Resource depletion, peak minerals and the implications for sustainable resource management[#]

Prior, T.[a*], Giurco, D.[a], Mudd, G.[b], Mason, L.[a] and Behrisch, J.[a]

[a] Institute for Sustainable Futures, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia.

[b] Environmental Engineering, Department of Civil Engineering, Monash University, Wellington Road, Clayton, VIC 3800, Australia

Abstract

Today's global society is economically, socially and culturally dependent on minerals and metals. Production patterns are driven by the consumption of mineral resources, which continues to rise in middle- to high-income countries, and is reaching unprecedented levels in low-income countries, whose appetite for the world's minerals reflects their rapid development. However, minerals are by definition 'non-renewable' in the traditional sense of the term, and their stocks are finite. This raises the spectre of 'peak minerals' – the time at which maximum (peak) production occurs from terrestrial ores and prompts a focus on what role ocean resources, recycling and dematerialisation will play in supplying metals in future.

Current rates of production and consumption are unsustainable. Whilst dematerialisation and recycling have developed, there is still a heavy reliance on primary processing of terrestrial ores. As the production peak approaches (and passes), understanding and monitoring the dynamics of peak minerals will become essential for informing and establishing mechanisms for sustainable global resource governance into the future. Taking a cross-scale approach, this paper explores the economic impacts of peak production, and how changes in the production profile might influence, or be influenced by, technological, environmental or social drivers. Specifically we examine the impacts of peak minerals in Australia, which is a major global minerals supplier.

Following a review of economic approaches to resource depletion, a new framework was developed to assess the changes in environmental and social impacts before and after peak production. This framework aims to encourage discussion of transitions in how such services can be provided in a future, more sustainable economy.

This research has profound implications for local and global sustainability of mineral and metal use. The focus on services is useful for encouraging discussion of transitions in how such services can be provided in a future more sustainable economy. The research also begins to address the question of how we approach the development of strategies to maximise value from mineral wealth over generations.

Introduction

Today's global society is economically, socially and culturally dependent on minerals and metals. Production patterns are driven by the consumption of mineral resources, which continues to rise in middle- to high-income countries, and is reaching unprecedented levels in low-income countries, whose appetite for the world's minerals reflects their rapid development (CRU International, 2001). However, minerals are by definition 'non-renewable' in the traditional sense of the term, and their stocks are finite.

Many authors have considered the issue of mineral depletion (for example, Tilton, 2003), but there is disagreement about the exact mechanism by which depletion may (or may not) occur (Gordon *et al.*, 2006; Tilton and Lagos, 2007; Young, 1992). Much of this debate centres around the question of whether rising commodity prices, driving technological

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[*] Corresponding author: timothy.prior@uts.edu.au, ph: +61295144956, fax: +61295144941

advancement in exploration, production and processing (WAIAC, 2000; Foran and Poldy, 2001), will compensate for falling primary resource stocks (Willett, 2002).

While lithographic stocks of minerals are unquestionably finite, at present Australian minerals are being produced at greater rates than at any time in history (Mudd, 2010; Giurco *et al.*, 2010; ABARE, 2009; Geoscience Australia, 2009). This paradox raises the prospect that traditional mineral supplies will eventually be exhausted (Giurco *et al.*, 2010). However, for most minerals physical depletion is not the primary determinant of a mineral's availability. Whilst a concern at the level of national and sub-national or regional economies (Maxwell and Guj, 2006; Willett, 2002), limitations resulting from social and environmental constraints and impacts are likely to result in economic scarcity well before physical depletion (Giurco *et al.*, 2010; Tilton, 2003; Mudd, 2010).

The social and environmental consequences of mining in Australia (and elsewhere) have to-date been externalised from the costs of production. To date, few empirical examinations of these important aspects of commodity production have been made with respect to physical or economic resource depletion (but see Mudd, 2009; Mudd, 2010). In this paper we show that as Australia approaches (and in some commodities, passes) peak mineral production, the social and environmental consequences of production increase to a point where their costs can no longer be externalised. Here we present a depletion model based on the growing social and environmental consequences of mining in Australia. Using data reported by the Australian mining industry, and collected from industry by the Australian Government (Australian Bureau of Agriculture and Resource Economics, Geoscience Australia and the Australian Bureau of Statistics) we demonstrate the importance of incorporating "externalities" into a calculation of the costs of production when considering the future sustainability of the industry (for example, Tilton, 2003).

Mineral depletion in Australia

Mineral resources are finite in a geological sense. Given continuing extraction in Australia, the mineral endowment will ultimately become depleted well into the future without a considered resource management strategy. However, of more immediate importance than physical depletion *per se* is the changing cost and impact profile of resource extraction in Australia, which is likely to influence the economic viability of mineral resource extraction and processing for many of Australia's most important commodity exports.

Giurco *et al.* (2009) note that the debate about how to frame resource depletion is ongoing. Tilton and Lagos (2007) suggest using a fixed stock paradigm (that there is a given quantity of a resource available in the Earth) is a misleading indicator of resource availability, and that an opportunity cost paradigm (that suggests a useable resource quantity is better represented by price and the opportunity cost of using the resource) gives a better picture of resource depletion and availability. They argue that while minerals such as copper may become scarce, and thus more expensive, such minerals may also become more available. This is the case because technology and price have the capacity to move a resource from its base, to a reserve and into the stock in use, consequently increasing the amount in use or as waste. This will drive the development of new technologies that support the high returns on investment. Tilton and Lagos conclude that the resource base can be the only fixed stock, and there "…is no way to know the availability of copper decades in advance" (2007, p 23).

Since the late 1990s there has been little effort focussed on developing depletion models for mineral resources. This can firstly be attributed to the general expectations within the industry that knowledge and technology will address any shortfalls in production (*e.g.* the ability to maintain high production output even when ore grades are declining). Secondly, the historical record of growing global resource quantities with the globalisation of mining has made physical constraints at the national level less important beside considerations of how future needs will be supplied (Willett 2002, Tilton 1996). Many analysts conclude that depleted reserves could be effectively extended through regulatory interventions by government or private entities, or by higher real prices, leading for example to technology development that would allow profitable access to lower grade ores.

Gordon and colleagues (2006) contend that the relative proportions of minerals in the lithosphere, in use, and in waste deposits, are a useful indicator of how scarce a particular resource will be under such circumstances. They identify that a steady flow of mineral resources from virgin ores to waste is difficult to justify. The technology trend predicted by Gordon and colleagues is one that tends towards high levels of recycling and reuse, and substitution of appropriate alternatives where minerals are locked into use phases or whose useful qualities are dissipated by their use in particular applications (Gordon *et al*., 2006).

An example of this trend in practice can be seen in Japan, where product stewardship and extended producer responsibility initiatives are creating an increasingly large and progressively inexpensive pool of resources for use in new product lines. Metals (including copper, steel and aluminium) that may have originally come from a range of other continents are effectively captured by Japan's vertically integrated production, disassembly, recycling and reuse system (Department of Trade and Industry (UK), 2005).

The contrast between the fixed stock and opportunity cost paradigms align to some degree with technological pessimism versus technological optimism (see for example Foran and Poldy, 2001). Willets (2002, p 12) suggests that "the key issue is the appropriateness of the optimistic view of new discoveries and technological progress. The optimists, like the pessimists, have not provided adequate data to support their position, although history is on the side of the optimists."

In any case, most minerals and metals are unlikely to run out (unlike oil or coal, or minerals used in a dissipative fashion like phosphorous) in the near future. Metals are inherently recyclable (and are more readily recoverable from end uses where the metal is used in a pure form and not dissipated) and also accessible at a range of grades. However, although few metals are currently facing physical depletion, they are becoming harder to obtain, and the energy, environmental and social cost of acquiring them could constrain future production and usage.

