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Copper case study: Australian resources, technology and future scenarios

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EXECUTIVE SUMMARY

This report provides a comprehensive data-compendium on copper to explore the links between resources, technology and changing environmental impacts over time as a basis for informing future research priorities in technology and resource governance.

A comprehensive analysis of how the geological characteristics of copper resources in the world are changing is performed such as analysing the ore grade trends. Global and national copper resources in addition to key copper mines are investigated. Furthermore, demand and production trends and economic considerations of mining are also investigated. Finally, the environmental impacts of different stages in copper mining are quantified and analysed using life cycle impact assessment with a focus on the effect of regional and time specific factors.

Analysis shows that Australia is currently the fifth largest copper producer in the world and is third in terms of copper reserves. The ore grade of mined copper in Australia (and globally) continues to decline while copper demand is increasing globally. The main copper mines in Australia extract sulphide ores. The decrease in mined ore grade increases the quantity of ore which must be extracted to produce each tonne of copper. In turn, this affects the cost of mining and increases the environmental impacts associated with copper mining. Additionally, multi factor productivity in the mining sector in Australia has been decreasing since 2000. Between December 2009-2010 it did not contribute to GDP growth within Australia.

Technological options arising from changes in geological conditions for terrestrial mining include in-situ leaching and deep sea mining, however, these have significant environmental and social barriers to wide scale deployment.

Research should also be directed to linking mining to clean energy sources with higher energy efficiency processes and the pursuit of enhanced recycling technologies and logistics. Such options should be evaluated in the context of changing global scenarios affecting metal production and consumption in order to position Australian research and knowledge development for value creation across the remainder of this century.

1. BACKGROUND

This copper case study is part of the Commodity Futures component of the Mineral Futures Collaboration Cluster. The Commodity Futures research focuses on the macro-scale challenges, the dynamics, and drivers of change facing the Australian minerals industry and overall project aims are to:

- explore plausible and preferable future scenarios for the Australian minerals industry that maximise national benefit in the coming 30 to 50 years
- identify strategies for improved resource governance for sustainability across scales, from regional to national and international
- establish a detailed understanding of the dynamics of peak minerals in Australia, with regional, national and international implications
- develop strategies to maximise value from mineral wealth over generations, including an analysis of Australia's long-term competitiveness for specified minerals post-peak.

This report covers the case study on copper resources, mining and smelting in Australia with consideration of future environmental and technological challenges facing the copper related mining and mineral industries of Australia.

1.1. Aim

The aim of this report is to establish a comprehensive data-compendium on copper and to explore the link between resources, technology and changing environmental impacts over time as a basis for informing future research priorities in technology and resource governance.

1.2. Introduction

Copper's characteristics such as ductility, malleability, high electrical and thermal conductivity in addition to corrosion resistance have made it one of the base metals with high applications for thousands of years. It has been used in applications requiring electrical and thermal conduction, building materials, and is the main element of many alloys such as bronze and brass.

Copper continues to play an essential role in our society with electrical applications, power generation, transformers, motors, and cables and electrical equipment like wiring and contacts, televisions, PCs, and mobile phones. It is also used in construction such as plumbing and roofing, and transport. Although it has been used for thousands of years it is only the last hundred years that production of copper has significantly increased.

The importance of copper in industrial applications is expected to rise in the coming years due to its applications in energy efficiency projects and motors for electric vehicles.

1.3. Historical global copper production

World copper production has been increasing exponentially at 2.75% a year for over a hundred years, as shown in Figure 1.1.

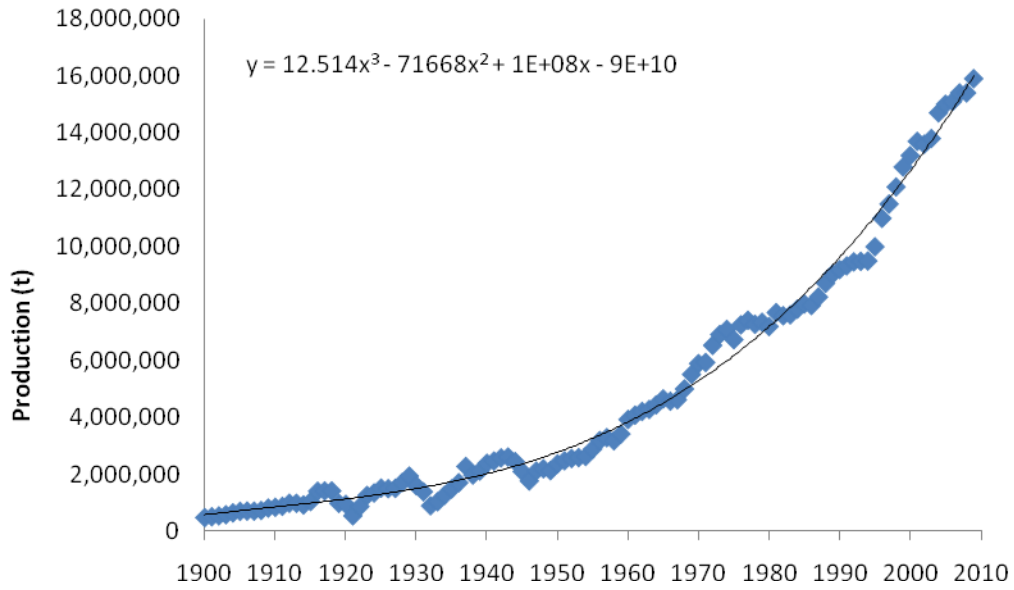


Figure 1.1: World copper production history from 1900, actual data from USGS DS140, 2010

World production is now approximately 16 Mt a year of copper (USGS DS140). As shown in Table 1.1, Chile produces almost one third of the world's copper, and the next 5 major countries (Peru, China, US, Australia, and Indonesia) produce another third of world production and the remaining production is spread across the rest of the world.

Table 1.1: World production of copper in 2010 (USGS MCS).

Country	Production (kt)
Chile	5,520
Peru	1,285
China	1,150
US	1,120
Australia	900
Indonesia	840
Zambia	770
Russia	750
Canada	480
Poland	430
Kazakhstan	400
Mexico	230
Other	2,300
World	**16,200**

1.4. Current global copper reserves

The world's reserves of copper are presented in Table 1.2. As expected Chile, which dominates copper production also dominates copper reserves with approximately 25%. The next two countries (Peru and Australia) combined represent another 25% of world reserves, with the remaining 50% of reserves spread evenly across the other nations. An interesting point to note is that although Australia is the fifth largest producer, it has the third largest reserves, indicating that Australia may be able to play a more significant role in world copper production in future.

Table 1.2: The reserves of copper (USGS Jan 2011).

Country	Reserves (kt)
Chile	150,000
Peru	90,000
Australia	80,000
Mexico	38,000
US	35,000
China	30,000
Indonesia	30,000
Russia	30,000
Poland	26,000
Zambia	20,000
Kazakhstan	18,000
Canada	8,000
Other	80,000
World	**630,000**

1.5. Changing copper ore grades

Copper ore grades around the world are declining as is evident in Figure 1.2. In the 1800s copper grades where very high, over 10% in Australia and around 8% in Canada, however by 1900 the grades had declined to under 4%. Currently Australia, Canada and the USA have copper ore grades of less than 2%.

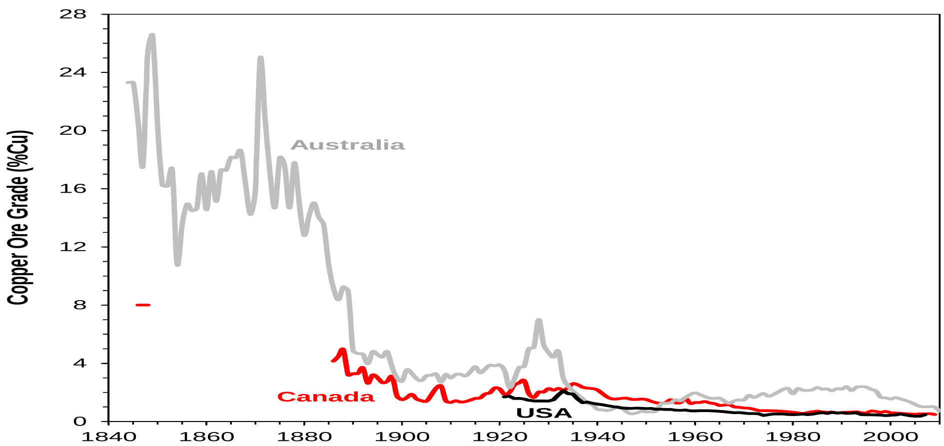


Figure 1.2: The ore grade declines in USA, Canada and Australia

1.6. Historical copper price

The price of copper in US dollars over time is shown in Figure 1.3; both the real price and inflational adjusted price relative to 1998 dollars are shown. The inflation adjusted price of copper had been declining since the 1970s until the earlier 2000s. Since 2003 the price of copper rapidly increased to a level not reached since 1970. Although copper prices declined in the global financial crisis of 2008, they have begun to increase once more.

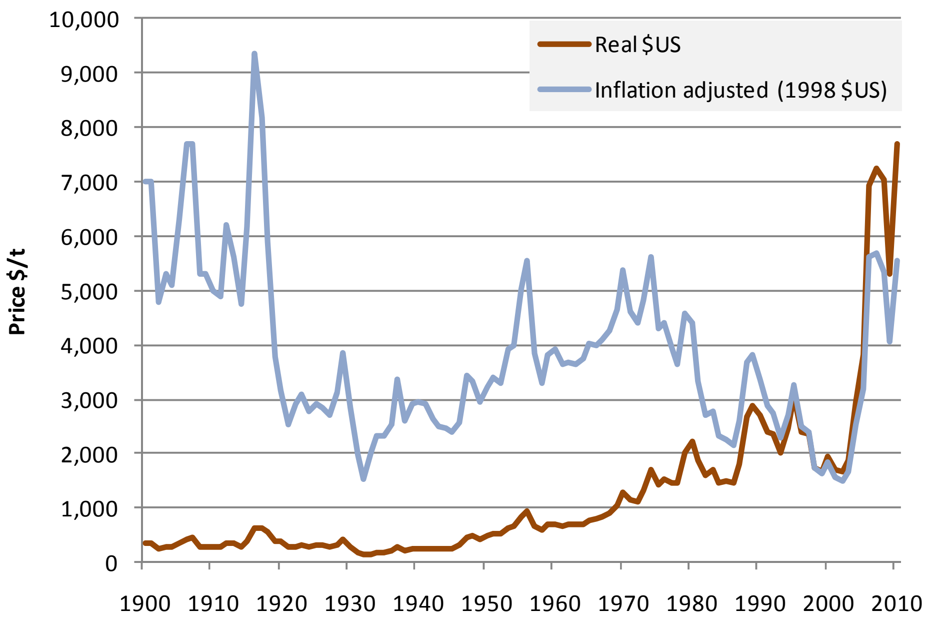


Figure 1.3: The price of copper over time (USGS DS 140 2010).

1.7. Copper demand by end use

The breakdown of copper uses is shown in Table 1.3. There is a strong demand for copper as it is used in electrical applications, power generation, transformers, motors, and cables and electronic devices. It is also used in construction such as plumbing and roofing, and transport. Copper is an important resource in the electronics and construction industries. Given that demand (~24-22 Mt in 2008-09) is greater than primary production (~16 Mt in 2010), the difference is met by production from secondary sources which recycle scrap (as well as smaller changes to annual inventories held).

Table 1.3: The demand for copper (kilotonnes) in recent years (International Copper Study Group, 2009, 2010)

Industry	Use	2008	2009
Construction	Plumbing	1,528	1,336
Construction	Building plant	137	133
Construction	Architecture	499	327
Construction	Communication	223	193
Construction	Electrical Power	3,712	5,273
Infrastructure	Power utility	2,624	2,541
Infrastructure	Telecom	874	725
Equipment Manufacture	Industrial	4,603	2,742
Equipment Manufacture	Automotive	1,909	1,590
Equipment Manufacture	Other Transportation	1,086	967
Equipment Manufacture	Consumer and General Products	2,001	1,814
Equipment Manufacture	Cooling	1,643	1,330
Equipment Manufacture	Electronics	856	768
Equipment Manufacture	Diverse	2,252	2,359
Total (kilotonnes)	**All**	**23,947**	**22,098**

2. COPPER IN AUSTRALIA

2.1. Production

Australia is the fifth largest producer of copper behind Chile, Peru, China, and USA and has been producing copper for around 160 years. The copper mines in South Australia during the 1850s-70s were important globally at the time. Australia's historic copper production is shown in Figures 2.1 and Australia's copper production from the 1950s onward is presented in Figure 2.2 (note the change of scale). As depicted Queensland and South Australia are the main producers of copper in Australia, with NSW and Western Australia making significant contributions.

Australia's remaining economic resources have the potential to maintain a position among the world's leading mineral nations. Consequently proper management of copper extraction and processing in Australia should be examined further to see what is required to ensure the provision of long term benefit for future generations.

