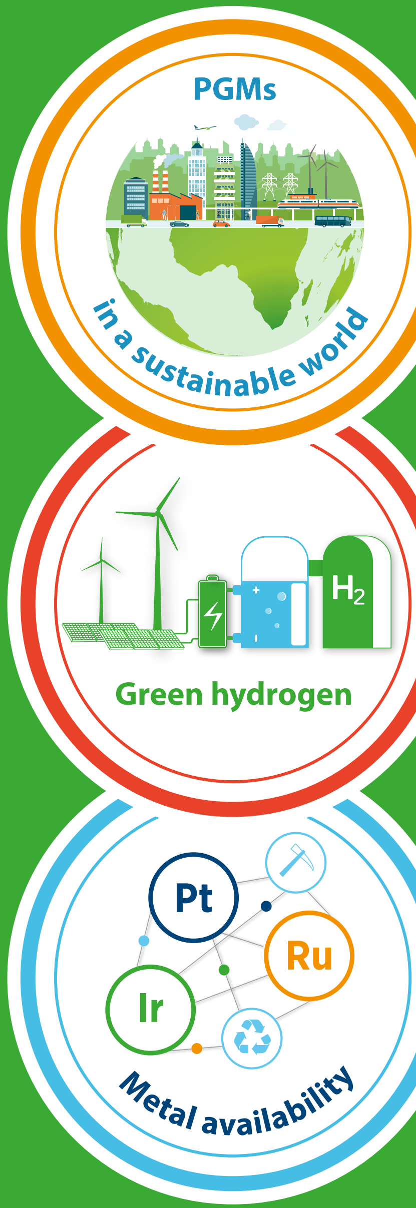
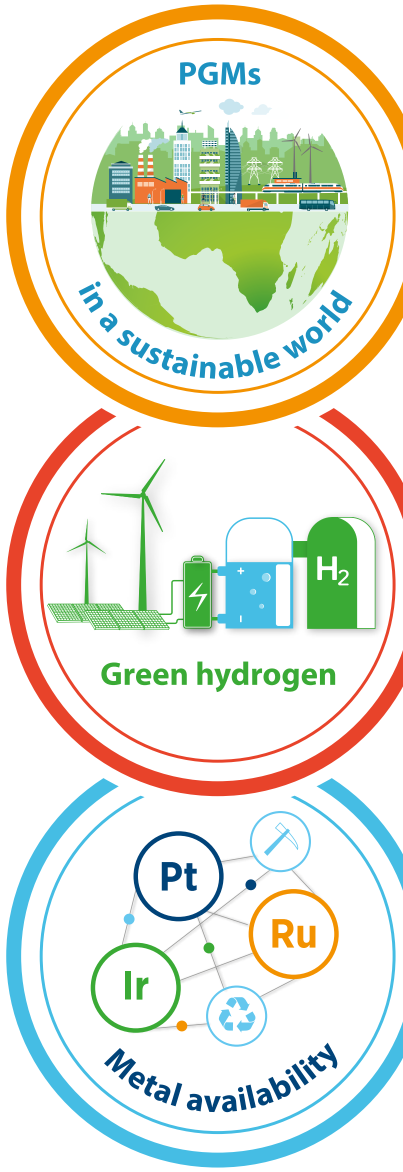
THE HYDROGEN METALS STANDARD

November 2021





THE HYDROGEN METALS STANDARD

November 2021

Issue 1

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TPS COLLECTION: AGENDA-SETTING COMMENTARY

The Palladium Standard was first published in September 2016, following the successful launch of The Platinum Standard in May 2014

One half-review, one-half preview, The Platinum and Palladium Standards comprise analytical commentary on those issues we believe will set the PGM agenda for the year ahead

If you are interested in reading the collection, you can now download the editions via our new website

FOREWORD

Foreword

Metals for a decarbonised future

Welcome to this first edition of *The Hydrogen Metals Standard*, a new publication from SFA (Oxford) which, in conjunction with its Green Metals and Hydrogen conference on 26th November 2021, puts into perspective the roles of platinum, iridium and ruthenium in decarbonisation. These are the metals within the platinum group which we call the 'hydrogen metals'. They are essential components of the hydrogen technologies which will enable the world to combat climate change by delivering a low-carbon future.

The broad strategy for containing global warming has been agreed: halve carbon emissions by 2030 and reach a state of net zero – in which the Earth absorbs as much carbon as mankind puts into it – by 2050. Achieve this by phasing out fossil fuels, by preventing deforestation, by improving energy efficiency and by replacing the burning of coal and gas with electricity derived from fast-expanding renewable sources – solar, wind and wave power.

At the COP26 summit in Glasgow this month there has been some progress towards these goals. Pledges have been given by many of the countries attending the conference to reverse deforestation, to cut methane emissions and to phase out coal plants and build no new ones. However, some of the largest emitters of carbon have not yet signed up to all of these targets. A perceived gap between words and deeds continues to draw criticism – that the COP process is too slow and an exercise in 'greenwashing', and that traditional energy production methods are too entrenched.

While we cannot yet know whether the desired state of net zero carbon by 2050 will be achieved, potential highways to arrive at this destination are fast being developed and are becoming realities. One of these highways is hydrogen, or, as it is often described, the 'hydrogen economy'. Hydrogen is, however, only a part – albeit a vital one – of the future low carbon economy. It cannot be the sole energy vector for zero carbon: the nature of hydrogen and the laws of thermodynamics do not allow it. Hydrogen does not occur freely; it must be extracted from some other compound or molecule, and in so doing, some energy is wasted.

So, in the low carbon future it will be renewable electricity which does most of the heavy lifting – where it can. But 'green' hydrogen made from renewables using large-scale electrolysers will be needed to decarbonise those sectors of the economy which direct use of renewable electricity and batteries cannot. These applications for hydrogen range from replacing coke for steel production, to hydrogen fuel cells for long-range transport, and to hydrogen as a store of renewable energy for securing reliable and stable energy supplies. How this green hydrogen will be produced; how and when it can become cost-competitive with existing sources of energy; the applications in which it will be used; and the contribution of platinum, iridium and ruthenium towards securing a green energy future, are all addressed in *The Hydrogen Metals Standard*.

Katsuhiko Hirose, WPI Visiting Professor at the International Institute for Carbon-Neutral Energy Research and former Professional Partner at Toyota Motor Corporation, considers the value of hydrogen and PGMs to society in 2050 in his contribution, 'The role of hydrogen and PGMs in the coming sustainable world'. An increasing number of nations are adopting hydrogen strategies, creating impetus for developing new hydrogen technologies, and the function of green hydrogen is changing from being an alternative fuel for transport to becoming a basic energy vector for the whole of society. As well as its contribution to decarbonisation and energy efficiency, the hydrogen economy will bring other powerful benefits: employment, wealth creation and the opportunity for national energy self-reliance, with PGMs as the essential enabling materials.

In 'The greening of hydrogen', Jeremy Coombes, Independent Consultant & Member of SFA (Oxford) Executive Committee, tracks the factors that will determine green hydrogen supply and its uses, including hydrogen's limitations and advantages and the costs and alternative methods of production of low or zero carbon hydrogen. His article also looks at how established and developing electrolyser technologies compare in terms of performance and application, and comments on the possibilities of substituting or thrifting PGMs to lower electrolyser costs and improve the long-term supply-demand balance.

Our third paper, 'Catalysing a low-carbon future: Mission-critical metals for the hydrogen economy', is by Francesca Price and Alex Biddle from SFA (Oxford) and surveys the future availability of iridium and ruthenium to support the growing demand for electrolysers and fuel cells. It examines the geological, economic, strategic and investment pressures which are influencing a trend to maximise production from iridium- and ruthenium-rich orebodies in South Africa – the main source of these 'minor' metals – as producers work to ensure their ability to meet future demand from the hydrogen economy.

Finally, a short review of the markets for the three critical PGMs is given, which includes a forecast of supply and demand in 2021.

Whatever the outcomes of COP26, a deep degree of decarbonisation of the world economy is now inevitable. Through this and future editions of *The Hydrogen Metals Standard*, and building on its commanding experience in commodity analysis, SFA (Oxford) intends to stimulate informed debate and understanding of the developing role that green hydrogen – enabled by PGMs – will play in this existential process.

THE ROLE OF HYDROGEN AND PGMs IN THE COMING SUSTAINABLE WORLD

The role of hydrogen and PGMs in the coming sustainable world

Pro-active PGMs' role in a peaceful and happier society

Dr. Katsuhiko Hirose, WPI Visiting Professor at the International Institute for Carbon Neutral Energy Research, former Professional Partner at Toyota Motor Corporation

The progress of hydrogen's recognition in the world

Hydrogen policy recognition

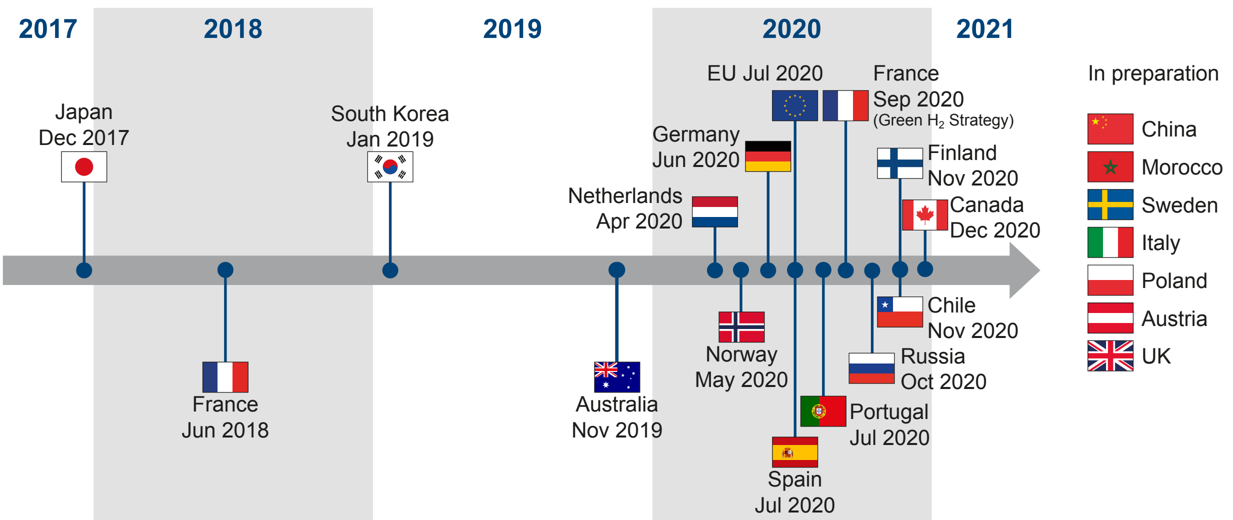
What has changed in the past five years?

Only a few years ago, I talked about hydrogen at the SFA Oxford Platinum Lectures. At that time, hydrogen was the fuel for the fuel cell vehicle, perceived as an alternative to battery electric vehicles (BEVs). Most of the audience recognised that *"hydrogen may have a chance, but it would be far into the future"*.

Hydrogen strategies abound

When I authored an article about metals for use in the hydrogen economy, no countries had committed to hydrogen use. Only Japan had a national roadmap for hydrogen, but it was more for R&D. The position of hydrogen has changed drastically since then, and it is changing rapidly now. Figures 1 and 2 show the countries which have set a national hydrogen strategy; they are growing rapidly, as is the number of countries in the world adopting a carbon-neutral/net-zero policy. Even the Kingdom of Saudi Arabia, which is recognised as an entrenched fossil-fuel producer, has announced the building of a hydrogen strategy.[1]

National hydrogen policy development (Figure 1)



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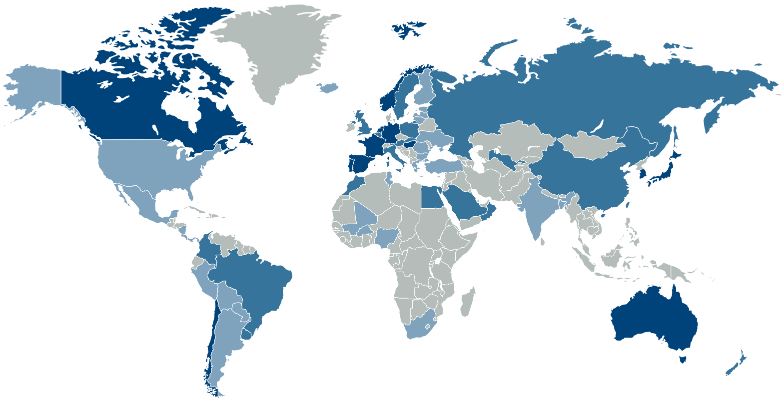
World map of hydrogen strategy (Figure 2)



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Substantial change occurred after late 2019. Before then, the Japanese experience was typical, in that a hydrogen strategy meant setting an introduction target for fuel cell vehicles (FCVs or FCEVs), preparing infrastructure for those vehicles, and setting the target number for hydrogen refuelling stations (HRSs). However, newer national/continental strategies have been setting targets for electrolysis, such as the EU's target of 40 GW of electrolyser capacity installed by 2030. I think this biggest change has resulted from a revolutionary report from the Hydrogen Council. Hydrogen will play a significant role in decarbonisation, and it will create $2,500 billion worth of business and 30 million jobs as well as a reduction of 6 Gt of CO_2 emissions annually (Figure 3). (I was involved in this report as Co-Chair of the Hydrogen Council team that wrote the report.) It changed the role of hydrogen from an alternative fuel for the automotive industry to a total energy system solution (Figure 4). Hydrogen, together with electricity, is the vector to decarbonise society through an increase in reliable, tradable and storable renewable energy. Hydrogen can decarbonise transport, industry and the home as a non-carbon heat source and feedstock (Figure 4).

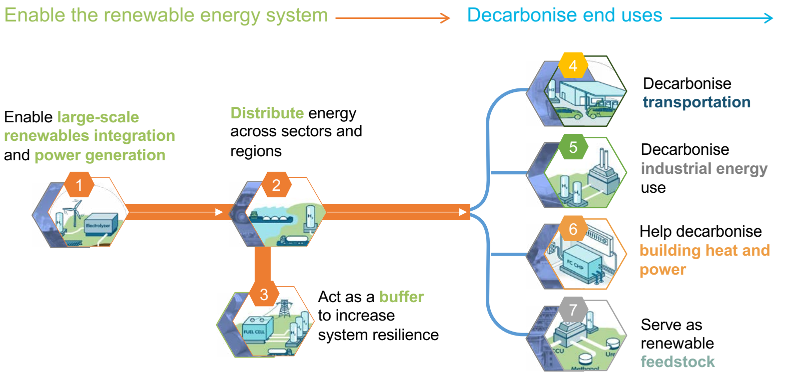
Hydrogen's importance as a vector to decarbonise society

Hydrogen's role in environment and business[2] (Figure 3)

*Source: Hydrogen Council. * Value add of fuel cells.*

And also to create 30 million jobs and $2,500 billion worth of business

Hydrogen's role in the decarbonised world[3] (Figure 4)



Source: Hydrogen Council

From enabling large-scale renewables' integration to decarbonising industry, transport, heat and power

Hydrogen has caught the crest of the wave of interest in climate change and the Covid-19 recovery plan. Hydrogen-related investments are no longer just for protection of the environment or for mitigating climate change, but an investment and a solution for the future society.

For hydrogen, significant penetration was a typical 'chicken and egg' issue between the number of FCEVs and number of HRSs, since no vehicles can be sold without infrastructure, and no infrastructure can be built without FCEVs. National intervention or regulation is necessary for the next steps. However, new national strategies show something completely different, as they commit to building large electrolysis facilities to cut the cost of hydrogen in order to transform society (energy/industries/homes) into a low-carbon/carbon-neutral society.

Electrolysis at scale is the focus of national strategies

EU Hydrogen Strategy (Figure 5)

Phase 1: 2020-2024

- **6GW** of renewable H_2 electrolysers
- 1 million tonnes renewable H_2
- Replacing **existing H_2 production**
- Regulation for liquid H_2 markets
- Planning H_2 infrastructure

Phase 2: 2025-2030

- **40GW** of renewable H_2 electrolysers
- 10 million tonnes renewable H_2
- New applications in steel & transport
- H_2 for electricity balancing purposes
- Creation of "hydrogen valleys"
- Cross-border logistical infrastructure

Phase 3: 2030-2050

- H_2 technologies matured and deployed at large scale in hard to abate sectors
- Expansion of hydrogen-deprived synthetic fuels
- EU-wide infrastructure network
- An open international market

Source: FCH

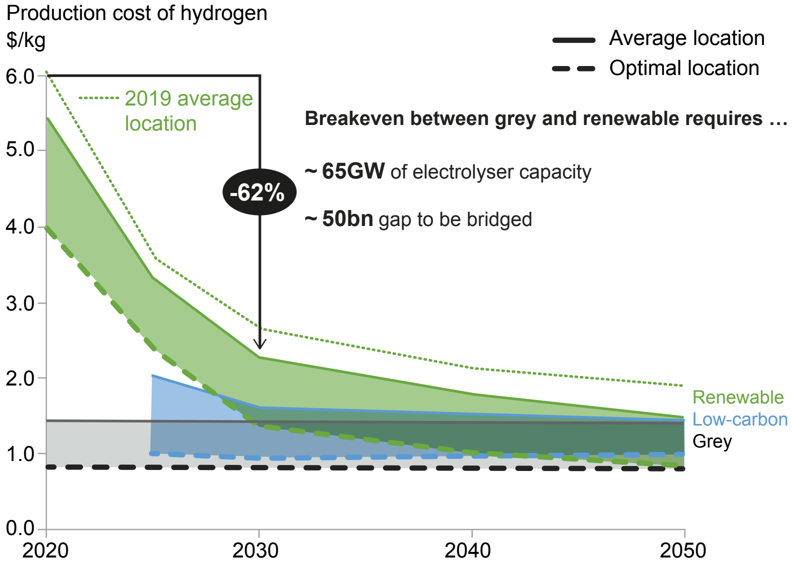
The Hydrogen Council report stated that 65 GW of electrolysis capacity would be needed to achieve a cost price of hydrogen that would be competitive with fossil fuel. The EU has set itself a target of 40 GW of electrolyser capacity within and 40 GW outside the EU by 2030, which exceeds the ambitious target of the Hydrogen Council report. EU planners intentionally set the target to accelerate the reduction of the green hydrogen price to compete at the fossil energy level.

