One Australian Perspective on Sustainable Mining : Declining Ore Grades and Increasing Waste Volumes

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Note : This is an original electronic version, only different in layout to the printed version. Full reference :

Mudd, GM, 2004, *One Australian Perspective on Sustainable Mining : Declining Ore Grades and Increasing Waste Volumes*. Proc. 11[TH] International Conference on Tailings & Mine Waste '04, Taylor & Francis Group, ISBN 04 1535 939 2, pp 359-369.

ABSTRACT: The perhaps nebulous concept of "sustainable mining" has become a major focus of debate in recent years. Traditionally, the debate has centred around known resources versus production rates as well as socio-economic and political paradigms. This debate is as old as mining itself, ranging from before ancient Greek times through Agricola in the 1500's to many scholarly works in modern times. The principal changes over this period are the range of minerals and metals mined, techniques in use as well as the location and scale – modern mining is truly a global enterprise. The global mining industry, as a major contribution to the 2002 World Summit on Sustainable Development, recently published the 'Minerals Mining & Sustainable Development' (MMSD) report to argue their case for 'sustainable mining'. The MMSD report covers a wide range of issues, including social impacts, abandoned mine sites and facilities, artisanal (small scale) mining, land use, conservation, economics, technology and corporate governance, as well as the need to move towards a greater degree of recycling in many basic mineral commodities and metals. In general, most commodities have increased production over time, some dramatically. Given that ore grades are decreasing over time, with some metals more rapidly than others, the quantities of tailings over time are increasing considerably commensurate with production rates. The balance between ore sourced from open cut versus underground mines is also important since open cut mining involves the excavation of a greater quantity of waste rock to access the ore of interest. Over recent decades, there is a strong trend internationally for the increasing use of open cut mining. The MMSD reports, however, do not present any data or systematic analysis on the declining ore grades of the major mineral commodities and metals produced in modern times or their associated wastes, principally tailings and waste rock. This paper will analyse the principal mineral commodities produced in Australia, namely black and brown coal, copper, gold, iron ore, lead-zinc-silver, diamonds, aluminium, tin, uranium and nickel. The Australian production data for these commodities will be presented, combined with the available data on ore grades and waste produced, followed by a discussion of the apparent trends in the various commodities and the implications for the concept of 'sustainable mining'.

1 INTRODUCTION

The mining industry has a long and critical role in the history of many regions around the world. The debate about mining's importance and impacts is quite old indeed. The first seminal monograph on the topic was "De Re Metallica" by Germany scholar Georgius Agricola, published in 1556 (see (Hoover & Hoover, 1950). While acknowledging many of mining's impacts (socially and environmentally), Agricola argued ardently that the overall benefits far outweighed the localised impacts and that metal mining was at the core and foundation of modern technological society.

In recent decades, the debate has progressed from the 'Club of Rome' reports to the most recent 'Minerals Mining & Sustainable Development' (MMSD) report published by the global mining industry (IIED & WBCSD, 2002). Over this time, the debate has shifted from production rates versus resource depletion to a more sophisticated dialogue whereby the MMSD report acknowledges a wide range of issues, including social impacts, abandoned facilities and sites, artisanal mining, conservation, technology, land use, economics and corporate governance, as well as the need to move towards a high proportion of recycling in many basic mineral commodities.

This paper will discuss the components of "sustainable mining" from various perspectives, a detailed presentation of mineral production over time in Australia and finally a discussion of the trends in production and the implications this has for the sustainability of the mining industry in Australia. Some key recommendations will then be given to improve reporting by industry and governments to facilitate a better quantification of sustainable mining.

2 DEFINING SUSTAINABLE MINING

Definitions of sustainable mining vary widely, often along the lines of whether a government, civic, environmental or industry perspective is advocated. The various concepts commonly concentrate on two key themes – resource depletion/availability and social/ environmental impacts.

The first major report to address these key issues was the Club of Rome report "The Limits to Growth" (Meadows *et al*, 1972) (a contemporary response to Agricola). During the 1980s, the United Nations auspiced the World Commission on Environment and Development (WCED), culminating in the final report titled "Our Common Future" in 1987 (known as the Brundtland Report) (WCED, 1990). Following this, the Australian Government launched the "Ecologically Sustainable Development" working groups, including one dedicated to mining which reported in November 1991 (ESDWG, 1991). In preparing for the 2002 Earth Summit in Johannesburg, South Africa, the global mining industry launched the "Minerals Mining & Sustainable Development" (MMSD) process to argue their case for sustainable mining (IIED & WBCSD, 2002).

The Club of Rome report argued from an environmental perspective that many mineral resources are being mined at unsustainable rates compared to known reserves, due to continued population growth and economic development. It was acknowledged that this was dependent on technology, social and economic issues, but they argued that the increasing use of mineral products was a key factor in the pollution burden of modern society. Modern mining was therefore most likely "unsustainable".

The Brundtland Report argued that the impacts of energy production were a key determinant of sustainability, due to the gradual depletion of resources (eg. oil) as well as the biosphere's ability to absorb by-products such as greenhouse gases (WCED, 1990). The sustainability of other minerals was considered less problematic, due to relatively stable consumption at that time and the changing nature of technology and the use of recycling and substitution. The official Australian response to the Brundtland Report identified the key issues for mining were resource depletion/discovery, in situ (environmental) impact, land use for conservation versus mining, and the greenhouse effect (WCED, 1990).

