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

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

a Institute for Sustainable Futures, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia
b Department of Civil Engineering, Monash University, Wellington Road, Clayton, VIC 3800, Australia

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ABSTRACT

Today's global society is economically, socially and culturally dependent on minerals and metals. While metals are recyclable, terrestrial mineral deposits are by definition 'non-renewable' over human timescales and their stocks are thus finite. This raises the spectre of 'peak minerals' – the time at which production from terrestrial ores can no longer rise to meet demand and where a maximum (peak) production occurs. Peak minerals prompts a focus on the way minerals can be sustainably used in the future to ensure the services they provide to global society can be maintained.

As peak minerals approaches (and is passed in some cases), understanding and monitoring the dynamics of primary mineral production, recycling and dematerialisation, in the context of national and global discussions about mineral resources demand and the money earned from their sale, will become essential for informing and establishing mechanisms for sustainable mineral governance and use efficiency into the future. Taking a cross-scale approach, this paper explores the economic and productivity impacts of peak minerals, and how changes in the mineral production profile are influenced not only by technological and scarcity factors, but also by environmental and social constraints. Specifically we examine the impacts of peak minerals in Australia, a major global minerals supplier, and the consequences for the Asia-Pacific region, a major destination for Australia's minerals.

This research has profound implications for local and regional/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, when mineral availability is constrained. The research also begins to address the question of how we approach the development of strategies to maximise returns from mineral wealth over generations.

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1. 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 (UNEP, 2011). This puts focus on our future ability to access minerals resources and the economic, social and environmental costs of doing so.

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 drive sufficient technological advancement in exploration, production and processing (Foran and Poldy, 2001; WAIAC, 2000), or whether recycling, reuse or dematerialisation (Maxwell, 2006; van Berkel, 2007) can compensate for diminishing primary resource stocks (Willett, 2002).

While lithospheric stocks of minerals (those remaining in the lithosphere, rather than in use) are unquestionably finite, improved technology and rising resource price have allowed mining companies in Australia to produce minerals and metals at rates greater than at any time in history (ABARE, 2009; Giurco et al., 2010; McKay et al., 2009; Mudd, 2010a). This paradox suggests that price-driven technology improvements are winning the race against resource depletion, because resources can be more readily converted to reserves, thereby increasing their relative availability. As such, in Tilton’s opportunity cost paradigm, physical depletion is not the primary determinant of a mineral’s availability, but the ability to produce the mineral in an economically successful manner.

However, it is likely that technology and resource prices can only prolong resource accessibility within certain environmental and social limits (Giurco et al., 2010; Mudd, 2010a; Mudd and...
Ward, 2008; Schandl and West, 2010). While reliable mineral availability and supply is certainly a concern for critical and scarce metals (in part due to rapidly rising demand and geopolitical forces), production limitations resulting from social and environmental constraints and impacts are likely to arise well before physical depletion, especially for bulk commodities like iron ore and coal, which are Australia’s dominant mineral exports (Giuro et al., 2010; Mason et al., 2011).

The social and environmental consequences of mining have to-date largely been externalised from the costs of production. Few empirical examinations of the costs of production have been made with respect to physical or economic resource depletion. Only recently have the importance of cumulative impacts from mining operations been highlighted (Franks et al., 2010). In this paper we use the concept of ‘peak minerals’ (Giuro et al., 2010; Mason et al., 2011) as a metaphor to describe how social and environmental consequences and impacts of mining may affect primary mineral production in Australia’s future. We argue that the costs of these consequences and impacts should no longer be externalised from mineral production costs, and that their internalisation will influence the overall productivity of the mining industry in Australia, and without adequate management, the accessibility and sustainability of resources in Australia and elsewhere.

We provide evidence that social and environmental impacts are already increasing the costs of production, and demonstrate how productivity in the mining industry in Australia has fallen since the beginning of the most recent resources boom (2000/2001). Finally we discuss the implications for sustainability in this extractive industry, and explore what peak minerals might mean for the industry’s future productivity, and reflect on the usefulness of the peak minerals metaphor for national and global analyses.