Green hydrogen is approaching being cost-competitive with fossil fuel energy

Recent national hydrogen strategies have set actions to fight against climate change which reflect a recognition of hydrogen's role in this effort. This change is also reflected in the size of hydrogen production targets. The earlier Japanese strategy in 2017 targeted 300 kt/year of hydrogen output, which was ambitious at the time. But the 2020 EU target for 2030 is 10 mt/year just for renewable hydrogen (Figure 5). These numbers are far bigger than the early national targets, indicating a change of scale in hydrogen production from being only a fuel for transport to becoming the basic energy for the whole of society.

Hydrogen production targets from governments are increasingly ambitious

Hydrogen production costs by production pathway[4] (Figure 6)



Source: Hydrogen Council, McKinsey & Company

Cost and value chain progress

Hydrogen's biggest issue is cost, especially when we need to replace natural gas. When hydrogen is produced from natural gas, conversion needs some extra energy which makes hydrogen always more expensive than natural gas. However, the cost of green hydrogen is independent from natural gas, since it is produced by electrolysis of water with renewable electricity, and the recent cost reduction of renewables has led to a cost of hydrogen potentially lower than that of the fossil fuel itself.

Recent cost reduction of renewables is vital to get hydrogen costs down

This price competition can be accelerated by the introduction of carbon taxes which provide a disincentive to energy originating from fossil resources and incentives for renewable sources such as green hydrogen. Current carbon tax rates (per tonne of CO_2 emitted) are diverse, ranging from low ($3 in Japan) to moderate ($50 in France) and to high ($128 in Sweden), but increasing values are likely to become the norm in most regions/countries.

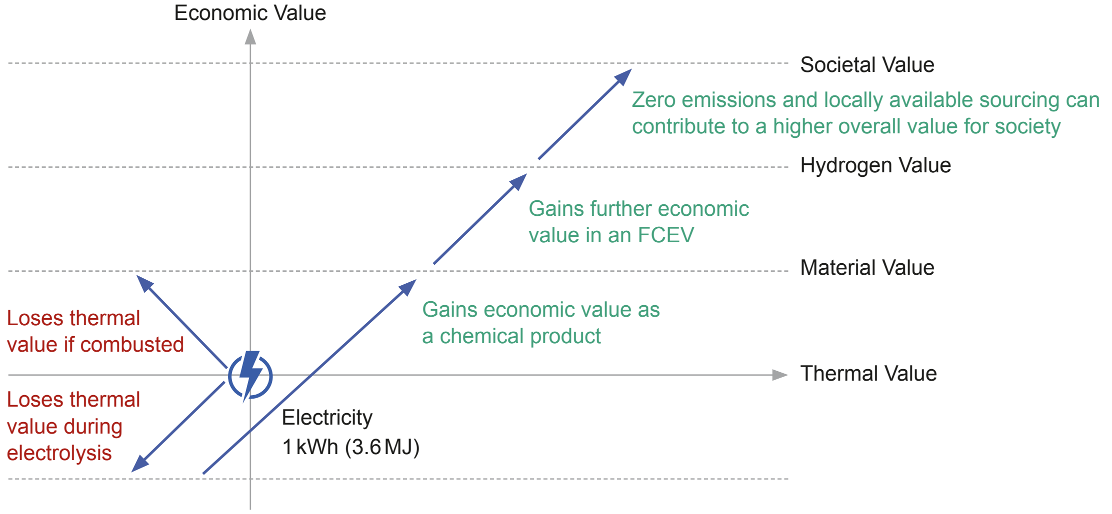
Rising carbon taxes are important in making hydrogen more cost-competitive

The value of hydrogen in society

Hydrogen gives diverse technological innovations to applications which use hydrogen directly (non-combustion) such as fuel cells. The uniqueness of hydrogen is that its acceptable price depends on its applications. For example, a fuel cell has an energy efficiency 2-2.5 times higher than an internal combustion engine (ICE) per kilometre of vehicle propulsion. Oil is most expensive per joule of energy, so the high price of hydrogen is acceptable if it is used as fuel for an FCV.

Efficiency of end-use determines competitiveness of hydrogen vs. other fuels

Societal value of hydrogen (Figure 7)



Source: HyWealth

Hydrogen's economic value in society

The value of hydrogen is measured not only by its energy value. In the near future, its value in society will increase as a factor in decarbonisation and in job creation. Figure 7 shows the societal value of hydrogen. When electricity electrolyses water, the thermal value of hydrogen decreases by about 20-30% but hydrogen gains economic value as a chemical product. If hydrogen is combusted, the electron-to-hydrogen conversion loses energy, but if hydrogen is used by a fuel cell vehicle which travels 2-2.5 times further from the same energy values, there is an economic gain. Other benefits of hydrogen, such as zero emissions, zero carbon and locally available sourcing etc. can be added to the final value.

It's not just about the money – zero emissions and local sourcing can make hydrogen attractive

Hydrogen in the real world

Hydrogen for the transport sector

When I started work on the fuel cell, it was heavy, bulky and expensive, but now it is becoming powerful and reliable. It is expanding its usage from passenger vehicles to heavy-duty trucks and marine applications. Hydrogen is also expected to power aviation (Figure 8). Many people feel the BEV vs. FCV contest is over as far as passenger vehicles are concerned. However, BEVs still make up only a few per cent of new car sales in most countries except Norway and China where government subsidies and incentives are substantial. Vehicle choice is very individual, and fuel is only a part of the decision parameter. People choose a vehicle which reflects their lifestyle (size of family, usage, hobbies, etc.). They may compromise on price depending on the comfort and power on offer, but they do not compromise on convenience. The penetration of zero emission vehicles (ZEVs) is a competition between several candidates (BEVs, FCEVs, xEVs). When the green society develops, hydrogen and electricity infrastructure will no longer be an issue since both fuels will be accessible everywhere. Of course, for transport use PGMs will play a significant role in the powertrain, as use of PGMs makes the fuel cell efficient, compact, powerful and reliable. The high efficiency of the PGM catalyst actually makes a fuel cell cheaper because it enables compactness which leads to a reduction in the material in the structure.

Hydrogen fuel will transport us on land, sea and air

PGM catalysts make fuel cells efficient, compact, powerful and reliable

Hydrogen for transport (Figure 8)

Source: Toyota Motor Co.

Source: Norled

Source: Toyota Motor Co.

Hydrogen in the energy system and industries

Hydrogen helps green some sectors that are hard to electrify

The energy transition is always discussed in terms of electrification. However, there are many fields in which electrification is difficult or impractical. Over half of CO_2 emissions are from industry and home applications such as steelmaking, cement-making, chemicals production and heating etc., where hydrogen will fill the gap between the real world and renewable energy which is mainly electricity.

Hydrogen as an energy storage and energy distribution vector

Hydrogen's key role as an energy buffer

Electricity is difficult to store. Most electric storage is either by conversion to chemicals (battery, hydrogen) or by mechanical methods (pumped hydro, inertia storage). There are no practical means of storing electrons. This means deep electrification will increase the use of hydrogen as a buffer, for storage and logistics (electricity cannot be transported long distances because of attenuation).

Hydrogen can be stored and transported very well – more robust than electricity

Electricity's biggest issue is its fragility in relation to the strict balance needed between generation and consumption. An imbalance between supply and consumption may result in a fatal blackout. Maintaining this balance is complex and expensive too. Because of this fragility, electricity cannot be the backbone of society's total energy system, whatever its size. We need a more stable and robust backbone system. I think hydrogen can be the backbone infrastructure for future energy systems with the combination of renewables and gas network/pipelines where energy in the form of hydrogen can be storable over the seasons and transportable over long distances.

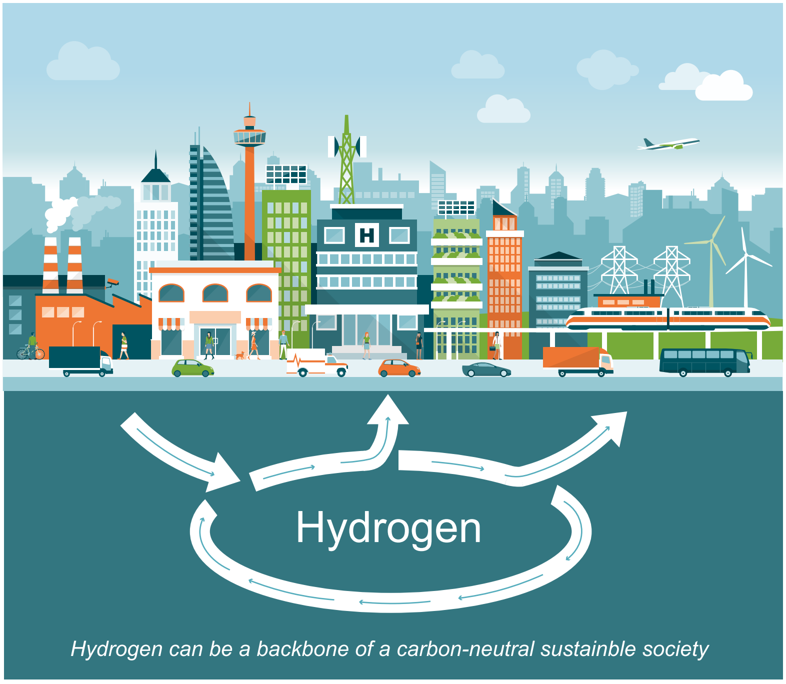
A gas pipeline can absorb input and output fluctuations in pressure and keep the energy quality consistent at 120 MJ/kg (LHV) or 140 MJ/kg (HHV) under any pressure. This is much superior to fragile electricity, which needs exact control of voltages and frequency, otherwise quality is impaired.

Hydrogen at home

The gas network also provides decarbonisation of the home at minimum cost. Heating in most northern hemisphere countries is by gas boilers which currently use natural gas. But it is difficult to convert from gas to electric heating, such as by installing a heat pump system, since significant modification of the heating system is necessary. But if the local gas network moves to the non-fossil-based hydrogen gas, heating of most homes is easily decarbonised without large investment. There is already an ongoing project for heating homes with hydrogen in Leeds in the UK.

Green hydrogen can easily decarbonise household heating

Hydrogen: the backbone of a carbon-neutral sustainable society (Figure 9)



Source: SFA (Oxford), HyWealth

PGMs in a sustainable society

Currently, one of the PGMs' roles is as an aftertreatment catalyst which cleans up the dirty exhaust of automobiles. Of course, another role is as a catalyst to convert gas and oil to other useful products, but the largest usage is as an aftertreatment catalyst. Aftertreatment demand for PGMs will decrease with the strong trend toward ZEVs, on top of the 'dieselgate'-related decline in demand for diesel ICE vehicles. However, in the coming low carbon society, energy sources will shift from fossil origins to a much greater reliance on renewable energy such as solar and wind generation to support our energy systems/lives. However, we are living in the material world; electrons from renewables cannot support all our needs, and materials such as hydrogen will also play a significant role in both material formation and in energy. Electrons to material conversion (Power-to-X – PtX) is a particularly important aspect of the energy system, and conversion efficiency is critical for the economic value of hydrogen. This is the playground of PGMs which are absolutely necessary for these energy conversions, especially PtX.

Opportunities for PGMs in hydrogen society grow, as opportunities in autocatalysts begin to decline in the longer term

However, in the future society, energy usage will also be different from the current situation which has developed mainly through the combustion process such as in a turbine/burner/ICE. Hydrogen can be more effectively used with fuel cells, which are 2-2.5 times more efficient than ICE use. A fuel cell uses quite a large amount of PGMs for the operation of its system. So, in the future PGMs will play a significant role in both the production and use of hydrogen. In other words, PGMs will have a more proactive role in the coming low-carbon sustainable society.

PGMs play a substantial role in production and use of hydrogen – an attractive future

Hydrogen in society

Hydrogen is the energy vector that will transform society from a fossil base to a sustainable renewable base. It may generate huge business but at the same time will require enormous investment.

Don't underestimate the investment required for hydrogen

How and when will society see a return on this huge investment? A simple current example is someone spending $1 for energy at a gas station (or, in the UK, a petrol station). Both Europe and Japan tax gasoline and diesel heavily, at a rate of about 40-50%, so I will explain this case without the tax. About 70-80% of the added value goes to the energy-producing country and 20-30% to the consuming domestic economy for refining and distribution. The proportion for natural gas is similar. For Europe, the cost is about $400 billion/year, for Japan $200 billion/year. Energy transition converts this money flow inward, and energy-consuming countries obtain the freedom to purchase this energy from a domestic source or cheaply from production somewhere else on Earth.

This may look the same as the current situation in total if the consumer pays the same amount, but it is completely different from the money distribution point of view, since renewable origin/ green hydrogen can be produced from much more diverse sources – from solar photovoltaic (PV), hydropower, wind (both onshore and offshore) and even from waste. This will create more jobs, from energy production to transport, where most of the investment is made in the home country. This is also a highly effective solution for developing countries, many of which spend a significant percentage of their income on oil, leaving little money for their own economy (the 'five thousand-dollar GDP per head trap'). Historically, most struggles/ wars are related to energy, but we no longer need to struggle when we can use our own energy from our own land. In the current fossil-fuel-based society, money flows are heavily differentiated by either possession or lack of possession of resources. In the hydrogen society, money will be more work-based rather than possession- and non-possession-based, since renewable energy will be much more widely spread over the globe. Thus, a hydrogen society will be more peaceful and happier for everyone.

Hydrogen can help developing countries – local energy means local jobs rather than imported oil

Renewable energy and the hydrogen society will be much more equally distributed around the world, easing geopolitical tensions

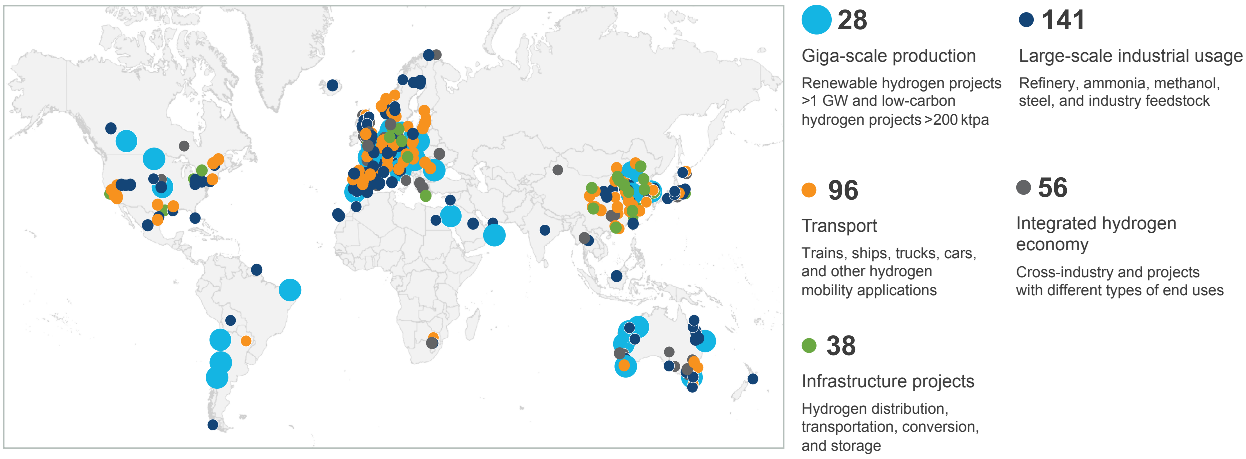
Business development of hydrogen

As the EU and many countries set their national hydrogen strategies, projects and investments are growing rapidly. Figure 10 shows the latest summary of hydrogen-related projects and investments. It stands at about 360 projects and a level of half-a-trillion dollars. The total amount of electrolyser capacity by 2030 is 69 GW and 7.7 mt/year of hydrogen produced. Not all the projects are fixed yet but most of them are currently in serious preparation.

Global hydrogen projects are happening – 69 GW electrolyser capacity by 2030 is real, not hype

The hydrogen business is no longer just hype for the future, it is already a substantial business.