The ESD Working Group argued that sustainable mining had to incorporate technological efficiency, greenhouse gas releases, land use planning, improved environmental management systems, coordination of decision making, better use of information through research, and public involvement, education and training (ESDWG, 1991).

The MMSD Final Report argued that there were nine key challenges for the global mining industry to address the move towards sustainability : (i) economic viability, (ii) land use planning, (iii) national economic development (eg. poverty reduction), (iv) social impacts, (v) environmental impacts and management, (vi) integrated approach to using minerals, (vii) information reporting, (viii) artisanal and small-scale mining, and (ix) mineral sector governance (IIED & WBCSD, 2002). Within this framework, many more specific issues were also identified, such as the large amount of waste rock produced by modern mining, acid mine drainage, and mining in protected areas (eg. national parks, world heritage).

As can be seen, the concept of sustainable mining varies widely, but generally includes social, environmental and economic aspects. In general, the question of resource scarcity is not considered as urgent in the current debate though the issue of environmental/social impacts is certainly very prominent (Young, 1992). These thematic issues are inextricably linked, however, due to the increasing scale of modern mining which exploits lower grade but larger orebodies, often through sizeable open cut mines. The volume of wastes generated is now some orders of magnitude higher than a century ago, which in some extreme cases has led to severe impacts for long distances from mine sites. In order to predict the future sustainability of the mining industry, it is therefore critical to examine the trends of ore grades and the amount of waste materials mined for a given mineral production.

3 MINING IN AUSTRALIA

3.1 *Economic Value*

The mining industry in Australia has always been closely associated with economic development and continues to be a prominent contributor to economic activity. Within the global context, Australia is a major mineral producer and exports numerous commodities around the world, a major source of national revenue. For the 2002-03 fiscal year, around 88,000 people were employed in the Australian resources industry producing products with a value of some AUS$55 billion (ABARE, 2003).

3.2 *Methodology*

In order to assess the sustainability of Australian mining, a detailed compilation of the production history of mining across all states in Australia has been undertaken, with a view towards establishing the extent of the changes in ore grades for various minerals and metals as well as quantifying the production of wastes (where possible). Some limited data on mine-site rehabilitation has also been collected.

There are a number of periodic or regular reports published on the Australian mining industry. These include the "Annual Mineral Industry Review" by the former Bureau of Mineral Resources (BMR) (BMR, various), various statistical publications (eg. (LP & Minmet, various; Riddell, various; RIU, various), State Department of Mines reports, annual reports of state and federal agencies and mining companies, as well as the older series "The Mineral Industry : Its Statistics, Technology and Trade" on the global mining industry (Various, Years 1892-1940). For some specific minerals (eg. coal, aluminium), industry associations and consultants also compile annual data over time. Primary data sources are detailed under references at the end of this paper.

The extent of and quality data varies considerably across all of these publications, with inevitable gaps. The reporting of data is not always consistent, such as mineral yield versus assay grade, concentrate vs ore, plus discrepancies between publications.

In general, the following rules were applied in assessing and compiling reported data :

- company data takes precedence;
- calendar year was preferred, otherwise financial year data was applied in the year it was reported;
- assayed ore grade was sought, with yield data corrected for recovery (where known);
- all data was converted to SI units;
- alluvial mining has (generally) not been included (due to the difficulty of data equivalence);
- where sources conflicted, the data considered closest to the company source was adopted.

The compilation of data is now mostly complete. As such, the following results and discussion should be regarded as preliminary. This type of analysis is believed to be unique in Australia, indeed globally. A final report with full data is due soon.

3.3 *Results : Australian Mineral Production*

The annual mine production of most minerals and metals is shown in Figure 1 with coal production in Figure 2. The estimated total production by state is given in Table 1. Mineral production is centred mainly within Western Australia, Queensland and New South Wales, with Tasmania, Victoria, South Australia and the Northern Territory mainly being important for particular minerals (eg. gold, copper).

3.4 *Results : Ore Grades and Waste Volumes*

The results for the quantity of ore milled, ore grade, waste rock production and the proportion derived from open cut mining over time for gold, lead-zinc, copper, nickel, diamonds and uranium, are shown in Figures 3 to 5. For most minerals, they represent 100% (or very close to this) of the ores mined and milled for that commodity.

3.5 *Results : Cumulative Minesite Rehabilitation*

As there is nationally compiled data on mineral production across Australia, there is now also the need to compile the appropriate data on the extent of rehabilitation of former and current mine sites as well as the long-term success of such efforts. At present, there is no standard approach for this aspect, with some states collating data while others do not appear to. The most recent data for Western Australia is given in Table 2.

