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Article

Resource Criticality and Commodity Production Projections

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Abstract: Resource criticality arising from peak production of primary ores is explored in this paper. We combine the Geologic Resource Supply-Demand Model of Mohr [1] to project future resource production for selected commodities in Australia, namely iron and coal which together represent around 50% of the value of total Australian exports as well as copper, gold and lithium. The projections (based on current estimates of ultimately recoverable reserves) indicate that peak production in Australia would occur for lithium in 2015; for gold in 2021; for copper in 2024; for iron in 2039 and for coal in 2060. The quantitative analysis is coupled with the criticality framework for peak minerals of Mason *et al.* [2] comprising (i) resource availability, (ii) societal resource addiction to commodity use, and (iii) alternatives such as dematerialization or substitution to assess the broader dimension s of peak minerals production for Australia.

Keywords: peak minerals; sustainable; dematerialization; metals

1. Introduction

Global demand for resources has continued to increase, driven by demand from China, India and other industrializing countries. A major supplier of these resources is Australia, whose minerals and energy exports account for more than 50% of export earnings of the country [3]. Such exports are dominated by iron ore and coal, but Australia is also home to the largest hardrock lithium mine and is a key supplier of gold and other commodities including copper, alumina and phosphorous.

The minerals industry in Australia was focused primarily on expansion whilst commodity prices were strong. However, new challenges are emerging. The quality of available remaining resources are declining, demand growth is stabilizing and social and environmental pressures are increasing as regions confront the cumulative impacts of mining, often with too little of the revenue generated being directed to supporting the long term benefit of communities and the nation [4]. Unlike projections of future minerals production which often adopt a two to twelve year time horizon (see for example [5,6]), this paper explores the full production trajectory of mineral production based on ultimately recoverable resources. This long term view is needed to better understand and respond to the changing economic and sustainability issues.

Aim

The aim of this paper is to model long term future production for key minerals in Australia, namely iron ore/steel, coal, gold, copper and lithium. A cross-commodity analysis is then undertaken. Using a peak minerals criticality framework, the paper then identifies challenges and potential areas where technology and policy could contribute to more sustainable resource management. The logic for the selection of case study minerals was informed by a range of factors including the preferences of the funding body as well as a motivation to study contrasting commodities with different dynamics. For example, coal and iron ore dominate the value of Australian exports; copper has had significant environmental impacts associated with historical mines (e.g., Mt Lyell, Tasmania) and the proposed expansion at Olympic Dam (South Australia); gold has had multiple boom/bust cycles and lithium is only recently increasing in global production and demand.

2. Peak Minerals and Resource Criticality

An increasing body of literature is studying peak minerals [7–9] and resource criticality to economies [2,10]; however, long term production projections for key minerals in Australia have been lacking.

2.1. Background to Peak Minerals

The “peak” concept in relation to peak minerals is a term with different interpretations amongst different groups, so for this reason it is important to be clear about how it is defined in this paper. Much of the popular media discussing peak oil and peak minerals puts focus on the question of “when will we run out?”; however this underemphasizes the early implications of peak mineral production—especially for minerals with limited scope for substitution. The year of peak mineral production reflects an inability to increase supply of terrestrial ores to meet demand, not from physical exhaustion, but from further resource development being uneconomic or inaccessible due to social or environmental pressure. The key characteristics of the peak minerals approach used in this paper are a focus on:

- A progression from cheaper easier processing to more complex and expensive;
- The need for transition post-peak, both in terms of:
  - finding substitutes for providing the services for which the metals were used;
  - considering alternatives to the mining industry for providing economic growth;
- Both a regional or national scale—a global peak analysis (as is common for oil) need not be the default scale of a peak analysis.

2.2. Criticality Framework: Availability, Addiction, Alternatives

Mason *et al.* [2] developed three criteria for assessing the potential impact of peak minerals on society, namely:

1. *Availability of the resource*: This included both geological availability and limits to accessibility which could arise through limited capital and infrastructure for developing the resource, but also limited access where prevented through land use conflict.
2. *Addiction to resource use by society:* This reflected both demand for the resource (and associated revenues) and the extent to which end uses for the metal (and monies) are pervasive and critical in society—the higher the addiction, the more difficult it could be to make a transition post-peak.
3. *Alternatives for transition:* This referred to the potential to substitute terrestrial ore reserves with alternatives—for example ocean based resources, recycled scrap, dematerialization or substitution with another metal or non-metal to fulfill the function.

For the first time, this framework is used to develop comparisons across commodities based on quantitative production projections.

