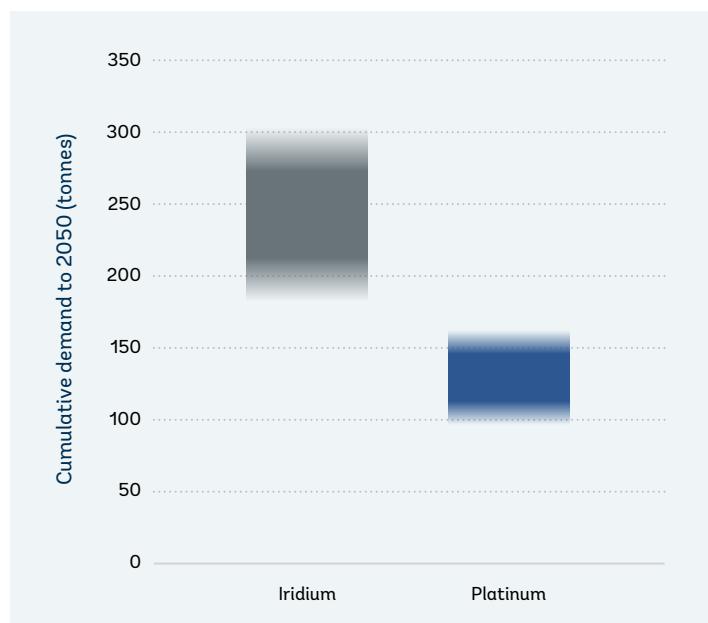


Figure 7b: Cumulative gross demand up to 2050 for Pt and Ir from hydrogen production under various assumptions



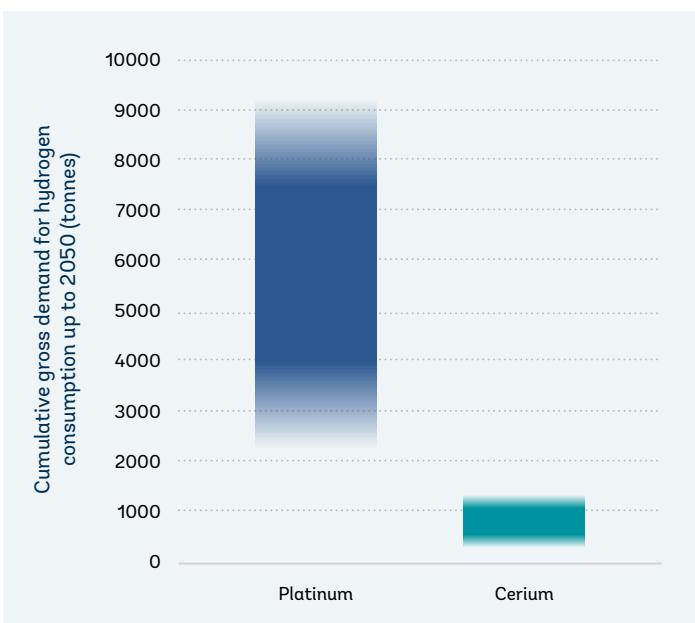
required in these technologies. Academic literature has projected potentially extremely low future iridium requirements – between 0.05 g per KW by the late 2020s and 2030s (Babic et al, 2017; Smolinka et al, 2018) and 0.01 by 2100 (Bernt et al, 2018). The US Department of Energy's H₂NEW consortium has established a range of targets for the industry including a target of 0.039 g per KW.¹⁵ Such targets, should they be achieved, would have a crucial impact on the gross demand for iridium. For example, meeting this target, compared to the future level forecast during the cleanroom process, would reduce 2050 gross demand for iridium by over 60%. Focusing investment and research and development in this area would therefore have substantial benefits in reducing any bottlenecks that could occur.

Consumption

As discussed in Section 1 hydrogen is projected to be a crucial energy carrier and feedstock for an increasing amount of end-uses, from providing the energy for fuel-cell vehicles and locomotives, to providing back-up power storage for intermittent renewables, powering industries such as steel and providing heating to homes and industries. Each of these uses will have material implications, although not necessarily greater or smaller than the high-carbon options that they replace. Materials are needed for boilers, turbines and furnaces, especially steel. However, the focus of this section, will be on the key materials needed for fuel-cells used for LDV and HDV transportation. A variety of materials are needed to produce fuel-cells with two materials identified as key, via the clean-room process: platinum, used as a catalyst in PEMFC; and cerium, used to improve fuel cell durability. Estimates for the cumulative gross demand from hydrogen consumption under a range of scenarios can be seen in Figure 8.

Demand for platinum and cerium from the hydrogen sector is higher if the specific types of fuel cells (PEMFC) that require these materials account for a greater share of technology deployment. Additionally, if fuel cell vehicles are used less often, then there is a need, for any specific volume of hydrogen, for more fuel cell vehicles, and in turn more platinum and cerium. If HDVs are assumed to be used less often per day, then the demand for these metals rises – because, given a fixed level of demand for hydrogen (which can be contextualized as demand

Figure 8: Cumulative gross demand for Pt and Ce from hydrogen consumption to 2050 under various assumptions.



Box 4: Hydrogen fuel cells

Fuel-cells are a device that can convert a fuel into electricity and heat. They are similar to a battery in that they have an anode, a cathode and an electrolyte. Fuel, such as hydrogen, is introduced to the anode, and air is fed to the cathode. A catalyst splits the hydrogen into protons and electrons, creating a flow of electricity. The protons flow through to the cathode, where they combine with oxygen producing by-products of water and heat. There are a range of fuel-cell types emerging, based on different electrolytes and serving different end-uses. PEMFCs are emerging as the most useful for transportation as they can operate at relatively low temperatures and quickly vary their output. Other types are also available such as alkaline fuel-cells, and solid-oxide fuel cells.

for transportation services) using vehicles less per day means that more vehicles are required overall, increasing the demand for the materials in the vehicles, including the fuel-cells, such as platinum and cerium. This highlights the importance of efficiency in the utilization of technologies, such as the efficient operation of transport infrastructure through, for example, the implementation of load management, which is likely to be implemented should sufficient pressure arise within the system. These techniques can help to meet the low-carbon transition by reducing the overall requirement for new infrastructure and technologies and in turn the demand for materials such as platinum, that could otherwise be a limit on the deployment of low-emission technologies.

Distribution and storage

Section 1 has highlighted that a variety of options will be required for the transportation, distribution and storage of clean hydrogen from transportation via pipelines and tankers, and storage in salt caverns or pressurized containers. It is likely that a wide range of these options will be utilized depending on geographies, production pathways, end-uses and whether a centralized or decentralized model of production emerges. Each of these options will have their own material implications. The global trade in hydrogen is anticipated to grow rapidly, along with hydrogen demand and production, driven by production cost differences (with an estimated fivefold difference between lowest and highest cost markets) and resource endowments.¹⁶ The Hydrogen Council have estimated that as much as 320 million tonnes of hydrogen may be traded internationally by 2050, almost half of total production, with regions such as east Asia and Europe relying on imports from exporting regions such as the Middle East, North Africa, South America and Australia. This trade will require a network of pipelines and tanker distribution.

In terms of distribution there is likely to be both the use of existing natural gas pipelines and also new hydrogen pipeline networks. Natural gas pipelines may need reinforcing and retrofitting to take high concentrations of hydrogen but the material implications are likely to be relatively low. Constructing new pipeline networks is likely to have a much higher material footprint, mainly steel. Currently steel pipes with grades X42, X52 and X60 are being used in hydrogen networks, very similar to pipes used in the natural gas network (Krieg, 2012). These steels have maximum tolerances for

trace elements such as carbon and manganese but much of these elements are already present in iron ore and generally need to be removed to reach these tolerances. The scale of steel required for new hydrogen pipeline networks is very difficult to quantify given the uncertainty on the extent that new pipelines will need to be constructed to complement re-use and repurposing of existing gas networks. As a sense of scale for an estimated 2,500km of pipeline, approximately the size of the hydrogen pipeline network in the US today an estimated 4 million tonnes of steel would be required (Angoher et al, 1999). The European Hydrogen Backbone initiative have proposed a future hydrogen pipeline infrastructure across 21 countries that would amount to 39,700km of pipes by 2040, of which 69% would consist of the existing gas network and 31% of new pipelines to connect to new off-takers. These new pipelines would require a total of approximately 20 million tonnes of steel – equal to about 1% of current annual global steel production. Beyond pipelines there is also likely to be demand for tankers and trucks to complement pipeline networks for international transport and to distribution to end-use. These will again require materials, predominantly steel, but may have other material implications depending on the nature of these vehicles, especially the power source, whether conventional, fuel-cell based or battery.

For storage the main material implications are likely to arise from the tanks needed to store hydrogen, either within vehicles or to complement other large storage solutions such as salt caverns. Again, the main material implication is likely to be related to use of steel and other elements that it is required to be alloyed with to make the stainless steel likely to be required. The distribution and storage of hydrogen is unlikely to be affected by shortages in steel, but there may be impacts from the rising demand for steel from other aspects of the energy transition, and also environmental implications from using such steel. Further analysis of the material implications of both distribution and storage is a crucial area for future research.



4. Wider low-carbon transition demand context

The estimated levels of demand for minerals from the hydrogen economy need to be seen in a wider context of the low-carbon transition. The scale of demand from competing technologies from within (and outside) the wider low-carbon transition may cause challenges to the security of supply of some of the minerals required. Some of the materials required for elements of the hydrogen sector are also potentially required in large volumes, beyond current production levels, for other components of the low-carbon transition. However, this higher level of demand is uncertain, given that the demand from other technologies in the low-carbon transition such as solar PV panels, wind turbines and lithium-ion batteries is unknown, along with demand from other sectors such as Information Communications and Technology.

The wider demand context of many of the materials needed for the low-carbon transition has been the focus of initiatives such as the World Bank Group's Climate-Smart Mining (CSM) Initiative (Box 5) and analyzed in reports such as IEA (2021) and Hund et al (2020). The latter study categorized the 'climate action minerals' required for the low-carbon transition into four broad categories via its Demand Risk Matrix. This matrix plots materials on two axes: a weighted coverage-concentration index that captures how cross-cutting or concentrated in a few technologies minerals are; and a production-demand index that captures the scale to which production must scale up (both relatively and absolutely) to meet future demand from the low-carbon transition. The four categories of materials based on these axes are:

- **High-impact minerals**

These have large levels of future absolute or relative demand compared to existing production levels but are concentrated in a small subset of technologies and therefore this level of demand is especially uncertain, given that demand may shift away from that particular technology, for example if alternatives to lithium-ion batteries emerge more strongly than predicted.

- **Cross-cutting minerals**

These minerals may not face as large absolute or relative increases in demand but are used across a wide range of technologies and thus this demand is likely to arise no matter the exact technological mix that occurs.

- **High-impact cross-cutting minerals**

These minerals fall both into the high-impact and cross-cutting categories and thus face high levels of future demand but are found across the low-carbon transition.

- **Medium impact minerals**

These minerals face neither the high levels of demand nor are used across a wide basket of low-carbon technologies, however they may be used in high concentrations in a particular technology or sub-technology.

Box 5: Climate-Smart Mining Initiative

Climate-Smart Mining (CSM) supports the sustainable extraction, processing and recycling of minerals and metals needed to secure supply for low-carbon technologies and other critical sectors by creating shared value, delivering social, economic and environmental benefits throughout their value chain in developing and emerging economies. The World Bank's Climate-Smart Mining Initiative is a public-private partnership led by the World Bank and IFC with the aim of achieving more sustainable mineral supply chains by providing technical and policy advice, direct investment financing, leveraging private sector financing, providing risk mitigation instruments, and helping countries define and craft tangible solutions for decarbonizing and improving ESG standards for climate action minerals. CSM achieves this objective by focusing its activities on a framework developed in consultation with key stakeholders in government, industry, and civil society, serving as guidance to help mineral-rich countries integrate climate-smart approaches through four pillars:

- Climate Mitigation
- Climate Resilience
- Circular Economy
- Creating Market Opportunities.



Figure 9 shows the mapping between the minerals modelled and the Demand-Risk Matrix. What it highlights is that materials needed for hydrogen fall into each of these four categories, and thus face differing broader demand-risk profiles. Some materials such as graphite and cobalt, needed in the hydrogen economy for electrolyzers and CCS respectively, face potentially massive increases in demand from singular technologies, namely lithium-ion batteries (Hund et al., 2020; IEA, 2021). There could therefore be considerable pressure on supplies should such demand arise – causing either potential shortages or increases in price. However, the concentrated nature of these materials in a specific technology makes the nature of this demand especially uncertain given that there may be major changes in for example, how many lithium-ion batteries will be demanded, or what the material composition of these batteries will be, raising questions about how supply will respond.

