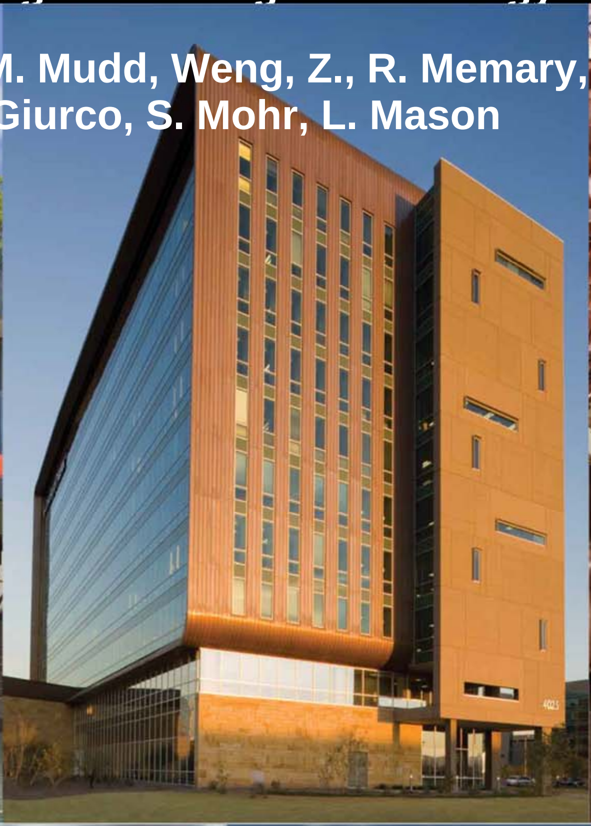
CLUSTER RESEARCH REPORT

No. 1.12

Future Greenhouse Gas Emissions from Copper Mining: Assessing Clean Energy Scenarios



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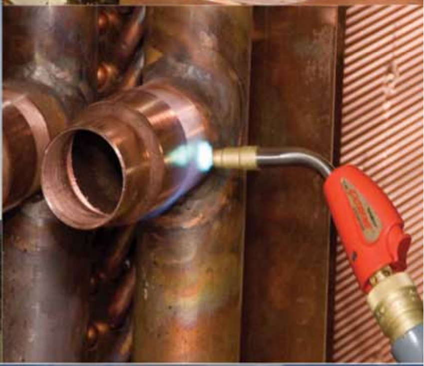

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For

CSIRO Minerals Down Under National Research Flagship

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1. BACKGROUND

This report is submitted as part of the Commodity Futures component of the Mineral Futures Collaboration Cluster as a case study on copper. The commodity futures project focuses on the macro-scale challenges, the dynamics, and drivers of change facing the Australian minerals industry. The Commodity Futures project aims 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 mining and smelting in Australia with a critical reflection on future environmental and technological challenges facing the copper related mining and mineral industries of Australia. A key focus is detailed life cycle assessment (LCA) modelling of the greenhouse gas emissions intensity of future copper mining and milling, based on a detailed copper resource data set.

1.1. Aim

The aim of this paper is to review the link between resources, technology and changing environmental impacts over time as a basis for informing future research priorities in technology and resource governance models.

2. Brief Review of Copper Mining and Demand

Copper's characteristics such as ductility, malleability, high electrical and thermal conductivity in addition to high corrosion resistance have made it one of the base metals with a variety of applications for thousands of years. It has been used in electrical and thermal conduction applications, 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, personal computers 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 demand for 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 as well as growing consumption in major countries such as China and India.

A detailed case study of Australian and global copper mines and resources was presented by Memary et al. (2012), including an historical model of greenhouse gas emissions (GGEs) intensity of some copper mines in Australia. The current report should be read as a follow-on from this previous study.

2.1. Global copper production

World copper production has been increasing at about 2.75% a year for over a hundred years, as shown in Figure 1, including by country in recent decades. Over the past century, the status of dominant copper producer has shifted from the USA to Chile, with moderate production from a range of countries such as Australia, Canada and across southern Africa and Europe, amongst others. Cumulative global copper production from 1770 to 2011 has been approximately 596 Mt Cu.

An assessment of global copper resources was given by Memary et al. (2012), based on a detailed compilation of individual project mineral resources as reported by numerous mining companies. Based on global resources data (from Memary et al., 2012, including updates from Mudd et al., 2012), Chile remains the dominant country with 658.2 Mt Cu, with important resources in numerous countries around the world, including the USA, Peru and Australia with 170.1, 168.2 and 126.9 Mt Cu, respectively. World copper resources were at least 1,860 Mt Cu (including China).

The ore grades of copper ore being processed around the world have been gradually declining, shown in Figure 2. In the mid-1800s copper grades were very high, over 10% Cu in Australia and around 8% Cu in Canada, however by 1900 the grades had declined to under 4% Cu. Currently Australia, Canada and the USA have copper ore grades of less than 1% Cu.

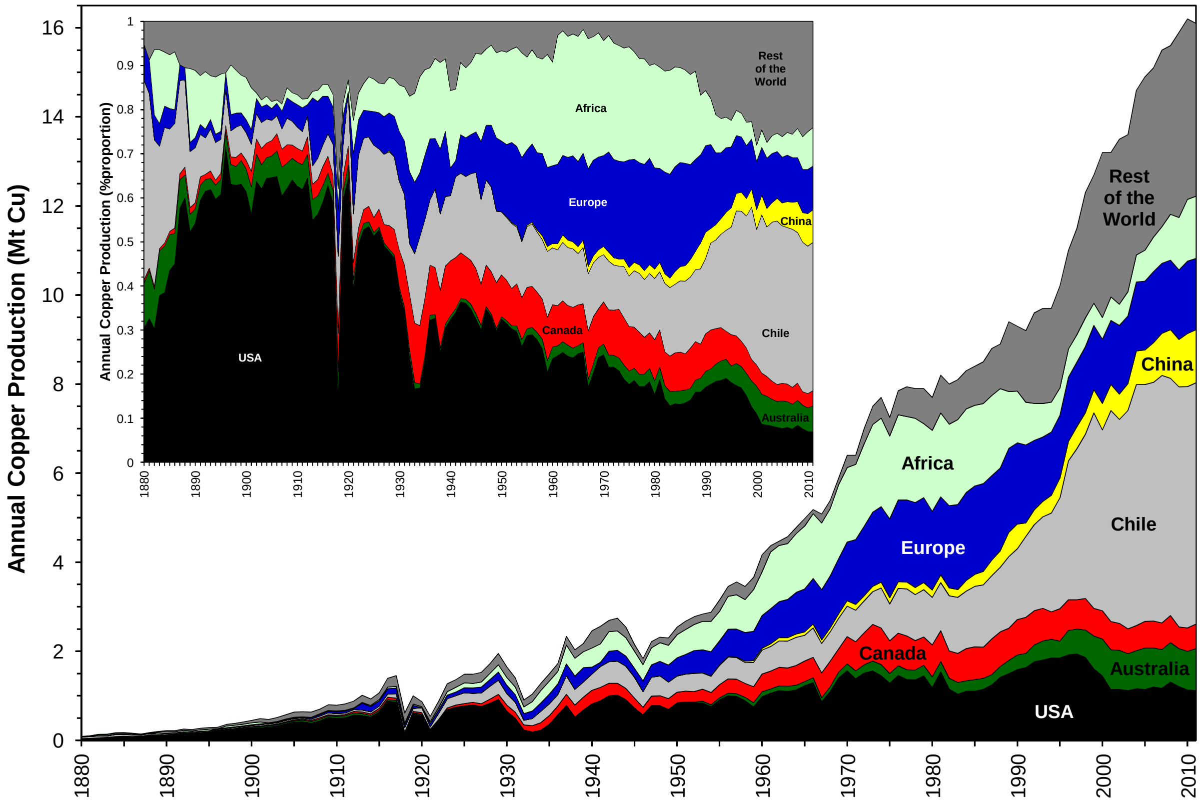

Figure 1: World copper production (ex-mine) by selected countries and region, 1880 to 2011, with inset of fractional production (data from Mudd et al, 2012).

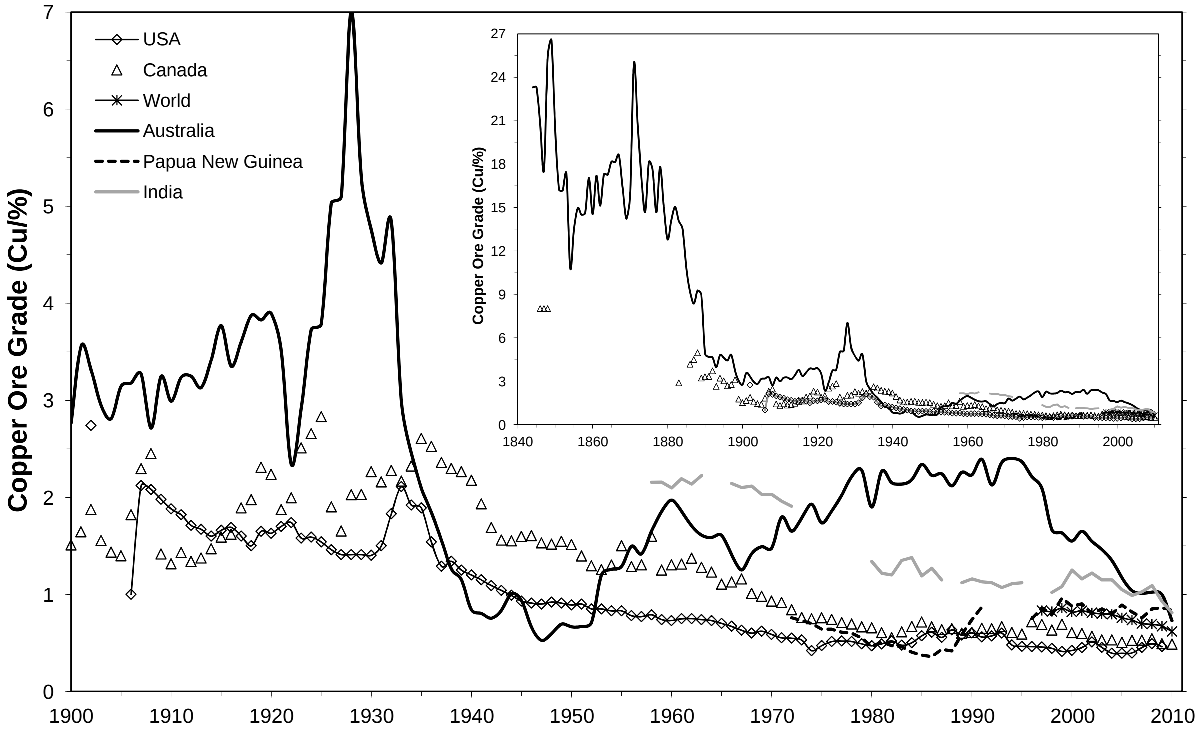

Figure 2: Copper ore grade over time in select countries (Mudd et al., 2012).