Global hydrogen projects and investment across the value chain (Figure 10)



Source: Hydrogen Council, Hydrogen Insights Report 2021

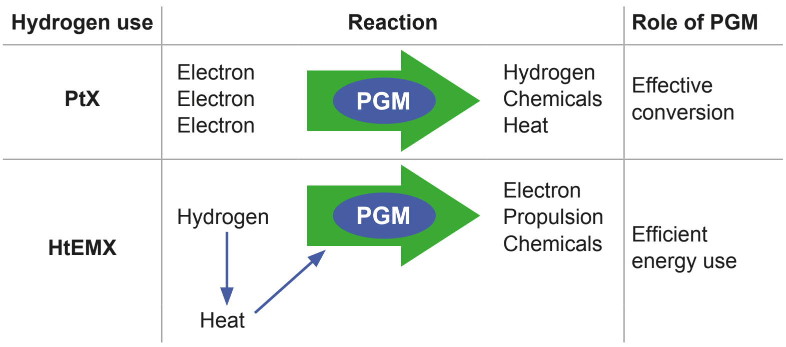
Conclusion: What hydrogen can do for you and the PGM industry

Climate change will drive the pivot to the hydrogen society

PGMs will be thrifted in energy conversion, but overall sustainable market growth is hugely positive

The energy transition stemming from climate change actions will lead to greater use of hydrogen in society and it will bring more freedom for most countries. Hydrogen usage in society needs huge energy conversion, in terms of both production – PtX (electrons to material) – and end-use – HtEMX (hydrogen to power (electrons) and material) such as fuel cells. Both technologies need huge amounts of PGMs. Although much R&D is focused on how to reduce the amount of PGM catalyst needed for energy conversion, total usage and function will increase as hydrogen usage grows. The role of PGMs will also change drastically from the current passive role (as vehicle catalysts which clean up pollution) to a proactive role in producing and using green hydrogen in electrolysers and fuel cells for a more sustainable world.

Role of PGM in the hydrogen society (Figure 11)



Source: HyWealth

Humanity has a chance to design its future

The energy system as it stands is built to chase economic growth and it has neither a master plan nor vision. Energy transition is still at a very early stage: its direction is clear and set, but the methods are still open. As human beings, we share the target of a sustainable world and a vision of a low-carbon society for the future. It is a very serious challenge for us all, but on the other hand we have a chance for the first time to design our future ourselves. The budget for this design is also huge, as we can convert the enormous expense of fossil energy to a new energy system. For Europe, this amount is \$12 trillion+ (\$400 billion × 30+ years) and for Japan, \$6 trillion+ (\$200 billion × 30+ years). The benefits expected after 2050 are even greater and will be a gift for our children.

PGMs are central to creating materials and functions for our future society

This is a competition of ideas towards the future. Energy transition provides a significant opportunity for everybody: for younger generations especially in jobs and hope, and for older generations in investment chances and returns. Emerging countries also obtain freedom for their future in terms of energy and space for growth. PGMs will have more roles to play in proactively creating materials and functions for the future society.

Designing the future, with PGMs centre stage

We cannot change the past and it is even more difficult to change the current situation. However, we *can* change our future; in fact, we can even design our future. Let us enjoy the challenge to design our own future world with peace and happiness, and with PGMs.

I dare to predict the energy transition with hydrogen (with PGMs) will provide:

Challenges and jobs for the young

Investment destinations and returns for older generations

A happier dream vision for all

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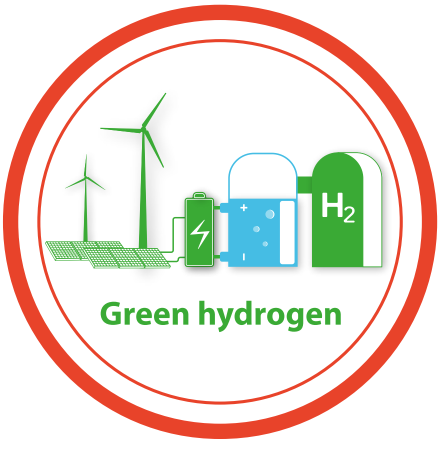
THE GREENING OF HYDROGEN



The greening of hydrogen

Jeremy Coombes, Independent Consultant & Member of SFA (Oxford) Executive Committee

COP26 – The background

Delayed by one year due to the pandemic, the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) in Glasgow, Scotland, in November 2021 is the scheduled occasion for the nations of the world to review their commitments to control global warming that they made in Paris at the end of COP 21 in 2015.

The Paris Agreement is a commitment to take actions to limit the increase in global temperature compared to pre-industrial levels to less than 2.0°C and aim for a limit of 1.5°C. It is generally accepted that to achieve the lower limit, world emissions of carbon need to halve over the decade to 2030 and by 2050 reach net zero – a state in which the amount of carbon entering the environment is no greater than the amount absorbed by it. Actions towards this goal of decarbonisation encompass phasing out the use of coal and natural gas, electrification of transport, controlling deforestation and making agriculture more sustainable.

Global carbon emissions need to halve by 2030 and reach zero by 2050

A total of 194 countries have submitted Nationally Determined Contributions (NDCs) or climate action plans to the United Nations, and as at July 2021 the total of countries adopting a net-zero target accounted for 80% of world GDP. Carbon reduction targets are partly determined by legacy issues: a nation's degree of dependence on fossil fuels or the extent of its economic development. Accordingly, some NDCs – notably from Saudi Arabia, Australia, China and India – do not fully meet the Paris targets. Another issue for debate is the provision of funds from advanced economies to support the climate control and mitigation efforts of developing nations, which has not matched expectations.

80% of global GDP is from countries with a net-zero target

Funds from advanced economies are insufficient to support climate efforts of developing nations

Although momentum towards global decarbonisation has developed, there is uncertainty (which will continue beyond COP26) about how much can be achieved. On the eve of the Glasgow conference, the United Nations Environment Programme (UNEP) published its 2021 Emissions Gap Report, in which it ominously declared that the updated NDCs still fail to put the world on track to meet the Paris Agreement's global warming target and that "unless there are immediate, rapid and large-scale reductions in GHG emissions, limiting warming to 1.5°C or even 2°C by the end of the century will be beyond reach". Even if targets are tightened, other barriers loom: an increase in the supply of the necessary raw material resources – nickel, cobalt and lithium, to name a few – is a massive challenge to meet in the time available.

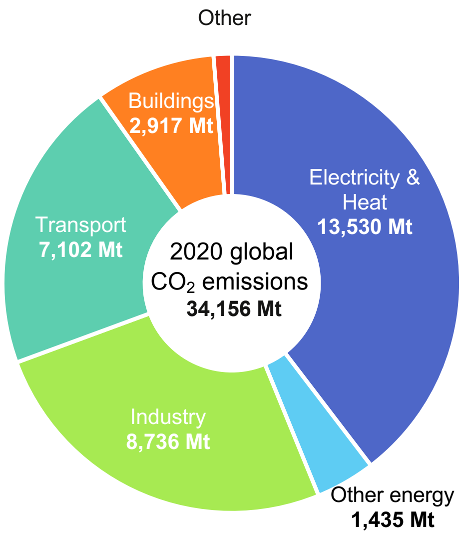
Raw materials supply for decarbonisation technology must increase rapidly

Decarbonisation and hydrogen

A Green Energy Transition is needed to replace fossil-derived energy (coal, oil and natural gas) with energy from renewable sources (wind and solar). In 2020, according to the International Energy Agency in its latest World Energy Outlook, total world CO_2 emissions were 34.2 gigatonnes (Gt). The energy sector (electricity, heat and other forms of energy) was the largest emitter of carbon with around 44% of the world total. Here, reductions in emissions can be achieved by transitioning from fossil fuels to renewable sources, along with more efficient energy use. Industry, with 26% of CO_2 emissions, can also incorporate renewable energy-based systems. Transport, which was responsible for 21%, can reduce emissions by using a range of electrified technologies and alternative fuels. In each of these sectors, hydrogen derived from renewable sources is expected to be an increasingly important part of the energy transition.

The energy sector is the largest global CO_2 emitter

CO_2 emissions by sector



Source: IEA, World Energy Outlook October 2021

Green hydrogen can play a part in reducing emissions from each sector

Hydrogen has very high energy density per unit of weight – 2.6 times that of natural gas; when burned, it has no carbon emissions that would contribute to global warming or air pollution, and it is a stable vector for energy storage and can be easily transported in gas pipelines. On the other hand, being the lightest of the elements, hydrogen has poor energy density by volume, so it has to be compressed or liquefied for transport or use; and, as it does not occur naturally, must be derived from other molecules such as natural gas or water. This incurs a loss of efficiency in the process, making the cost of producing the hydrogen always higher than the cost of the input power, with implications for the competitiveness of hydrogen

The cost of producing hydrogen is higher than cost of input power ...

... so hydrogen is not always the best choice when renewable electricity can be used directly

in applications where renewable electricity can be used directly, as in batteries for electric vehicles or in heat pumps for domestic heating.

Hydrogen pros and cons

Pro	Con
• High density by weight • No carbon emissions when combusted or converted to electricity • Vector for energy storage	• Does not occur naturally so costs energy to produce • Low density by volume, must be compressed or liquefied for use

Hydrogen will therefore likely make its contribution to decarbonisation in energy storage and in applications which are energy-intensive, where alternatives are unsatisfactory or where emissions are difficult to abate. In industry, it is already important for production of ammonia and other chemical products. Hydrogen would decarbonise these processes if sourced from renewable electricity instead of from natural gas. In steelmaking, combining hydrogen with coke in a blast furnace as a source of heat can make marginal reductions in carbon emissions, but alternatively, hydrogen can replace coke as the reducing agent in a direct reduction-electric arc furnace, resulting in close-to-zero carbon outputs. In Europe, 14 such projects are planned, nine of which have specific production targets amounting to 13% of annual EU steel production (source: https://bellona.org).

Green hydrogen is useful to decarbonise industrially important products such as ammonia and steel

As an energy vector, hydrogen can be blended with natural gas to generate electricity or for combustion in domestic boilers, but it will have a far greater effect on decarbonisation as a flexible store of energy to secure constant electricity supply. Increasing dependence on electricity generated by intermittent solar and wind power brings the challenge of balancing electricity flow and providing reserves for whenever supply diminishes. Hydrogen produced and stored when surplus power is available is ideally positioned to meet this need.

Grid balancing – hydrogen's role as a store of energy coupled with intermittent renewables

In the transport sector, combining hydrogen with oxygen in a fuel cell to produce electricity, with only water as a by-product, is the main alternative to batteries for the electrification of vehicles, particularly in heavy-duty, long-range transport applications in which the weight and limited range of batteries would not satisfy the operating requirements. Long-distance trucks, trains, some ships and even aircraft, if a suitable degree of compression or liquefaction of hydrogen can be achieved, are all potential adopters of fuel cells. Internal combustion engines running on 100% hydrogen instead of diesel are also being developed for use in the heavy-duty sector.

Hydrogen as a fuel for heavy-duty, long-range transport – in fuel cells and internal combustion engines

The production of hydrogen

The routes to hydrogen, broadly in order of environmental credentials and carbon footprint are:

Route	Carbon footprint
Grey from steam methane reforming (SMR) of oil, gas or coal	**High**
Turquoise from methane pyrolysis producing solid carbon as a by-product	**Low**
Blue from SMR but with the CO_2 emissions captured and stored (CCS)	**Low**
Pink from electrolysis from nuclear energy	**Low**
Green from electrolysis from renewable wind or solar energy	**Zero**

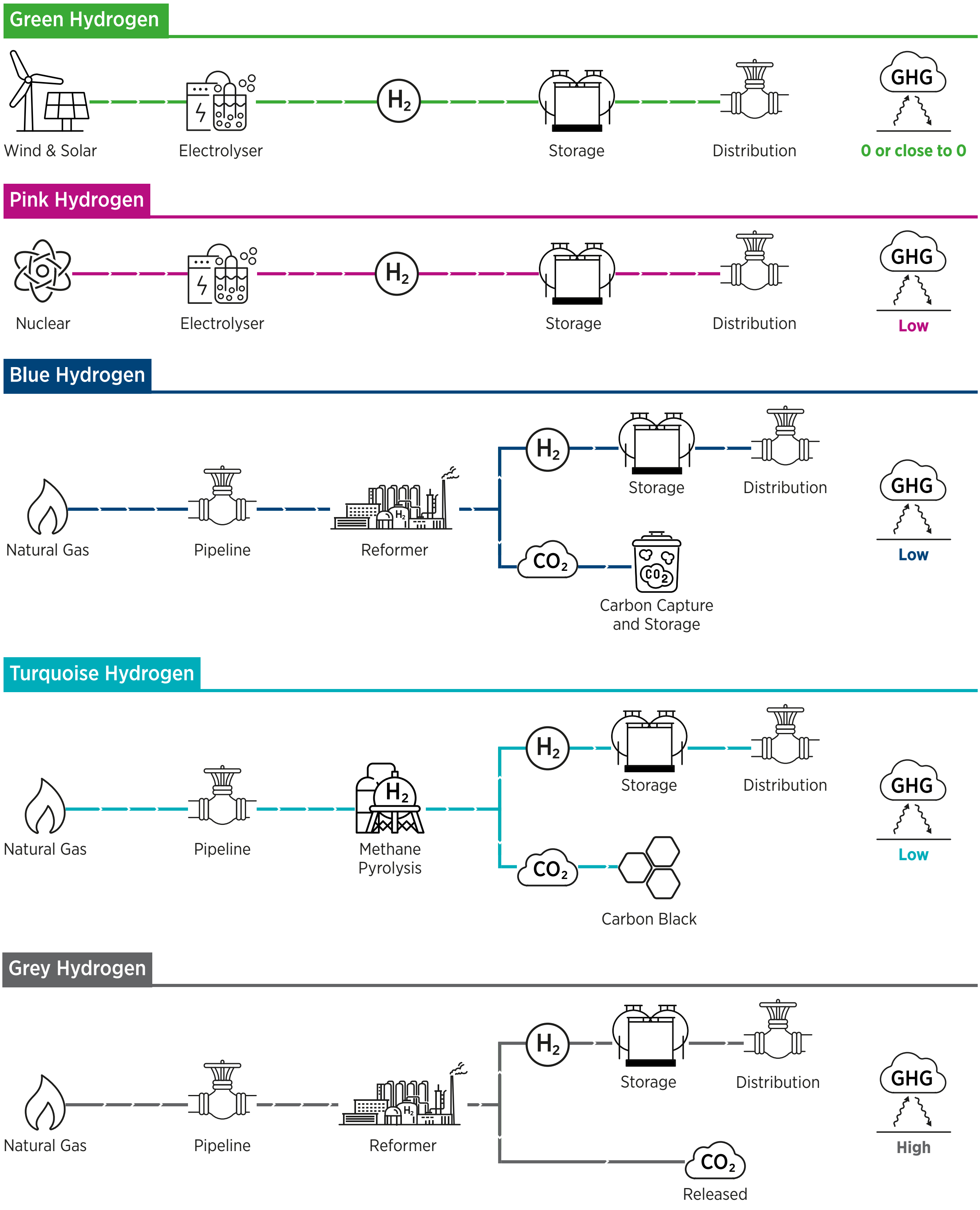
Most hydrogen in use today has a high carbon footprint

At present, 95% of hydrogen is made from hydrocarbons. This 'grey' hydrogen is cheap to produce, as low as $1 per kilogram (depending on the price of natural gas), but the associated greenhouse gas emissions are high. 'Blue' hydrogen, also from fossil fuels but with the carbon emissions captured and sequestered, costs a little more but may be only an interim solution: the process captures only 85-95% of emissions while the long-term liabilities of storing large volumes of CO_2 in underground geological or ex-industrial spaces are complex and hard to quantify. 'Pink' (sometimes named 'yellow') hydrogen, using nuclear energy as a source of electricity, is low-carbon but expensive and far from being a popular generating option. The only truly acceptable zero or close-to-zero emissions route is 'green' hydrogen made by using the infinitely renewable electricity from solar panels or wind turbines in an electrolyser to split water into hydrogen and oxygen.

Carbon storage is a limited solution

Electrolysis using renewable electricity is the route to hydrogen with a zero-carbon footprint

The colours of hydrogen

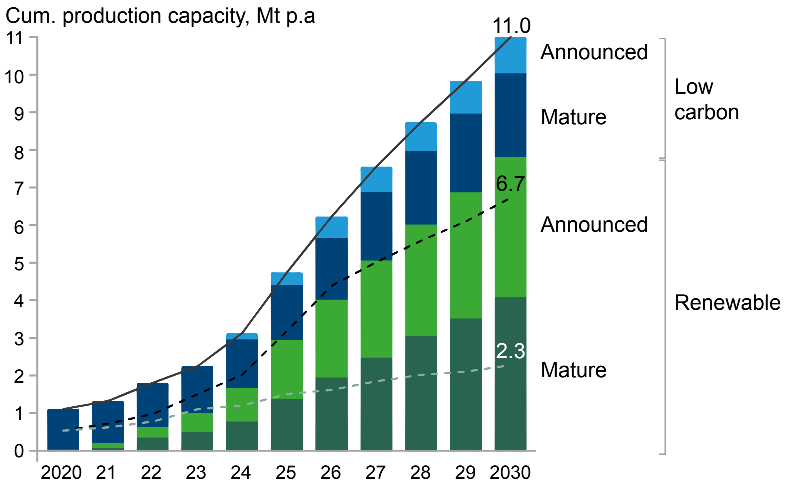


Source: Energy Industry Review

Hydrogen and electrolysers have accordingly become a focus of technology development. The EU's Hydrogen Strategy puts green hydrogen in the spotlight as a priority to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution. In its 2020 Green Deal, the EU targeted by 2030 an electrolyser capacity of 40 GW within its borders and another 40 GW in nearby countries that can export hydrogen. The United Kingdom is aiming for 5 GW of low carbon hydrogen capacity by the same date.

