The "Limits to Growth" and 'Finite' Mineral Resources: Re-visiting the Assumptions and Drinking From That Half-Capacity Glass

G M Mudd#

Environmental Engineering, Department of Civil Engineering,
Monash University, Clayton, Melbourne, Australia; #Gavin.Mudd@monash.edu

Major Theme: Limits to Growth

Abstract

The famous 1972 study "Limits to Growth" (LtG) created global controversy about its dire assessment of the potential future of humanity in the 21st century – eg. global population crash, rampant pollution, and running out of major non-renewable resources. Amongst some of the most fervent critics of LtG (after economic rationalists) were the mining industry, who argued that mineral resources are easily recyclable, new technology can increase known resources, price drives supply-demand balances, as well as exploration continuing to find new mineral deposits. This paper will re-visit the fundamental assumptions in the LtG study, comparing them in detail to the mega-trends in the global mining industry over the past century – trends such as declining ore grades, increasing tailings and mine waste rock, more refractory ores, deeper and/or larger mines, etc. Overall, the paper points to strong evidence for both points of view regarding non-renewable mineral resources: in one corner is the 'glass half-full' (industry) crew who look back and always remain optimistic about the future; while in an opposing corner is the 'glass half-empty' (LtG) crew who think about the future and believe the past justifies pessimism. Given the massive global scale of the modern mining industry, a detailed analysis of the assumptions regarding mineral resources in the LtG study is long overdue. This paper therefore provides a unique and thorough assessment of the primal factors governing the sustainability of mineral resources, pointing to significant limits to mining sometime this century – although the glass remains at half-capacity, a pessimist might argue that optimism is proving harder to maintain.

1 Introduction

Ever since the dawn of the Industrial Revolution in the late 18th century, human population and resource consumption has grown substantially. By 2009, human population has now reached some 6.8 billion people and is expected to reach some 9.1 billion by 2050 (UNDESA, 2008). At about the same time, global food consumption reached 1.1 billion tonnes (Gt) of coarse grains, 22.6 Gt of dairy products, 273.1 million tonnes (Mt) of meat products plus a range of other food and agricultural products (eg. oils, wines, textiles, etc), as well as 1,725 Mt of iron ore, 39.3 Mt of aluminium, 15.5 Mt of copper, 11.7 Mt of zinc, 3.9 Mt of lead, and a range of other base, precious and specialty metals (nickel, gold, platinum, etc) (ABARE, 2009). The long-term growth in resources production over time is clear, but the crucial question is can growth be maintained into the future to meet future population projections ?

This has been a recalcitrant question to address, from Malthus' time in the early 19th century to more recent policy issues in populous countries such as China, India or in smaller countries in Africa or South America. There have been numerous contributions since Malthus, including Paul R. Ehrlich's 'Population Bomb' (1968), the response by Julian Simon's 'The Ultimate Resource' (1981), more recently by Jared Diamond's 'Collapse' (2005) and so on. Suffice to say, population issues remain contentious and controversial.

One of the most famous and well respected studies on population and consumption was the 1972 study "Limits to Growth" (LtG), led by Donella Meadows (see Meadows *et al.*, 1972). The study became a best selling book and created global controversy about its dire assessment of the potential future of humanity in the 21st century – eg. global population crash, rampant pollution, and running out of major non-renewable resources. The primary hypothesis of the LtG study was that exponential growth in a finite world is unsustainable. A systems dynamics model called 'World3' was developed to assess trends and links in population, consumption, resources, pollution and the economy. The World3 model was essentially qualitative, but was tested via different scenarios or possible futures – the standard run (or business-as-usual), comprehensive technology or a stabilised world. Under the first two scenarios, global population crashed by the mid 21st century due to exhaustion of non-renewable resources, environmental pollution and related problems.

One of the most strident industries critical of the LtG study was the mining industry – arguing that most mineral resources are easily recyclable, that new technology can increase known resources, prices drive supply-demand balances, as well as exploration continuing to find new mineral deposits. Thus, for the foreseeable future, there was no shortage or constraint in sight for 'non-renewable' mineral resources.

It is somewhat surprising that, given the gravity of LtG's model projections and criticisms of the LtG study by the mining industry, there is yet to be a thorough assessment of the assumptions behind LtG's World3 model with respect to historical trends in mining and mineral resources. After all, every new car (conventional, hybrid or electric), electronic gadget, building, computer, plane, etc., requires substantial mineral resources. Given the high growth in countries such as China, and with India expected to follow soon (and not forgetting Africa, South America, Eurasia and South-east Asia), whether currently known mineral resources can support similar western-style consumption patterns on a global basis is much more than a mere mathematical exercise. In terms of transitions for sustainability, it is crucial to understand the evidence behind economic mineral resources, thereby allowing informed technological choices, consumption patterns and a range of trade and policy initiatives.

This paper seeks to compile such a study, compiling a range of data on key mega-trends in the global mining industry, and comparing these to the original assumptions of the LtG study. The ongoing availability of resources and various materials is fundamental area of sustainability which is becoming increasingly important to address given rising consumption and more complex technological needs. The results should provide a unique and valuable contribution to the ongoing debate concerning resources and material consumption.

2 The World3 Model, Mineral Resources and Case Study Methodology

This section will only briefly review the hypotheses used by the World3 model for mineral resources. Further detail is given by Meadows *et al.* (1972), including the 30 year LtG update (Meadows *et al.*, 2004).

The two primary hypotheses used by the World3 model for non-renewable resources include:

- **Finite resources:** In most scenarios, minerals, metals and fossil fuels are assumed to be 7000 times that produced in 1900 (in the remaining scenarios, half this amount is adopted).
- **Increasing extraction cost:** As rich and easily extracted resources are invariably developed first, the unit discovery and production cost gradually increases over time.

These two hypotheses will be explored by case studies of trends in major mineral and metal resources, namely coal, iron ore, bauxite-aluminium, copper, lead, zinc, nickel and platinum group metals (PGMs). These are chosen since they play a crucial role in energy, built infrastructure, manufactured goods and appliances or pollution control. The primary countries analysed will include the major mining nations of Australia, Canada and the United States, but also global trends where possible. The key aspects to be analysed, where data are available, include production, mining method, economic resources and ore grades. Finally, evidence on extraction cost will be reviewed, such as energy costs and pollution intensity of resource extraction. Overall, this leads to a comprehensive and, most importantly, *quantitative* assessment of the LtG hypotheses.

