DERA German Mineral Resources Agency
Federal Institute for Geosciences and Natural Resources

Booklet

Mineral raw materials for water electrolysis

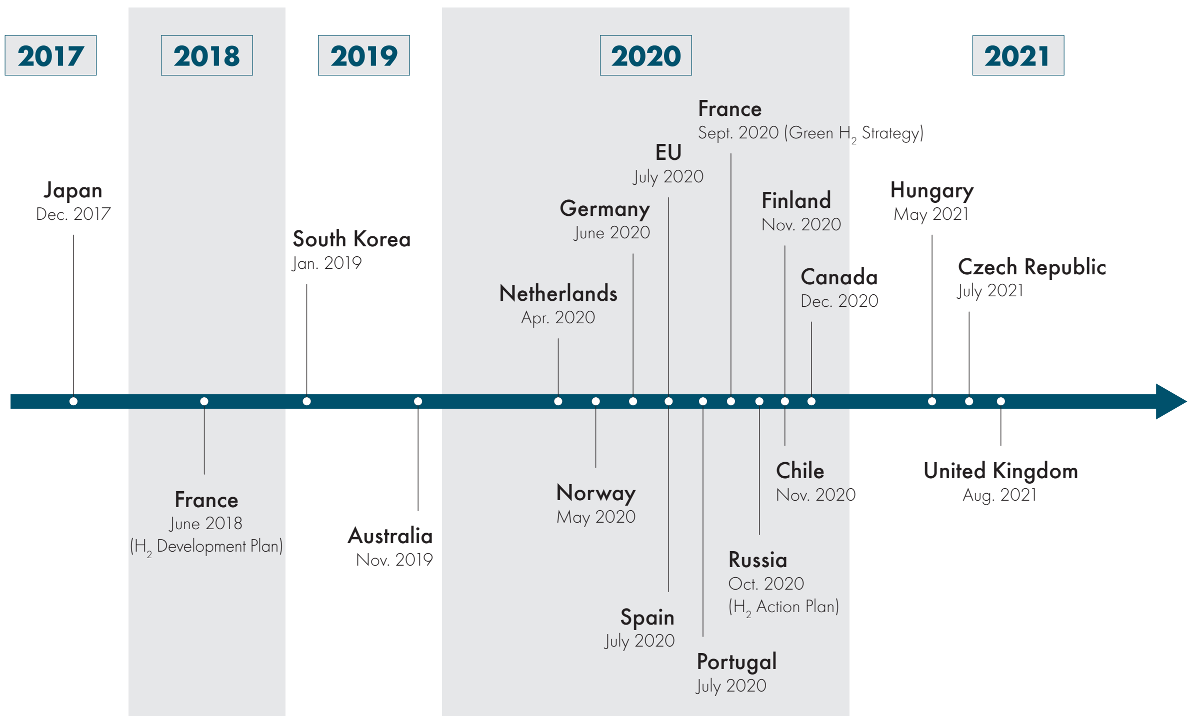
Introduction

Hydrogen has long been a major resource for industry, and many synthetic energy carriers are derived from it. To date, hydrogen is used mainly in the petrochemical and basic chemicals industries to produce petrol and diesel fuels, ammonium and chemicals. There are also a wide range of additional fields of application for hydrogen, the first element in the periodic table. It can serve as feedstock, fuel or as an energy store in many industrial and transport applications, the energy and buildings sectors.

When pure hydrogen is used, no CO_2 and hardly any air pollutants are emitted. The element therefore has a high potential for the decarbonisation of a range of industries, thus contributing to climate neutrality. Across the globe, most hydrogen is still produced from fossil fuels, mainly natural gas and coal. Depending on the production technology used, this releases considerable amounts of CO_2. For hydrogen to actually contribute to climate neutrality, its production therefore has to be decarbonised as well.

With its wide range of possible applications and increasing importance for the energy transition, hydrogen attracted considerable interest in politics and among the public in 2020, when many countries across the globe published their new hydrogen strategies. This development continued in 2021. With these strategies, every country is pursuing its own path towards the development of a hydrogen market.

Although the countries' reasons for formulating a national hydrogen strategy may not be the same, their objectives tend to be similar: decarbonisation, in particular, and economic growth. Some countries will not be able to satisfy their own demand for hydrogen, because of a limited potential in renewable energies, for instance. They are expecting to have to import large volumes of hydrogen in the future. In some strategies, international partnerships therefore play an important part.



In preparation (selection): China | Italy | Morocco | Austria | Poland | Sweden | Slovakia | Ukraine | Uruguay

Overview of adopted hydrogen strategies (last updated: September 2021)

Hydrogen plans in Europe and Germany

Hydrogen strategies – key points

In the long term, both strategies focus on the generation of hydrogen using electricity from renewable energy sources.

On 8 July 2020, the EU published its hydrogen strategy as part of the Green Deal, aiming for climate neutrality from 2050. Despite the many uncertainties created by the Covid pandemic in 2020, the EU Commission stayed committed to its Green Deal as a European strategy for growth.

The focus of the European hydrogen strategy is on green hydrogen, generated using electricity from renewable energy sources. Other forms of low-carbon hydrogen can also be used as an interim solution.

The existing plants for the generation of hydrogen from natural gas are to be retrofitted to capture the CO_2 produced, for subsequent storage or reuse.

Cumulative investments in renewable hydrogen in Europe could amount to between € 180 and € 470 bn by 2050. The gradual transition should take place in three phases.

The three phases of the European hydrogen strategy

Phase I

2020 – 2024

- Installation of at least 6 GW electrolyser capacity
- Generation of 1 Mt of green hydrogen

Phase II

2025 – 2030

- Increase in electrolyser capacity to 40 GW
- Generation of 10 Mt of hydrogen
- Estimated investments of € 24 to € 42 bn for the development of electrolysers by 2030
- € 220 to € 340 bn for the necessary expansion of solar and wind power capacity

Phase III

2031 – 2050

- Green hydrogen technologies will be sufficiently mature to be used on a large scale for the decarbonisation of all those industries which did not achieve this before Phase III.

The German government's National Hydrogen Strategy, adopted on 10 June 2020, is similar to the European strategy in that it relies on green hydrogen in the long term. On 3 June 2020, the Package for the Future – part two of the German Stimulus Package in response to the Covid pandemic – stated that the National Hydrogen Strategy would require € 9 bn of funding. The strategy specifies how quickly production should be expanded and to what capacity.

Production plants with a total capacity of up to 5 GW, including the necessary offshore and onshore power generation facilities, are to be built by 2030. For the period until 2035, another 5 GW will be added if possible, and this capacity should be available by 2040 at the latest. The National Hydrogen Strategy spans the entire value chain – technologies, generation, storage, infrastructure and use, including the logistics and key aspects of the quality infrastructure.

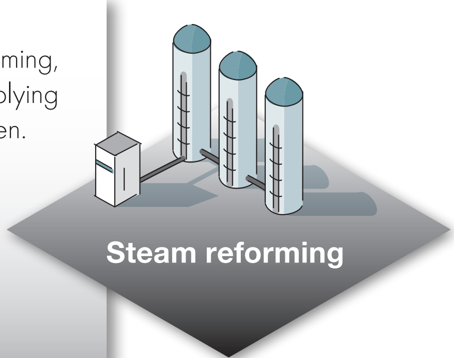
The strategy aims to support a speedy market ramp-up and to establish new value chains. Among the main beneficiaries of the strategy will be those sectors that have had no alternatives to hydrogen to decarbonise process-related emissions, such as the chemical, cement and steel industries. The German government is expecting to import most of the hydrogen required from abroad – one reason why its National Hydrogen Strategy relies heavily on cooperation with partner countries. Of the € 9 bn, € 2 bn are earmarked for international partnerships in this area.

The colours of hydrogen

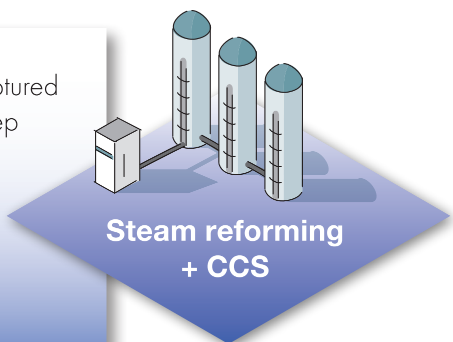
And what they mean

Although hydrogen is an odourless and colourless gas, we use colour codes when we talk about its origins. Hydrogen can be generated using a range of very different processes and technologies, which also vary considerably in terms of their carbon footprint and thus the reduction of greenhouse gases. The type of production is therefore crucial for the emissions balance.

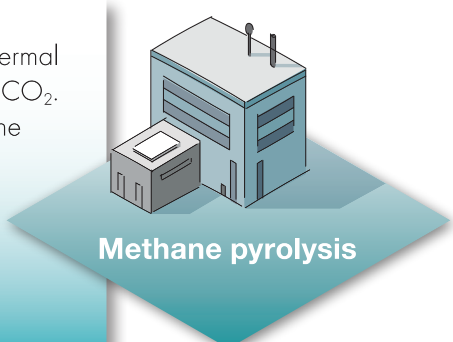
At present, most hydrogen is generated from fossil fuels. In steam reforming, methane – the main constituent of natural gas – is broken down by applying heat. This results initially in a mixture of carbon monoxide and hydrogen. In a second step, referred to as the water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and hydrogen. The carbon dioxide is released into the atmosphere unused. Around ten tons of CO_2 are generated in the production of one ton of hydrogen. Hydrogen produced using this method is referred to as **grey hydrogen**.