Table 1. Total Australian Mineral Production by State

	VIC	NSW	QLD	TAS	SA	NT	WA	Aust	Period
Bauxite (Mt)	0.217	0.235	313.7	0	0	~163.5	»501 [#]	~1,114	1927-2002
Black Coal (Mt) [§]	22.7	3,543	2,709	23.7	96.2	0	168.4	6,763	1829-2002
Brown Coal (Mt) [§]	1,793	-	-	-	-	-	-	1,793	1919-2002
Copper (kt)	17.2	1,874	6,581	1,552	2,026	364	576	15,675	1842-2002
Diamonds [*]	-	~0.3	-	-	-	~0.21	~628.7	~629.2	1867-2002
Gold (t)	2,359	706	1,242	163	38	439	5,330	10,190	1851-2002
Ilmenite (kt)	<0.5	»432 [#]	»1,396 [#]	0.56	1.04	<0.5	»25,816 [#]	50,251	1934-2001
Iron Ore (Mt)	0.04	4.5	0.67	68.0	~220	6.88	3,482	4,002	1901-2002
Lead (kt) [#]	~53.6	»22,045 [#]	»7,068 [#]	»2,091 [#]	~18.1	431.5	598.0	~35,532	1883-2002
Manganese (kt)	0.44	76.4	158.4	0.76	62.7	53,083	5,550	59,127	1946-2002
Nickel (kt)	0	0	327.4	0.6	0	0	~2,541	2,868.3	1967-2002
Rutile (kt)	<1	»4,041 [#]	»2,895 [#]	40	~2	<1	1,934	10,810	1934-2001
Silver (t)	55.0	30,389	13,336	3,321	30.1	174	573	71,950	1870-2002
Tin (kt)	13.7	180.5	175.0	385.8	<0.1	6.0	48.6	~810	1870-2002
Uranium (t)	0	0	8,893	0	31,543	84,349	0	124,805	1954-2002
Zircon (kt)	<0.5	»3,972 [#]	»2,202 [#]	39 [†]	0.37	<0.5	8,869	16,368	1934-2001
Zinc (kt) [#]	~19.5	»20,790 [#]	»6,432 [#]	»4,758 [#]	~371	1,441	2,219	~39,980	1883-2002

[*] Mcarats [#] / ~ Data incomplete / approximate. » Much greater than. [§] Raw (not washed).

References & Data Sources : ABARE, BMR, DM's, mining company annual reports and/or supplied data, (Brown, 1908; Carne, 1908; Kalix *et al*, 1966; Mudd, 2004).