Minerals such as nickel and copper could also face large increases in demand, but face a different type of demand risk, as they are used across a wider basket of technologies. The IEA project demand for nickel from low-carbon transitions at over 140% of

current production levels by 2040 under the SDS, predominantly from batteries (IEA, 2021). Demand for copper from low-carbon technologies was projected by the IEA to reach 72% of current production levels, two-thirds of which to be used for electricity networks. These cross-cutting minerals face both large increases in demand but also from a range of sources across the transition, implying that the demand is more likely to materialize than for those technologies for which demand is concentrated. This creates a different demand risk profile, in that the hydrogen sector would be competing with a wide range of increasing demands from across the low-carbon transition for these products, but suppliers would face a more certain demand profile and may adjust accordingly.

For a range of other minerals such as vanadium, titanium and zinc, the size of the demand from the low-carbon transition compared to current levels of demand and production are much smaller, and these materials are concentrated in a small subset of technologies, implying technological shifts across the transition may affect their demand in a substantial way. For example, vanadium, needed in the production of low-carbon hydrogen, may also play a substantial role in stationary energy storage, being used for redox flow batteries. However, the emergence of such batteries at scale is uncertain, with many other substitutes available. Thus, hydrogen may face large, or small competition for materials such as vanadium, dependent on the wider technological mix of the low-carbon transition.

Although not covered in the Hund et al (2021) study cerium may also face a similar demand context as other rare-earth metals such as neodymium. Given the supply challenges with rare earths this could create challenges if the demand from competing technologies increases more dramatically.

The wider context for the materials required for hydrogen is made more complex by the fact that for some minerals there is a variety of types available, for which demand may arise. For example, there are two classes of nickel, Class 1 and Class 2, depending on the quality. Technologies such as lithium-ion batteries require the high purity Class 1 that represents about half of current production. Therefore, components of the hydrogen economy that require this purity of nickel, such as electrolyzers, are potentially competing with a more concentrated level of demand than the overall nickel market.

Figure 8: Demand risk matrix and materials needed for the hydrogen economy





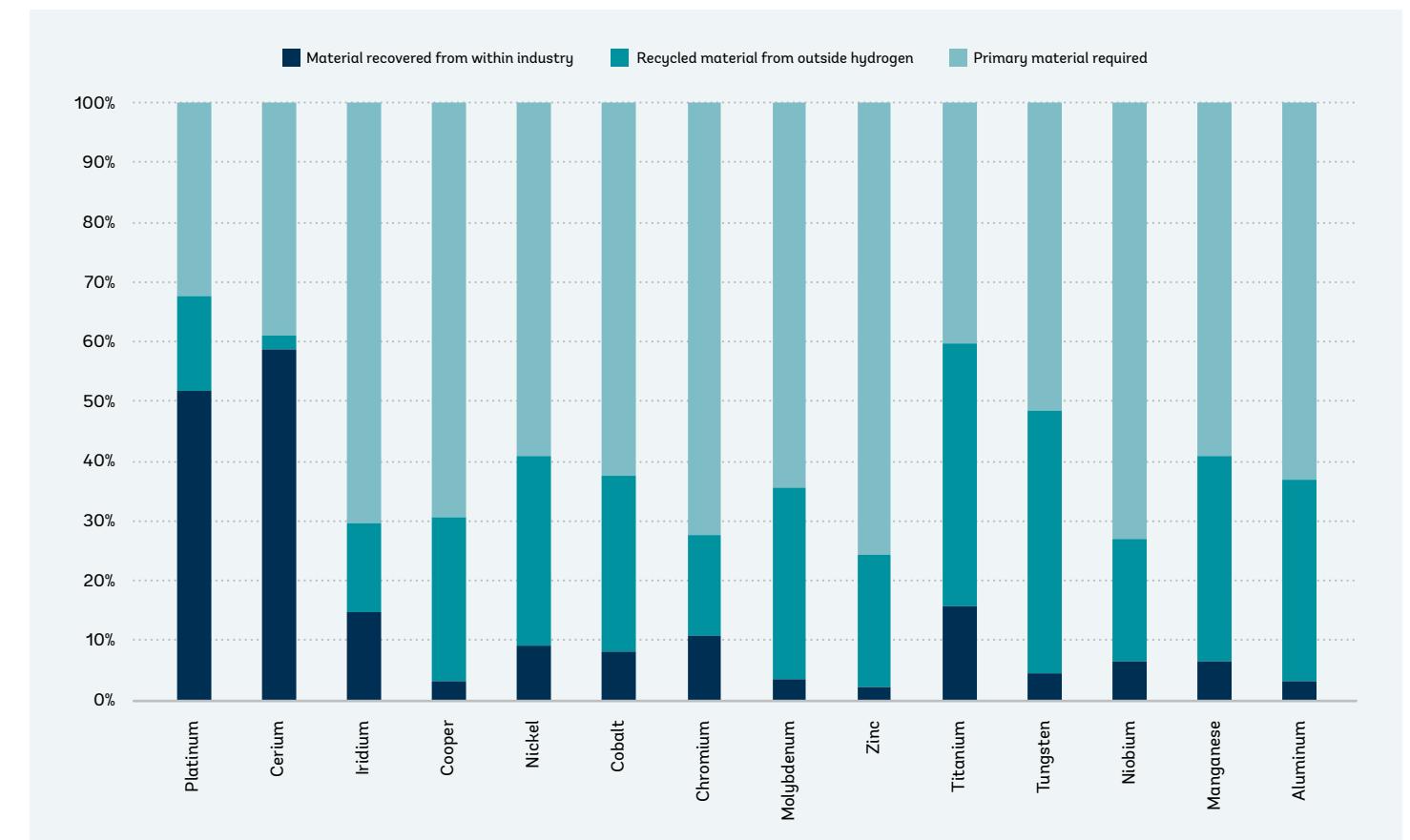
5. Primary and secondary sourcing and supply context

The estimates presented in the previous section are for the material demanded by key technologies involved in the hydrogen economy, covered by the scope of the model, such as electrolyzers, reformers (steam methane and autothermal), fuel cells, and the renewable technologies needed to power renewable hydrogen. They do not represent the actual amount of primary material that needs to be mined and processed. To do so assumptions must be made regarding how much can be acquired from secondary sources, such as recycled material from within, but predominantly outside the hydrogen sector given the nascent scale of the sector. The scale of the availability of secondary material varies from material-to-material and depends on the ease of recyclability, the availability of scrap and the economics of secondary production. Predicting future recycling rates is extremely challenging, given the scarcity of data on even

recycling rates today. The assumptions made in this analysis regarding the scale of recycling are highlighted in Section 2 above with notably the assumption that recycling rates are unchanged up to 2050.

Figure 10 highlights that the share of primary material to overall demand varies significantly between materials, as does the ability to access material from within the hydrogen sector compared to outside. This latter component is dependent both on the ability to source material from hydrogen producing and consuming technologies at the end of their lives (end-of-life rates) but also on the scale of material is available to be reclaimed. This in turn depends on the scale, and speed, at which technologies are deployed, and their estimated lifetimes. Increased lifetimes, for example, would reduce the demand for materials for replacement,

Figure 10: Share of demanded material by source for materials for hydrogen¹⁷



¹⁷ Vanadium and graphite were excluded here due to lack of data on recycling rates.

but also reduce the availability of scrapped materials to be recycling into new technologies. Increasing lifetimes could be particularly significant for materials in which future reductions in material intensity are greatest as it would help to shift forward demand to a time when R&D and technological improvements have reduced the materials required for these technologies.

As seen in Figure 10 the smallest share of primary material required compared to overall demand is for platinum and cerium. This is due to the high estimated recovery rates within the sector, and, in the case of platinum, high recycled content rates for the material generally. These phenomena are often a function of high prices for the materials, that drive the incentives for recovery, along with features of how the materials are used in the various technologies that aid recovery. Materials such as niobium (used in reforming) have much higher shares of primary material due to lower recovery rates and return to the open market, both in the hydrogen sector and the wider economy, coupled with smaller sources of available material. This potentially makes primary sourcing of these materials even more important. Materials such as cerium, used predominantly in fuel-cells – with 15% for LDVs and 85% for HDVs, face challenging wider recycling environments – meaning that recovery of secondary material from within the hydrogen sector is even more important – though this also creates the challenge that even with high internal recovery rates there is a significant time-lag at which this material will be available due to the lifetimes of the technologies involved.

Should recycling rates increase up to 2050, due to increased collection, improved recovery from waste products and wider moves to a circular economy – this would reduce the level of primary material required. Even with ambitious increases in recycling rates, however, the requirement for primary material is unlikely to disappear completely, due to, amongst other factors, limited availability of scrap.¹⁸ For example, if higher rates of recovery are assumed for platinum recovery from within the hydrogen sector (to 99% recovery of available material) the requirement for primary platinum falls by only 18%. Greater recycled content of platinum from outside the hydrogen sector (from 33% to 50%) reduces primary requirement by 25% - and if both rates increase primary demand still only falls by 39%. This

highlights both, the important role that increased recycling can have in providing the materials required for the hydrogen sector (along with providing them at lower emissions, as discussed in Section 6 below), but also the limitations that increased recycling will have, and therefore the likely need for residual primary production.

Crucial is action to increase recycling and, where appropriate, re-use. Designing-in circularity, re-use and recyclability helps to assist in technical and economic barriers to secondary material collection and helps avoid potentially expensive and energy-intensive recycling processes where components can be re-used. Designing also for loading thrift, material substitution potential and crucially increased lifetimes can also help to reduce primary material demand. A variety of material substitution potentials exist in the various technologies such as substituting titanium by graphite in electrolyzers, and even substituting iridium with materials such as ruthenium.¹⁹

Given this likely requirement for at least maintained or possibly increased primary production from the materials required for the hydrogen sector it is important to ask the question of whether there are sufficient quantities of these materials available to meet the requirements of the hydrogen economy, and where there may be challenges in meeting this demand. This overall question leads to three sub-questions:

- Are there sufficient reserves (or resources) in the ground to meet this demand for materials?
- Is there sufficient production capacity to meet projected levels of primary demand?
- Are there alternative sources of supply that can be used to meet the levels of primary demand?

Primary demand v resources

There are two measures for the level of materials that are in the ground. Resources are a concentration or occurrence of material of economic interest that has reasonable prospects for eventual extraction (Nurmi & Rasilainen, 2015) while reserves are a subset of resources and are defined as the economically mineable part of resources. Reserves are a more proven component of material in the ground, whilst it is uncertain whether resources will turn into reserves. Given this, the chosen variable for analysis here is reserves. Figures 9a and 9b show how the level of cumulative demand to 2050 from the hydrogen sector compares to estimated levels of reserves from USGS (2022). These figures highlight that the materials required for the hydrogen sector have sufficient reserves in the ground to meet the projected primary demands of the hydrogen sector. It should be noted however that, as noted in Section 4, increased or reduced demand from other aspects of the low-carbon transition, and from the wider economy, also need to be factored in to highlight any resource constraints.

The greatest utilization of reserves by the hydrogen sector is estimated to be for the materials required in building the renewable electricity generating facilities for renewable hydrogen (zinc, nickel, copper, aluminum) along with platinum group metals (platinum, iridium) (Figure 11a, 11b).

Given that there is unlikely to be an absolute shortage of materials in the ground to meet the demands of the hydrogen sector, the second question to examine is whether there may be bottlenecks in production capacity to meet the demands of the sector. Figure 12 gives a comparison between average annual primary demand from the hydrogen sector of materials compared to current (2021) production levels (USGS, 2022).²¹ Four groups of materials are evident in this chart. For iridium and platinum potential primary demand from hydrogen could represent a substantial share of current levels of production, with iridium demand from hydrogen, on average, accounting for almost half of current levels of production to 2050. The scale of these increased levels of relative demand could potentially have significant effects on the markets for these materials.