2.3. Production Projections: Geologic Resource Supply-Demand Model

The Geologic Resource Supply-Demand Model (GeRS-DeMo) has been developed to model the supply (and demand) of resources and has been successfully used for coal [11], natural gas [12], other fossil fuels [1] and lithium [13]. GeRS-DeMo has been described in detail in Mohr [1], with extra functionality described in Mohr [14]. In order to project the production of key minerals the model was limited to the "mining" component only (Static mode, no demand calculated—meaning that the model assumes a buyer for the commodities which are produced.). In the "mining" component, production is estimated by assuming that individual mines have a trapezium production profile, with a 4 year ramp up to maximum production level, and a 4 year ramp down at the end of the mine's life. For example, the Greenbushes lithium mine is undergoing expansion plans in which production started at 292 kt Li concentrate/year in 2010 and will increase to 433 kt Li concentrate/year by 2014; thereafter maintaining this production plateau for 5 years [15]. The number of new mines brought online each year is determined by a rate constant linked to fractional amount of cumulative production (relative to the user inputted Ultimately Recoverable Resources estimate). The model has a technology component that allows for the mine life and maximum production level of new mines to increase over time. Disruption can be added to the model which results in mines shutting down earlier than initially planned and being brought back on stream at a later date Mohr [1].

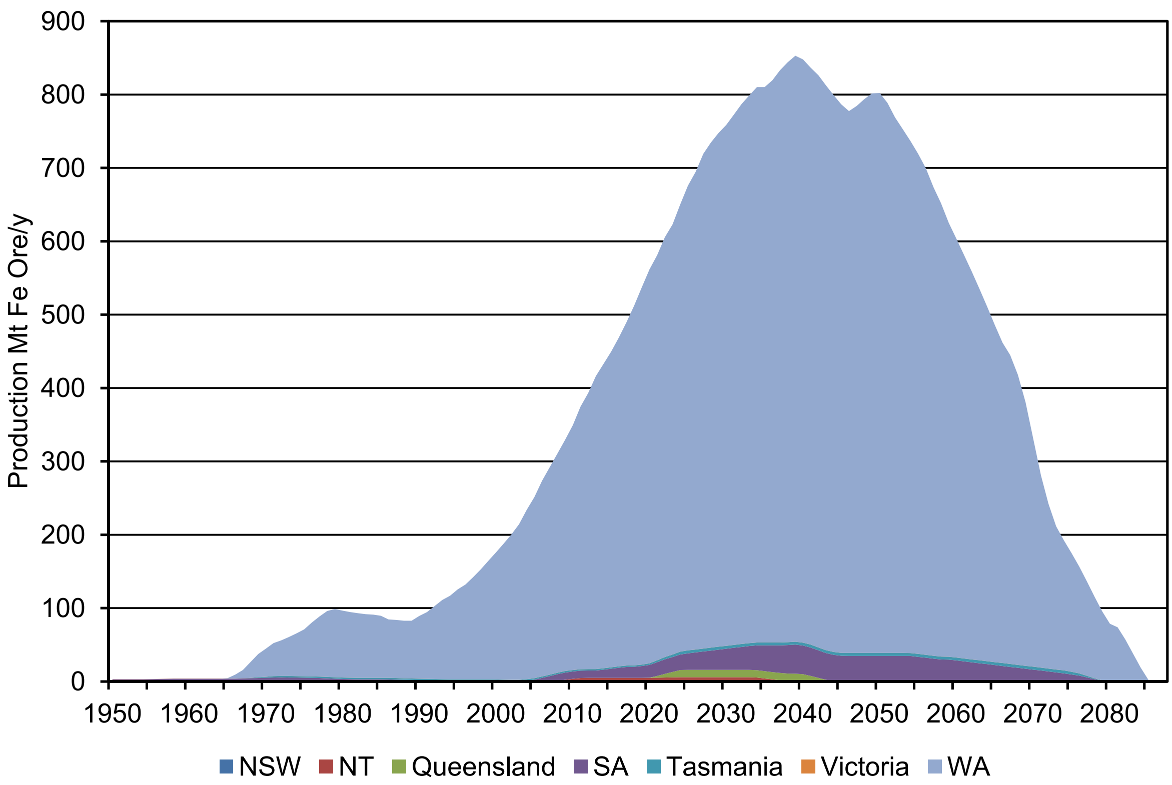
3. Results

3.1. Peak Production Projections

This section highlights the predicted future production of the minerals constructed using GeRS-DeMo, for Australia: in Figure 1. The specific inputs and the model used to generate these projections are available in the electronic supplement.

Figure 1 shows projected production for iron ore which is dominated by production from Western Australia (WA) and smaller contributions from South Australia (SA) and Queensland. There are negligible contributions from New South Wales (NSW), Northern Territory (NT) and other states.

Figure 1. Projected peak iron ore production for Australia by state (Resource estimate from Geoscience Australia database).