The nominal and real price of copper over time is shown in Figure 3, showing that the real price has generally declined since 1900, even allowing for boom-bust price cycles. The factors influencing the world average copper price are many, and can include energy (especially diesel and electricity), water, transport, demand / supply balance, mining and ore processing technology, labour, mine waste management, government and industry policy, new (or declining) uses, scale and rate of industrial and urban development (eg. China, India, Africa, etc.), and so on.

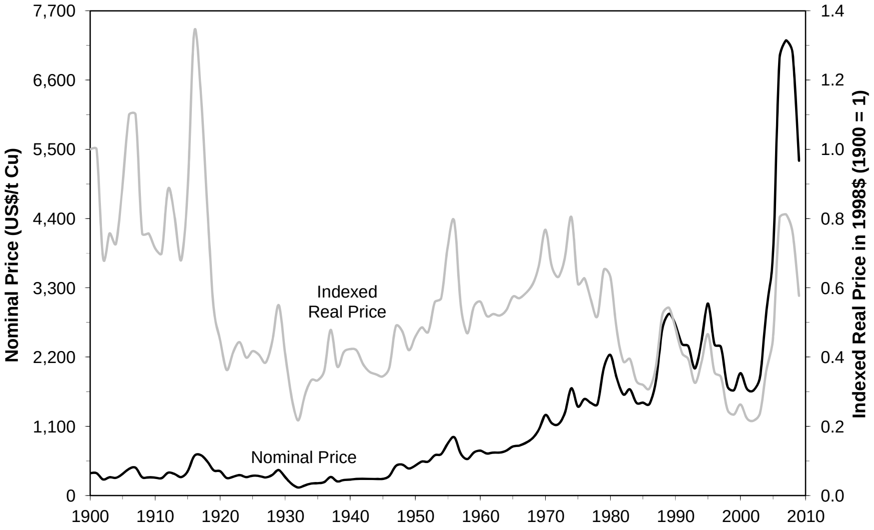

Figure 3: The price of copper over time (data from Kelly & Matos, 2012).

2.2. Copper demand

The breakdown of copper uses is shown in Table 1. 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.

In general, copper consumption is closely linked to per capita GDP, with more developed countries having a higher consumption rate than less developed countries. Trends in per capita copper consumption in recent decades are shown in Figure 4 for the USA, Australia and the world. For the USA and Australia, per capita copper consumption was relatively stable throughout the latter half of the twentieth century, averaging between 6 to 10 kg Cu/person/year, but has declined steadily over the 2000s (now ~6 kg Cu/person/year). In contrast, world per capita copper consumption has been gradually rising over the past fifty years from ~1.6 to ~2.8 kg Cu/person/year.

In global terms, per capita consumption is expected to continue to increase, given the ongoing industrialisation and urbanisation of China and India (with other regions such as Africa, South-East Asia and South America also likely to emerge in coming decades as major development hubs) as well as ongoing population growth (shown in Figure 5).

Table 1: Copper demand in recent years (kt Cu; ICSG, 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	**23,947**	**22,098**

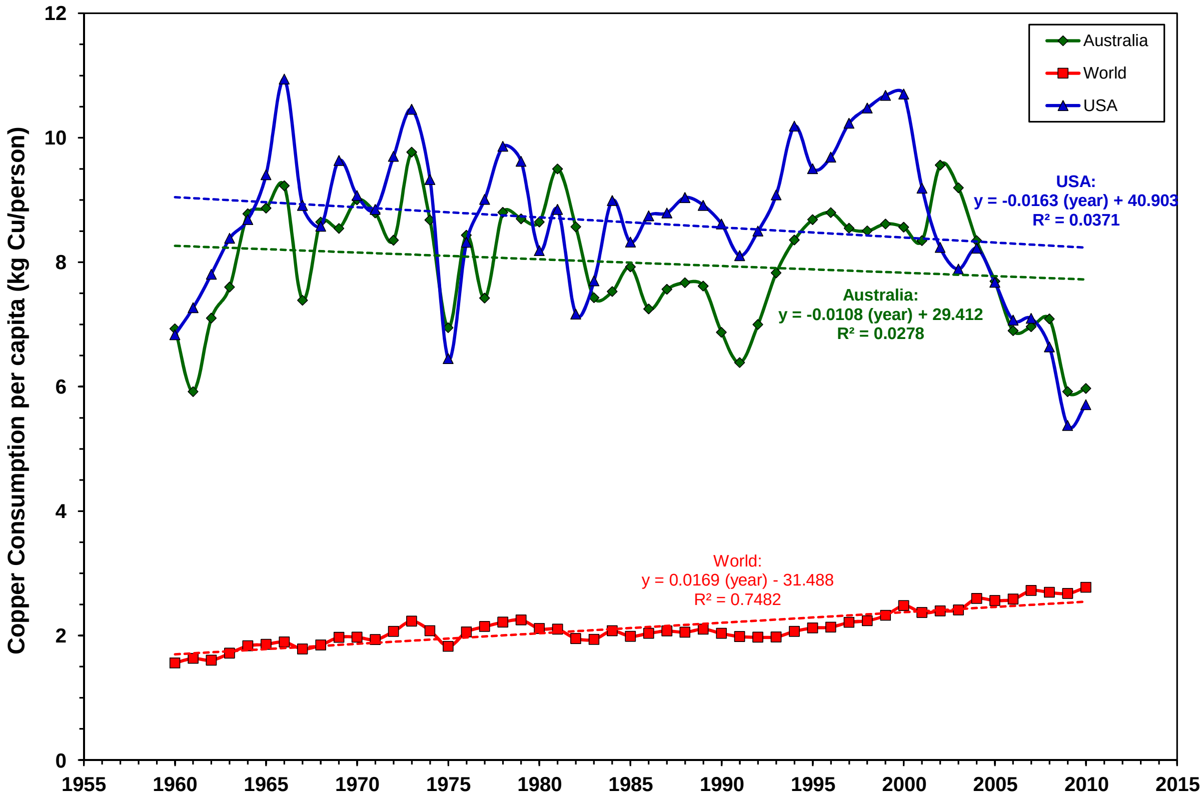

Figure 4: Per capita copper consumption over time for Australia, USA and World (data combined from ABARE, various; BREE, 2011; USGS, 2012; ICSG, 2007, 2009, 2010; UNDESA-PD, 2011a,b; USCB, 2012).

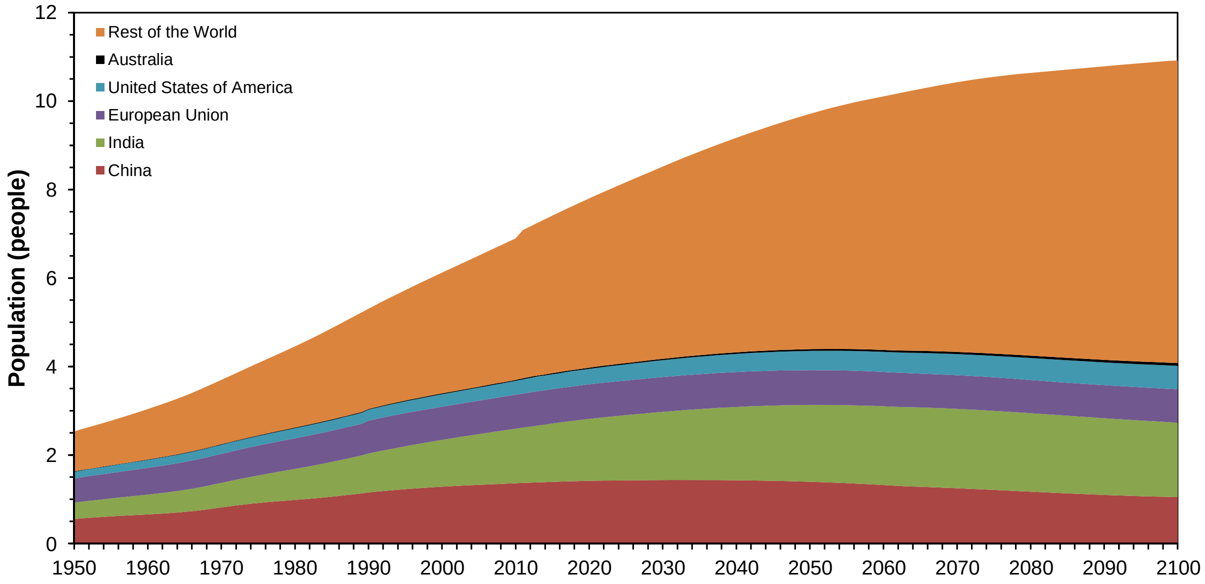

Figure 5: Recent and projected population for select countries and the world (data combined from ABS, 2011b; USCB 2012, UN 2011b; UNDESA-PD, 2011a,b; USCB, 2012).

3. Climate Change Impacts of Copper Mining

3.1. Life cycle assessment of copper production

Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). Many studies have used LCA to show the footprint of different commodities including copper (see Norgate & Rankin, 2000; Norgate et al., 2004, 2007; Fthenakis et al., 2009). The LCA guideline of Leiden University is used in this study (Guinée et al., 2001). LCA has four main stages including goal and scope definition; inventory analysis; impact assessment; and interpretation (ISO, 2006).

A recent study of the carbon footprint of copper mining is the work by Memary et al. (2012), which maps the carbon equivalent of one kilogram copper produced in major Australian copper mines. Based on this study, the carbon footprint of copper produced at five main Australian mines ranges from 2.5 to 8.5 kg CO_{2e}/kg Cu and the difference between different locations can be up to 6 kg CO_{2e}/kg Cu. This study also explores the contribution of different stages in the mining process to the global warming potential of copper mining as an example, the pie chart in Figure 6 shows that mining and milling and then smelting are responsible for a major portion of copper mining carbon footprint.

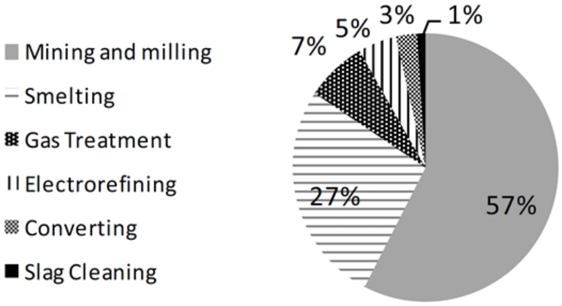

Figure 6: Contribution of each mining operation to GWP of copper mining in Mt Isa (2008) (Memary et al., 2012).

3.2. Energy inputs into mining stages

The greenhouse gas emissions of the different stages of copper processing are dependent on the direct or indirect source of energy used in that stage. Briefly, diesel (for trucks and mining equipment) and electricity are used in mining stage (open cuts typically consume less electricity than underground). Coking coal and natural gas are the main energy source in smelting. Some electricity and natural gas is used in fire refining while electricity is the main energy source used in electro-refining (Davenport et al., 2002). The carbon footprint of electricity used in the process depends on the energy source of electricity generation. This could be coal, diesel or natural gas (for an off grid generator), hydro or other renewables.