Figure 11a: Cumulative primary demand for Zn, Ni, PGM²⁰, Cu and Al for the hydrogen sector to 2050 as a % of reserves: base-case scenario

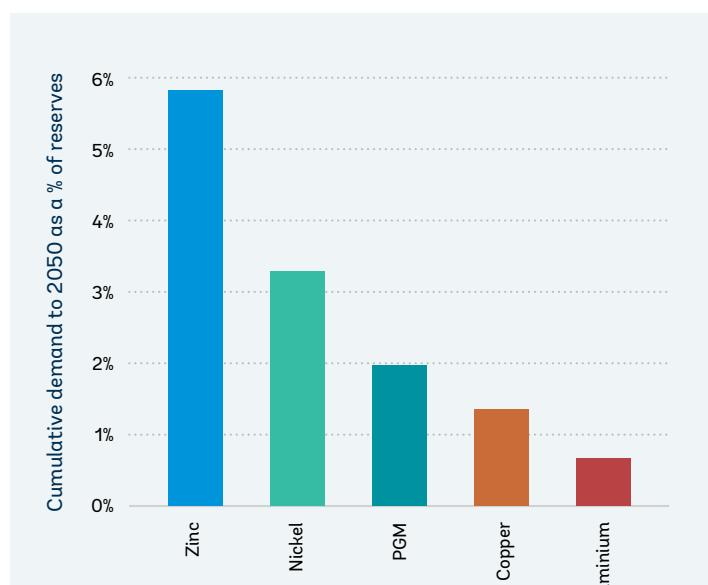
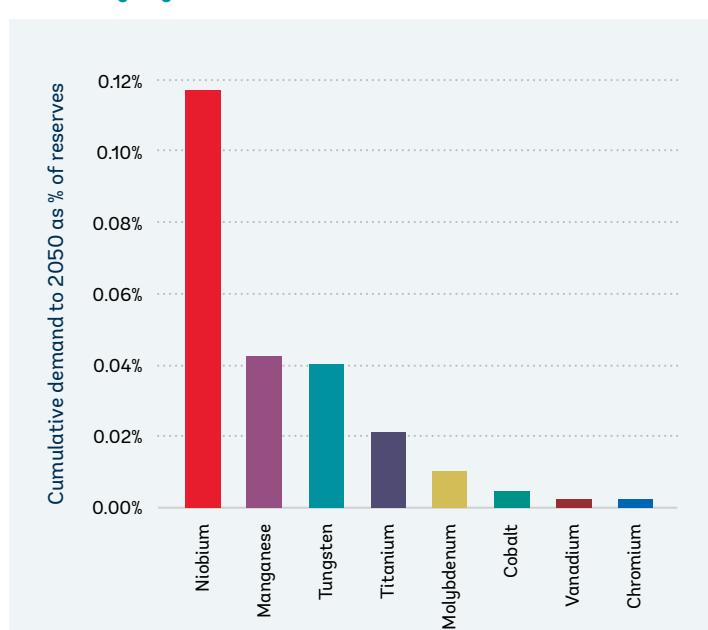


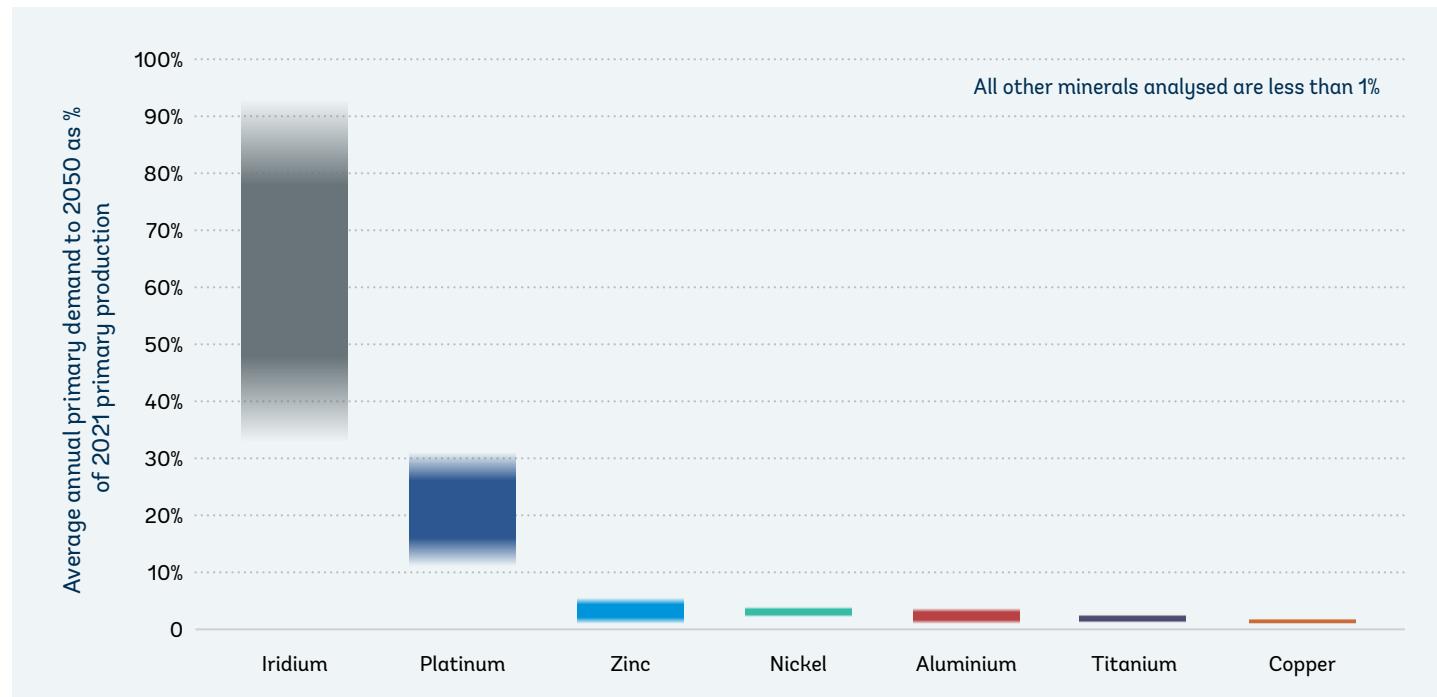
Figure 11b: Cumulative primary demand for Nb, Mn, W, Ti, Mo, Co, V and Cr for the hydrogen sector to 2050 as a % of reserves: base-case scenario



¹⁸ For example, materials such as aluminum effectively recycle almost all of the available scrap therefore increasing recycling of these materials requires increasing the scale of available scrap (either from within smelters or recovered after consumer use) in order to increase the scale of secondary production.

¹⁹ https://www.miningweekly.com/article/use-of-ruthenium-in-fuel-cells-set-to-turn-down-as-green-hydrogen-trend-turns-up-heraeus-2021-05-04/rep_id:3650

Figure 12: Average annual primary demand from hydrogen production and consumption to 2050 as a percentage of current primary production under various assumptions



For a second group of minerals including nickel, aluminum, zinc, and copper, for which a large share of demand from the hydrogen sector comes from constructing renewable electricity generation capacity, the hydrogen sector would increase demand by just a small percentage on an average annual basis (between 1.5 and 5%). Although these materials may experience only a small relative demand from the result of hydrogen production, these materials are generally produced in large quantities and so, in terms of tonnage, the scale of increase in demand is potentially significant, especially in markets that could be tight going forward, such as copper.

The third group of materials includes titanium, niobium and graphite that also have small relative increases in demand because of hydrogen production – at around 1%. These materials are used variously across renewable and low-carbon hydrogen production, but their production increases due to hydrogen are relatively small, and for the most part are also small in absolute terms. Graphite is potentially an anomaly here, especially due its wider demand context, with potentially large increases in demand from lithium-ion battery production.

The fourth grouping of materials covers a wide basket of the remaining materials, such as manganese, cerium, cobalt, vanadium, tungsten, and chromium. For these materials, the demand from hydrogen is a very small share of total current production (0.1% and below), and thus there is little risk of the market being unable to meet the supply required for the hydrogen sector, nor is there likely to be any significant effect of the hydrogen sector on the market for these materials. There could, however, be other supply challenges due to issues surrounding geographical concentration of supplies (for example cobalt and cerium) especially if that is connected with a challenging geopolitical context.

Although examining the average annual demand to 2050 can assist in understanding the relative impact that the hydrogen sector on production, there may be dynamics over the time-period that averaging demand may hide. Projected time-paths for annual demand for platinum and iridium are shown in Figures 13 and 14. Caution should be used for the values in any individual years as they are the result of broad assumptions such as the lifetime of products, however the time-paths can be illustrative of key broad trends.

Platinum: Opportunities?

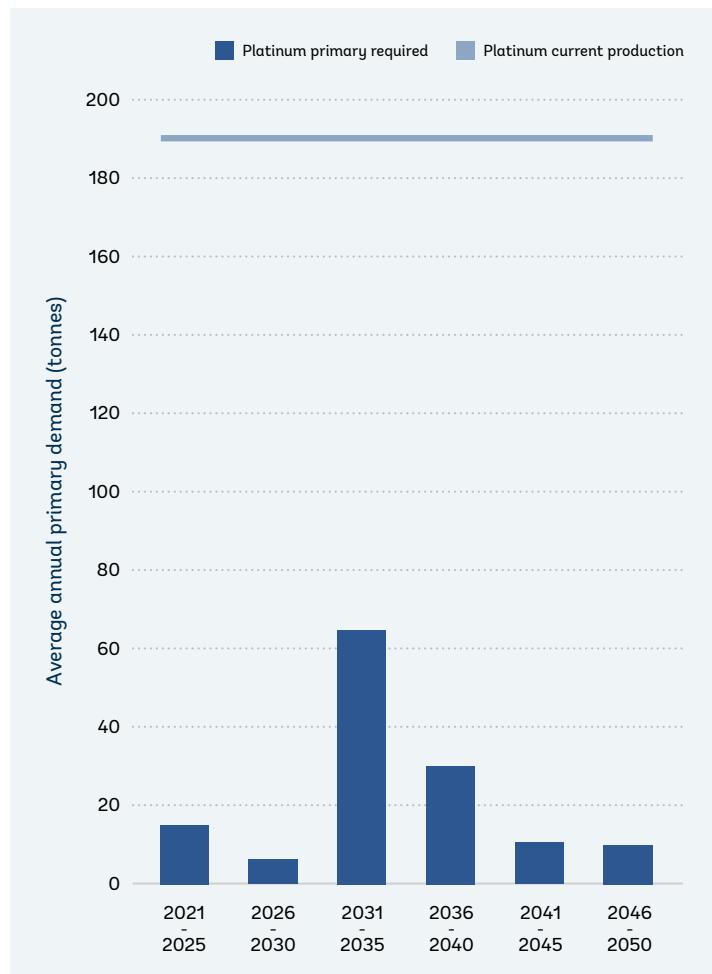
The time-path for platinum, highlights a large scale-up in primary demand from the hydrogen sector across the 2030s reaching over a third of current production levels in the base scenario (Figure 13), due to two factors:

1. The rapid projected rise in demand for platinum from both PEMELs but especially from PEMFCs – and especially for fuel-cells for HDVs that account for over 90% of the demand for platinum. Should the share of PEMFCs in general fuel-cell demand be even greater than assumed then this spike in demand could be even greater.
2. A lack of available platinum from within the hydrogen sector due to a lack of previously deployed fuel cells and electrolyzers reaching the end of their life.

By the 2040s the demand for primary platinum from the hydrogen sector is projected to drop-off for a variety of reasons. First the platinum intensity of electrolyzers and fuel cells is projected to fall, reducing, relatively, the demand for platinum as an input into the hydrogen sector per unit of technology; and, secondly, there is much greater availability of platinum from within the sector that can be utilised as scrap for input into new technologies.

This time-path potentially raises challenges but also opportunities for the supply of platinum to hydrogen, and the platinum sector as a whole. Although the scale of increased demand in the 2030s is below current levels of production, it could be large enough to have impacts on the market for platinum, including on the price. But there is a lot of uncertainty. For one, higher prices may help bring on to the market available platinum from above-ground stocks to buffer temporary supply/demand mismatches. Declining demand for platinum for catalytic converters in internal combustion engines (ICEs) and for jewelry²² further mitigates the risk that there may be bottlenecks of the supply of platinum to the hydrogen industry. Catalytic converters used in today's internal combustion engine fleet use contain up to 7g of platinum per vehicle. With over 1 billion vehicles on the roads globally, and almost 80 million being produced every year, there is potential for both a large source of scrapped platinum as catalytic converters become redundant with increased electric and fuel-cell vehicles in the fleet, and also a reduced demand for platinum from outside the hydrogen sector. The auto-catalytic sector currently accounts

Figure 13: Projected time-path for net demand for primary platinum from the hydrogen sector to 2050



for about 40% of current demand for platinum (Reverdieu et al, 2021) and a tail-off in demand for this area could create space for increased demand from the hydrogen sector to fill. In turn increased scrap availability from an increased movement of the vehicle fleet away from ICEs would also facilitate the supply of platinum to the hydrogen sector. Recovering the platinum from the vehicles scrapped each year in just the EU would meet approximately 25% of the peak primary material demand for platinum from the hydrogen sector in the base-case scenario. However, recovery rates from this source are already extremely high due to the value of the platinum. But increased rates of scrappage due to moves to electric vehicles, coupled with

increased efforts to recover platinum could greatly assist with meeting the primary demand from the hydrogen sector.

The majority of platinum production occurs in southern Africa, with seventy-two percent of global platinum production comes from South Africa (USGS, 2022), which has approximately twenty, operating mines for which platinum is the primary commodity.²³ While there are several platinum mining projects currently in exploration or feasibility stages in South Africa, there are still a few platinum mining projects on hold, moth balled or closed. All of this highlights the potential for bringing more production capacity on stream in South Africa to help overcome spikes in demand for platinum, should the right economic and regulatory conditions exist. While waiting for these various potential projects to materialize, clear incentives and sustained capital investment will be required to maintain production levels in the country as existing shafts and infrastructure reach the end of their life.