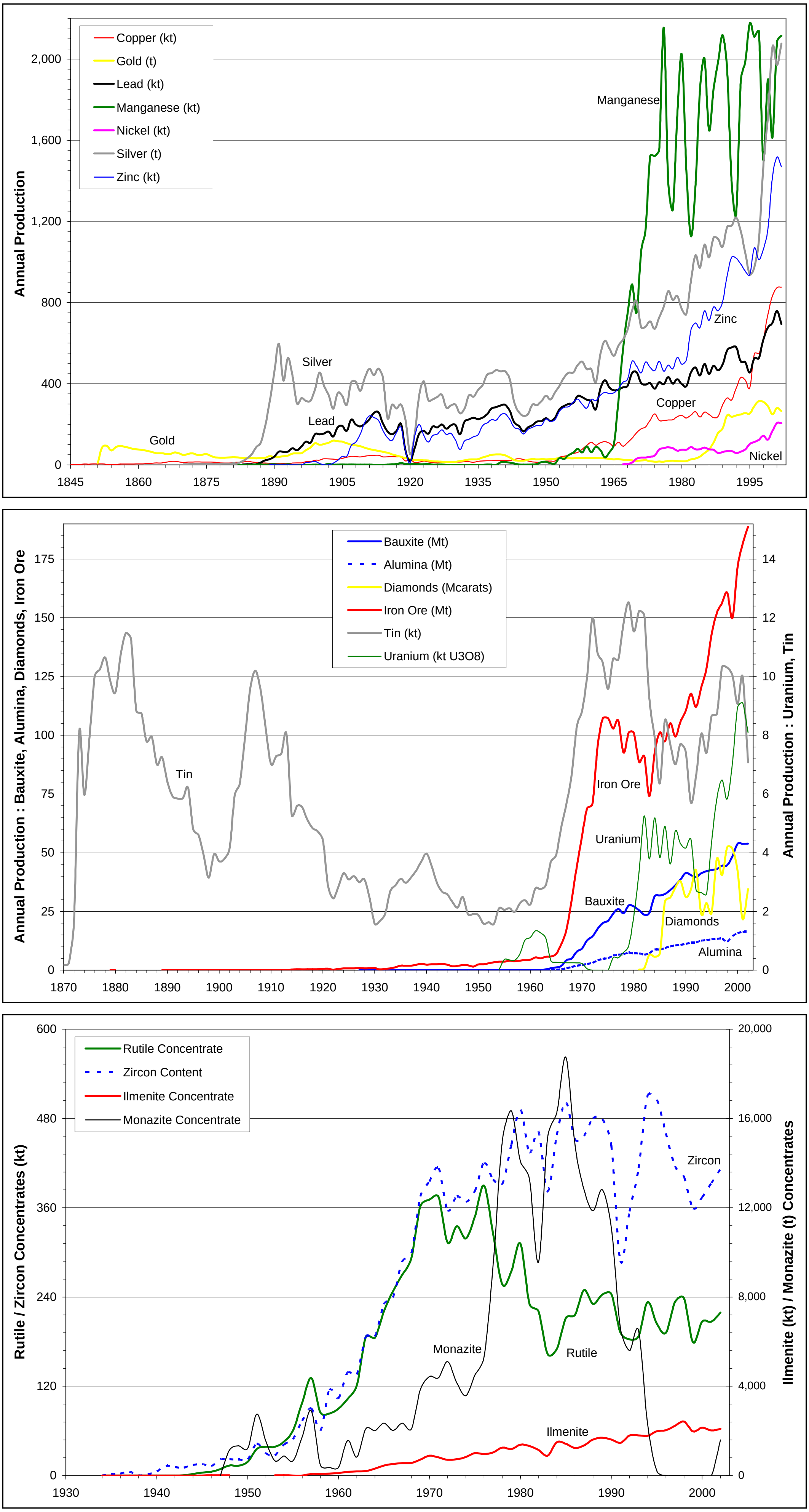

Figure 1. Annual Mineral Production in Australia

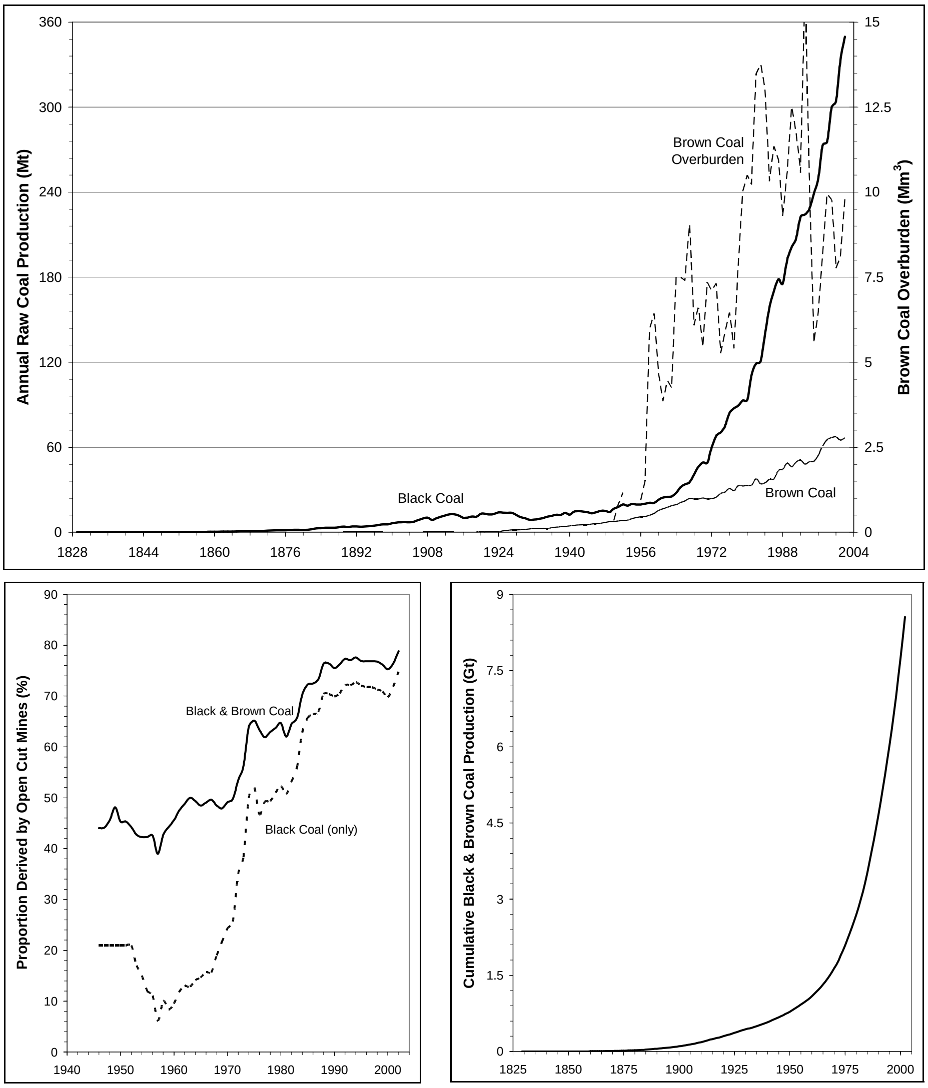

Figure 2. Australian black and brown coal production over time

Note : Brown coal overburden includes all Loy Yang and Hazelwood data & Yallourn 1956-1992 (missing 1920-55, 1993-2002). No data has been obtained for the Angelsea brown coal mine, ***nor any data for black coal mines***.