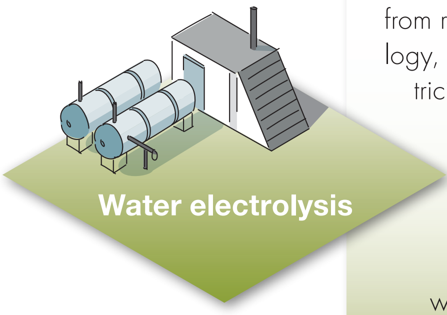


Blue hydrogen is grey hydrogen whose CO_2 emissions are captured and stored (carbon capture and storage, CCS), for instance, in deep subsurface geological formations such as exhausted natural gas reservoirs. The CO_2 produced in hydrogen generation is not released into the atmosphere, which is why blue hydrogen is considered to be carbon-neutral.

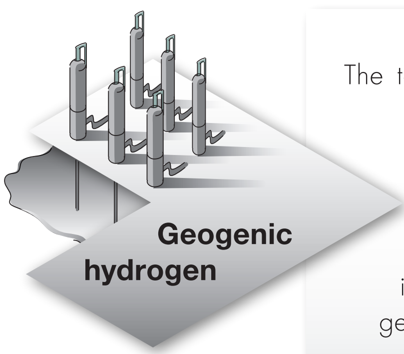


Turquoise hydrogen is produced using methane pyrolysis, the thermal decomposition of methane, which produces solid carbon instead of CO_2. For the process to be carbon-neutral, the heating energy supply of the high-temperature reactor must be from renewable sources. The elemental carbon produced can be used as a raw material; if not, it is at least easier to dispose of than the CO_2 produced in steam reforming.





Green hydrogen is produced from water by electrolysis using electricity from renewable energies only. Whatever the choice of electrolysis technology, the production of hydrogen will be carbon-free, since all of the electricity used is from renewable sources. Where the power for electrolysis comes from different sources and is therefore not carbon-free, the hydrogen is labelled with a different colour term. Electricity and water are essential for the production of hydrogen using electrolysis. According to IRENA (2020), between 18 and 24 kg of purified water are needed to produce 1 kg of hydrogen. In combination with photovoltaics, the requirement is even higher. Around 50 kWh of electricity are needed per kilogramme of hydrogen.



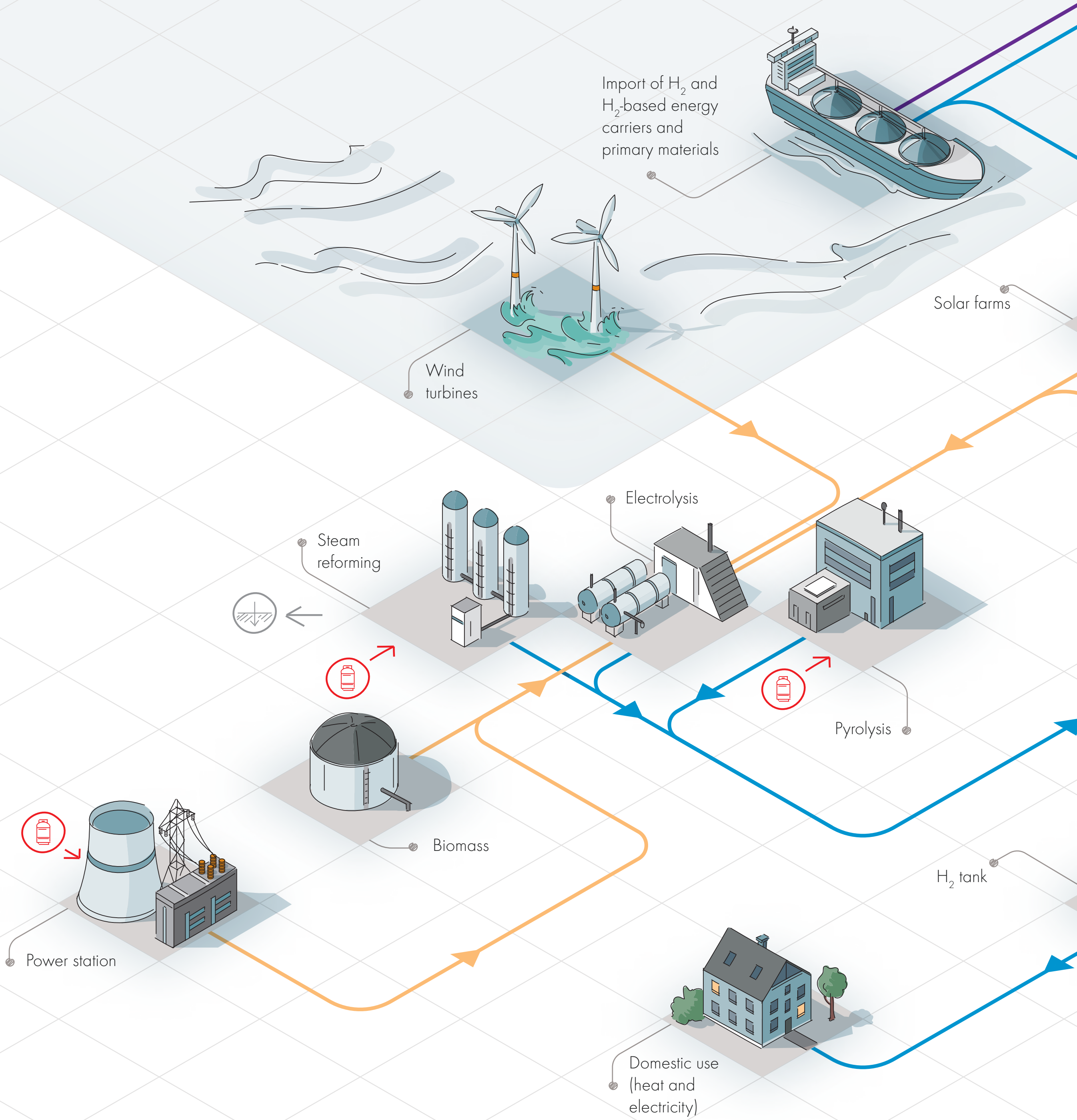
The term **white hydrogen** refers to geogenic or natural hydrogen. In fact, a number of processes result in the formation of hydrogen in the deep geological subsurface. Scientists at the Federal Institute for Geosciences and Natural Resources (BGR) have been investigating what geological conditions are favourable to the accumulation and long residence times of hydrogen in trap structures that may exist in the subsurface, and whether the commercial use of geogenic hydrogen will be possible in future.

In 2020, around 900 Mt of CO_2 were released in the generation of hydrogen from fossil fuels to meet the global hydrogen demand of around 90 Mt (IEA 2021). Regarding the question of how hydrogen should in future be produced, governments are pursuing different paths in their hydrogen strategies.

In the medium term (until 2030), most countries that have adopted a hydrogen strategy consider the use of blue hydrogen, some even the use of grey hydrogen, as an opportunity for affordable market ramp-up and the development of a hydrogen market. Turquoise hydrogen is relevant only for few countries. Both the European and the German hydrogen strategies focus primarily on green hydrogen for achieving the climate goals, particularly in the long term.

Routes of hydrogen

From sources to applications



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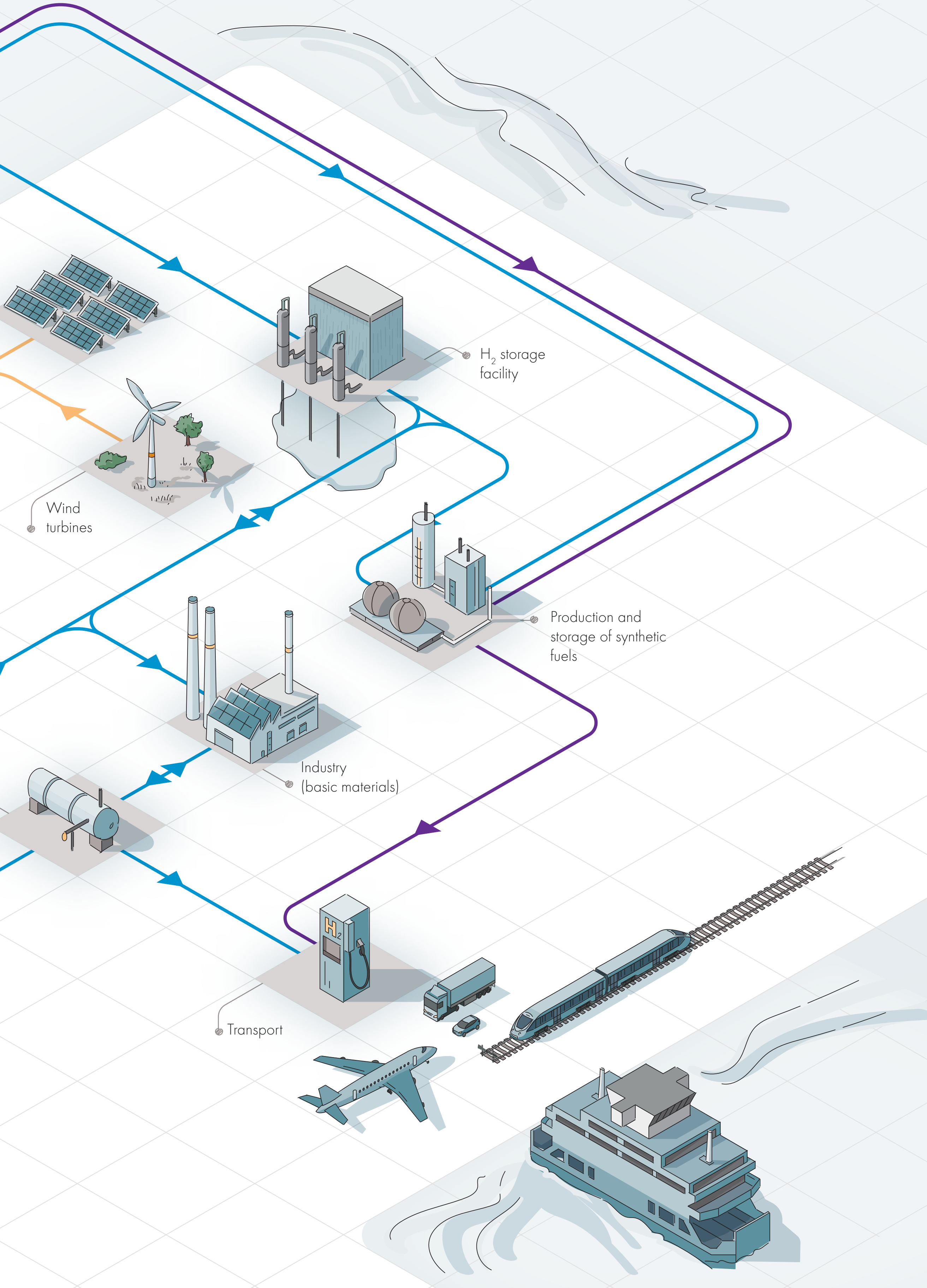