Box 6: Hydrogen and platinum mining

In 2022, Anglo-American, one of the world's largest producers of platinum, launched a prototype of the world's largest hydrogen-powered mine truck, for use in one of its PGM mines in South Africa. With diesel emissions from mining trucks accounting for approximately 15% of its scope 1 emissions, the deployment of such trucks, that can be powered by renewable hydrogen produced on-site, is an important step in the company providing lower-emissions platinum. Such action, in turn, can help to reduce the environmental impact of renewable hydrogen production, which in turn could help boost the demand for platinum. Encouragement of such virtuous circles between increasing the sustainability of mining and the supporting the deployment of low-carbon technologies is a vital task for policymakers. Documenting, learning and communicating such endeavors can help strengthen the wider move to Climate-Smart Mining practices.

Iridium challenges

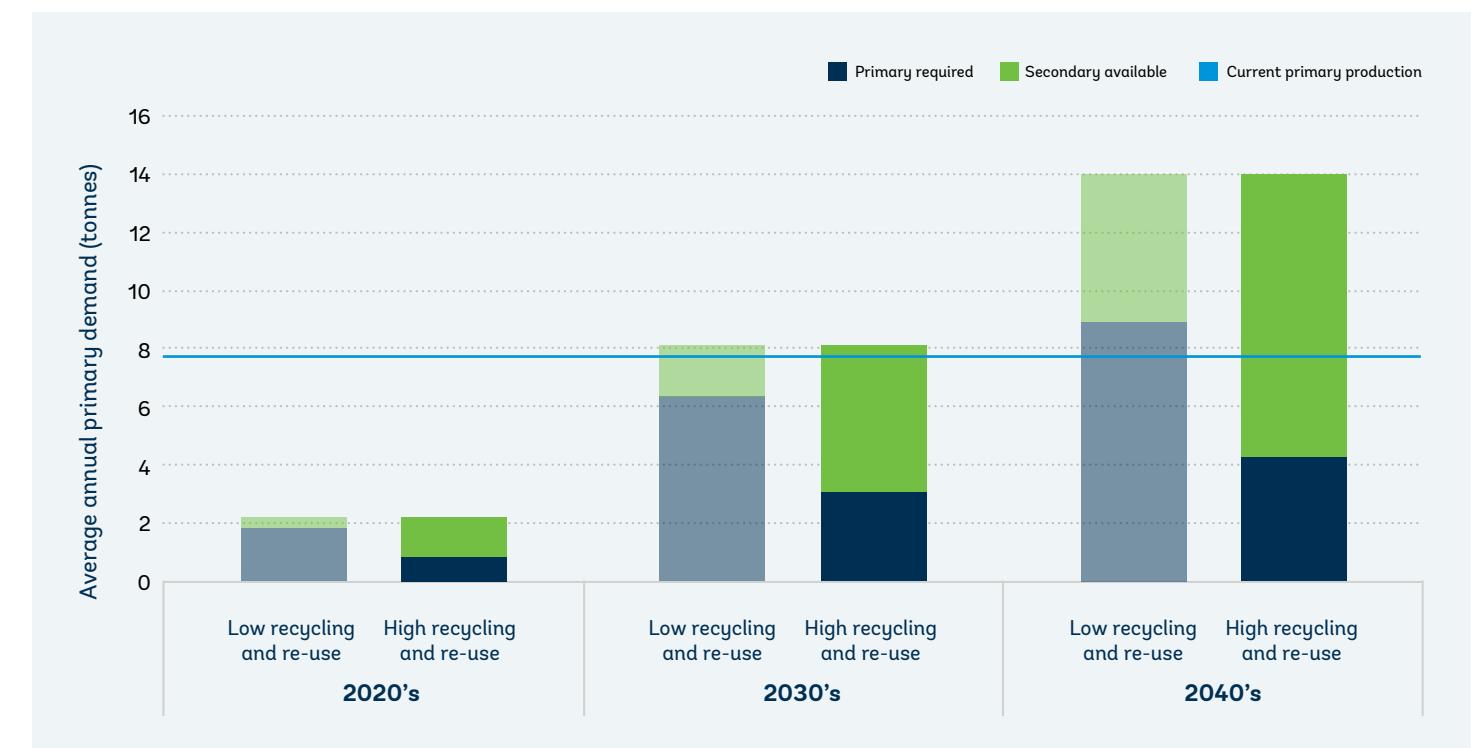
The projected time-path for iridium, used in PEMELs, is shown in Figure 14 for a low and high recycling and re-use scenario. The low recycling scenario shows increasing demand for primary iridium through the 2020s and 2030s – surpassing current production in the 2040s. Higher recycling and re-use scenarios show a slower growth in primary demand – reaching only just over 50% of current production levels in the 2040s. A key assumption in this time-path is the speed and scale of change in loading in electrolyzers. For example, a faster move towards the US Department of Energy's (DOE) target for loading as discussed above, would mean that primary iridium demand would more rapidly level-off and indeed start to fall in the 2040s below current production levels.

This time-path for iridium raises different challenges than that for platinum. A low-recycling and reuse scenario would take iridium primary demand from hydrogen above current levels of production, without any changes or increases in demand from other sources. Should these also increase there is potential for great stress on the supply of iridium potentially leading to shortages or price rises.

The challenge for iridium is made even larger due to the nature of its production. Iridium is mainly produced as a minor by-product of platinum mining and of certain types of nickel and chrome mining. Iridium is extracted from the ore after other metals such as silver, gold, palladium, platinum, and rhodium are removed. The nature of this production makes large scale increases in production generally unresponsive to iridium prices, with production more related to the markets of the other minerals, chiefly platinum. Rises in iridium prices could however lead to more efforts to increase extraction from ores along with increasing the incentives for recovery and increasing secondary production.

The vast majority of iridium mining takes place in South Africa and Zimbabwe but there are no reported mines for which iridium is the primary commodity, highlighting its nature as a co-product. The lack of a clear pipeline of future projects, and also previous facilities that could be brought back to production further highlights potential challenges of meeting higher levels of demand for iridium.

Figure 14: Projected time-path for net demand for primary iridium from the hydrogen sector to 2050



Crucial in whether a low or high recycling or re-use model emerges for the material is the ability to access above-ground iridium from other uses. There is a substantial amount of iridium circulating constantly in 'closed loop', i.e. it is recovered and usually reused in the same application.²⁴ How far wider recycling and re-use of iridium can be increased is a critical question. For example, iridium is present, in many types of premium spark plugs – but recovery rates are generally low due to the low-concentration in any one plug. Increasing the rate of iridium recovery from this source could substantially mitigate any challenges in sourcing primary iridium for the hydrogen sector. Similar to the story with platinum and catalytic converters, increasing scrappage of ICE vehicles could also assist in this area, assuming increased recovery was in place. Several alternative options exist for meeting the demand for materials beyond primary production and recycling and re-using material. A potentially large, but uncertain, amount of various minerals has been extracted from the ground previously but

not processed into the final material. They may lie in extracted overburden, discarded ore, or in tailings. Historically, this source of supplying materials has generally been overlooked by the private sector, and governments. However, increasing attention on the criticality of minerals to the low-carbon transition has attracted increasing attention on the area with projects on recovering material from tailings by both the USGS and the EU.²⁵ Academic attention has also increased on the topic (Avina et al, 2018, Araya et al, 2020), highlighting the technical feasibility of extracting platinum and other critical minerals including rare earths from tailings dams around the world. In addition tailings reprocessing has already begun with the PGM mining industry in South Africa. What is needed is further moves from technical feasibility towards commercial exploitation of such resources, which requires action on behalf of the private sector, but also policymakers to overcome remaining technical issues, but most crucially economic, environmental, and regulatory barriers.



6. Emissions and water intensity

The material footprint of the production of clean hydrogen, whether renewable or low-carbon, will bring with it a range of environmental impacts and challenges. This is not to say that these challenges are sufficient to negate the broader benefits of producing and consuming clean hydrogen, however they should be considered, and action taken, as far as possible, to reduce these impacts, to maximize the benefits that clean hydrogen can provide. This section covers just the production component of hydrogen and does not cover the emissions nor water footprint of consumption of clean hydrogen via fuel-cells.

Two categories of these impacts are examined here: GHG emissions, and the water footprint.

GHG emissions

A wide range of estimations of the relative direct and indirect emissions from renewable and low-carbon hydrogen production have been produced in the literature and these vary based on the assumptions made regarding material content, the scope of the analysis and the technologies involved. The variation can be seen in Figure 15.

An estimation of the ‘average’ indirect emissions of the production of renewable and low-carbon hydrogen per ton is given in Figure 16, for three time-slices, 2020-2030, 2031-2040 and 2041-2050. It should be noted that the scope of these emissions is limited to the impact of the selection of materials for which data is available, important potential sources of emissions such as from a wider basket of materials (including any steel involved), manufacturing of equipment, transportation and distribution of hydrogen and leakage of hydrogen which in itself is a GHG, are thus excluded. The emissions calculations should not therefore be used as a life-cycle analysis of different hydrogen technologies, instead they indicate the scale of the scope of emissions covered.

Emissions associated with renewable hydrogen are all indirect, arising from material flows and manufacturing associated with renewable energy. This analysis is restricted to just the emissions from the mining and processing of materials. A simplifying assumption was made that the emissions for primary and secondary production are constant over time. In reality the emissions intensity of material production is likely to change in future with factors such as the inclusion of renewable energy and/or clean hydrogen into mining and processing operations reducing emissions, whilst factors such as declining ore grade potentially

Figure 15: Relative emissions from renewable and low-carbon hydrogen, IEA, IRENA and Hydrogen Council

	Other hydrogen	Low-carbon hydrogen	Renewable hydrogen
Process	Reforming without carbon capture	Reforming with carbon capture	Electrolysis
Energy source	Fossil fuels	Fossil fuels	Renewable electricity
Estimated emissions from the production process (kg CO ₂ e/ kg H ₂)	9 – 11	0.4 – 4.5	0

working in the opposite direction. Even with this simplifying assumption the emissions intensity of total material production declines through the 2030s and 2040s due to a reduced demand for primary material because of higher availability of secondary scrap from within the hydrogen sector – that has a lower GHG footprint than primary production.

A major contribution is from the aluminum assumed to be needed for solar panels to power renewable electrolyzers. A reduction in any of the amount of solar power used in renewable hydrogen production; the aluminum content of solar panels; or the emissions from aluminum production would reduce the overall emissions associated with renewable hydrogen production substantially. The latter is critical given the large disparity between the emissions from primary and secondary aluminum (secondary aluminum has an emissions footprint on average around 5% of primary aluminum, ANL, 2022) and also from the difference between aluminum produced from different supply chains across the world, for example, emissions from aluminum produced from hydropower can be over five times lower than aluminum produced using coal-fired electricity generation.

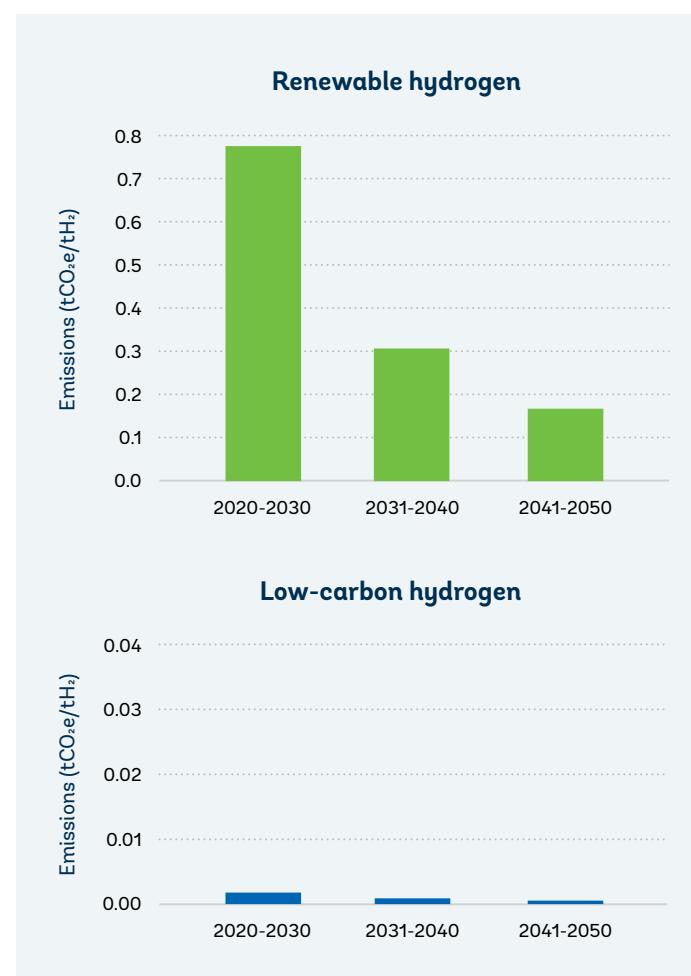
An example of the shifting emissions over time from the production of renewable hydrogen can be seen in the case of platinum. Even assuming constant emissions associated with the production of platinum, the emissions from platinum per GW of electrolyzer capacity is projected to fall from 7.9 tCO₂e / GW in the early 2020s to just 1.5t CO₂e in 2050 as a result of projected reduced platinum intensity of electrolyzers and fuel-cells and increased use of secondary platinum that has emissions intensity of less than 5% that of primary production. Further action to reduce material intensity, increase the use of secondary platinum and reduce the emissions from primary and secondary production would help to reduce these emissions further.