Mineral depletion signifies a need for transition

As early as 1945, Harold Williamson described the role of 'prophesies of scarcity' in generating a conservation response for both renewable and non-renewable resources (Williamson, 1945). He concluded that concepts of resource exhaustion are triggers for thinking about how a particular resource is managed. This has been explored in some depth where renewable resources are concerned, most notably with respect to forestry and fisheries (for example, Castilla and Defeo, 2005; Costanza *et al.*, 1999). However the depletion of non-renewable resources, such as minerals, has not received the same amount of attention. This paper seeks to focus beyond scarcity *per se*, to a deeper understanding of the impacts of mining and processing 'harder' (more complex or difficult to access) ores as a basis for framing a considered response in terms of economic scarcity or depletion.

The most popular contemporary focus for mineral resource depletion is for oil (or petroleum) resources. In 1956, oil geologist M. M. King Hubbert famously predicted that conventional oil production from the lower 48 (mainland) states of the United States would peak by 1970 and then enter a terminal decline, shown in Figure 1 (see Hubbert, 1956). This model was subsequently proven to be accurate (although the peak year was 1971). Hubbert also predicted that global conventional oil production would peak around the year 2000, which has proved to be slightly out given that conventional oil production has only plateaued recently (see Bardi, 2005). This phenomenon is now commonly referred to as 'Peak Oil', with peak production curves known as 'Hubbert Curves'.

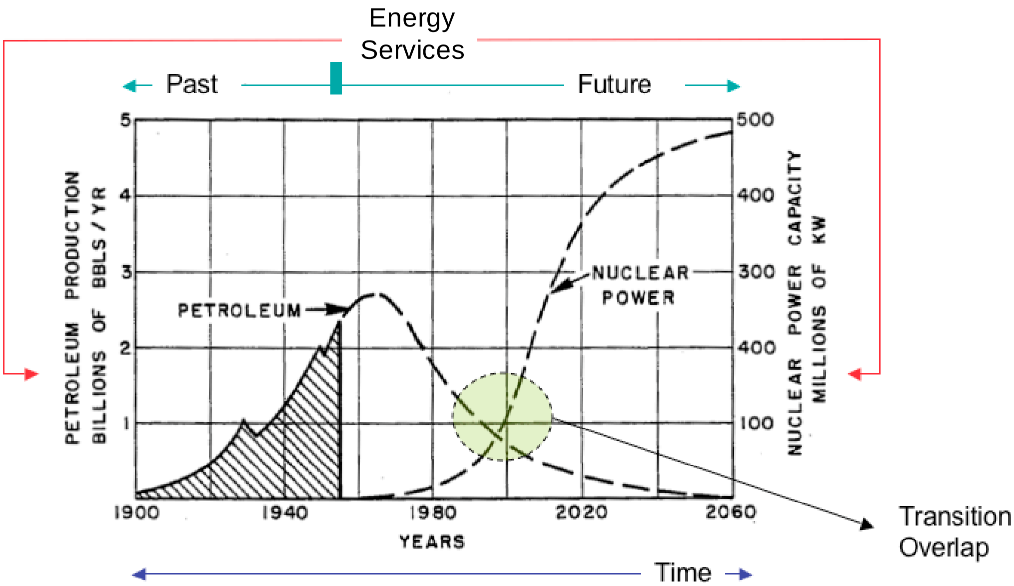


Figure 1: Hubbert's prediction for peak oil production in the lower 48 states of the United States and the energy transition to nuclear power (adapted from Hubbert, 1956)

Over the past decade there has been a rapidly growing global movement analysing and debating Peak Oil. The collective work has helped to reach a broad consensus that global Peak Oil will happen, though timing of the peak is still contested. The use of the peak metaphor for resource management is useful for several reasons. In addition to representing an approximate model for predicting annual production, it introduces a focus on the services provided by the resource – in this case the energy services provided by oil – and highlights the need to provide such services by different means post-peak to avoid disruptions to the economy. In this context, Hubbert anticipates a rise of nuclear power to provide energy services post oil peak (Figure 1). Although the need to plan an energy transition was Hubbert's primary goal in conducting his work, this objective has largely been overlooked because greater focus has been directed at examining when the peak might occur.

Likewise, a consideration of practical (non-energy) mineral exhaustion is useful in the same context (Giurco *et al.*, 2010). Much of the evidence to date suggests Australian minerals are unlikely to run out in the near future (Mudd, 2010; Lambert, 2010), but are becoming more difficult to obtain and produce the quantities (and quality) of product demanded by the market. In order to maintain the services that metals provide to our society, and to do so in a sustainable fashion, it is important to anticipate the nature of mineral. Here we propose a model of mineral depletion that considers the growing environmental and social costs of production as key limiting factors. We argue that calculations of the resource base and the actual peak in production are secondary to the need for planning a transition in the way mineral services are provided in the future. Eventually, the internalisation of environmental and social costs will reduce our ability to provide services from these resources in future, because current mining practices will become uneconomic.

Peak minerals: a practical depletion metaphor?

Rising fuel costs associated with peak oil provide some sense of the complexities and interdependencies that make planned transitions between services provided by minerals very important. Whilst peak oil will directly affect the minerals industry through rising fuel costs, it also offers a useful conceptual model for understanding the impact of going from 'easier and cheaper' to 'complex and expensive' resource processing, and critically, to planning a transition to new ways of providing energy services. This paper establishes a conceptual model of 'peak minerals' as a powerful tool for communicating the cross scale impacts (*i.e.* local, national, global) of 'complex and expensive' processing with respect to economic, social and environmental issues.

As with energy services provided by oil, the peak minerals paradigm helps to foment discussion anout the ultimate use of minerals and metals. With an understanding of when processing becomes 'very complex and expensive', it then focuses on what transitions can

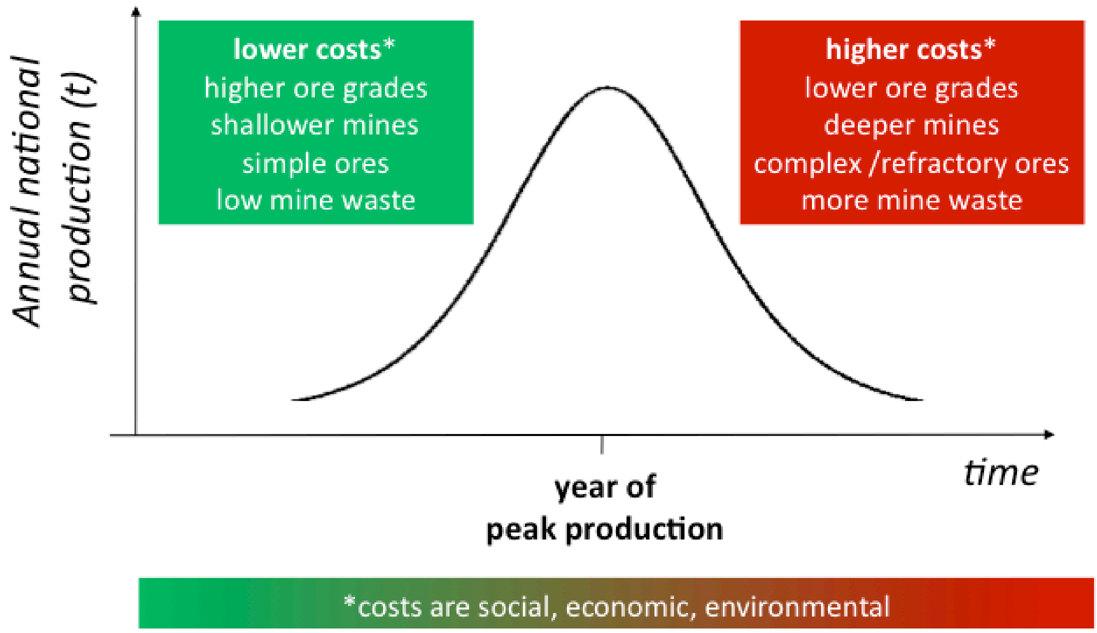


Figure 2: Conceptual model of peak minerals; illustrating higher costs post-peak.

deliver the same useful functions that minerals and metals perform (*e.g.* ocean-based resources, greater recycling or reprocessing, dematerialisation, substitution with other materials) and which enabling technologies and policies can support these functions.