3.3. Relationship between ore grade and carbon intensity of final product

For copper and some other metals, there is an increasing recognition that future mineral deposits will be discovered deeper (eg. Mudd, 2010) which requires more energy to reach. Furthermore, Figure 2 shows a declining trend for copper ore grade in some regions including Australia. As shown in Figure 7, as ore grade decreases, the energy intensity of copper production rises and consequently global warming potential. Together, mining deeper deposits with lower ore grades produces higher amounts of mine waste (tailings plus waste rock) which also consumes more energy in the process. This reduction in grade also has an intense effect on sulfur dioxide emissions (SO_2; which leads to acid rain formation) from metal production processes (Norgate & Rankin, 2002).

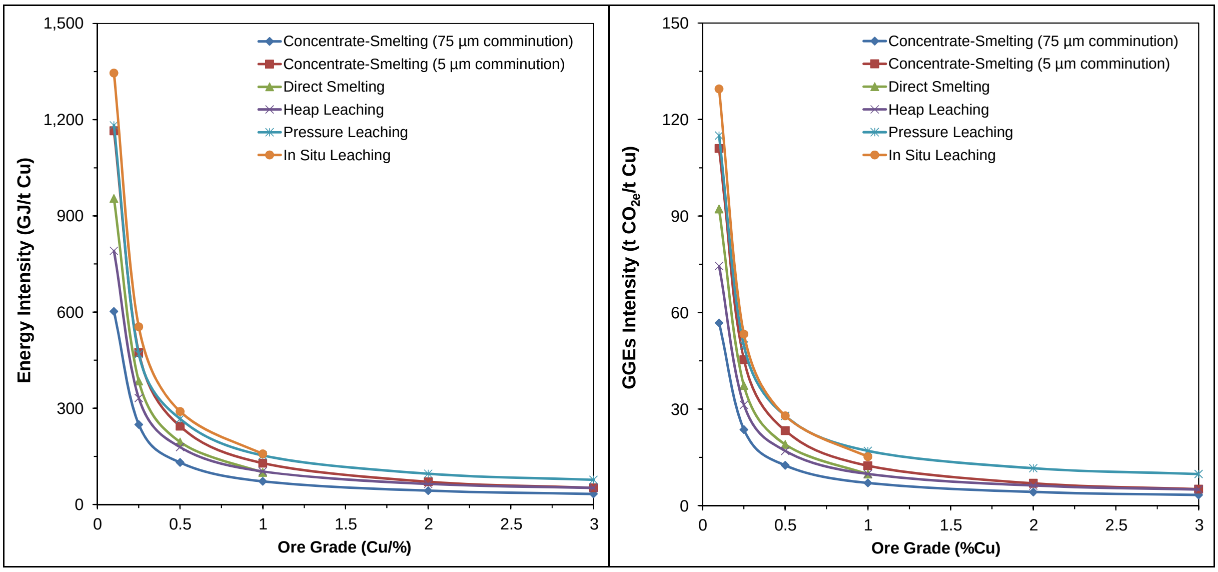

Figure 7: Energy and greenhouse gas emissions (GGEs) of copper versus ore grade by process configuration (Norgate & Jahanshahi, 2010).

4. Methodology

4.1. Peak modelling of future copper production

In order to model future copper production, the fossil fuel model of Mohr (2010) was used to assess and predict future copper mines. The model, known as the "Geological Resources Supply-Demand Model" or GeRs-DeMo, works by applying a standard production profile to a mine (or field), as shown in Figure 8, using various input parameters. By listing all mines, including their ultimate recoverable resource (or 'URR') and production and applying supply-demand parameters, GeRs-DeMo models the cumulative production over time, as shown in Figure 9. Further details of the GeRs-DeMo model are given by Mohr (2010).

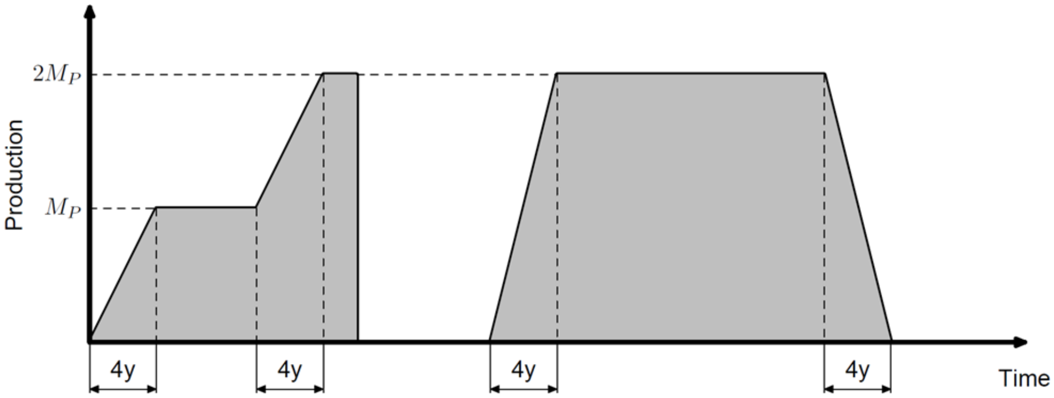

Figure 8: Standard production profile for a mine in the GeRs-Demo model (Mohr, 2010). (Note: 4y is the 4 year ramp up time assumed for mines)

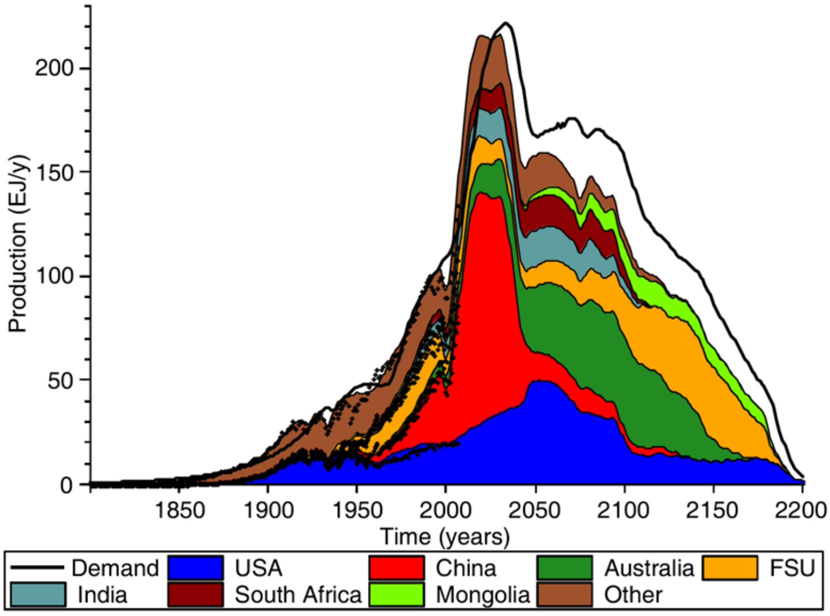

Figure 9: Modelled world production profile for coal using the GeRs-DeMo model (Mohr, 2010).

The Australia and global copper resource data set used for this study was obtained from the copper case study (Memary et al., 2012), including some minor updates (Mudd et al., 2012).

One issue with GeRs-DeMo is that it only predicts a tonnage or quantity of mineral production, and not other aspects such as ore grade which are crucial for metal mining. To address this gap, Northey (2012) developed an approach to take the model outputs from GeRs-DeMo and use these to calculate ore grades over time, based on the copper resource data. This then allows the carbon intensity to be modelled directly from ore grades over time as well as other aspects important in life cycle assessment modelling. The results for modelling Australia's future copper production are taken from Northey (2012) (included in later section).

The modelling by Northey (2012) assumes that all known copper deposits will be eventually developed over time, although there always remains uncertainty over whether any particular project will be mined (depending on economics, input costs, market conditions, social and environmental issues, etc.).

Australian and global copper productions and demands are driven by complex local factors including population growth rate, economic development, industrial applications, recycling efficiencies etc. Population growth and increasing per capita copper consumption are the two most significant contributors to global Cu demand boost since the industrial revolution began. Given that population growth was addressed earlier (Figure 5), we now focus on the trend of per capita copper consumption.

Historical data of copper consumption intensity is estimated by dividing national copper consumption by national population statistics. As illustrated in Figure 4, linear regression lines were developed for the USA, Australian and global per capita copper consumption trends. In Figures 10 and 11, the per capita consumption regression lines are extended to 2090 and combined with projected population to estimate future Australian and global total copper consumption, which is contrasted with GeRs-DeMo modelled mine production trends.

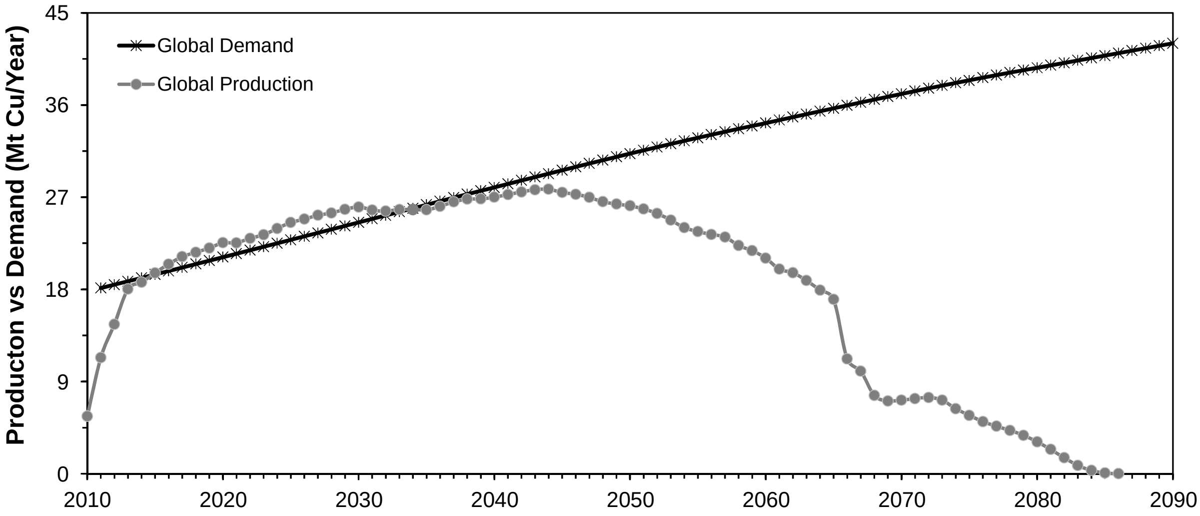

Figure 10: Projected global copper demand and mine production to 2090.