All data is sourced from government periodicals and series on mining, as well as industry sources, mining companies and academic literature. Major sources include Australia (ABARE, 2009; GA, var.; Mudd, 2009), Canada (CDBS, var.; NRC, var.), and United States (Kelly *et al.*, 2010), global data (USBoM, var.; USGS, var.) or for specific commodities such as coal (EIA, var.; Mohr, 2010; Mohr & Evans, 2009), iron ore (Niemiec, 2009), nickel (Mudd, 2010), platinum group metals (Glaister & Mudd, 2010).

3 Coal

Coal has been the most widely used fuel since the dawn of the Industrial Revolution, and is a major contributor to electricity generation in numerous countries as well as being critical in steel production. There are varying grades or ranks of coal, depending on its geologic age, and in general they range from lignite (high moisture, low energy content), through bituminous (low moisture, moderate energy) to anthracite (low moisture, high energy).

Accurate historical production statistics are challenging for coal, since not all countries use the same basis for classifying coal ranks nor do they gather and/or report relevant statistics (eg. open cut/underground, overburden, resources). However, the available data is shown in Figures 1-2, including production by country, open cut mining and overburden-to-coal ratios.

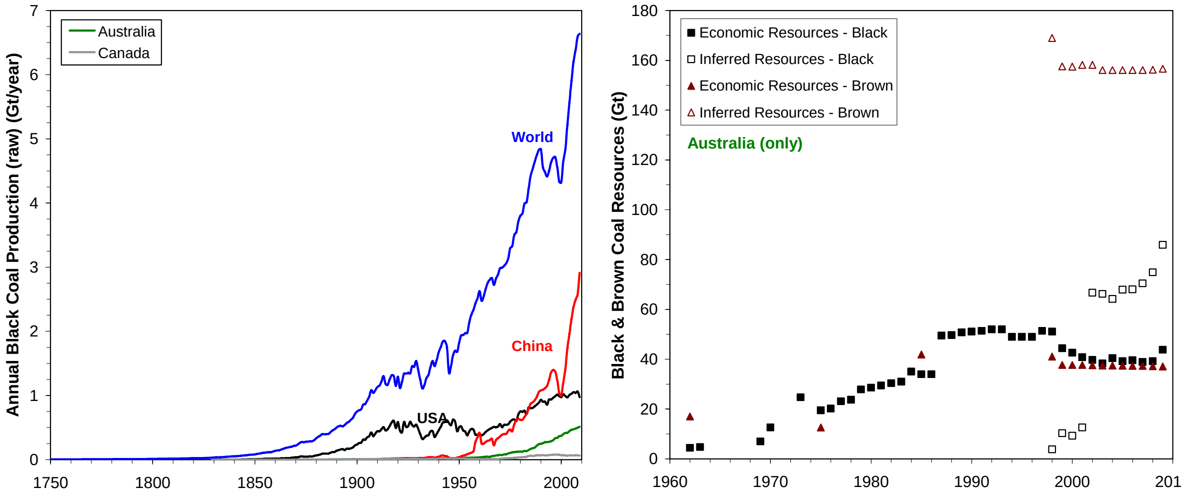

Figure 1: World coal production (left); reported Australian coal resources over time (right)

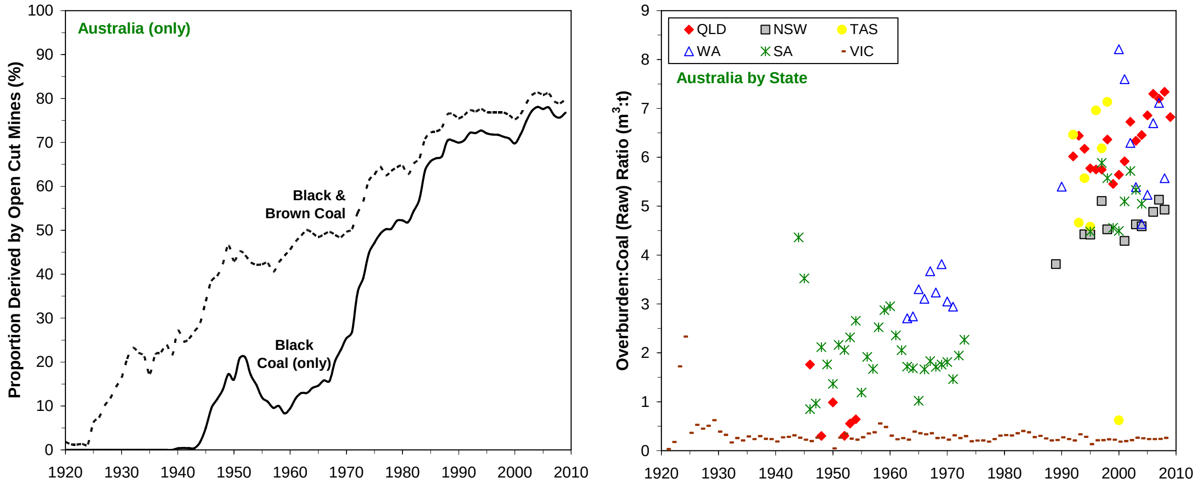

Figure 2: Australia – proportion of open cut coal (left); overburden:coal ratio over time (right)

4 Iron Ore

Similarly to coal, iron has been a fundamental contributor since the Industrial Revolution, and is almost exclusively used for steel production. Iron is widely distributed in nature, and is a common element in the earth's crust. The main iron minerals which can be used to make steel are hematite, magnetite, limonite and goethite, plus possibly pyrite and pyrrhotite to a lesser extent. The preferred mineral for steel making is hematite, though data on iron ore production by ore type is uncommon. There have been perhaps three main growth phases in iron ore production – the early 20th century (including interruptions by the economic depressions of the 1920s-30s), the western post war boom (1950s-70s), and the burgeoning modernisation of China (2000s). Iron ore production over time is shown in Figure 3, including detailed graphs for Australian iron ore resources, estimated iron ore grades by country and beneficiated iron ore quality for the USA.

The sudden decline in world average iron grade is due mainly to the substantial growth in iron ore production in China, which is very low grade (~30-34 %Fe). For the USA, the long term rise in beneficiation has allowed a progressively lower grade in raw ore to be processed, as opposed to the grade of beneficiated product (see Figure 3).

5 Bauxite-Aluminium

Aluminium is a very light metal used in a variety of products, especially food packaging. The production of Al starts with bauxite mining, an alumina refinery and then an Al smelter, and makes it one of the most energy intensive metals (due mainly to total energy consumed given the size of the Al sector). Australia is the world's largest bauxite miner, with major alumina refineries and Al smelters, while Canada is only involved in Al smelting as is the USA. Bauxite production over time is shown in Figure 4.

