Resources and reserves in a carbon-constrained world

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Abstract
For many years, definition and production of non-renewable resources has been crucial to meeting industrial and societal demands for energy and materials. In the evolving energy transition, the priority is to meet not only the world’s increasing energy requirements but also societal expectations of net zero by 2050 or sooner. Renewable energy will play a key role in achieving this, but this will require key and critical minerals and materials, whether for use in wind turbines or for building new energy distribution systems. Fossil fuels will continue to be used for some energy and industrial processes and increasingly for the production of hydrogen. Essential to the energy transition will be ongoing assessment of resources and reserves, including of critical minerals, geological sites for CO₂ and H₂, carbon-based and carbon-free fuels. Some of the principles underpinning the traditional use of the terms reserves and resources can be usefully applied to provide rigour and uniformity to the assessment of renewable energy opportunities. Carbon offsets, negative emissions and recycling will also be used to achieve net zero. Whatever the energy transition pathway that countries choose to take, knowledge of and ready access to non-renewable resources and reserves will be essential to achieving a clean energy future.

Keywords Resources · Reserves · Carbon

Introduction
It is an honour and pleasure to have the opportunity to acknowledge the outstanding contribution that Professor Friedrich-Wilhelm Wellmer, Fred, has made to the earth sciences, throughout his long and distinguished career. It is a career that has covered the private and the public sectors both nationally and internationally. It has embraced management and leadership, research and exploration, onshore and offshore geology, climate change and environmental geology, metallic and industrial and energy resources. This is an extraordinarily diverse range of interests and impacts by any standard.

My knowledge of and friendship with Fred extends back 30 years or more, first through our common interest in resources, especially phosphate resources, and then through a shared wish to strengthen the role of national geological surveys, in my case as Director of the British Geological Survey (BGS) and in Fred’s case as President of the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)). Related to this, we both had a common vision (along with Martin Kursten and others) of encouraging closer collaboration between Europe’s geological surveys, through the establishment of EuroGeoSurveys.

The first efforts to formally classify mineral deposits were made more than a century ago on the basis of whether or not their exploitation was commercially viable. Since that time, classification systems have become more comprehensive and more complex, moving from the relatively simple question “what have we found?” to “can we commercially exploit it?” to “how do we minimise the environmental impact of its exploitation” and “what scope for recycling?”.

The pioneering work of M King Hubbert (1956) produced the bell-shaped Hubbert curve and the concept of “peak oil”. But as pointed out by Wellmer in a number of papers (Wellmer 2008; Wellmer and Dalheimer 2012; Wellmer and Scholz 2015, 2017; Weller and Hagelüken 2015), the actual pattern of resource production is found to deviate significantly from the ideal Hubbert curve. To illustrate this point, it is worth quoting at length from Wellmer and Scholz (2017) on their conceptual and empirical historic analysis...
of applications, misunderstandings and fallacies surrounding the Hubbert curve as it applies to phosphate and gold resources and reserves, but which includes principles that can be applied to other non-renewable resources, including energy.

The ultimate recoverable resources (URR) cannot be predicted by fitting a symmetric curve to the data of past (historic) production for any commodity on a global scale. Without knowledge of the URR, it is not possible to determine the peak production time. For well-confined areas, in the case of a supply market, it might be possible today to construct a satisfactory Hubbert Curve and to determine peak production. For phosphate, the case of Nauru Island is a good example, but so far, it is not possible for any commodity worldwide. URR comprise past production, presently known reserves, and future reserves developed from resources (known, but uneconomic at present) and parts of the geopotential (not yet known, but by geological reasoning and technological innovations, reserves can be expected to be discovered). The concept of reserves is a dynamic one, determined by economic conditions, technological developments, etc. The reserves of today can be the resources of tomorrow and vice versa. These factors also influence production curves. Therefore, it is not justified to interpret every peak as caused by geological constraints. In most cases so far, peak curves are demand driven and not at all influenced by geological availability. In only a very few cases (like the curve for the lower 48 states of the USA for oil by Hubbert in 1956 or gold production in South Africa), they are supply driven, i.e., true Hubbert Curves.

These insights led Wellmer and his co-authors to adopt an approach to reserves and resources that was more compatible with the “McKelvey box” (McKelvey 1972) rather than the Hubbert curve. They based their approach on the degree of certainty that a deposit exists (which in turn is reflected in the distinction between reserves and resources) and the profitability that will arise from the exploitation of the deposit.

Wellmer extended this model to take into account the potential for recycling; an important addition if we are to plot a future course of mineral exploitation that takes the principle of sustainability and a circular economy into account (Sinding-Larsen and Wellmer 2012). Recycling of minerals and mineral products is not always feasible. In the case of phosphorus for example, it is not possible to recycle this essential commodity to any significant extent. Wellmer suggested that despite the abundance of phosphate reserves and resources, it nevertheless warrants particular attention because of its social significance in meeting the essential nutritional needs of society. He elevates phosphate, along with energy, to the top of the resource pyramid.

Wellmer, through BGR, also contributed to the UN Framework Classification for Resources (UNECE 1997, 2021a, b) which allows a distinction to be made between the environmental, social economic and governance (ESEG) contingencies that need to be in place for a project to proceed. In 2021, the Sustainable Energy Subprogramme of the UNECE recognised his contribution to the UN Committee on Sustainable Energy.

These contributions by Wellmer and others provide the basis for now considering energy-relevant resources and reserves in the context of the transition to low carbon energy and the pathway to net zero.