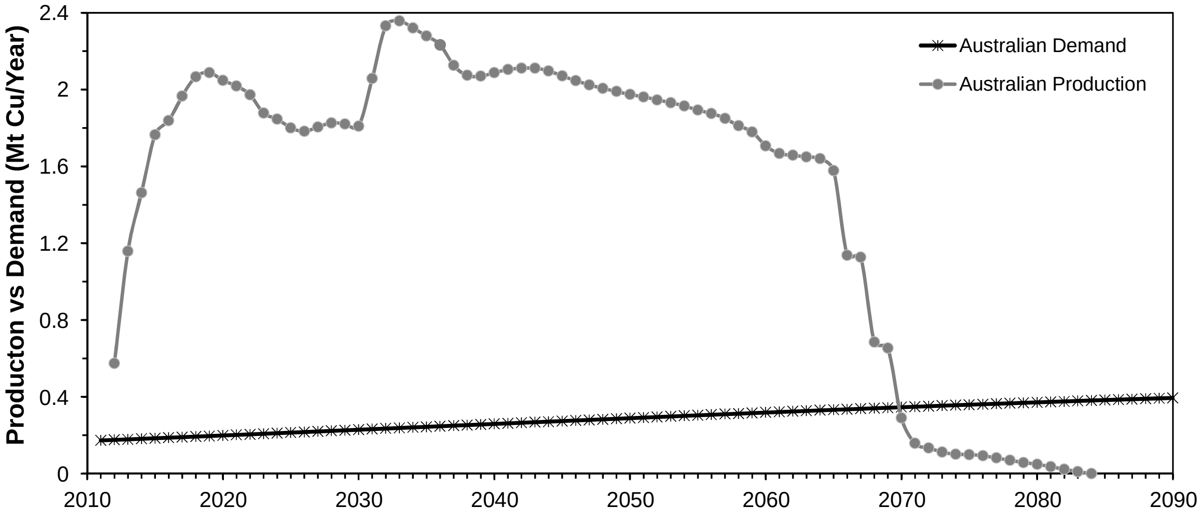

Figure 11: Projected Australian copper demand and mine production to 2090.

Figure 10 shows global copper demand could be readily satisfied by mine production until the early 2040s, with a peak annual global production rate of 27.7 Mt Cu in 2044. Beyond this time, increasing global demand cannot be met by mine production alone. In other words, more emphasis on copper recycling and improving efficiency is not only a choice but rather a necessity on a global scale.

Projections of Australian copper demand and mine production over the next century (Figure 11) show that Australia will produce far in excess of demand until 2070, when all deposits are effectively exhausted. Until this time, this allows Australia to continue to be a major copper exporter.

4.2. LCA model of copper mining

All Australian copper projects (from Memary et al., 2012) were classified based on mine type and processing configuration for existing mines, while assumptions were made about deposits concerning their likely development (eg. open cut or underground, flotation or heap leach with solvent extraction-electrowinning). The main configurations are thus:

- ***Open cut and flotation*** – producing a copper concentrate;
- ***Underground and flotation*** – producing a copper concentrate;
- ***Open cut and heap leach-solvent extraction-electrowinning*** – producing refined copper metal;
- ***Underground and heap leach-solvent extraction-electrowinning*** – producing refined copper metal;
- ***Miscellaneous*** – mixed open cut and underground mine with flotation, mixed open cut and underground mine with heap leach, or underground mine and heap leach.

The full list of Australian copper deposits and their mine and process configuration is provided in Appendix 1.

In this way, the LCA model for copper mining by Giurco (2005) can be applied based on the primary stages involved in copper production. This model was also used to model historical copper mining in Australia by Memary et al. (2012). Although the Giurco model includes all four primary stages of mining, milling, smelting and refining, this study will only analyse mining and milling since the vast majority of projects (existing and future) do not include a smelter at the project site. The only existing copper smelters (Mt Isa and Olympic Dam) and refineries (Olympic Dam and Townsville) in Australia are very unlikely to be expanded based on current cost pressures in the industry, with the Mt Isa and Townsville facilities currently scheduled by owner Xstrata to be closed in 2016 and the proposed Olympic Dam expansion recently postponed indefinitely by BHP Billiton. Hence all existing and future copper projects in Australia will be essentially mining and milling only (except for heap leach projects, which, based on deposit types and assumed configurations, appear likely to be minor in scale and production compared to flotation-based projects).

There were two primary approaches to LCA modelling of future Australian copper production:

1. ***State / Local Grid Model*** – all mines were grouped based on their respective electricity grid (or source), to allow for a specific carbon intensity for electricity. Although most states only have a single electricity grid, states such as Queensland and Western Australia have numerous mines in remote areas not connected to the main state grid. An LCA model was then developed for each grid-based group and project configuration. For example, all copper projects around Mt Isa were grouped since they are connected to the gas-fired electricity grid for Mt Isa, while projects in eastern Queensland were assumed to be connected to the black coal-based electrical grid.

2. ***Australian Model*** – Based on the copper produced from all projects of a given configuration, such as open cut-flotation or underground flotation. A separate LCA model was developed for each configuration, using the modelled copper production from Northey (2012) and calculated ore grade from the projects involved in this configuration. Four LCA models were run separately and then combined to give the Australian total.
3. ***Global Model*** – Based on the global copper production model by Northey (2012), a basic global LCA model was developed assuming a constant ratio of 85%-15% by open cut-underground (Scenario 1), or starting at 85%-15% and moving to 50%-50% by 2100 (Scenario 2), respectively. It was assumed that all projects used flotation.

The dominant energy inputs to copper mining and milling are electricity and diesel, leading to significant greenhouse gas emissions per tonne of copper (ie. carbon intensity). In order to assess the effectiveness of low carbon energy inputs to decrease the carbon intensity, different energy scenarios were modelled, specifically:

1. ***Grid-based Electricity*** – electricity sourced from the local grid, either state main grid or separate regional grid, transportation is assumed to be petroleum-derived diesel. This is a "business-as-usual" scenario.
2. ***Natural Gas-based Electricity*** – all electricity sourced from natural gas. This is a "partial transition" scenario.
3. ***Solar Thermal Electricity*** – assuming that electricity was obtained from baseload solar thermal power plants, with a carbon intensity of 0.05 kg CO_{2e}/kWh (see Lenzen, 2010). This represents a more "comprehensive transition" scenario.
4. ***Solar Thermal Electricity and Biodiesel Transport Fuel*** – all diesel consumed in mine vehicles comes from biodiesel, with a carbon intensity of 10.63 kg CO_{2e}/t diesel; based on biodiesel being a renewable fuel, with the carbon released being absorbed in re-growing the source oil feedstock (as defined by climate change carbon accounting conventions; see DCCEE, 2011). All electricity consumed in mining process are assumed be satisfied by solar power network. This represents a "very optimistic transition" scenario.

Details of emission factors implemented are summarised in Table 2.

Table 2: Greenhouse gas emission factors for electricity implemented in the LCA modelling (kg CO_{2e}/kWh) (Australian grid and gas data sourced from DCCEE, 2011; solar thermal from Lenzen, 2010; global data from IEA, 2011).

	Global	Australia	VIC	NSW	SA	NT	WA	TAS	QLD
Grid	0.502	1.04	1.35	1.06	0.81	0.75	0.93	0.33	1.00
Gas	0.39	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Solar	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

4.3. Copper production and ore grade projections

Global and Australian copper production to 2090, based on the GeRs-DeMo modelling, are summarised in Figure 12. Both graphs show increasing trend of Cu production until Australia peaks at 2033 and global peaks at 2046. Peak production rate of Australia estimated to be 2.35 Mt Cu per year whilst peak global Cu production is 27.7 Mt Cu per year.

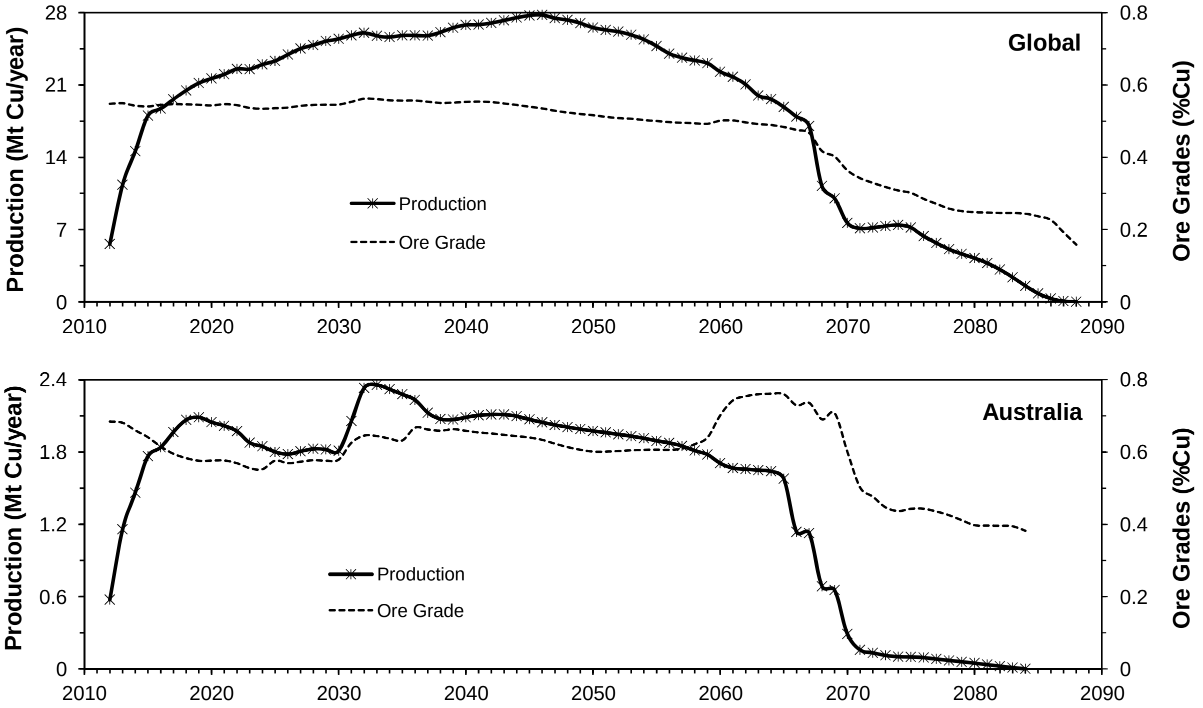

Figure 12: Projected Global (top) & Australian (bottom) copper mine production and ore grade to 2090.

Ore grade is another primary factor in predicting environmental impacts of Cu mining. In the global scenario, ore grade shows a very gradual declining trend to 2067, when the rate of decline increase, and overall ore grade reduces from 0.55% Cu in 2012 to 0.16% Cu by 2088. From the 2070s, the decline in ore grade is principally due to the exhaustion of high grade ore resources. Australian ore grade does not show declining trend as significant as global scenario, although a minor decline occurs around 2070 when majority of local porphyry deposits become exhausted.

5. Results

5.1. Greenhouse gas emissions projections of global copper mining

There are two scenarios of Global Copper production which were implemented in LCA modelling. Scenario 1 assumes constant 85% open cut and 15% underground mining configurations of all copper mines (based on production data in Mudd & Weng, 2012); Scenario 2 initially assumes the ratio of 85% open cut and 15% underground mining and moving to 50-50% open cut and underground mining by 2100. By combining each production scenario with emissions factors from Table 2, results of global copper mining emissions are plotted in Figure 13.