Tilton points out that "environmental and other social costs incurred in the extraction, processing, and use of mineral commodities might severely constrain their availability" (2003, p 83). These concerns are now realities in Australian mineral production, and can be supported by a range of company reported and government data. Ultimately, with continuing production, the characteristics of Australian ores are changing, and these changes are being reflected in a range of indicators. We present data indicating increasing environmental costs associated with changing ore grades, mine depth, waste rock, inputs (energy, water, labour and capital), and instances of growing social costs associated with regional development and quality of life in mining regions in Australia.

Ore grades are declining

A crucial determinant of the peak minerals phenomenon is declining grade and quality – that is, the concentration of a particular mineral or metal (or metals) being mined, as well as the quality of the ore with respect to processing (*e.g.* fine or coarse grained ore, mineralogy, impurities such as arsenic or mercury, *etc*). Production of Australian rare earth oxides provides a case in point. While the nation has a reasonably large economic demonstrated resource for these commodities, a significant proportion is locked in the monazite component of the heavy mineral sand deposits in which they are found. These deposits are currently sub-economic because of the costs involved in the proper disposal of thorium and uranium present in the monazite (Geoscience Australia, 2009).

Recently compiled historical data sets (Mudd, 2009) show that long-term trends for copper, gold, nickel, lead, silver and zinc ore grades in Australia are declining (Figure 3). In many cases, high quality ores have largely been exploited, and ores that require more complex processing remain. As such, falling ore grades are a precursor to a range of other environmental and social impacts. For example, falling grades prompt exploration and increasing mine depth or surface expansion; more inputs (energy, water, labour, capital) are required to extract and process larger ore throughput to yield the same unit of output; more waste (waste rock, tailings) is produced.

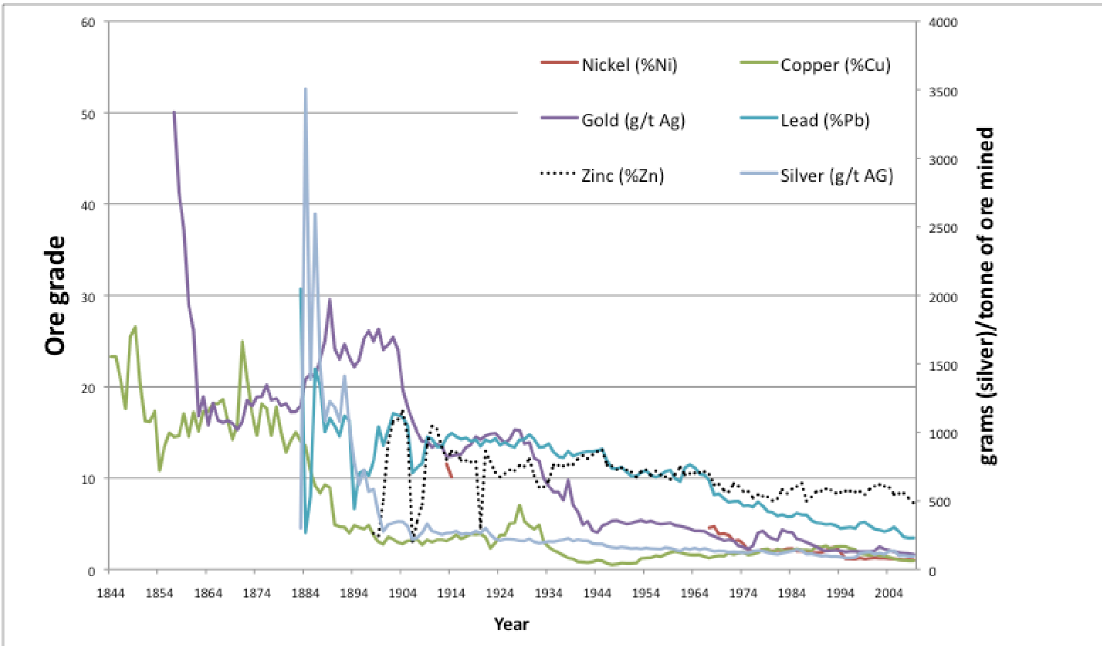


Figure 3: Ore grades are steadily declining for a variety of base and precious metals in Australia

Case study: Nickel

The changing nature of nickel deposits provides a good example of how changing ore quality has influenced the economic viability of nickel operations. Mudd (2009) provides a brief history of nickel production in Australia. Nickel was historically mined from nickel sulphide complexes, but large nickel deposits also exist in more difficult lateritic ores. In the early 1990s, high pressure acid leaching (or HPAL) was introduced to Australian nickel mining, and promoted as a “workable technology offering low capital and unit production costs” (Mudd, 2009, p 107). HPAL uses titanium-lined autoclaves at high temperature (245 to 270°C) and pressure (up to 5.4 MPa) to liberate the diffuse nickel from the laterite ore. The metal-rich solutions are then processed through conventional hydrometallurgical techniques.

A major attraction of the HPAL technology was its application for production from nickel laterite ore resources, which are considerably more abundant than sulfide deposits in Australia. Larger scales of production were believed to push down unit costs of production. A minor nickel laterite boom occurred as a consequence, and three new Nickel production/processing projects were quickly developed at Cawse, Bulong and Murrin Murrin in Western Australia (where 99% of Australia’s nickel is produced). Although Cawse and Bulong yielded quick financial windfalls, they were technical failures and closed. The Murrin Murrin project survived, but production must be monitored constantly to ensure financial viability. The lower-grade nickel laterite ores were ultimately too expensive to produce. Mudd (2010, p 110) points out that “the ability to consider refractory or ‘impurity-rich’ ores as an economic mineral resource will continue to be a function of technology, economics and environmental conditions".

Energy costs and other inputs are increasing

As ore quality declines, the energy requirements and pollution burdens increase substantially as companies maintain production output. A recent analysis of the carbon intensity of gold production (*i.e.* t $CO_{2\text{-}e}$/kg Au) *versus* gold ore grade (Figure 4 – Mudd, 2010) shows not only the effect of primary electricity source on overall carbon intensity but also that as ore grades decline the energy used, and carbon intensity begins to increase significantly. The scatter is most likely due to the varying configurations of gold mines and mills (*e.g.* underground/open cut, several mines, heap leach *versus* carbon-in-pulp, relative contribution of energy sources, project age, depth, ore types, *etc*.).

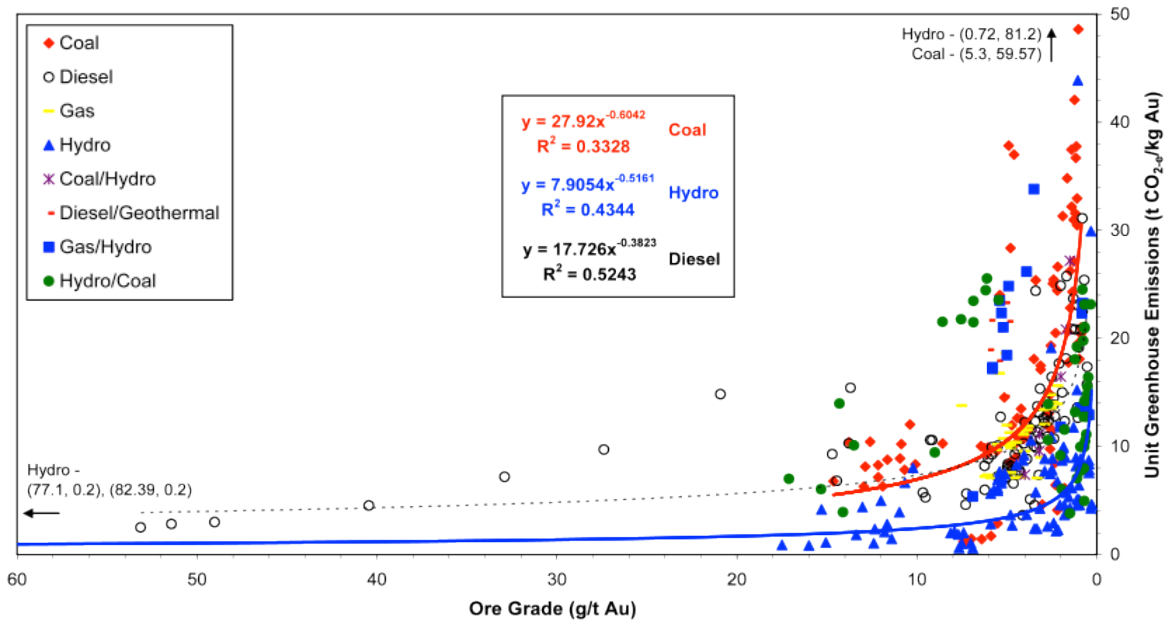


Figure 4: Carbon intensity of Australian gold production *versus* ore grade (Mudd, 2007b; Mudd, 2009; Mudd, 2010 including unpublished data).