### Fossil energy

The original Hubbert curve and the peak oil concept was based on the oil production of the lower 48 states of the USA. Hubbert (1962) assumed that after fossil fuel reserves are discovered, production at first increases approximately exponentially, as more extraction commences, and more efficient facilities are installed. At some point, a peak output is reached, and production begins declining until it approximates an exponential decline. Notable features were that the curve was symmetrical; the peak of production was reached when half of the fossil fuel had been produced, and it was a single peak. Significantly, the curve indicated a peak in conventional oil production for the USA in 1970–1971, which initially proved to be correct, and which gave the Hubbert curve great credibility in the eyes of industry and government (Inman 2016). The peak oil of 1970 (9.64 million barrels per day) was followed by the Hubbert-predicted slide in oil production down to around 5 million barrels per day by 2006. But then, as a result of the new technological development of fracking, oil production rose rapidly to surpass the 1970 peak by 2018 (10.96 million barrels per day). The IEA (2021b) forecasts that global oil demand will rise by 3.3 mb/day in 2022, when it returns to pre-pandemic levels at 99.5 mb/day, but obviously the details of oil production can be distorted by economic or political developments such as current political uncertainties in Eastern Europe.

Technological developments for one resource can have a profound impact on another resource. The development of fracking increased US gas reserves and decreased gas costs, which in turn led to large-scale substitution of gas for coal in electricity generation in the USA. Along with this, there was also substitution of renewables for coal-fired generation. Together, these produced a marked decrease in US CO₂ emissions associated with power generation, closed many US coal mines, reduced economic coal reserves and in the period 2010–2020, bankrupt more than 50 coal companies in the USA alone. Similar trends took place in a number of other OECD countries, with a major transfer of coal reserves to uneconomic coal resources. The IEA forecasts a sharp truncation of the coal production curve by 2040, and much earlier in some countries.
The history of coal production in Australia over the period 1901–2020 (Fig. 1) serves to illustrate some of the complexities that can occur at the national level. In 1901, Australian black coal production was approximately 10 million tonnes and exports were negligible. By 2020, Australia was producing more than 450 million tonnes of coal per annum, 130 million tonnes for domestic use, the remainder (approximately half thermal coal and half metallurgical coal) for export to Asia. Figure 1 shows a very modest decrease in domestic demand for coal in the past few years and in that time, a number of black coal-fired power stations in Australia have closed, but that is largely masked by the demand for coal exports. The most significant domestic downturn is for brown coal, a less acceptable fuel because it produces approximately 30% more CO₂ emissions per megawatt of power than black coal. The other trend illustrated by Fig. 1 is the impact of technology. In 1901, 20,000 coal workers produced approximately 10 million tonnes of coal; in 2020 50,000 coal workers (aided by major technological advances) produced 450 million tonnes of coal.

So, for Australia we see the domestic market reacting to greenhouse gas concerns, whilst the export market continues to grow. Internationally, the IEA (2021b) projects that there will be a major increase in energy demand from emerging markets and developing economies, with coal contributing 36% of global power generation, which in turn will drive CO₂ emissions higher. There is clearly a gap between ambition and action in terms of the speed at which the global energy transition can be achieved. The difficulty in forecasting those future trends is highlighted by the impact of recent political developments in Eastern Europe, leading to gas shortages and a marked increase in coal production and in the price of thermal coal, though the expectation is that this is just a temporary blip in the progressive decrease in global coal production.

Coal is not only used in power generation; the iron and steel industry accounts for 10–15% of global coal demand and produces 5–8% of the world’s carbon dioxide emissions. Future options to decrease or eliminate CO₂ emissions include CCS, electric arc furnace (EIF) technology with zero-carbon electricity or direct reduced iron (DRI) technology using hydrogen. There is also extensive coal use by the chemical, cement and other industries. The age of the plants can be a critical part of any decision on technology uptake. Ng (2022) reports that the average age of steel plants in Europe is 40 years but only 12 years in China. Consequently, in China, on cost grounds, it is more likely that a CCS retrofit approach will be used to cut steel plants emissions, rather than EIF or DRI. So, there could be a long tail to the coal production curve, driven by industry demand rather than energy demand. Given current trends and the important role coal plays not only in power generation but in industry more broadly, it is unlikely that world coal production and use will have ceased by 2050 and we will need to minimise the likely greenhouse gas impact of this. What is also clear is that the end of the global coal industry will not be from depletion of coal resources and reserves but from overriding global concerns regarding CO₂ emissions.

Global identified gas reserves are of the order of 7,000 trillion cubic feet (Knoema 2021). This is enough to meet current world demand for more than 50 years. Gas resources are an order of magnitude greater. Consequently, availability is not an issue for gas, but associated greenhouse emissions are. The energy transition is reshaping some gas demand at national levels, but globally there is no evidence that a move from gas is happening quickly. The IEA (2021c) forecasts natural gas and LNG gas will be the strongest-growing fossil fuel and demand will increase by 0.9% per annum from 2020 to 2035. From 2035 to 2050, the IEA expects gas demand to decline, but only by an average of 0.4% per annum. This relatively moderate rate of decline is at least in part due to hard-to-replace gas use in the chemical and industrial sectors. Demand for LNG is expected by the IEA to peak around 2040, with the share of LNG in the global gas supply increasing from today’s 13 to 23% by 2050. Importantly, 138 MT per annum of LNG capacity is currently under construction around the world and realistically, given the longevity of a major LNG facility, is likely to still be in production (and producing greenhouse gases) in 2040–2050.