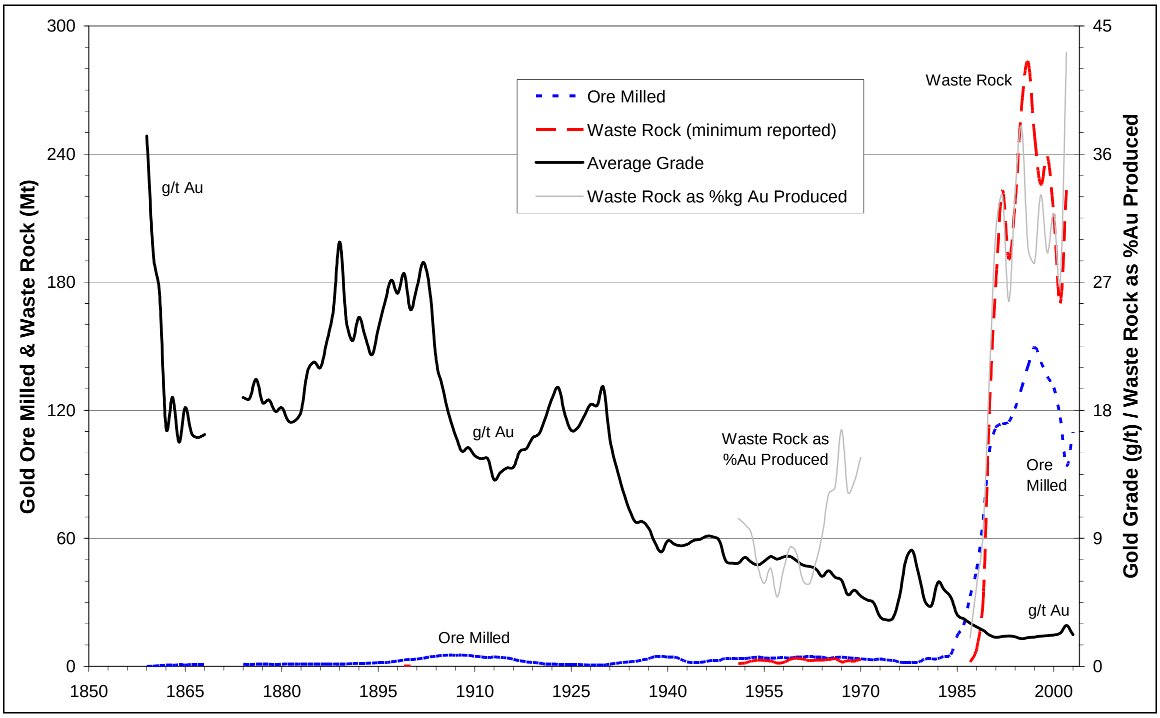

Figure 3. Australian Gold Ore Milled, Ore Grades and Waste Rock

Note : Includes the following years (i) VIC 1859-1869, 1874-1958, 1960-1976, 1983-2003; (ii) NSW 1875-1919, 1939-1940, 1947-1951, 1986-2003; (iii) QLD 1877-1920, 1949-1982, 1985-2003; (iv) SA 1892-1895, 1902-1955, 1988-2003; (v) NT ; (vi) WA 1895-1947 (some ore data estimated), 1948-2003; (vii) TAS 1900, 1996-2003 (excludes by-product gold).

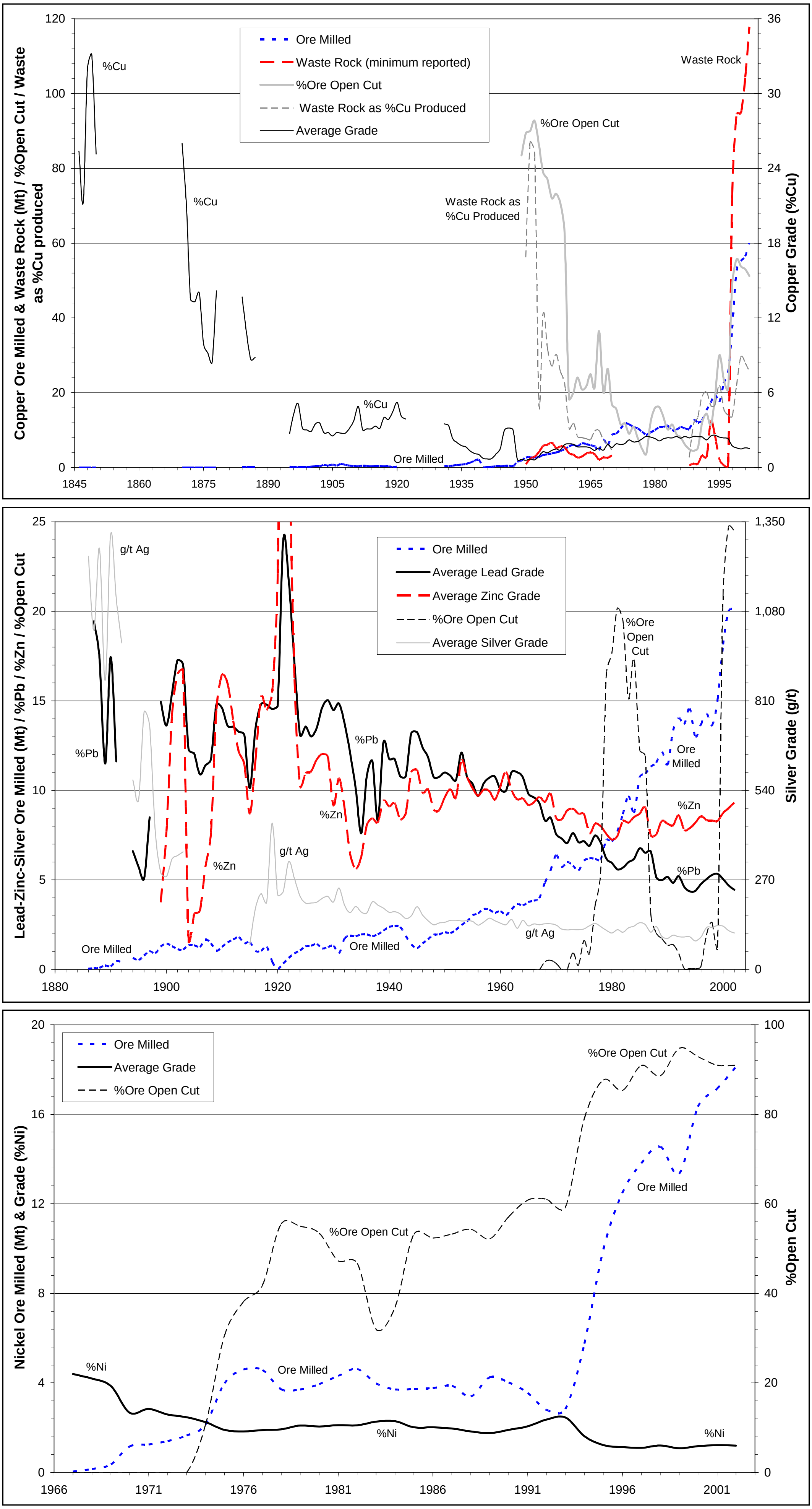

Figure 4. Australian Copper, Lead-Zinc-Silver and Nickel Ore Milled, Ore Grades, Waste Rock and %Ore Open Cut
Note : Data for copper prior to 1948 is sparse and indicative only.