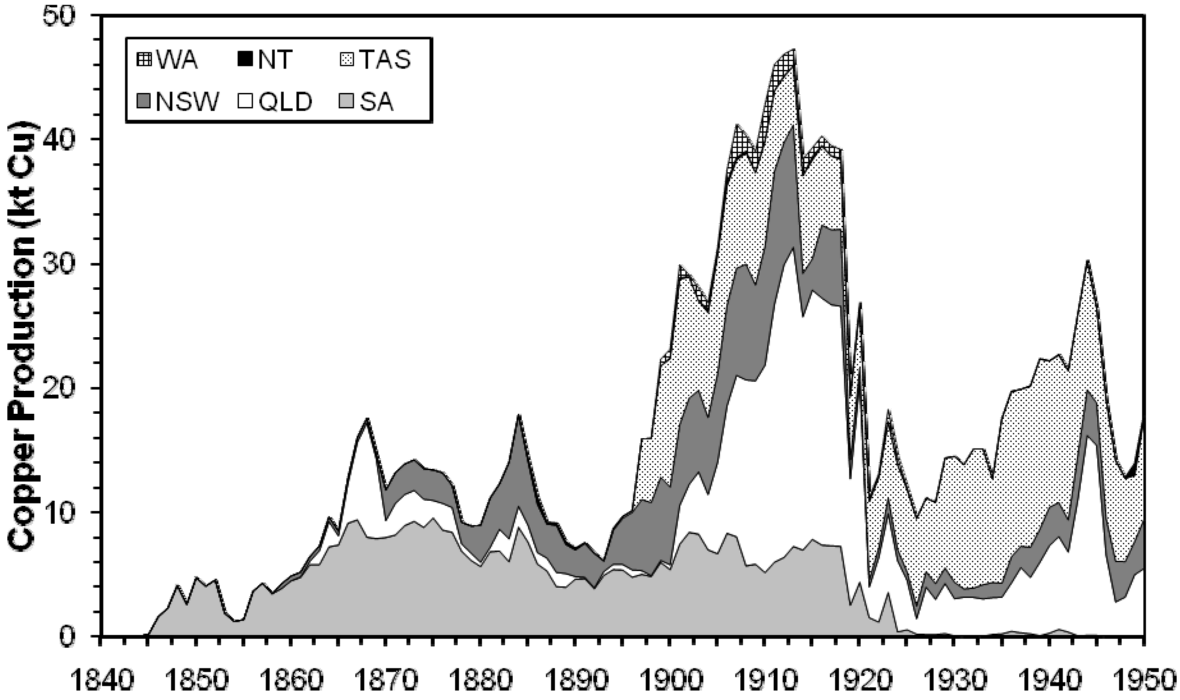


Figure 2.1: Australian Copper production between 1840 – 1950 by state (Mudd, 2010)

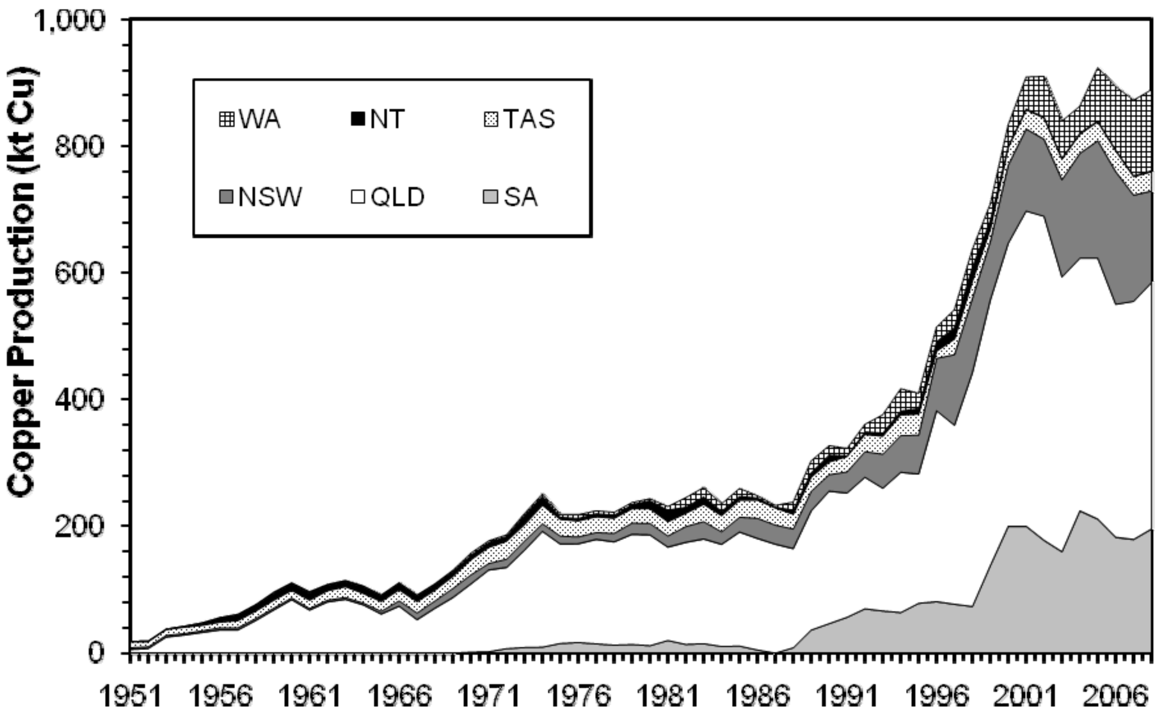


Figure 2.2: Australian Copper productions between 1950 – 2010 by state (Mudd, 2010)

Regarding peak annual production, the copper resource life using national Economic Demonstrated Resources divided by annual production is 91 year however (Mudd and Ward, 2008) states that ultimately, the world may not physically 'run out' of copper, coal, gold or other minerals, but aggregate primary production of copper will peak and decline as new mining operations become increasingly constrained by lower grade mineral deposits, greenhouse emissions, energy costs and water. Prior et al. (2012) also highlight the importance of social constraints on future production. A modelled peak point for copper production is shown in Figure 2.3.

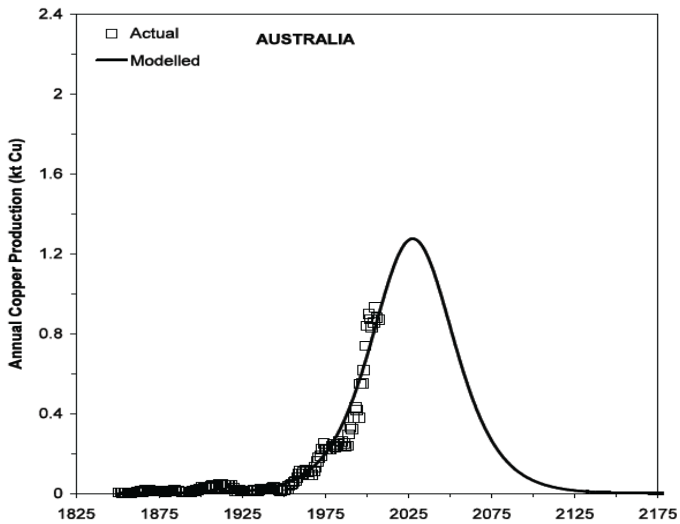


Figure 2.3: Modelled copper production with peak prediction (Mudd and Ward, 2008).

2.2. Producing copper mines

Australia's major copper mine producers are shown in Table 2.1, and summary information is provided in Table 2.2. As depicted, prior to the late 1980s Mt Isa dominated Australia's copper industry. Since the late 1980s Australia's copper production has significantly increased from around 250 kt Cu to just less than 900 kt Cu currently. The significant increase in production has been due to major new mines opening, including but not limited to Olympic Dam in 1988, Nifty in 1993, Osborne in 1995, NorthParkes in 1996, Ernest Henry in 1997, Ridgeway in 2000, Telfer in 2005 and Prominent Hill in 2009. Interestingly, the size of large mines appears very stable, with the large mines typically producing between 20 and 150 kt Cu per annum.

As indicated in Table 2.1, copper production from Mt Isa, Olympic Dam and Prominent Hill dominate production and these three mines combined produce nearly 50% of Australia's copper production. Currently, all of Australia's copper producers use conventional underground or open cut mining in combination with a flotation mill to produce a copper concentrate (which often contains gold as a by-product or in some cases as the primary product with copper a by-product). Only the Olympic Dam project has a combined mine, mill, smelter and refinery complex, with the Mt Isa project also containing a mine, mill and smelter complex (a copper refinery is located in Townsville). Although there have been some moderate scale projects which have used heap leaching and solvent extraction-electrowinning technology, these are closed at present due to recent copper price volatility (e.g. Lady Annie) or, following exhaustion of oxide ore, converted to a conventional mine-mill for sulphide ores (e.g. Nifty). In general, there has not been any substantive or radical change in technological approach for copper production in Australia for some decades, with most changes occurring as incremental improvements over time.

Table 2.1: Copper producing mines in Australia in 2010 (Mudd, 2010).

Mine / Project	M	C	S	R	Ore Type	t ore	%Cu	g/t Au	g/t Ag	t Cu	kg Au	kg Ag	t waste rock	%ore OC	%Cu OC	Company
Mt Isa	X	X	X		Cu	6,092,414	2.91			157,696				0	0	Xstrata
Olympic Dam	X	X	X	X	Cu-U-Au-Ag	7,046,000	0.54	5.01	1.88	131,800	2,127.8	17,634	563,680	0	0	BHP Billiton
Prominent Hill	X	X			Cu-Au-Ag	9,537,461	0.82	2.96	1.32	112,171	6,108.0	19,152	53,353,057	100	100	OZ Minerals
Ernest Henry	X	X			Cu-Au	9,838,428	0.69	0.34		74,595	2,838.2		16,782,266	100	100	Xstrata
Nifty	X	X			Cu	2,250,610	2.90			61,061			6,527,600	0	0	Aditya Birla Minerals
Northparkes	X	X			Cu-Au	5,248,000	0.82	0.51		39,000	2,030.8			0	0	Rio Tinto
Golden Grove	X	X			Pb-Zn-Ag-Cu-Au	1,597,026	0.71	37.0	2.37	34,291	1,129.1	59,169		0	0	MMG
Telfer	X	X			Au-Cu	22,944,000	0.17	1.06	0.6	33,213	21,164.7	13,766	24,721,000	74.53	40.22	Newcrest
Boddington	X	X			Au-Cu	26,619,062	0.12	1.03		26,309	22,640.8			100	100	Newmont
Cadia Hill	X	X			Au-Cu	17,512,000	0.17	0.82		26,026	11,621.5	5,400	5,627,000	100	100	Newcrest
Mt Lyell	X	X			Cu-Au-Ag	2,120,000	1.21	0.3	3	23,777	3800	380		0	0	Vedanta Resources
Osborne[#1]	X	X			Cu-Au	1,026,043	2.33	0.89		22,676	839.7			0	0	Ivanhoe Australia
Mt Garnet Group	X	X			Pb-Zn-Ag-Cu-Au	956,767	2.03	0.29	22.9	17,773	106.0	14,800	3,025,000	6.64	6.64	Kagara Zinc
Ridgeway	X	X			Au-Cu	4,312,000	0.46	1.23		17,351	4,330.2			0	0	Newcrest
Tritton	X	X			Cu	683,110	2.14			14,274				0	0	Straits Resources
Jaguar	X	X			Pb-Zn-Ag-Cu	363,567	3.24		63	9,660		18,336		0	0	Jabiru Metals
Sally Malay	X	X			Ni-Cu-Co	630,716	0.59			3,626				0	0	Panoramic Resources
Rosebery	X	X			Pb-Zn-Ag-Cu-Au	724,791	0.38	1.72	125.0	2,087	981.2	78,709		0	0	MMG
Kambalda Field	X	X			Ni-Cu	1,060,823	0.22			1,923						Various
Cairn Hill	X	X			Fe-Cu	124,444	0.52			324			3,098,600	100	100	IMX Resources
Cadia East[#2]	X	X			Au-Cu	79,000	0.36	0.79		240	51.1			0	0	Newcrest
Angas	X	X			Pb-Zn-Ag-Cu-Au	392,144	0.23	0.35	28.2	145	94.9	7,699		0	0	Terramin
Peak	X	X			Au-Cu									0	0	New Gold
					Totals	**121,158,407**	**0.59**	**1.7**	**1.6**	**810,017**	**79,864**	**235,045**	**113,698,203**	**66.69**	**60.19**	

Note: M – mine, C – concentrator, S – smelter, R – refinery, OC – open cut.

2.3. Copper resources, reserves and their ore geology in Australia

In terms of economic and sub-economic resources, new deposits continue to be discovered as well as major expansions at existing deposits. A compilation of the top 10 copper deposits and top 10 copper operating mines in Australia by contained copper is given in Table 2.2. As shown, Australia has an estimated 113 Mt of copper resources, with the vast bulk of resources of almost 79 Mt of copper in the Olympic Dam mine. Almost all copper deposits contain gold, with some also containing silver, uranium, lead or zinc. Of these deposits, over half have been found in the past 30 years, with some near surface (e.g. Rocklands) while others are at significant depth (e.g. Olympic Dam, Carrapateena). The discovery of the Olympic Dam deposit in 1975 heralded a major breakthrough in exploration targeting, since the deposit was the first major discovery using combined geophysics and geological theory – although the deposit turned out to be an entirely new type of mineralisation previously unrecognised in the global copper industry (the breccia complex, now known as iron oxide copper-gold-silver deposits).

Table 2.2: Top 10 operating copper mines and Top 10 copper deposits in Australia by contained copper in 2010 (Mudd, 2010).

State	Mine / Deposit	Status	Mineral Type	Mt ore	%Cu	g/t Au	g/t Ag	kt Cu	kg Au	kg Ag	Others
SA	Olympic Dam	Operating	Sulfide	9,075	0.87	0.32	1.50	78,952.5	2,904,000		U
NSW	Cadia East	Operating	Sulfide	2,347	0.28	0.44	0.47	6,571.6	1,032,680	1,103,090	
WA	Boddington	Operating	Sulfide	1,531.2	0.10	0.59		1,577.2	899,148		
NSW	Cadia Hill	Operating	Sulfide	408	0.12	0.42		489.6	171,360		
WA	Telfer Main Dome	Operating	Sulfide	369	0.10	0.88		369.0	324,720		
NSW	Northparkes	Operating	Sulfide	365	0.55	0.27		2,000.2	99,720		
SA	Prominent Hill	Operating	Sulfide	285.35	0.89	0.79	2.39	2,540.2	225,922	682,919	
WA	Telfer West Dome	Operating	Sulfide	247	0.06	0.65		148.2	160,550		
QLD	Mt Isa	Operating	Sulfide	200	2.01			4,028.0			
NSW	Ridgeway	Operating	Sulfide	155	0.38	0.73	0.81	589.0	113,150	125,550	
WA	Spinifex Ridge	Deposit	Sulfide	843	0.085			712.6			Mo
QLD	Mt Elliott	Deposit	Sulfide	570	0.44	0.24		2,490.0	135,000		
QLD	Mt Isa (Open Cut)	Deposit	Sulfide	283	1.11			3,130.0			
QLD	Rocklands	Deposit	Sulfide	245	0.21	0.04		505.6	9,420		Co
NSW	Marsden	Deposit	Sulfide	224	0.32	0.17		716.4	37,160		
SA	Carrapateena	Deposit	Sulfide	203	1.31	0.56	6.0	2,659.3	113,680	1,218,000	U
NSW	Copper Hill	Deposit	Sulfide	173	0.31	0.26		536.3	44,980		
SA	Hillside	Deposit	Sulfide	170	0.7	0.2		1,190.0	34,000		
QLD	Mt Dore	Deposit	Sulfide	145	0.52	0.1	5.9	751.1	14,500	861,300	Re, Mo
NSW	Temora	Deposit	Sulfide	142.2	0.32	0.29		461.4	40,825		Mo

Copper minerals are mostly in the form of sulphide ores in Australia but there are also oxide ores such as Lady Annie and Roseby Group mines in Queensland and Nifty in Western Australia (Nifty also has sulphide ore) . The smelting process for sulphide ores is mainly pyrometallurgical and is hydrometallurgical for oxide ores. An overview of mining sites is shown in Figure 2.4.