Therefore, present trends offer no evidence that fossil energy will cease to be part of the energy mix anytime soon. This is not what is demanded by the 2015 Paris Agreement or a net zero target and it is essential we aspire to a much faster uptake of renewable energy. But at the same time, it would be foolish to predicate zero emission futures on the assumption that all fossil fuels will disappear from

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**Fig. 1** Production of Australian coal and exports 1901–2020 (in million metric tonnes, left axis). Number of coal workers (in thousands, right axis) (Bureau of Statistics 1970). Diagram courtesy of Alfonso Arranz.
the energy scene by that time or sooner, when there is no evidence of this happening. Nor, unfortunately is there any evidence of the political will at national and international levels to change the current trajectory. Therefore, the logical approach at this time has to be to take account of the evidence that the use of fossil fuels will continue in some countries, especially developing countries, to 2050 and beyond and that we must take action to minimise the impact of this, by mitigating and if possible totally eliminating the associated CO₂ emissions.

Cutting emissions

There is abundant evidence (Le Quere et al. 2018; IPCC 2018, 2022; National Academies Science Engineering Medicine 2021) that if we are to avoid dangerous climate change, we must make deep cuts in emissions by 2050 or earlier. For some, perhaps many, that equates to ceasing all use of all fossil fuels by 2035 if not sooner. But as is evident from the previous discussion, the global trends in the production and use of fossil fuels are currently not compatible with the agreed Paris Agreement objective of keeping the global temperature rise to 1.5 °C or below, nor with the target of net zero carbon by 2050 or sooner. So, despite the predictions of the end of coal or oil or gas, it is likely that they will still be part of the global energy mix by 2050 and it would be wise to address this in future clean energy options through permanent storage of the associated CO₂ emissions, not instead of more renewable energy, but in addition to more renewable energy.

CO₂ emissions can be captured and permanently stored at scale (IPCC 2005), or on a more modest scale, can be incorporated into useful “long-lived” product such as cement or other building products (Hitch and Dipple 2012; Kliejne et al. 2022). Typically, the CO₂ is reacted with rocks such as serpentinites, containing calcium or magnesium, to produce a carbonate product (Sanna et al. 2014). Ideally the reactive rock is a ground-up product of a current mining operation (to avoid the cost and the energy penalty involved in rock crushing and grinding) and such material could be regarded as a “reserve”, in that its quantity, chemistry and reactivity is known and it is in a location where it could potentially be used. There are also large resources of reactive rock that could be mined in the future if it became commercially feasible to do so and where there is a market for the products. Use of CO₂ should be encouraged where it is economically and logistically feasible, and where the CO₂ sequestration is long term. Carbonate mineralisation could make a valuable contribution to decreasing CO₂ emissions to the atmosphere, be a useful carbon offset or create negative emission. But it is unlikely to operate at the scale necessary to have a major impact on the global emissions profile.

Carbon capture and geological storage (CCS) is seen by many as a major mitigation option (IPCC 2005; Cook 2012) and its technical feasibility is well established (GCCS1 2021). But is the available geological storage resource likely to be sufficient to meet the mitigation need to cut CO₂ emissions by billions of tonnes of CO₂ per annum? Globally, yes, according to the IPCC (2005), although this conclusion was based primarily on theoretical storage potential, with a significant level of uncertainty. Like mineral or energy resources, realisation of that potential and upgrade of a storage resource to a storage reserve is dependent on parameters such as the level of geological knowledge, commercial viability, environmental impact, social acceptance and government approvals. It also depends on distance of the storage site from the CO₂ source, for the greater the distance to transport the CO₂ (by pipeline, though ship transport is possible) the greater the cost of the transport infrastructure. It is possible to overcome the “tyranny of distance” through economies of scale, and a number of low emission nodes and networks are being considered for Europe, North America and Australia. But obviously, the starting point has to be that the geology is suitable, which generally means porous and permeable rocks (such as a sandstone) at the right depth (800 m or more), overlain by an impermeable seal (such as a mudstone) in a structurally simple location (limited faulting and fracturing) that is tectonically stable.

This set of attributes, usually referred to as site characterisation, has been defined by Cook (2006) as “The collection, analysis and interpretation of subsurface, surface and atmospheric data (geoscientific, spatial, engineering, social, economic, environmental) and the application of that knowledge to judge, with a degree of confidence, if an identified site will geologically store a specific quantity of CO₂ for a defined period of time and meet all required health, safety, environmental and regulatory standards”.

The McKelvey box, with its various modifications (SPE 2007, 2011, 2018), can be used to represent the CO₂ mitigation potential of geological storage capacity (Fig. 2). Terms such as operational, contingent and prospective capacity have been readily and usefully incorporated into the scheme. Together, they offer the opportunity to standardise the assessment of this resource and future reserves. The conceptual McKelvey box (as in Fig. 2) along with a probabilistic approach can be usefully applied. Total pore volume can be subdivided into discovered and undiscovered pore volume, which in turn can be classified as either commercial or sub-commercial. Operational storage capacity (discovered pore volume that is considered commercial) can be separated into proven reserves with a 90% probability of commercial use (1P), proven plus probable reserves with 50% probability of commercial use (2P) and proven plus probable plus possible, with a 10% probability of commercial use (3P), following standard
petroleum industry nomenclature (SPE 2007, 2011). Other more speculative categories include contingent storage capacity (discovered pore volume which is expected to be commercial in the future) and prospective storage capacity (undiscovered pore volume which might become commercial at some future time). The prospect of contingent and prospective storage capacities achieving commerciality requires a probabilistic approach identifying the high, low and best estimates, in much the same way that a probabilistic approach is taken to oil and gas resources and reserves.