2. Peak minerals and mineral depletion

The activity of modelling peaks in resource production has been used extensively as a means of exploring when resource availability may decline (for example Bardi, 2009; Cordell et al., 2009; Hubbert, 1956; Mohr and Evans, 2009). While these processes are informative as conceptual tools, they rely fundamentally on continued mineral exploration to identify the extent of economic mineral resources, and the ultimate recoverable resources, without which, peak modelling is flawed. This makes using peak curves for accurate projections of long-term supply difficult to implement, and technological developments in exploration, recycling and dematerialisation (increasing a material’s use efficiency while still maintaining its service in society), or changes in resource price further complicate the usefulness of peak modelling approaches.

Notwithstanding, projecting future production trends has important implications for society, and the debate about the processes and consequences of resource depletion are ongoing (Bridge and Wood, 2010; Gordon et al., 2006, 2007; Graedel, 2010; Steen, 2006; Tilton, 2003; Tilton and Lagos, 2007). Importantly, this debate has focussed (like peak models) on when and how a resource might become physically or economically depleted. By contrast, the concept of peak minerals acknowledges that the social and environmental consequences and impacts of mineral resource production and processing may stimulate a resource production peak that is completely unrelated to resource stocks, reserves or the ultimate recoverable resource.

2.1. Peak minerals: a metaphor for life-of-resource constraints?

The ‘peak minerals’ metaphor suggests that as a resource is exploited, production can be characterised as being cheap and easy early, becoming progressively more expensive and difficult. Production is cheap because the resource is abundant, and the ore quality is on average relatively high – extracting the resource, and making a profit from its sale is therefore relatively easy. However, as production continues, high grade and easily accessible and simple to process ores are depleted, or are subsumed into larger, lower average grade mines as a result of technological improvements in extraction and processing (see West, 2011). As a consequence, exploitation is directed at lower grade, deeper or more complex ores – those considerably more difficult and expensive (economically, environmentally and socially) to extract (Mason et al., 2011).

The need to supply increasing demand for most mineral resources produced in Australia (which has forced commodity prices up) has meant that although production might be more difficult, production rates have nonetheless increased for many mineral resources, particularly in Australia (Mudd, 2010a). In order to maintain or increase production rates, exploitation has become more intensive, with a range of environmental and social consequences. Environmental constraints include increased mine waste, mine size, and energy intensity, as well as water table drawdown, and water pollution (Bridge, 2004; Mudd and Ward, 2008). Social constraints include land-use conflicts, cumulative impacts of mining activities, and mine closure consequences for mining companies and regions (Breshears et al., 2008; Franks et al., 2010; Ivanova et al., 2005; Lockie et al., 2009; Petkova et al., 2009; Solomon et al., 2008; Worrall et al., 2009). The peak minerals metaphor acknowledges that these consequences increase the costs and difficulties associated with mineral resource production, and will therefore ultimately constrain the ability to produce these resources (evidence of this is provided in Section 3).

As a metaphor, peak minerals aims to encourage discussion about the ultimate use of minerals and metals (Mason et al., 2011). It focuses on what transitions could deliver resources that fill the same useful services, both in terms of the export revenue they provide a country like Australia, and in terms of the services they perform in society (for example in pipes and pumps for providing clean water, and in wires to carry electricity and structures that support today’s urban settlements). Following these considerations, the focus can then turn to possible alternatives for these services, if the existing service providers are lost (e.g. deep seabed resources, greater recycling or reprocessing, dematerialisation, substitution with other materials), and which enabling technologies and policies might support these alternatives.