6 Copper

Copper is a widely used metal in a variety of applications from pipes to electrical equipment and electronics to chemicals. Copper is also widely found throughout the world, in a range of deposit types, though porphyry deposits are now the major source of copper, especially from North and South America (eg. Chile, Arizona, British Columbia) (Gerst, 2008). The rise of electricity from the late 1800s saw a sustained growth in demand for copper, with production until the mid-20th century dominated by the USA.

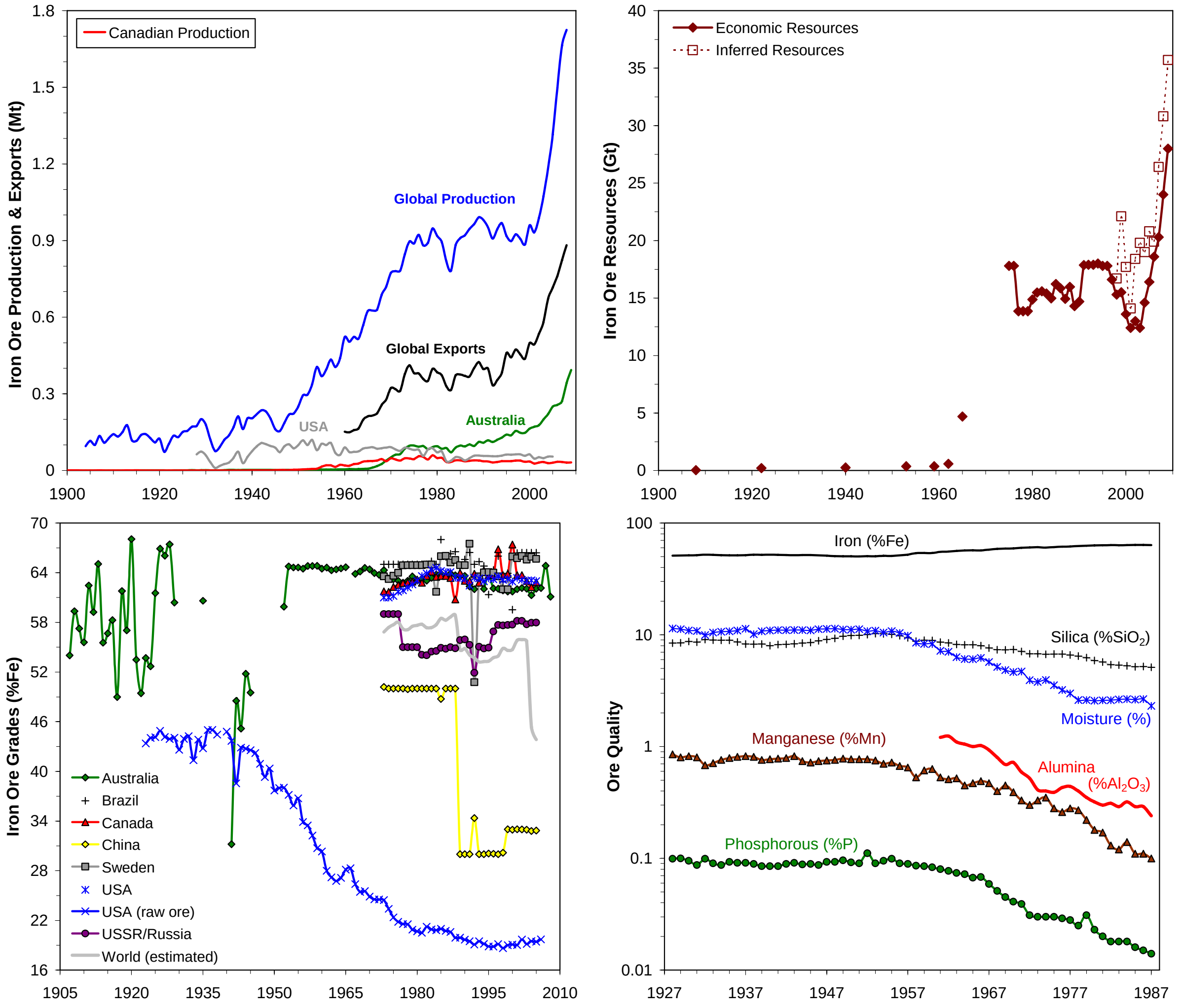

Figure 3: Iron ore production trends over time (top left); Australian economic and inferred iron ore resources (top right); estimated ore grades for select countries (%Fe) (bottom left); beneficiated iron ore quality in the USA (bottom right)

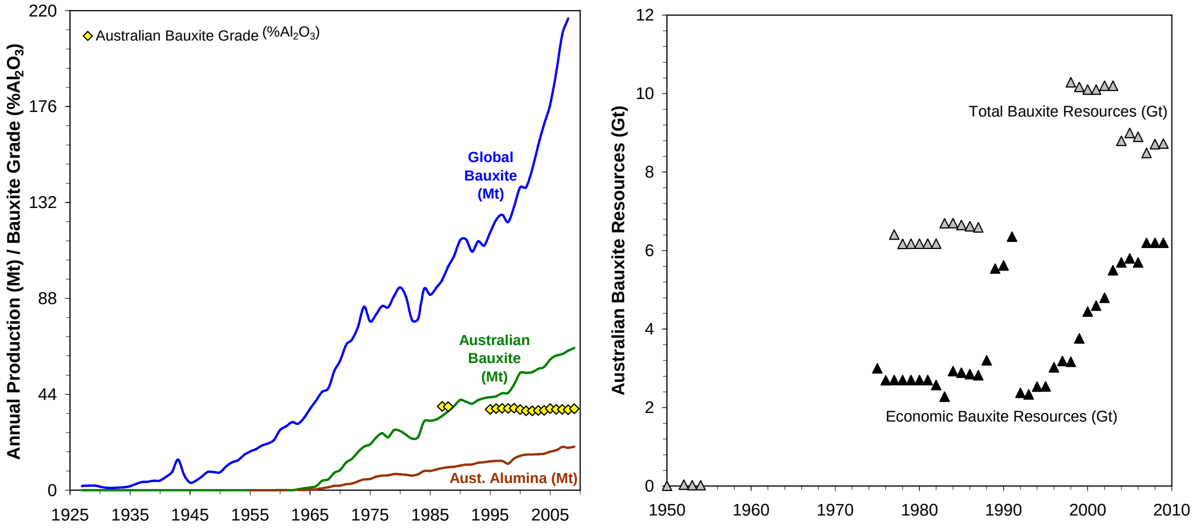

Figure 4: Global and Australian bauxite-alumina production trends over time (left); Australian economic and inferred (total) bauxite resources (right)

Overall, global production mirrors major events such as the 1920s and 1930s economic depressions, followed by major industrialisation after World War 2. By the 1990s, Chile had emerged as the world's biggest Cu producer, from large to super-giant porphyry mines along the high altitude Andean Cordillera. Historical and recent Cu production is shown in Figure 5, long term ore grade trends in Figure 6, and economic Cu resources and Cu prices shown in Figure 7. Most Cu is produced from open cut mining.