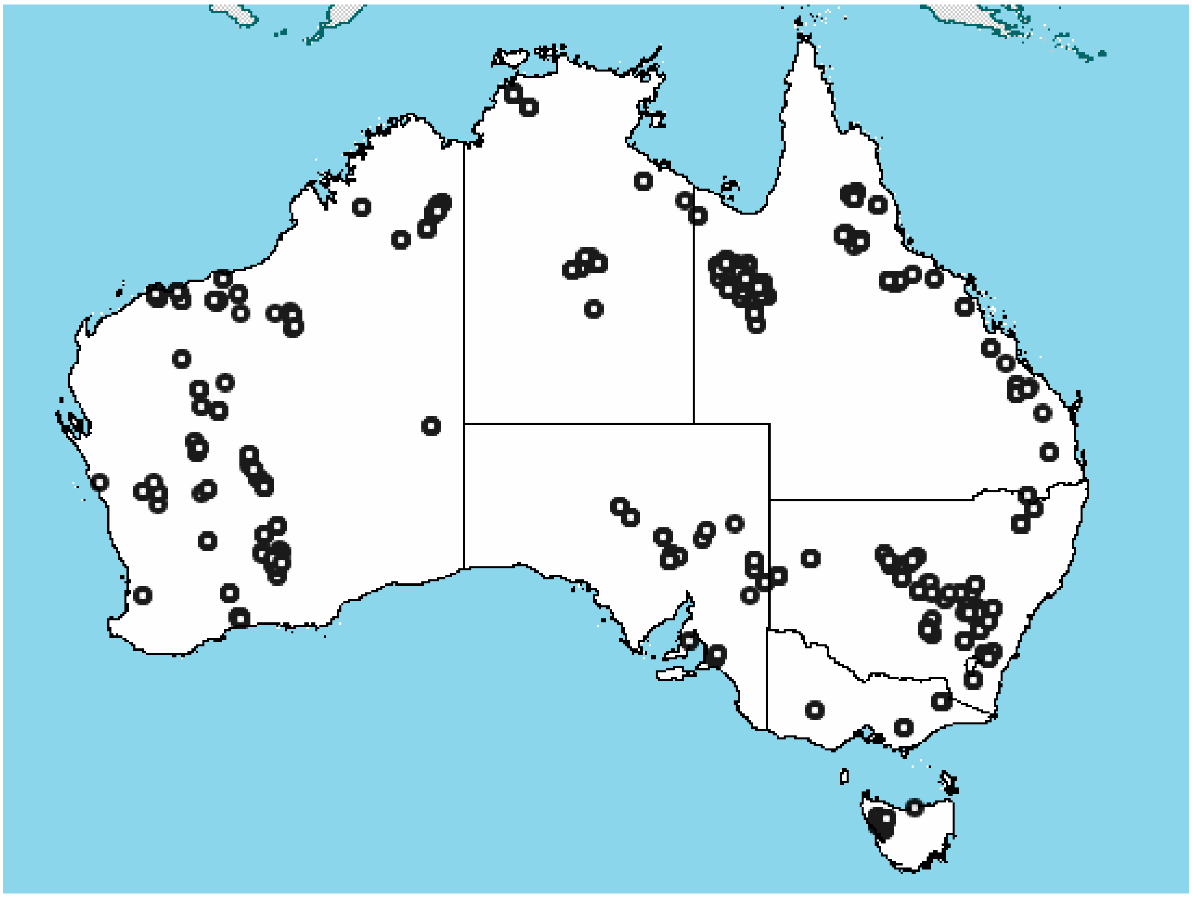


Figure 2.4 Australia's copper mines (Australian mines atlas)

2.4. Exports of copper

The export of natural resources is the main source of Australian export income (dominated by coal and iron ore). The copper sector contributes 0.4% to GDP and more than AUD 6 billion export earnings from concentrate and refined copper. The quantity of copper Australia has exported is shown in Figure 2.5, and the values of copper exports are presented in Figure 2.6. It shows that the volume and value of copper exports have increased over time.

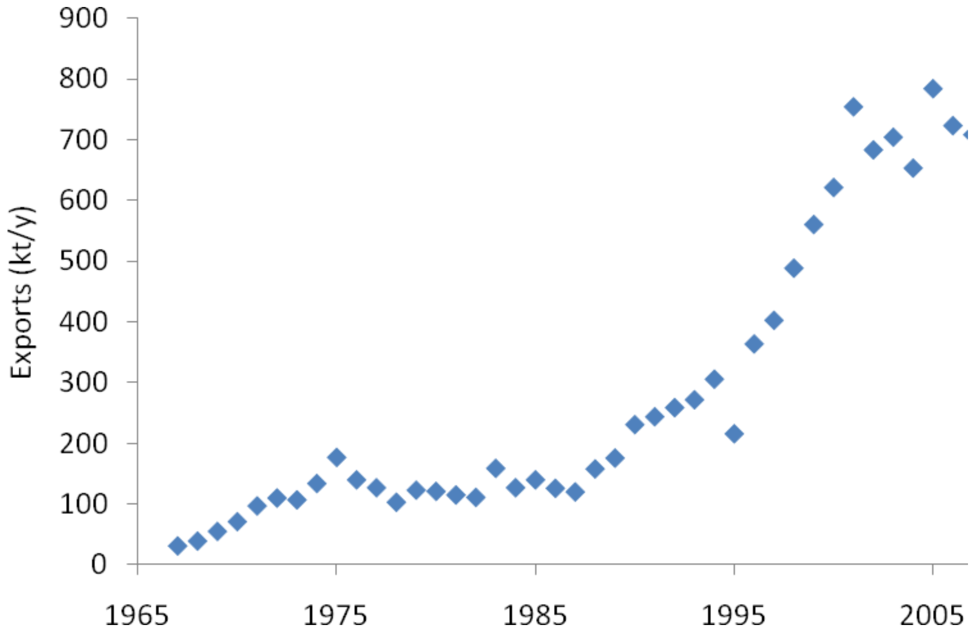


Figure 2.5: Australia's exports of copper (ABARE, 2010).

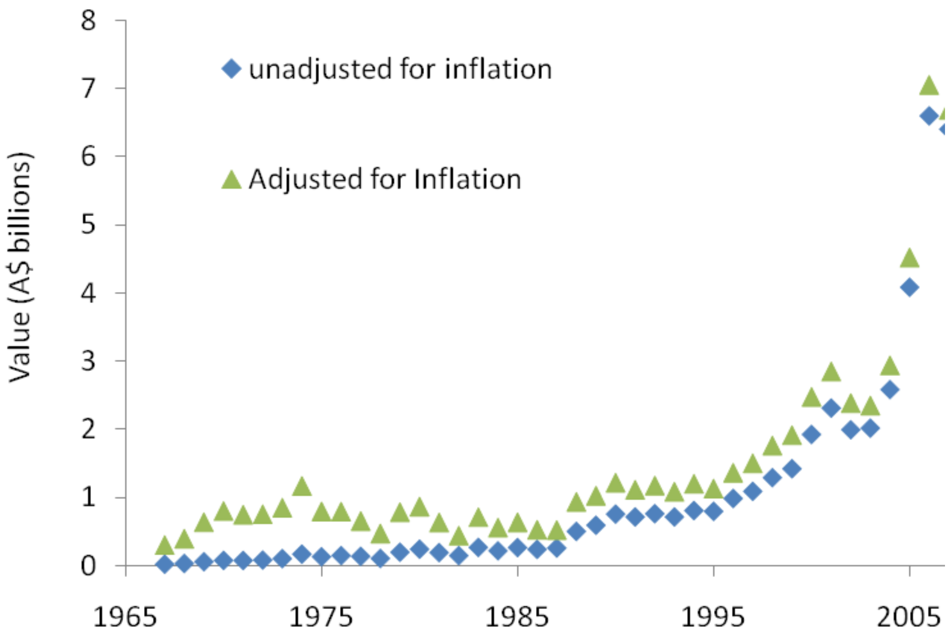


Figure 2.6: The value of Australia's copper exports (ABARE, 2010) [1].

[1] The inflation rate is taken from http://www.rateinflation.com/consumer-price-index/australia-historical-cpi and then is used to calculate the adjustment for inflation.

3. GLOBAL ECONOMIC COPPER RESOURCES

3.1. Quantifying copper resources

This study compiles a range of copper resources reported by mining companies based on statutory mineral resource codes. In Australia, all mineral resources are reported based on the Joint Ore Reserves Committee Code (or 'JORC'), which provides a detailed methodology to assess and quantify a given deposit as economic. The use of JORC in the context of peak metals is discussed further by Giurco et al. (2010). Some countries also have similar codes, such as SAMREC in South Africa or NI-43-101 in Canada.

For this report, an extensive list of global copper resources was compiled in order to assess and compare Australia's global position in the copper sector. All resources are based on company or government reporting, based on mineral resource reporting codes or a similar approach.

3.2. Overview of copper deposit types

In general (but at the risk of unfair over-simplification), the major geologic processes which form ore deposits include hydrothermal processes, granite intrusions, magmatic formation, volcanism, metamorphism, sedimentary formations, or meteorite-related impacts. A combination of processes can also be important, such as hydrothermal solutions in sedimentary environments or metamorphism of previous mineralisation. It is also common for some metals to occur together, such as Cu-Ni, Pb-Zn or Pb-Zn-Cu (mainly related to their individual elemental geochemistry and the primary processes of ore body formation), along with precious metals, such as Au, Ag or platinum group elements (PGEs), though in widely varying concentrations from 0.1 to 5 g/t Au, <1 to 500 g/t Ag and <0.2 to 10 g/t PGEs.

Copper is dominantly found in mineral deposits broadly classified as porphyry, sediment-hosted and volcanic massive sulfides (VMS), and together these ore types account for some 90% of copper production throughout most of the twentieth century (Gerst, 2008). Porphyry Cu deposits are formed by igneous intrusions which introduce hydrothermal alteration and precipitate Cu, often in association with Au, Ag and/or molybdenum (Mo), with grades often ranging from 0.2 to 1% Cu but sizes reaching up to billions of tonnes. Sediment-hosted Cu deposits are formed by hydrothermal solutions released into a water reservoir, commonly the ocean, leading to the formation of metal-rich layers. These are also known as sedimentary exhalative (or 'SedEx') deposits, with common grades of 1 to 3% Cu and sizes from tens to hundreds of millions of tonnes. VMS Cu deposits, as the name implies, are closely related to volcanic activity, whereby hydrothermal solutions derived from volcanism, generally on the ocean floor, lead to the formation of sulfide minerals rich in Cu and commonly associated with Pb, Zn, Au and Ag. Grades can be rich, ranging from 1 to 10% Cu and highly variable grades for other metals, but sizes are commonly smaller and in the order of tens of millions of tonnes, although there are often many such deposits in a region. Other important types of Cu deposits include iron oxide copper-gold (or IOCG), magmatic (or basalt-related) Ni-Cu ores, as well as oxide deposits (i.e. weathered ores) and native (elemental) Cu ores.

3.3. Global Copper Resources

National estimates of economic Cu resources over time for selected countries are shown in Figure 3.1.

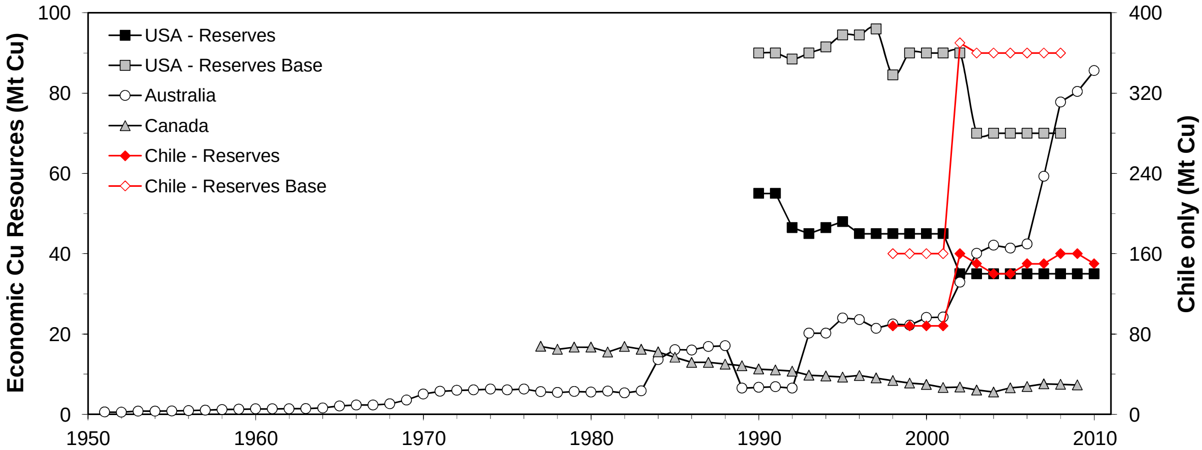


Figure 3.1: Historical trends in economic Cu resources for Australia, Canada, Chile and the USA (Mudd & Weng, 2012)

A comprehensive compilation of Cu resources undertaken for this report by deposit and country is summarised in Table 3.1, with the 20 largest Cu deposits in Table 3.2.