2.2. Managing resources as service providers

The peak minerals metaphor outlined in this paper has origins in the work undertaken in the middle of last century by Hubbert (1956), who modelled oil production in the lower 48 states of the United States, and signalled an oncoming oil production peak. Although this work has largely been cited in the context of geological resource scarcity, Hubbert was more interested in assessing resource availability in order to inform mechanisms for transitioning from the energy services provided by oil to alternative energy sources (nuclear power in Hubbert’s case). Williamson (1945) too concluded that concepts of resource exhaustion are triggers for thinking about how a particular resource is managed.

Hubbert (1956) introduced the idea of ‘energy services’ (services that oil supports, including for example transport and construction), and questioned how these services could be maintained if oil resources were exhausted or if production targets could not be met. This work highlighted how a disruption of energy services would have serious consequences for the economy and for society. The consequences of a disruption in the production (whether due to sustainability constraints or otherwise) of a base metal like copper or nickel would also have serious implications for...
society, and should trigger new approaches to mineral resource use and management that acknowledge the important services these resources play in society.

For Australia, extracting and selling the resource and losing the economic windfall from this activity has important consequences because of the nation’s current economic dependence on mineral commodity exports. While much of the evidence to date suggests Australian minerals are unlikely to run out in the near future (Lambert, 2010; Mudd, 2010a), they are becoming more difficult to obtain and produce in the quantities (and quality) of product demanded by the market.

3. Evidence for ‘peak minerals’ from Australia

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). We provide evidence to demonstrate that these concerns are now realities in Australian mineral production, and can be supported by a range of company reported and government data (Mudd, 2009). 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 showing increased environmental costs associated with changing ore grades, mine depth, wasterock, mining inputs (energy, water, labour and capital), and instances of growing social costs associated with regional development, cumulative impacts and quality of life in mining regions in Australia.

3.1. 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 (McKay et al., 2009), and because of the ore’s complexity.

Fig. 1. (a) Ore grades are steadily declining for a variety of base and precious metals in Australia. (b) Falling gold ore grades are also an issue for other gold producing countries. Data from: Mudd (2007c, 2009, 2010a, updated and unpublished data).

Recently compiled historical data sets (Mudd, 2009) show that long-term trends for copper, gold, nickel, lead, silver and zinc ore grades in Australia have declined (Fig. 1a). In addition, similar trends have been observed in gold (Fig. 1b) and nickel (Mudd, 2010b) ore grades on the international scale. 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. Additionally, in some mineral rich regions of Australia, expanding mine operations are increasingly stirring conflicts with local communities because of cumulative localised impacts from mining (Franks et al., 2010), and because of land-use conflict (Ivanova et al., 2005).

West (2011) provides a contrary opinion regarding ore grade declines. He notes that technological advancements in extraction and processing during the 21st Century permitted the exploitation of lower grade ores than was previously possible. As a result mine sizes grew, often in places where higher grade ores were previously (and sometimes concomitantly) mined, effectively reducing the mine’s average ore grade. However, as West points out, the issue of falling average grades over the last century is a ‘low-order’ problem when compared with the sustainability constraints associated with increased mine size and mining intensity. The case of nickel as illustrated in Section 3.1.1 demonstrates how the combination of ore grade and mineralogy influences productivity and mining profitability.

3.1.1. Case study: nickel

The nature of nickel deposits, and nickel markets, provides a good example of how ore type can influence the economic viability of a commodity extraction operation. Nickel was historically mined from nickel sulfide complexes in Australia, but large nickel deposits also exist in more difficult and complex lateritic ores (lower-grade nickel ores requiring complex processing). In response to strong markets for Australian nickel, 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) in the late 1990s. A major attraction of the HPAL technology was its application for production from nickel laterite ore resources, which are considerably more abundant than the higher-quality sulfide deposits in Australia. A minor nickel laterite boom occurred as a consequence of high nickel prices and the possibility of increasing the scale of operations to push unit costs of production down. Three new nickel production/processing projects were quickly developed at Cawse, Bulong and Murrin Murrin in central Western Australia (the dominant source of Australia’s nickel production and resources). All three nickel laterite projects faced major technical hurdles, and Cawse and Bulong collapsed financially when they failed to meet production targets and achieve profitable operations. The Murrin Murrin project survived, partly thanks to the nickel price boom of the mid-2000s, but production must be monitored constantly to ensure financial viability. A very recent example of the risks of imputities affecting processability is the Armstrong nickel mine in the Kambalda field of Western Australia. Developed by Titan Resources in 2004, the deposit proved to have unacceptably high arsenic content, which led to rejection of the ore by the Kambalda nickel mill, nearly sending Titan Resources bankrupt in the process. Mudd (2010a, 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”.