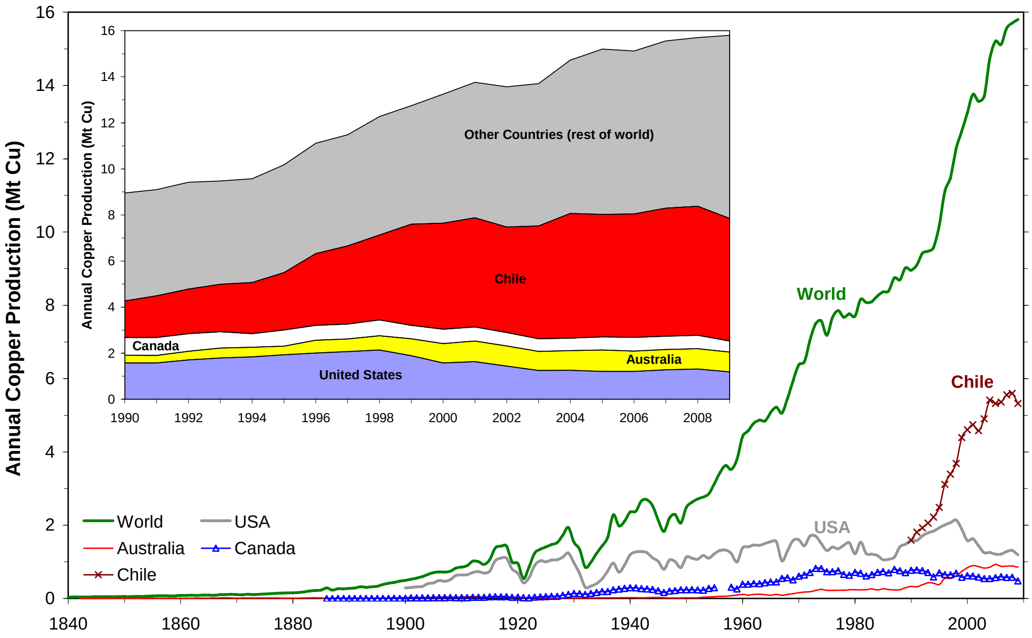

Figure 5: Global Cu production over time

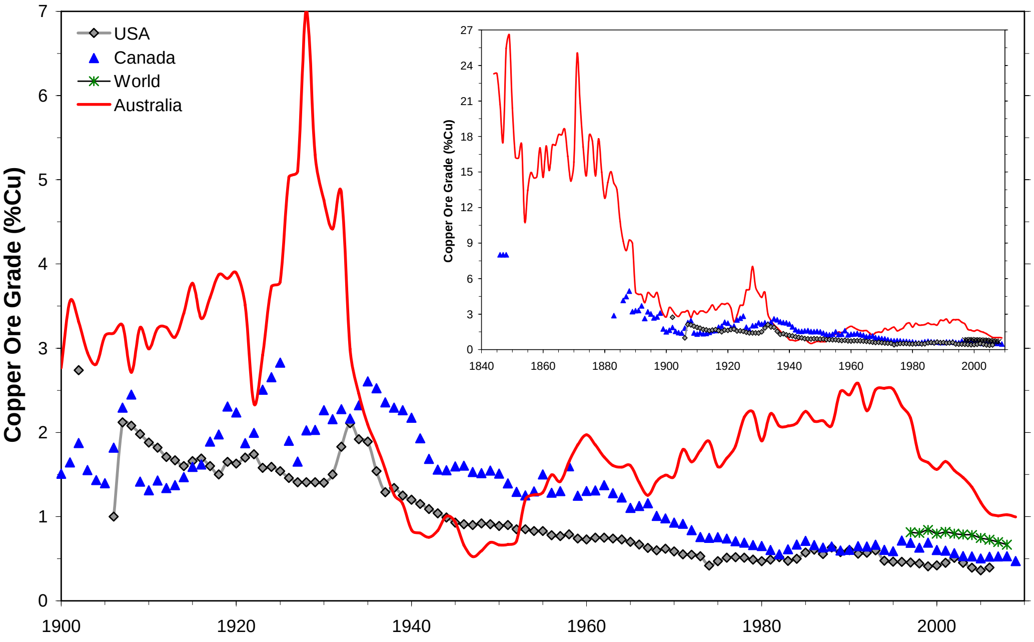

Figure 6: Trends in Cu ore grades for Australia, Canada and the USA

Although Australia shows increasing resources over time, the USA and Canada appear to be in very gradual but terminal decline. However, a critical trend for all countries is the long term decline in ore grades, as well as the evolving nature of ore types from oxide ores of the mid-1800s to the large low grade porphyry sulfides now dominant in the Cu industry globally.

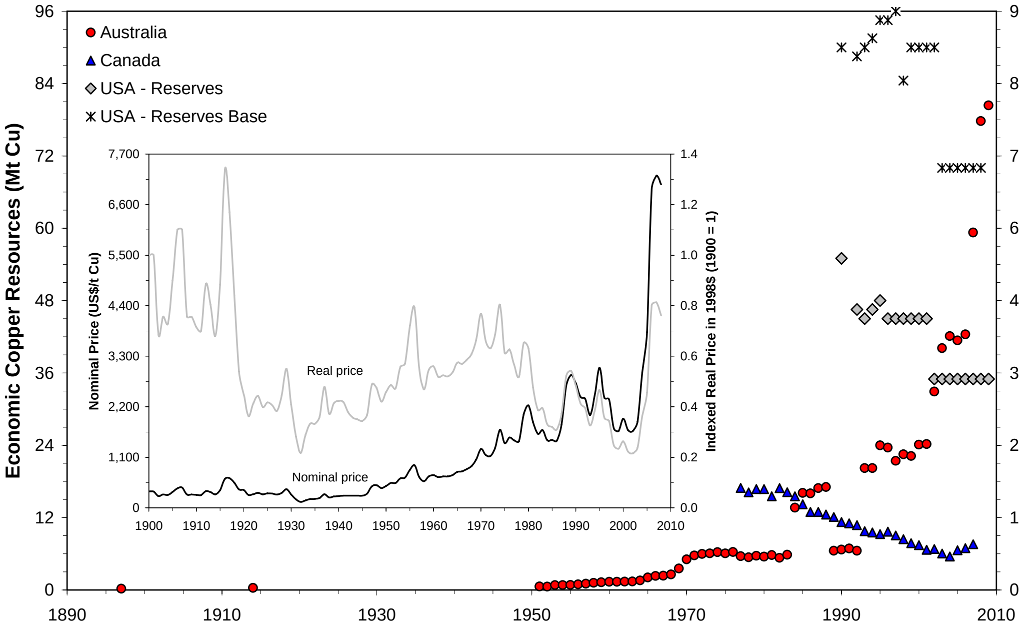

Figure 7: Economic Cu resources over time for Australia, Canada and the USA (main), with nominal and real (US$1998) Cu prices over time (inset)