Storage capacity (Fig. 3) can also be represented as a resource pyramid (CSLF 2007; Kaldi Gibson-Poole 2008) with the best-known and highest-quality capacity at the apex of the pyramid and the poorly known or poor-quality capacity at its base. Theoretical storage capacity—the physical limit of what the geological system can store—is represented by the entire pyramid. Effective storage capacity is a subset of the theoretical capacity. Practical storage capacity is a subset of the effective capacity, which is obtained by considering other technical, regulatory, infrastructure and other constraints. The matched storage capacity involves detailed matching of large stationary CO₂ sources with well characterised geological storage sites.

To what extent has this been done to date? There are a number of sites that have been well characterised, and their storage capacity risked and assessed. An excellent example of a mature project is provided by the Sleipner Project (Furrea et al. 2017); CarbonNet provides a developing example (Barker and Mendes da Costa 2018). The value of the accessible (in situ) pore space may need to be discounted on the basis of the “source-sink” distance, which impacts on transport costs. The injectivity of a reservoir impacts on how many injection wells are needed to inject, for example a million tonnes of CO₂ per annum. Heterogeneity exerts a major influence on capacity and the extent to which a CO₂ plume will spread (Benson et al. 2018).

The value of a storage resource or reserve can be calculated and risked if there is a market for carbon through, for example the EU Emissions Trading System, which over the past year has had a carbon price ranging from 40 to 90 euros per tonne of carbon. In the USA, a tax initiative (45Q) encourages geological storage, by offering a tax credit of US $55 for each tonne of anthropogenic CO₂ stored in a saline aquifer. This provides a different but equally valid basis for monetising a storage site. Alternatively, if there is no national basis for placing a dollar value on a storage site, and no 45Q, then the value of the contingent or prospective

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**Fig. 2** CO₂ storage volume classification system after Kaldi and Gibson-Poole (modified from SPE 2007)
storage capacity (Fig. 2) can be based on a carbon price arrived at by agreement between the CO₂ producer (steel plant, power station etc.) and the CO₂ mitigator (the company taking on responsibility for geologically storing the CO₂).

So, whilst there are new geological parameters to consider, the established principles of reserves and resources can be applied to sites or geological formations or structures suitable for CO₂ storage, a resource that is likely to be increasingly in demand. The same principles can be applied to underground storage of hydrogen and this is discussed later.

**Carbon-free fuels**

For some countries, their choice of a carbon-free fuel is uranium. But for many others, hydrogen is seen as an important component of the future clean energy mix. Natural hydrogen gas does exist as a minor resource in a number of geological settings (Zgonnik 2020). In Australia for example, it was first reported to occur in South Australia by Price (1933). Many would regard these occurrences as no more than a geological curiosity! A review of natural hydrogen in Australia by Boreham et al. (2021) concludes that “Natural hydrogen is carbon-free, but unlike fossil fuels it is continuously being generated from the same source over a wider range of depths and temperature providing ‘timeless hydrogen’. Given the enormous, cumulative amount of H₂ that has been generated since the earth was formed, the likelihood of potentially large H₂ reservoirs is considered high, awaiting discovery using proven exploration guidelines”. Boreham et al. suggest that the Australian continent has a hydrogen inferred resource potential between 1.6 and 5.8 Mm³ year⁻¹ down to a depth of 1 km. This annual hydrogen flux is small compared to current hydrogen demand. Nonetheless, over the past year, 18 exploration licences have been granted or applied for in South Australia, by six companies searching for natural hydrogen, with a view to identifying hydrogen resources and ultimately commercially significant hydrogen reserves (Peacock 2022). At a recent meeting of the Geological Society of London (2022), a number of occurrences of natural hydrogen were documented including the Sao Francisco Basin, Brazil, which is emitting several hundred kg H₂ per km² per day. A question that has important implications for natural hydrogen resources or even reserves is whether the hydrogen is a seep, or whether there is scope for large-scale subsurface trapping of hydrogen analogous to a conventional gas trap? It has been suggested (London, 2022) by Michael Webber of Engie, France, that “Natural hydrogen has the potential to cause the biggest disruption to the global energy system in the coming decades”.

The current reality is that steam reforming of natural gas presently produces 95% of the world’s hydrogen—and large quantities of carbon dioxide. Consequently, if natural gas or coal is to be used for blue hydrogen production and if a target of net zero emissions is to be met by 2050 or earlier, then carbon capture and geological storage (CCS) would need to be deployed at large scale. There are a number of national hydrogen strategies now in place or under development. The Australian hydrogen strategy and roadmap (Finkel 2018; COAG 2019; CSIRO 2020) includes production of
blue hydrogen from brown or black coal or natural gas, and green hydrogen from electrolysis. In the proposed Hydrogen Energy Supply Chain (HESC) project located in Victoria for example, hydrogen will be produced through brown coal gasification and gas-refining, then liquefied and shipped to Japan. The carbon dioxide would be captured and geologically stored in the offshore Gippsland Basin (Barker and Mendes da Costa 2018). This is just one of a number of hydrogen projects being developed around the world.