3.2. Energy costs and other inputs are increasing

As ore quality declines, the energy requirements and pollution burdens increase substantially. A recent analysis of the carbon intensity of gold production (i.e. t CO2–e/kg Au) versus gold ore grade (Fig. 2) shows that as ore grades decline the energy used, and carbon intensity begins to increase significantly (points represent individual mines). While this pattern is clearly demonstrated in Fig. 2, the scatter can be accounted for by differences in the mine type (open cut, underground) and the varying configurations of the operation: whether they employ heap leach versus carbon-in-pulp processing, the relative contribution of energy sources (e.g. diesel, electricity, gas), the project age, depth, or ore types. 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 intensively 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 (how efficiently capital and labour inputs can be converted into outputs) 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 Asia (Access Economics, 2008).

Water for processing ores is also a limitation on production capacity, especially for processing techniques in copper and high pressure acid leaching in the processing of nickel laterite ores, where large quantities of water are used (Mudd, 2010a). 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 and reports the mine’s consumption. Gold production is regularly cited as having the greatest embodied water content of any Australian mineral commodity (as kl/kg Au) (Mudd, 2007b; Norgate and Lovel, 2006).

Fig. 2. Carbon intensity of Australian gold production versus ore grade (Mudd, 2007b, 2009, 2010a including updated and unpublished data).

At the mine level, success can be achieved in water efficiency, but with project expansion (as is occurring for most commodities), this can be overshadowed by total consumption. In Australia (the driest inhabited continent), water is often 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, 2010a). There is also the issue of water quality, which is not directly reported consistently as a part of water accounting by mine operators. Indeed, water has been such a prominent issue that it has been influential in the blocking of permission to open new mines, such as the Wallarah 2 underground coal mine in the rich coalfields of the New South Wales Hunter Region (Merhab, 2011).

3.3. Pollution from mining is growing

As 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 trends have shifted progressively from underground to open cut mining, allowing project scales to increase substantially. However, along with mine expansion, pollution from waste rock, tailings and CO₂ emissions have increased dramatically.

Much of the tailings and waste rock is relatively benign (Mudd, 2010a), and in instances where the waste is older, has been successfully reprocessed as the primary mine site ore grade has fallen below historical levels (Mudd, 2007a). However, a large quantity of this mine waste 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. Given that there are in excess of 32,000 legacy mine sites in Australia requiring rehabilitation, mine waste presents a significant management challenge (Worrall et al., 2009). There are currently no regulations for consistent mine site reporting of waste rock quantities or qualities, so figures reported here are indicative only (Fig. 3). Additionally, it requires significant energy to move the rock and in the case of the proposed Olympic Dam expansion, two billion tonnes of overburden will be removed in the conversion from underground to open cut mine to access the ore at a depth of 350 m.

As noted in Section 3.2, 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 (Fig. 4a). At the same time, the consumption of cyanide has also increased in processing (Fig. 4b) – and cyanide use is now a key indicator of a gold 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” (see also Csagoly, 2000).

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 ability to implement new technologies at closure. For example, engineering principles of unsaturated flow are widely used in rehabilitation planning and designs, but there remain cases where this approach has not prevented environmental degradation (Mudd, 2010a). In the 1980s, the Commonwealth Government of Australia spent AUD 25 million in the rehabilitation of the former Rum Jungle uranium mining field. Even so, as recently as 2007, the adjacent East Finniss River was still heavily polluted with acid and metalliferous drainage leaching from the rehabilitated mine site (Mudd and Patterson, 2010).