The emissions from producing low-carbon hydrogen on the other hand are predominantly direct, arising from the operation of the facilities, with a much smaller contribution from indirect emissions via its material footprint. The emissions from low-carbon hydrogen are also anticipated to fall in the 2030s and 2040s with improvements in efficiency and CCS. To give a sense of scale internal World Bank modelling place the emissions from low-carbon hydrogen, post carbon capture and storage at 2.6 tCO₂e/tH₂ for the 2020s, falling to 1.1 tCO₂e/tH₂ for the 2040s. However,

estimates of the emissions from low-carbon hydrogen are subject to wide uncertainty based on the efficiency of production and the CCS and other factors such as leakage of methane, as highlighted by Figure 15. Assuming best available technology and operational practices the Hydrogen Council (2021) gives a range between 0.8 to 3.9 tCO₂e/tH₂ for low-carbon hydrogen production.

The indirect emissions from materials used for low-carbon hydrogen production predominantly arise from copper (31%), manganese (27%), nickel (12%), zinc (12%) and niobium (11%). In a similar vein, greater use of secondary material through the 2030s and 2040s reduces the material emissions of the production technology, while greater material intensity and reduced emissions from primary and secondary production would also assist.

Figure 16: Projected GHG emissions from mining and processing of materials per ton hydrogen produced 2020-2050

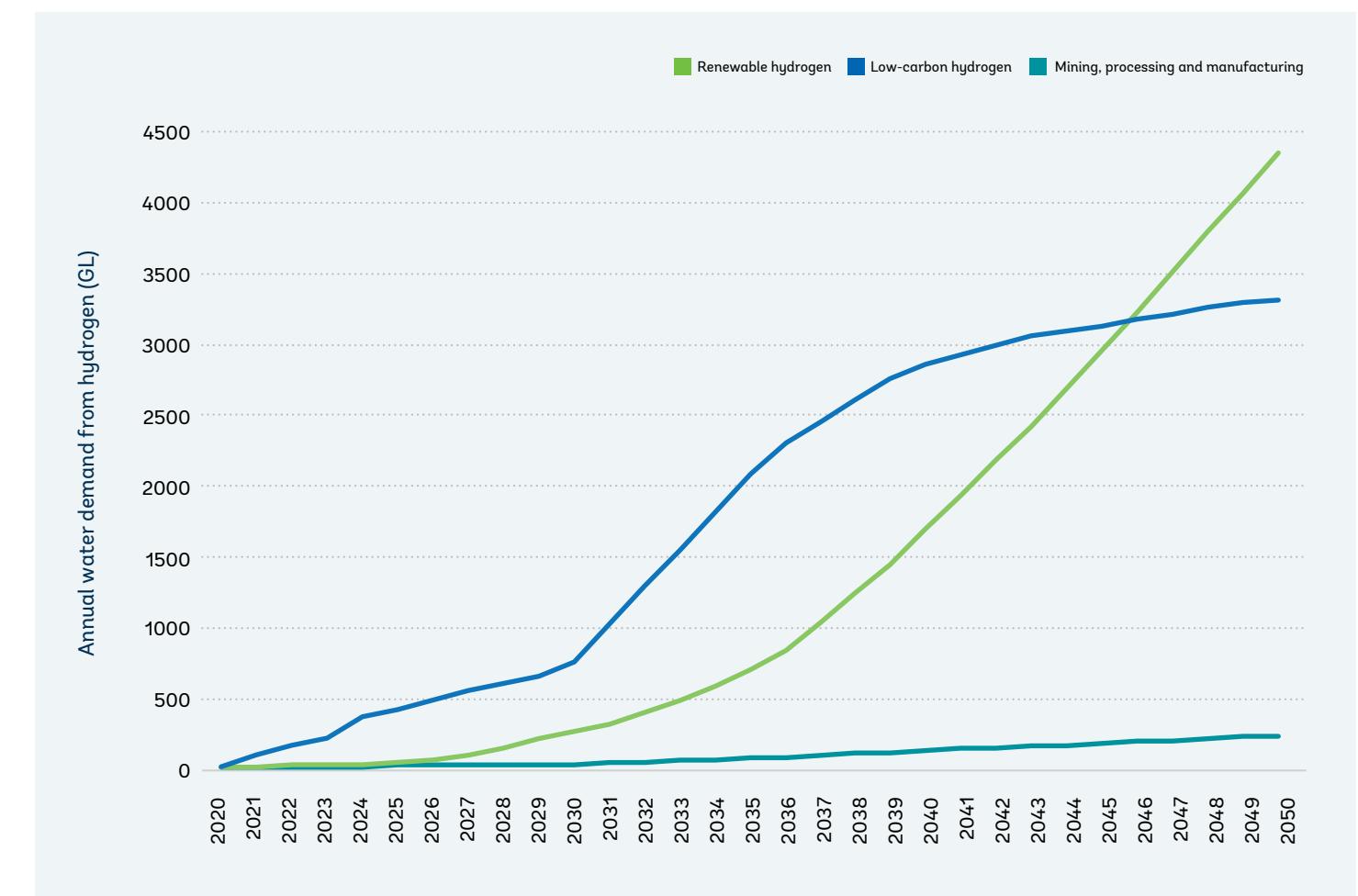


Water footprint

Water is utilized in renewable and low-carbon hydrogen for various uses, along with being used in the mining and processing of the materials required to produce hydrogen. Water is vital in the production of renewable hydrogen, with the process using renewable energy to split hydrogen from water molecules. In low-carbon hydrogen heated water is brought together with natural gas to create hydrogen in the reforming process.

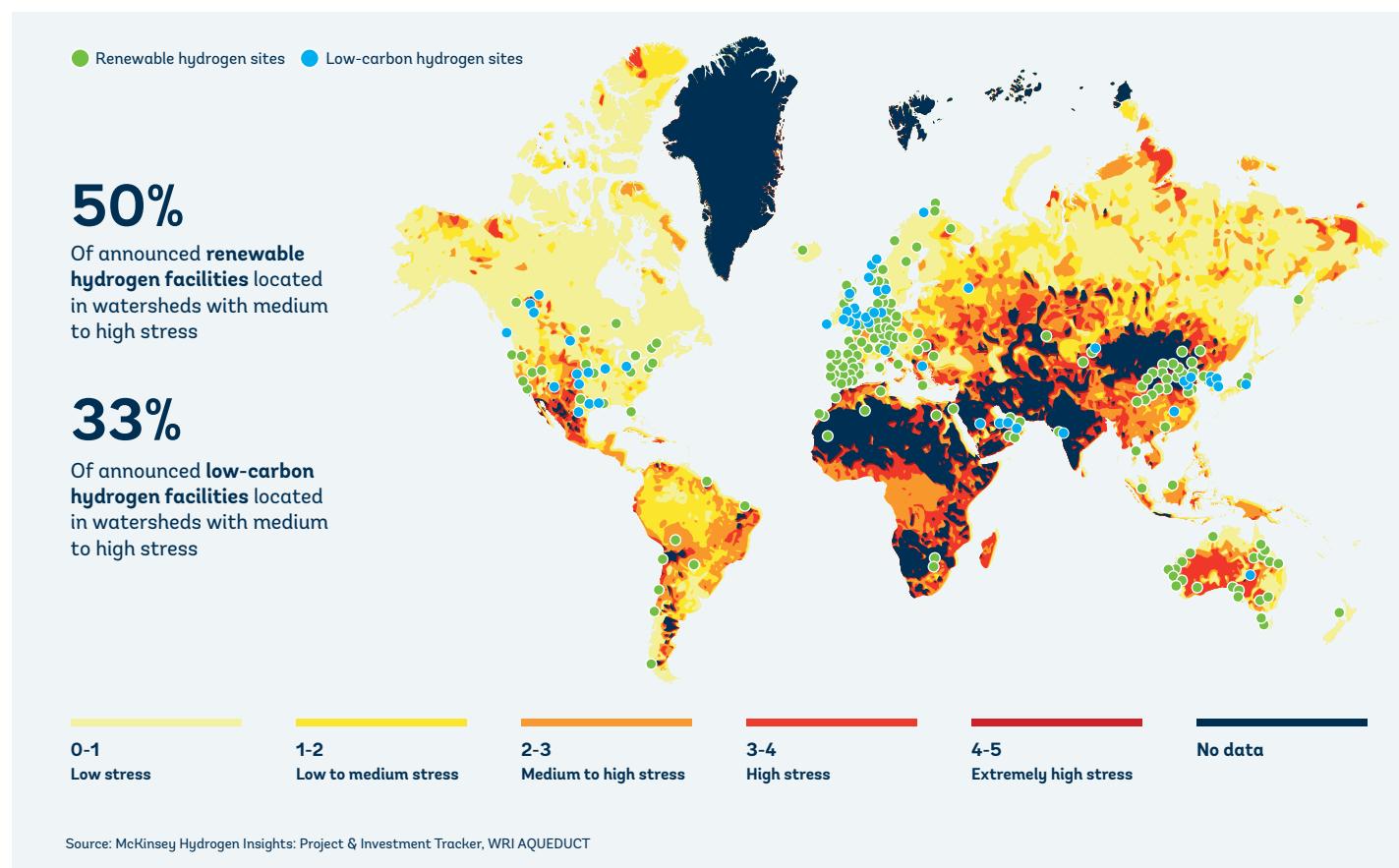
A projection of the global annual water requirements from clean hydrogen is given in Figure 17. The scope of this estimation includes water needed for production, cooling and manufacturing the materials needed for the technologies but excludes water involved in processes such as extraction of natural gas required

Figure 17: Annual water demand to 2050 from clean hydrogen by production route



in low-carbon hydrogen. To put these numbers in context the IEA projects that, under their Sustainable Development Scenario, total water consumption from the energy sector in 2030 will be over 72,000 gigalitres, approximately 70 times the estimated level for clean hydrogen.

Total requirements increase through to 2050 with low-carbon starting to level out in the 2040s with a levelling out of production. In 2050, 42% of the water used by hydrogen is projected to come from low-carbon, with 55% from renewable and just 3% from the mining and processing of the minerals required along with the manufacturing of equipment. Cumulatively up to 2050, 40% from renewable, 56% from low-carbon and 4% from mining, processing, and manufacturing. This result does not imply that low-carbon

Figure 18: Announced low-carbon and renewable hydrogen locations, and 2020 watershed stress

hydrogen necessarily uses more water than renewable per unit of production – it is also a function of the higher initial levels of deployment of low-carbon hydrogen projected in the underlying scenarios. As highlighted in Figure 2, the direct water use of low-carbon hydrogen is between 12-19 kg/kg H₂ with renewable slightly lower at approximately 9 kg/kg H₂ – although the latter's footprint is greater than this figure if the water associated with sourcing the materials required is included. As the trend of low-carbon hydrogen growth in the scenario reverses and renewable hydrogen deployment increases through the 2030s, the total water demand from renewable hydrogen accelerates and eventually overtakes water demand from low-carbon hydrogen.