Table 3.1: Compilation of global copper resources by country (sorted by Mt Cu)

Country	No.	Ore/Mt	%Cu	Mt Cu		Country	No.	Ore/Mt	%Cu	Mt Cu
Chile	47	115,102.5	0.54	627.23		South Africa	39	14,610.3	0.08	11.66
Peru	39	27,851.9	0.48	134.47		India	14	1,394.4	0.82	11.42
USA	48	32,785.6	0.41	134.20		Brazil	8	2,331.3	0.48	11.29
Australia	150	20,160.5	0.63	126.71		Iran	1	1,200	0.7	8.4
DRC	21	2,288.9	2.34	53.64		Fiji	1	2,287.7	0.35	8.01
Mexico	29	16,442.6	0.32	53.17		Botswana	9	1,287.7	0.51	6.59
Indonesia	5	7,458.9	0.67	50.07		Sweden	18	2,607.6	0.23	5.91
Zambia	19	4,524.5	1.03	46.74		Finland	31	2,197.7	0.19	4.28
Canada	78	13,093.7	0.33	42.62		Laos	4	399.8	0.80	3.20
Russia	12	4,128.3	0.95	39.13		Zimbabwe	4	2,138.5	0.11	2.41
Mongolia	6	4,485.0	0.87	39.09		Portugal	1	67.2	2.75	1.85
Kazakhstan	7	6,682.0	0.47	31.22		Namibia	9	175.2	0.80	1.41
Poland	4	1,539.0	2.00	30.77		Spain	3	33.3	3.48	1.16
PNG	12	5,333.8	0.49	26.08		Saudi Arabia	3	81.3	1.38	1.12
Philippines	13	5,363.3	0.47	25.10		Eritrea	4	94.2	1.13	1.06
Argentina	6	6,451.5	0.39	25.00		Greece	2	192.2	0.55	1.06
Pakistan	1	5,867.8	0.41	24.06		Thailand	2	200.0	0.51	1.02
Panama	1	6,465.0	0.30	19.36		Various	23	1,551.4	0.28	4.38
						Total	**674**	**318,875**	**0.51**	**1,614.9**

Notes: No. – number of deposits; USA – United States of America; DRC – Democratic Republic of Congo; PNG – Papua New Guinea.

Table 3.2: Top 20 copper resources by deposit/project (sorted by Mt Cu)

Deposit/Project	Status	Ore/Mt	%Cu	g t^{-1} Au	Mt Cu	t Au	Other Metals
Andina, Chile	Op	19,162	0.59		113.63		
El Teniente, Chile	Op	16,756	0.56		93.50		
Olympic Dam, Australia	Op	9,075	0.87	0.32	78.95	2,904	U-Ag
Collahuasi, Chile	Op	9,554	0.81		77.54		
Chuquicamata, Chile	Op	10,497	0.55		57.31		
Escondida, Chile	Op	8,509	0.61		52.13		
Grasberg, Indonesia	Op	4,946	0.81	0.71	40.21	3,493	Ag
Pebble, USA	Dep	10,777	0.34	0.31	36.56	3,337	
Taimyr Peninsula, Russia	Op	2,188	1.45	0.22	31.74	486	Ni-PGMs
Los Pelambres, Chile	Op	5,818	0.53	0.04	30.84	233	Mo
Los Bronces, Chile	Op	6,420	0.44		28.39		
Buenavista del Cobre, Mexico	Op	8,388	0.33		27.80		
Radomiro Tomic, Chile	Op	7,247	0.37		26.67		
Reko Diq, Pakistan	Dep	5,868	0.41	0.22	24.06	1,291	
Resolution, USA	Dep	1,624	1.47		23.87		Mo
Hugo Dummett North, Mongolia	Dev	1,426	1.39	0.35	19.81	492	
Cobre Panama, Panama	Dep	6,465	0.30	0.05	19.36	342	Ag
Toquepala, Peru	Op	5,029	0.36		18.18		
Los Sulfatos, Chile	Dep	1,200	1.46		17.52		
Cerro Verde, Peru	Op	4,038	0.41		16.72		
Total		**144,987**	**0.58**		**834.8**	**12,578**	

Notes: Op – operating; Dev – under development; Dep – deposit; USA – United States of America.

For Australia, an additional 46.0 Mt Cu (to the figure of 85.6 Mt Cu in Figure 3.1) is reported as sub-economic or marginal resources, giving Australia a total of 131.6 Mt Cu of identified resources. Over time, it is common for identified resources to be upgraded to economic status after further drilling, metallurgical and other studies, and be developed for production, showing that the higher resource figure is of importance for long-term planning or modelling of Cu production scenarios. The Olympic Dam deposit, at 79.0 Mt Cu, represents some 60% of Australia's identified Cu resources, showing the importance of super-giant deposits.

Chile is clearly in a dominant position in global Cu resources, with some 39% of global Cu resources based on our data and 9 of the top 20 deposits – 627.2 Mt Cu also contrasts with the USGS reserves estimate of 150 Mt Cu (and 2008 reserves base estimate of 360 Mt Cu).

The USGS 2010 global estimate of Cu reserves is ~635 Mt Cu, while the 2008 reserves base estimate was 1,000 Mt Cu – yet the 674 deposits compiled in this study represent 1,614.9 Mt Cu, some 60% higher. Our data, however, although certainly comprehensive, are not exhaustive, as it does not include any Cu deposits in China or other countries with known sizeable Cu resources (eg. the data used for Sarcheshmeh in Iran being several years old, as well as several smaller sites). As of the late 1990s, China had identified 913 Cu deposits containing 73.7 Mt Cu, although only a third of these resources were considered economic (Hongtao et al. 2011). Furthermore, Canada's national estimate for economic Cu resources in 2009 was 7.29 Mt Cu (NRC, various years) – yet our data suggests 42.6 Mt Cu. This large discrepancy is mainly related to the fact that Natural Resources Canada (NRC) only include resources at operating mines or those undergoing development in national estimates and exclude mineral resources at other known deposits. Similarly, the USGS estimates the USA's Cu reserves at 35 Mt Cu, the 2008 reserves base at 70 Mt Cu, while our data suggests 134.2 Mt Cu.

An important aspect to note is that of the Cu resources compiled, over half (834.8 Mt Cu) are contained in the 20 largest deposits alone, with these deposits also containing substantial Au (and sometimes Ag, Mo). In addition, the vast majority of these deposits are already being mined, meaning that future expansion in Cu production mainly needs to come from expansion at existing mines (i.e. brownfields growth), not merely new projects alone (i.e. greenfields).

Finally, the trends over time in Figure 3.1 suggest gradual declines in Cu resources for the USA and Canada, compared to strong (almost exponential) growth for Australia. While this is tempting to label the declines as 'peak copper', when contrasting the data contained in Figure 3.2 with Table 3.1 (and noting discussion above), it is clear that the USGS estimates of various national Cu resources are a significant under-estimate of identified Cu resources. For example, the recent (~2000) discovery of the giant but deep Resolution Cu deposit in Arizona in an area of intensive historical Cu mining (the Magma Cu field) shows that there remains excellent prospects for exploration to continue to find new deposits, though most likely at greater depth than current and previous Cu mines. Indeed, Australia has continued to find major new deposits over the past 30 years, such as Prominent Hill, Rocklands, Cadia-Ridgeway, Northparkes, Nifty and most recently Carrapateena as well as ongoing expansion at existing projects (e.g. Mt Isa, Mt Lyell, and Olympic Dam).

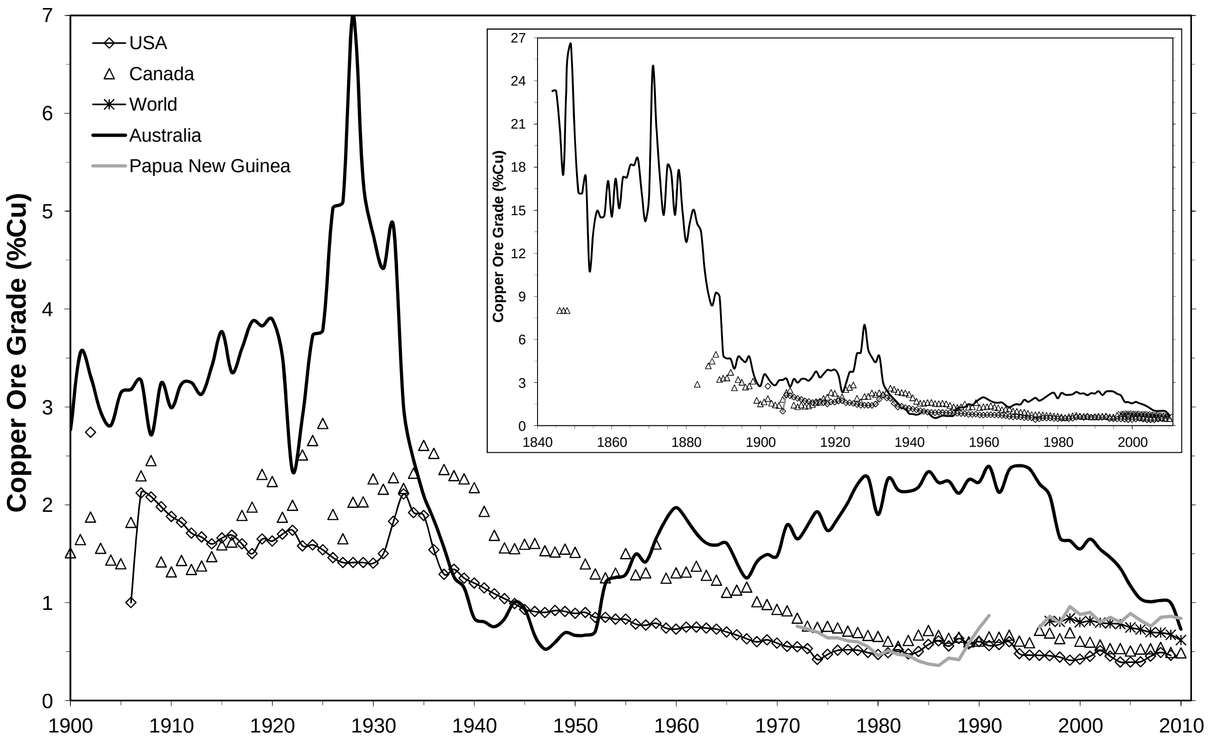


Figure 3.2: Historical trends in Cu ore grades for Australia, Canada and the USA (Mudd & Weng, 2012)

At global production of ~16 Mt Cu in 2010 and economic resources of more than 1 600 Mt Cu, this allows for production growth for some decades yet. For comparison, global cumulative production from 1820 to 2010 was ~580.7 Mt Cu.

The next section discusses factors affecting the economics of copper production and explores the environmental impacts of such historical declines in ore grade for Australia.

4. ECONOMIC AND ENVIRONMENTAL ISSUES WITH COPPER MINING IN AUSTRALIA

4.1. Overview of case study mines[2]

Five Australian mines with different histories of production, ore grade, and technology are selected to enable further discussions on economic and environmental issues. A short evaluation of mine operations is reviewed in the next paragraphs to provide a general understanding of case studies specifications.

Olympic Dam located in South Australia is the world's fourth largest remaining copper deposit owned by BHP Billiton. This poly metallic mine is currently operating underground and does all three steps of mining, smelting, and refining. Olympic Dam reached the production of 196,000 tonnes of copper by 2008 which is almost 20 % of Australia copper production in that year.

Osborne mine located in Queensland is a copper concentrate producer currently owned by Ivanhoe Australia began production in 1995 and changed from open cut to underground three years and in recent years changed to open cut again.

The history of mining in Mt Lyell located in Tasmania belongs to almost hundred years ago. Mt Lyell was the first mine used large scale open cut mining technologies and the first mine smelted the ore using natural pyrite within it without any extra coke. In 1972 Mt Lyell changed to an underground mine and shot the smelters in 1969. Currently, Mt Lyell is owned by Copper Mines of Tasmania Pty Ltd.

Mt Isa owned by Xstrata Mount Isa Mines Ltd is an underground mine located in Queensland which changed its technology from reverberatory furnace to flash smelting in 1978. Mt Isa is a blister copper producer. Mt Isa produces copper anodes which are then railed to Townsville copper refinery for refining to cathode copper.

Ernest Henry copper-gold mine is located in Queensland and is owned by Xstrata. This mine commercial production began in May 1998. This is an open cut operation mine producing concentrate. The concentrate output is then transferred to Mt Isa for smelting. Recently Xstrata has exported the first magnetite concentrate originating from Ernest Henry.

Together these five case study mines stand for 60% of Australia’s copper production and almost 50 % of Australia’s copper resources.

[2] Parts of this chapter are taken from Memary et al. 2012, Life Cycle Assessment: a time series analysis of copper, Journal of Cleaner Production

4.2. Economic factors affecting competitiveness

Parameters affecting the future economic benefits of copper mining are divided into production and ore grade[3]. Production and ore grade history of case study mines from 1940 to 2008 as major mining parameters are analysed in this section in order to enable debates on future economic perspectives.

As shown in Figure 4.1, average production is going up in all mines, while ore grade average is decreasing rapidly in all mines except Mt Lyell. Mt Lyell started with the ore grade of 24 % in 1894 which is not shown in Figure 4.1 (b) that starts from 1940, clarifying that all mines in this study are facing a decline in their ore grade. It is also interesting to note that Olympic Dam resources are half the grade of operating mine.