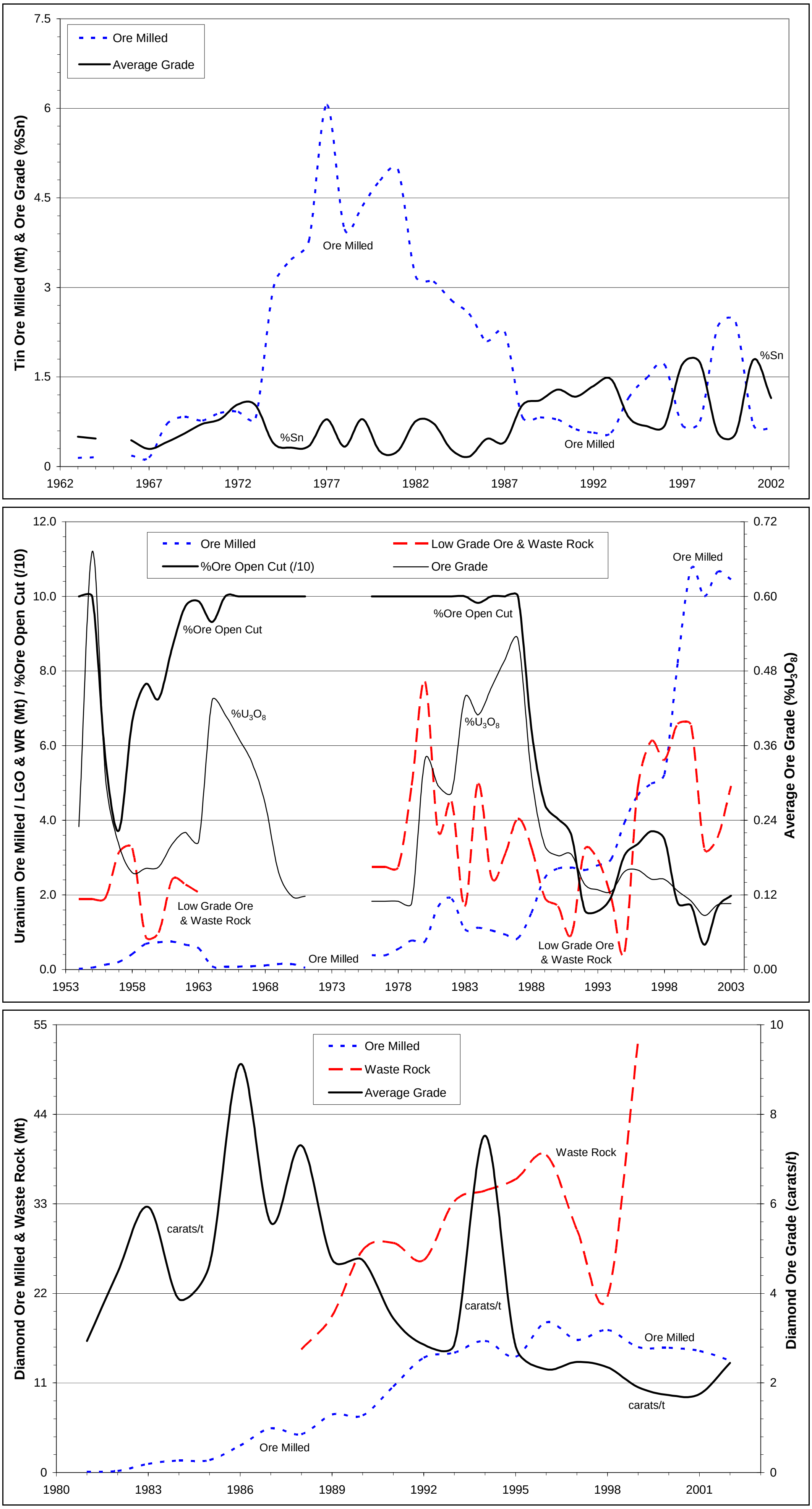

Figure 5. Australian Tin, Uranium and Diamond Ore Milled, Ore Grades, Waste Rock or %Ore Open Cut

Note : Data for tin over the 1990s is incomplete (lacking some years for Greenbushes, WA). All diamonds by open cut / alluvial mining.

Table 2. Extent of Rehabilitation of Mine Sites in Western Australia

Activity	2003 Annual (ha)			Cumulative Total to 31 Dec 2003		
	Disturbed by Mining	Preliminary Rehabilitation	Revegetation	Disturbed by Mining	Preliminary Rehabilitation	Revegetation
Borefields & pipelines	9	4	6	1,930	415	85
Camp site	8	3	2	1,366	394	304
Exploration	57	15	6	4,980	1,513	836
Mine Infrastructure	395	182	166	51,171	5,263	4,037
Open Cuts	655	285	109	35,678	8,815	6,105
Tailings Evaporation Dams	271	319	278	33,693	2,753	2,117
Waste Rock Dumps/ Heap Leach Piles	632	695	828	36,222	17,799	11,639
Total	**2,027**	**1,503**	**1,395**	**165,040**	**36,952**	**25,123**

Reference : Data Courtesy of WA Department of Industry & Resources (WADoIR).