H2 storage facility
Wind turbines
Production and storage of synthetic fuels
Industry (basic materials)
Transport

Water electrolysis

Technologies for the production of green hydrogen

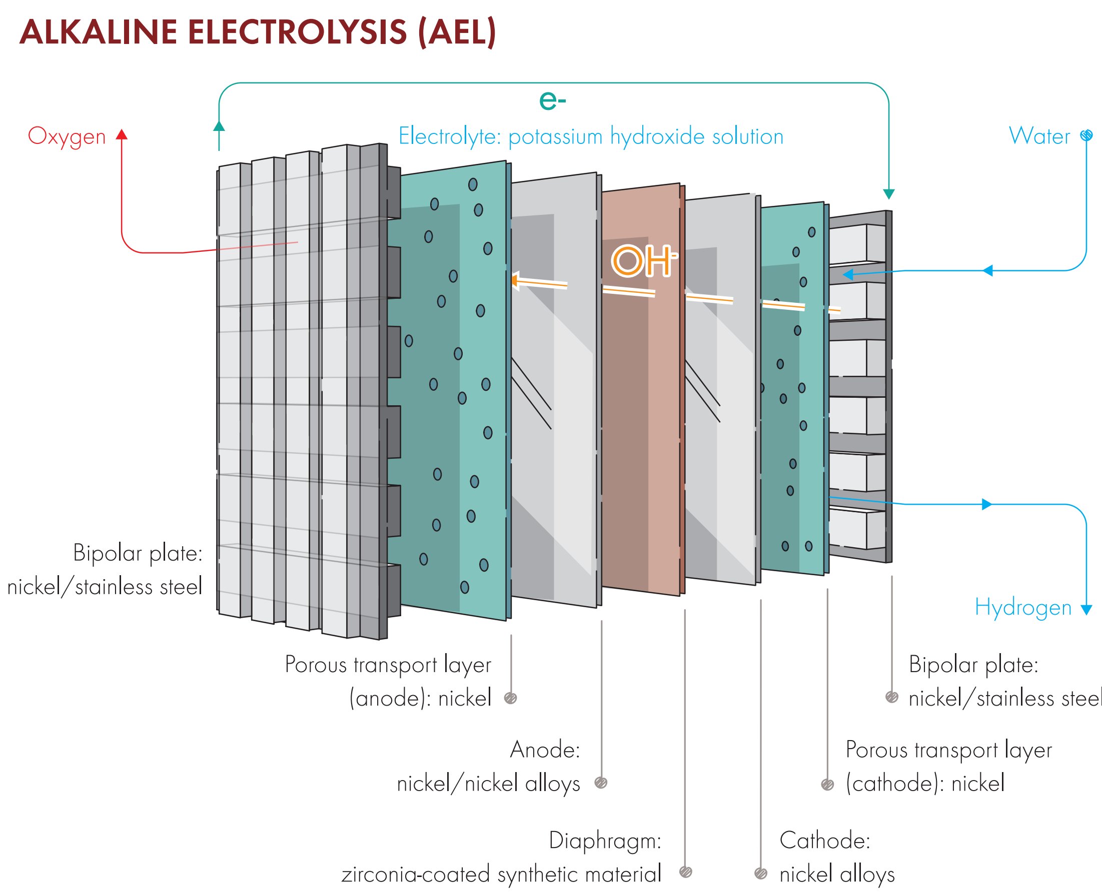
While the hydrogen economy is under development, blue hydrogen can be used as an interim solution in the EU and in Germany. But the future belongs to the production of green hydrogen using water electrolysis, which permits the conversion of water into hydrogen and oxygen using electrical power from renewable energies.

The production of hydrogen in a water electrolysis plant involves several process steps, from power supply to electrolysis, gas drying, compression and storage. The central system component of such a plant is the electrolyser, which produces the hydrogen. At present, there are three major electrolysis technologies: alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEMEL) and solid oxide electrolysis (SOEL).

AEL, and to a large extent also PEMEL, have already reached technical maturity. SOEL is not widely used at present. Since the methods have slightly different characteristics, the suitability of each depends on the specific application.

Alkaline electrolysis (AEL)

AEL uses a potassium hydroxide solution, with hydroxide ions (OH^-) as the charge carriers. The cathode and anode are separated by a zirconia-based diaphragm (e.g., Zirfon®), which is impermeable to the product gases hydrogen and oxygen.



Structure of an AEL cell

By applying a voltage to the electrodes, the hydrogen is separated from the water and the hydroxide ions form at the cathode. They can pass through the diaphragm and move towards the anode, where they form oxygen.

AEL is the oldest and most mature water electrolysis technology. It is already commercially available on a large scale. However, when volatile power sources are used, problems are a slow response to load changes and a relatively small part load range. Moreover, AEL has quite a long cold start-up time of about 50 minutes.

A major advantage of AEL is that production requires no potentially critical raw materials. Standard electrolyser concepts generally use nickel or nickel alloys for both the anode and the cathode, making the plants relatively low-cost. But their large physical footprint and because of the use of potassium hydroxide solution, they are not suitable for every location.

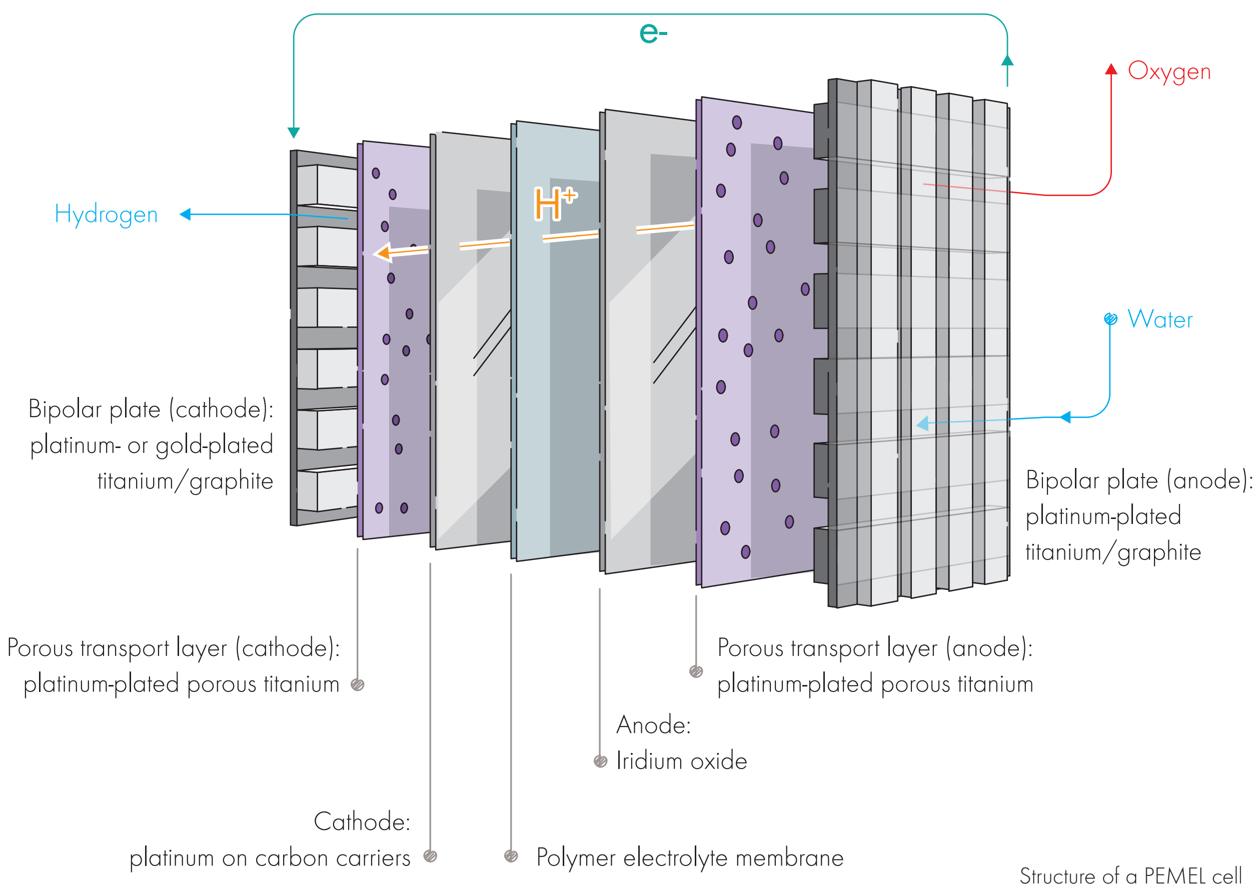
Polymer electrolyte membrane electrolysis (PEMEL)

This technology uses proton-exchange membranes, also abbreviated as PEM. These membranes, solid polymer electrolytes, are permeable to protons but not to gases such as hydrogen or oxygen. The charge carriers are protons, positively charged hydrogen ions (H^+), which can pass through the membrane.