7 Lead and Zinc

Lead ores had been mined on a small to moderate scale in Europe for many centuries, but it was not until the large discoveries in the USA, Canada and Australia in the late 1800s and early 1900s that global lead production began to grow rapidly. This occurred at the same time as the rapid deployment of lead-based munitions, as well as a range of other uses (eg. petrol additive). At sites such as Broken Hill in Australia, the new technology of ore flotation was invented by 1905 to allow efficient separation of lead and zinc sulfides – one of the most pivotal technologies of mining throughout the 1900s and remains so today. Lead, however, is a toxic heavy metal and since the 1970s has been under significant pressure to reduce lead emissions to the environment from uses such as a petrol additive.

Zinc is a widely used metal, especially in galvanising steel or other metal alloys such as brass and die casts. Zinc often occurs in conjunction with lead and silver, and they are all mined and extracted together. Zinc can also be found in association with Cu, such as the large low grade Antamina Cu-Zn mine in Peru.

In the past decade, somewhat surprisingly, China has emerged as the world's largest producer of lead and zinc, though virtually no mine-specific data is available. Australia, Canada, India and the USA remain large global producers, dominantly from large high grade mines such as Century, Brunswick, Rampura Agucha and Red Dog, respectively. Production trends, ore grades and economic resources over time for lead and zinc are shown in Figure 8.

8 Nickel

Until the late 1800s, nickel had only minor uses and was only mined on a small scale in Europe and was just beginning in French-controlled New Caledonia in the Pacific. By the 1880s, the role of Ni in stainless steel and armour plating was established and this caused a growing demand for Ni, especially for navies keen to modernise. Also in the 1880s, the Sudbury field of northern Ontario, Canada was discovered, proving to be a rich and super-giant resource of Ni as well as Cu and a small producer of cobalt and platinum group metals.

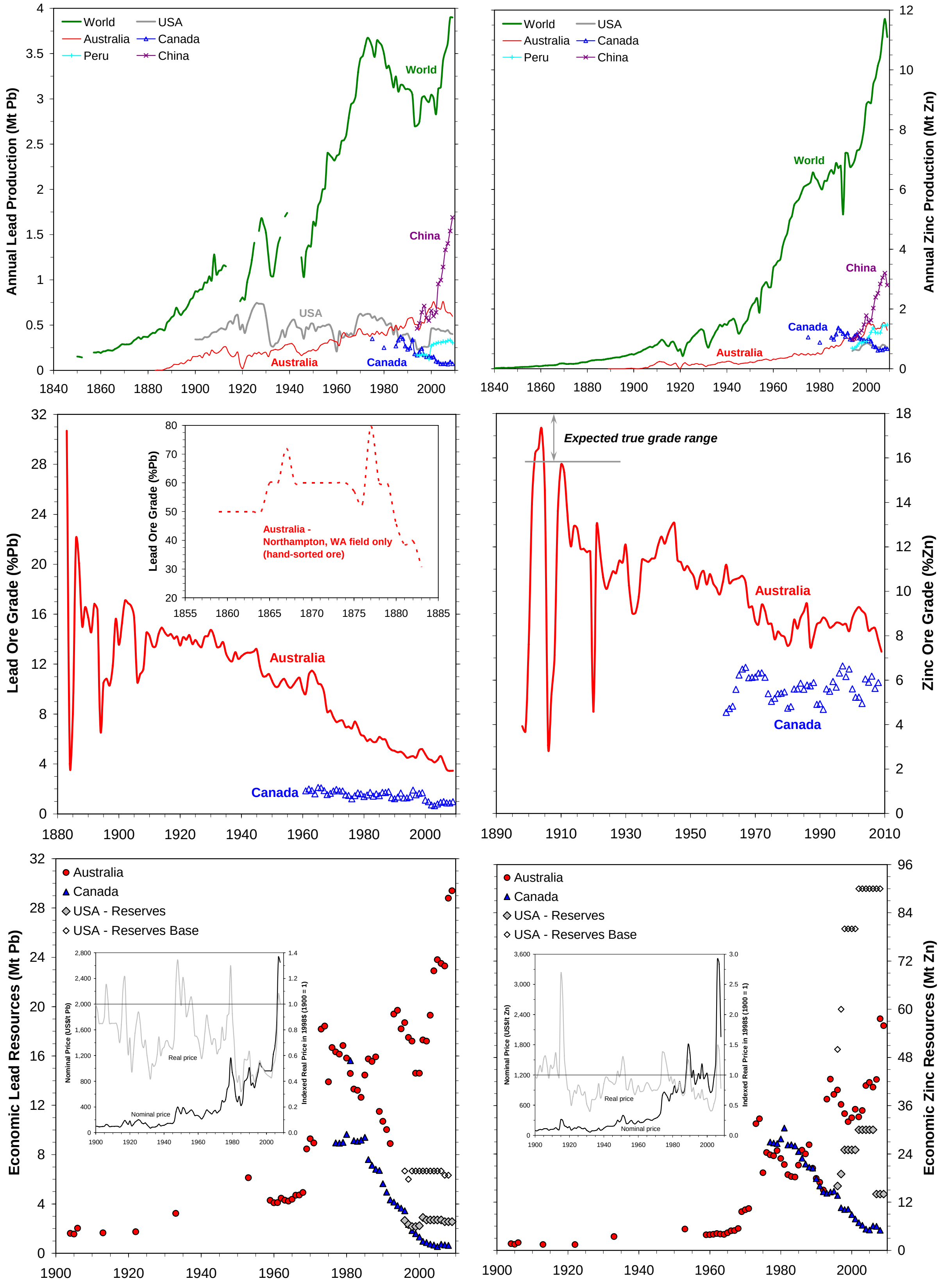

Figure 8: Lead and zinc production over time (top); Ore grades over time (middle); Economic resources over time (bottom), with nominal and real (US$1998) Pb-Zn prices over time (inset)

Until about 1950, Canada was the dominant Ni supplier of the western world. After 1950, other countries emerged as major Ni producers, such as Russia (especially the Norilsk-Talnakh field of Siberia), Australia (eg. Kambalda), Indonesia, China and others.