Thus, in Western Australia, there is still a large tract of land that has yet to be rehabilitated. The actual areal extent of operating mines is not known, but as the data in Table 2 shows, the total area of impacts for mining is principally controlled by open cuts, tailings dams, water management dams, infrastructure, waste rock and ore/heap leach stockpiles. A similar pattern has been noted for Queensland (Anderson, 2002), and is likely to be a similar challenge in all states as well as globally. Most states in Australia have an ongoing budget, albeit generally minor, for the rehabilitation of old and abandoned mine sites, causing either environmental impacts or presenting public safety hazards.

4 DISCUSSION : IS THE AUSTRALIAN MINING INDUSTRY "SUSTAINABLE" ?

Overall, it can be seen that ore grades in Australia are reducing (tin and uranium being the exceptions), with some declining rapidly over the past century or so (eg. gold, copper). This general trend has also been noted for gold mining in the USA (Craig & Rimstidt, 1998) as well as internationally for many minerals (IIED & WBCSD, 2002). This has several major implications – first, it takes more ore per unit of mineral production; second, to continually expand mineral production requires an even more significant increase in ore throughput; and third, inputs such as energy and water for mining and processing per unit mineral production may increase, perhaps in spite of broad industry efforts to make mining and milling more efficient overall with respect to energy, water and environmental emissions.

Clearly there has been exploration success in Australia in recent decades to allow this situation to develop, whereby almost all minerals have seen noteworthy increases in production from progressively lower grade ores. Although it has not yet been possible to collate production versus known economic resources for given minerals in Australia, there does not appear to be much concern about potential mineral scarcity in the immediate future.

As noted in some graphs, there is a strong trend towards the use of open cut mines. For copper, the major mines of Mt Lyell and Mt Morgan led the introduction of large-scale open cut mines throughout the first fifty years of the twentieth century. As new mines such as Mt Isa began production, however, the trend shifted back to mostly underground mining until recently with the startup of Nifty (WA), Cadia (NSW), and numerous mines in the Clonclurry-Mt Isa copper belt of Queensland. The extent of open cut mining has generally been minor in scale for lead-zinc mines until the recent start of the Century Zinc project (QLD). The prominence of large-scale, low grade nickel mines such as Mt Keith and Murrin Murrin in WA has caused the shift from mostly underground to mostly open cut mining for nickel.

Although percentage open cut mining for a commodity has been estimated based on ore, there would be only minor difference if the proportion was calculated using the contained mineral. The immense scale of gold mining over the past 25 years has meant that it has not been possible to estimate the proportion of open cut mining for gold, though anecdotally it would be reasonable to expect a significant fraction (eg. half). The picture is further complicated for gold given that numerous mines operate both open cut and underground mines and do not distinguish the ore from each source during milling.

For most minerals, there is little or no waste rock data, with only a limited number of mines or companies publicly reporting the quantities produced each year in their annual corporate or environment reports. The waste rock shown for gold mining, which is more than the ore milled, only represents approximately 30-40% of the gold produced in the 1990's – much data is missing and not reported by the gold industry. Similarly, for copper, the waste rock data in the 1950's represented up to 80% of Australian copper production (ie. Mt Lyell and Mt Morgan), but in the 1990s it only represents 12-30% of copper production (including Cadia, Red Dome and Nifty) – that is, still not all operating mines.

A major issue associated with the scale of open cut mines and the waste rock they produce is acid mine drainage – oxidation of sulfidic minerals within waste rock (and/or tailings). Thus, as well as reporting the total quantities of solid wastes produced for a given mine site, it is important to assess and report on this critical issue. The MMSD report fails to articulate both the scale and seriousness of waste rock production in mining.

The trends shown by these numerous graphs are central in understanding the links between the environmental and social impacts of modern large scale mining and the resource base from which the minerals are produced.

In Australia, the Fimiston 'Super Pit' open cut gold mine in Kalgoorlie (WA) was recently opened in 1989 and the substantive Cadia (NSW) and Ernest Henry (QLD) Cu-Au and Century Zinc Zn-Pb-Ag (QLD) open cut mines were recently opened in the past decade. There are currently potential proposals for substantial open cut mines at Mt Isa Cu (QLD), Olympic Dam Cu-U-Au-Ag (SA) as well as McArthur River Pb-Zn-Ag (NT).

The exact future trend is uncertain but it is likely that open cut mining will continue to be a major feature of the Australia mining industry for the forseeable future. The scale and nature of the waste rock produced by such mines often causes community concern, especially regarding final rehabilitation.

By performing various regression analyses (using Microsoft Excel) on commodities such as coal and iron ore, which have seen almost exponential growth over the past forty years, some interesting correlations for future prediction can be found. Taking a 200-year timeframe only and using cumulative iron ore production over the past forty years, the total cumulative production can be estimated to reach some 25 Gt by the year 2200 using a linear regression (R^2 = 98.64%). Alternatively, for a 2-power polynomial , cumulative iron ore production reaches more than 80 Gt (R^2 = 99.82%). By 2002, cumulative iron ore production was 4 Gt. For coal, the same polynomial regressions give cumulative coal estimates by the year 2200 of some 33 and 4,400 Gt (R^2 = 83.92% and 99.98%), respectively. Whether these trends eventuate is difficult to predict.