Peak production for coal is given in Figure 2, dominated for the rest of this century by NSW and Queensland and thereafter by SA. For the case of copper, Figure 3 shows a "lumpy" curve indicating the influence of individual mines. Figure 4 shows that gold has already experienced multiple peaks, due to discovery of alluvial gold in Victoria and NSW around 1850 and then later in WA which now dominates production. Lithium production over time is modeled in Figure 5, showing a peak in 2015 but production lasting to about 2045.

Figure 2. Projected peak coal production for Australia by state (data from [16]).

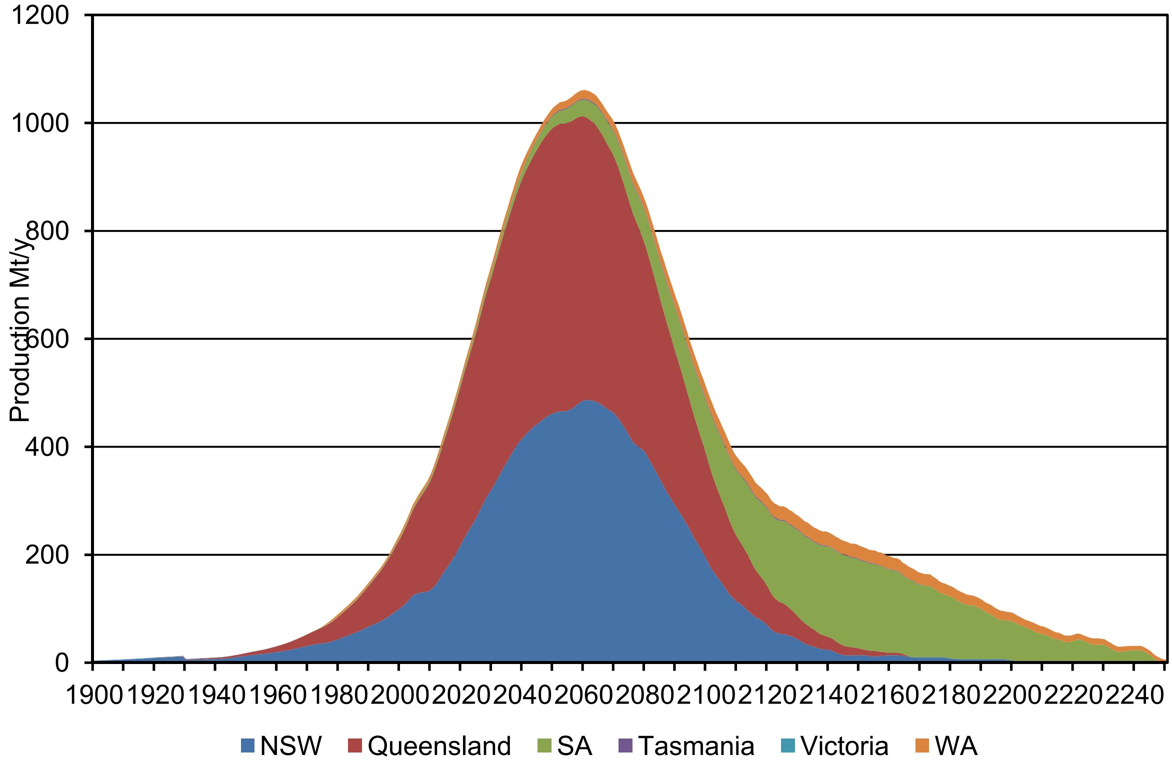


Figure 3. Projected peak copper production for Australia by state (Ultimately Recoverable Resource estimate from Geoscience Australia database).