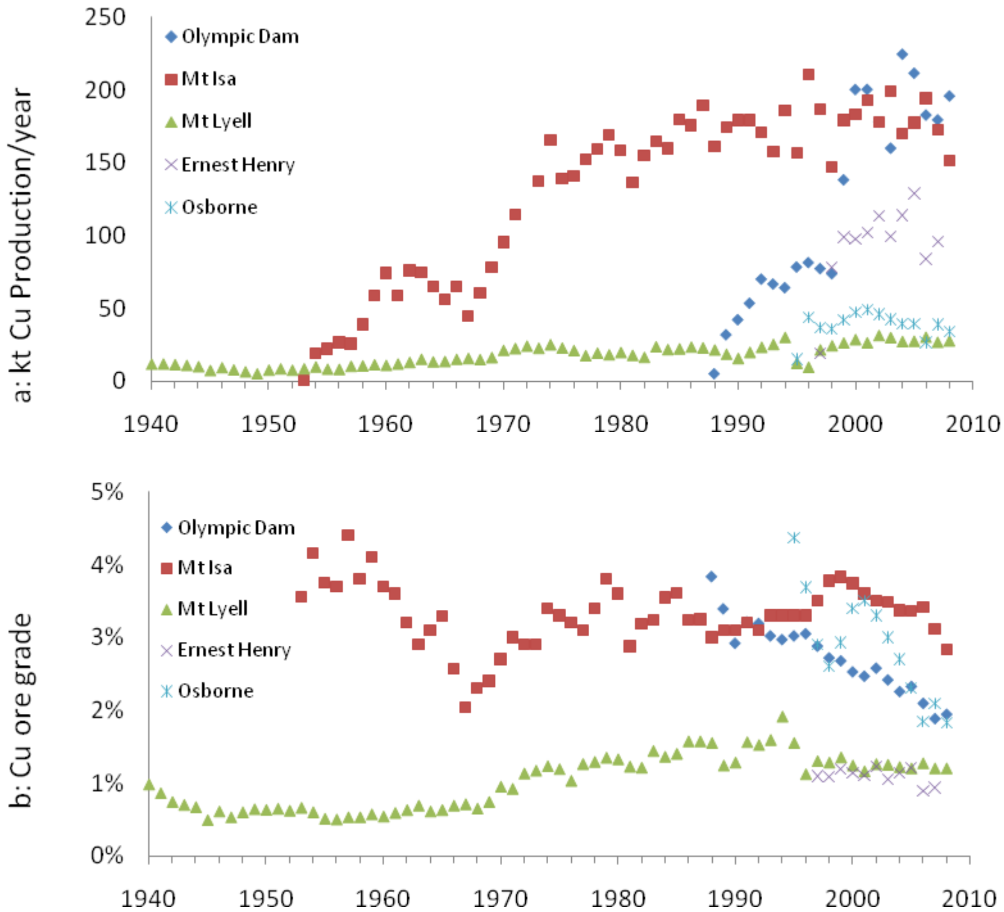


Figure 4.1: production (a) and ore grade (b) through time

The rate of production increase for Olympic Dam is higher than other mines; furthermore, its production increases sharply in 1998 although there is a decline in its ore grade in the same year. Other mines show evidences of increase in production while ore grade is declining too as a case in point Ernest Henry shows a continuous increase in production from 1998 to 2005 although there is a decrease in its ore grade from 1998 to 1999 specifically and generally from 1998 to 2005.

[3] This paper does not deal explicitly with labour costs and other economic costs such as fuel inputs, transport

These results illustrate that Australia is facing increasing production of lower graded mines that increases energy consumption (Norgate and Haque, 2010). However if an industry faces energy consumption increase, it should provide relatively more economical benefit to maintain the profitability for the nation.

However, although analysing energy consumption by different sectors with projections to 2030 also shows that the highest rate of growth will occur in the mining sector, which is predicted to undergo 4.7% annual growth between 2004 and 2030 (Akmal and Riwoe, 2005), Topp and colleagues have shown that the productivity of Australia's mineral industry is decreasing, with multifactor productivity (MFP) falling since 2000, the beginning of the most recent mining boom (Topp et al., 2008). The authors attribute two thirds of this decline to falling average ore grades, which require higher capital and labour inputs to produce the same quantity of ore specifically in case of energy density. The final remainder can be attributed to investments not providing returns yet. This decline in productivity is reflected in the stagnant growth in mining's contribution to Australia's GDP as Topp and colleagues have also noted the impact of the mining industry's reliance on non-renewable inputs, such as oil, which are increasingly imported as Australian's own resources are exhausted. Although the highest rate of energy consumption growth has been seen in mining, this energy has not been converted very efficiently into product, resulting a null contribution to GDP growth between December 2009 and December 2010 (ABS, 2011). This is shown in Figure 4.2.

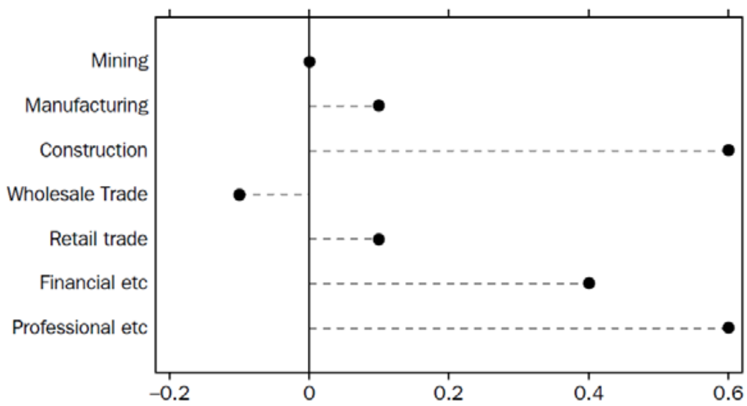


Figure 4.2: Contribution to GDP growth by sector (ABS, 2011)

Consequently, regardless of the levels of remaining resources, the physical presence of resources does not guarantee the profitability of extracting and exporting them if business continues as usual in the mining industry.

4.3. Environment analysis of copper mining using LCA

Life Cycle Assessment (LCA) is used to assess the environmental considerations of copper mining in Australia. This report adapts the LCA guide developed by CML at Leiden University (Guinée et al., 2001) to conduct a time-dependent LCA analysis for a better understanding of impacts over time as proposed by Jeswani et al. (Jeswani et al., 2010) in their discussion of options for broadening and deepening the assessment. The four main stages of LCA analysis include goal and scope definition; inventory analysis; impact assessment; and interpretation (ISO, 2006). In this report the inventory analysis is re-calculated at yearly time steps to generate a time-series impact assessment. CML provides practices for midpoint indicators and operationalising the ISO14040 series of Standards. Normalisation and weighting of impact categories is not undertaken.

LCA models used are based on dominant pyrometallurgical processes which have been used in Australian case study mines in the study period from 1940-2008 which are direct to blister flash smelting, reverberatory furnaces, and Isasmelt although no reverberatory furnaces are currently used in Australia. Hydrometallurgy has been used in some Australian mines such as Nifty, but this technology is not discussed in this report since none of the case study mines has used it during the study period of this paper. Analysis is done for five main Australian copper mines including Olympic Dam, Ernest Henry, Mt Isa, Mt Lyell, and Osborne.

4.3.1. Analysed technologies

Reverberatory furnace:

Before 1950s Reverberatory smelting was the main copper smelting technology in the world (Davenport et al., 2002). Through this process, Fluid bed or multi-hearth roasters are used to produce a low sulphur calcine for injection into the hearth area in lieu of green charging. Flux material is added with the red hot calcine by means of fettling pipes which distribute the charge material along the inside long walls of the rectangular furnace lined with basic and insulating refractories (Moskalyk and Alfantazi, 2003).

This traditional method of concentrate smelting is still used worldwide (Moskalyk and Alfantazi, 2003), but in recent decades, reverberatory furnaces are being superseded for more efficient, lower-cost flash smelters (Davenport et al., 2002). The process flow of reverberatory furnace operation used in LCA models is shown in Figure 4.3 (Giurco et al., 2006).

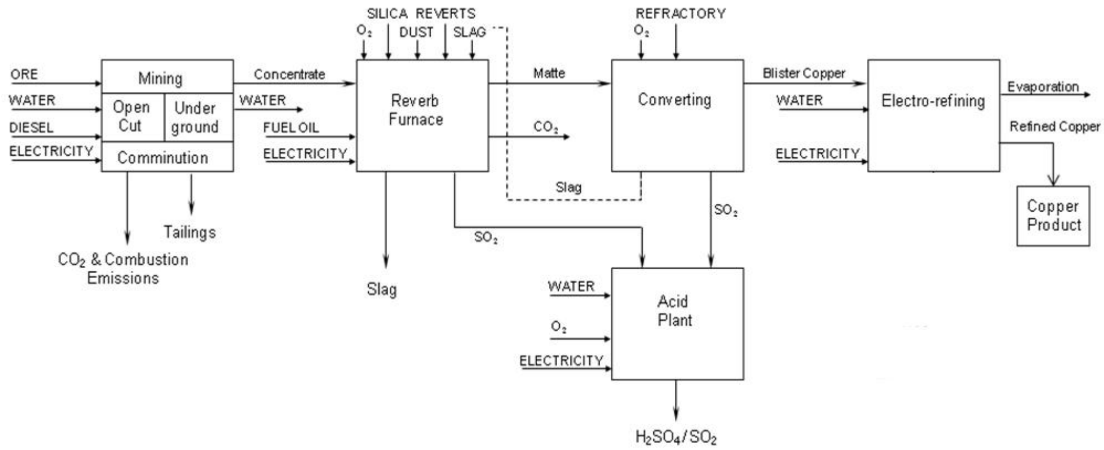


Figure 4.3: Reverberatory furnace process flow (Giurco et al., 2006)

Flash smelting and direct to blister:

Flash smelting was developed by Outokumpu company after World War II in response to the electric energy shortage in Finland in 1949 (Kojo et al., 2000). Around half of all smelters operating use this technology, and is still being installed in new mining sites (Hanniala et al., 1999). Flash smelting employs oxygenated air to promote autogenous conditions. Today, it is perceived that Outokumpu installations account for 35– 50% of installed smelting capacity worldwide (Moskalyk and Alfantazi, 2003). The process flow in flash smelting used in LCA models is shown in Figure 4.4 and further detail on the inventory inputs and outputs can be found in (Giurco et al., 2006).

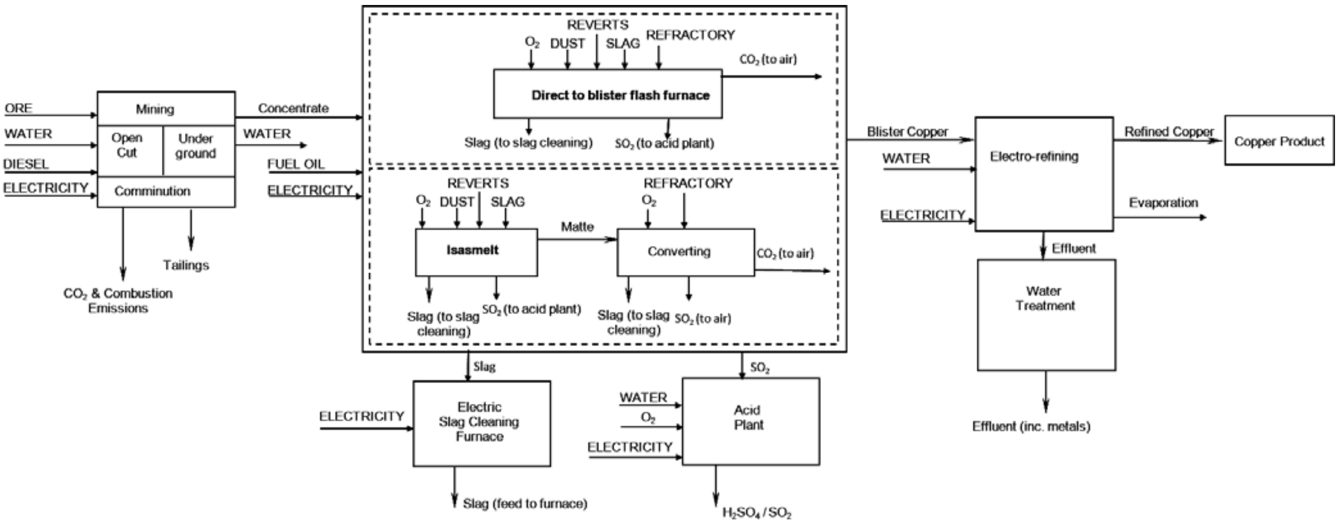


Figure 4.4: Flash smelting process flow (Giurco et al., 2006)

A variation on flash smelting is called 'direct to blister', which combines the smelting and converting stages together and produces blister copper directly from concentrate in one stage. 'direct to blister' is a continuous auto thermal process that possesses advantages such as the isolation of sulphur dioxide into a single gas stream, reduced energy consumption, and reduced capital and operation costs (Davenport et al., 2002). In order to model 'direct to blister'; the converting stage in the flash smelting model is merged into smelting stage. Inputs, such as oxygen-enriched air blast and the percent of copper in ore feeds, and outputs are reset based on 'direct to blister' principles. It is worth noting that direct to blister flash smelting generates high percentages of dust, and recycling them consumes energy but this effect is not considered in the models.

IsasmeltTM

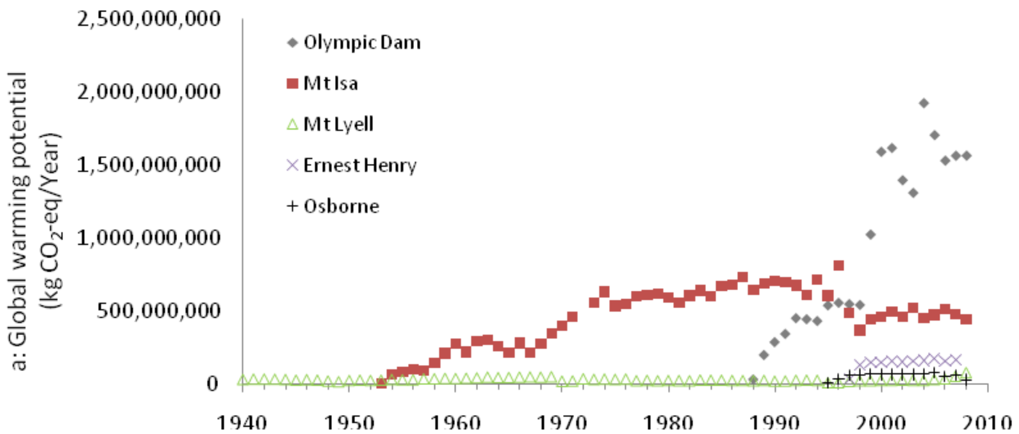
The Isasmelt^{TM} process was developed in Mount Isa, in Queensland, Australia as a collaboration with CSIRO (Errington et al., 1997). It is a bath smelting technology that features the insertion of a lance into the slag to inject oxygen-enriched air in the molten bath. This modification creates turbulence that increases the productivity of reaction with feed materials (Arthur and Edwards, 2003). Here it is worth noting that operations at Mt Isa manage sulphur dioxide emissions from this process in distinctive ways, with sulphur dioxide emitted to the air at the conversion stage, but captured in smelting stage, and since 1999 converted to sulphuric acid. However, as compared with Isasmelt™, the feed concentrate in direct to blister flash smelting has to be pre-dried, introducing additional energy requirements and GHG emissions.

4.3.2. LCA Results

This section outlines the results of the time series life cycle assessment models with time-varying input parameters for Global Warming Potential, Acidification potential and Photochemical Ozone Creation Potential. Water access and disposal is also a significant environmental issue for copper mining and processing but is not examined in detail in this case study.