Nickel is found in two main ore types – sulfides and laterites. The Sudbury field is sulfides, while the Russia and Australia fields are mostly sulfides with some moderate laterite mines. In contrast, many tropical countries possess substantial laterite Ni resources and mines, such as Indonesia, Cuba, the Philippines, Columbia and New Caledonia. In general, sulfides are relatively easily processed through conventional pyrometallurgy (eg. mine, mill, smelter, refinery), while laterites require more complex processing (such as rotary kiln electric furnaces or high pressure acid leach and hydrometallurgical plants). Production trends, ore grades and economic resources over time for lead and zinc are shown in Figure 9, with the relationship between unit energy and greenhouse intensity for Ni production in Figure 10.

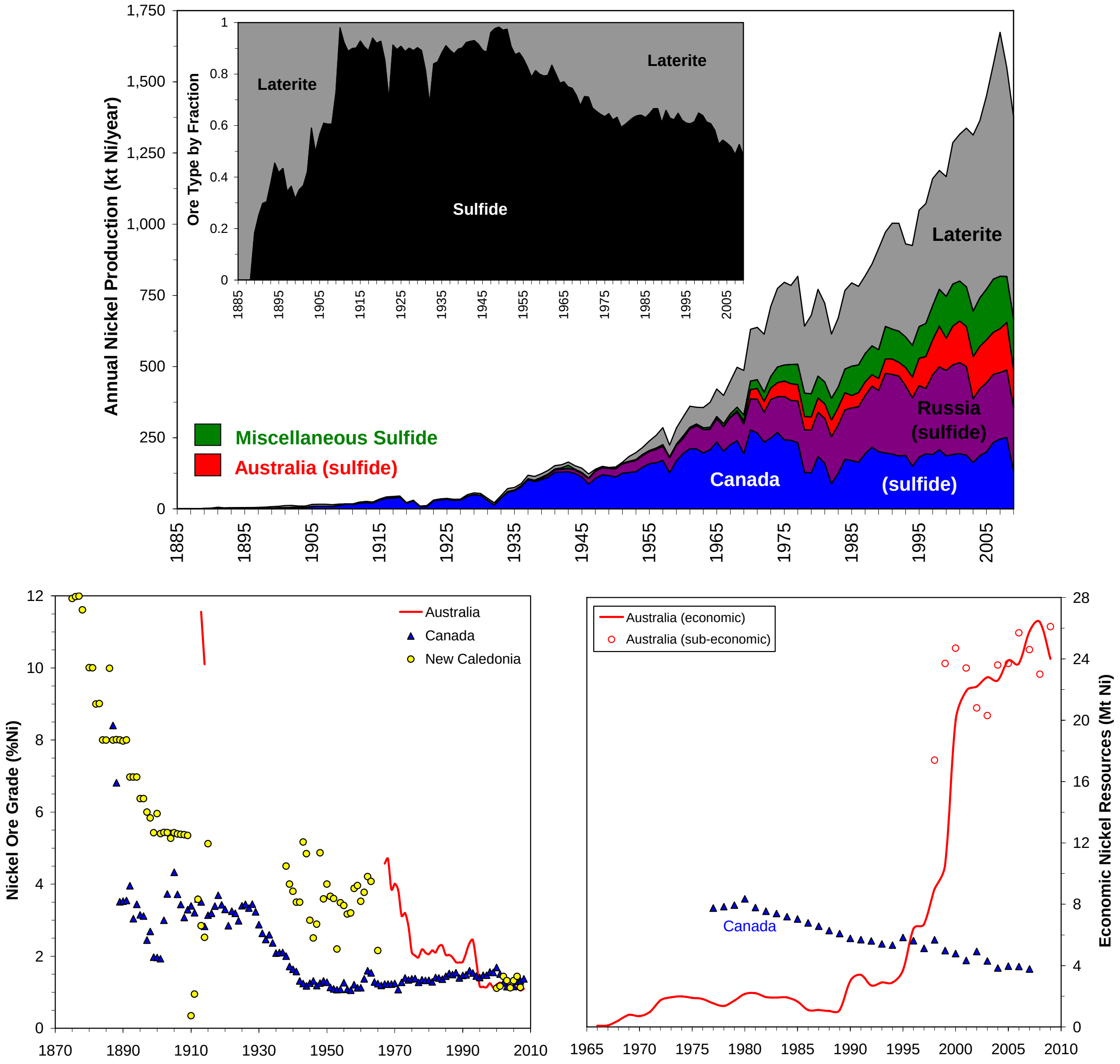

Figure 9: Nickel production by country and ore type (top); Nickel ore grades over time (bottom left); Economic and sub-economic (inferred) nickel resources (bottom right)

As shown in Figure 10, in general, Ni laterite is more intensive to produce than sulfides, but this can be site-specific. For example, the Yabulu project uses the older Caron ammonia lead process while Murrin Murrin uses high pressure acid leach – meaning Yabulu remains more energy-CO_2 intensive. Curiously, for the same unit energy intensity for the Thompson and Sudbury fields of Canada, the CO_2 footprint is substantially different – highlighting the critical importance of energy sources and configuration.

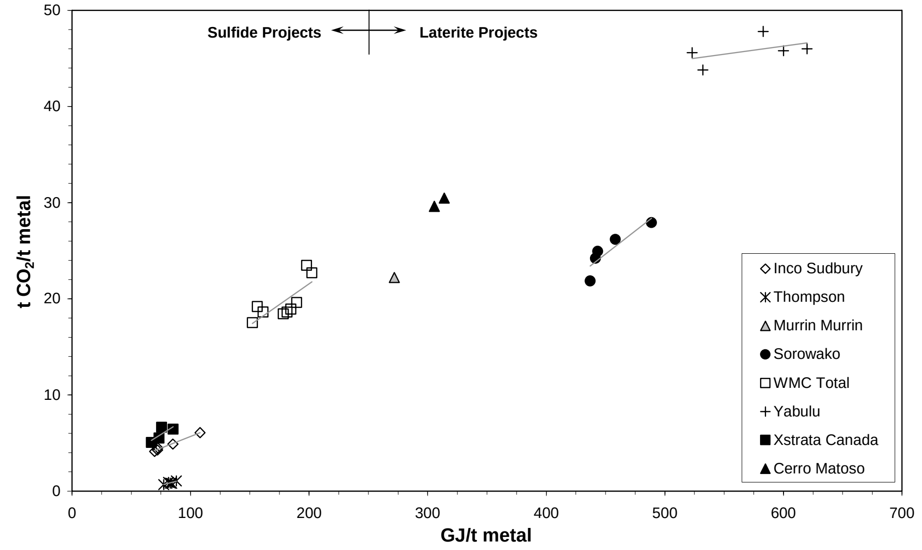

Figure 10: Unit energy and greenhouse intensity for Ni(±Cu±Co) production (Mudd, 2010)

9 Platinum Group Metals

The platinum group of metals (namely platinum, iridium, osmium, palladium, rhodium, and ruthenium; or PGMs) are increasingly important in a range of environmentally related technologies and uses, such as catalytic converters to control vehicle exhaust emissions, chemical catalysts in process plants (especially oil refineries), electronic components, and hydrogen fuel cells. Many of these applications have only grown in demand since the 1960s. South Africa dominates world PGMs production (mainly platinum), followed by Russia (mainly palladium), with minor production from Canada and the USA. The South African industry is unique in that it contains some 90% of the world's PGMs resources, all in the Bushveld Igneous Complex in North West Province (just north of Johannesburg and Pretoria).