The EU's Hydrogen Strategy sets an ambitious target of 40 GW of electrolyser capacity by 2030

Announced clean hydrogen capacity through 2030



Source: Hydrogen Council, McKinsey & Company, Hydrogen Insights July 2021 Update

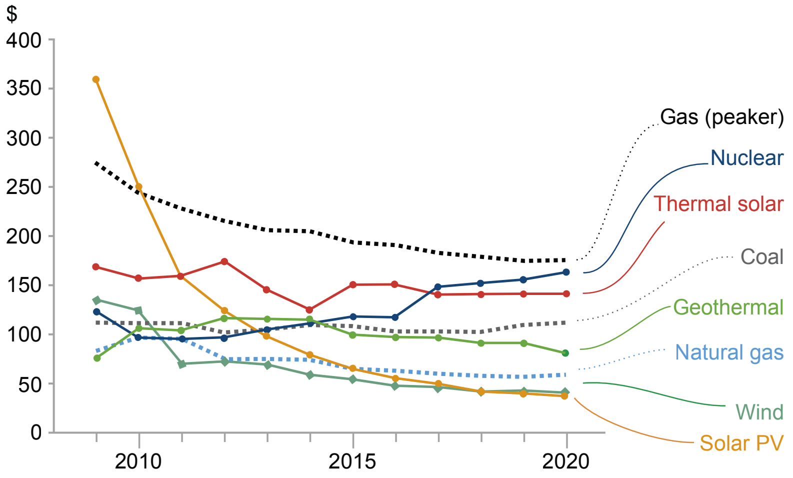
The use of renewables in hydrogen production is set to increase rapidly

The cost of producing green hydrogen – between $2.5 and $6 per kg at present – must reduce substantially for it to become a serious contender, yet given adequate investment and sufficient supply of materials this should be achievable in the long term. The cost of generating the renewable electricity on which green hydrogen relies has declined over time to the point where the levelised cost of electricity (LCOE – the discounted lifetime cost of building and operating a generating plant) from solar and wind is already below the cost of electricity derived from coal and natural gas. Current world electrolyser capacity is about 3 GW; scaling this up to 70 GW by 2030, as predicted by McKinsey & Company in a July 2021 *Hydrogen Insights* report for the Hydrogen Council, will go a long way to reduce electrolyser CAPEX.

Reducing the cost of hydrogen relies on reducing the cost of renewable electricity

Solar and wind are already competitive with coal and gas for electricity generation

LCOE of energy from fossil and renewable sources



Source: RCraig09 – Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=99427431

When will green hydrogen reach price parity with blue and grey hydrogen?

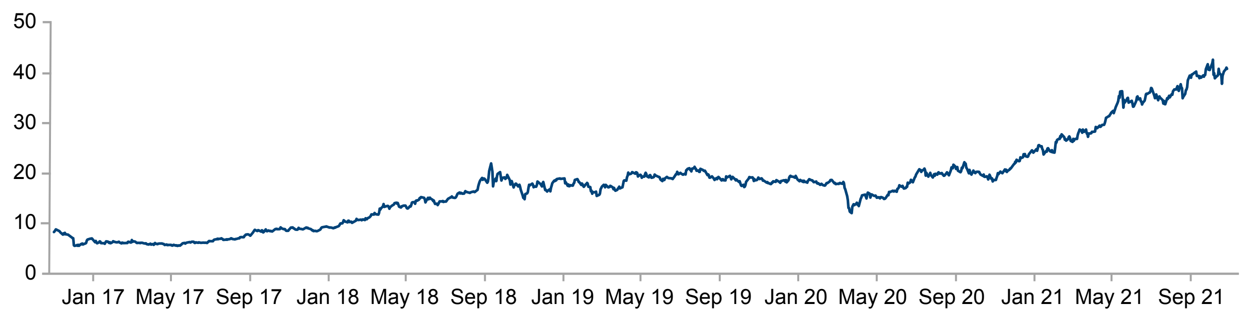
As a result of these trends, the cost of green hydrogen is likely to fall to levels competitive with existing methods of production. According to BloombergNEF, the price of green hydrogen using proton exchange membrane (PEM) electrolysis could be comparable with blue hydrogen by 2030. Credits for renewable electricity production and subsidies for electrolysers, such as those currently in force in the US, could even enable green hydrogen to compete with grey in a few years' time, according to Morgan Stanley.

It's not just about scaling up PEM electrolysers – credits and subsidies are needed too

Carbon pricing is recognised as a potentially pivotal element in steering towards net zero. The cost of carbon credits as indicated by the IHS Markit global carbon index in the following chart is trending upwards (80% of the constituent data is from the markets for carbon credit futures in the EU27 and California). A more universal adoption of carbon pricing, whether as an Emissions Trading System (ETS) or as a carbon tax, would reinforce the future competitiveness of green hydrogen as it would factor in the real cost of producing grey and blue hydrogen.

Paying the real price for carbon emissions will support the pivot to green hydrogen

Global carbon index (USD)



Source: IHS Markit

Electrolyser options

There are four types of water electrolyser for producing green hydrogen. Alkaline (ALK) and PEM electrolysers are already in commercial use at scale. Both are considered expensive relative to the current cost of producing grey hydrogen. Anion exchange membrane (AEM) and solid oxide (SOE) electrolysers are still under development, although they may hold great potential. All four technologies have their challenges, ranging from use of critical materials to performance, durability and maturity. There is no outright winner, and future use will depend on the application to which each is put.

Several electrolyser technologies are available to produce green hydrogen from water

Current (2020) state of the art for PEM and ALK technologies

	PEM	ALK
Cold start (to nominal load) / minutes	<20	<50
Lifetime (stack) / hours	50,000-80,000	60,000
Stack unit size / MW	1	1
Capital costs (stack) minimum 1 MW	USD 400 / kW	USD 270 / kW
Capital costs (system) minimum 10 MW	USD 700-1,400 / kW	USD 500-1,000 / kW
Hydrogen production rate / $m^3\ h^{-1}$	400	1,000

Source: (1) IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, International Renewable Energy Agency, Abu Dhabi. (2) Yujing Guo et al (2019), IOP Conf. Ser.: Earth Environ. Sci., 371 042022

ALK electrolysers have a simple design and manufacturing process; they benefit from high efficiency and a large scale and are relatively low-cost, and they run best on a base load without significant fluctuations. PEM electrolysers rely on platinum-group metal catalysts, so at present are 50-60% more expensive than ALK, but they demonstrate good dynamic response and the capability to work well under intermittent operation, a feature of renewable electricity supplies. The focus for development of ALK electrolysers is to improve their dynamic response and capability for intermittent operation, while for PEM it is to operate at larger scale with higher efficiency and lower cost.

ALK and PEM are commercially scaled, while AEM and SOE are earlier stage

AEM's potential combines the less harsh operating environment of ALK with the simplicity and efficiency of PEM but without the expensive metals, but overall performance and stability is lacking. SOE's potential lies in its high temperature efficiency, so it can use cheap metals, but its main challenge is durability.

There is no outright winner

Electrolyser technologies compared

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature / °C	70-90	50-80	40-60	700-850
Operating pressure / bar	Jan-30	< 70	< 35	1
Electrolyte	Potassium hydroxide (KOH) 5-7 mol L-1	PFSA membranes	DVB polymer support with KOH or $NaHCO_3$ 1 mol L-1	Yttria-stabilised Zirconia (YSZ)
Separator	ZrO_2 stabilised with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium Oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (e.g. LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni / YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon cloth	None
Bipolar plate anode	Nickel coated stainless steel	Platinum coated titanium	Nickel coated stainless steel	None
Bipolar plate cathode	Nickel coated stainless steel	Gold coated titanium	Nickel coated stainless steel	Cobalt coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSE, ETFE	PFE, Silicon	Ceramic glass

Source: IRENA

Hydrogen and platinum-group metals (PGMs)

Deep links exist between hydrogen and PGMs in the fields of energy, industry and transport, and demand for PGMs in these applications will expand progressively over the next decades, with the strongest growth coming from the greening of hydrogen production using electrolysers.

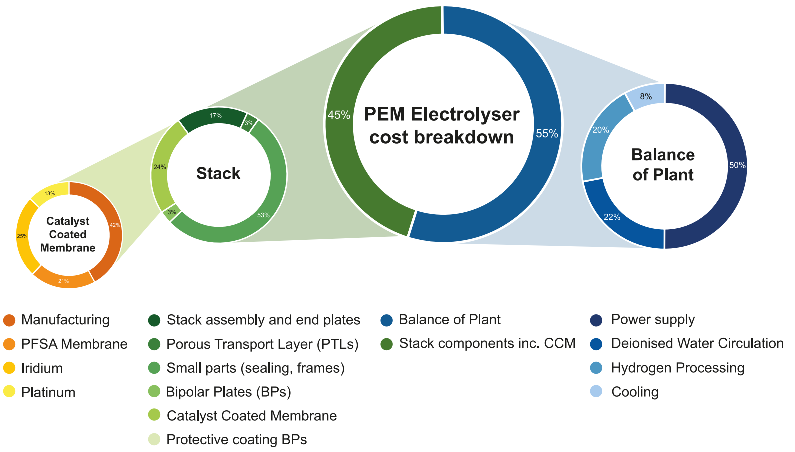
In PEM electrolysers, the electrode at which hydrogen evolves (the cathode) uses platinum-based materials and the electrode at which oxygen is generated (the anode) is usually based on iridium.

PEM electrolysers rely on platinum and iridium

At the core of the PEM electrolyser, the catalyst-coated membrane (CCM) containing the PGMs represents about 10% of the entire system cost. Reducing this cost element will involve reduction of PGM loadings, particularly iridium which is a by-product of platinum refining and which therefore has limited availability.

The need for PGMs adds cost concerns for PEM electrolysis adoption

PEM electrolyser cost breakdown



Source: IRENA

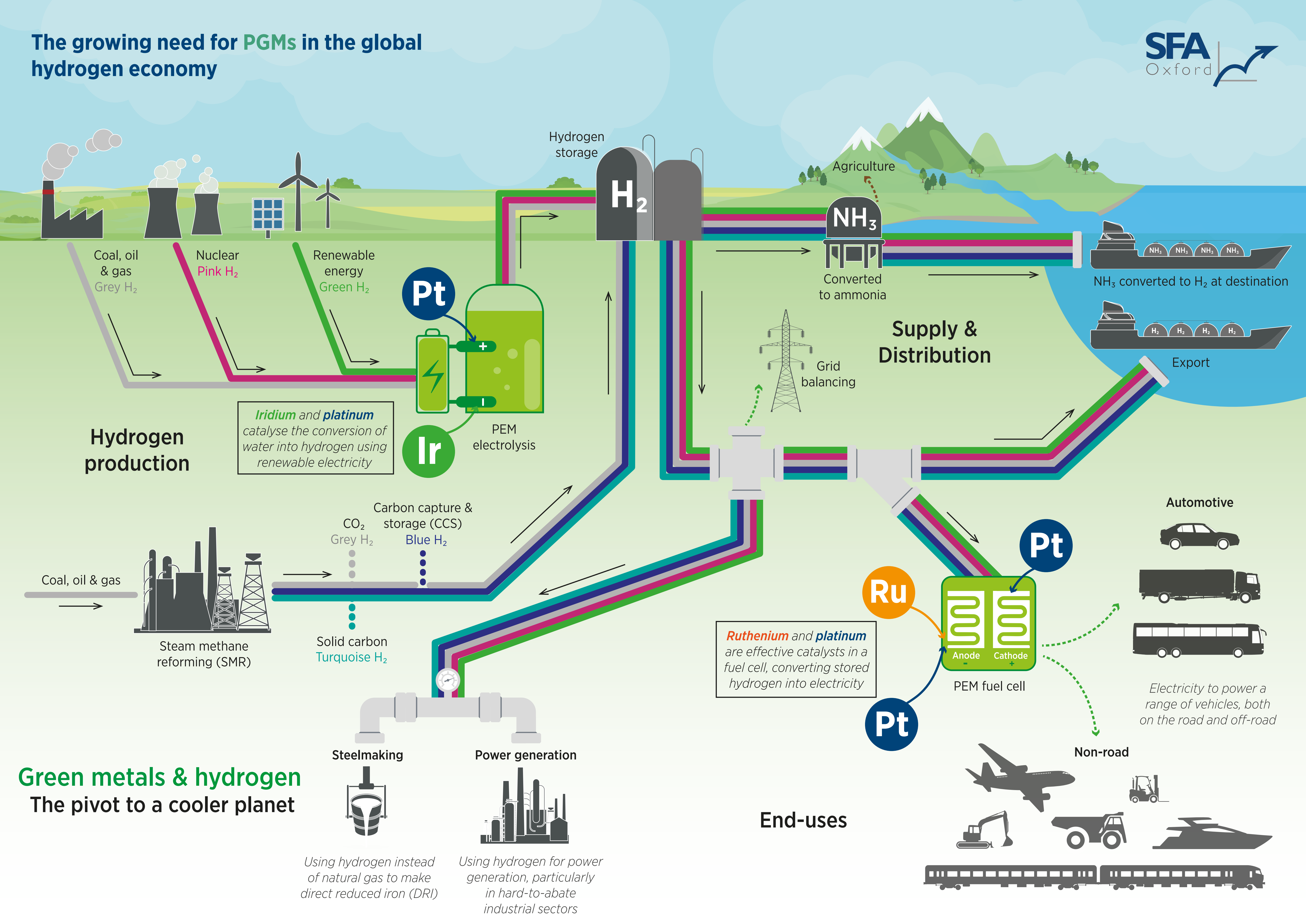
Iridium and platinum would be hard to substitute entirely as they are technically the best fit for PEM electrolysers. Innovation to reduce the intensity of PGM use is based on some familiar themes in catalyst surface chemistry and engineering – for example, by increasing the catalyst surface area and using thinner layers of catalyst coating material. PGM fabricators have had high success rates using these methods over many years in reducing PGM loadings while at the same time increasing the performance of their products – autocatalysts and fuel cells being prime examples.

Confidence based on experience that PGM intensity of use can be reduced through technology innovation

In PEM fuel cells, whether used for transport or industrial applications including back-up, portable or grid-independent power, platinum is used as the catalyst at both the cathode and anode, with ruthenium added to protect the platinum from impurities in the hydrogen feed. Green hydrogen is higher purity than grey, and as uncontaminated hydrogen becomes more widely available there will be scope to reduce the ruthenium content.

Hydrogen engines may not require PGM autocatalysts as gasoline and diesel engines do, because of the absence of hydrocarbon and CO emissions. There may be some NO_x emissions, but they can be limited by controlling engine temperature. Removal of any residual emissions can be performed by selective catalytic reduction (SCR), which does not use PGMs, although there might – as in diesel catalyst NO_x removal systems – be a little platinum used to remove any ammonia slip from the SCR. However, platinum and iridium demand could gain from previously diesel engines now requiring spark plugs.

Using hydrogen in combustion engines may have implications for autocatalysts and spark plugs

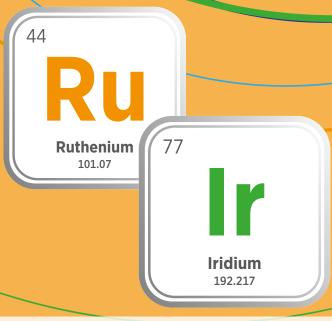


The growing need for PGMs in the global hydrogen economy
SFA Oxford
Hydrogen storage
H_2
Agriculture
NH_3
Coal, oil & gas
Grey H_2
Nuclear
Pink H_2
Renewable energy
Green H_2
Pt
Converted to ammonia
NH_3 converted to H_2 at destination
Supply & Distribution
Grid balancing
Export
Iridium and platinum catalyse the conversion of water into hydrogen using renewable electricity
Ir
PEM electrolysis
Hydrogen production
Carbon capture & storage (CCS)
CO_2
Grey H_2
Blue H_2
Coal, oil & gas
Steam methane reforming (SMR)
Solid carbon
Turquoise H_2
Automotive
Pt
Ru
Anode
Cathode
Ruthenium and platinum are effective catalysts in a fuel cell, converting stored hydrogen into electricity
PEM fuel cell
Pt
Electricity to power a range of vehicles, both on the road and off-road
Non-road
Steelmaking
Power generation
Green metals & hydrogen
The pivot to a cooler planet
Using hydrogen instead of natural gas to make direct reduced iron (DRI)
Using hydrogen for power generation, particularly in hard-to-abate industrial sectors
End-uses

SFA Oxford

The Iridium & Ruthenium Markets

Quarterly Core Analysis Package Q4'21



Stay up-to-date with short-term supply and demand developments of the iridium and ruthenium markets and our latest five-year outlook

Critical metals for the hydrogen economy

SFA (Oxford) is the only company in the world that has derived iridium and ruthenium mine production and developed detailed demand modelling of all major end-uses to provide an authoritative view of the current and future iridium and ruthenium markets.

The Iridium and Ruthenium Quarterly Core Analysis Package looks at the current market and with analysis, charts and commentary provides a **watching brief on the evolution of the market.**

It utilises **SFA's extensive knowledge and expertise in the iridium and ruthenium markets** and provides an independent review. It gives an overview of the changing technological developments and highlights the underlying evolution of demand and end-use applications, and the emerging hydrogen economy.

It offers **commercial insights into primary metal supply** and the link to the rest of the PGM basket, plus insights into end-uses, their price elasticity and the risks of substitution.

The Quarterly Core Analysis Package is a hands-on examination of events and trends currently impacting the iridium and ruthenium markets.