Blue hydrogen produced from natural gas with carbon capture and storage (CCS) is seen by the IEA and other international bodies, as an important option, with lower cost. Low carbon blue hydrogen the preferred hydrogen pathway for many countries, at least initially building on the existing gas industry and related infrastructure. Using Australia as an example, LNG has been an increasingly important export for Australia. In 2003–2004, exports were 7.1 million tonnes. In 2022, export volumes will be approximately 80 million tonnes and worth more than US$ 40 billion. Concerns regarding scope 3 CO₂ emissions arising from the use of gas and LNG in countries such as Japan and Korea could drastically cut this market. An option to address this is by moving to hydrogen. For Australia and a number of other countries, a zero-emission hydrogen industry could potentially be built on the technical, commercial and financial competencies of the existing gas industry.

Like natural gas, hydrogen can be stored for delivery, shipping and use. It can be liquefied via compression or cryogenic cooling and converted into an energy carrier such as methanol, a liquid organic hydrogen carrier (LOHC) such as methylcyclohexane, or ammonia. So, rather than gas production tailing-off, we might see a bimodal production curve for gas, as blue hydrogen gains acceptance, not instead of green hydrogen, but as part of the clean energy mix. As discussed earlier, global gas reserves and resources are massive and have the capacity to meet the future demand for hydrogen for decades to come. This potential will be dependent on CCS being applied at scale, to deal with the related CO₂ emissions.

Hydrogen can of course be produced by electrolysis of water using renewable energy and this is often labelled “green hydrogen”, which is seen by many as more sustainable and therefore more acceptable than blue hydrogen, but renewable energy is still in limited supply. Perhaps for some, the label of “green” carries with it the connotation that is a fully sustainable and essentially unlimited supply of energy. But as pointed out later, wind turbines, electrodes and increased electricity requirements all require significant and sometimes large quantities of non-renewable minerals and materials. From that perspective, there is no such thing as “absolutely” green hydrogen! In many ways, the labelling of hydrogen as blue or green is not helpful to the development of any energy transition that includes hydrogen as we will need both of them. As Alan Finkel, Australia’s Chief Scientist, stated in his 2019 presentation to the IEA, “We need an internationally agreed threshold for the amount of carbon dioxide that can be emitted during production and still qualify to be called ‘carbon-free’ hydrogen”. Put another way, it really should not matter whether hydrogen is generated from natural gas, or by electrolysis, or more speculatively natural (geological) hydrogen or indeed (in countries that have nuclear power as an energy option) via electrolysis using nuclear power. What matters is how much CO₂ is emitted in total in the production of the hydrogen.

**Renewable energy**

This paper and many others have drawn attention to the fact that current global aspirations for a low carbon future, as exemplified by the Paris Agreement, are not in accord with the present and increasing use of fossil fuels and the slow uptake of carbon-free energy. We must take this into account in planning the future energy mix and the technologies that will be essential to that future, but there can be no doubt that the development and deployment of renewable energy on a massive scale is a critical part of the future energy mix if we are to have a low carbon world. So, in a world dominated by renewable energy, will “resources” and “reserves” have any relevance?

More efficient wind turbines or solar panels will increase the future energy output, but such future developments frequently also require increased use of critical minerals, often ones with limited reserves such as cobalt, graphite, lithium, rare earths and tungsten. A recent (2022) report by the Geological Society estimates that each wind turbine requires “at least five tonnes of copper wiring, three tonnes of aluminium, 1200 tonnes of concrete and two tonnes of rare earth elements”. Batteries, an increasingly important part of any renewable energy system also require critical minerals. But it is not just critical minerals that are required for a low carbon future. Copper is a key mineral if we are to develop new energy distribution systems for example. There is a need to secure the supply of these minerals as an integral part of the clean energy pathway. Increased recycling will become ever more important, but this alone will not provide all the necessary minerals. Do we have enough critical mineral resources and reserves to meet the projected massive increase in renewable energy necessary for a low-carbon economy? No! Therefore, ongoing exploration for critical and key minerals accompanied by evaluation of any resources and reserves found, including those in existing mine waste, must be part of any renewable energy strategy.

The term “resource” is widely used in the renewables sector, for example a windy or a sunny area is often described as having a good wind resource or solar
resource. However, the term “reserve” is used not to indicate a level of commerciality (as in minerals or petroleum or geological storage), but to indicate a specific area set aside because of particular characteristics such as special flora or fauna or somewhere of unique cultural attributes. In other words, the term “reserve” does not readily fit into the lexicon of renewable energy. But the resource classification system of the SPE (2018) has as its stated aim the need to bring to the resource assessment process, consistency, transparency and reliability, all of which are attributes required for any energy production proposal or project, whether non-renewable or renewable.

The need to formalise the approach to “wind resources” for example is increasingly recognised as issues such as visual, environmental, commercial, social and other issues impact on the opportunity to exploit wind resources and other renewable resources. A crucial factor in the development, siting and operation of a wind plant is the ability to assess and characterise available wind resources. With this in mind, the US Department of Energy (2022) through the Wind Energy Technologies Office (WETO) “is leading a portfolio of wind resource assessment and characterization projects that will help the industry understand how to reliably integrate large quantities of wind energy into system operations, as well as develop capabilities that will enable these new wind installations to actively improve the quality of electric grid”. To facilitate this process, WETO has developed a schema to formalise the stages of a wind development within a framework which echoes that used for non-renewable resources and reserves. At the far end of the assessment process is total wind resource potential (which includes gross recoverable and unrecoverable wind resources); then gross resource potential; technical resource potential; economic potential and finally deployment. The last two of these terms are comparable to a mineral reserve in that they reflect something that it is quantifiable and commercially viable, although they do not formalise underlying principles such as probability, nor use precisely the same terminology. Nonetheless, the same underlying principles are evident, and it is desirable, and likely that major wind and solar development will move to a more uniform style of characterisation of the scope and scale of wind and solar resources.