The Australian Productivity Commission has demonstrated that as ore grades have fallen, and high-grade deposits have been depleted in Australia, capital and labour inputs into the mining industry have risen (Topp *et al.*, 2008). The authors point out that when the quality of the resource input falls, other inputs must be used more intensely to compensate. They also suggest that high commodity prices exaggerate the intensity of capital and labour inputs because higher prices make it economically viable to continue to mine deposits that would otherwise have become uneconomic through resource depletion (Topp *et al.*, 2008). They demonstrate that although inputs of capital and labour continue to increase, multifactor productivity (MFP) in the Australian mining industry has fallen sharply since the beginning of the most recent mining boom (around 2000), which has largely been driven by huge demand from China and India as they undergo rapid industrialisation (Figure 5).

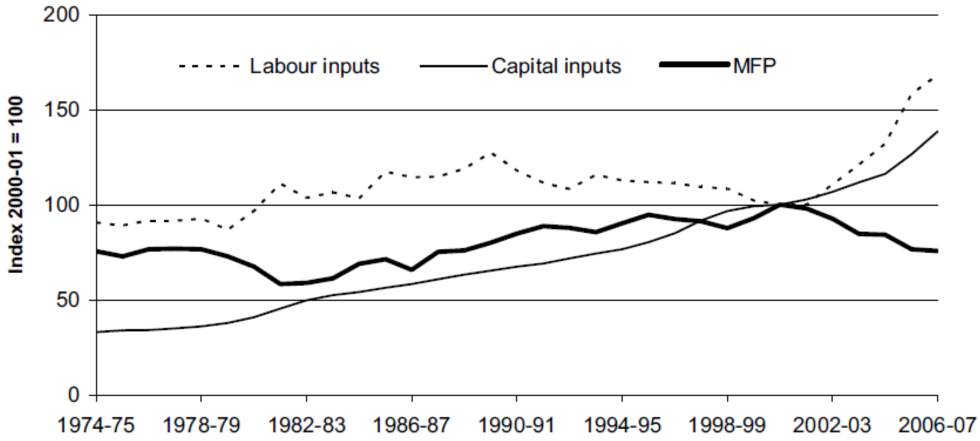


Figure 5: Capital and labour inputs to the mining industry have increased dramatically since 2000, but multifactor productivity (MFP) has declined.

Water for processing ores is also a limitation on production capacity, especially for processing techniques like acid heap leaching in copper recovery and high pressure acid leaching in the processing of nickel laterite ores, where large quantities of water are used (Mudd, 2010). However, obtaining accurate data on water use is difficult given reporting mechanisms are rudimentary, so it is impossible to make large scale analyses or claims regarding increases or declines in water use (Mudd, 2009). Water use varies at the mine level, across companies and across commodities. An individual mine can show highly variable water consumption, or unbelievably low consumption – depending on how the mine operator measures their mine's consumption. Gold production is regularly cited as having the greatest embodied water content of any Australian mineral commodity (Mudd, 2007b; Norgate and Lovel, 2006).

At the mine level, success can be achieved in water efficiency, but with project expansion (as is occurring for most commodities), this is overshadowed by total consumption. In Australia (the driest inhabited continent), water is already fully allocated or used, and so mining companies have had to find alternatives or become more efficient. This can be achieved through water recycling, capital upgrades, or technological changes to allow processing of thickened tailings for example (Mudd, 2010). There is also the issue of water quality, which is not directly reported consistently as a part of water accounting by mine operators.

Pollution from mining is growing

As ore grades have fallen, and demand for Australian minerals has increased, Australian mining companies have sought to increase their economies of scale to allow production to meet demand, while reducing unit costs of production (Mudd, 2007a). Since the 1950s production has shifted from underground to open cut mining, allowing project scales to increase substantially (Mudd, 2010). However, along with mine expansion, pollution from waste rock, tailings and CO_2 (Figure 4) has increased dramatically.

As mine scale has increased, the by-product waste rock has risen sharply (Figure 6). Much of this waste rock is relatively benign (Mudd, 2010), and in instances where the waste is older, has been successfully reprocessed as the primarily mine site ore grade has fallen below historical levels (Mudd, 2007b). However, a large quantity of this rock has unknown characteristics, and is likely to present challenges for mine site rehabilitation when it contains harmful acid-forming sulfides, or when it is deposited close to human settlements or sensitive environments (Mudd, 2010). There are currently no regulations for consistent mine site reporting of waste rock quantities or qualities (Mudd, 2010), so figures reported here are indicative only.