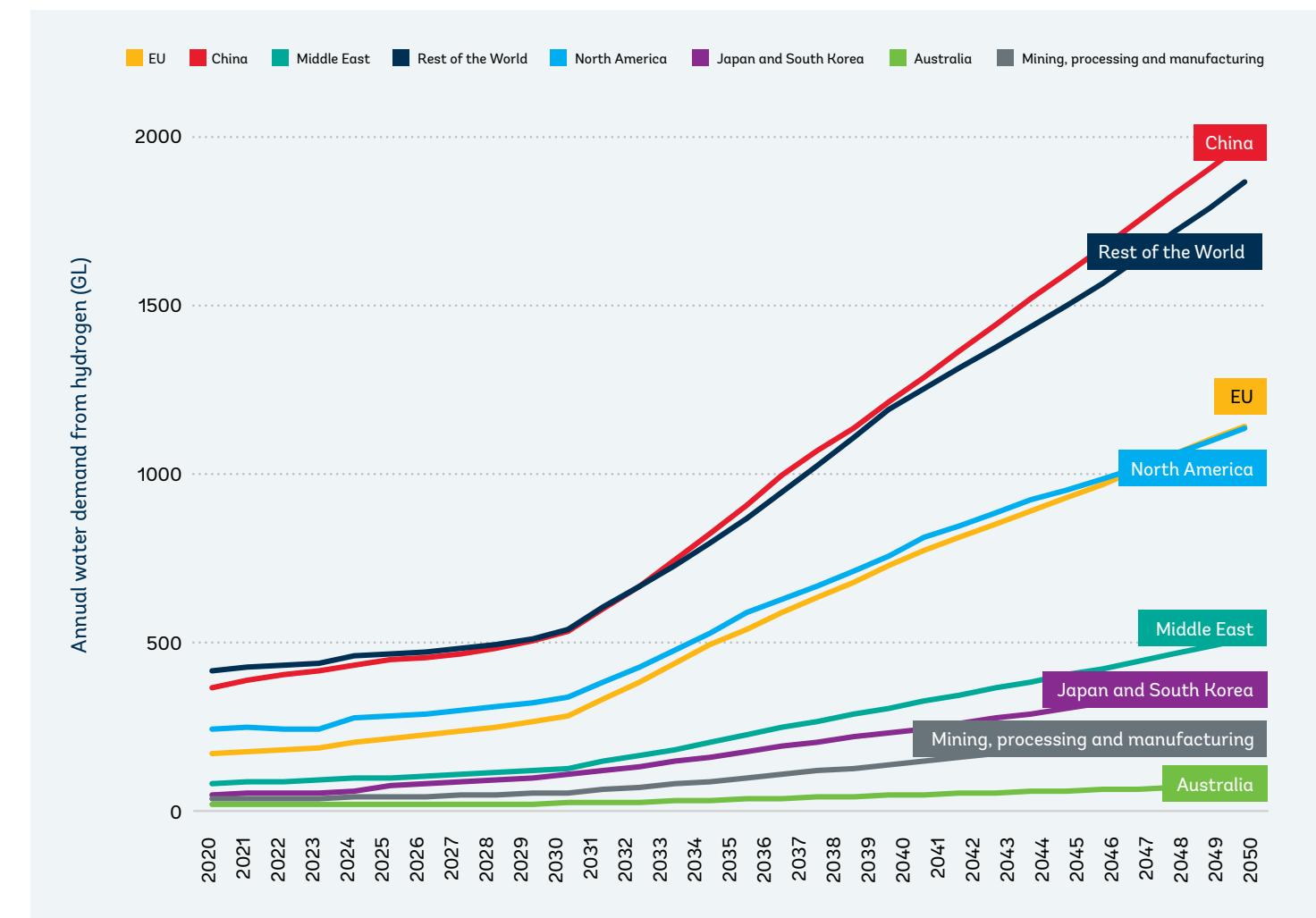
There is however considerable variability in the water footprint of different hydrogen production pathways routes, i.e. those utilizing

renewable energy and electrolyzers versus those using reformers with CCS. For example, a combination of steam methane reforming using energy crops has a water footprint almost four hundred times higher than the use of solar PV with renewable electrolyzers (Hydrogen Council 2021b). The specific mix of technologies in each region is therefore important in determining the full water intensity of hydrogen production.²⁶

Another crucial issue relates to the nature of the water required across the different production pathways. Electrolyzers require high-quality water to produce hydrogen, unlike the water needed for cooling in other components of the sector, and inadequate water treatment can impact the operation and damage electrolyzers as they require pure water. Estimates by the Hydrogen Council and McKinsey²⁷ project that by 2030 39% of the

water needed in the hydrogen sector will be used for cooling, with the remainder required to be higher-quality needed for production. For renewable hydrogen production this share is greater with almost 70% of the water required needing to be deionized. This potentially creates additional costs – since producing pure water is more costly – and other challenges, especially if the location of renewable hydrogen production coincides with water-stressed areas (or areas that could be in increasing water-stress due to climate change). The same study by Hydrogen Council and McKinsey estimate that approximately 50% of announced renewable hydrogen facilities are located in watersheds with medium to high stress, with a third of low-carbon projects also located in such areas (Figure 18).

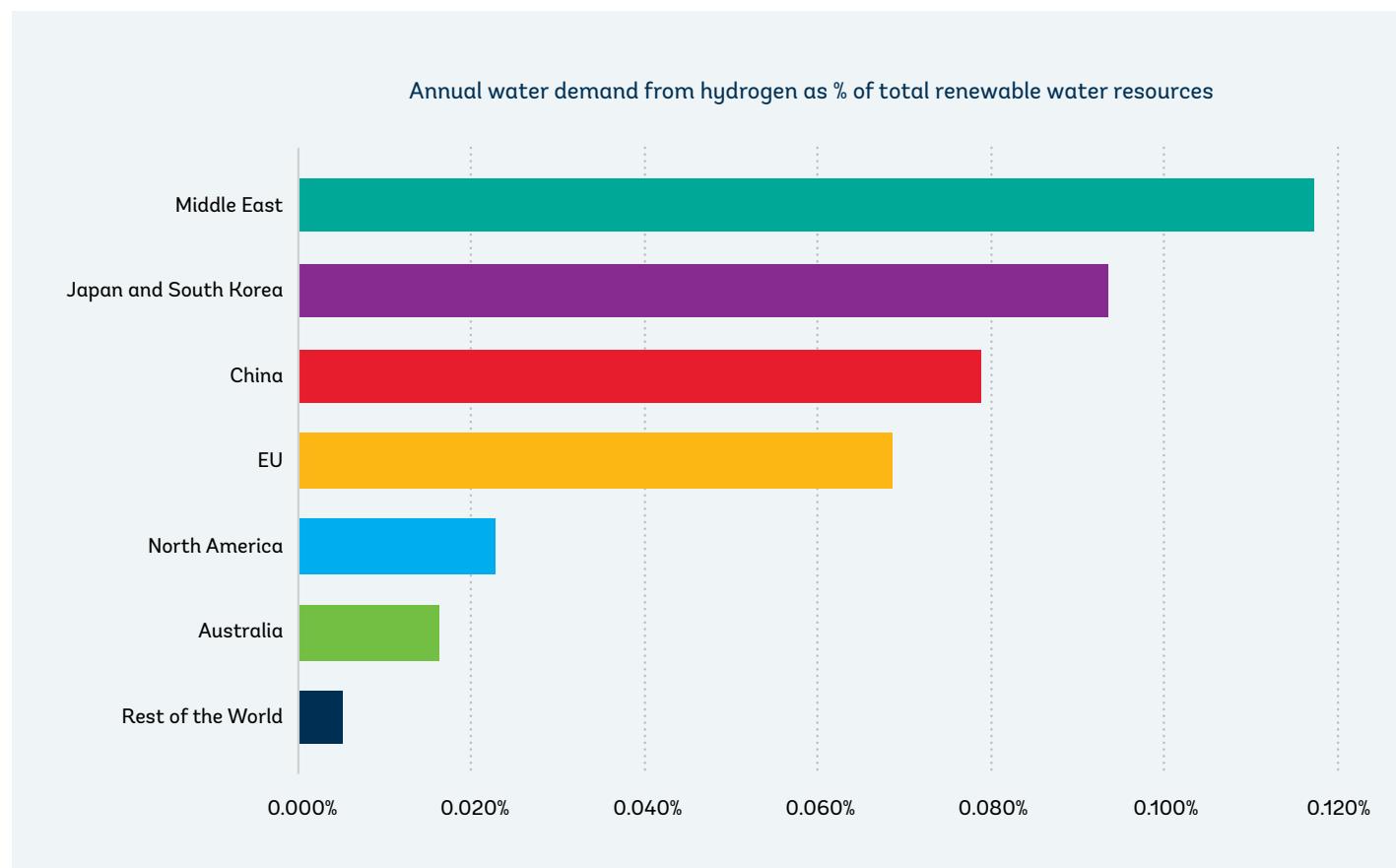
The regional context for water is especially important as different regions will have different levels of water availability and water stress. Figure 19 shows the annual water demand from hydrogen by region up to 2050. The greatest water demand occurs in China and the “rest of the world”, reflecting their larger shares of hydrogen production. The EU and North America have comparable water demand from hydrogen up to 2050, with smaller amounts in the Middle East, Australia and Japan and South Korea. Mining, processing, and manufacturing, which occur across the world due to the varying geographic locations of mining and processing accounts for 4% of global water demand associated with clean hydrogen production.

Figure 19: Annual water demand to 2050 from hydrogen by region

²⁶ Chart drawn from Hydrogen Council; McKinsey Hydrogen Insights (2022)
²⁷ Hydrogen Council; McKinsey Hydrogen Insights (2022)

A second dimension needs to be examined when looking at the impact that this water demand may place on local water resources and ecosystems, which is: is there a source of sustainable water available in the region to meet local demand? This will vary depending on various climatic and geographic factors. Figure 20 shows the percentage of current total renewable water resources that 2050 water demand from hydrogen would represent. This figure implicitly assumes that water resources do not shift by 2050, which, given climate change, is likely to be inaccurate, but it does indicate the scale of demand for water from hydrogen across the different regions. It also fails to take into account growing populations, which would reduce the available water resources per capita, and also increasing demands from other sectors, such as agriculture. The greatest share of renewable water resources is utilised in the Middle East region – nearly four times the level in North America, with also a notable level of consumption in Japan, South Korea and China.

Figure 20: Annual water demand in 2050 from hydrogen as a % of present total renewable water resources

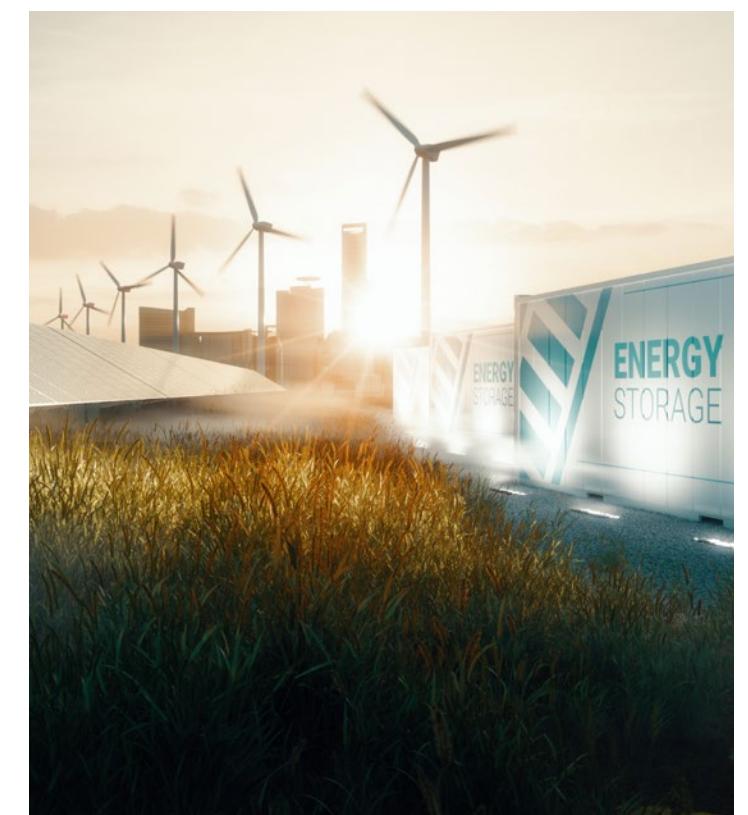
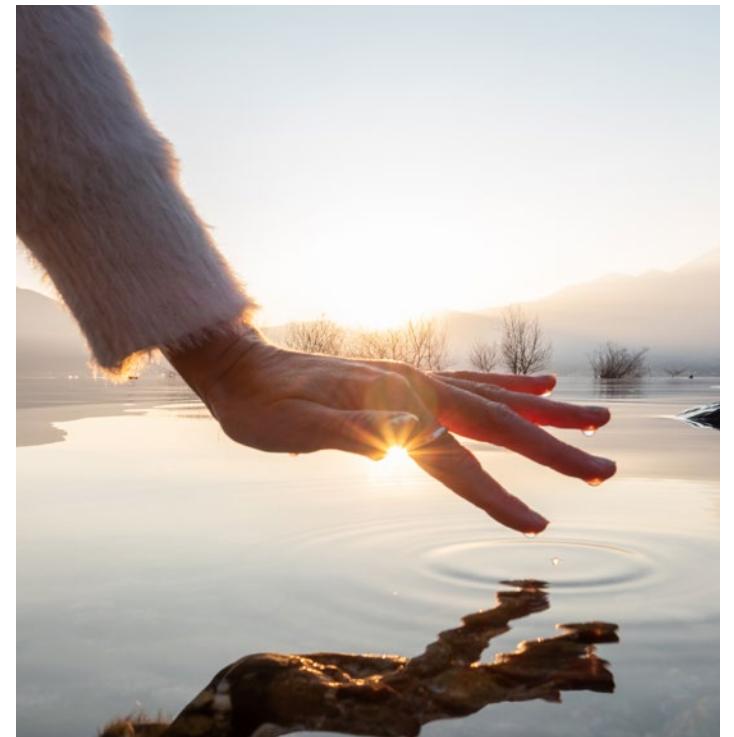


These different analyses of the potential water stresses of the hydrogen sector raises a mixed picture. On the one hand the overall scale of water demand from the hydrogen sector is unlikely to be a major constraint at a global or even regional level. Indeed, the global water footprint of the sector is likely to be much smaller than some other renewable alternatives, such as biofuels, with the IEA projecting demand from that route at almost 47,000 gigalitres in 2030 in their SDS. However, at a watershed or project level there may be challenges in sourcing water, especially as it relates to the high-quality water required for use in electrolyzers. Therefore, more granular hydrological assessments until the project level are required, to ensure that sufficient quantities of water are sustainably available, and where stress is high alternatives such as desalination are fully examined.