Historical production by country is shown in Figure 11, with unit greenhouse gas emissions versus ore grade (left) and over time for some South African mines shown in Figure 12.

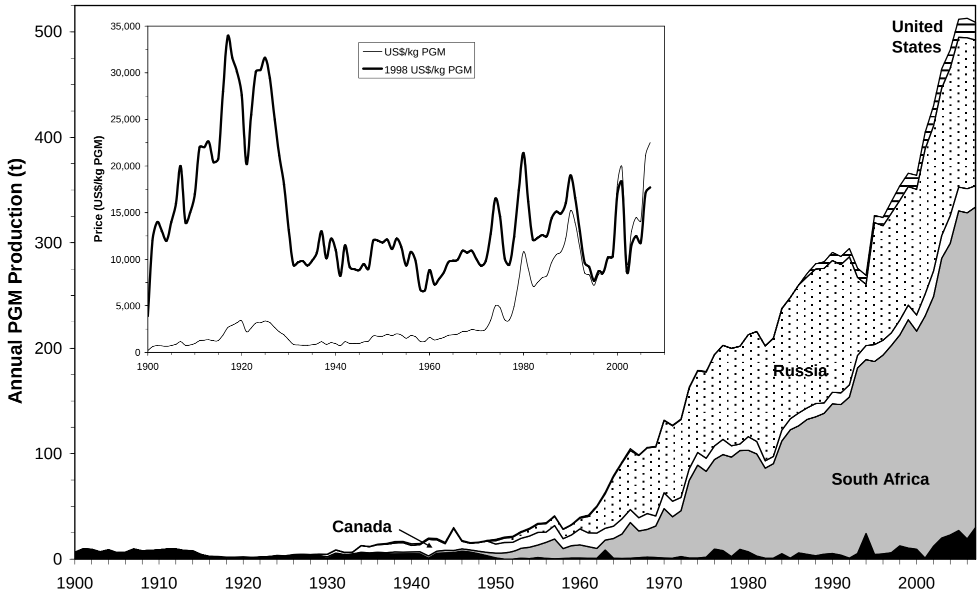

Figure 11: Platinum group metal production by country (main); and nominal and real prices (US$1998) over time (inset) (Glaister & Mudd, 2010)

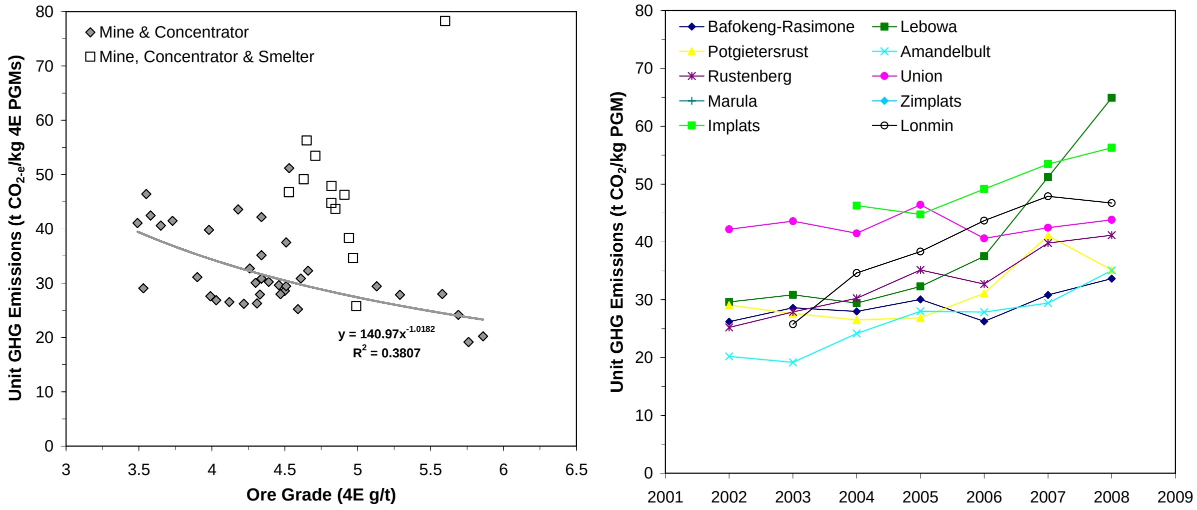

Figure 12: Unit greenhouse gas (GHG) emissions versus ore grade (left) and over time (right) for platinum group metals production (Glaister & Mudd, 2010)

10 Discussion

The extensive data sets in this paper provide a unique insight into the hypotheses used for non-renewable mineral resources.

The extent of 'finite resources' is variable depending on commodity and country. For example, Australia's Ni resources have increased substantially over the past 50 years (especially if sub-economic resources are included) whilst Canada's have declined steadily. Based on reported resources at operating mines and undeveloped deposits, Canada's known Ni resources are clearly more than report. This apparent discrepancy is simply due to the stringent standard set by Canada – only Ni remaining at operating mines and in economic reserves are included in national estimates, and not additional resources. This seemingly contradictory picture is also true for lead, zinc and copper and possibly for coal also. Although the data is not available, based on the history of the PGMs sector in South Africa, it can be expected that there are substantial PGMs resources remaining (Glaister & Mudd, 2010). Part of these patterns can be explained by new technology, either allowing more intensive and productive exploration (especially geophysics) or mining and processing of previously uneconomic or difficult ores (eg. carbon in pulp for gold, high pressure acid leaching of Ni laterites).

The obvious question is whether these 'patterns of the past' can be continued into the future – an optimist would look to history and feel comfortable that we are far from approaching limits to extractable mineral resources; whilst a pessimist would consider future demands for business-as-usual (eg. exponential growth in metals demand), and conclude that no scenario of new discoveries or more technology can meet demand, especially considering the pollution costs of minerals and metals production. The evident issue is therefore the patterns of this century which will govern mineral resources and their utilisation – not merely the extent of 'recoverable' or finite resources.