Global Warming Potential (GWP)

Figure 4.5(a) shows the total annual global warming potential of mines which is used to measure GWP from 1940 to 2008. Olympic Dam has sharply surpassed all operations by 2000 and reached more than 1922 kt of carbon dioxide equivalents by 2004 coinciding with a rapid increase in production. The next highest rate of global warming potential belongs to Mt Isa that reached to more than 800kt by the end of 1996 before installing Isasmelt™ furnace. Average annual carbon dioxide production per mine is gently inclining in Mt Lyell (excluding the drop in 1969 due to smelter shutdown). However, this mine only produces copper concentrate, rather than refined copper as is the case for Olympic Dam and Mt Isa/Townsville. Osborne shows a smooth decrease in GWP after 2005 which is due to changes in production, ore grade, and transitions to open cut mining.



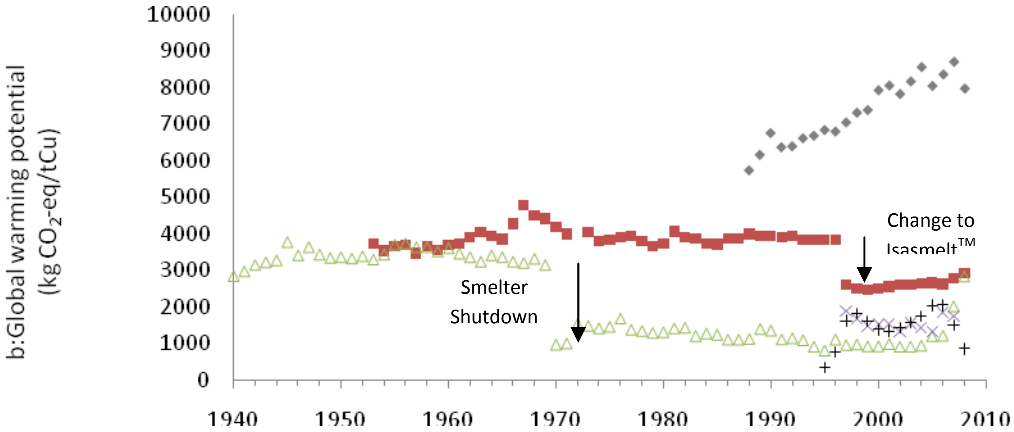


Figure 4.5: Global warming potential through time (Olympic Dam – Mine/Smelter; Mt Isa – Mine/Smelter; Mt Lyell – mine only; Ernest Henry – mine only; Osborne – mine only)

In order to clarify which steps are the main contributors to carbon dioxide production in mining, a deeper look into the LCA models is undertaken. Comparing the results of Mt Isa and Olympic Dam, after 2000, shows a higher level of carbon dioxide in Olympic Dam although the level of production in both mines is very close. This indicates that the lower ore grade at Olympic Dam, combined with the use of 'direct to blister' flash smelting results in higher GWP per year, when compared Mt Isa, which has higher ore grades and uses the Isasmelt^{TM} process. Regarding the impact of changes to the type of mining, figures for Mt Lyell show an increase in annual carbon dioxide production from 1972 due to the higher electricity feed rate in underground mining. The other important point in Figure 4.5 is Mt Isa GWP per unit of copper which drops after installing Isasmelt^{TM}, but starts to increase after some years. This fact confirms that the positive effect of technology improvement, after 1997, was lost in few years due to change in other parameters, such as a decrease in ore grade.

The contribution of each type of operation to carbon dioxide production at Mt Isa, is compared in Figure 4.6. This comparison shows that the main part of CO_2 production comes from mining and milling, then from smelting. The smelting contribution is almost half the mining and milling contribution. Ore grade decline and production increases appear to have a dominant effect on carbon dioxide production in mining, with a major impact on concentrate production. This process starts with the ore milling and ends with a concentrate that is the input to smelting process. Consequently, lower ore grade makes the concentrate production more energy intense, requiring more ore to be milled to produce the same amount of concentrate. Hence, if a technology is expected to reduce carbon dioxide production of copper mines in the future, it should have a direct effect on concentrate production or the early processing of ore.

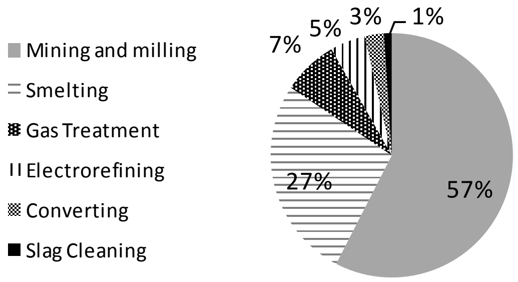


Figure 4.6: Contribution of each mining operation to carbon dioxide production In Mt Isa (2008)

In order to look at the global warming potential, from the perspective of final copper consumers concerned about their carbon foot print, plotting the carbon dioxide production over unit of copper as shown in Figure 4.5(b) is helpful. Figure 4.5(b) shows the average impact per tonne of copper produced in Mt Lyell drops after shutting down the smelters which removes the impacts from smelting but again increases after switching to underground mining and increase in electricity use. Interestingly, by 2008 the level of GWP per unit of copper surpasses the level in 1965 before shutting down the smelters that highlights the effect of increasing production which almost reaches double the level in 1965. The other interesting point in Figure 4.5(b) is higher levels of GWP per unit of copper in Olympic Dam comparing to Mt Isa although in some years, production is higher and ore grade is lower in Olympic Dam which shows the effect of different technologies.

Ernest Henry and Osborne show fluctuating carbon dioxide production per tonne of copper. This variability creates uncertainty regarding future environmental performance of the mines, and the copper they produce. This result clarifies the importance of mining parameters and regional LCA factor in footprint calculation of products that use mineral commodities. It also confirms the importance of LCA for decision-making in the mineral industry, particularly when considering the difference in global warming potentials of products associated with different mines.

Acidification Potential (Sulphur dioxide)

Sulphur dioxide emissions are the main source of acidification, and are used as the acidification calculation source in this paper. As shown in Figure 4.7 (below), a notable point of difference between Mt Isa and Olympic Dam in acidification graphs is the sudden decrease in Mt Isa sulphur dioxide production level after change from reverberatory to Isasmelt^{TM} in 1997. Mt Isa processes include smelting, converting, slag cleaning, smelter and gas treatment as well as mining and milling, with a copper recovery rate of 90%.

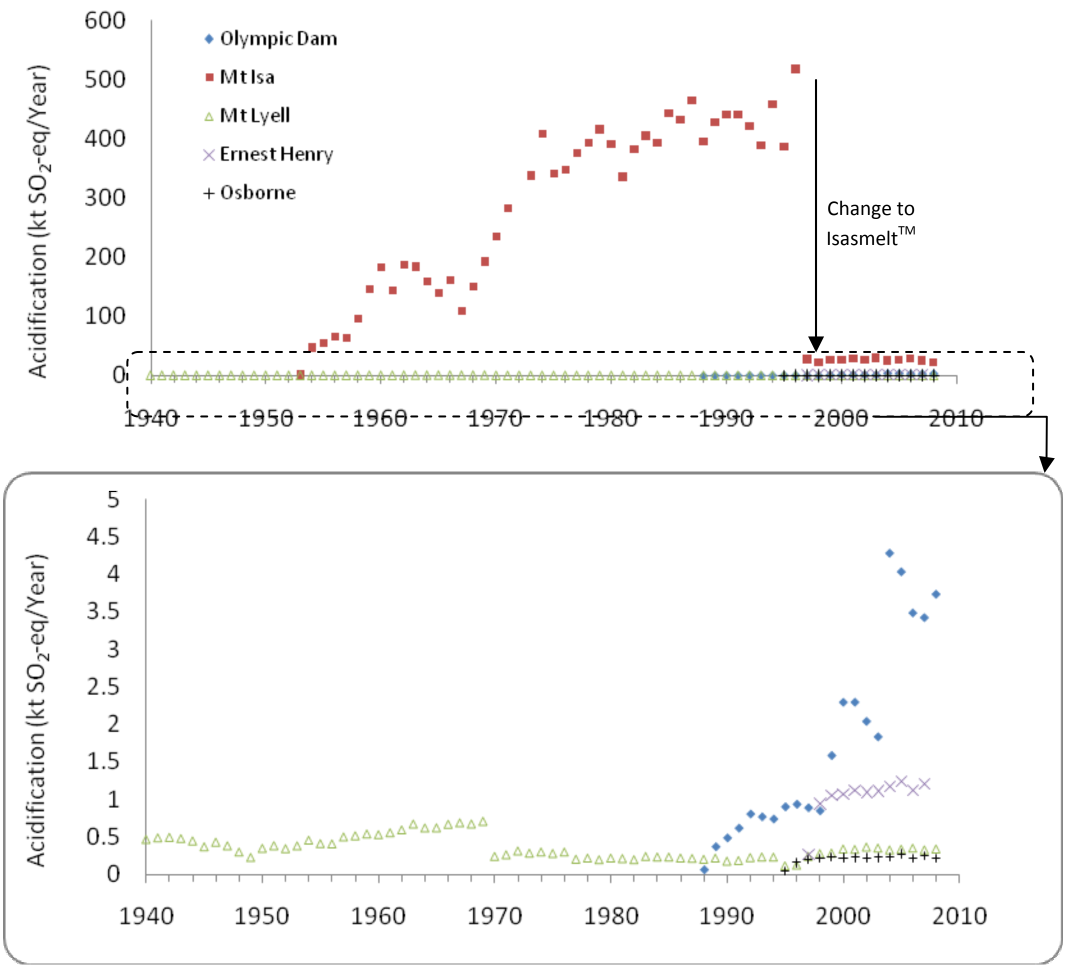


Figure 4.7: Calculated acidification potential through time

The main contributors to acidification are coming from smelter emissions exiting at the gas treatment stage (85% from wastes, 1% from input mainly through electricity and oxygen use) then smelting (6% from fuel oil use, 1% from electricity and oxygen use), mining and milling (5.8% from electricity use, 0.2% from diesel), and electro refining (1% from electricity). In the Mt Isa smelting process, the SO_2 stream is concentrated as a sulphuric acid 'product' (H_2SO_4), whose potential for environmental damage is not calculated in this cradle-to-gate model. Generally, this decrease in acidification level can be considered as the dominating effect of technology change, however, the treatment of sulphuric acid as a 'by-product', is noted as problematic and also that no allocation was undertaken.

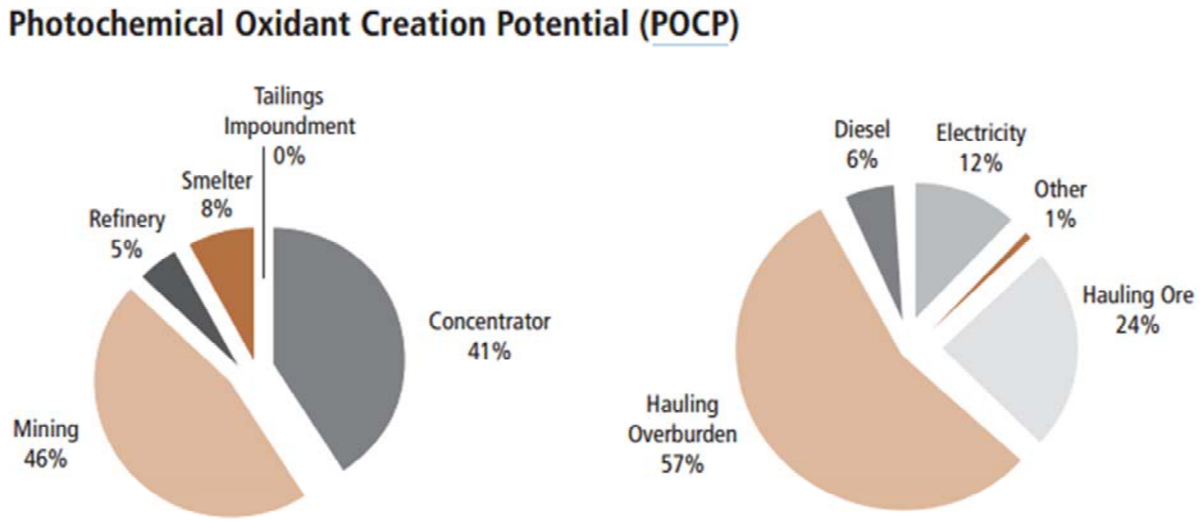
At Olympic Dam, sulphur dioxide production shows a smooth increase until 1998, and then experiences a faster increase but remains less than Mt Isa. This result is interesting and shows that the effect of higher SO_2-eq/kWh in Mt Isa's electricity source is stronger than production and ore grade effect in this case. Furthermore, Olympic dam captures all SO_2 but Mt Isa just captures SO_2 coming from smelting and let the SO_2 from converters emit to air.

The important application of acidification potential to highlight here is the measure that it provides to compare between different projects and technologies in different locations. For example presence of acidification in places near tropical forests has different consequences comparing to projects in deserts. These numbers provide a basis to benchmark for safer or more environmentally friendly choices.

Photochemical ozone creation potential (POCP)

Photochemical ozone creation potential (POCP) graphs, calculated in kilograms of ethylene equivalent as a potential for smog are shown in Figure 4.8. During the reverberatory furnace use in Mt Isa and Mt Lyell, higher production in addition to higher regional LCA characterization factor in Mt Isa results in higher POCP in Mt Isa. This difference remains with decrease in distance after upgrade to Isasmelt^{TM} in Mt Isa. The decrease in distance is because of the less fuel use in Isasmelt^{TM} compared to the reverberatory furnace. The highest levels of POCP after 1998 belong to Olympic Dam due to higher production and in most cases lower ore grades in addition to lower POCP-eq./KWh. LCA models show that POCP originates from diesel and fuel oil (52%), and electricity (48%).

For comparison, the sources of POCP for Kennecot Copper are shown in Figure 4.8, split into origins by mining and by smelting. Absolute values of emissions were not given to enable comparison.