When a voltage is applied to the membrane surrounded by water, protons pass through it. Hydrogen is produced at the cathode and oxygen at the anode. The anode, which has an oxidative and therefore highly corrosive atmosphere, is coated in thin layers of iridium oxide (IrO_2) as a catalyst.

Iridium is very corrosion-resistant and considered irreplaceable at present, since no other material with the necessary properties has so far been found.

POLYMER ELECTROLYTE MEMBRANE ELECTROLYSIS (PEMEL)



Structure of a PEMEL cell

Platinum is also used as a catalyst coating of the electrodes in PEMEL cells, mostly on the cathode side. The bipolar plates, usually made from titanium, are often platinum-coated as well, to reduce the electrical resistance of the surface. The porous transport layers on both the anode and cathode sides are made from highly corrosion-resistant titanium and often platinum-coated, too.

PEMEL responds better to load variations than AEL, which is of particular benefit when combined with renewable energies. Since it can operate at higher current densities than AEL, a more compact design is possible. In locations where only limited space is available or the use of alkaline solutions is not possible, PEMEL is preferable to AEL. It can, for instance, be used immediately next to offshore wind farms. On the other hand, PEMEL is a relatively expensive technology because it uses precious metals as catalysts.

Fuel cells (FC) use the reverse principle of electrolysis to generate energy from the reaction of hydrogen and oxygen to form water. PEMFCs, used primarily in electric mobility, use almost the same resources as PEMEL, except for iridium oxide.

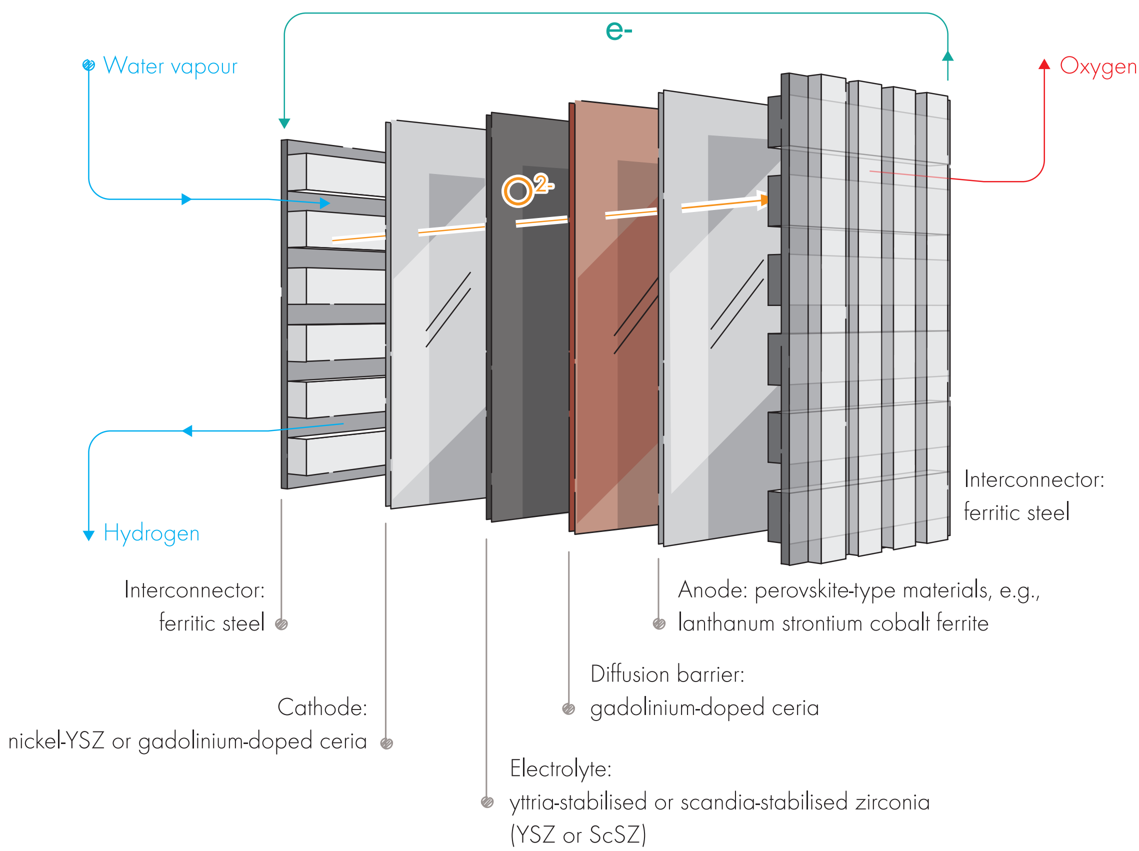
Solid oxide electrolysis (SOEL)

As its name suggests, SOEL uses a solid that conducts oxygen ions as the electrolyte. This electrolysis technology is at the transition between research and industrial application. What distinguishes it is the fact that it works at very high temperatures (700 – 850 °C).

In SOEL, water is added not in liquid form but as steam, which dissociates at the cathode into protons and oxygen ions. The protons combine with electrons to form hydrogen at the cathode, while the oxygen ions move through the solid electrolyte towards the anode, where they shed electrons to form oxygen.

The solid electrolyte is either yttria-stabilised zirconia (YSZ) or scandia-stabilised zirconia (ScSZ).

SOLID OXIDE ELECTROLYSIS (SOEL)



Structure of an SOEL cell

For the cathode, nickel-YSZ materials, ScSZ or gadolinium-doped ceria (GDC) are used; for the anode, perovskite-type materials such as lanthanum strontium cobalt ferrite (LSCF), lanthanum strontium cobalt (LSC) or lanthanum strontium manganite (LSM). A diffusion barrier, generally GDC, serves to prevent a chemical reaction between the electrolyte and the anode.

Interconnectors separate individual cells while electrically connecting the cathode and anode of different cells. They are in most cases made from ferritic steel (nickel-, iron- or chrome-based alloys).

One major advantage of SOEL is that it has a higher efficiency potential than the other technologies, permitting theoretical efficiencies of between 80 and 90 %, although at present they are between 45 and 55 %. The high temperature level and the combination with heat applications are promising.

Disadvantages of this technology are the necessary long cold start-up times of currently several hours and a short lifespan. SOEL technology is suitable for a large number of full-load hours.

Solid oxide fuel cells (SOFC) use the reverse principle of SOEL and require the same resources as SOEL.

Water electrolysis

Raw material demand

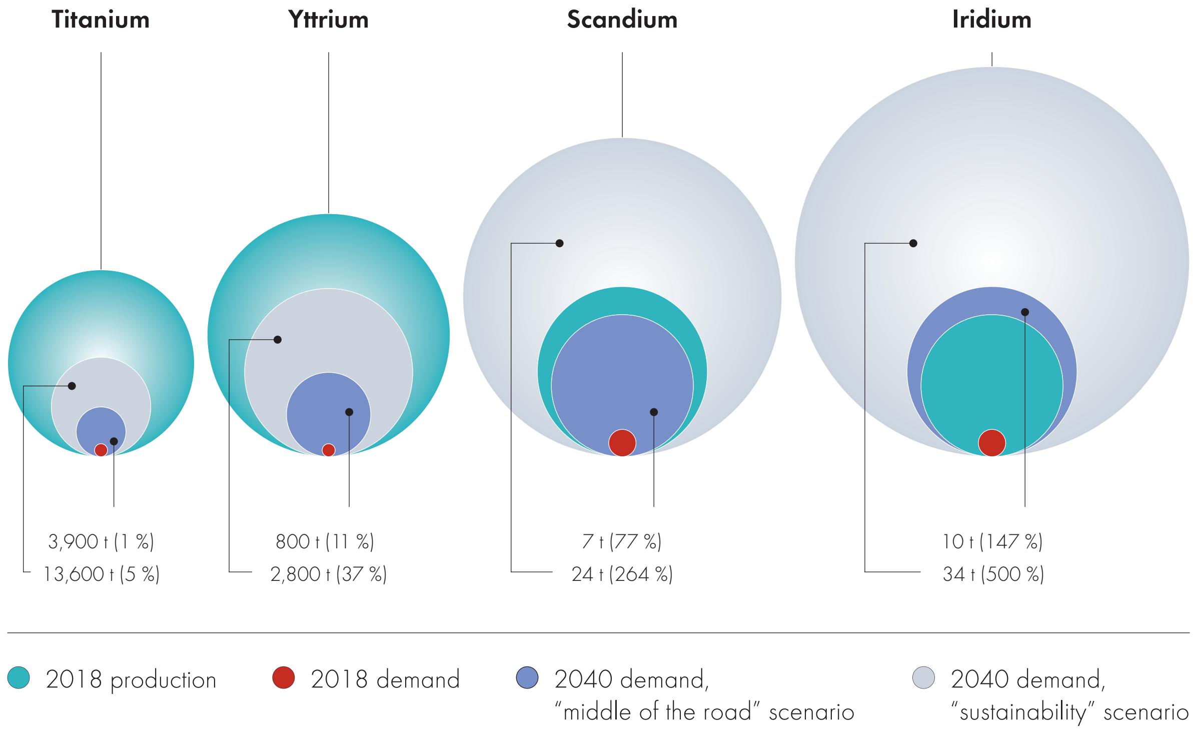
The "Raw materials for emerging technologies 2021" study commissioned by DERA determined, among other things, the mineral raw materials demand from water electrolysis until 2040. It considered the three technologies AEL, PEMEL and SOEL and determined the raw material demand of three different scenarios: "sustainability", "middle of the road" and "fossil-fuelled development".