Generally, due to higher percentages of open cut mining in Scenario 1, its emission rate and intensity is almost always higher than Scenario 2 in the three electricity source (Grid, Gas and Solar) models. The only exception is the 'Solar Thermal Electricity and Biodiesel Transport Fuel' model in which Scenario 2 has slightly higher emission rate and intensity. Overall trends of total greenhouse gas emissions from Cu mining are driven mainly by annual Cu production while the pollution intensities are closely related to ore grade (as expected). As shown from Figures 12 and 13, when global ore grade begins to rapidly decline from the late 2060s, the greenhouse gas emissions intensity of Cu mining also increases significantly.

5.2. Greenhouse gas emissions projections of Australian copper mining

For the Australian models, all Victorian (VIC), Tasmanian (TAS) and New South Wales (NSW) projects are connected to the state grid for LCA modelling purposes, using the respective state average grid emissions factors. The Mt Isa region is dependent on natural gas-fired power station. Where a project not connected to the state grid is using natural gas for electricity, we allocated it to the "Mt Isa Group". While some West Australian (WA) projects are reliant electricity from diesel-based generators, the emissions intensity for such electricity is virtually identical to the WA state grid factor, and hence such projects were included in the "WA grid model". Full details of the classification of all mines and projects are provided in Appendix 1. Deposits with complex open cut and underground configurations are assumed to have a production ratio between open cut and underground of 50-50%. As such, the "State Sum" model is the summary of all individual state and regional based models while the "Australia" model is based on national average emissions factor and Cu production rates. All modelling results are plotted in Figure 14.

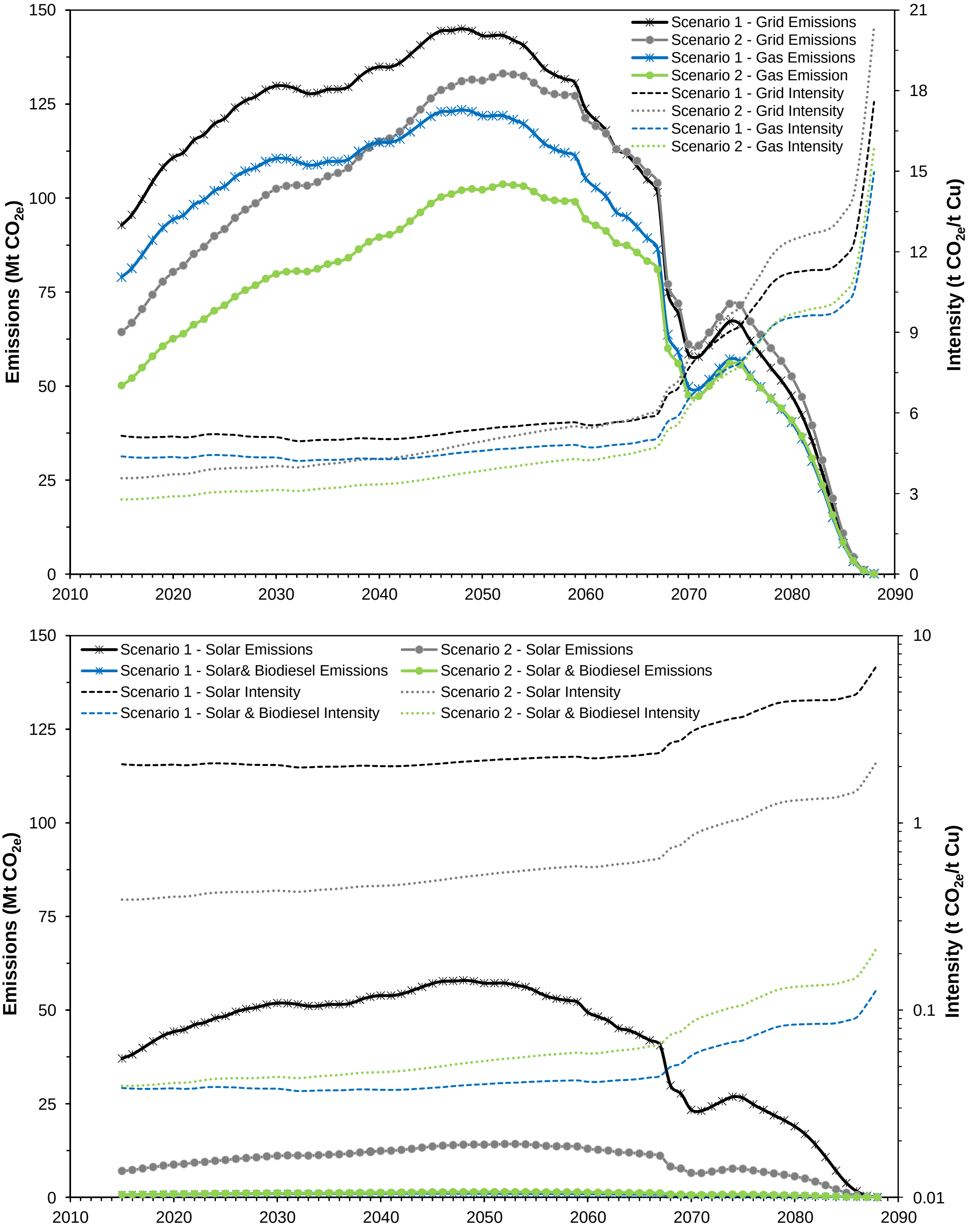

Figure 13: Global greenhouse gas emissions and intensity for the grid and gas electricity scenarios (top) and solar thermal electricity and solar thermal plus biodiesel scenarios (bottom).

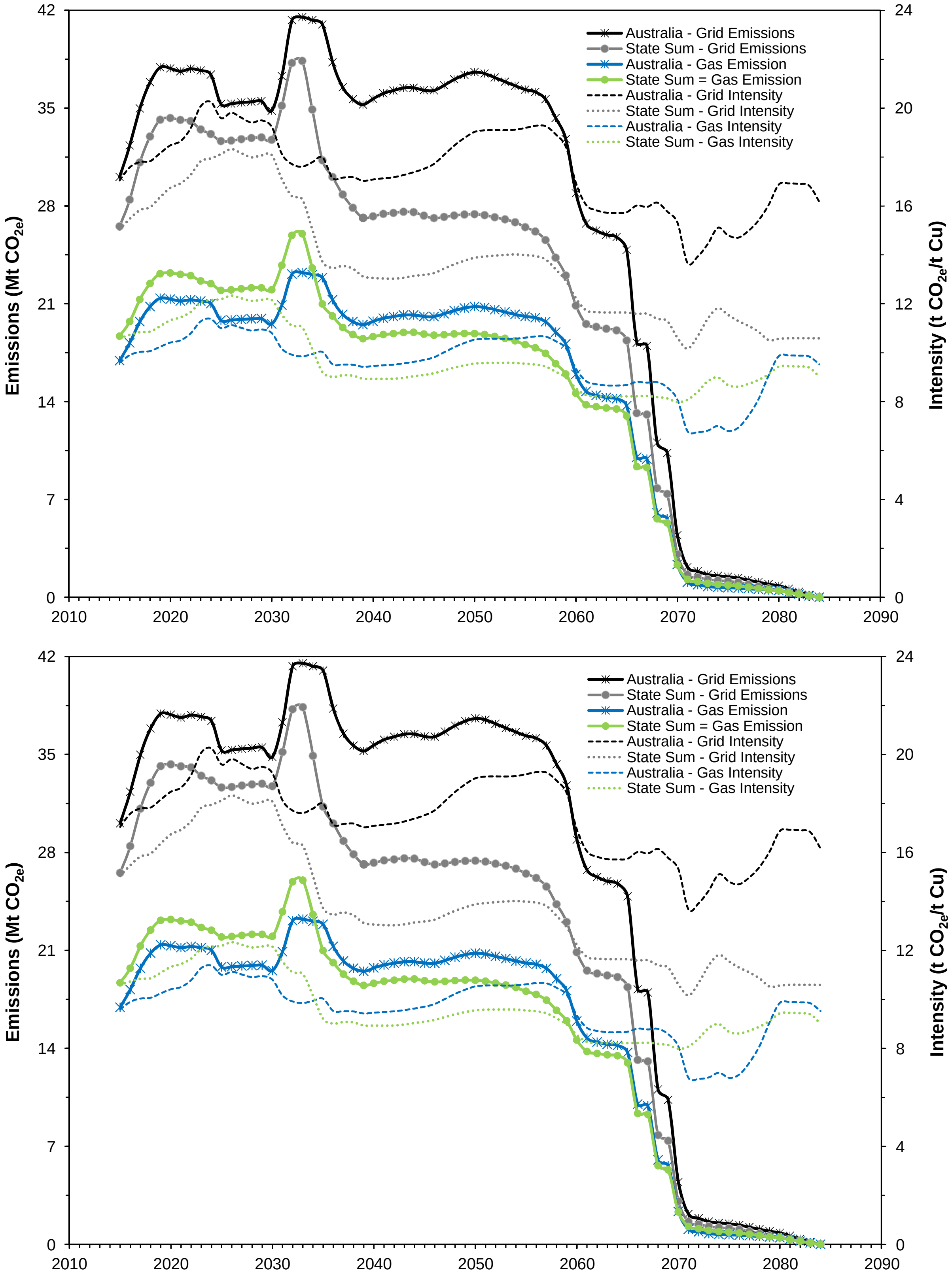

Figure 14: Australian greenhouse gas emissions and intensity of grid and gas Electricity Scenarios (top) and solar thermal electricity and solar thermal plus biodiesel scenarios (bottom).

In the grid electricity scenario, the "Australia" model often significantly overestimates total greenhouse gas emissions compared to the "State Sum" model. This is due to the fact that state grids have varying emissions factors which are lower than the Australian average grid factor of 1.04 kg CO_{2e}/kWh (i.e. Mt Isa group is natural gas, TAS is on hydroelectricity while South Australia, where considerable production occurs, is mainly coal but has significant wind). By 2033 the Australian copper production achieves a peak annual rate of 2.36 Mt Cu. The corresponding peak emissions totals and intensities and production data based on the different models are summarised in Table 3.

Table 3: Australian greenhouse gas emissions totals and intensities in the peak production years of 2033 and 2050.

	Prod.	Grade	Demand	Electricity Source	Emissions (Mt CO_{2e}/year)		Emission Intensity (t CO_{2e}/t Cu)	
	Mt Cu	%Cu	Mt Cu		Australia	State Sum	Australia	State Sum
2033	2.36	0.64	0.024	Grid	41.51	38.37	17.61	16.28
2050	1.97	0.60	0.029		37.57	27.41	19.03	13.88
2033	2.36	0.64	0.024	Gas	23.22	26.01	9.85	11.03
2050	1.97	0.60	0.029		20.80	18.87	10.53	9.56
2033	2.36	0.64	0.024	Solar	5.96	7.12	2.53	3.02
2050	1.97	0.60	0.029		5.37	5.13	2.72	2.60
2033	2.36	0.64	0.024	Solar & Biodiesel	0.19	0.21	0.080	0.088
2050	1.97	0.60	0.029		0.17	0.15	0.087	0.077

The results of the solar thermal with biodiesel scenario show the most significant reductions in total greenhouse gas emissions as well as intensity. Compared to 38.37 Mt CO_{2e} in 2033 from the State Sum grid model, the solar thermal-biodiesel combination could effectively reduce total greenhouse gas emissions to 0.21 Mt CO_{2e} per year. However, by simply changing the electricity source to solar thermal alone could achieve an 81% reduction in annual greenhouse gas emissions from copper mining even without biodiesel.