3.4. 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 1980s, fortified by several significant international environmental incidents, public concerns about mining operations have broadened and increased (Hamann, 2003; Jenkins and Yakovlova, 2006; Warhurst and Mitchell, 2000). Changing social perceptions, and increasingly vocal opposition to mining activities 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.

![Fig. 3](image-url): 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.

Data sourced from: Mudd (2009, 2010a, updated and unpublished data).

associated with mining (Brereton and Forbes, 2004; Brereton et al., 2008; Franks, 2009; Franks et al., 2009). As miners seek to exploit new or higher quality deposits, they are increasingly facing issues of land use and water use conflict. Proposed coal mines in the agriculturally-rich Liverpool Plains area of Central New South Wales have resulted in mine operators suffering considerable backlash from the community, who argue mining is disrupting agricultural production, and will challenge 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). How to manage an over-abundance of water following severe flooding in the Bowen Basin in 2011 has also been an issue. Flooded mines must be pumped clear before production can resume, causing pollution concerns in the community.

Although Hajkowicz et al. (2011) do not find 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, community-level 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 et al., 2009). While 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.

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 (Bridge, 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 (see for example MCA, 2005). Where the mining industry does not take appropriate action to manage or mitigate these impacts, obtaining regulatory approval or community support for mine establishment and expansion is likely to become 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 global and Australian mining industry into the future (ICMM, 2008).

4. Implications for sustainability and resource depletion

The peak minerals metaphor 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 (Mason et al., 2011). Economic, social and environmental costs change along this continuum, and understanding how these changes affect the mineral industry will become increasingly important. The trends highlighted above, and considered in a mining sustainability context, suggest the metaphor of peak minerals has considerable merit in a national context, as well as globally.

Using the peak minerals metaphor, Mason et al. (2011) established a three-criteria framework to assess the impact that changing patterns of mineral production would have on the provision of services that rely on minerals. The criteria include the availability of a resource, society’s addiction (material and financial) to a resource, and the likelihood that alternatives could be found to replace the service provided by a resource. The analysis assessed several important Australian export commodities against these three criteria, illustrating that changes in production circumstances require critical consideration in the governance of resource production and use. The work also informs how to best manage a transition between ‘cheap and easy’ and ‘expensive and difficult’ production and processing, along with the necessity to recognise and realise opportunities, and address the challenges that social and environmental impacts may present in the future.

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. The Mining Minerals and Sustainable Development Project (2002, p. 286) highlights that “connecting the production and use of mineral-related materials is critical to ensuring that the minerals sector contributes optimally to sustainable development”.

The relationship between the economic value and environmental impact of stages in the mining-production chain is illustrated in Fig. 5 (Clift and Wright, 2000). This shows how the initial stages of a mineral production chain 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. As a major primary producer of minerals, Australia is burdened with significant environmental impacts relative to
footprint of metals is motivating aluminium producers to locate in places like Iceland (with geothermal energy) and Mozambique (with hydropower), shifting the global influence of major commodity producers like Australia.

Understanding the true costs of mineral production, and re-valuing mineral resources, ultimately influences the 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. The potential 'new' value attributed to in-use stocks presents opportunities for Australia – 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 develop end-use services that provide long-term access to minerals and national wealth without relying solely on traditional resource extraction.

5. Implications for mining industry productivity in Australia

Even though the mining industry in Australia has contributed substantially to the nation's growth in export income over the last decade, multifactor productivity in the industry has fallen during the same period (Topp et al., 2008). While mineral ores are obviously one of the primary inputs in the mining industry, their quality is not considered in standard measures of productivity, which assume the resource input is of geographically and temporally homogenous quality. However, as we have described in this paper, the quality of resource inputs across a range of Australian commodities is by no means homogenous. The sustainability constraints detailed in Section 3 will continue to impact on the productivity of the mining industry in Australia in the future. Addressing these constraints will require innovative and proactive responses by industry and government in order to deliver sustainable national benefit from the mineral endowment.