The findings from the study for the two scenarios aiming for a low-carbon economy are presented here. The "fossil-fuelled development" scenario is not covered, as it does not involve hydrogen technologies.

For iridium, which is used in PEMEL, both scenarios forecast a demand in 2040 from water electrolysis alone that is significantly higher than the 2018 production. In the "sustainability" scenario, demand is five times the refinery production, which was about 6.8 t in 2018.

The demand for scandium from SOEL in 2040 could be 2.7 times the 2018 production in the "sustainability" scenario. Mine production in 2018 was at around 9.1 t. In the "middle of the road" scenario, demand would be about 7 t just from this technology, equivalent to 77 % of the 2018 production.

Demand for yttrium and titanium from water electrolysis is below the 2018 refinery production in both scenarios. However, technologies other than water electrolysis might compete for these resources – and also for scandium and iridium. A detailed look at the individual commodity markets is needed to assess how to satisfy the future increase in demand.



Raw material demand for water electrolysis (AEL, PEMEL and SOEL) (data source: Marscheider-Weidemann et al. 2021)

Scandium: the little-known minor element

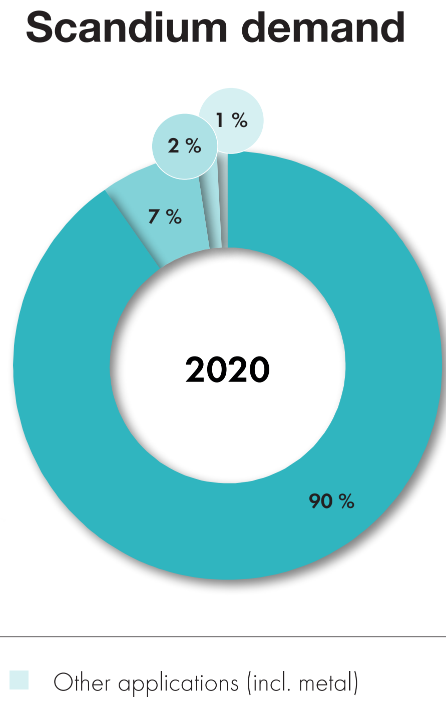
Fuel cells are already the most common application

Scandium (Sc) is a common element that is present in small amounts in many deposits. Global demand used to be rather low and only few tons of scandium as a by-product were therefore produced annually. In recent years, however, solid oxide fuel cell technology (SOFC) has led to a significant increase in demand. This technology and solid oxide electrolysis (SOEL) use both yttrium-stabilised and scandium-stabilised zirconia as the electrolyte. The advantages of the scandium-stabilised material are better conductivity and greater stability at lower operating temperatures.

Scandium occurs as an associated element in many deposit types, at concentrations of about 0.5 to 100 ppm. Scandium concentrations that are significantly higher than 20 ppm can be found particularly in titanium, tungsten, tin, rare-earth and zirconium deposits. Bauxite, nickel and uranium deposits are also of commercial interest generally, because of the large tonnages involved. Data availability for scandium output is very patchy, with annual production figures of around 10 – 20 t of scandium at present, depending on the source. DERA assumes the figure to be around 14 – 16 t.

Both demand and supply are highly concentrated, because of the high country concentration in production and the few processing companies. The largest producer of scandium by far is China, with an estimated > 10 t annually (> 75 % share of global production), followed by Russia with up to 1 – 2 t and the Philippines with about 1 t annually. In China, scandium is a by-product in the processing of titanium ores and zirconium. According to the CM Group (2021), capacity utilisation there is only at about 20 %. In Russia, scandium is obtained from residual solutions of in-situ leaching of uranium deposits.

In the Philippines, a pilot plant has recently also started to produce small amounts of scandium oxalate from nickel-cobalt ores. Taganito HPAL Nickel Corporation, 75 % owned by Sumitomo Metal Mining Ltd. of Japan, has stated their intention to



Demand for scandium oxide in 2020 (data source: CM Group 2021)

increase annual capacity to up to 7.5 t of scandium. The scandium oxalate will be processed in Japan to obtain scandium oxide. In Quebec, Canada, the company Rio Tinto has started to produce scandium from titanium processing residues to manufacture Al-Sc alloys. RUSAL has announced similar plans in Russia for scandium originating from red mud, generated during the production of aluminium from bauxite.

Overall, a considerable increase in global production would appear possible in the medium term, since there are a number of other companies who could already produce larger amounts of scandium from their residues today. Whether or not output can keep pace with the increase in demand remains to be seen. To date, a relatively high price and low level of global output were obstacles to an increased use of this raw material.

According to the CM Group (2021), around 90 % of scandium oxide is today used for SOFC, with Al-Sc alloys for aeronautics and sports equipment accounting for only a minor share. However, the present increase in demand for use in SOFC is essentially due to one company that relies on scandium-stabilised zirconia as an electrolyte.

As the "Raw materials for emerging technologies 2021" study commissioned by DERA stated, scandium demand could rise to 34 – 72 t depending on the scenario, just for the SOFC and SOEL technologies. And it could even be considerably higher if scandium oxide rather than yttrium oxide was primarily used as a stabilising element. A much tighter market can thus be expected in the future. Free capacities in China and elsewhere could very quickly be used up. The market is thus set to become more dynamic and has higher price and supply risks overall, despite the fact that two large mining companies, Rio Tinto and RUSAL, have announced their plans to produce scandium for Al-Sc alloys, which may further boost use of the metal.

Iridium: the most corrosion-resistant element

As yet irreplaceable in PEM electrolysis

Alongside ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os) and platinum (Pt), iridium (Ir) is a so-called platinum-group metal (PGM). The rare precious metal occurs in the continental crust at a concentration of just 1 ppb.

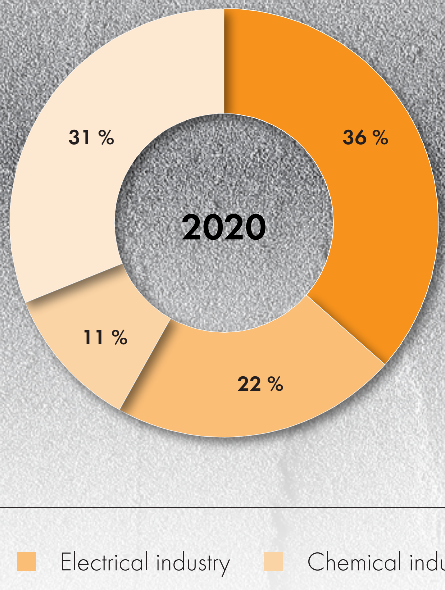
PGMs occur together in different deposit types across the globe, primarily in association with nickel and copper. Magmatic PGM deposits are the largest and most significant. There are generally two types: PGM-dominated deposits with a low concentration of basic metal sulphides (such as in South Africa), and nickel-copper-dominated deposits, where PGMs are produced as by-products (such as in Russia).

PGMs are not produced by many companies and only in a few countries, where they are also processed in the first stages of the value chain because of their financial value. There are no exports of PGM ores and concentrates, except for transfers within companies.