Breakdown of POCP by process group for copper production – Kennecott Copper

Breakdown of POCP by process in mining – Kennecott Copper

Figure 4.8: Photochemical ozone creation potential by source (Kennecott, 2004)

As shown in Figure 4.9 (below), average POCP is sharply rising in Mt Isa during the reverberatory furnace usage, but increases more gently after change to Isasmelt^{TM} because production and ore grade in Mt Isa have changed less over this period furthermore fuel oil rate is less in Isasmelt^{TM} comparing to reverberatory furnace. Other mines are also showing slight growth in POCP.

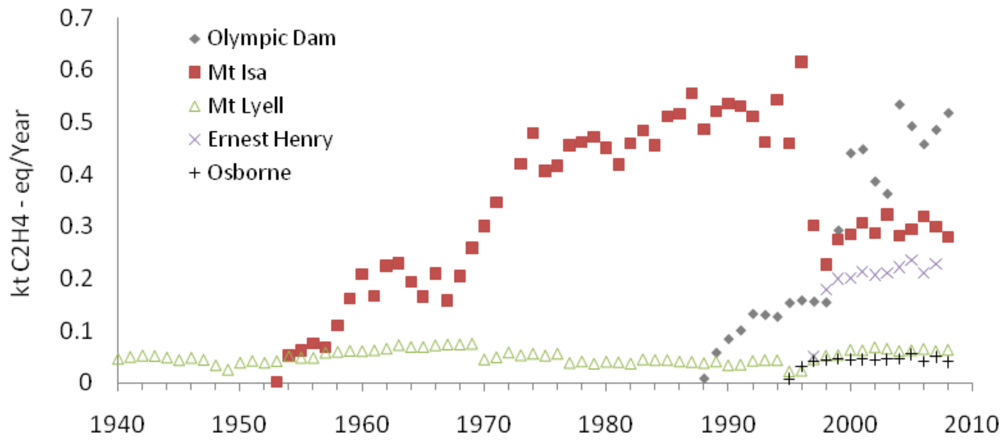


Figure 4.9: Calculated photochemical ozone creation potential

Presence of particles in the air has different implications in different regions. For example, near cities, POCP related air quality issues have higher impact to humans rather than in remote areas.

4.4. Summary of economic and environmental challenges

The economical overview shows that falling ore grades and delayed production (following capital expenditure) are decreasing the productivity in the mining industry. Furthermore, the changes in geological characteristics also increase the environmental impacts of copper mining. Consequently if business happens as usual in the copper mining industry, it faces more environmental impacts.

Alternative solutions could be moving to new technologies to increase the energy efficiency and decrease the environmental impacts, using clean energy, and moving to new business models which enhance recycling.

A review of possible technologies and improvements are provided in the next chapter followed by future suggestions based on World Economic Forum (WEF) scenarios.

5. TECHNOLOGY ADVANCES IN COPPER MINING AND SMELTING[4]

Terrestrial copper deposits on earth are mainly in the forms of copper-sulphide, copper-iron-sulphide, and oxidized minerals (Davenport et al., 2002). Traditional methods of copper smelting include pyrometallurgy, generally for sulphide ores and hydrometallurgy, mostly for oxide ores. Copper sulphides are more commonly processed via pyrometallurgy in Australia.

5.1. Hydrometallurgy and Pyrometallurgy

Historically the dominant pyrometallurgical processes used in Australian mines were flash smelting and reverberatory furnaces although the SO_2-polluting reverberatory furnaces ceased production. Hydrometallurgy has been used in some Australian mines such as Nifty which is currently closed.

The most prominent hydrometallurgical processing route is Heap Leach, Solvent Extraction and Electro Winning (SX/EW). SX/EW is a two level process. At first copper ions are extracted from leach solutions derived from passing sulphuric acid over an ore heap and concentrated into electrolyte, and then copper is formed using an electrolytic procedure. Solvent extraction followed by electrowinning. SX/EW has become is a key process for the recovery of copper from solutions obtained by leaching low-grade copper oxide ore (Aminian et al., 2000).

In addition to the methods described above, new methods are under development at the moment with the potential for increasing application. Studying the effect of these new technology classes and new methods of trading and adding value to metal cycles is useful for considering how they would change the environmental impacts of copper mining. Bio leaching, in-situ mining and deep sea mining are considered to be future technologies happening in the copper mining industries. Regarding other advances, increasing desire for recycling and using product-service systems are reviewed in this paper.

5.2. Bioleaching

Bioleaching is proposed as a simple and effective technology extracting metals from low grade ores or concentrates (Bosecker, 1997). This technology has developed rapidly in the course of the last decade (Rohwerder et al., 2003). This is considered to be an alternative for smelting or roasting when there are lower concentrations of metal in ore. The bacteria feeds on nutrients in minerals, thereby separating the metal that leaves the organism's system; then the metal can be collected in a solution and recovered using Solvent Extraction and Electro Winning (SX/EW).

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[4] Parts of this and the following chapter are taken from Mudd et al 2011. Commodity futures: life-of-resource strategies for copper and gold, Minerals Engineering (submitted).

The economic feasibility of bioleaching is related to the level of preciousness of metal; however other factors such as relative cost of metal to extraction cost and available infrastructures for smelting may affect the feasibility. For some types of metal, such as copper, bioleaching is not always economically feasible or fast enough, even with its low capital cost.

5.3. In-Situ Leaching (ISL)

In-Situ Leaching (ISL) is also called in-situ recovery (ISR) or solution mining. It works by pumping a solution which is diluted sulphuric acid in case of copper through boreholes underground in the ore body to dissolve the copper deposit. Next, the metal-rich solution is pumped to the surface and refined, using for example solvent extraction and electrowinning. The movement of solution in the ore body is controlled through differential pumping rates or natural impermeable barriers.

Using this process helps eliminating main parts of conventional mining and grinding. While mining companies state that it is possible to collect all the solution, this process has the potential for significant environmental impacts such as contaminating underground water (Taylor et al., 2004).

Advantages of this method could be lower operating and capital cost, no movement of ore and waste, avoiding leach pads, tailings, and waste dumps. Economic feasibility of this method is very dependent on geological characteristics of the ore such as grade. There are other characteristics required in order for an ore to be appropriate for this method such that the ore body should be under the water table, the rock should have appropriate permeability for controlling the solution, and the ore chemistry should be dissolvable.

Examples of this include a proposal for a copper mine in Florence, USA (see http://www.florencecopper.com/s/Home.asp) and the Gunnison Copper Project by Excelsior Mining (http://www.excelsiormining.com/index.php/projects) with resource of 3.21 billion pounds of oxide copper (511 M tons at 0.31%) and an inferred resource of 0.88 billion pounds of oxide copper (159 M tons at 0.28%)[5].

5.4. Deep sea mining

The first continuous pilot scale deep sea mining production was installed in the floor of the Pacific ocean in 1978 and the interests for production of ore-bearing minerals from the deep increased in 1979 (Bath, 1989). Deposits in terrestrial copper mines usually contain less than 1% copper however says there are evidences of higher available ore grades under water like 10% copper. Whilst the technology offers potential despite technical hurdles, social and environmental issues must be managed before large scale deployment can be expected. The first seafloor massive sulphide mines are likely to begin production in 2013 in New Zealand and Papua New Guinea (ELLIS, 2003; Munro, 2011).

[5] Part of this section is taken from Gunnison copper project (http://www.excelsiormining.com/index.php/projects)

5.5. Recycling

Recycling is a way to get copper from end of life products which contains copper with potentially less environmental impacts compared with primary mining and with less cost, especially for highly pure copper streams which can be remelted rather than lower quality scrap which needs to be sorted and re-smelted. The economics often depend on the costs of collecting material and the value of precious and other metals. Formal recycling is also expected to provide jobs and social benefits, however there are serious environmental and social impacts of the informal recycling sector occurring in countries such as India.

The potential for increasing the copper recycling in Australia is estimated as 30% of the end of life material generated in Australia which is not currently recycled and equals to 23,000 t per year (Van Beers et al., 2007). Considering the value of copper in first quarter 2011 as 8300 $/t the potential value of the not recycled copper in Australia would be almost 190 million dollars which shares a high portion of benefit because of the less costs of recycling comparing to full mining process.

The main cost associated with collecting the copper stocks is the cost of transportation however the spatial analysis on end-of-life copper and zinc indicate that about 50% of all waste material originates in just 10% of Australia's local government areas, and mostly in the urban centres (Van Beers et al., 2007). Which means recycling points near stocks which are mainly in urban areas will decrease the cost. Figure 5.1 shows the in use copper stocks in Sydney which shows a high density in central city.

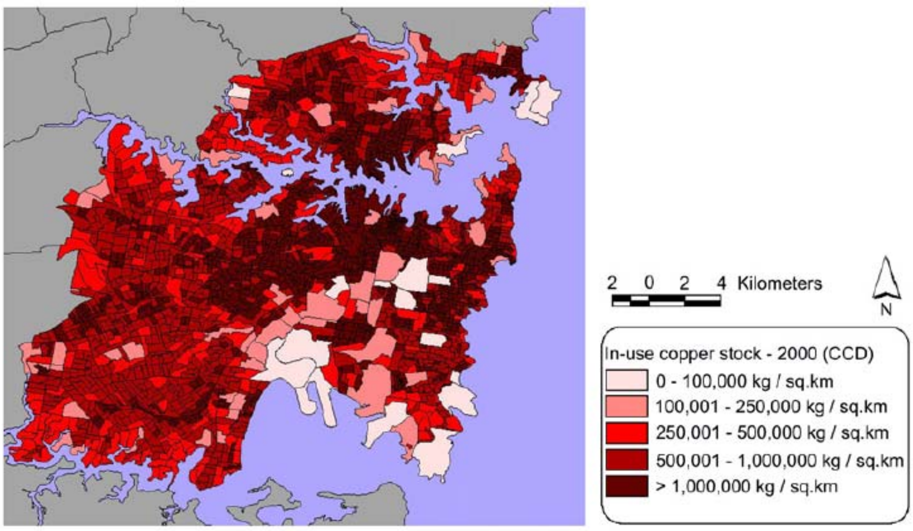


Figure 5.1: Sydney in use copper stocks in 2000 (Van Beers and Graedel, 2007)

Study by (Van Beers et al., 2007) on the potential quantities and policy options of copper recycling in Australia shows the priority of copper recycling in Australia as followings:

- Plumbing tube from single family houses
- Built-in electrical from industrial buildings
- Transformers from power distribution

- Motor vehicles
- HV power cables
- Overhead wiring from railway transport
- Industrial machinery

They also state that recycling of all copper end of life in Australia could supply up to 50 % of Australia's demand over the coming three years; whilst only part of the solution, it is an area needing further research.

5.6. Product-Service System (PSS)

A business model which facilitates recycling, reuse, and remanufacturing of products is Product-Service Systems (PSS). Business models are important parts of a product or service system and have influential effect on the whole life cycle management of products or services. Combining products and services and giving motivations to consumer or producer to care about product life cycle is going to be a promising model to decrease total environmental impacts of products.

A PSS is an integrated product and service offering that delivers value in use, for example the purchasing of "hourly car usage" or a given number of "travel kms" via an electric vehicle car share program, rather than purchasing the car and fuel outright. A PSS offers the opportunity to decouple economic success from material consumption and hence reduce the environmental impact of economic activity. The PSS logic is premised on utilizing the knowledge of the designer manufacturer to both increase value as an output and decrease material and other costs as an input to a system (Baines et al., 2007b).

Benefits of a PSS are offering of higher value that is more easily differentiated to the customer; lease from the responsibilities of asset ownership, and to society at large a more sustainable approach to business. However, consumers may not be enthusiastic about ownerless consumption, and the manufacturers may be concerned with pricing, absorbing risks, and shifts in the organization, which require time and money to facilitate (Baines et al., 2007a).

Technologies compared in Table 5.1 show an overall view of how new technologies may affect environmental, Social, and economical benefits of copper mining.

Table 5.1: comparing new technologies for copper

	Environmental	Social	Techno-economics	Indicative references
Bio-leaching	-Less energy intensity required		-Can be cheaper than traditional methods - Offers potential for refractory chalcopyrites	(Watling, 2006)
In-situ mining	-Potential for groundwater contamination - Potential for less grinding energy	-Reduced land disturbance - Opposition due to its application for uranium mining	-Can be cost effective, not efficient for all kinds ores	(Hancock and Hinneapolis, 1977)
Deep sea mining	-Higher ore grades -Structures are taken away after mining -threatens sea-floor life	- Community concern	-Higher ore grades so a higher value; technical challenges	(Scott, 2001)
Recycling	-Decreasing impacts where high grade copper recycled; -Informal vs formal recycling	-Strengthen innovation and value capture from recycling	-Cheaper than getting copper from low quality ores; requires transport, collection	(Ayres, 1997)
PSS	-Decreasing the impact by managing the end use	-Creating service industries and new jobs	-Decreasing nations demand for new ores	(Schweitzer and Aurich, 2010)

5.7. Energy options

In addition to using new processing technologies which may be more energy efficient, it is also possible to concentrate on energy efficiency in existing processes and linking clean energy to the mining operations.

Energy efficiency has a big potential to decrease the environmental impacts while decreasing the cost which is of mining sector interest. In mining, there are many opportunities to increase the efficiency. The Department of Resources, Energy, and Tourism report on “first opportunities in depth: the mining industry” states that there is an opportunity to save 8.4PJ using energy efficiency measures including process control (41.1%), maintenance (15.6%), energy measurement (14%), retro-fitting (12.8%), new technology (8.4%), management systems (4.8%), staff operation (2.5%), and research and development (0.8%). For example, in a 2007 example the Xstrata Coal New South Wales was identified as being able to save 13686 GJ through implementing 47 cost-effective energy efficiency projects which means reduction of 3,700 tonnes of carbon dioxide. The other example is the opportunity identified by BHP Billiton (2008) in using auto shutoffs for lighting plants which could save up to 17 TJ annually. Some other energy efficiency opportunities in mining industry are shown in Table 5.2 which some of them are not yet taken up. For further cases see http://www.ret.gov.au/energy/Documents/energyefficiencyopps/sig-opp register/MiningRegisterDec2010.pdf

Table 5.2: Examples of energy efficiency opportunities in mining.