It is clear that such exponential growth in production, which would have to come from massive scale mines even bigger than at present, cannot occur without significant long-term environmental risks.

As noted by (IIED & WBCSD, 2002), there is a trend for increasing mineral production from developing countries. The Australian trends are very evident in many of these large mines around the world – large, low grade deposits being mined through considerable open cuts (Young, 1992; Aswathanarayana, 2003; Ayres *et al*, 2003; Lottermoser, 2003). Good examples include Escondida in Chile, Grasberg in West Papua, Ok Tedi in Papua New Guinea and Bingham Canyon in Utah, USA, among numerous others. At most if not all of these open cut mines, it is the management and rehabilitation of both waste rock as well as tailings which is proving to be a major economic, environmental and social burden. For sites such as Grasberg and Ok Tedi, the only rational economic solution for solid wastes is riverine disposal – a practice which has caused and continues to lead to very significant and wide-spread environmental and social impacts.

A major issue which has not been given its due weight in the current sustainable mining debate is that of long-term rehabilitation. The recent generation of mines in Australia is rarely less than fifty years old, often being half that. While most modern mines have been developed under stricter legislation to mitigate both short- and long-term environmental risks, there is still a legacy of abandoned mines from earlier generations of mines when there were no effective legal requirements for rehabilitation. It is encouraging to see that many mining companies now report the area of land that they both disturb and rehabilitate each year in their environmental reports, as well as keeping cumulative respective totals.

The extrapolation of the long-term effectiveness of rehabilitation works is far from certain, however, despite the best engineering and science that can be bought to bear. If, in the long-term, there remains the gap between abandoned and rehabilitated land, the potential liability and scale of environmental problems could be sizeable. There has been considerable effort required in Australia to rehabilitate some former and/or abandoned mine sites (eg. Captain's Flat, NSW; Brukunga, SA; Mt Lyell, TAS; Rum Jungle, NT). The fact that ongoing research and/or monitoring often identifies various problems (eg. acidic drainage, erosion, weeds) raises legitimate concerns regarding any optimistic extrapolation of minesite rehabilitation performance over the long-term. Add to this the vast number and bigger scale of modern mines (due to open cut mining, tailings and waste rock), it can be argued that significant uncertainty remains regarding the mining cycle and its long-term environmental sustainability.

An underlying factor in the increasing scale of modern mining is the abundance of relatively low-cost energy, principally fossil fuels (coal, oil and gas). This provides the fundamental basis for long distance transport of products, services and people, the energy used for processing, the servicing of local mining communities, and other facets of modern life. If the cost of energy were to significantly increase in real terms, this would have a major impact on the relative economics of many commodities as well as the ability to profitably work numerous large scale open cut mines. Whether this would result in ore grades increasing, primary supply decreasing and recycling and substitution increasing remains to be seen and is very difficult to predict. It has been beyond the scope of the present research work to address this overall issue, but it will clearly be critical in the immediate future.

5 CONCLUSIONS

To answer the question of whether the Australian mining industry is sustainable, it is necessary to first determine one's perspective. From a production perspective, the answer would clearly have to be yes, since new technology and bulk earth moving machinery have combined to make it profitable to exploit larger, lower grade ore deposits and yet still significantly increase production over time. Whether the industry can maintain this pattern for a similar number of decades into the future is unknown (eg. 2100 AD), though there are some optimists. From an environmental perspective, however, the answer is clearly uncertain and fraught with challenges. Can rehabilitation technology keep pace with the scale of modern mining ? Will the increasing burden of waste rock and tailings per unit of mineral production continue to hamper serious efforts at sustainability ? These are not easy questions to answer, but it is abundantly clear that the environmental burden of mining per unit mineral production is and will continue to increase for the forseeable future.

To properly position the mining industry to answer these strategic questions requires that all the requisite data be publicly reported on an annual basis and regularly collated and published by a state or federal department or another appropriate organisation. At present, a considerable amount of relevant data is not publicly reported nor compiled. Thus, to help assess "sustainable mining", all mining companies need to be reporting the quantity of ore milled, assayed ore grades of all minerals extracted, the amount and nature of solid wastes produced such as waste rock and tailings (especially impurities and potential for acid mine drainage), all relevant environmental monitoring during operations and the extent and long-term success of rehabilitation works. Only over time with this data in hand can we begin to more accurately assess whether modern mining remains both economically, socially and environmentally sustainable.

6 ACKNOWLEDGEMENTS

This paper is a based on a broader research project examining the sustainability of mining in Australia. There have been many people and agencies who have helped generously to date, including the Tasmanian, Western Australian, Northern Territory and New South Wales 'Department of Mines' (their respective equivalents); Techa & Alice from the Mineral Policy Institute; Daniel Keane; various Monash University Librarians; Barlow-Jonker Pty Ltd; numerous mining companies (though not all asked were helpful); Minmet Australia Pty Ltd, and many others. There are also innumerably more individual references upon which the broader research of this paper is based on. If people would like the raw data upon which the graphs are based, please feel free to request it or ask for more specific detail regarding references. Eventually (and ideally) the "best possible" data set will be arrived at, with almost all years covered and minimal gaps. This paper is of course the author's own views.

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