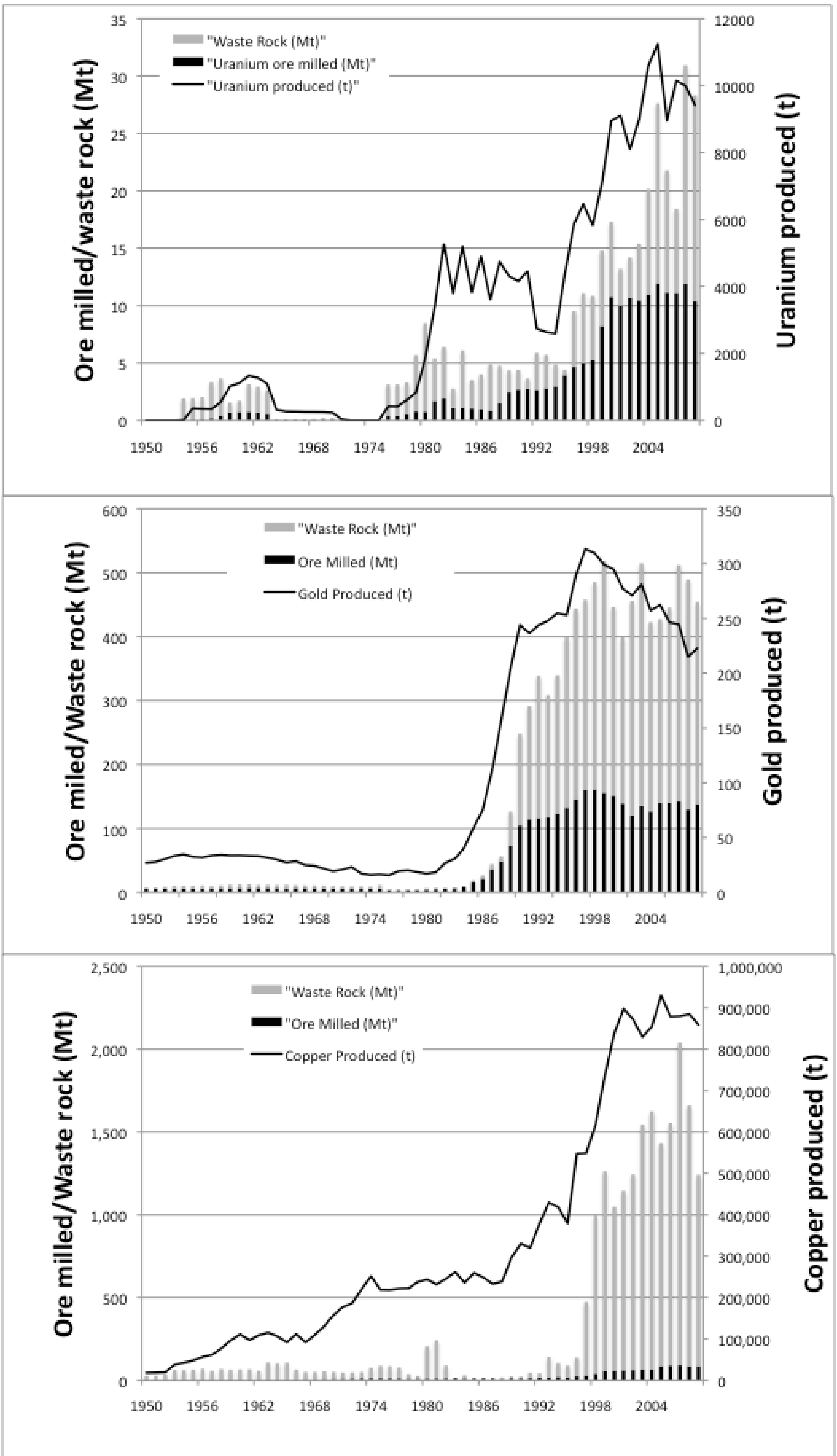


Figure 6: The relative quantity of waste rock to ore milled for a) uranium, b) gold, and c) copper, has increased dramatically in the last 20 years. Production in each case has fallen in the last decade.

As noted above, gold is perhaps the most water-hungry production process in Australia, using around 250 kL/kg of gold produced (Norgate and Lovel, 2006). Mudd (2007b) shows that water consumption in Australian gold production has increased with falling ore grades (Figure 7a). At the same time, the consumption of cyanide has also increased (Figure 7b) – and cyanide use is now a key indicator of a mine's environmental sustainability, as well as being an important `financial operating cost (Mudd, 2007b). Mudd points out that "both tailings and waste rock have the potential to become major point sources of listed pollutants such as cyanide and metals" (2010, p 112; see also Csagoly, 2000).

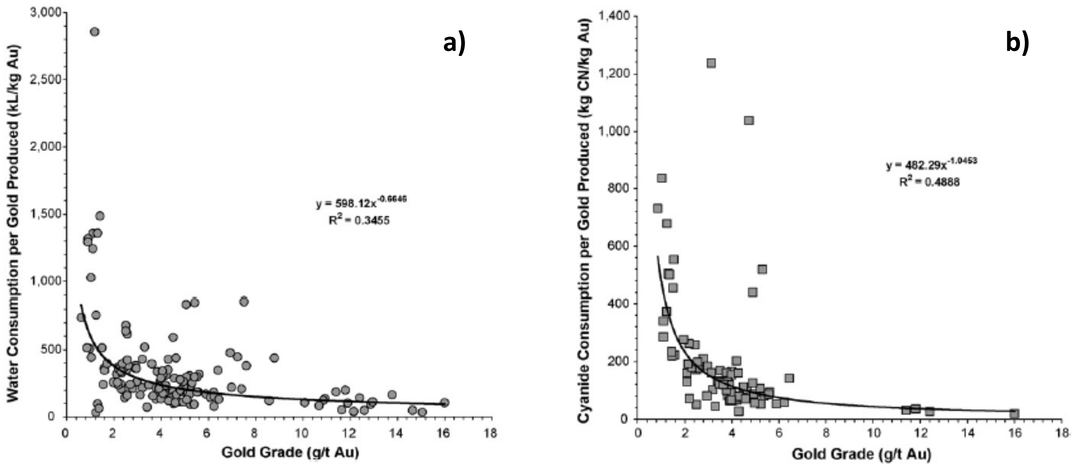


Figure 7: Water consumption (a), and cyanide consumption (b) in Australian gold production (from Mudd, 2007b)

Mine site rehabilitation, including addressing tailings and drainage issues, has become a progressively more important component of mining operations and mine feasibility planning. However, adequate rehabilitation is often limited by the technology available at the time of the mine's development, and the implementation new technologies at closure. For example, historical engineering principles of unsaturated flow dynamics are still evident at many currently operating mines in Australia, even though there are cases where these technologies have not prevented environmental degradation. In the 1980s, the Commonwealth Government of Australia spent AUD 25 million in the rehabilitation of the former Rum Jungle mining field. Even so, as recently as 2007, the adjacent East Finniss River was still heavily polluted with acid mine drainage leaching from rehabilitated waste rock dumps (Mudd, 2010).

Growing social pressures leading to higher operating costs

The social landscape surrounding the mining and minerals industry is steadily changing. With increasing environmental awareness during the 1970s and 80s, fortified by several significant environmental incidents (Hamann, 2003; Warhurst and Mitchell, 2000), public concerns about mining operations have broadened and increased (Hamann, 2003; Jenkins and Yakovlova, 2006). Changing social perceptions, and solidified social will has also encouraged greater regulatory scrutiny of corporate behaviour and responsibility (Solomon *et al.*, 2008; Warhurst and Mitchell, 2000), much of which has occurred through mining industry self-regulation (Brereton, 2003) instead of formal governance arrangements.

In Australia, land use conflict, near-neighbour impacts, mine closure and rehabilitation are contributing to higher social costs associated with mining. As miners seek to exploit new or more high-quality deposits, they are increasingly facing issues of land use and water use conflict. Coal mine expansion in the agriculturally-rich Liverpool Plains area of Central New South Wales has resulted in mine operators suffering considerable backlash from the community, who argue mining is disrupting agricultural production, and will contribute to a decline in Australia's future food security (Smith, 2009). In the Bowen Basin of Central Queensland, coal-seam gas exploitation is influencing the quality and quantity of water available for local fruit growers (Ivanova *et al.*, 2005). Although Hajkowicz and colleagues (2009) identify no evidence of negative associations between quality of life social indicators and the value of mineral production in Australia, they do demonstrate considerable anecdotal and empirical evidence of the negative impacts of mining, pointing out that regional benefits could mask localised disadvantage and inequality.

Nearest neighbour impacts vary with the mining operation. In interviews and workshops with community members in a high-density mining locality, Brereton and Forbes (2004) demonstrated that noise pollution, dust, water source pollution or conflict over water use, visual pollution (particularly in open-cut mining locations), and conflict over land use were the most important near neighbour impacts (Franks, 2007). While the community members recognised their dependence on mining as a foundation in the local economy, the cumulative impact of these mining side effects were sources of concern. The prospect of multiple mine closures would also cause considerable social and cultural upheaval in high-density mining areas (Franks *et al.*, 2009).

Environmental and social criticism, and changing public perceptions regarding the sustainability of mining practices is changing the way mining companies operate and interact with the community (Brigde, 2000; Hilson and Murck, 2000; Jenkins and Yakovlova, 2006). For an industry whose sustainability performance is increasingly scrutinised, concepts like 'corporate social responsibility' and 'social license to operate' are drawing serious consideration – from companies and communities alike. Where the mining industry does not take appropriate action to manage or mitigate these impacts, obtaining regulatory or community approval for mine establishment and expansion will be more difficult (Brereton and Forbes, 2004). An increase in socially cognisant regulation will affect production costs, and continue to shape the economic capacity of the Australian minerals industry into the future (ICMM, 2008).

Implications for sustainability and resource depletion

The peak minerals paradigm referred to in this paper splits access and utilisation of resources into 'cheap and easy' at one end of a time/production continuum, and expensive and difficult at the other. Economic, social and environmental costs change along this continuum, and understanding how these changes affect the mineral industry is paramount. The trends highlighted above, and considered in a mining sustainability context, suggest the depletion metaphor provided by the concept of peak minerals, has considerable traction for the Australian mining industry.

Importantly, the peak minerals paradigm acknowledges that both challenges *and* opportunities can be identified with regard to the sustainable management of mineral resources production and processing in Australia. Drawing from Hubbert's (1956) model of peak oil, understanding how to best manage a transition between 'cheap and easy' and 'expensive and difficult' production and processing, will influence Australia's ability to recognise and realise opportunities, and address the challenges that social and environmental impacts may present in the future. For this reason, the model's focus lies in two distinct areas: firstly, how environmental and social factors may affect future production and consumption of minerals and metals; and secondly, how environmental and social impacts of minerals processing may affect the long-term competitiveness of Australia's mineral industry.