Company	Opportunity	Category	Expected energy saving
Anglo Gold Ashanti Australia Limited	Removal of Scats to Increase Mill Efficiency	Investment in new technologies	6,060 GJ/year
Anglo Gold Ashanti Australia Limited	Water management	Improvement in process control	704 GJ/year
Downer EDI Limited	Compressor air leak	Changes in maintenance practices	475GJ/year
Gold Fields Australia Pty Ltd	Reducing the number of vehicles leaving the site	Changes in staff operation	1026 GJ/year

The other option is using clean energy sources. As current electricity prices are higher in remote locations, the cost effectiveness of installing clean energy power plants near mines in remote places will increase in the future if the power plants can provide the required base load power during the mine life. However, how different drivers might increase clean energy use in the copper mining industry requires analysing the possible clean energy options in Australia (see Memary et al. 2011). Possible clean energy options in Australia include:

- Solar (solar thermal and solar photovoltaic)
- Wind turbines
- Energy from biomass and waste materials
- Hybrid fuels.

The economic viability of each option depends on the location of mine and potential of renewables in that point. As a case in point looking at concentrated solar thermal technology and solar radiation map of Australia merged with copper mining maps in Figure 5.2 shows a high potential for using concentrated solar thermal power plants to supply copper mines especially mines in western Queensland such as Mt Isa which are not connected to the national grid. The other opportunity is Olympic dam as a huge copper mine and deposit in South Australia.

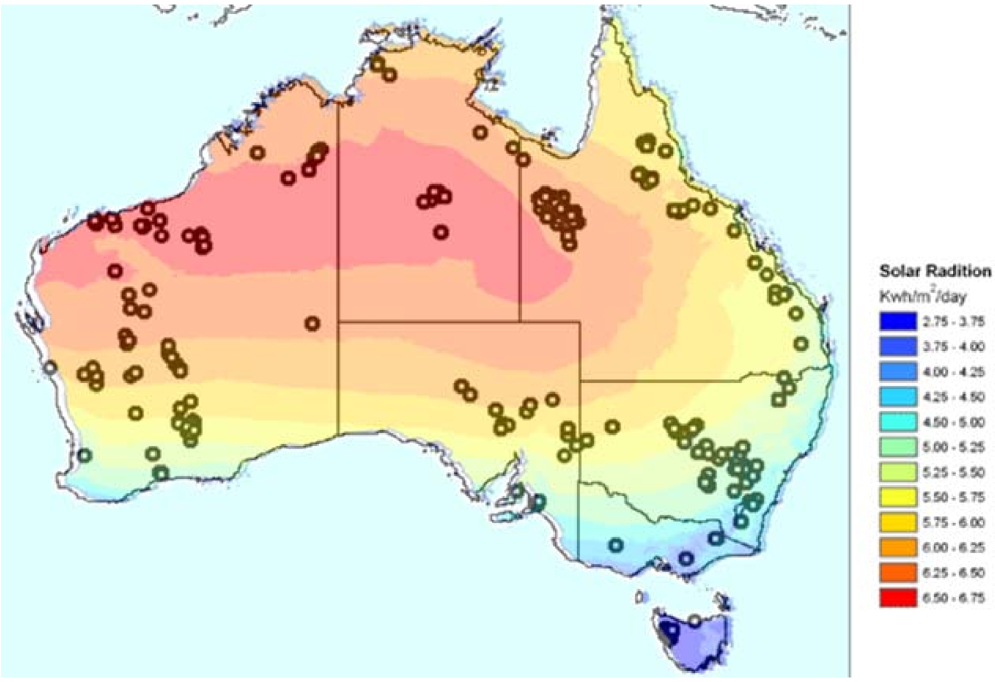


Figure 5.2: Locations of copper mines on the solar radiation map of Australia (Australian Mines Atlas and CRES ANU)

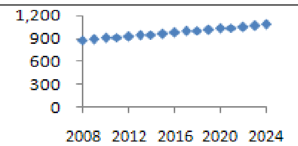
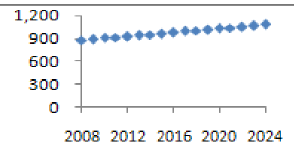
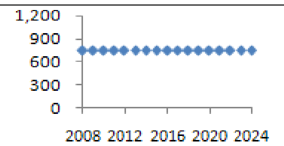
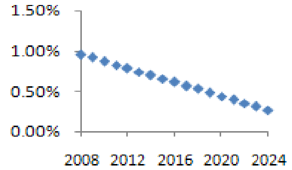
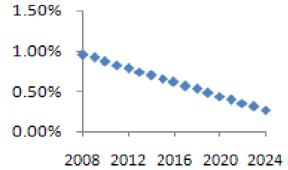
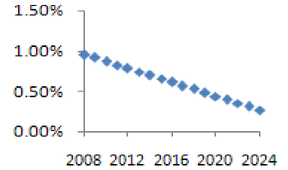
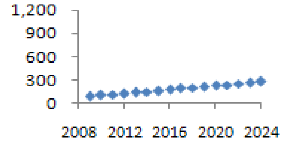
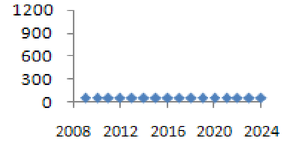
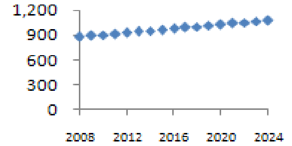
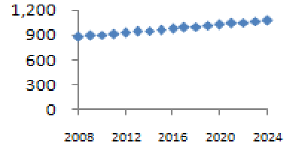
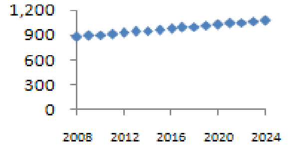
6. EXPLORING FUTURE SCENARIOS FOR COPPER

6.1. EFFECTS OF ORE GRADE CHANGE, TECHNOLOGY IMPROVEMENTS AND BUSINESS MODELS

In order to get a better understanding of how changes in the future copper mining industry may affect impacts of mining, environmental life cycle models for analysing a selection of different options which are shown in Table 5.1 are used. Developed models are used to evaluate the effect of changes in ore grade, using cleaner energy technologies. Applications of recycling and product-service systems are also considered.

As shown in Table 6.1, three different options are analysed to show the effect of different future approaches for covering Australia's demand.

Table 6.1 Modelling future copper technology options for Australia*

	Option 1	Option 2	Option 3
Details	100% Flash smelting with fossil fuel feed	100% Flash smelting with clean energy (Hydro) feed	Flash smelting with clean energy feed and fixed demand at 750000 tonnes. Rest of demand is covered by increasing demand for recycling and fixed demand for PSS at 50000 tonnes
Flash smelting Production (kt)			
Flash Smelting Ore grade			
Recycling Production (kt)	-	-	
PSS utilization(kt-demand is decreased 50 kt)	-	-	
Total demand (kt)			

**whilst the supply of a large Australian copper mine with hydro-electricity is unlikely (as outlined in Scenario 2), it has been explored as an illustrative case of cleaner energy. In addition, imports and exports are not considered in these scenarios.*

The results of different option analysis are shown in figure 6.1 Based on the results, continuing copper production as business as usual and using flash smelting with fossil fuel feed ends to incremental global warming. However using flash smelting and moving to hydropower ends to almost 50 percent decrease in global warming potential and by decrease in ore grade and increase in production this distance increases meaning higher affectivity of clean energy application in reducing the impacts. Furthermore, in case of moving towards upgraded business approaches and enabling recycling and PSS, it is possible to decrease impacts by almost 15 percent more.

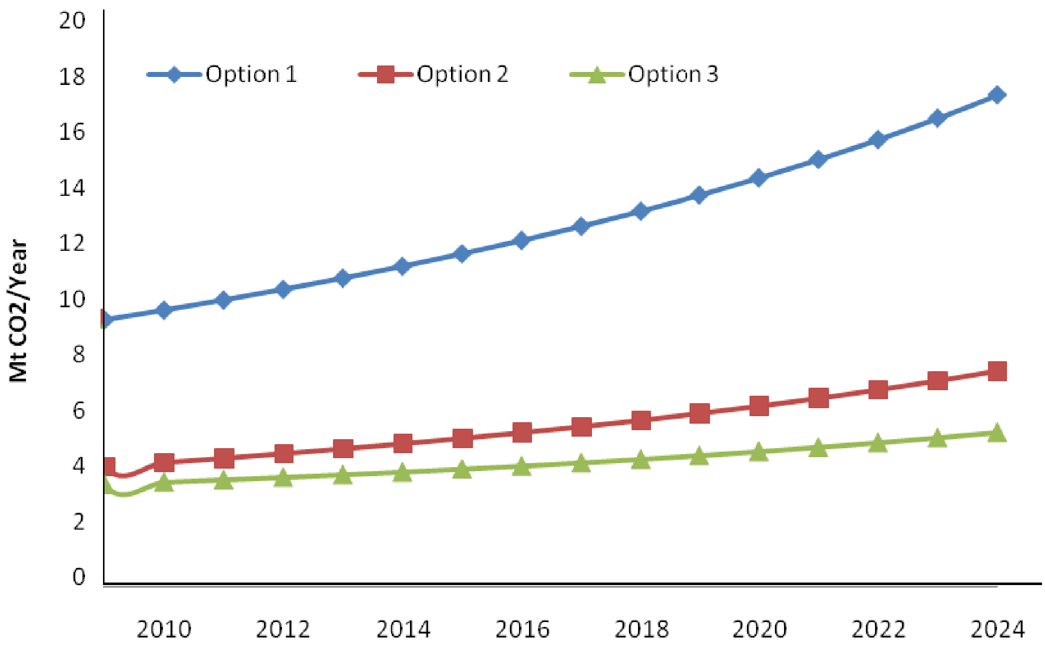


Figure 6.1: Global warming potential of each scenario till 2024

In summary, analysis shows that when ore grade is decreasing and production increases the effect of using clean energy, recycling, and PSS is clearer. Meaning in long term, in order to decrease environmental impacts with a fixed level, using new business models are necessary. And in order to increase the rate of decrease in global warming, investments towards using clean energy in copper mineral industry are required.

Technology options analysed in this chapter were based on general technologies used for mining however with more insight from CSIRO on the current technologies being developed in Australia we will be able to offer a more comprehensive technology analysis.

6.2. GLOBAL CONTEXT: WORLD ECONOMIC FORUM SCENARIOS

Australia is facing a more competitive mineral future, with the high prices paid by China in recent years likely to fade. Prosperity in this context will depend on productive operations.

Current possible options to decrease the environmental impacts and increase the productivity for the copper mineral and energy industry are increasing the energy efficiency using new technologies, increasing the recycling, and moving towards using sources of clean energy (Giurco and Petrie, 2007; Memary et al., 2011). Companies decide between these options based on the relative costs of such options and the degree to which they need to decrease their environmental impact. Current Australian mineral sector is facing emergence of suppliers in developing countries who are able to provide copper and other minerals with lower price and lower environmental pressures. These facts will weaken the position of Australia as a power house in global mineral sector and requires adaption from mineral sector to overcome the challenges. World Economic Forum (WEF) provides scenarios discussing the future of global mineral industry. These scenarios are Green Trade Alliance (GTA), Rebased Globalism (RG), and Resource Security (RS). In order to understand how drivers and regulations in the mineral industry might change, these three comprehensive WEF scenarios on mining and metals to 2030 are analysed (see http://www.weforum.org/reports/mining-metals-scenarios-2030) and possible options for mineral industry to maintain its position are evaluated. Each of these scenarios explains how global and national conditions for mining is changing providing a base line to discuss possibilities for the mining and energy sectors to collaborate.

6.2.1. Green trade alliance

The First scenario of WEF mining and metals scenarios states that future global mineral trade happens based on global alliances with shared environmental standards, consequently cash flows will be limited between countries with same levels of emission rates. Currently, average emissions per unit of primary metals production in Australia is higher than world average (Lund et al., 2008). This fact shows that Australian copper mines need to decrease their environmental impacts using both new technologies which enhance energy efficiency and decrease the environmental impacts,

6.2.2. Rebased globalism

Rebased Globalism highlights the emergence of new mineral providers from the developing world. Rich resources of minerals with higher ore grades will change the global market of mining towards countries who can offer resources with cheaper price. This fact is very important for Australian society and government because mining in Australia has formed a big part of Australian economy so the way Australian mines deal with future mineral markets will affect the job opportunities and society in the future. The bar for Social Licence to operate is also set higher under this scenario.

If Australian mines decide to continue business as usual, social licence and market access will be important factors in securing future job opportunities losses and restraining damage to the environment. Consequently, one option in this scenario is moving towards innovations in the mineral industry, such as recycling or establishing new business models like product service systems. The second choice could involve the mineral industry in activities that can provide benefits for the Australian society such as exporting mining knowledge and ensuring positive legacy from mining operations to increase social licence.

6.2.3. Resource security

Resource security highlights the limit on international trade of scarce materials. This fact will make prices more volatile and decreases access to financial capital. Under this scenario, countries are encouraged to increase in-country value adding processes, which requires extending the current business market of Australia from extracting raw materials to processed products, however access to foreign capital required for development could be difficult.

The use of such future scenarios provides a lens through which potential future research directions pursued in Australia can be assessed for their robustness.

7. CONCLUDING DISCUSSION

Australia as one of the nations with high reserves of copper and long history of copper mining has very well developed infrastructure for copper mining and smelting and has been earning profits from this industry for many years. Available deposits in Australia show that there are still good remaining deposits of copper in the country. For the first time, a comprehensive database of copper deposits for Australia has been complied on a mine-by mine basis primarily using company data from annual reports and government statistics.

Notwithstanding significant reserves, the geological characteristics of copper mines in Australia shows that ore grades are coming under 2% in most of the mines which results in high amounts of energy intensity for extraction. As energy prices rise, this fact increases the cost of mining and decreases the profitability of the industry with current technologies.

The analysis presented in this report shows the changing impact profile associated with copper mining over 70 years in Australia. In short, efficiency gains made by the introduction of new technologies such as flash smelting in place of reverberatory smelters have largely been eroded by declines in ore grades. Furthermore, higher efforts required to extract copper with lower grades further pressures the natural environment and public health.

Options to address the changes in geological and social conditions for mining include using new technologies. Whilst significant focus in technological development is on in-situ and deep sea mining, these have significant environmental and social barriers to wide scale deployment. Research focus should also be directed to linking clean energy sources with higher energy efficiency processes and the pursuit of enhanced recycling technologies and logistics. These should be evaluated in the context of changing global scenarios to position Australian research and knowledge development for value creation across the remainder of this century.

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