As discussed earlier, the future growth of renewable energy must take into account the availability of non-renewable resources and reserves. Land suitable for industrial scale wind or solar farms can also be seen as a finite resource. Community opposition places a major constraint on land availability and access, just as it does on land availability for gas or minerals exploration and production.

**Negative emissions**

As pointed out previously, if the current emissions trajectory is maintained it will be impossible to meet the Paris targets and we will need negative emissions through direct removal of CO₂ from the atmosphere (Fuss et al. 2018; Minx et al. 2019; National Academy of Sciences 2019; Realmonte et al. 2019). There are a range of negative emission technologies available or under development that will require consideration of non-renewable resources and reserves (Cook and Arranz 2020). The potential for removing CO₂ from the atmosphere through technologies such as direct air capture of CO₂ (DACCS) could become an essential part of the CO₂ mitigation portfolio. Access to low-cost clean energy, probably wind power or solar, will also be vital for viable low-carbon DACCS projects. But in parts of the world where land is a limited resource, communities may find it unacceptable to have hundreds of capture units, each the size of a shipping container or larger, together with wind turbines, distributed over large areas of the countryside. As previously discussed, whilst the captured CO₂ could in some instances be made or incorporated into useful products such as building materials, the quantity of CO₂ that will need to be captured if our present trajectory of emissions continues, makes it inevitable that geological storage of CO₂ will be required as part of DACCS. As discussed earlier, whilst subsurface pore space resources are large, they are not infinite, nor are they necessarily where they are needed. One of the positive features of DACCS is that the units can be selectively placed where there are good subsurface storage resources, where there are no community concerns and where there is no need for expensive pipelines.

**Conclusions**

The reserve-resource concepts developed over the past century have served us well, though the symmetrical bell-shaped Hubbert curve and the embedded concept of peak oil is largely redundant. Fossil fuel resources and reserves are very large and the use of fossil fuels, whether coal or gas, will end not because of resource or reserve constraints, but because of societal concerns regarding the concentration of CO₂ and other greenhouse gases in the atmosphere. With the aim of renewable energy meeting all our energy needs in the future, is there still a need to be concerned about non-renewable resources? The short answer is yes, and many of the resource-reserve principles established by McKelvey, Wellmer and others are as relevant now as they ever were.

A global economy with zero use of fossil fuels by 2050 is unlikely. This is not a view based on a lack of
enthusiasm for renewable energy, but on the evidence of current trends and informed forecasts for fossil fuels, plus what has and has not been achieved in recent years. What can be achieved by 2050 is net zero emissions of CO₂. This will require a massive increase in the adoption of renewable energy, smarter and more comprehensive energy networks, greater energy efficiency and lifestyle changes. But it will also require deep cuts in CO₂ emissions arising from decreased but ongoing use of fossil fuels in energy production and chemical and manufacturing processes and from increased hydrogen production.

In the early stages of its development, the main application of CCS was expected to be mitigate CO₂ emissions from coal-fired power stations. In most OECD countries, this now seems unlikely because of the large-scale uptake of renewables. But in Asia in particular, there are many new coal-fired power plants and more under construction, which will be producing CO₂ for decades to come and where CCS is currently their only option for decreasing emissions.

CCS serves to illustrate how the concepts of non-renewable resources and reserves can be meaningfully applied to some mitigation options. The McKelvey box, with its various modifications, can be used to represent storage reserves and resources and the CO₂ mitigation potential of geological storage capacity. Terms such as operational, contingent and prospective capacity can be readily and usefully incorporated into the scheme. Together they offer the opportunity to standardize the assessment and potential of CO₂ storage resources and reserves and its contribution to achieving net zero. Much the same approach could be taken to underground storage of hydrogen.

Hydrogen will be important to a clean energy future. Natural hydrogen resources exist in various geological settings, but there are few if any fully assessed reserves. It has been suggested that natural hydrogen has the potential to be a major disruption to the future global energy system. Initially, hydrogen derived from steam reforming of natural gas (or gasification of coal) with CCS as an essential adjunct will provide the starting point for a large-scale hydrogen economy, given the abundance of gas reserves and the reach and know-how of the gas and LNG industry. Longer term, electrolysis using abundant low-cost renewable energy will become the dominant source of hydrogen. Are there likely to be resource and reserve constraints on this progression? Underground geological storage of hydrogen will become increasingly important.

Access to critical minerals in quantities sufficient to meet the massive increase in renewable energy required between now and 2050 is essential. Minerals such as copper are also a vital component not only of wind turbines but also of the new energy networks that will be required. Recycling and the development of a circular economy approach will meet some of that need, but a major effort is required to recycle and especially to find new critical and key mineral resources and define adequate critical mineral reserves, including those that might be found in existing mine waste.