Desalination is already being examined as a key option for reducing water stress within the sector (Rystad, 2021). It is likely

to be important for large production facilities in water-stressed regions. Use of desalination may increase costs marginally for renewable hydrogen production, mainly related to the extra electricity required, although this may be mitigated if cheap renewable power is available to power the process. The level of additional electricity consumption however may be small – with some studies estimating that it is below the accuracy of the indicated efficiency of the electrolysis plant. Investments will also be needed to manage the brine that is produced to minimize its potential impacts. There may also be slight increases in material demand. For example, if desalination facilities are powered by additional solar PV capacity, this would further increase the demand for materials such as aluminum, copper, and silver – depending on the types of solar PV technologies utilized. There may also be material implications if desalination facilities need additional pipelines to transport water, although increases in materials such as steel as a result are likely to be very small compared to the material footprint of the hydrogen sector, or indeed the low-carbon transition as a whole.

An additional caveat to the analysis above is that a substantial share of the water used in the production of hydrogen has the potential to be re-used in a closed-loop system, or can be utilized in other areas, with the potential also to produce hydrogen from wastewater (Rioja-Cabanillas et al, 2020). There may also be potential to link water demand challenges with the global climate change challenge. For example, when CO₂ is extracted from the air using direct air capture (DAC) water is also made available as a by-product. Therefore, subject to local humidity in the air, sufficient water may be provided to cover electrolyzer water demand for hydrogen production in these areas (Concawe et al, 2022). Thus, the total impact on water supplies may be less than illustrated. What is crucial is understanding where and how such re-use, recycling and capture of water is possible and what technical and economic barriers need to be overcome to implement innovative solutions.



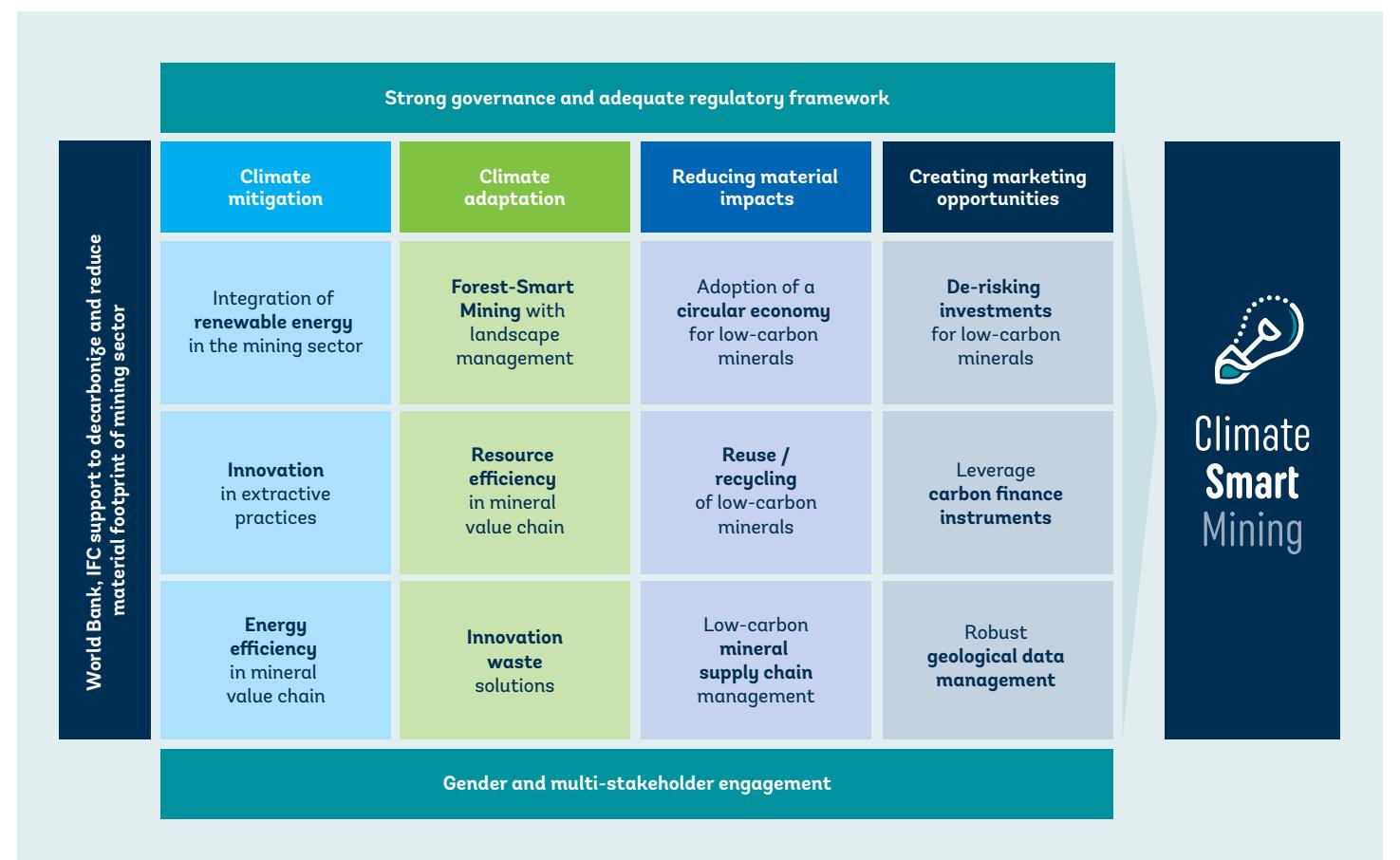


7. Conclusion: Meeting the challenge to produce hydrogen sustainably

Hydrogen is projected to be a crucial decarbonization option in hard-to-abate sectors such as heavy-duty transportation, heavy-industry, and heat. This report has examined the material impacts of the mass deployment of clean hydrogen production and a portion of consumption technologies. The overall picture shows a sector that could have a substantial material impact, especially if the wider scope of the sector, encompassing the renewable energy technologies are covered. However, the scale of this material impact is generally small relative to the scale of both current demand, and the low-carbon transition as a whole. This, however, does not mean that the scale should be ignored, nor that there may be implications from the material impact for the ability to deploy hydrogen at scale. Adoption of frameworks such as the WBG's CSM Framework (Box 5, Figure 21) can help to mitigate these impacts, along with providing a security of supply for the key minerals needed for the deployment of hydrogen.

The largest absolute demand for materials from the components of the hydrogen supply chain modelled comes from the materials needed to build the renewable energy generating capacity, including aluminum, zinc, copper, and nickel. There is unlikely to be bottlenecks in supply from this production, but it should be remembered that the deployment of hydrogen is taking place in the context of a wider low-carbon transition. Significant demand for these materials may also occur from other avenues, raising implications for the supply, and therefore price of these materials. Materials such as cobalt, graphite and to a lesser extent nickel and copper, face large (but uncertain) increases in demand from the wider low-carbon transition. Although the added demand for hydrogen to this wider demand is likely to only have a small impact on the wider picture – this context could create challenging supply contexts for these materials. A lack of supply, or higher prices for graphite, could impact the

Figure 21: CSM Framework





relative competitiveness of technologies such as AELs whilst higher cobalt prices or uncertainty over supplies has implications for the deployment of low-carbon hydrogen. Understanding this wider context is crucial for all actors in the hydrogen sector, from governments to the private sector.

The largest relative increase in material demand comes in the platinum group metals, specifically platinum and iridium. Hydrogen could account for a significant share of future demand in these materials but there may be different implications for either mineral. Rising demand for platinum from hydrogen could compensate for reduced demand from ICE vehicles for platinum in catalytic converters. Indeed, the scrappage of increasing numbers of these converters could provide a source for platinum for hydrogen, for both electrolyzers and fuel-cells, before large-scale recycled material from the sector itself becomes available. A strong pipeline of new and developing extraction projects also indicates that the increased demand for platinum should be able to be met by the market – assuming that incentives to maintain existing capacity are sufficiently strong.

The picture for iridium, however, is more complex. Its status as a minor by-product of predominantly platinum production means that isolated market signals fail to lead to increases in capacity. There is less availability of secondary material that could be tapped in to and increases in primary production are dependent on increased platinum mining capacity. This creates a stronger risk that there could be shortages in the supply of the material, with possible knock-on effects for availability and price – potentially impacting hydrogen technologies such as PEMELs. Strategic action by governments and the private sector may be needed in this area, to overcome technical and economic barriers, by providing clear signals to the market that future demand will be in place, and to source iridium from alternative sources, such as re-use of the iridium in spark plugs. The adoption of measures supporting de-risking investment and improving the provision of geological and commodity data will also be key. Material substitution within the hydrogen sector may also be an important avenue to investigate to reduce the possibilities of supply shortages.

The impacts from the materiality of key components of hydrogen production and consumption, both in terms of the wider environmental challenges that it may present, along with the impacts it may have on deployment, can also be mitigated through strengthening the role that secondary material may play in meeting the demand for materials. Barriers exist to increasing the use of recycled content in the production of new technologies, and these vary from material-to-material with some within the scope of the hydrogen sector whilst others lying outside. Within the hydrogen sector maximizing recycling and re-use of components is crucial, especially in materials such as platinum and iridium that could face challenging primary production environments. Working across the supply-chain to ensure that recycling and reuse is prioritized from design through to end-of-life is vital. Building business models that allow for efficient recovery of materials and repurposing into new technologies. Extending the lifetime of technologies will also assist in reducing overall demand for materials.

However, even if full action is taken within the hydrogen sector, the sheer shortage of availability of the scrap of some materials means wider action across the economy will be needed. Aluminum, for example, is highly recyclable, but increasing secondary production is limited by scrap availability. The wider transition to a circular economy model is vital in this regard and the hydrogen sector can both take internal action, but also work with wider suppliers to help facilitate this transition. Policy support from governments is crucial here to provide the right regulatory, economic, and logistical environment for scrap recovery and transportation.

Utilizing alternative sources of supply such as the repurposing of tailings, and the reworking of previously mined ore, could play a critical role in both reducing the challenges relating to primary supply and also the wider environmental impacts of new mining activity. Close collaboration between the hydrogen sector and the mining sector regarding the nature of demand and the materials required could help facilitate this – along with policy support for overcoming the technical and economic barriers to such action.

The mining and processing of the materials needed for the low-carbon transition create wider socio-environmental challenges for the clean hydrogen sector, whose key reason for growth is its environmental advantage over established competitors. These challenges may not be so significant as to negate the benefits

of deployment of clean hydrogen, but this does not mean that they should not be a source of action for the hydrogen sector and beyond. These impacts differ between different production paths within the hydrogen sector: for the materials analyzed in this report renewable hydrogen is likely to be more material-intensive than low-carbon hydrogen – chiefly relating to the wider renewable generation infrastructure that they require. The technology could also be more water intensive than low-carbon hydrogen – though the potential water intensity ranges for the technologies overlap. Wider socio-environmental risks, such as impacts on communities, land, and biodiversity also need to be considered and further analysis in these areas is required.

With regard to GHG emissions, it is anticipated that the material impacts from the key components of the supply chain covered in the report will decline over time, as material intensity improves, and the use of secondary inputs (that generally have lower emissions intensities) increases. However, although these are projected, they should not be taken as a given. Ensuring that material intensities improve in the sector through supporting R&D and wider innovation is crucial, to both the environmental impacts from the sector, but also for economic challenges. Facilitating the supply of low-cost, available, secondary material will also have similar double-benefits in terms of the environment and cost. Working across supply chains so all actors take responsibility for reducing emissions across their production is a key part of the challenge.

Beyond this, concerted action at the level of mining and processing to reduce the emissions and water intensities of material production is crucial to reducing the wider socio-environmental impact of the low-carbon transition. What this action will consist of will vary from material to material and region to region, and encouraging, incentivizing, and facilitating learning from this action is a key role for policymakers, through measures aimed to help reduce emissions and also build adaptive capacity to the impacts of climate change. Policy instruments such as carbon prices, support for renewable energy, innovation funds and technology transfer can assist, and there are interesting examples of virtuous circles emerging linking action on mining and processing and wider demand for low-carbon technologies. An example of this is shown in Box 6 – with the integration of hydrogen into platinum mining, and vice-versa.