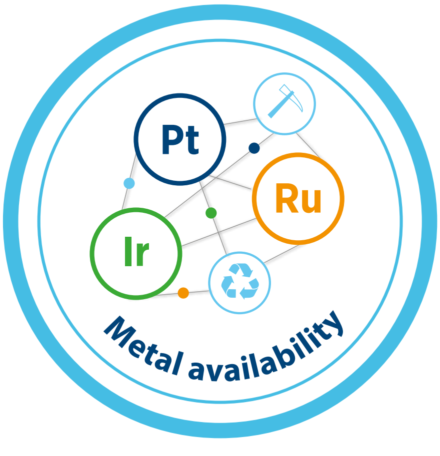
Key report features:

- Market summary
- Price outlook and drivers to 2025
- Demand trends
- The only S-D market balance available
- Trade flow analysis
- Supply challenges and mine economics

The **latest quarterly report** includes commentary and analysis on:

- Improving **metal liquidity** and medium-term opportunities in **increasing supply** from South Africa
- Impact on demand of short-term and longer-term changes to the **automotive market**
- Prospects for increased **recycling** in some market sectors
- **Technology developments** sustaining demand in electronics and memory markets

CATALYSING A LOW-CARBON FUTURE: MISSION-CRITICAL METALS FOR THE HYDROGEN ECONOMY



Catalysing a low-carbon future: Mission-critical metals for the hydrogen economy

Francesca Price & Alex Biddle, SFA (Oxford)

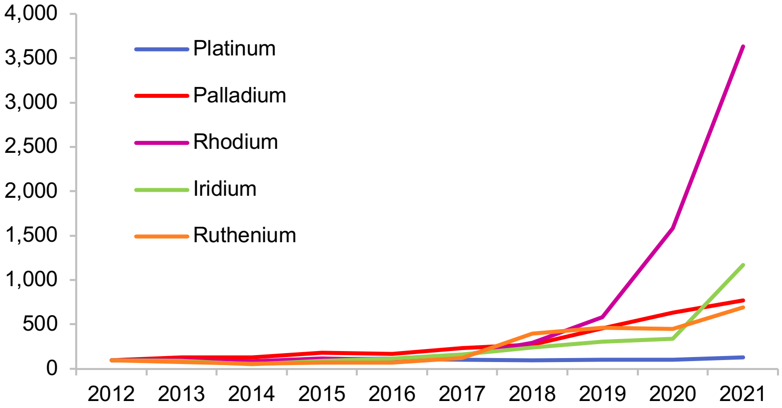
As the hydrogen economy becomes increasingly centre stage, so too is interest in securing long-term supply of the mission-critical metals to facilitate it: platinum, iridium and ruthenium. The use of iridium in some electrolysers and ruthenium in fuel cells represents entirely new markets for these metals which are already forming an exciting part of the supply and demand landscape.

Platinum, ruthenium and iridium are the key catalyst metals for hydrogen

Historically, market development initiatives have been few and far between for iridium and ruthenium (unlike those for platinum), with a limited number of 'new' end-uses despite the considerable stocks that producers held a decade ago. It wasn't until recently that producers even began reporting production volumes for iridium and ruthenium, and the lack of transparency deterred end-users from confidently adopting. Their adoption was also curtailed by the small scale of the markets, particularly for iridium, which is by far the smallest of all the PGM markets. Iridium is nearly one-twentieth the size of the platinum market at just 300 koz, and ruthenium is around one-sixth smaller (~1 moz).

South African 5E revenue

Index 100 = 2012



Source: SFA (Oxford). Note: ZAR real 2021 revenues presented.

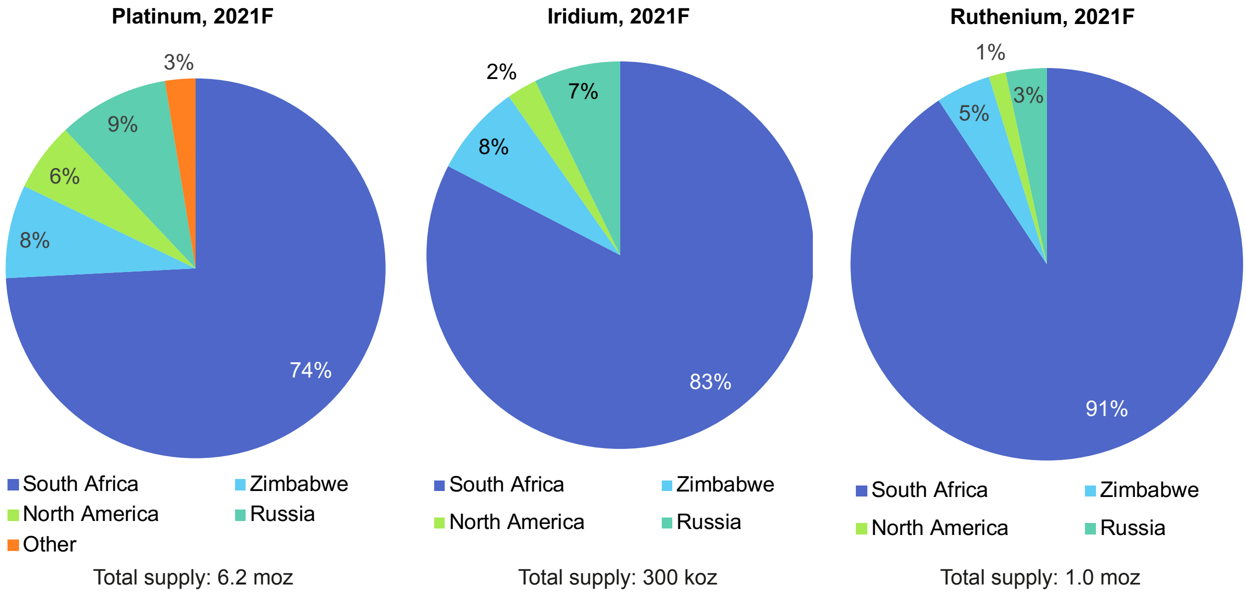
However, as the orebodies in South Africa have changed, iridium and ruthenium revenues have been rising, with these co-products becoming an increasingly important part of the PGM basket of revenues, and producers are starting to take notice.

This mix of metals is becoming an increasingly important part of mine revenues

Hydrogen metals will fuel South Africa's greener future

Primary supply of the 'hydrogen metals' – platinum, iridium and ruthenium – is almost entirely recovered from South African 'greener' ores, with the country accounting for 74%, 83% and 91% of global mine production, respectively. Supply is also derived from PGM mining on the Great Dyke in Zimbabwe as well as from Russia and Stillwater in the US, but iridium and ruthenium production is not reported.

Primary supply of key hydrogen metals



Source: SFA (Oxford)

While the recycling of platinum is a well-established industry, the closed-loop recycling industry in iridium and ruthenium is extremely opaque and is likely to involve limited volumes. In addition, given that a microscopic amount of metal is used in many applications for iridium and ruthenium, recovery by way of recycling is largely uneconomic, especially given the low historical prices for these metals.

Recycling of ruthenium and iridium is difficult to assess and trigger growth

As a result, South African PGM mining is vital in terms of the future supply of the hydrogen metals, while electrolyser and fuel cell companies will continue to develop the technology to better align with the ratio of metals coming out of the ground. Taking into account the effect of thrifting (using less metal) or even partial substitution of PGMs in hydrogen applications over the next 10-15 years, the availability of metal is not a concern. Current reserves in South Africa are in the region of 150 moz of platinum, >5 moz of iridium and >25 moz of ruthenium.

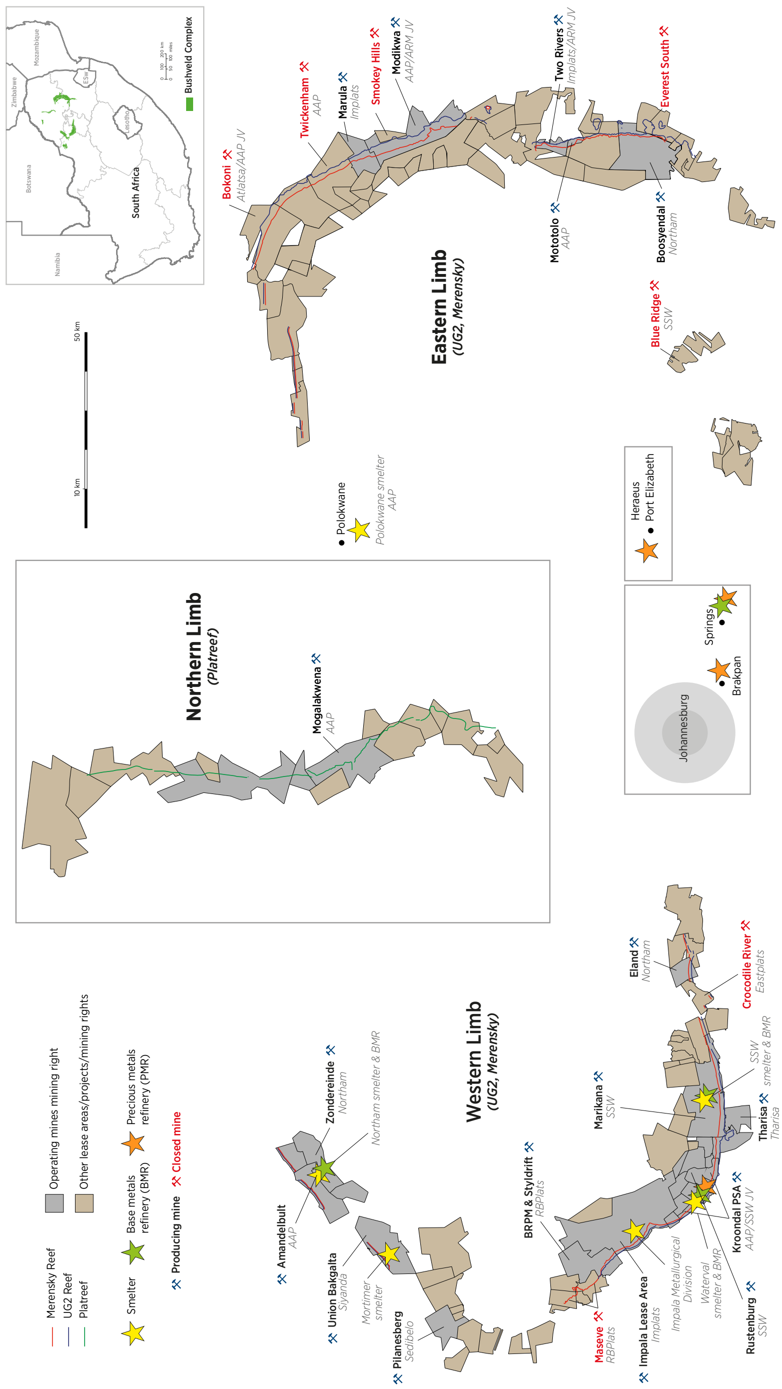
Mining is therefore the key provider of metals for the hydrogen economy

South Africa: the world's hydrogen metal basket

In South Africa, PGMs occur within a large, layered igneous intrusion called the Bushveld Igneous Complex (BIC) in which more than 70% of the world's known platinum resources exist. The BIC is a basin-shaped intrusion of some 370 km in diameter which contains distinct, magmatically-differentiated layers, three of which contain economic concentrations of PGMs. The main PGM-bearing layers, referred to as 'reefs', are called the UG2 Reef, the Merensky Reef and the Platreef.

South Africa's BIC, at 66,000 km^2, is the world's largest known resource of catalyst metals for hydrogen

Map of the Bushveld Igneous Complex PGM deposits, South Africa



Source: SFA (Oxford)

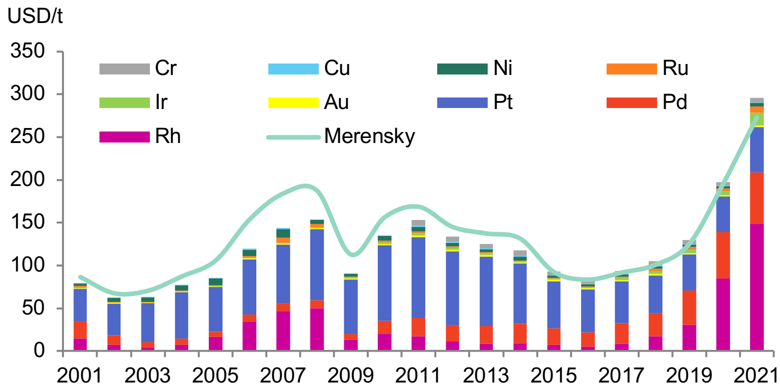
A secure supply chain for the hydrogen metals:

- *16 operating PGM mines plus various other sources (e.g. chrome mining and tailings reprocessing)*
- *fully capitalised*
- *huge resource base with several active projects*
- *known geology*
- *established, skilled labour force*
- *extraction technology refined over many decades*
- *mine-to-market routes in place*

The UG2 Reef is mined on the Western and Eastern Limbs of the BIC and provides the highest concentration of 'minor' PGMs – rhodium, iridium and ruthenium – in South Africa. The Merensky Reef is also observed on the Western and Eastern Limbs and is more heavily weighted towards platinum. In the mid-2000s, UG2 Reef extraction became an important source of primary PGM production owing to the high rhodium price, with a number of UG2 mine start-ups. When the rhodium price crashed shortly afterwards, many producers placed uneconomic mines on care and maintenance.

The UG2 orebody currently achieves the highest revenue/ tonne of South African orebodies, and is likely to trigger added mine output of hydrogen metals

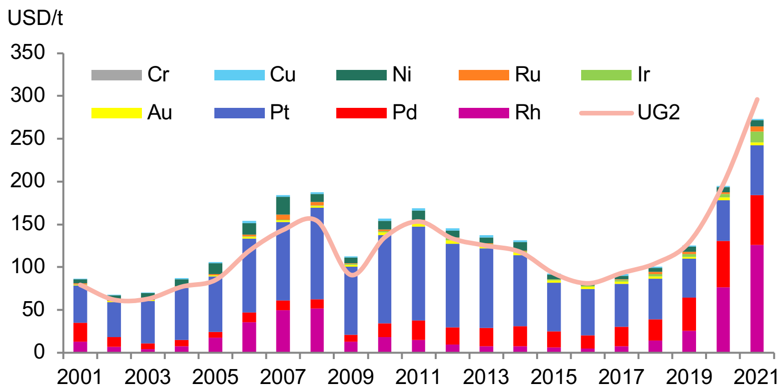
UG2 Reef revenue per tonne



Source: SFA (Oxford)

UG2 has begun to outperform Merensky in recent years owing to the high rhodium price ...

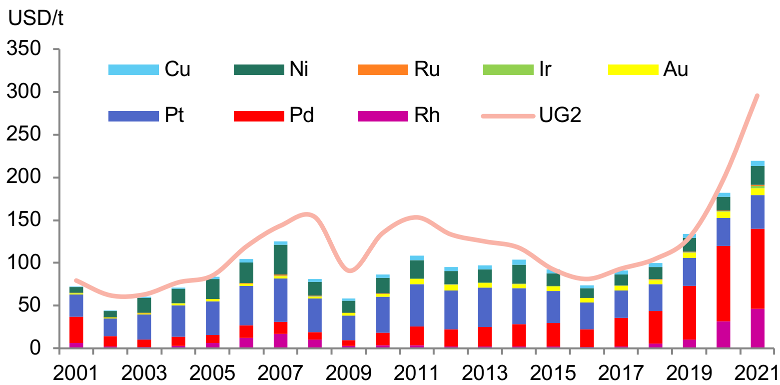
Merensky Reef revenue per tonne



Source: SFA (Oxford)

... but when the platinum price was high, Merensky was the dominant revenue stream for producers

Platreef revenue per tonne



Source: SFA (Oxford)

Lack of rhodium, iridium and ruthenium hinders Platreef revenues

Both the Merensky and UG2 Reefs contain valuable copper and nickel by-products, but base metal concentrations are lower in the UG2. The UG2 Reef also contains chromite, which during low PGM price regimes became an important part of the UG2 basket of revenues and helped to keep some higher-cost operations in profit. The Platreef is observed on the Northern Limb of the BIC and has a more balanced palladium-to-platinum ratio than the UG2 or Merensky.

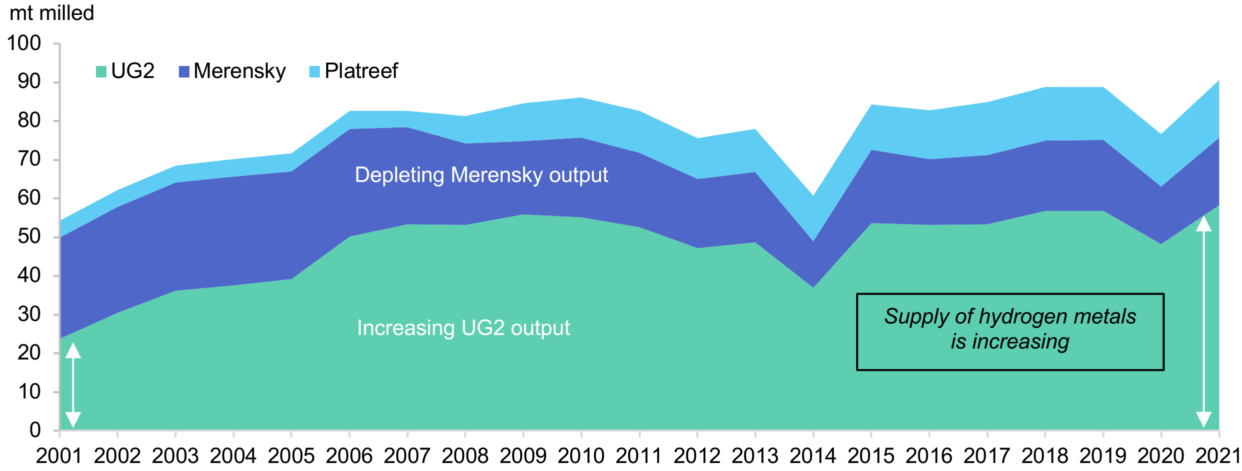
When Merensky ore was the dominant revenue stream for South Africa's PGM producers, investment was very much dictated by the platinum market alone. When rhodium and palladium prices picked up again in 2019 and revenue was led by the UG2 basket of metals, rhodium and palladium became the main drivers of growth, which had the bonus of yielding additional iridium and ruthenium supply.