Development and deployment of renewable energy on a massive scale will be essential to the future energy mix. This transition requires consideration of resource-reserve issues including critical minerals such as rare earths and platinum used in wind turbines and key minerals such as copper in order to enhance the energy networks. A range of issues such as social license and environmental issues impact on the availability of land for large-scale wind turbine deployment. In the USA, the Wind Energy Technologies Office (WETO) has usefully formalised the stages of developing wind project within a framework which echoes that used for non-renewable resources and reserves.

Keeping the future rise of the global temperature to 1.5 °C or less will require not only deep cuts in emissions but also removal of CO₂ from the atmosphere using a range of technologies. Direct air capture (DACCS) is an important option, but will require access to abundant low-cost renewable energy, land availability, CO₂ storage resources and increased need for critical and key minerals.

Discovering, assessing and extracting non-renewable resources and reserves will be an essential part of the clean energy transition. Fossil fuels, uranium, storage space for CO₂ and H₂ (natural, blue or green), critical minerals for solar panels or wind turbines, key mineral such as copper for new electricity distribution, the land area for large-scale wind or solar farms will all be needed to achieve net zero.

Mineral and energy resource discovery and ensuring reserve availability is a long-term progression. It has provided the basis for sensible and considered decisions by industry, governments and communities. Similarly it is vital to ensure the ready availability of the critical and key minerals required for renewable energy, increased access to low carbon fuels, notably hydrogen, and to geological storage resources for hydrogen and captured CO₂ if we are to achieve net zero by 2050, and preferably sooner.

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Declarations

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References

Barker M, Mendes da Costa V (2018) The CarbonNet project and its regulatory journey - an overview & key learnings. The APPEA Journal 63:163–191

Benson S, Bickle M, Boon M, Cook PJ, Haese R, Kurtev K, Matthai S, Neufeld J, Watson M, Winkelman G (2018) The GeoCQuest project: quantifying the impact of heterogeneity on CO2 migration and trapping in saline aquifers 14th international conference on greenhouse gas control technologies. SSRN Electron J. https://doi.org/10.2139/ssrn.3365814

Boreham CJ et al (2021) Hydrogen in Australian natural gas: occurrences, sources and resources. The APPEA Journal 63:163–191

COAG (2019) Australia’s national hydrogen strategy. Commonwealth of Australia

Cook PJ, Arranz AM (2020) Negative emissions in Australia. Report on 2019 roundtable discussions. University of Melbourne, 44p

Cook PJ (2006) Site characterization. In: International symposium on site characterization for CO2 geological storage, 20–22 March 2006, Berkeley, California, USA. Lawrence Berkeley National Laboratory (LBNL), pp 3–5

Cook PJ (2012). Clean energy climate and carbon. CSIRO Press Melbourne 215p

CSIRO (2020) National hydrogen roadmap https://www.csiro.au/-/media/Do-Business/Files/Futures/18-00314_EN_National_Hydrogen_2020.pdf

CSLF (2007) Estimation of CO2 storage capacity in geological media - phase II. Prepared by the Task Force on CO2 Storage Capacity Estimation for the Technical Group (TG) of the Carbon Sequestration Leadership Forum (CSLF) (Bachu, S, Bonijoly, D, Bradshaw, J, Burruss, R, Christensen, N P, Holloway, S and Mathiassen, O M). http://www.csforum.org/documents/PhaseIII_ReportStorageCapacityMeasurementTaskForce.pdf

CSLF (2021) Accelerating carbon capture, utilisation and storage. Carbon sequestration technology roadmap. Clean Energy Ministerial Meeting June 2021 https://www.cleanenergymisterial.org

Department of Industry, Science, Energy, and Resources (2021) Australian energy statistics, table P (consumption and production of coal), Commonwealth of Australia: Australian Government. URL: https://www.energy.gov.au/government-priorities/energy-data.australian-energy-statistics

Finkel A (2018) Hydrogen for Australia’s future, Commonwealth of Australia https://www.chiefscientist.gov.au/sites/default/files/HydrogenCOAGWhitePaper_WEB.pdf

Furrea KA, Eikenb O, Alnesa H, Vevatnea JN, Kierer AF (2017) 20 years of monitoring CO2-injection at Sleipner. Energy Procedia 114(2017):3916–3926

Fuss S et al (2018) Negative emissions—part 2: costs, potentials and side effects. Environ Res Lett 13(6) https://doi.org/10.1088/1748-9326/aabf9f

GCCSI (2021) Global status of CCS 2021. Global CCS Institute, Melbourne 80p https://www.globalccsinstitute.com/resources/global-status-report

Geological Society of London (2022) Natural hydrogen: the new frontier. Geoscientist Spring 2022, pp 32–37

Hitch M, Dipple GM (2012) Economic feasibility and sensitivity analysis of integrating industrial-scale mineral carbonation into mining operations. Miner Eng 39:268–275. https://doi.org/10.1016/j.mineg.2012.07.007

Hubbert MK (1956) Nuclear energy and the fossil fuels. Technical report publication no. 95. Shell Development Company, Exploration and Production Research Division, Houston, Texas

Hubbert MK (1962) Energy resources. National Academy of Sciences, Publication 1000-D

Hydrogen Strategy Group (2018) Hydrogen for Australia’s future. Report for COAG. Australian Government Canberra 59p

IEA (2021a) Coal analysis and forecast to 2024. International Energy Agency, Paris, p 125p

IEA (2021b) Oil market report December 2021b https://www.iea.org/reports/oil-market-report-december-2021

IEA (2021c) Gas market report, Q3–2021c https://www.iea.org/reports/gas-market-report-q3-2021