Key recommendations

This analysis has provided estimates of the materials required for some key components of the clean hydrogen supply chain, from different production pathways to consumption via fuel cells, and some of the associated impacts. However, this should be seen as the starting point of analysis in this area, with a need to increase the scope and depth to give a more complete picture of the material impacts of hydrogen along its value chain, including crucial aspects such as transportation, storage, and distribution. This exercise will require additional data in both the material intensity of the types of technologies and infrastructure required in these areas, and projections, consistent with global scenarios, for the scale of infrastructure needed. In addition, there are a myriad of impacts beyond GHG emissions and water from the mining and processing of materials for use in the hydrogen economy, these vary from land and biodiversity to social impacts, both positive and negative. Further analysis in these areas is also important, to strengthen the understanding of how the positive benefits from the deployment of clean hydrogen can be maximized, whilst minimizing any negative impacts.

A starting point for addressing the material impacts identified through the present analysis is the adoption of the WBG's CSM practices. Key actions are detailed below and organized around three of CSM's four main pillars:

- Climate mitigation
- Climate resilience
- Circular economy
- Creating market opportunities.

Climate mitigation

- Develop and implement policy and create incentives to increase energy efficiency and promote the integration of renewable and low-carbon energy into the extraction, processing and transportation of climate action minerals, including those contemplated in the analysis. Virtuous circle solutions, such as the use of clean hydrogen-based technologies in the mining sector adopted for platinum in South Africa, should be encouraged.
- Develop and implement policy and create incentives based on the forest-smart mining guidelines²⁸ that encourage the exploration of the potential for carbon sequestration activities in mining operations to reduce emissions and help meet biodiversity objectives.
- Support the acquisition of geospatial data to monitor potential GHG emissions and air quality impacts from mineral production and assess the mining sector's impact on biodiversity and forested areas.

Climate resilience

- Hydrological assessments should be undertaken for hydrogen projects (both low-carbon and renewable) to ensure that impacts to local and regional water systems are minimized and that suitable options, including desalination and water recycling, where relevant, are implemented.

Circular economy

- Identification and policy support to overcome key barriers (economic, financial, and technical) to scaling up supply of secondary materials to the hydrogen sector and the low-carbon transition more generally. Policy support should include aspects such as prevention of sub-standard recycling treatments and setting of suitable collection targets.
- Support for research and development and innovation for increasing recovery of climate action materials from tailings and other above-ground stocks. Demonstrating technical and crucially economic feasibility is key in this area.

²⁸ Forest-Smart Mining: Guidance to Applying Nature-Based Solutions in the Mining Sector, World Bank, 2021 <https://documents1.worldbank.org/curated/en/099120005072233028/pdf/P1722450216fbf0fe0a1940eb4798287bc1.pdf> and Developing Forest-Smart Artisanal and Small-Scale Mining (ASM) Standards, World Bank, 2021 <https://openknowledge.worldbank.org/bitstream/handle/10986/37363/P1722450cd79500c30bea007bf7496c1e66.pdf?sequence=1&isAllowed=true>

- Technical and economic assistance to the wider hydrogen sector to improve material intensities, design-in circularity, and encourage solutions for material substitution in areas where potential bottlenecks may occur
- Support to overcome technical and economic barriers to the implementation of closed-loop water systems for hydrogen production, along with increasing recycling and re-using water within the sector and producing hydrogen from wastewater sources.

Creating market opportunities

- Support the acquisition of geological data to better understand countries' geological occurrences with respect to reserves of climate action minerals (including those needed for hydrogen technologies). This will help countries have a better idea of their resources but also potentially enhance supply diversification.
- Leverage the suite of available financial, and risk and mitigation products to de-risk investments in production of climate action minerals in mineral-rich countries, through new or replacement mines or enhanced recovery from tailings and other above-ground stocks. This includes key minerals such as platinum and iridium.

Crucially these recommendations are interconnected, and implementation should be concurrent. They are mutually reinforcing, for example, action to address material intensities and encourage material substitution reduces the scale of action that is required to incentivize new primary production. Also crucial is implementing these recommendations whilst maintaining international best practice, respecting diversity, including gender²⁹, and encouraging innovation throughout all aspects of the value chain.

In implementing these actions there are significant roles for both the private sector and governments. Governments' action is needed to create a stable and clear policy framework – for example in giving clear direction as the scale of hydrogen deployment; the establishment of recycling policy; and wider support for research and development into tailings recovery and improving material intensities. The private sector has a key role in responding to this policy framework, but beyond that to lead efforts to transfer technologies across the sector and to push

forward with cutting-edge research and development at all stages of the value chain, but especially as it pertains to extraction and recovery of key materials such as platinum and iridium, improving material intensities, increasing re-use and designed in circularity and enhancing material substitution.

Timing, agility, and pro-activeness is crucial. Governments can lead with targets and frameworks but early action from the private sector can demonstrate leadership and can help guide policymakers as to the most suitable course of action for the sector. The sector must also be agile in order to respond to its role in the wider low-carbon transition. With many of the materials it requires potentially in high demand across this transition price spikes, and shortages could result, and the sector needs to be able to respond in innovative and creative ways. Understanding and addressing these challenges before they arise can help create resilience in the sector and ensure that it is able to meet its significant potential in mitigating emissions.

Hydrogen has significant potential to play a key role in mitigating otherwise hard-to-abate sectors such as industry and transportation, along with helping to balance intermittent renewable electricity generation. The development of the industry could also bring wider economic and social benefits including employment and poverty reduction, but to do so it must overcome challenges to its deployment, including those relating to availability of materials required. From the beginning of widespread deployment, the industry and relevant policymakers should proactively identify, address, and mitigate the impacts such as emissions and water that arise from the production of the materials needed for the sector, and the wider production of hydrogen generally, for long-term sustainable outcomes.



References

- Araya, N., Kraslawski, A. and Cisternas, L.A., 2020. Towards mine tailings valorization: Recovery of critical materials from Chilean mine tailings. *Journal of Cleaner Production*, 263, p.121555.
- Avina, S.I., Loboyko, O.Y., Markova, N.B., Sincheskul, O.L. and Bahrova, I.V., 2018. Research into platinum-based tailings derived from a recovery boiler of the production of nitric acid and its preparation for the extraction of platinum group metals.
- Babic, U., Suermann, M., Büchi, F.N., Gubler, L. and Schmidt, T.J., 2017. Critical review—identifying critical gaps for polymer electrolyte water electrolysis development. *Journal of The Electrochemical Society*, 164(4), p.F387.
- Bernt, M., Siebel, A. and Gasteiger, H.A., 2018. Analysis of voltage losses in PEM water electrolyzers with low platinum group metal loadings. *Journal of The Electrochemical Society*, 165(5), p.F305.
- BNEF, 2020. Hydrogen Economy Outlook
- Concawe, Aramco, LBST, E4tech: E-Fuels Study; 2022 (ongoing)
- Dominic, M. and Goldberg, S.L., 2022. The Business Case for Gender-Responsive Climate-Smart Mining: Executive Summary and Recommendations.
- Energy Transitions Commission (ETC), 2021. Making the Hydrogen Economy Possible: Accelerating clean hydrogen in an electrified economy
- Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F. and Sonnemann, G., 2011. What do we know about metal recycling rates?. *Journal of Industrial Ecology*, 15(3), pp.355–366.
- Hund, K.L., La Porta, D. and Drexhage, J., 2017. minerals and metals to meet the needs of a low-Carbon economy.
- Hund, K., La Porta, D., Fabregas, T.P., Laing, T. and Drexhage, J., 2020. Minerals for climate action: The mineral intensity of the clean energy transition. *World Bank*, 73.
- Hydrogen Council, 2021a. Hydrogen decarbonization pathways: Potential supply scenarios, January 2021.
- Hydrogen Council, 2021b. Hydrogen decarbonization pathways: A life-cycle assessment, January 2021.
- Hydrogen Council & McKinsey & Company, 2021a, Hydrogen for Net-Zero: A critical cost-competitive energy vector. November 2021.
- Hydrogen Council & McKinsey & Company, 2021b, Hydrogen Insights: An updated perspective on hydrogen investment, market development and momentum in China. July 2021
- Hydrogen Council & McKinsey & Company, 2022, Hydrogen Insights 2022: An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale
- IEA, 2020. Energy Technology Perspectives 2020
- IEA, 2021a. Hydrogen Tracking Report
- IEA, 2021b. The Role of Critical Minerals in Clean Energy Transitions
- IEA, 2021c. Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030, IEA, Paris <https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030>
- IEA, 2022. Global Hydrogen Review
- IRENA, 2020. Renewable hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5 Climate Goal
- IRENA, 2021. Making the breakthrough: Renewable hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi.
- IRENA, 2022. Geopolitics of the Energy Transformation: The Hydrogen Factor, International Renewable Energy Agency, Abu Dhabi.
- Johnson Matthey (2022) PGM Market Report
- Krieg, D.: Konzept und Kosten eines Pipelinesystems zur Versorgung des Straßenverkehrs mit Wasserstoff; Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt / Energy & Environment, Band / Volume 144, ISSN 1866-1793, ISBN 978-3-89336-800-6, 2012
- Minke, C., Suermann, M., Bensmann, B. and Hanke-Rauschenbach, R., 2021. Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?. *International journal of hydrogen energy*, 46(46), pp.23581-23590.
- NOW, 2018. Studie IndWEDE – Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme; Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW), Berlin, 2018
- Nuss, P. and Eckelman, M.J., 2014. Life cycle assessment of metals: a scientific synthesis. *PLoS one*, 9(7), p.e101298.
- Nurmi, P.A. and Rasilainen, K., 2015. Finland's Mineral Resources: Opportunities and challenges for future mining. *Mineral deposits of Finland*, pp.753-780.
- Reverdieu, G., Le Dugou, A., Alleau, T., Aribart, T., Dugast, C. and Priem, T., 2021. Will there be enough platinum for a large deployment of fuel cell electric vehicles?. *International Journal of Hydrogen Energy*, 46(79), pp.39195-39207.
- Rioja-Cabanillas, A., Valdesueiro, D., Fernández-Ibáñez, P. and Byrne, J.A., 2020. Hydrogen from wastewater by photocatalytic and photoelectrochemical treatment. *Journal of Physics: Energy*, 3(1), p.012006.
- Rystad, 2021. Renewable hydrogen projects will stay dry without a parallel desalination market to provide fresh water, Available at: <https://www.rystadenergy.com/news/events/news/press-releases/green-hydrogen-projects-will-stay-dry-without-a-parallel-desalination-market-to-provide-fresh-water>
- Smolinka, T., Wiebe, N., Sterchele, P., Palzer, A., Lehner, F., Jansen, M., Steffen, K., Miehe, R., Wahren, S., Zimmermann, F., 2018. Industrialisierung der Wasser elektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme, https://www.ipa.fraunhofer.de/content/dam/ipa/de/documents/Publikationen/Studien/Studie_IndWEDE.pdf.
- USGS, 2022. Mineral Commodity Summaries.
- Wieclawska, S. & Gavrilova (2021a) Towards a green future. Part 1: How raw material scarcity can hinder our ambitions for renewable hydrogen and the energy transition as a whole, *TNO*
- Wieclawska, S. & Gavrilova (2021b) Towards a green future. Part 2: How we can prevent material scarcity and turn our renewable hydrogen ambitions into reality, *TNO*

Appendix

Base case assumptions

Parameter	Value
Share of electrolyzers in production (PEMEL:AEL:other)	40%:40%:20%
Electrolyzer efficiency: kWh of electricity required per kg of hydrogen	50
Wind capacity factor	50%
Solar PV capacity factor	30%
Wind turbine lifetime	20 years
Solar PV lifetime	30 years
Capacity factor of electrolyzers	50%
Fuel cell lifetime (LDV)	5500 hours
Fuel cell lifetime (HDV)	23000 hours
Fuel cell conversion efficiency	60%
LDV fuel cell run time per day	4 hours
HDV fuel cell run time per day	8 hours
PEMFC share in LDV and HDV transportation fuel cell use	50%
Wind-solar ratio for electricity production for electrolyzers	50:50
Bill of materials	As per clean-room process
Recycled content and recovery rates	As per Graedel et al (2011) and clean room process

Scenario assumptions

Scenario Name	Variable	Scenario Value
Higher EL efficiency	kWh of electricity per kg of Hydrogen	40
Lower EL efficiency	kWh of electricity per kg of Hydrogen	60
Higher Wind	Wind-solar ratio for electricity production	75:25
Higher Solar	Wind-solar ratio for electricity production	25:75
Lower PEMEL penetration	Share of PEMEL in electrolyzer use	30%
Higher PEMEL penetration	Share of PEMEL in electrolyzer use	50%
Lower PEMEL penetration	Share of PEMFC in total fuel cell deployment	75%



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