This raises the second hypothesis – the increasing cost of mineral resource extraction. This can be considered in numerous ways – either through increasing unit energy costs (eg. GJ/t Cu) as ore grades decline, the increasing waste rock from open cut mining and tailings, water resources impacts, greenhouse gas constraints (eg. emissions trading), and so on. Given that ore grades are in effectively terminal decline for all minerals and metals analysed, this means that unit energy costs will continue to increase in the absence of new technology or substantial energy efficiency efforts. In the face of climate change risks, this is a substantial challenge for the global mining industry. For example, if one extrapolates increased production and declining ore grades to say 2050 in conjunction with reductions in greenhouse gas emissions of 50% from 2000 levels by this time, it is clear that a considerably greater reduction in unit greenhouse intensity is required per tonne of mineral than just 50%.

Furthermore, in some regions of the world, especially coal regions such as the Appalachians in the USA or the Hunter Valley of Australia, cumulative environmental and social impacts are already significant, and leading to growing community concern. The availability of water and/or impacts on water resources are also becoming more critical to the future of the mining industry globally (Mudd, 2008).

As such, although the World3 model argued for increasing environmental costs of resource extraction from a largely conceptual standpoint, it is clear that this hypothesis is being observed in reality. For example, the recent energy intensity of the Australia mining industry, in kWh/$ value, was shown to have increased by some 50% over the past decade (Sandu & Syed, 2008). Thus the hypothesis is eminently reasonable, regardless of whether one is an optimist or pessimist.

11 Conclusions

This paper compiled a range of data on key mega-trends in the global mining industry, and comparing these to the original assumptions of the "Limits to Growth" study. The ongoing availability of resources and various materials is a fundamental area of sustainability which is becoming increasingly important to address given rising consumption and more complex technological needs. The LtG study, namely the World3 model, used two principal hypotheses for non-renewable resources – finite resources and increasing extraction cost. Although there is clear evidence of increasing extraction costs over time, especially as ore grades are in terminal decline, the evidence for finite resourecs is more complex and varies across commodities and countries. In this regard, it is possible for the LtG study to be both right and wrong at the same time – optimists look to history and say we have yet to run out, while pessimists extrapolate diligently into the future and argue that such historical patterns are clearly not sustainable. In effect, the glass remains at half-capacity, although a pessimist might argue that optimism is proving harder to maintain.

12 Acknowledgements

This paper is part of continuing work on the sustainability of mineral resources. Specific thanks to Steve Mohr for coal data. The CSIRO Mineral Futures Collaboration Cluster is also acknowledged for funding of peak minerals research work. The Mineral Policy Institite also deserves recognition for their in-kind support of this research.

13 References

ABARE, 2009, *Australian Commodity Statistics 2009*. Australian Bureau of Agricultural & Resource Economics (ABARE), Canberra, ACT, 367 p.

CDBS, var., *Annual Report on the Mineral Production of Canada*. Mining, Metallurgical & Chemical Branch, Canadian Dominion Bureau of Statistics (CDBS), Ottawa, Canada, Years 1921 to 1946.

EIA, var., *International Energy Annual*. Energy Information Administration (EIA), US Dept. of Energy (USDoE), DOE/EIA-0219(year), Washington DC, USA, Years 1993 to 2008, www.eia.doe.gov.

GA, var., *Australia's Identified Mineral Resources*. Geoscience Australia (GA), Canberra, ACT, Years 1999 to 2009, www.ga.gov.au.

Gerst, M D, 2008, *Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore Types*. Economic Geology, 103: pp 615-628.

Glaister, B J & Mudd, G M, 2010, *The Environmental Costs of Platinum-PGM Mining and Sustainability: Is the Glass Half-Full or Half-Empty?* Minerals Engineering, 23(5): pp 438-450.

Kelly, T D, Matos, G R, Buckingham, D A, DiFrancesco, C A, Porter, K E, Berry, C, Crane, M, Goonan, T & Sznopek, J, 2010, *Historical Statistics for Mineral and Material Commodities in the United States*. US Geological Survey (USGS), Data Series 140, Version 2010 (Online), USA, Accessed 9 February 2010, minerals.usgs.gov/ds/2005/140/ (Last updated 14-Jan-2010).

Meadows, D H, Meadows, D L & Randers, J, 2004, *The Limits to Growth : The 30-Year Update*. Chelsea Green, White River Junction, Vermont, USA, 338 p.

Meadows, D H, Meadows, D L, Randers, J & Behrens, W W, 1972, *The Limits to Growth : A Report for the Club of Rome's Project on the Predicament of Mankind*. Potomac-Earth Island, London, UK.

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

Mohr, S H & Evans, G M, 2009, *Forecasting Coal Production Until 2100*. Fuel, 88(11): pp 2059-2067.

Mudd, G M, 2008, *Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining*. Mine Water & the Environment, 27(3): pp 136-144.

Mudd, G M, 2009, *The Sustainability of Mining in Australia : Key Production Trends and Their Environmental Implications for the Future*. Dept. of Civil Engineering, Monash University and Mineral Policy Institute, Melbourne, VIC, October 2007; Revised April 2009, 277 p (users.monash.edu.au/~gmudd/sustymining.html).

Mudd, G M, 2010, *Global Trends and Environmental Issues in Nickel Mining: Sulfides Versus Laterites*. Ore Geology Reviews, 38(1-2): pp 9-26.

Niemiec, M J, 2009, *Examining the Limits to Growth: A Case Study of Mineral Resources*. Final Year Project, Dept. of Civil Engineering, Monash University, Clayton, VIC, October 2009, 61 p.

NRC, var., *Canadian Minerals Yearbook*. Mining Sector, Natural Resources Canada (NRC), Ottawa, Canada, Years 1944 to 2009, www.nrcan-rncan.gc.ca/mms-smm/busi-indu/cmy-amc-eng.htm.

Sandu, S & Syed, A, 2008, *Trends in Energy Intensity in Australian Industry*. Australian Bureau of Agricultural & Resource Economics (ABARE), Canberra, ACT, December 2008, 41 p.

UNDESA, 2008, *World Population Prospects: The 2008 Revision*. Population Division, United Nations Department of Economic & Social Affairs (UNDESA), New York, USA, esa.un.org/unpd/wpp2008/.

USBoM, var., *Minerals Yearbook*. US Bureau of Mines (USBoM), USA, Years 1933 to 1993.

USGS, var., *Minerals Yearbook*. US Geological Survey (USGS), USA, Years 1994 to 2008, minerals.usgs.gov/minerals/pubs/myb.html.