Resulting from gradually declining ore grade, emissions intensities in all electricity and energy scenarios increase slightly. Considering all modelling results supports the proposition that solar thermal with biodiesel as the best energy solution for sustainable mining, leading to annual greenhouse gas emissions and intensity reductions of some 99%. Such a transition would allow the copper sector to address all potential future implications of carbon pricing and other climate change policy action and targets (see next section).

6. Analysis & Discussion

The mining and use of copper is inextricably linked to technology in a variety of ways – from exploration, mining and refining through manufacture to use and possible recycling. This study has focussed on modelling the mining and milling stages of copper production, especially the greenhouse gas emissions intensity, using a variety of energy and electricity scenarios. This section presents a brief discussion and analysis of the findings and their implications for copper mining in Australia, as well mining more generally, especially with respect to long-term greenhouse gas emissions targets.

6.1. Greenhouse gas emissions targets and trajectories

The medium and long-term targets for reductions in total greenhouse gas emissions for Australia are (DCCEE, 2012):

- 5% from 2000 levels by 2020 without any global commitments;
- 15% from 2000 levels by 2020 if global commitments seek to achieve stabilisation of atmospheric CO_{2e} levels of between 510 to 540 ppm;
- 25% from 2000 levels by 2020 if global commitments seek to achieve stabilisation of atmospheric CO_{2e} levels of 450 ppm;
- 80% from 2000 levels by 2050 as an aspirational goal.

Australia's total greenhouse gas emissions in 2000 were 558 Mt CO_{2e} (DCCEE, 2010), although there is no breakdown of emissions inventory data whereby copper mining is separated out for its reported emissions. As such, approximate emissions from 1990 to 2010 are calculated based on a nominal value of 15 t CO_{2e}/t Cu and national copper production. For the year 2000, where production was 839,000 t Cu, this gives estimated emissions of 12.6 Mt CO_{2e}. The medium and long-term emissions targets are then estimated from this value and compared to the electricity and energy scenarios presented previously, using the state sum model, and this is shown in Figure 15 and summarised in Table 4. It is assumed that all emissions reductions are shared equally across the economy.

From this graph, it is clear that adoption of solar thermal technology as the dominant electricity source allows substantial emissions reductions to be achieved and this would ensure that the copper sector is well below the nominal target of 12.0 Mt CO_{2e}. By 2050, however, the target becomes 2.52 Mt CO_{2e} and the solar thermal only scenario projects emissions of 5.13 Mt CO_{2e} – still above the 2050 goal. The solar thermal plus biodiesel scenario projects emissions of 0.15 Mt CO_{2e} – significantly below the 2050 goal. Another alternative approach, not modelled in this study, is to electrify mining vehicle fleets and provide the electricity via solar thermal plants also. Given the increased energy efficiency of such an approach (i.e. high conversion of the embodied electricity into application), this could present even further opportunities for reducing energy inputs and reducing the environmental footprint of copper production.

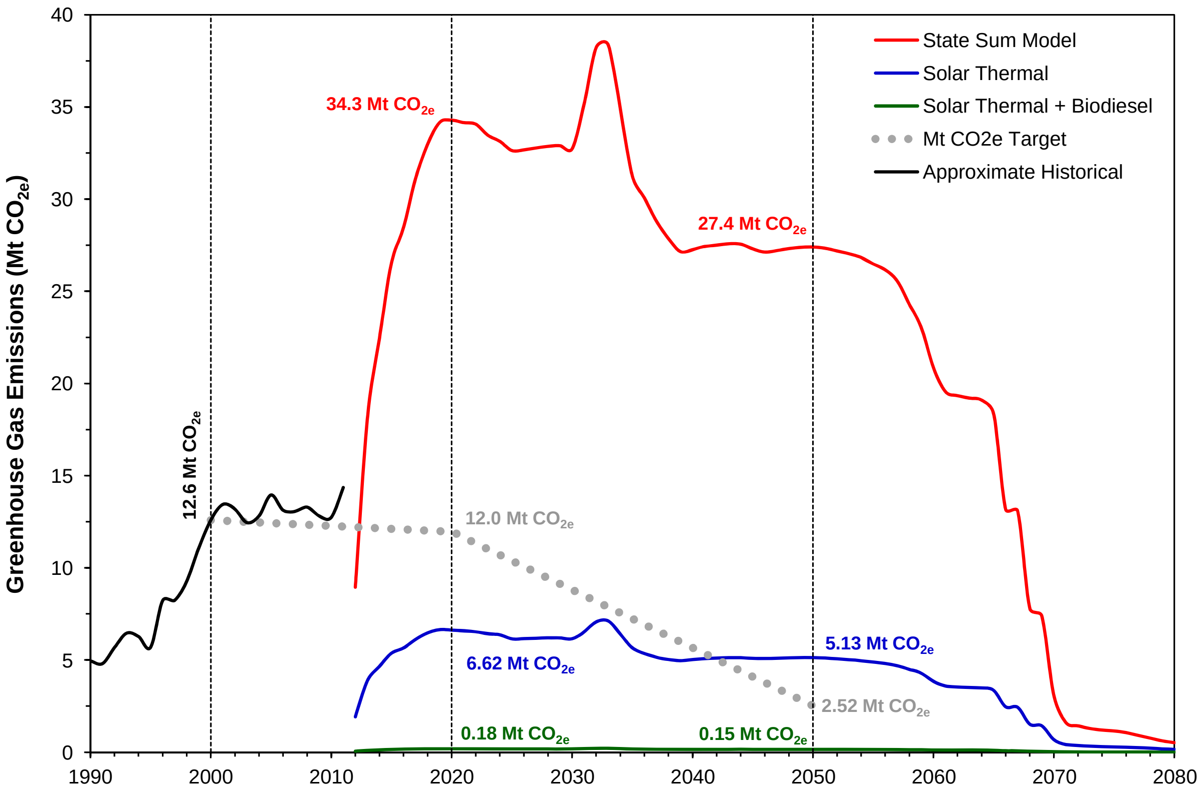

Figure 15: Comparison of estimates of annual greenhouse gas emissions over time and potential target levels for the Australian copper sector.

(Note: the State Sum model is effectively a 'business-as-usual' approach)

Table 4: Greenhouse gas emissions scenarios for the years 2000, 2020 and 2050 for the Australian copper sector (Mt CO$_{2e}$).

	Historical	State Sum (Local Grid)	Solar Thermal	Solar Thermal & Biodiesel	Target
2000	12.6	-	-	-	-
2020	-	34.3	6.62	0.18	12.0
2050	-	27.4	5.13	0.15	2.52

Combined, the analyses of the modelled emissions scenarios and nominal emissions targets for 2020 and 2050 suggests that the copper sector can achieve sufficiently low emissions intensity to be below the target values, but this requires virtually a complete transformation to renewable electricity sources (such as solar thermal) as well as a large fraction of biodiesel as inputs to mining (especially open cut).

It is beyond the scope of this study to examine the feasibility of such an energy transformation, let alone the economic implications. Although predicting the future economics of renewable energy is fraught with difficulty, given that a carbon price has now been established in Australia, it is clear that the prospects for solar thermal and other renewable electricity technologies (e.g. wind, solar photovoltaic panels) are likely to be increasingly positive.

A final point should be made that energy efficiency remains a crucial part of future mining, and can be a very low cost manner in which to reduce the environmental footprint of mining and metal production, as well as giving an important reduction in operating costs.

Overall, the 'business-as-usual' approach in the copper sector (i.e. the State Sum model) will see it increasingly exposed to the price of carbon, mainly as production increases in Australia with either brownfields expansions or new projects coming on-stream. Based on the scenarios modelled in this study, transformation of the copper sector to 100% renewable energy sources for both electricity and liquid fuels (or even perhaps electrification of mining vehicle fleets) would ensure that the sector can contribute to Australian and global action on reducing greenhouse gas emissions and substantially eliminate its exposure to a carbon price.

6.2. Implications for the future of copper

The long-term future of the copper industry is difficult to project given the complexity of uses and challenges it faces. There are two primary aspects to examine – production and use, with this study focussed on production.

From a resource perspective, as shown by Memary et al. (2012) and Mudd et al. (2012), there are abundant deposits of copper already identified worldwide to sustain and increase production to meet likely demand scenarios for several decades. The primary challenges will therefore be in how production occurs – the technology used and associated environmental (and social) impacts.

At present, open cut mining is the dominant form of ore extraction, while underground mining is used at some deeper and generally higher grade projects. Given the increasing depth of projects, it can be expected that in coming decades there will be a higher proportion of underground mining, though this will be dependent on diesel prices, other mining costs and especially site-specific geological conditions at each project. For example, the Cadia East copper-gold project was originally planned as an open cut mine but this was converted to underground only when seeking environmental approvals. An unusual example of underground mining is the giant El Teniente copper mine in Chile, with an annual extraction rate of about 47 Mt ore/year – making it one of the largest underground mining operations in the world. In reality, it is hard to predict the future trends in mine type, except to say that open cut mining will remain dominant for at least a few decades with underground like to gradually increase its proportion over time, perhaps becoming dominant later this century.

The main technologies used for copper mining are grinding and flotation to produce a copper concentrate (often with significant values of gold and silver) or heap leaching combined with solvent extraction and electrowinning ('SX-EW') to produce a refined copper metal. Although grinding and flotation remains the most widely used technology, heap leaching with SX-EW has averaged about 19% of global copper mine production over the past decade (USGS, various). Based on the global copper resource data, a modest increase in the use of heap leaching with SX-EW can be expected in the future, although grinding and flotation can be expected to remain the dominant process flowsheet.

A major issue with respect to grinding is the average particle size of grinding. In general, a finer average grind size allows for improved recovery, especially from more refractory ores. As analysed by Norgate and Jahanshahi (2010), if the average particle size is reduced from 75 µm to 5 µm the energy and emissions intensity of copper production increases substantially as ore grades decline below 1% Cu. A detailed survey of grind size at existing projects is beyond the scope of this study, although it is recognised in the mining industry that finer grind sizes will be increasingly required at existing and future copper projects. This focusses attention on the need to ensure energy efficient grinding, and that any new technology is assessed against the energy intensity of existing technologies.

An alternative production approach is the use of ‘in-situ leaching’ (ISL), whereby a deposit exists either in a permeable horizon and process solutions can be injected via groundwater bores and the copper-rich solution then simply pumped out and passed through SX-EW. The use of ISL appears to be restricted to a very few projects with suitable geologic conditions, although as shown in Figure 7, ISL-based copper production appears to be more energy and emissions intensive than standard coarse grinding, flotation and smelting-refining.