Ultimately, it is not only resource exhaustion that is of concern with respect to sustainability, but the change in costs and impacts from processing 'easier, lower cost' ores prior to peak production for a given mineral, to 'more difficult, higher cost' ores post-peak. Understanding the environmental impacts associated with production and consumption of metals is imperative. The Mining Minerals and Sustainable Development project highlights that "connecting the production and use of mineral-related materials is critical to ensuring that the minerals sector contributes optimally to sustainable development" (2002).

The relationship between the economic value and environmental impact of stages in the mining production chain is illustrated in Figure 8. This shows that the initial stages are characterised by low value, but high environmental cost – resource extraction, and then processing and refining have the highest impacts respectively. By contrast, later stages like forming and assembly, cause less environmental impact and generate the majority of the economic value. While this example is drawn from a production chain associated with a mobile phone, the convex nature of the impact/value curve also applies more generally to other products. As the environmental impacts of resource extraction increase due to declining ore grades and increased waste, and hence the curves associated with the first two stages of the production chain become even steeper, it prompts the question: What business models could harness more economic value from extraction and processing, whilst reflecting the true costs of these production stages?

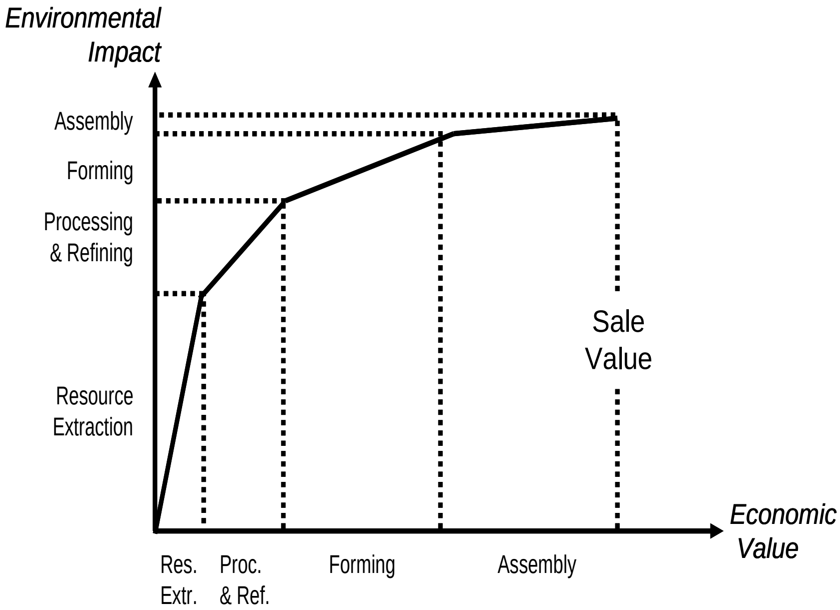


Figure 8: The relationship between added economic value and environmental impact at resource processing stages (after Clift and Wright, 2000).

Life Cycle Assessment (LCA) has also been used to understand and examine environmental impacts along the production chain. In the metals context, cradle to gate studies (for example, Giurco and Petrie, 2007; Norgate and Rankin, 2000; Norgate *et al.*, 2007) have been more prominent than cradle to grave studies because of the complexity of end uses to which metals are put, and the relative infancy of the recycling and reuse industries. Yellishetty and co-authors (2009) offer a review of issues relating to the application of LCA to minerals and metals.

In Australia, value from mining and mineral processing is derived in two ways: through the provision of metals (we value the properties and functionality of metal-containing goods and the services they provide), and from the money earned from their production (we value the ability to purchase goods and services with the revenue and royalties mining and metal processing provide).

With the onset of peak minerals, and the consequences these changes could bring, the mining industry must focus technological advancement efforts towards those processes that circumvent traditional lifecycle phases, and promote alternative technologies while at the same time minimising the social and environmental consequences of any ongoing mining activities that do continue (Figure 9). Most importantly, addressing these 'new' costs (new because these costs are only now being incorporated into the full costs of a mining operation) will contribute significantly to the industry's ability to remain economically viable.

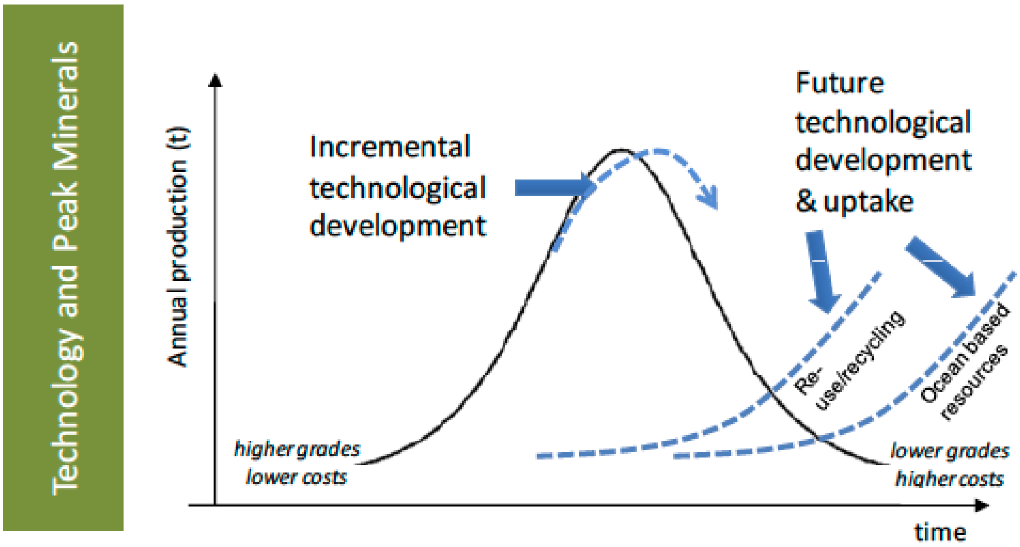


Figure 9: The traditional and future roles of technology in relation to the peak minerals paradigm (from Giurco *et al.*, 2010).

Understanding the true costs of mineral production, and re-valuing our mineral wealth ultimately influences our capacity to provide minerals and metals to market. As the economic, environmental and social costs of traditional minerals and metal production increase with peak minerals, in-use stocks will become more valuable. Our ability to realise this value through investment in recycling and re-processing technologies for existing products will yield significant national benefit – both in the contexts of ethical consumption and international competition from countries already acting to realise the value of in-use stocks. Revaluing these product-bound resources will also promote the necessity to realise end-use services for providing long-term access to minerals *and* national wealth without relying solely on traditional resource extraction.

Implications for mining industry productivity in Australia

Australia is known globally as a significant mineral producing country, and the economic, political, social and cultural importance of the sector drives a close societal reliance on the local minerals industry. This reliance may be a reflection of Australia's rich mineral resource base. Indeed, Australia's Economic Demonstrated Reserves (EDR) – known resources that are economically retrievable – of nickel, silver, uranium, zinc and lead, rank as the world's largest, with EDRs of copper and gold the second largest globally (Geoscience Australia, 2009). Australia has fully embraced this vast mineral endowment, and mineral production contributed almost $160 billion in export earnings to the Australian economy in 2009 (ABARE, 2009), 7.7% of total GDP.

Even though the Australian mining industry has contributed substantially to the nation's growth in income over the last decade, multifactor productivity in the industry has fallen during the same period (Figure 5) (Topp *et al.*, 2008). Multifactor productivity (MFP) is effectively an indicator of the efficiency by which combined inputs are converted into units of output. The major inputs in mining are the capital used to establish and operate a mine, the labour, and the natural resource that the mine exploits. Topp and colleagues point out that “because substantially increased usage of capital and labour has accompanied only a modest increase in output, multifactor productivity has fallen” (2008, p xv).