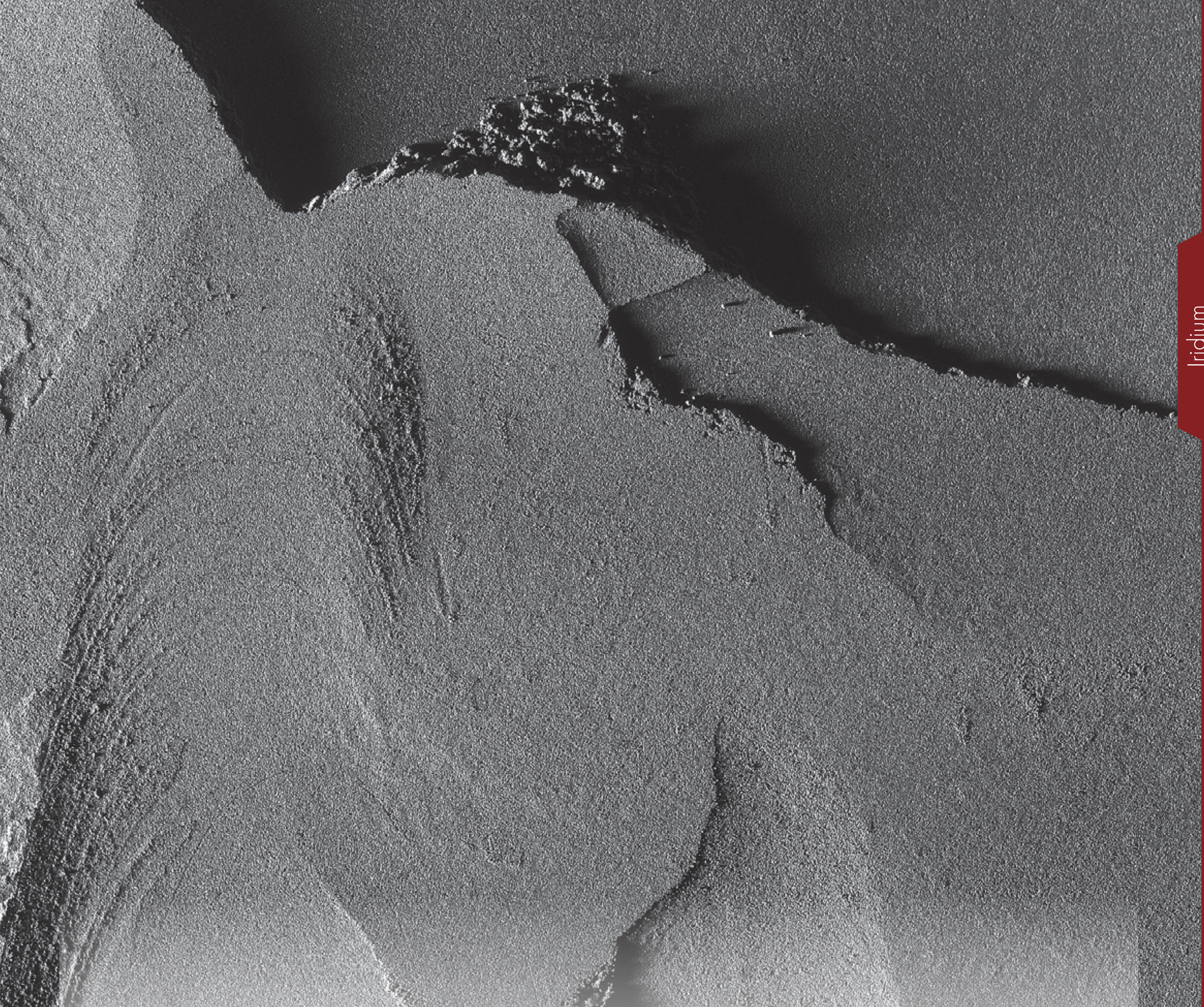
Annual production levels or output volumes are currently around 190 t of Pt, approx. 220 t of Pd and 25 t of Rh. Since markets are very small, only few data are available about the remaining PGMs. Depending on the source, around 6 – 10 t of iridium are produced annually; DERA currently assumes around 8 t for 2020. The annual supply of iridium is derived from demand, since a balanced market can be assumed. According to Hobson (2021), South Africa is the main producer of iridium, with 80 – 85 %, followed by Russia. Because of a lack of data, it is impossible to verify to what extent the global nickel industry contributes to the supply of iridium.

PGMs occur in specific ratios across the globe. The platinum content in South Africa, for instance, is in the range 1.26 – 3.25 g/t; the palladium content varies between 1.38 and 2.04 g/t of ore, while the iridium content is just 0.02 – 0.1 g/t of ore. Changes in the output volumes of platinum and palladium thus affect the other PGMs mined as by-products.

Iridium demand



Demand for iridium in 2020 (data source: Johnson Matthey 2021)



Prices for PGMs are generally very volatile. For platinum, palladium and rhodium, they are particularly affected by developments concerning catalytic converters in automobiles. Since platinum and palladium are also used as investments (ETFs) because of their financial value, pricing is highly complex. Iridium, on the other hand, is not used as an investment, because of the small market.

PGMs are used mainly in catalysts for the chemical industry and in exhaust gas treatment for all types of vehicles. Properties such as their high melting point and corrosion resistance are major factors in these applications. Iridium is considered the most corrosion-resistant element of all. This makes it currently irreplaceable in polymer electrolyte membrane electrolysis (PEMEL), where the precious metal is used in an acid environment on the anode in the form of iridium oxide. While at present, iridium is still mainly used in the electronics and electrochemical industries, its greatest potential is in PEMEL.

According to the "Raw materials for emerging technologies 2021" study commissioned by DERA, demand for iridium from the PEMEL technology alone could rise to 10 and 34 t for the "middle of the road" and "sustainability" scenarios respectively by 2040.

The market for this technology and thus the demand for iridium is likely to become much more dynamic. Given this and its supply situation as a by-product, it is subject to considerably higher price and supply risks. From a current perspective, a significant increase in iridium production does not appear possible. It would require a simultaneous considerable rise in platinum and palladium production, which is not currently expected, particularly since the PGM sector is facing considerable socioeconomic challenges, especially in South Africa. It seems unlikely that the forecast demand for iridium could be satisfied via the secondary sector.

Yttrium: supply depends on China

Demand for hydrogen technologies to rise

Yttrium (Y) belongs to the group of rare-earth elements, which also includes the 15 lanthanoid elements. They are classified as light or heavy rare earths, and yttrium is grouped with the heavy rare earths. Almost all heavy rare earths currently produced originate from China.

In the vast majority of rare-earth deposits, heavy rare earths are found in only very low concentrations. Yttrium is one of the most common, which is also reflected in the output volume. Heavy rare earths including yttrium are concentrated mainly in ion adsorption clay (IAC) deposits and in the mineral xenotime.

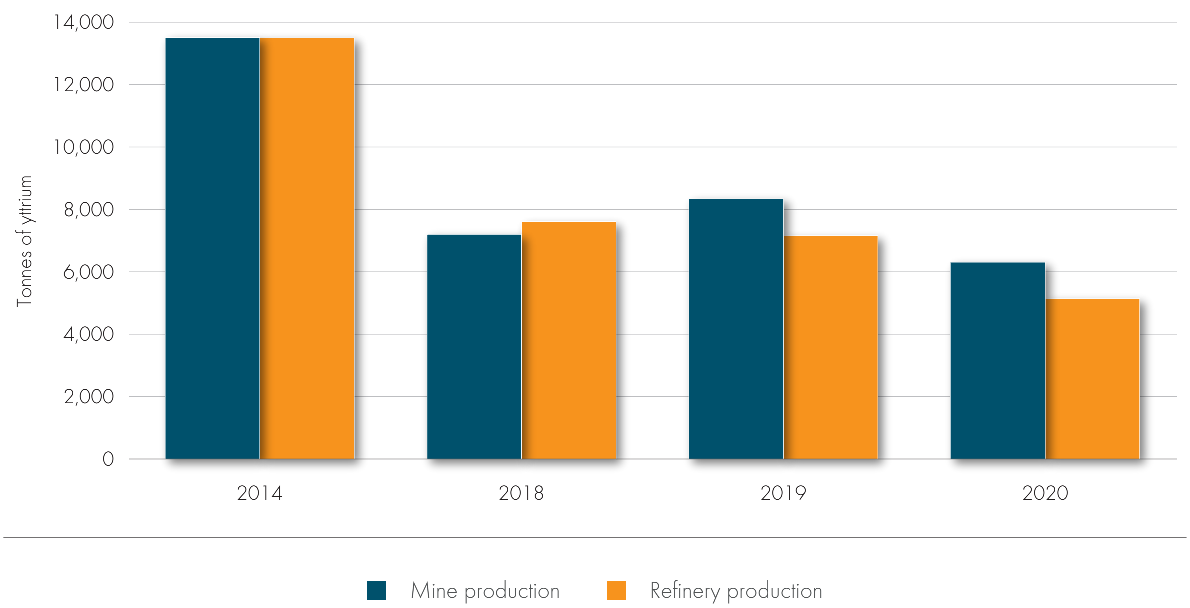
IAC are mined mainly in China's southern provinces and in Myanmar, with additional deposits under development in Chile, Brazil, Uganda and Madagascar. The composition and concentration of the individual rare-earth elements vary considerably between deposits.

Xenotime occurs in placer deposits such as heavy mineral sands in Australia and as a by-product in the cassiterite deposits of South East Asia. It used to be a by-product of tin mining in Malaysia, Indonesia and Thailand, but mining has been severely restricted due to environmental problems. Although xenotime is still recovered from some deposits, current output is very low and hardly contributes to the global yttrium production.

Other deposits with a high yttrium concentration can be found in, for instance, Australia, Brazil, Canada, the United States, and also in Europe, in Greenland and Sweden (Norra Kärr).

In 2019 and 2020, the annual global yttrium production was estimated to have been 8,300 and 6,300 t respectively. Just a few years earlier, it had been much higher at 13,500 t (2014). This was due to the high production level of IAC in China at the time, which at times exceeded the production quota. In recent years, it has been severely restricted, partly because of environmental problems.