Overall, there is a strong need to ensure that existing and future technologies used in copper mining and milling (as well as smelting and refining) are assessed against current performance benchmarks for energy and greenhouse gas emissions intensity. That is, if a new technology or process configuration is proposed, it should be more efficient than existing process technology.

As shown in Figure 4, some developed countries like the USA and Australia display a significant reduction in domestic copper consumption per capita. In general, this is due to a few different reasons (Takashi, 2005; Edelstein, 2008):

1. copper smelters and refineries with heavy pollution intensity are shifting to low cost developing countries such as Chile and China;
2. modest recovery in refined copper demands but remains in low recession level;
3. increasing ratio of imported refined copper.

A similar declining trend of per capita copper consumption has occurred in Japan since 1990 as the focus of the national economic shifted from heavy industry and manufacturing to a more service-based economy (Takashi, 2005). In contrast, developing countries such as China and Chile will keep increasing in both total copper demand as well as per capita copper consumption due to strong urbanisation and industrialisation (Takashi, 2005). By 2015, China is expected to achieve an annual copper demand of 8 Mt Cu and 6 to 7 kg Cu per capita demand (Cheng and Weixuan, 2011).

For Australia, copper demand will remain very modest by world standards compared to China, India, North America and Europe, although the decline of manufacturing is likely to continued downwards pressure on Australian copper demand.

Overall, the proportion of copper demand met by recycling will most likely continue to be modest until the latter half of this century – depending on relative costs and benefits. For example, if recycled copper was produced using renewable energy, the environmental footprint would be considerably lower than primary production. In the long-term, there is a clear need and basis for copper recycling, although such detailed research was beyond the scope of this study.

7. Conclusion

In this study, we focussed on analysing the likely future environmental footprint of primary copper supply, rather than how to meet copper demand. We develop a peak copper production model, based on a detailed copper resource data set, and combine this with a comprehensive life cycle assessment model of copper mining and milling to predict greenhouse gas emission rates and intensities of Australian and global copper production up to 2100. By establishing a quantitative prediction of both copper production and corresponding greenhouse gas emissions of Australian and global copper industry, we then analysed the emissions intensity of various energy input scenarios, such as business-as-usual, solar thermal electricity and solar thermal electricity with biodiesel.

The Australian Government has an aspirational goal long-term greenhouse gas emissions of an 80% reduction from the 2000 level by 2050. For the copper sector, this means moving from about 12.6 Mt CO_{2e} in 2000 to a goal of some 2.52 Mt CO_{2e} in 2050 (assuming equal emissions reductions across the economy). Based on the energy sources modelled, only the solar thermal plus biodiesel scenario was capable of achieving this goal at about 0.15 Mt CO_{2e}, since the solar thermal alone scenario still includes normal petro-diesel as a major source of emissions.

Overall, it is clear that there are abundant resources which can meet expected long-term copper demands, the critical issue is more the environmental footprint of different copper supplies and use rather than how much is available for mining. It is clear that the switch to renewable energy can have a profound impact on the carbon intensity of copper supply and a complete conversion to renewable energy will position the copper sector to meet existing annual greenhouse gas emissions targets and goals.

8. References

ABARE, various, *Australian Commodity Statistics* (Years 1995-2010). Australian Bureau of Agricultural and Resource Economics (ABARE), Canberra, ACT

ABS, 2008, *S3105.0.65.001 - Australian Historical Population Statistics*, Australian Bureau of Statistics (ABS), Canberra, ACT.

ABS, 2011a, *3101.0 Australian Demographic Statistics*, Australian Bureau of Statistics (ABS), Canberra, ACT.

ABS, 2011b, *3222.0 Population Projections, Australia 2006 to 2101*, Australian Bureau of Statistics (ABS), Canberra, ACT.

BREE, 2011, *Resources and Energy Statistics 2011*. Bureau of Resource & Energy Economics (BREE), Canberra, ACT, 174 p.

Cheng, M & Weixuan F, 2011, *The Lifecycle Growth Trend and Demand Prediction of China Copper Industry*. **Advanced Materials Research**, 361-363 (##), pp 31-38.

Davenport, W G, King, M, Biswas, A K & Schlesinger, M, 2002, *Extractive Metallurgy of Copper*. Pergamon Press.

DCCEE, 2010, *Australia's Emissions Projections 2010*. Department of Climate Change and Energy Efficiency (DCCEE), Australian Government, Canberra, ACT, December 2010.

DCCEE, 2011, *National Greenhouse Accounts Factors 2011*. Department of Climate Change and Energy Efficiency (DCCEE), Australian Government, Canberra, ACT, July 2011.

DCCEE, 2012, *Fact Sheet: Australia's Emissions Reduction Targets*. Department of Climate Change and Energy Efficiency (DCCEE), Australian Government, Canberra, ACT, www.climatechange.gov.au/government/reduce/national-targets/factsheet.aspx (Accessed 5 August 2012; Last Updated 20 March 2012).

Edelstein, D, 2008, *Trends in the U.S. Copper Industry*. Proc. "ICSG 36th Regular Meeting", International Copper Study Group (ICSG), Antofagasta, Chile, September 2010.

Fthenakis, V, Wang, W & Kim, H C, 2009, *Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics*. **Renewable and Sustainable Energy Reviews**, 13 (3), pp 493-517.

Giurco, D, 2005, *Towards Sustainable Metal Cycles: The Case of Copper*. PhD Thesis, Department of Chemical Engineering, University of Sydney, Sydney, 340 p.

Giurco, D, Prior, T, Mudd, G M, Mason, L & Behirsch, J, 2010, *Peak Minerals in Australia: A Review of Changing Impacts and Benefits*. Prepared for CSIRO Minerals Down Under Flagship - Mineral Futures Collaboration Cluster, by the Institute for Sustainable Futures (University of Technology, Sydney) and Department of Civil Engineering (Monash University), March 2010, 109 p.

Guinée, J B, Gorree, M, Heijungs, R, Huppes, G, Kleijn, R, de Koning, A, Sleeswijk, A W, Suh, S, de Haes, H A U & de Bruijn, J A, 2001, *Life Cycle Assessment: An Operational Guide to the ISO Standards*. Centre of Environmental Sciences, Leiden, The Netherlands.

ICSG, various, *The World Copper Factbook* (Years 2007, 2009 and 2010), International Copper Study Group (ICSG),

IEA, 2011, *CO_2 Emissions From Fuel Combustion – Highlights (2011 Edition)*. International Energy Agency (IEA), Paris, France.

ISO, 2006, *ISO14040: Environmental Management – Life Cycle Assessment – Principles and Framework*. International Organization for Standardization (ISO).

Kelly, T D & Matos, G R (Editors), 2012, *Historical Statistics for Mineral and Material Commodities in the United States*. US Geological Survey (USGS), Data Series 140 (Supersedes Open-File Report 01-006), Version 2010 (Online Only), Reston, Virginia, USA, Accessed 4 May 2012, minerals.usgs.gov/ds/2005/140/ (Last updated 6 Feb. 2012).

Lenzen, M, 2010, *Current State of Development of Electricity-Generating Technologies: A Literature Review*. **Energies**, 3, pp 462-591.

Memary, R, Giurco, D, Mudd, G M & Mason, L, 2012, *Life Cycle Assessment: A Time-Series Analysis of Copper*. **Journal of Cleaner Production**. 33, pp 97-108.

Mohr, S H, 2010, *Projection of World Fossil Fuel Production With Supply and Demand Interactions*. PhD Thesis, Department of Chemical Engineering, University of Newcastle, Newcastle, NSW, 783 p.

Mudd, G M, 2010, *The Environmental Sustainability of Mining in Australia: Key Mega-Trends and Looming Constraints*. **Resources Policy**, 35 (2), pp 98-115.

Mudd, G M & Weng, Z, 2012, *Base Metals*. In "Materials for a Sustainable Future", Editors T Letcher, M G Davidson & J L Scott, Royal Society of Chemistry, UK".

Mudd, G M, Weng, Z & Jowitt, S, 2012, *A Detailed Assessment of Global Cu Resource Trends and Endowments*. **Economic Geology**, In Press.

Norgate, T E & Jahanshahi, S, 2010, *Low Grade Ores – Smelt, Leach or Concentrate?* **Minerals Engineering**, 23 (2), pp 65-73.

Norgate, T E & Rankin, W J, 2000, *Life Cycle Assessment of Copper and Nickel Production*. Proc. "Minprex 2000: International Conference on Minerals Processing and Extractive Metallurgy", September 2000, pp 133-138.

Norgate, T E & Rankin, W J, 2002, *The Role of Metals in Sustainable Development*. Proc. "Green Processing 2002: International Conference on the Sustainable Processing of Minerals", Australasian Institute of Mining & Metallurgy (AusIMM), Cairns, QLD, May 2002, pp 49-55.

Norgate, T E, Jahanshahi, S & Rankin, W J, 2004, *Alternative Routes to Stainless Steel – A Life Cycle Approach*. Proc. "10th International Ferroalloys Congress: Transformation through Technology", Cape Town, South Africa, February 2004, pp 693-704.

Norgate, T, Jahanshahi, S & Rankin, W J, 2007, *Assessing the Environmental Impact of Metal Production Processes*. **Journal of Cleaner Production**. 15 (8-9), pp 838-48.

Northey, S A, 2012, *Peak Copper: A Bottom Up Approach to Modelling the Future Ore Grades, Energy Demands and Greenhouse Gas Emissions of an Exhaustible Resource*. Final Year Project (ENE4604), Environmental Engineering, Monash University, Clayton, VIC, 38 p.

Takashi, N, 2005, *The Roles of Asia and Chile in the World Copper Market*. **Resource Policy**, 30 (2), pp 131-139.

UN, 2011a, *World Population Prospects: The 2010 Revision*, United Nation (UN) Dept. of Economic and Social Affairs Population Division.

UN, 2011b, *World Population to 2300*, United Nation (UN) Dept. of Economic and Social Affairs Population Division.

USCB, 2012, *Historical Estimates of World Population*. United State Census Bureau (USCB), www.census.gov/population/international/data/worldpop/table_history.php

USGS, 2012, *Minerals Commodity Summaries 2012*. US Geological Survey (USGS), Reston, Virginia, USA, 201 p.

USGS, various, *Minerals Yearbook – Copper (Years 1996 to 2010)*. US Geological Survey (USGS), Reston, Virginia, USA.