UG2 is the 'hydrogen reef'

Since the mid-2000s, South African producers have increasingly focused on the extraction of ore from the UG2 Reef, as older Merensky operations deplete and newer generation shafts become deeper (higher cost).

UG2 production is on the rise ...

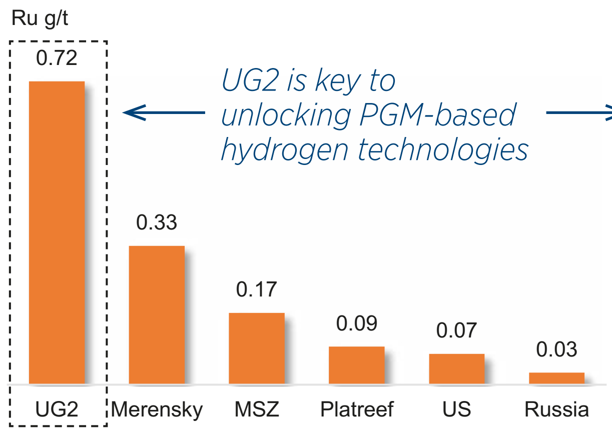
South African output by reef



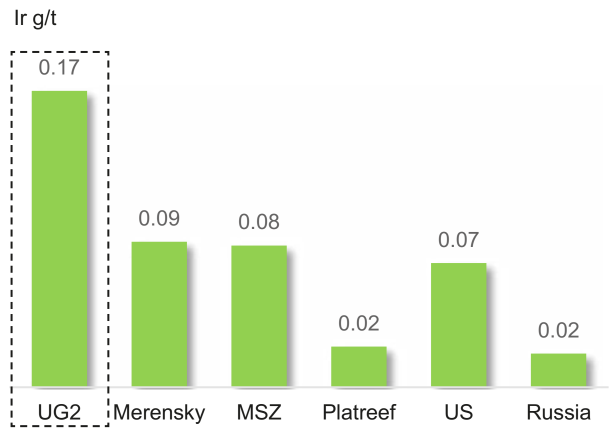
Source: SFA (Oxford)

As a result, the PGM production mix is gradually shifting closer towards the metals required for the hydrogen economy, as the UG2 Reef prill split is much more weighted towards iridium and ruthenium than any other PGM orebody worldwide.

Ruthenium grade per ore type



Iridium grade per ore type

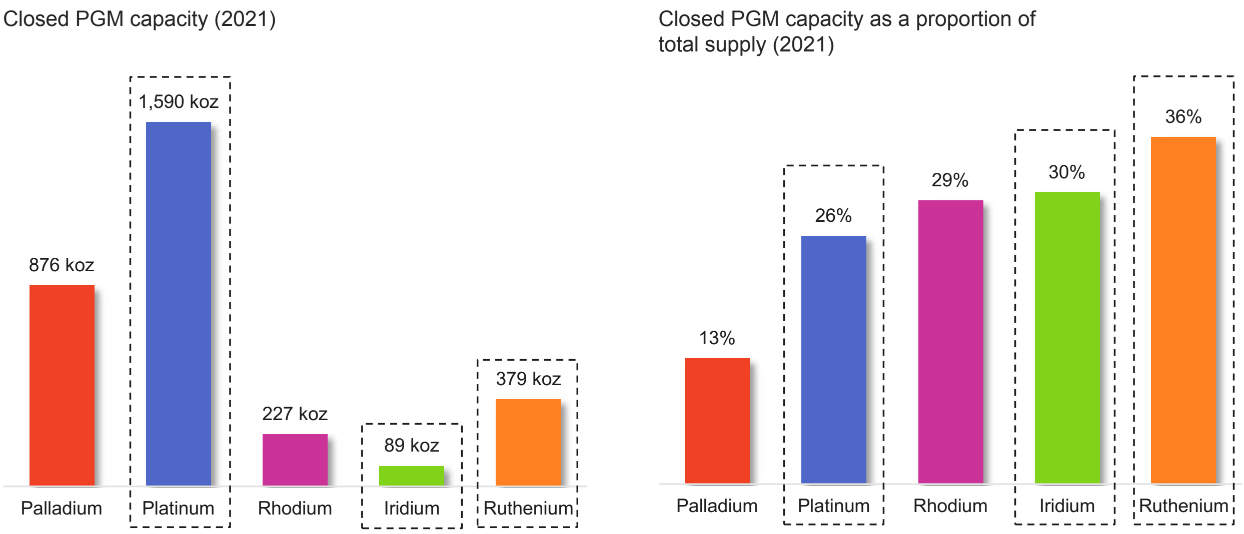


Source: SFA (Oxford)

When the rhodium price collapsed from a peak of more than \$10,000/oz in June 2008 to <\$2,000/oz in 2011, and subsequently to \$693/oz in 2016, there were several PGM mine closures in South Africa as well as projects mothballed during development, most of which involved UG2 mines as they are rhodium-rich and poorer in base metal by-products. As most of these shaft closures occurred in South Africa, the capacity currently closed as a proportion of total supply is significant for the hydrogen metals (26% of Pt, 30% of Ir and 36% of Ru).

... and current prices are likely to trigger the restart of mothballed UG2 mines

Huge potential for hydrogen metals capacity already exists



Source: SFA (Oxford)

Brownfield projects can unlock 1.3 moz of future hydrogen metal supply

Owing to the shaft closures that have taken place since 2009, there is now significant production capacity that can be restarted with relatively low capital requirements and shorter (1-2 year) lead times to production than those for greenfield projects. Producers are actively working to balance the metal mix of their portfolios to meet future demand from the hydrogen economy, and there has been significant investment in replacement projects to extend the life of mine of some mature operations which is lifting supply projections for platinum, iridium and ruthenium. Even with the recent fall in the South African basket price[1], producers are still comfortably making record profits, with plenty of cash available for increased brownfield investment.

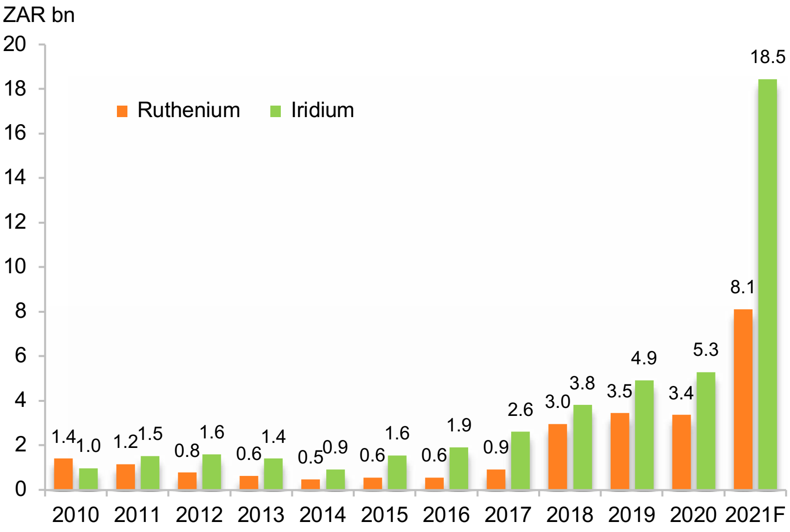
[1] Basket price refers to the collective revenue of metals, divided by 4E (Pt, Pd, Rh, Au) oz.

Mine revenues are more aligned to hydrogen metals

Iridium and ruthenium revenues are rising and becoming an increasingly noticeable part of the PGM revenue basket. This year, iridium revenues for South African producers are forecast to reach an estimated ZAR18.5 billion as record prices boost revenue, while ruthenium is also predicted to increase to ZAR8.1 billion.

Between 2016 and 2020, ruthenium and iridium revenues increased at an annual average of 59% and 28% respectively

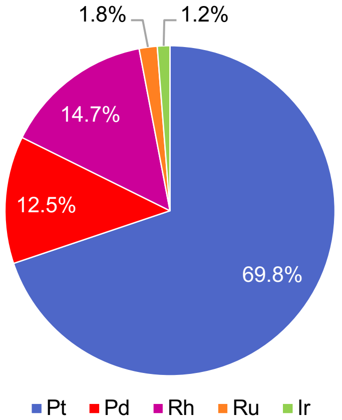
South African ruthenium and iridium revenues



Source: SFA (Oxford)

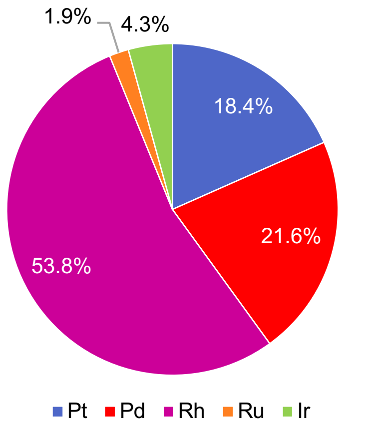
As well as high prices, today's revenues also reflect the changing orebodies in South Africa. Over the past decade, rhodium and iridium revenues as a proportion of total revenues from South African PGM mines have shown the greatest increases of 1,878% and 1,777%, respectively.

SA producer PGM revenues, 2010



Total PGM revenues: ZAR79.7 billion

SA producer PGM revenues, 2021F



Total PGM revenues: ZAR430.1 billion

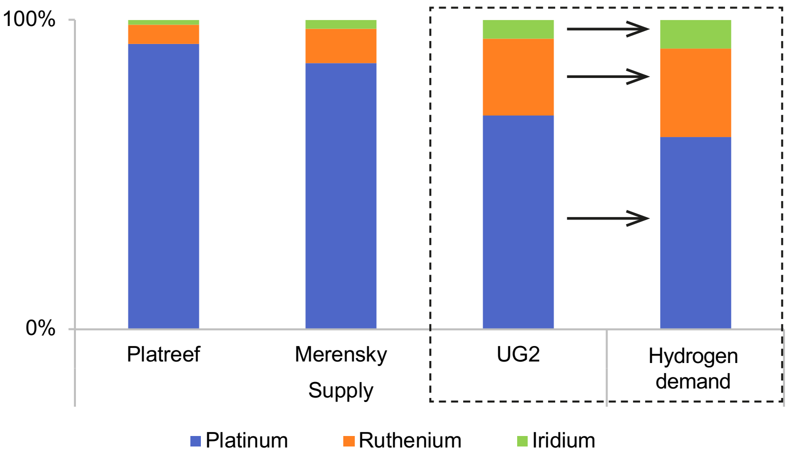
Source: SFA (Oxford)

Despite their growing contribution to mine revenue (which is currently dwarfed by rhodium), iridium and ruthenium still account for only a very small proportion of the overall PGM market and producers' revenue. However, mining is a game of strategy, and it is in producers' best interests to ensure the long-term availability of iridium and ruthenium, which will ultimately benefit the platinum market and, consequently, the producers' long-term profitability.

Metals out of the ground are aligning to the hydrogen industry's needs

With the best PGM mix to meet growing demand requirements, low-cost, mechanised, shallow UG2 projects are being favoured, such as Der Brochen (Anglo American Platinum) and Marula (Impala Platinum). Both projects contain high proportions of iridium and ruthenium, which has strengthened the case for extending the life of mine and replacing depleting output. Sibanye-Stillwater's K4 shaft and the Two Rivers Merensky expansion projects have been approved, and Eastern Platinum is continuing work on repairing the Zandfontein vertical shaft at Crocodile River with a view to restarting underground mining. The sale of the Bokoni mine to African Rainbow Minerals, jointly owned by Anglo American Platinum and Atlatsa Resources, is reported to be concluding which could also signal a restart. Brownfield projects have the potential to supply an additional >1 moz Pt, 220 koz Ru and 60 Ir over the long term if given the go-ahead.

South Africa's supply ratios vs. hydrogen demand



Source: SFA (Oxford)

Supply is a match made for hydrogen use: looking at the ratio of metal requirements for hydrogen, the UG2 metal mix is the best aligned

South Africa's supply chain can provide a one-of-a-kind pivot to a greener planet

The South African PGM industry is intrinsically linked to the world's cleaner, greener future, and with platinum, iridium and ruthenium being essential components in the hydrogen economy, long-term viability depends on proving green credentials. A completely 'green' mine-to-market value chain, combined with the long-term environmental benefits of transitioning to a hydrogen economy, supports investment, with PGMs already providing a net-positive environmental impact via their use in autocatalysts. Therefore, improving ESG compliance and proving those credentials is the next vital step for the PGM industry in South Africa to attract investment from a rapidly emerging class of sustainable investors, with the UG2 Reef, rich in critical metals for the hydrogen economy, front and centre. If mining companies can achieve this, the future production of the minor PGMs can be secured.

Just as the auto sector has aligned metal use with the mix of metals mined and recycled, the hydrogen sector will more than likely follow suit

THE PGM MARKETS IN 2021

The PGM markets in 2021

Dr. Ralph Grimble, SFA (Oxford)

Summary

The platinum market is forecast to have a surplus in 2021 (excluding investment) of close to 1.3 moz. Investment demand in 2020 absorbed the surplus, but so far this year it has been weak. ETF holdings have fluctuated, coming close to 4.0 moz in July before falling back. At the end of October, global holdings were down 64 koz from the start of the year as a result of net sales from South African and Japanese ETFs outweighing gains in other regions. Investors in Japan were also net sellers of platinum bars in the first half of the year, taking profits when the price exceeded ¥4,000/g.

The platinum market has a large surplus

This year began with tight refined supply for iridium and ruthenium owing to the lingering effects of the pandemic lockdown, which closed mines, and processing plant outages in South Africa in 2020, which resulted in reduced refined metal output and a build-up of stock. With refined output failing to keep up with demand in the first few months of the year, prices rallied sharply which took iridium to a record high. Prices have subsequently retreated, as not only has South African output returned to normal levels, but also it has been boosted by processing of stockpiled material. As a result, both the iridium and ruthenium markets are projected to be in surplus for the year as a whole, of 44 koz and 123 koz, respectively.

The year began with constrained iridium and ruthenium supply …

… but output has recovered in South Africa

Supply

The PGM markets were hit by a supply shock again this year, but the impact on platinum, iridium and ruthenium was modest. In February, two of Nornickel's mines suffered from flooding and there was an accident at a concentrator which is currently estimated to have cut approximately 115 koz from platinum supply and a few thousand ounces from iridium and ruthenium output.

Incidents in Russia cut PGM output

Primary platinum supply is projected to increase by 26% to 6.2 moz this year, despite Nornickel's problems resulting in Russian production falling by 17%. South African refined production is estimated to jump by 42% to 4.6 moz, recovering to pre-pandemic levels. With the Anglo Converter Plant (ACP) now back in full operation after an outage in 2020, some of the stockpiled smelter matte is being processed which is boosting the rebound in refined output. North American supply is recovering after some pandemic-related stoppages last year and Zimbabwean output is set to expand modestly.

Global iridium supply is forecast to rebound by 28% to 290 koz, while ruthenium output jumps by 31% to 1.0 moz this year.

Secondary platinum supply is predicted to grow by 7% to 1.8 moz in 2021. Jewellery recycling is expected to recover somewhat to 440 koz. Autocatalyst recycling is projected to rebound this year to 1.4 moz despite refineries operating close to capacity and the difficulty of processing silicon carbide diesel particulate filters.

Demand

The automotive market suffered a demand shock this year as a shortage of semiconductor chips gradually worsened as the year progressed, resulting in a shortfall of over 10 million units of light-vehicle production compared to expectations at the start of 2021. With platinum much less exposed to automotive demand than palladium, the reduction in platinum demand is estimated at 275 koz. Despite that, automotive platinum demand is still predicted to rise by 19% to 2.8 moz in 2021. This reflects not only some recovery from the pandemic-induced slump in demand last year but also gains from substitution and tighter emissions legislation. This year, the impact of substitution of platinum for some palladium in three-way catalysts is modest, but it does help the overall improvement in demand.

Despite supply chain issues, automotive platinum demand rises 19% this year ...

Despite diesel passenger car sales in Western Europe continuing to slide, the introduction of tighter emissions legislation in China and India has helped to lift platinum demand from heavy-duty diesel vehicles. China VI legislation came into force in July and requires heavy-duty diesel vehicles to be fitted with PGM-containing catalysts for the first time. Chinese automotive platinum demand is projected to climb by over 50% to 720 koz this year. In addition, 2021 is the first full-year of Bharat VI legislation in India following its introduction in April 2020.

... aided by gains in heavy-duty vehicle requirements

Global platinum jewellery demand is forecast to recover some, but not all, of the losses suffered last year, rising by 14% to 1.8 moz. North American consumption has recovered strongly, aided by platinum's price discount to gold. China has also performed better than expected so far this year, but with usage estimated at 875 koz, the largest market for platinum jewellery remains far below its peak. The rises in Covid cases in other regions and lockdowns in India, in particular, have restricted the recovery.

Industrial platinum demand is expected to see strong growth of 16% to 2.2 moz this year, not only recovering from the Covid-related drop of 2020 but also comfortably exceeding 2019 consumption levels. While all industrial demand segments are likely to have higher requirements this year, gains from the petroleum industry are particularly strong, accounting for just over half the increase. This is driven by new oil refining and gas-to-liquids capacity, some of which has been delayed from last year. Chemical demand is also recovering well, with growth in silicone production and new paraxylene capacity in China. Glass demand is higher owing to a jump in new capacity installations in China after the government policy was changed, plus rhodium is still being thrifted and replaced by platinum.

Platinum is used as a catalyst in proton exchange membrane (PEM) electrolysers (with iridium) and fuel cells (with ruthenium), and although requirements for platinum in hydrogen applications are still relatively modest, they are growing rapidly from a low base.