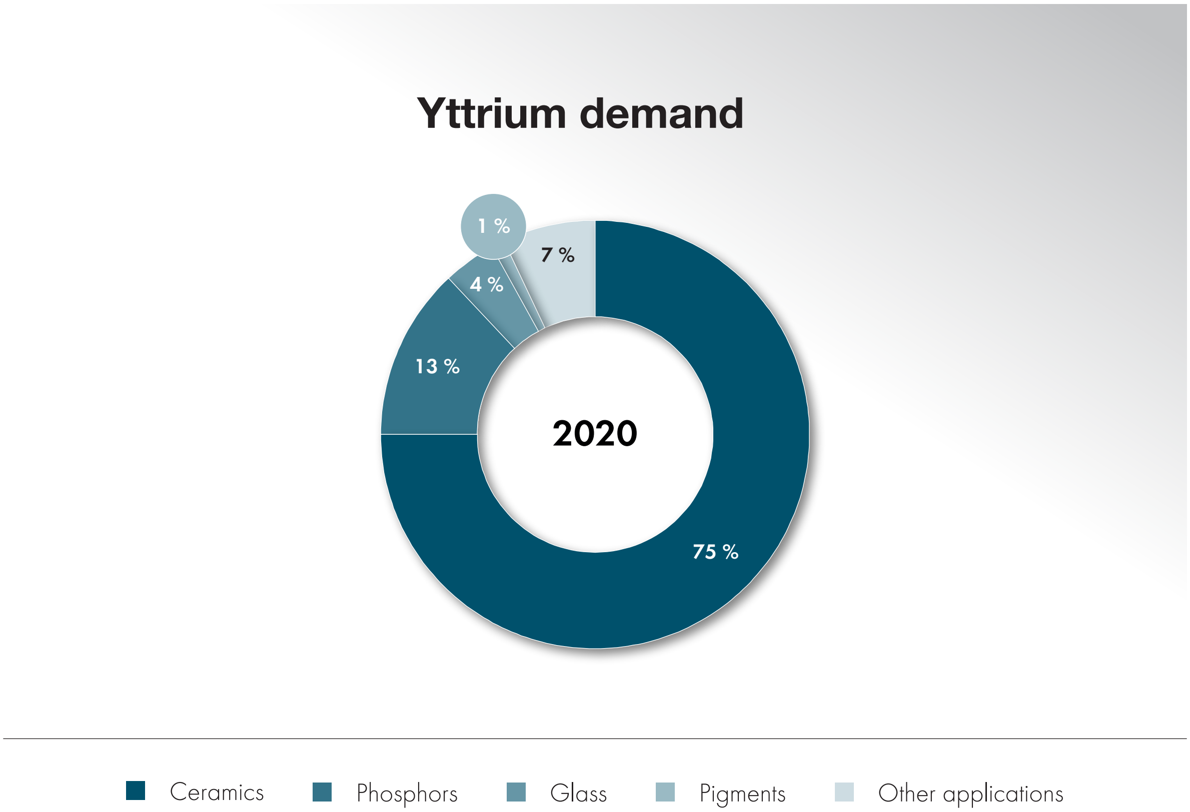
The main area of application for yttrium is in the form of yttrium-stabilised zirconia (YSZ) in the manufacture of high-resistance ceramics. These are used, for instance, as fireproof materials in the aerospace industry, in solid oxide fuel cells (SOFC) and solid oxide electrolysers (SOEL), and also in artificial joints and prosthodontics.



Production of yttrium (data source: based on Roskill 2021)

YSZ has long been used in the hydrogen technologies SOEL and SOFC and it is still the most commonly used electrolyte material today. Yttrium oxide can be replaced by scandium oxide in the stabilisation of zirconia. While scandium-stabilised zirconia (ScSZ) has better conductivity and greater stability, YSZ is more easily available and more economical.

In 2018, demand for yttrium for SOEL and SOFC amounted to around 3 t. The "Raw materials for emerging technologies 2021" study commissioned by DERA shows that global yttrium demand from SOEL and SOFC alone could rise to 1,270 – 3,642 t by 2040, depending on the scenario. Assuming an output of 6,300 t, that would be equivalent to 20 – 57 % of the current supply.



Yttrium demand (data source: based on Roskill 2021)

Yttrium is also used as a sintering agent in the production of silicon nitride and in SiAlON ceramics (silicon-aluminium oxide-nitride). A major use is in yttrium aluminium garnet (YAG), for instance, in YAG laser systems.

Another important area of application for yttrium is the manufacture of phosphors, for instance, for neon lights, fluorescent lamps or flat-panel displays.

Demand for yttrium is expected to increase most in the field of high-resistance ceramics in the next few years.

The supply concentration for yttrium in mining is high, the concentration in processing to yttrium oxide and metal even higher. Refinery production of almost all heavy rare earths is carried out in China. Changes in economic circumstances, environmental problems or licensing and trade restrictions could prejudice the availability of many rare-earth elements including yttrium.

Titanium, nickel, zirconia and cerium

A number of mineral raw materials are used in different electrolyser components. Even though future demand in this area is unlikely to exceed current production levels for some metals, plant manufacturers should still monitor the markets for these raw materials.

Titanium sponge

Titanium

Because of its high corrosion resistance, titanium is used in the bipolar plates and porous transport layers for polymer electrolyte membrane electrolysis (PEMEL).

Titanium is highly abundant in the Earth's crust and a major light metal. However, by far the largest share of titanium ores is used for non-metallic applications, i.e. in the form of titanium dioxide for white pigments. Only 6 % are processed into titanium sponge and subsequently to titanium metal, which is then used mainly in titanium alloys. Titanium sponge is produced in only seven countries worldwide. Global production in 2019 amounted to around 210,000 t, with China accounting for 40 %, followed by Japan with around 20 to 25 %, and Russia with around 20 %.

Demand for titanium metal is closely connected to the aeronautical industry, which slumped severely at the start of the Covid pandemic, but has since recovered.

Nickel

Nickel is used in different components of the electrolysis cell in alkaline electrolysis (AEL). It is used as an anode and cathode material, in the bipolar plates, and in the transport layer of the anode (as Raney nickel). In addition, various hydrogen technologies rely on nickel-bearing soft martensitic and austenitic special steels for the production, transport and storage of hydrogen.

Global mine production of nickel in 2019 was around 2.54m t. With around 853,000 t nickel content in the ore, Indonesia was the largest producer (33.6 % market share), followed by the Philippines (12.7 % market share), Russia (8.8 %) and New Caledonia (8.2 %). At present, China accounts for 34 % of refinery production, the largest share, Indonesia for 15.8 %.

Nickel is in demand mainly for the production of stainless steels and nickel alloys. In future, however, battery production will be the main driver of demand.

Zirconia

Zirconium dioxide (ZrO_2), also referred to as zirconia, is one of the most frequently used oxide ceramics. With its high resistance to chemical, thermal and mechanical impacts, it has a wide range of applications. The most important of these are in fireproof materials for furnaces and turbines, in catalysts for vehicles and industrial processes, high-performance ceramics and electronic materials.

Zirconia can be produced from the mineral zircon ($ZrSiO_4$) using different methods. The largest zircon producers are Australia and South Africa. Current global demand for zircon is about 1 Mt, most of which is used for producing tile coating and tiles. Only a very small part is processed into zirconia.

Because of its electrolytic conductivity for oxygen ions at high temperatures, zirconia is used as a solid electrolyte in, for instance, solid oxide electrolysis (SOEL) and solid oxide fuel cells (SOFC). With rises and falls in temperature, the crystal structure of zirconia changes, as does its volume, which can cause tension and thus cracks in components. To prevent this, zirconia is stabilised using various oxides (doping).

Yttrium oxide is most commonly used for the solid electrolyte in SOEL and SOFC, but also scandium oxide. SOEL can rely on scandium and cerium-stabilised zirconia (ScCeSZ), while SOFC can use gadolinium-doped ceria (GDC) and ceria gadolinium oxide (CGO).

Cerium

Cerium, a rare-earth element, is one of the light rare earths (cerium group), together with lanthanum, neodymium and praseodymium. Rare earths can only be mined together, and the volume of individual rare-earth oxides (REO) that can be extracted thus depends on the composition of a deposit. In most deposits, cerium occurs far more frequently than the other rare earths.

In 2019, the refinery production of cerium was around 53,000 t, and mine production even around 71,000 t. That corresponds to a share of 40 % of all rare earths produced. The major mining producers of light rare earths were China, the United States and Australia. Refinery production takes place mainly in China and Malaysia.

Stabilised zirconia for a range of applications

Commodity prices

Scandium and Yttrium

Scandium and yttrium are traded primarily in the form of oxides (Sc_2O_3, Y_2O_3) and metals (Sc, Y). Alongside these key commodities, there are a range of other products. In the case of scandium, there are especially aluminium alloys with a scandium content of 2 %, as well as iodine, chlorine, fluorine and acetate compounds. Yttrium is sold in the form of chloride, fluoride, acetate and hydroxide.

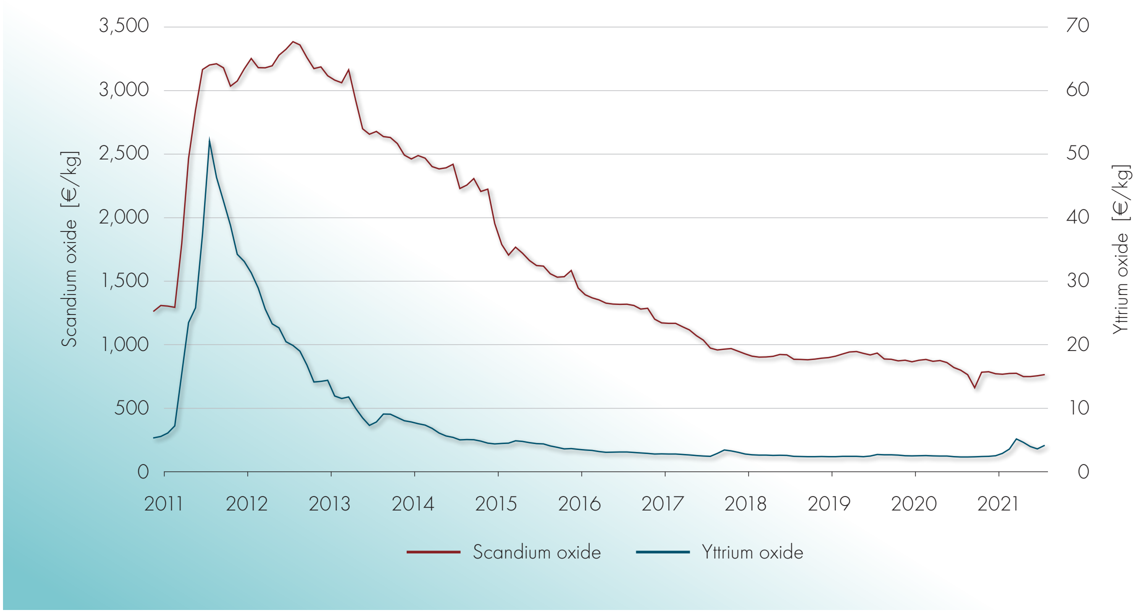
Although rare earths including scandium and yttrium are traded at two Chinese commodity exchanges, price information is not easily accessible. Trade in scandium and yttrium takes place mainly outside the commodity exchanges, with prices agreed individually between buyers and sellers. As a result, they are not publicly available. Prices are determined by the prevailing demand and supply, and particularly also by quality requirements and the size of the delivery. There is no price hedging via futures markets. The Shanghai Futures Exchange is currently looking into the option of offering futures trading in rare earths.