Inman M (2016) The oracle of oil. Norton, New York, p 419p

IPCC (2005) IPCC special report on carbon dioxide capture and storage. In: Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds) Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York

IPCC (2022) Climate change 2022: impacts adaptation and vulnerability. Sixth assessment report https://www.ipcc.ch/report/ar6/wg2/

IRENA (2020) Green hydrogen: a guide to policy making. International Renewable Energy Agency, Abu Dhabi https://www.irena.org

Kaldi JG, Gibson-Poole CM (Eds) (2008) Storage capacity estimation, site selection and characterisation for CO2 storage projects CO2CRC report no: RPT08–1001 52p

Kleijne K, Hanssen SF, Dintner L, Huijbregts MAJ, van Zelm R, de Jong P, v d Schuur MF (2012) Limits to Paris compatibility of Australia’s national hydrogen strategy. Clean Energy Ministerial Meeting June 2021 https://www.cleanenergymisterial.org

Knoema (2021) Reserves of natural gas reserves by country 2021 https://knoema.com/atlas/topics/Energy/Gas/Reserves

Le Quere C et al (2018) Global carbon budget 2017 articles. Earth Syst Sci Data 10:405–448, https://essd.copernicus.org/articles/10/405/2018/180815.1088/

McKelvey VE (1972) Mineral resource estimates and public policy. Am Sci 60(1):32–40 https://www.jstor.org/stable/27842943
Minx JC et al (2019) Negative emissions—part 1: research landscape and synthesis. Environ Res Lett 13(6). https://doi.org/10.1088/1748-9326/aabf9b

National Academies of Sciences, Engineering, and Medicine (2021) Accelerating decarbonization of the U.S. energy system. The National Academies Press, Washington, DC. https://doi.org/10.17226/25932.

National Academy of Sciences (2019) Negative emissions technologies and reliable sequestration: a research agenda. The National Academies Press, Washington, DC. https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

Ng E (2022) Climate change: technology key to decarbonisation of Chinese steel mills. South China Morning Post 20 Feb 2022

Peacock B (2022) Natural hydrogen exploration ‘boom’ snaps up one third of South Australia. PV Magazine February 2022 https://www.pv-magazine.com/2022/02/02/natural-hydrogen-explo ration-boom-snaps-up-one-third-of-south-australia/

Price LK (1933) Inflammable gases occluded in the pre-Palaeozoic rocks of South Australia. Trans R Soc S Aust 57:42–47

Sanna A, Ubu M, Caramanna G, Kuusik R, Maroto-Vale MM (2014) A review of mineral carbonation technologies to sequester CO₂. Chem Soc Rev 43:8049 https://pubs.rsc.org/en/content/articlelanding/2014/CS/C4CS00035H

Sinding-Larsen R, Wellmer FW (Eds) (2012) Non-renewable resource issues: geoscientific and societal challenges (International Year of Planet Earth) Springer (ISBN 978–90–481–8678–2)

SPE (2007) Petroleum resources management system. Oil and Gas Reserves Committee Society of Petroleum Engineers

SPE (2011) Guidelines for application of the petroleum resources management https://www.spe.org/industry/docs/PRMS_Guidelines_Nov2011.pdf

SPE (2018) Guidelines for application of the petroleum resources management system https://www.spe.org/en/industry/petroleum-resources-management-system-2018

UNECE (1997) United Nations International Framework Classification for reserves/resources https://unece.org/DAM/energy/se/pdfs/unfcscl ENERGY.WP1.R.70_e.pdf

UNECE (2021a) UNFC and sustainable resource management https://unece.org/sustainable-energy/unfc-and-sustainable-resource-management

UNECE (2021b) Report of the expert group on resource management, Committee on Sustainable Energy. Economic Commission for Europe https://unece.org/sites/default/files/2021b-05/ECEREnergy_GE.3_2021_2_EGRM-12_report.pdf

United Nations (2021) Policy brief: transforming extractive industries for sustainable development. https://www.un.org/sites/un2.un.org/files/sg_policy_brief_extractives.pdf

US Department of Energy (2022) Wind resource assessment and characterisation. Wind Energy Technologies Office, Washington https://www.energy.gov/eere/wind/wind-resource-assessment-and-characterization

Weller FW, Hagelüken C (2015) The feedback control cycle of mineral supply, increase of raw material efficiency, and sustainable development. Minerals 5:815–836

Wellmer FW (2008) Reserves and resources of the geosphere, terms so often misunderstood. Is the life index of reserves of natural resources a guide to the future? Z dt Ges Geowiss 159/4:575–590

Wellmer FW, Dalheimer M (2012) The feedback control cycle as regulator of past and future mineral supply. Mineral Deposita 47:713–729

Wellmer FW, Scholz R (2015) The right to know the geopotential of minerals for ensuring food supply security—the case of phosphorus. J Ind Ecol 19(1):3–5

Wellmer FW, Scholz R (2017) Peak minerals: what can we learn from the history of mineral economics and the cases of gold and phosphorus? Miner Econ. https://doi.org/10.1007/s13563-016-0094-3

Zgonnik V (2020) The occurrence and geoscience of natural hydrogen: a comprehensive review. Earth Sci Rev 203:103–140. https://doi. org/10.1016/j.earscirev.2020.103140

IPCC (2018) Global warming of 1.5°C. In: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf

Realmont G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle AC, Tavoni M (2019) An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10(1):1–12

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