Ruthenium demand is forecast to climb by 4% this year to 939 koz, driven by growth in the chemical, electrical and hydrogen sectors. Chemical sector demand for ruthenium is projected to grow by 8% in 2021 as there is ongoing expansion in caprolactam synthesis in China, while electrochemical demand is supported by ballast water treatment legislation.

Ruthenium demand is forecast to grow by 4% this year

The hydrogen economy has received a great deal of press attention this year, although it is still relatively early in its development. Industrial fuel cells (for stationary applications and non-road vehicles) are currently the largest segment of ruthenium demand in the hydrogen economy as only a small number of fuel cell cars and trucks are being produced. Ruthenium is particularly important in PEM fuel cells where the hydrogen feed gas contains impurities.

In hard disk drives, the long-anticipated move to technologies that do not use ruthenium keeps being deferred, maintaining ruthenium electrical usage. Demand from other end-uses is forecast to dip by 7% this year.

Ruthenium use in hard disk drives is holding up

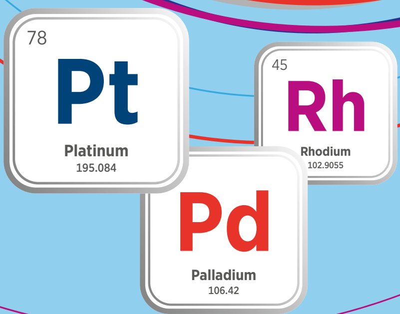
Iridium consumption is predicted to grow by 8% this year to 252 koz with small gains in each of the main end-uses. Iridium use in spark plugs in the automotive sector is set to rise this year despite light-vehicle production being much lower than expected. Demand for iridium from PEM electrolysers is growing rapidly from a small base. PEM competes with several other electrolyser technologies (ALK, AEM, SOE), none of which use iridium. However, PEM electrolysers are uniquely well suited to use highly intermittent renewable energy, making them ideal for green hydrogen production. Electrical demand for iridium comes from crucibles used to make lithium tantalate crystals for surface acoustic wave (SAW) filters and is supported by smartphone sales and the expansion of 5G phones.

Iridium demand is predicted to rise by 8% in 2021

SFA Oxford

Long-term PGM Market Outlook

The changing nature of the PGM market out to 2031



Well-reasoned, value-adding market intelligence on the upstream and downstream chain-linkages of the PGM industry

SFA (Oxford)'s Long-term PGM Market Outlook is an in-depth, forward-looking report on the current and long-term trends and influences acting on the global PGM markets, their sources of supply and demand, and their investment vehicles.

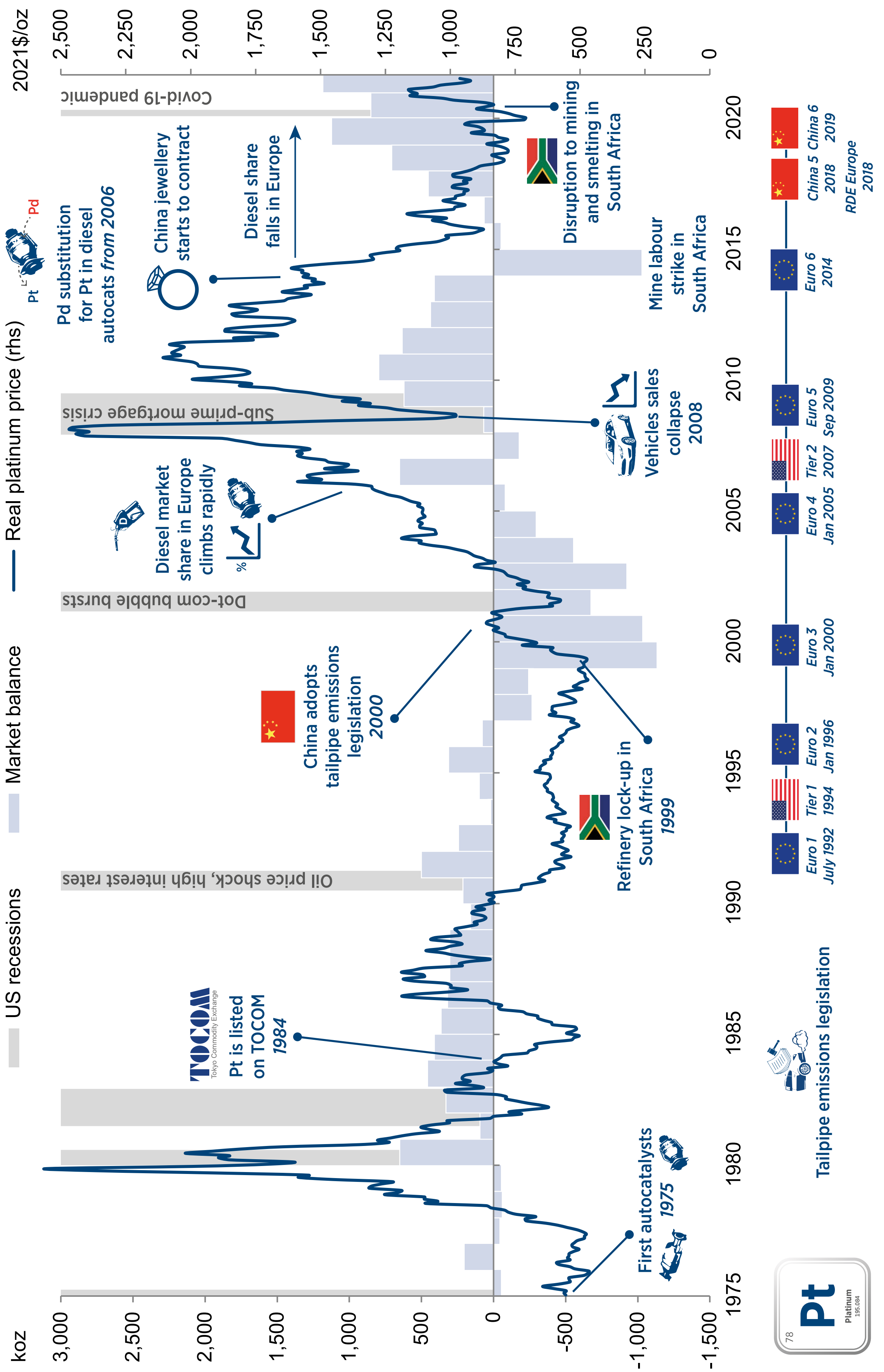
This report examines the changing nature of the PGM market out to 2031. It provides a **long-term sensitivity analysis of demand** with vital information needed to best gauge the impacts in the usage of palladium, platinum and rhodium as a result of **tightening tailpipe emissions standards**, intra-metal **substitution** trends, shifts in powertrains (advances in electrification of powertrains and pure battery electric vehicles), and **recycling**. It provides an analysis of the changes in and economics of global supply, as well as **long-term production profiles**. Also included is a detailed forecast evaluation of the PGM markets (including metal prices and their influence on the jewellery, industrial, chemical, petroleum and investment sectors) out to 2031.

The October 2021 issue is a fully updated view taking into account latest semiconductor chip shortage impacts, powertrain influences be it hybrids, electric and fuel cell vehicles, and latest producer results, mine economics and projects.

- **How have changes to battery electric vehicle forecasts** impacted the fundamentals and prices for palladium over the next ten years?
- What are the realistic views of Pt-Pd, Pd-Rh and Pd-Pt **substitution** over the next ten years and implications for prices?
- What do we know about **Euro 7 legislation** and what might the implications be for PGMs?
- Having had a period of very strong PGM prices, what are the prospects for supply? Is **reserve depletion** still a strong feature? Which **projects** will realistically feature over the next ten years and how might they impact the PGM markets?
- What is the latest view on **hydrogen uptake** and requirements of platinum?
- **Special report: *South Africa: Politics, Covid and Prospects***, by Professor William Beinart.