In summer 2011, prices for scandium oxide and the other rare-earth elements reached an all-time high of more than € 3,000 per kg. Since then, it has steadily decreased and was listed around € 760 per kg in August 2021.

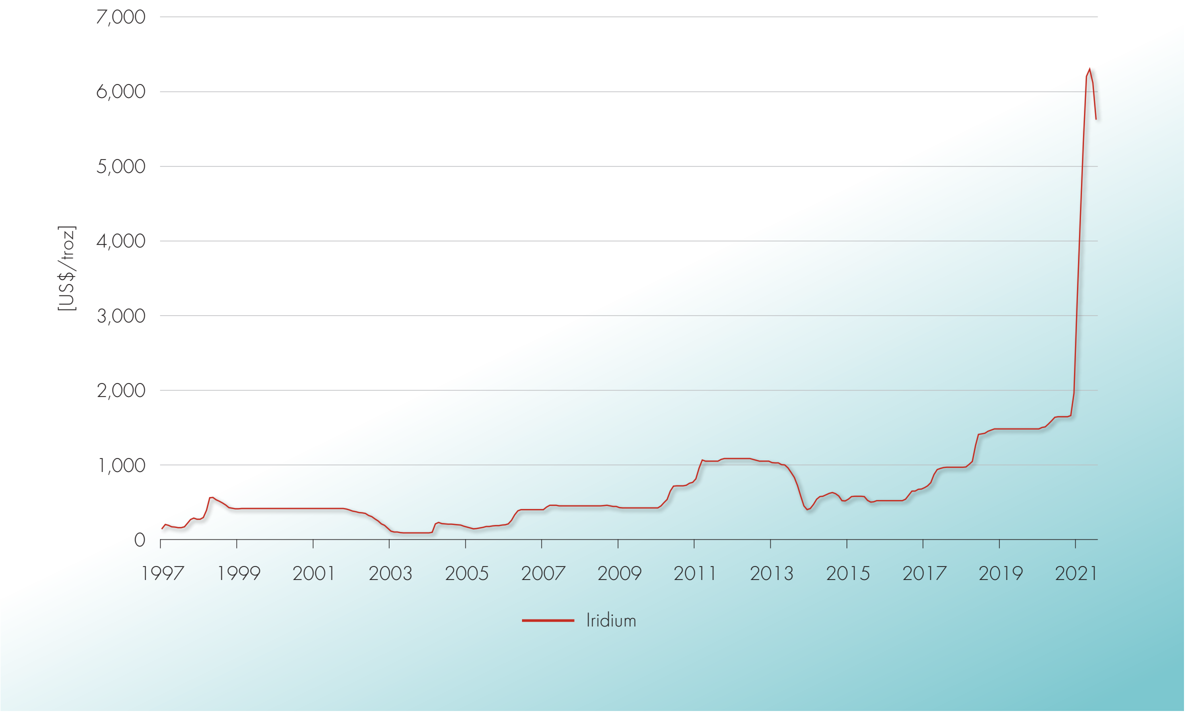
Global production of scandium is mainly in the form of scandium oxide. Additional, complex process steps are required to obtain scandium metal. This is reflected in a higher price, currently around four times the scandium oxide price.

Rio Tinto's new scandium plant in Quebec, Canada, started production in June 2021. Following the start-up phase, it will have an annual capacity of 3 t of scandium oxide, which is equivalent to about 20 % of current supply. In the absence of demand, this additional supply volume could further reduce the scandium price. Rio Tinto say they could expand capacity to increase output in the event of a rise in demand.

The price for yttrium oxide also reached an all-time high of over € 50 per kg in 2011. The subsequent downward trend continued into 2018, when a kilogramme of yttrium oxide cost just € 2.50. Between January 2021 and August 2021, the price for yttrium oxide rose by about 90 %. Alongside an increase in demand, the main reason was the availability of yttrium ore.



Price trends for scandium oxide and yttrium oxide



Price trend for iridium

Yttrium is produced mainly from ion adsorption clay (IAC) deposits. In 2021, China, the largest producer of yttrium, imported IAC from Myanmar to cover 60 % of its own demand. Yttrium prices rose in 2021 due to the political situation in Myanmar and a temporary Chinese import ban on ores from Myanmar.

Iridium

The daily price for iridium is published by the major precious metal traders and processors. Exchange-based hedging via futures contracts, such as for platinum and palladium, does not exist for iridium.

Between December 2020 and May 2021, the iridium price rose significantly from around US$ 1,700 per troz at the end of 2020 to US$ 6,300.

The reason for this price increase was that a relatively small, balanced market faced an increase in demand and simultaneous supply bottlenecks. Iridium is used for a number of niche products.

With the advent of the new 5G technology for mobile technology, demand has risen for iridium crucibles to grow synthetic crystals. At the same time, iridium supply has been severely reduced due to the Covid pandemic and technical problems in South Africa.

Iridium is a by-product of palladium and platinum production, which is why it is not possible to simply adjust mine production to match demand. Moreover, the iridium market is highly concentrated, with the largest share of global mining by far taking place in South Africa. As observed in 2021, production losses can therefore result in dramatic price increases.

Supply risks

An assessment of the supply risks always reflects specific parameters at a set point in time. That applies equally to the risks and market situation in mine and refinery production. The assessment of price and supply risks is not static, but changes over time.

We consider the supply risks to be highest for iridium and scandium – because of the very high demand, arising from water electrolysis alone, that these commodity markets could face. These commodities already have high supply risks today. The markets for scandium and iridium are very small, annual production is in the two-digit and single-digit tonnage ranges, supply is highly concentrated and limited to only a few countries, and data transparency is poor.

Iridium is produced mainly in South Africa and Russia, as a by-product of platinum and palladium. A significant rise in iridium production is unlikely. The surge in the price of iridium from December 2020 is an expression of the uncertainty over the future supply situation.

Scandium production is focused mainly in China and this is not likely to change in future, given the country's relatively large capacities. However, with the entry of RUSAL and Rio Tinto into scandium and Al-Sc alloy production respectively, there are now relatively big players in the market who might be able to reduce this dependency slightly in the future.

The yttrium market is also highly concentrated. China dominates particularly the processing into yttrium oxide and metal. The supply situation is affected especially by uncertainties over China's environmental and trade policies.

Relevance analysis

What is the financial and strategic importance of the commodities used?

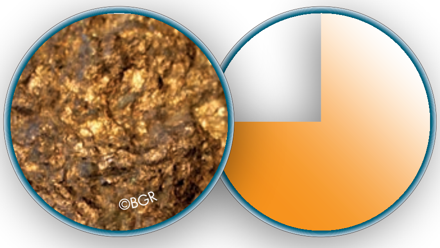
Screening
for international distortions of competition

Which of the potentially critical system-relevant raw materials are additionally subject to trade restrictions?

Detailed analysis

What other procurement risks exist for potentially critical system-relevant raw materials?

Low supply risk High supply risk



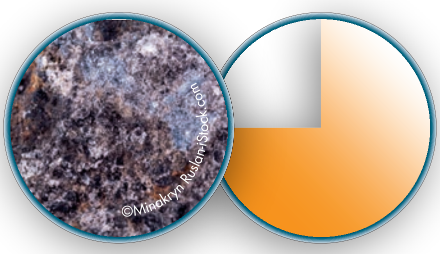
Iridium:

High supply risk, very low production

As a by-product dependent on platinum and palladium production

A marked rise in iridium production is unlikely, as this would require a considerable increase in platinum and palladium production

The global market is highly concentrated



Scandium:

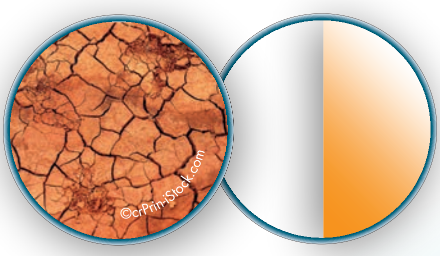
Opaque market

Low data transparency regarding current producers

The global market is highly concentrated and dominated by China

As a by-product dependent on titanium, zirconium and aluminium production

Expansion of supply possible with planned projects outside China



Yttrium:

China's market power

High concentration of supply in production and particularly in processing

China dominates refinery production

Changes in economic circumstances, environmental problems and licensing or trade restrictions could prejudice the availability of yttrium

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