9. Appendix 1

Project classification for LCA modelling of Australian copper projects

Project Names	Process	Mine Configuration	Power Source	State	Model
Cloncurry Miscellaneous	Grinding and flotation	OP & UG	Gas	QLD	Mt Isa Group_MIX_FLOT_GAS
Kalman	Grinding and flotation	OP & UG	Gas	QLD	Mt Isa Group_MIX_FLOT_GAS
Monakoff	Grinding and flotation	OP & UG	Gas	QLD	Mt Isa Group_MIX_FLOT_GAS
Mt Elliott	Grinding and flotation	OP & UG	Gas	QLD	Mt Isa Group_MIX_FLOT_GAS
Starra Line	Grinding and flotation	OP & UG	Gas	QLD	Mt Isa Group_MIX_FLOT_GAS
Golden Grove	Grinding and flotation	OP & UG	Gas	WA	Mt Isa Group_MIX_FLOT_GAS
Sandiego-Onedin	Grinding and flotation	OP & UG	Gas	WA	Mt Isa Group_MIX_FLOT_GAS
Mt Dore	heap-leach,SX-EW	OP & UG	Gas	QLD	Mt Isa Group_MIX_HL_GAS
Home of Bullion	Grinding and flotation	OP	Gas	NT	Mt Isa Group_OP_FLOT_GAS
Prospect D	Grinding and flotation	OP	Gas	NT	Mt Isa Group_OP_FLOT_GAS
Barbara North	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Corkwood	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
E1 Camp	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Ernest Henry	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Gem	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Great Australia	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Kulthor	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Mt Isa -Open Cut	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Mt Oxide	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Mt Remarkable - Barbara	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Rocklands	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Roseby Group	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Walford Creek	Grinding and flotation	OP	Gas	QLD	Mt Isa Group_OP_FLOT_GAS
Boddington	Grinding and flotation, carbon in leach	OP	Gas	WA	Mt Isa Group_OP_FLOT_GAS
Emull-Lamboo	Grinding and flotation	OP	Gas	WA	Mt Isa Group_OP_FLOT_GAS
Just Desserts (Yuinmery)	Grinding and flotation	OP	Gas	WA	Mt Isa Group_OP_FLOT_GAS
Maroochydore	Grinding and flotation	OP	Gas	WA	Mt Isa Group_OP_FLOT_GAS
Telfer Group	Grinding and flotation, carbon in leach	OP & UG	Gas	WA	Mt Isa Group_OP_FLOT_GAS
O'Callaghans	Grinding and flotation	OP	Gas	WA	Mt Isa Group_OP_FLOT_GAS
Lady Annie	Heap-leach, SX-EW	OP	Gas	QLD	Mt Isa Group_OP_HL_GAS
White Range Group	heap-leach,SX-EW	OP	Gas	QLD	Mt Isa Group_OP_HL_GAS
Young Australian	heap-leach,SX-EW	OP	Gas	QLD	Mt Isa Group_OP_HL_GAS
Explorer 108	Grinding and flotation	UG	Gas	NT	Mt Isa Group_UG_FLOT_GAS
Tennant Creek Group	Grinding and flotation	UG	Gas	NT	Mt Isa Group_UG_FLOT_GAS
Dugald River	Grinding and flotation	UG	Gas	QLD	Mt Isa Group_UG_FLOT_GAS
Merlin	Grinding and flotation	UG	Gas	QLD	Mt Isa Group_UG_FLOT_GAS
Mt Colin	Grinding and flotation	UG	Gas	QLD	Mt Isa Group_UG_FLOT_GAS
Mt Gordon	Grinding and flotation	UG	Gas	QLD	Mt Isa Group_UG_FLOT_GAS
Mt Isa	Grinding and flotation	UG	Gas	QLD	Mt Isa Group_UG_FLOT_GAS
Eastman/Laura river	Grinding and flotation	UG	Gas	WA	Mt Isa Group_UG_FLOT_GAS
Mulgul-Jillawarra	Grinding and flotation	UG	Gas	WA	Mt Isa Group_UG_FLOT_GAS
Napier Range-Wagon Pass	Grinding and flotation	UG	Gas	WA	Mt Isa Group_UG_FLOT_GAS
Nifty	Grinding and flotation	UG	Gas	WA	Mt Isa Group_UG_FLOT_GAS
Wildara-Horn	Grinding and flotation	UG	Gas	WA	Mt Isa Group_UG_FLOT_GAS
Big Cadia	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Browns Reef	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Bushranger	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Cadia Hill	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Canbelego	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Chakola-Harnett Central	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Copper Hill	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Kangiara	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Koonenberry-Grasmere	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Lewis Ponds	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Marsden	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Mayfield	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
McPhillamys	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Peelwood North-South	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Sunny Corner	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Temora	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Tottenham	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Webbs	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Wellington	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Yeoval	Grinding and flotation	OP	Grid	NSW	NSW_OP_FLOT_Grid
Belara	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Cadia East	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Conrad-Kind Conrad	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
CSA	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Endeavour	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Hera	Grinding and flotation, cyanide leach of Au Ag	UG	Grid	NSW	NSW_UG_FLOT_Grid
Northparkes	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Parkers Hill	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Peak	Grinding and flotation, carbon in leach	UG	Grid	NSW	NSW_UG_FLOT_Grid
Peak Hill	Grinding and flotation, carbon in leach	UG	Grid	NSW	NSW_UG_FLOT_Grid
Ridgeway	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid
Tritton	Grinding and flotation	UG	Grid	NSW	NSW_UG_FLOT_Grid

Project classification for LCA modelling of Australian copper projects (continued)

Project Names	Process	Mine Configuration	Electricity	State	Model
Area 55	Grinding and flotation	OP	Grid	NT	NT_OP_FLOT_Grid
Browns -Browns East	Grinding and flotation	OP	Grid	NT	NT_OP_FLOT_Grid
Mt Bonnie	Grinding and flotation	OP	Grid	NT	NT_OP_FLOT_Grid
Mt Fitch	Grinding and flotation	OP	Grid	NT	NT_OP_FLOT_Grid
Iron Blow	Grinding and flotation	UG	Grid	NT	NT_UG_FLOT_Grid
Rover 1	Grinding and flotation	UG	Grid	NT	NT_UG_FLOT_Grid
Mt Garnet Group	Grinding and flotation	OP & UG	Grid	QLD	QLD_MIX_Grid
Mungana	Grinding and flotation, carbon in leach	OP & UG	Grid	QLD	QLD_MIX_Grid
Red Dome	Grinding and flotation, carbon in leach	OP & UG	Grid	QLD	QLD_MIX_Grid
Baal Gammon	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Great Whitewash	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Kroombit	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Mt Cannindah	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Mt Carlton	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Mt Chalmers	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Nightflower-Digger Lode	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Tally Ho	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Foresthome-Develin Creek	Grinding and flotation	OP	Grid	QLD	QLD_OP_FLOT_Grid
Texas-Silver Spur	heap leach	OP	Grid	QLD	QLD_OP_HL_Grid
Einasleigh Group (Cu, PbZnCu)	Grinding and flotation	UG	Grid	QLD	QLD_UG_FLOT_Grid
Mt Gunson Group	Grinding and flotation	OP & UG	Grid	SA	SA_MIX_Grid
Osborne	Grinding and flotation	OP & UG	Grid	SA	SA_MIX_Grid
Prominent Hill	Grinding and flotation	OP & UG	Grid	SA	SA_MIX_Grid
Hillside	Grinding and flotation	OP	Grid	SA	SA_OP_FLOT_Grid
Kalkaroo	Grinding and gravity	OP	Grid	SA	SA_OP_FLOT_Grid
Kanmantoo	Grinding and flotation	OP	Grid	SA	SA_OP_FLOT_Grid
Muturoo	Grinding, roasting, gravity, leaching	OP	Grid	SA	SA_OP_FLOT_Grid
North Portia	Grinding and gravity	OP	Grid	SA	SA_OP_FLOT_Grid
Mountain of Light-Lyndhurst	Heap leach-cement	OP	Grid	SA	SA_OP_HL_Grid
Angas	Grinding and flotation	UG	Grid	SA	SA_UG_FLOT_Grid
Carrapateena	flotation and acid leach	UG	Grid	SA	SA_UG_FLOT_Grid
Olympic Dam	Grinding and flotation, smelter, refinery, SX-EW	UG	Grid	SA	SA_UG_FLOT_Grid
Hellyer Tailings	Flotation	OP	Grid	TAS	TAS_OP_FLOT_Grid
Mt Lyell	Grinding and flotation	OP	Grid	TAS	TAS_OP_FLOT_Grid
Cleveland-Luina	Grinding and flotation	UG	Grid	TAS	TAS_UG_FLOT_Grid
Fossey	Grinding and flotation	UG	Grid	TAS	TAS_UG_FLOT_Grid
Rosebery	Grinding and flotation	UG	Grid	TAS	TAS_UG_FLOT_Grid
Mt Ararat	Grinding and flotation	OP	Grid	VIC	VIC_OP_FLOT_Grid
Mt Unicorn	Grinding and flotation	OP	Grid	VIC	VIC_OP_FLOT_Grid
Thursdays Gossan	Grinding and flotation	OP	Grid	VIC	VIC_OP_FLOT_Grid
Thomson River	Grinding and flotation	OP	Grid	VIC	VIC_OP_FLOT_Grid
Stockman	Grinding and flotation	UG	Grid	VIC	VIC_UG_FLOT_Grid
Deflector	Grinding and flotation	OP & UG	Grid	WA	WA_MIX_FLOT_Grid
Doolgunna-DeGrussa	Grinding and flotation	OP & UG	Diesel	WA	WA_MIX_FLOT_Grid
Panton	Grinding and flotation,cyanide leaching	OP & UG	Grid	WA	WA_MIX_FLOT_Grid
Teutonic Bore	Grinding and flotation	OP & UG	Grid	WA	WA_MIX_FLOT_Grid
Trilogy	Grinding and flotation, carbon in leach	OP & UG	Grid	WA	WA_MIX_FLOT_Grid
Redbank	Grinding and flotation	OP	Diesel	NT	WA_OP_FLOT_Grid
Cairn Hill	Grinding	OP	Diesel	SA	WA_OP_FLOT_Grid
Copernicus	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Gabanintha	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Horseshoe Lights	Grinding and flotation	OP	Diesel	WA	WA_OP_FLOT_Grid
Kundip	Grinding and flotation, carbon in leach	OP	Grid	WA	WA_OP_FLOT_Grid
Lennons Find	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Liberty-Indee (Evelyn)	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Mons Cupri	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Munni Munni	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Pardoo-Highway	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Quartz Circle-Igloo	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Quinns-Austin	Grinding and flotation	OP	Diesel	WA	WA_OP_FLOT_Grid
Salt Creek	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Savannah-Sally Malay	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Spinifex Ridge	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Whim Creek	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Whundo Cu-Zn	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Whundo Zn	Grinding and flotation	OP	Grid	WA	WA_OP_FLOT_Grid
Camp Dome-17 Mile	Grinding and flotation	OP	Gas	WA	WA_OP_FLOT_Grid
Eloise	Grinding and flotation	UG	Diesel	QLD	WA_UG_FLOT_Grid
Bentley	concentrator, pre-flotation	UG	Grid	WA	WA_UG_FLOT_Grid
Jaguar	concentrator, pre-flotation	UG	Grid	WA	WA_UG_FLOT_Grid
Panorama-Sulphur Springs	Grinding and flotation	UG	Grid	WA	WA_UG_FLOT_Grid
Radio Hill	Heap Leach, SX-EW	UG	Grid	WA	WA_UG_HL_Grid