While mineral ores are obviously one of the primary inputs in the mining industry, their quality is not considered in standard measures of productivity (Topp *et al.*, 2008), which assume the resource input is of geographically and temporally homogenous quality. However, as we have demonstrated in this paper, the quality of resource inputs across a range of Australian commodities is by no means homogenous. Ore grades for each commodity vary across mines and mineral-rich regions, but average ore grades are falling (Mudd, 2009; Mudd, 2010).

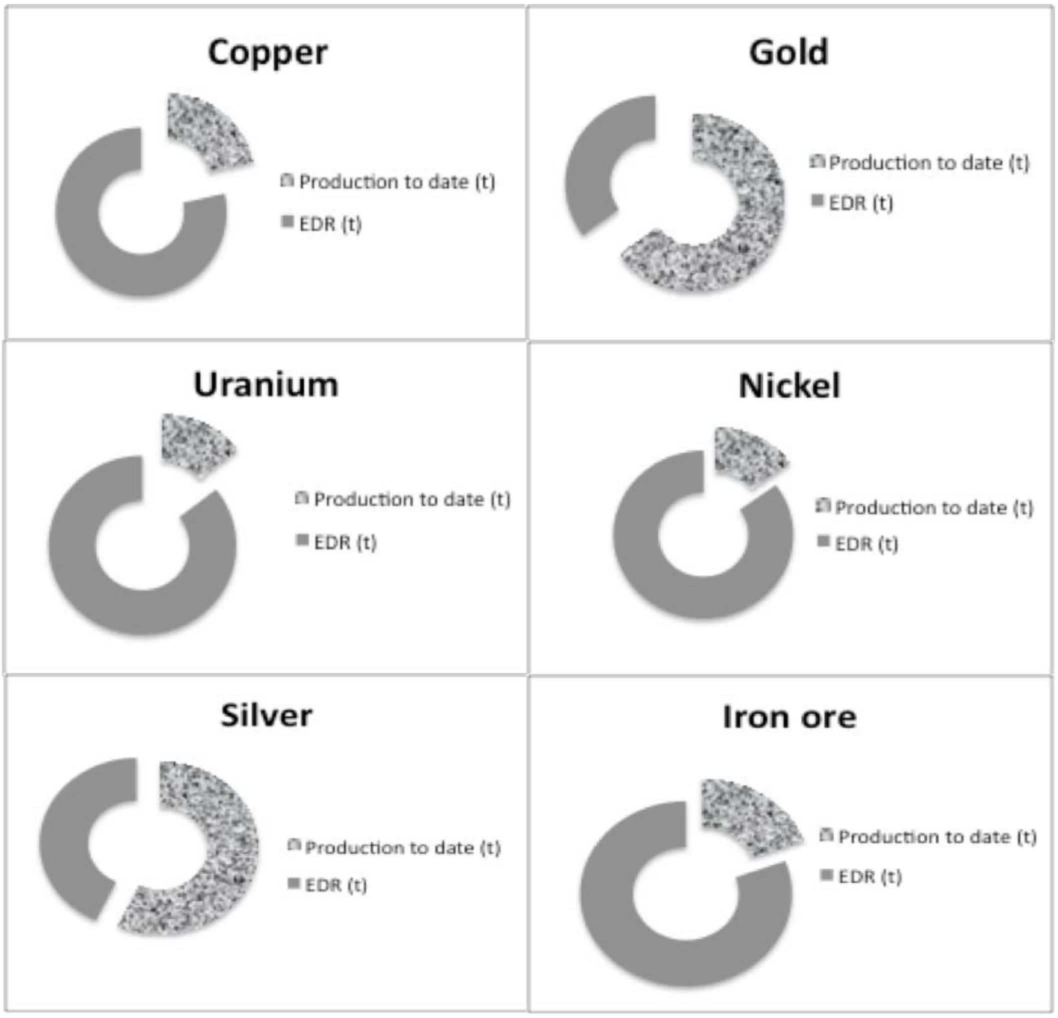


Figure 10: Production to date and economic demonstrated reserves for six major Australian export commodities (Geoscience Australia, 2009; Mudd, 2010 and unpublished data).

By their very nature, minerals are non-renewable (relative to human life expectancies), and primary stocks become depleted with ongoing extraction. Because miners initially favour high-grade, easily accessible deposits to benefit from the higher returns they yield, the remaining deposits are generally less accessible and contain lower-grade ores (though in Australia the discovery of the Olympic Dam complex represents a relatively recent high-grade/high quantity discovery). Falling ore grades and falling productivity likely signify the initial stages of mineral resource exhaustion in Australia (Topp *et al.*, 2008).

At present the economic demonstrated reserves (EDRs) of many of Australia’s key export minerals are high relative to cumulative production (Figure 10), and are still growing (Geoscience Australia, 2009) even though no major discoveries have been made in Australia in recent times (Mudd, 2009)[1]. As noted previously, production of most Australian commodities is rising with increasing demand, and higher commodity prices not only encourage greater exploitation of lower-grade ores (that may be uneconomic at lower prices) (Tilton, 2003), but also exaggerate EDRs of most commodities. Apart from several notable exceptions (*e.g.* silver, gold and zinc), EDRs for most of Australia's key mineral exports are substantially larger than the total units produced since production began (Figure 10).

It is informative to consider this point in the context of the cumulative supply curve (Figure 11) (Tilton and Skinner, 1987). Higher commodity prices, driven by consumer demand, allow exploitation of lower-grade ores, and so as prices rise, so does cumulative production (Figure 11a). However, many factors contribute to resource availability (for example, ore grade) such that situations arise where increases in cumulative supply can only be met by step-changes in commodity price (Tilton and Skinner, 1987). Geologic factors like ore grade, deposit size and location, influence the shape of the cumulative supply curve for a commodity, while factors like consumer demand determine the pace at which society moves along the curve. The cumulative supply curve can be used to demonstrate how resource availability may be affected by the increasing difficulty and expense of mining lower-grade ores in Australia.

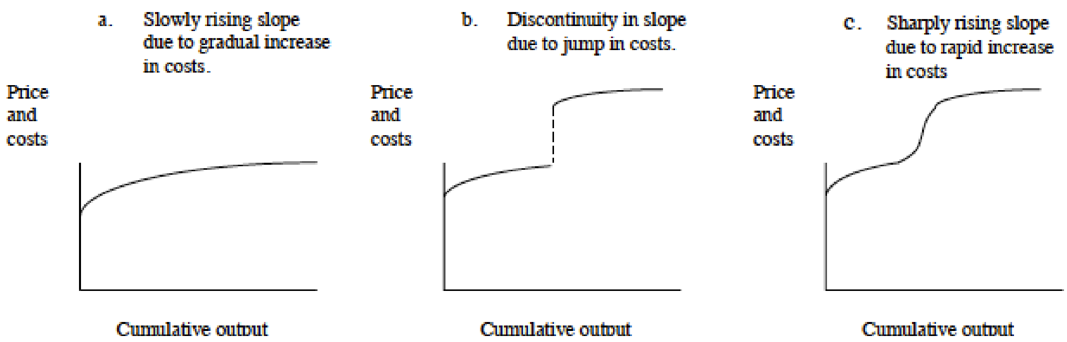
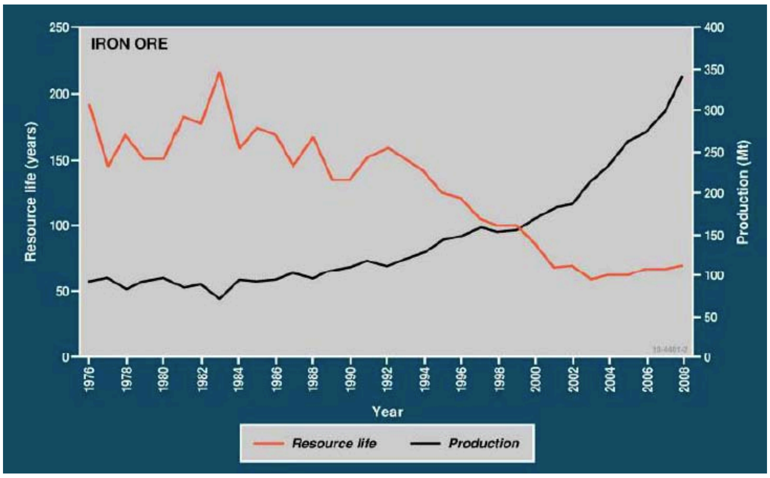


Figure 11: Illustrative cumulative supply curves (Source: Tilton and Skinner, 1987).