By their very nature, minerals are non-renewable, and primary stocks become depleted with ongoing extraction (Fig. 7). 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. Falling ore grades and falling productivity likely signify the initial stages of mineral resource exhaustion in Australia (Topp et al., 2008). Fig. 7 shows that while the economic demonstrated resources (EDR) of many of Australia's key export minerals are high relative to cumulative production, the resource life (shown in the centre of the commodity doughnut chart) of many of these resources are surprisingly short. However, 'years left' remains uncertain due to competition between increasing production and ongoing deposit discovery and mine development.

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 Miekiss, 1998; Goodman and Worth, 2008; Larsen, 2006). 'Dutch Disease' and the related 'Resource Curse' 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., 2011), but unlike other countries, to date Australian policy makers have made little proactive effort to manage these very real threats. The ‘Resource Curse’ describes a situation, contrary to economic theory, where many resource-rich countries have not converted the potential wealth from resources into development progress (Papparikas and Gerlagh, 2003; Shaxson, 2007; Stevens and Dietsche, 2008). Dutch disease’ describes the relationship between resource abundance and dependence, and the contraction of non-resource sectors of the economy (Krugman, 1987). 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).

While few authors believe that Australia’s minerals boom is likely to end in the near future, the economic viability and productivity of the industry will continue to be challenged by environmental and social sustainability constraints that drive production costs higher (Giurco et al., 2010; Topp et al., 2008). A failure to anticipate how these added costs may influence the economic viability of the mining industry in Australia may result in adverse macro-economic impacts. 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.

6. International implications of peak minerals in Australia

Australia has actively embraced its vast mineral endowment. Mineral resources contributed almost AUD138 billion in export earnings (54% of total earnings) to the Australian economy in 2009–2010 (ABARES, 2011). These figures place Australia firmly within the United Nation’s criteria for a mineral-dependent economy (Eggert, 2003; Maxwell and Guj, 2006). If the value to society of minerals and metals lies in the services these resources provide, not in the resources themselves, then Australia is doubly dependent: minerals and metals play critical and central roles in industry and society, and the sector represents the largest source of export earnings for the nation (Mason et al., 2011).

The financial dependence is partly a result of rapid industrialisation of Australia’s near neighbours in the Asia-Pacific region. The relatively inexpensive and highly accessible resources from Australia underpin the development of Australia’s regional neighbours, and this development is projected to drive demand for Australian resource exports over the coming decade (Access Economics, 2008) beyond the ability to supply them in a sustainable manner (Schandl and West, 2010). Australia’s dependence on the mining industry for export earnings has shaped and continues to shape the industry and the nation’s international relationships. It is essential that Australia consider the global context in which its minerals sales occur when establishing mechanisms for sustainable management of its mineral resources.

Growing international demand, and steadily rising production rates of most commodities leads to increasing ‘resource intensity’ (Schandl et al., 2008), and likely an intensification of social and environmental consequences, and therefore a continued decline in multifactor productivity in the Australian mining sector. Given that most mining companies now operating in Australia are multinational in scale, relying on international investment to finance their activities, worsening sustainability constraints and productivity will undoubtedly increase the uncertainty and risk associated with international investment. An analogue to this issue occurred in 2010, when mining companies lobbied against the application of a profits-based resource rent tax, arguing that it would deter international investment, thus creating a sovereign risk issue for Australia. Sustainability constraints in the future will drive production costs higher, reducing the profitability of mining operations, and increasing the financial risk associated with investment in these operations.

Growing demand (i.e. consumption) also strengthens and prolongs the dependence of resource-rich countries on mineral

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<td>Resource Curse (reflected by stagnant growth)</td>
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exports, and this dependence is likely to result in national and global societies that are increasingly vulnerable to falling resource availability or accessibility. However, strong demand for commodities need not be a bad thing for Australia, as long as the mining sector, and the wider economy, is supported by stronger sustainability focussed legislation and macroeconomic policy – particularly that which fosters innovation in resource governance (e.g. a sovereign wealth fund, or resource rent tax), in production, processing and mining business models (e.g. a move away from the traditional dig-and-sell model or quarry mentality).