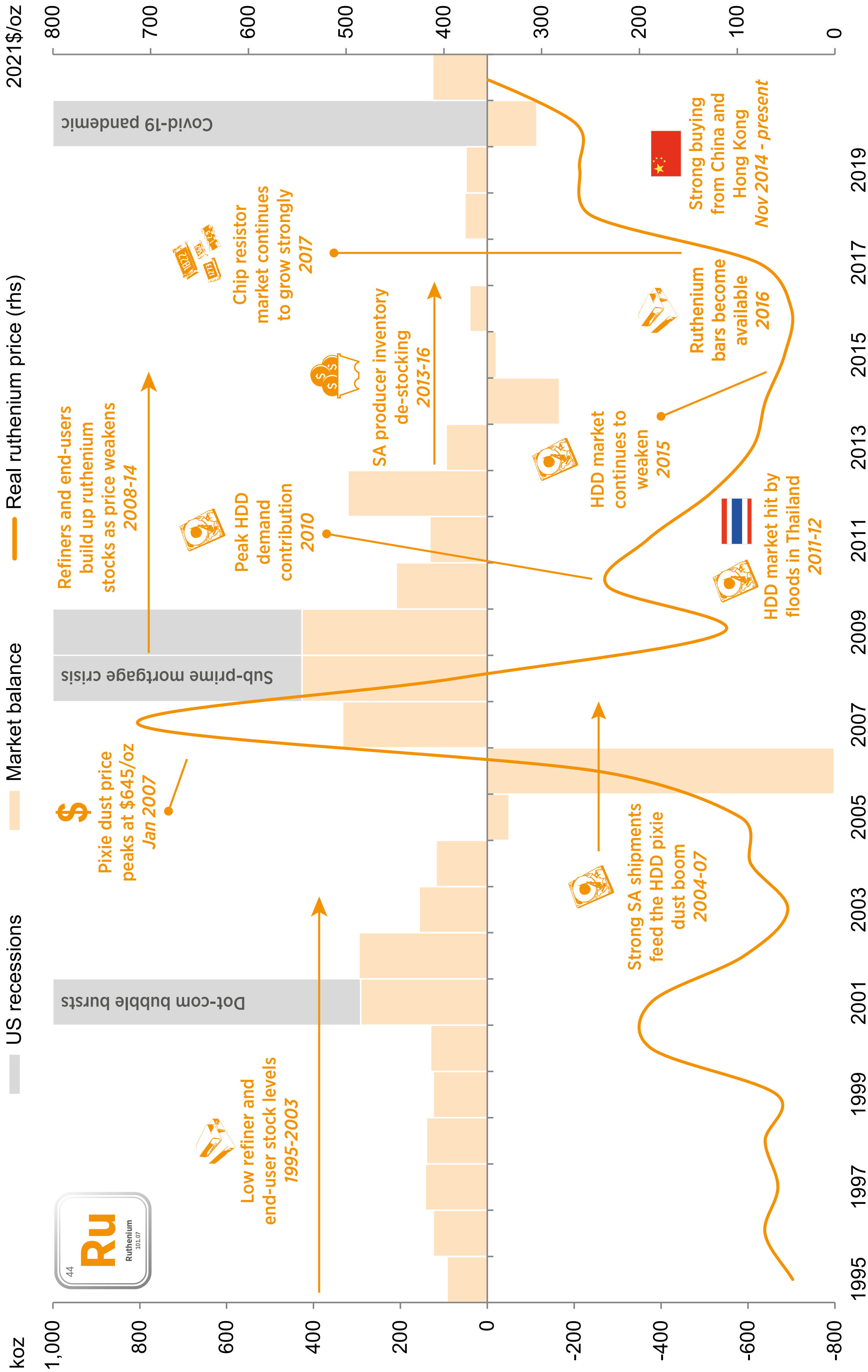
PGM PRICE HISTORY

Platinum



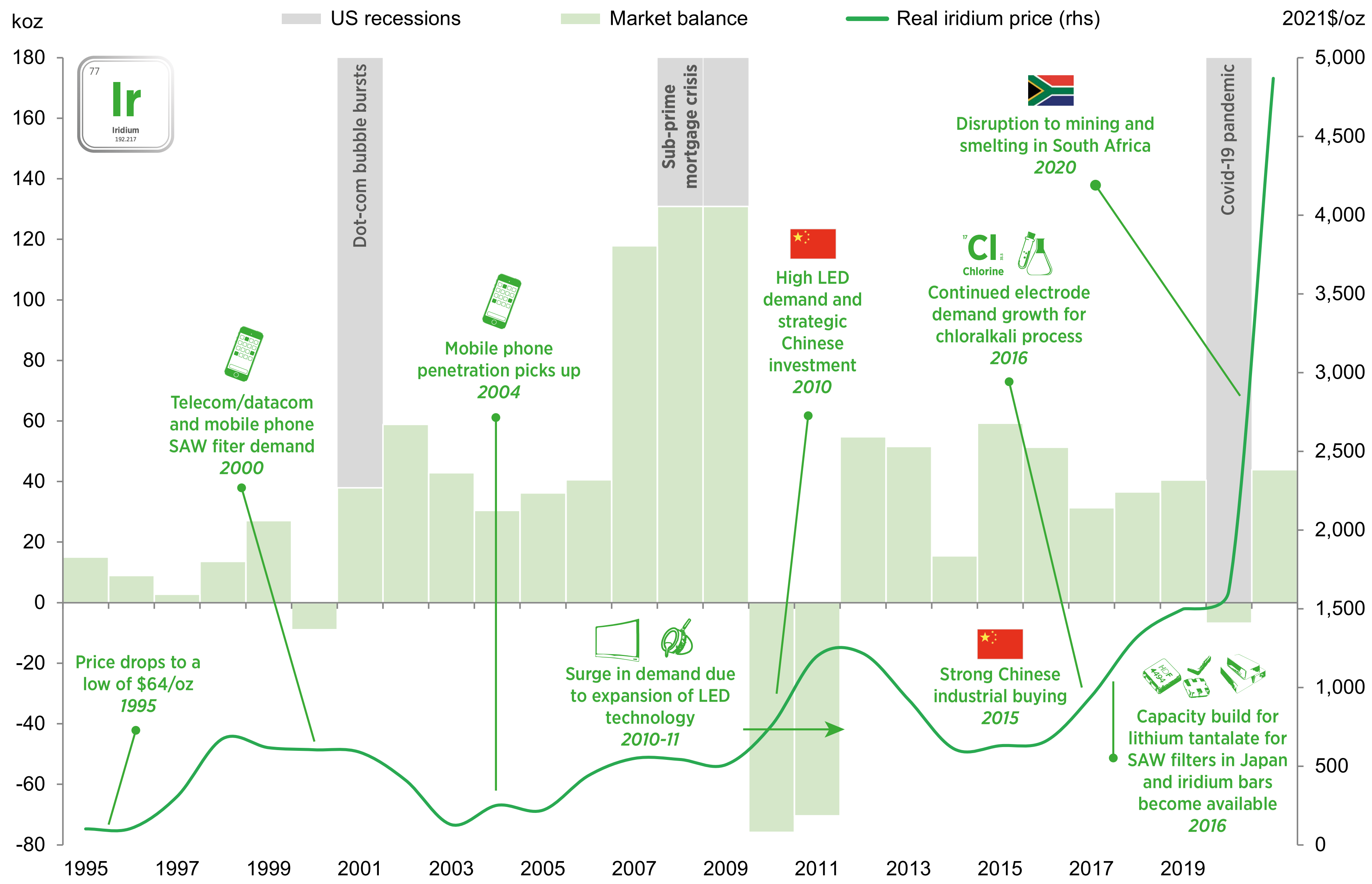
Source: SFA (Oxford), Bloomberg

Ruthenium

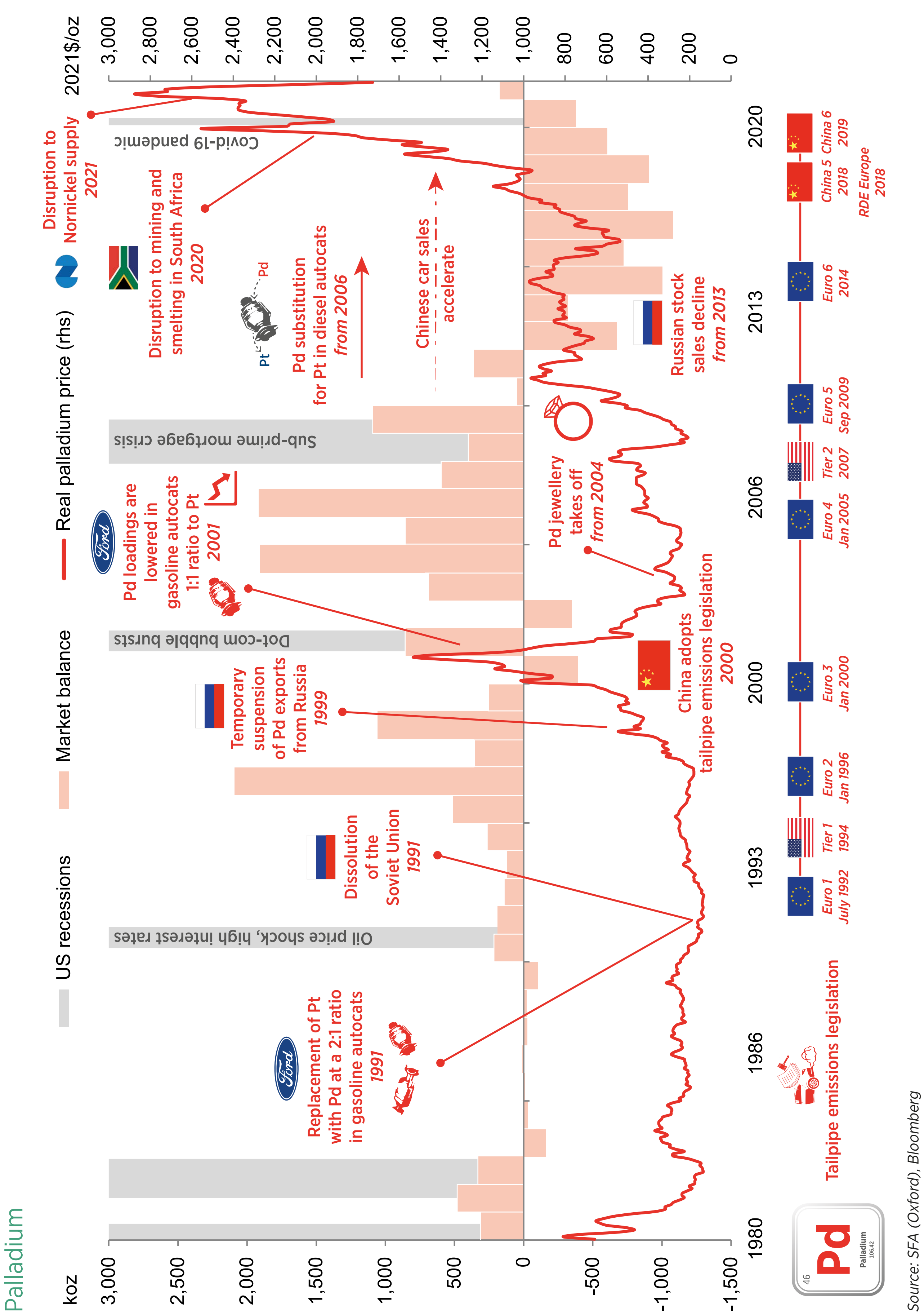


Source: SFA (Oxford), Bloomberg

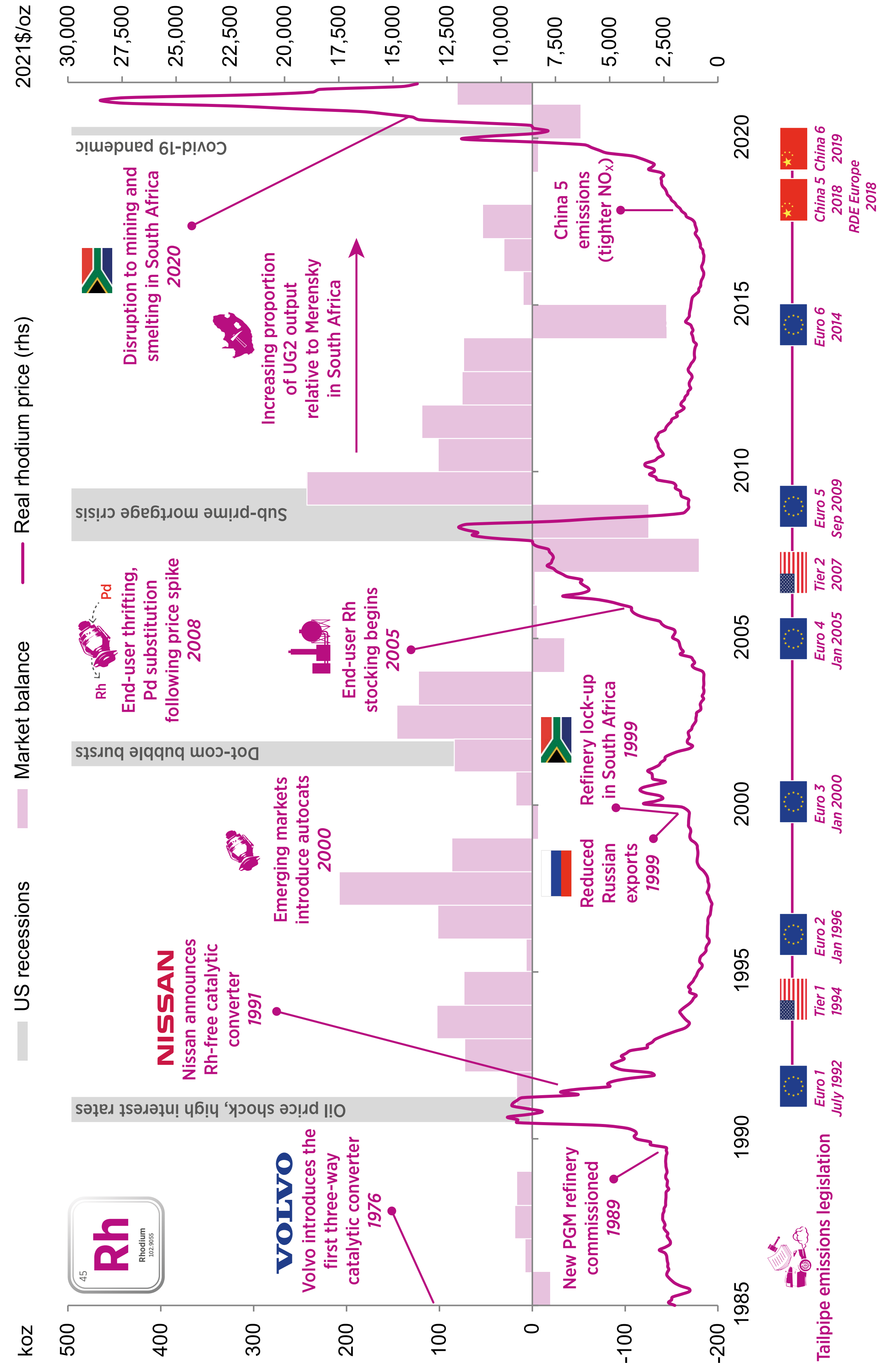
Iridium



Source: SFA (Oxford), Bloomberg


Palladium
koz
US recessions
Market balance
Real palladium price (rhs)
2021$/oz
Oil price shock, high interest rates
Dot-com bubble bursts
Sub-prime mortgage crisis
Covid-19 pandemic
Replacement of Pt with Pd at a 2:1 ratio in gasoline autocats 1991
Dissolution of the Soviet Union 1991
Temporary suspension of Pd exports from Russia 1999
Pd loadings are lowered in gasoline autocats 1:1 ratio to Pt 2007
China adopts tailpipe emissions legislation 2000
Pd jewellery takes off from 2004
Pd substitution for Pt in diesel autocats from 2006
Chinese car sales accelerate
Russian stock sales decline from 2013
Disruption to mining and smelting in South Africa 2020
Disruption to Nornickel supply 2021
Tailpipe emissions legislation
Euro 1 July 1992
Tier 1 1994
Euro 2 Jan 1996
Euro 3 Jan 2000
Euro 4 Jan 2005
Tier 2 2007
Euro 5 Sep 2009
Euro 6 2014
China 5 2018
China 6 2019
RDE Europe 2018
Source: SFA (Oxford), Bloomberg

Rhodium



Source: SFA (Oxford), Bloomberg

APPENDIX

Platinum supply-demand balance

koz	2013	2014	2015	2016	2017	2018	2019	2020	2021f
Primary supply									
Regional									
South Africa	4,355	3,135	4,480	4,265	4,385	4,470	4,405	3,255	4,625
Russia	740	740	710	715	720	665	710	705	590
Zimbabwe	405	405	405	490	480	465	460	480	495
North America	355	395	365	390	360	345	350	330	365
Other	215	200	200	185	185	180	185	175	160
Total	**6,070**	**4,875**	**6,160**	**6,045**	**6,130**	**6,125**	**6,110**	**4,945**	**6,235**
Demand & recycling									
Autocatalyst									
Gross demand	3,130	3,240	3,250	3,360	3,295	3,105	2,830	2,320	2,745
Recycling	1,120	1,250	1,180	1,220	1,325	1,420	1,490	1,300	1,395
Net demand	**2,010**	**1,990**	**2,070**	**2,140**	**1,970**	**1,685**	**1,340**	**1,020**	**1,350**
Jewellery									
Gross demand	2,945	3,000	2,840	2,505	2,460	2,245	2,095	1,560	1,775
Recycling	855	775	510	625	560	500	500	415	440
Net demand	2,090	2,225	2,330	1,880	1,900	1,745	1,595	1,145	1,335
Hydrogen	**5**	**25**	**25**	**45**	**45**	**70**	**40**	**40**	**75**
Industrial demand	**1,565**	**1,665**	**1,805**	**1,905**	**1,760**	**1,940**	**2,025**	**1,900**	**2,210**
Other recycling	**5**	**10**	**10**	**5**	**10**	**10**	**10**	**10**	**10**
Gross demand	**7,645**	**7,930**	**7,920**	**7,815**	**7,560**	**7,360**	**6,990**	**5,820**	**6,805**
Recycling	**1,980**	**2,035**	**1,700**	**1,850**	**1,895**	**1,930**	**2,000**	**1,725**	**1,845**
Net demand	**5,665**	**5,895**	**6,220**	**5,965**	**5,665**	**5,430**	**4,990**	**4,095**	**4,960**
Market balance									
Balance (before ETFs)	405	-1,020	-60	80	465	695	1,120	850	1,275
ETFs (stock allocation)	905	210	-240	-10	100	-240	995	505	
Balance after ETFs	**-500**	**-1,230**	**180**	**90**	**365**	**935**	**125**	**345**	

Source: SFA (Oxford)

Platinum demand and recycling summary

koz	2013	2014	2015	2016	2017	2018	2019	2020	2021f
Gross demand									
Autocatalyst									
North America	425	465	480	410	390	390	380	285	385
Western Europe	1,350	1,395	1,450	1,640	1,550	1,330	1,140	790	810
Japan	585	585	510	450	435	430	400	310	295
China	130	125	145	195	230	220	245	425	670
India	165	170	180	170	175	195	155	110	150
RoW	475	500	485	495	515	540	510	400	435
Total	**3,130**	**3,240**	**3,250**	**3,360**	**3,295**	**3,105**	**2,830**	**2,320**	**2,745**

Platinum demand and recycling summary (continued)

koz	2013	2014	2015	2016	2017	2018	2019	2020	2021f
Gross demand									
Jewellery									
North America	200	230	250	265	280	280	275	210	255
Western Europe	220	220	235	240	250	255	260	175	190
Japan	335	335	340	335	340	345	330	245	260
China	1,990	1,975	1,765	1,450	1,340	1,095	945	755	875
India	140	175	180	145	175	195	210	120	135
RoW	60	65	70	70	75	75	75	55	60
Total	**2,945**	**3,000**	**2,840**	**2,505**	**2,460**	**2,245**	**2,095**	**1,560**	**1,775**
Hydrogen									
North America	5	10	5	10	10	15	10	10	15
Western Europe	0	0	0	5	0	0	0	0	5
Japan	0	5	15	25	30	35	15	20	40
China	0	0	0	0	0	0	0	0	0
RoW	0	10	5	5	5	20	15	10	15
Total	**5**	**25**	**25**	**45**	**45**	**70**	**40**	**40**	**75**
Industrial									
North America	335	330	260	400	345	350	300	235	325
Western Europe	200	245	310	285	280	315	300	280	270
Japan	95	30	90	80	40	100	105	85	100
China	535	500	585	650	590	510	620	725	825
RoW	400	560	560	490	505	665	700	575	690
Total	**1,565**	**1,665**	**1,805**	**1,905**	**1,760**	**1,940**	**2,025**	**1,900**	**2,210**
Total gross demand									
North America	965	1,035	995	1,085	1,025	1,035	965	740	980
Western Europe	1,770	1,860	1,995	2,170	2,080	1,900	1,700	1,245	1,275
Japan	1,015	955	955	890	845	910	850	660	695
China	2,655	2,600	2,495	2,295	2,160	1,825	1,810	1,905	2,370
RoW	1,240	1,480	1,480	1,375	1,450	1,690	1,665	1,270	1,485
Total	**7,645**	**7,930**	**7,920**	**7,815**	**7,560**	**7,360**	**6,990**	**5,820**	**6,805**
Recycling									
Autocatalyst									
North America	560	560	505	535	585	640	645	575	565
Western Europe	365	465	370	400	440	465	505	425	495
Japan	95	105	95	95	100	110	110	100	115
China	20	30	55	40	40	35	40	30	35
RoW	80	90	155	150	160	170	190	170	185
Total	**1,120**	**1,250**	**1,180**	**1,220**	**1,325**	**1,420**	**1,490**	**1,300**	**1,395**
Jewellery									
North America	0	0	5	5	5	5	5	5	5
Western Europe	0	5	5	5	5	5	5	5	5
Japan	250	235	160	150	160	145	140	110	115
China	600	530	335	460	385	340	340	285	305
RoW	5	5	5	5	5	5	10	10	10
Total	**855**	**775**	**510**	**625**	**560**	**500**	**500**	**415**	**440**
WEEE	**5**	**10**	**10**	**5**	**10**	**10**	**10**	**10**	**10**
Total recycling									
North America	560	560	510	540	590	645	650	580	570
Western Europe	365	470	375	405	445	470	510	430	500
Japan	345	340	255	245	260	255	250	210	230
China	620	565	395	500	430	380	385	320	345
RoW	90	100	165	160	170	180	205	185	200
Total	**1,980**	**2,035**	**1,700**	**1,850**	**1,895**	**1,930**	**2,000**	**1,725**	**1,845**

Source: SFA (Oxford)

Ruthenium supply-demand balance

koz	2013	2014	2015	2016	2017	2018	2019	2020	2021f
Primary supply									
Regional									
South Africa	865	680	935	915	915	930	910	685	965
Russia	40	40	40	40	40	40	45	45	35
Zimbabwe	35	40	40	45	45	45	45	45	50
Other	25	20	20	15	15	15	15	15	15
Total	**965**	**780**	**1,035**	**1,015**	**1,015**	**1,030**	**1,015**	**790**	**1,065**
Demand									
Hydrogen	5	20	20	35	40	55	35	35	55
Industrial demand									
Chemical	420	465	540	465	465	460	460	435	460
Electrical	340	370	380	365	395	360	345	315	315
Other	100	90	120	105	110	100	130	115	110
Gross demand	**865**	**945**	**1,060**	**970**	**1,010**	**975**	**970**	**900**	**940**
Market balance									
Balance	100	-165	-25	45	5	55	45	-110	125

Source: SFA (Oxford)

Iridium supply-demand balance

koz	2013	2014	2015	2016	2017	2018	2019	2020	2021f
Gross demand									
Regional									
South Africa	175	155	225	225	220	225	230	175	245
Russia	25	25	25	25	25	25	25	25	20
Zimbabwe	20	20	20	20	20	20	20	20	25
Other	10	10	10	5	10	5	5	5	5
Total	**230**	**210**	**280**	**275**	**275**	**275**	**280**	**225**	**295**
Demand									
Jewellery	15	15	15	15	10	10	10	10	10
Hydrogen	1	0	1	0	2	1	2	1	4
Industrial demand									
Automotive	25	25	25	30	30	30	30	30	35
Chemical	70	75	70	75	80	80	80	85	85
Electrical	35	40	65	65	75	70	75	70	75
Other	35	35	35	40	40	40	45	40	45
Gross demand	**180**	**190**	**210**	**225**	**235**	**230**	**240**	**235**	**255**
Market balance									
Balance	50	20	70	50	40	45	40	-10	40

Source: SFA (Oxford)

GLOSSARY OF TERMS

AEM
Anion exchange membrane.

ALK
Alkaline water electrolysis.

BEV
Battery electric vehicle.

CAPEX
Capital expenditure.

CCM
Catalyst-coated membrane.

CO
Carbon monoxide.

CO_2
Carbon dioxide.

COP26
26th Conference of the Parties.

ESG
Environmental, social and governance.

ETF
Exchange-traded fund.

FCV/FCEV
Fuel-cell electric vehicle.

GDP
Gross domestic product.

GHG
Greenhouse gas.

Gt
Gigatonne.

GW
Gigawatt.

HHV
Higher heating value.

HRS
Hydrogen refuelling station.

ICE
Internal combustion engine.

koz
Thousand ounces.

kt
Kilotonne, equal to a thousand tonnes.

LCOE
Levelised cost of energy.

LHV
Lower heating value.

Merensky Reef
A PGM-bearing horizon within the Bushveld Igneous Complex, South Africa. Also contains nickel and copper sulphides that are mined as by-products.

MJ
Megajoule.

moz
Million ounces.

MSZ
Massive Sulphide Zone.

Mt
Megatonne, equal to a million tonnes.

MW
Megawatt.

NDC
Nationally Determined Contributions.

NO_x
Nitrous oxide.

PtX/P2X
Power-to-X.

PEM
Polymer electrolyte membrane.

PGM
Platinum-group metals, including platinum, palladium, rhodium, iridium, ruthenium and osmium.

Platreef
A PGM-bearing horizon within the Bushveld Igneous Complex, found only on the Northern Limb.

R&D
Research and development.

SCR
Selective catalytic reduction.

SMR
Steam methane reforming.

SOE
Solid oxide electrolyser.

UG2 Reef
A PGM-bearing horizon within the Bushveld Igneous Complex, located stratigraphically below the Merensky Reef. One of the main chromite-bearing reefs of the Bushveld Igneous Complex. Typically comprises lower base-metal content than the Merensky Reef.

UNEP
United Nations Environment Programme.

ZEV
Zero emission vehicle.

Currency symbols
$ US dollar.

ZAR South African rand.

METHODOLOGY

Primary supply is calculated from actual mine production and excludes the sale of stock in order to provide pure production data. Stock sales are treated separately in SFA's database as movement of stocks. Therefore, state stock sales from Russia are excluded in tabulations.

Gross demand is a measure of intensity of use.

Net demand is a measure of the theoretical requirement for new metal, i.e. net of recycling.

Automotive demand is based on vehicle production data, not sales.

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NOTES

Please note: Some tabulated data may not add up owing to rounding of individual numbers. © Published in November 2021 by SFA (Oxford) Ltd.

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