An analysis Australia's mineral inventory by Geosciences Australia (Lambert, 2010) comparing resource production and resource life (where resource life is a function of economic demonstrated reserves over production), shows that the resource life of iron ore has fallen steadily since the mid-1970s (Figure 12). Higher demand in the last decade, driving the iron ore price higher, and increasing Australia's EDR for iron, has contributed to a slight lengthening of the resource life (Figure 12a). However, this gain is negated when the lower-grade magnetite ores are removed from the EDR (Figure 12b). In the latter case, the current iron ore EDR is forecast to last just 50 years. Importantly, because these EDRs are calculated in light of present iron ore production costs, they do not consider the growing environmental and social costs of mining. Developing accurate measures of these costs, and internalising them into current operating costs, will likely see the present EDR for iron ore (and other commodities) fall dramatically. If production continues at present rates, or

[1] Given the complexity of defining a mineral resource as profitable, and the need to provide clear communication of such results to the public and investors, the Australian mining industry established the Joint Ore Reserves Committee (JORC) Code for reporting mineral resources. There are two primary categories of mineral resources under the JORC code – ore reserves and mineral resources. The typical distinction is that ore reserves have a very high economic and geologic probability of profitable extraction, while mineral resources have a reasonable geological probability but are less certain economically. Only ore reserves are quoted in Figure 10.

increases as forecast (Access Economics, 2008), resource lives for many commodities will fall even further.



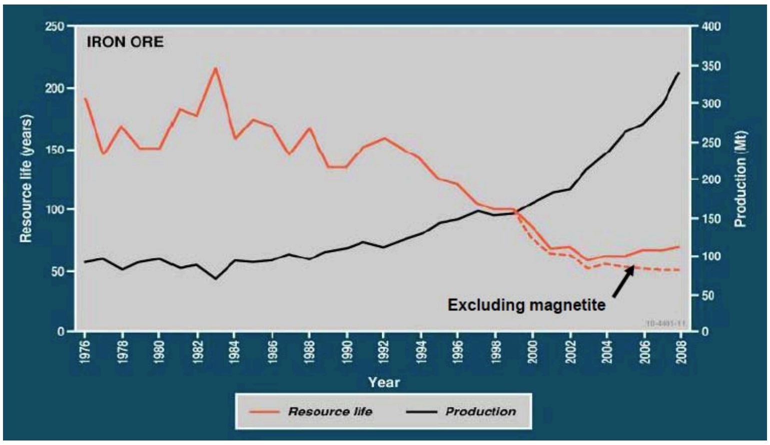


Figure 12: Resource life and production for iron ore in Australia: including (a) a nd excluding (b) lower-grade magnetite ores (Courtesy Ian Lambert, Geosciences Australia).

Although Australia's mineral industry is strong, and provides a significant proportion of the country's GDP (7.7% in 2009), many commentators argue that economic dependence on resources comes with dangers (Auty and Mieksell, 1998; Goodman and Worth, 2008; Larsen, 2006). The Resource Curse and related Dutch Disease have historically been associated with countries whose wealth is derived from rich resource endowments. Whether Australia suffers from either of these macro-economic challenges is contested (Goodman and Worth, 2008; Hajkowicz *et al.*, 2009), but unlike other countries (see for example, Larsen, 2006), to date Australian policy makers have done little to manage these threats. Larsen (2006) distinguishes the Resource Curse from Dutch Disease by noting the former implies stagnant growth, while the latter is associated with contracted manufacturing (Table 1).

Table 1: A comparison of the Resource Curse and Dutch Disease (after Larsen, 2006).

	Resource Curse (reflected by stagnant growth)	
	No	**Yes**
No Dutch Disease	• Overall growth • Diverse export base	• Stagnant growth • Diverse export base
Dutch Disease Present	• Overall growth • **Strongly contracted manufacturing**	• Stagnant growth • **Strongly contracted manufacturing**

In the Australian context, Dutch Disease is also called the Gregory effect after Professor Robert Gregory from The Australian National University, who described in 1976, the potential burden an expanding mining sector would have on rural and manufacturing sectors (Gregory, 1976). Simply suppressing resource-based industries where a nation has the comparative advantage is not the answer (Willett, 2002). Craig Emerson (the Australian Federal Minister for Small Business, Independent Contractors and the Service Economy and Minister Assisting on Deregulation) wrote that to avoid the Dutch Disease, "Australia needs a new program of productivity-raising reforms" with a focus on the seamless flow of capital, labour and skills across state boundaries, and on education, innovation and wise infrastructure investment (Emerson, 2008).

While few authors argue that Australia's minerals boom is likely to end in the near future, the economic viability of the industry will continue to be challenged by declining ore grades and the increased environmental and social costs associated with the expanded scale of mining that must compensate for this decline (Mudd and Ward, 2008; Topp *et al.*, 2008). A failure to anticipate how these added costs may influence the economic viability of the Australian mineral industry may result in adverse impacts associated with the resource curse. In particular, as the internalisation of previously externalised costs (like those from social or environmental impacts of more intensive mining) may constrain the economic reward associated with a resource boom before mineral reserves are exhausted, the necessity to plan for such eventualities with economic, regulatory or technological measures becomes critical.

Conclusion

Importantly, the discussion about mineral resource depletion is as much about falling resource quality as a reduction in resource quantity. The concept of 'peak minerals' describes a paradigm that parallels most of Australia's mineral production: from easy and cheap in the industry's infancy, changing to harder and more expensive now and into the future. The concept helps to frame a discussion concerning the management of Australia's mineral endowment, and the wealth it provides to our society. This paper has explored the concept of peak minerals in the context of Australia's mineral industry, and has examined the implications of peak mineral production by exploring its economic, technological, environmental and social implications for the industry and for Australia's long-term wealth.

Australia's mineral endowment has contributed significantly to our national wealth and development, and should continue to do so into the foreseeable future. However, heavy dependence on natural resources presents benefits and threats for national wealth. In this context, Australia must renew its vision for the minerals industry and associated technologies that underpin its performance. Effective macro-economic policy that simultaneously ensures long-term productivity from our mineral endowment, while encouraging mineral exploitation from alternative sources will be necessary to contribute to maximising Australia's long-term national benefit from minerals.

Technology has always been, and remains, a fundamental part of the mining industry and its ability to transform mineral resources into mineral wealth and useful end products. The technological advances in the industry also have social and environmental implications, both positive and negative, and how we apply future effort towards further advancement in these spheres will play a significant role in the future of the industry's sustainable development. However, technology is not likely to be a panacea for sustainable mining. Rather than being constrained by social, environmental and economic pressure, investment in technology (mechanical and conceptual) that addresses or mitigates the social or environmental costs of mining will begin to yield profitable outcomes for mining companies.

Mineral production in Australia is currently unsustainable, not primarily because of resources being finite, but because of impacts associated with processing and use. The concept of peak minerals raises the spectre of resource depletion, and the necessity to begin to plan for transition in the way we produce (through recycling) and use and reuse (sustainable design and extended producer responsibility) minerals in our society. Supplementing traditional production with alternative mineral and metal sources will contribute our ability to maximise long-term wealth from minerals by:

- Reducing our national economic dependence on in-ground mineral resources and boosting the activity and competitiveness of secondary (and tertiary) sectors that establish to realise value from in-use stocks and end-use mineral services.

- Avoiding or minimising many of the environmental and social implications of traditional mining that are reducing the nation's genuine gains from exploitation of our minerals endowment.

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