7. Conclusion

Importantly, the discussion about mineral resource depletion is as much about falling resource quality and accessibility as it is about a reduction in resource quantity and availability. This paper has explored peak minerals in the context of the mining industry in Australia, as well as the Asia-Pacific region where much of Australia’s mineral exports are sold. It has examined the implications of peak mineral production by exploring its economic, environmental and social implications for the mining industry, given a continued focus on primary production. The peak minerals metaphor 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 governance of national mineral endowments, and the wealth and sustainable provision of mineral services to society.

Australia’s mineral endowment has contributed significantly to the country’s 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 mining industry and associated innovation that underpins its performance. Effective macro-economic policy that simultaneously ensures long-term productivity from the mineral endowment, while embracing innovative governance and encouraging mineral exploitation from alternative sources and materials efficiency among consumers, will be necessary for Australia to maximise long-term national benefit from the mineral endowment. Focusing on and ameliorating sustainability issues as possible constraints to production will be fundamental in ensuring long-term productivity.

Technology has always been, and remains, a fundamental part of the mining industry and its ability to productively transform mineral resources into mineral wealth and useful end products. Technological innovation in the industry may also have positive and negative social and environmental implications, and how future innovation effort is applied will play a significant role in the future of the industry’s sustainable development. While technology is not likely to be a panacea for sustainable mining or resource efficiency (Schandl and West, 2010), a focus on and investment towards innovations (mechanical, material, social and conceptual) that address or mitigate the social or environmental impacts and consequences of mining will begin to yield profitable and sustainable outcomes for mining companies.

Mineral production in Australia is currently unsustainable, not primarily because of resources being finite, but because of impacts associated with extraction and processing. Peak mineral production raises the spectre of resource depletion, and the necessity to begin to plan for transition in the way minerals and metals are produced (through recycling), used and reused (sustainable design, material efficiency, and extended producer responsibility) in society.

On a global scale, mineral and metal use is also unsustainable, and addressing the concurrent and related challenges of increasing resource consumption along with an increasing global population has become a core focus for international sustainable resource governance processes and programs (ICMM, 2008; Schandl and West, 2010; The Mining Minerals and Sustainable Development Project, 2002; UNEP, 2011).

As a major supplier of minerals and metals to the world economy, Australia can play a significant role in leading and encouraging sustainable production, use and governance of mineral resources. As a start, supplementing traditional production with alternative mineral and metal sources will not only contribute to Australia’s ability to maximise long-term wealth from minerals by reducing the national economic dependence on in-ground mineral resources, but it would also boost capacity, innovation, activity and international competitiveness in secondary (and tertiary) sectors that establish to realise value from in-use stocks and end-use mineral services.

For example, innovation in governance might extend to the introduction of a resource rent tax and associated sovereign wealth fund. Such mechanisms could be used to distribute wealth more equitably among society, to smooth the boom-bust nature of the resource dependent economy (Chile Finance Ministry, 2009), or to support economic diversification (investment in local manufacturing would increase the feasibility of local recycling and recovery of metals from end-of-life products). Innovation in business models may involve a move away from the ‘dig-and-sell’ business model to one of ‘servicisation’ (Reiskin et al., 1999), where mining products are leased rather than sold, thus encouraging greater sustainability in metal product chains (Giurco and Petrie, 2007). These measures should seek to decouple primary production from economic development and recognise that the value of resources lies in the services they provide in society, not the products themselves. These forms of innovation will encourage efficient use of resources and ultimately contribute to avoiding or minimising many of the environmental and social implications of traditional mining practices.

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References


Young, J.E., 1992. Mining the Earth. Worldwatch Institute, Washington DC, USA.