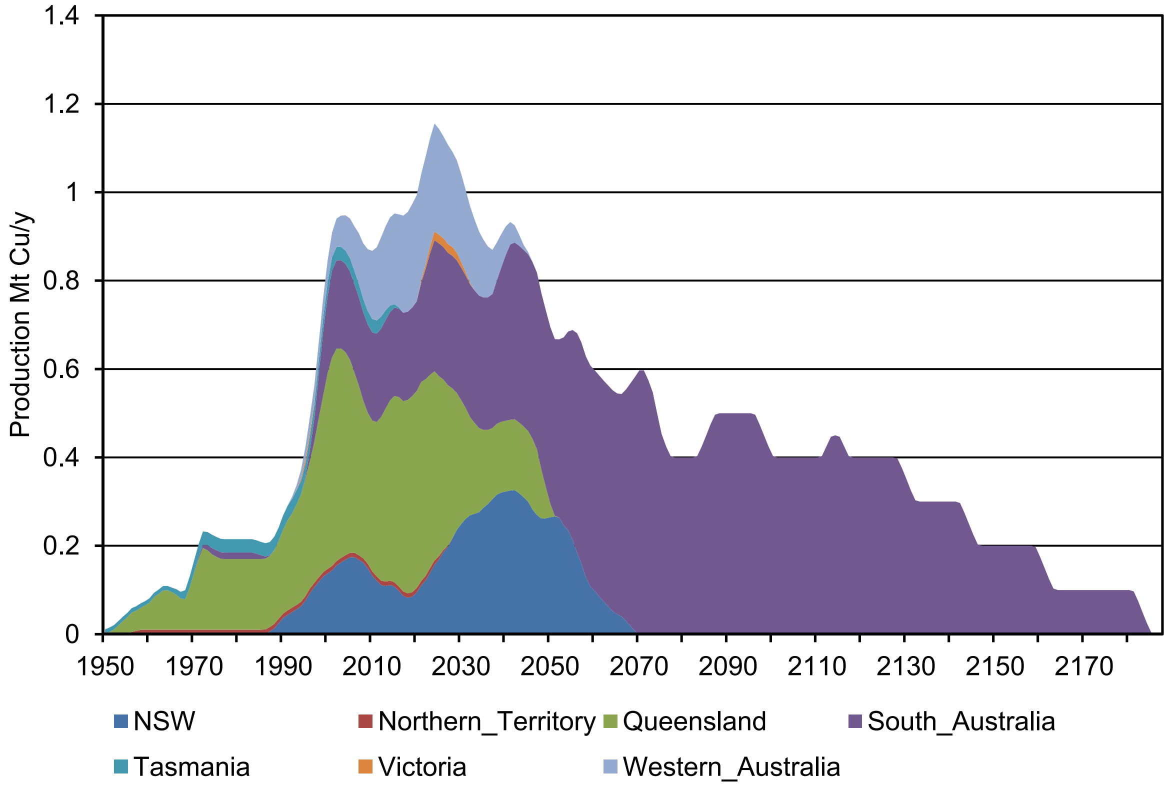


Figure 4. Projected peak gold production for Australia by state (Ultimately Recoverable Resource estimate from Geoscience Australia database).

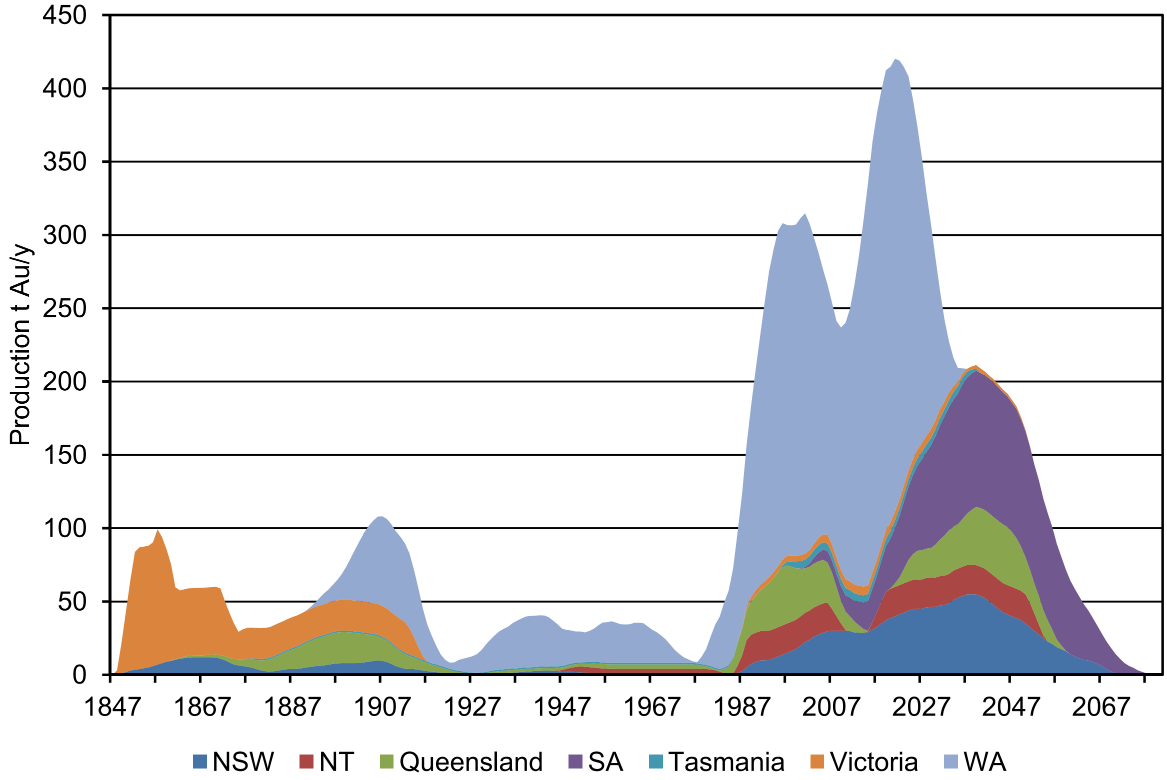
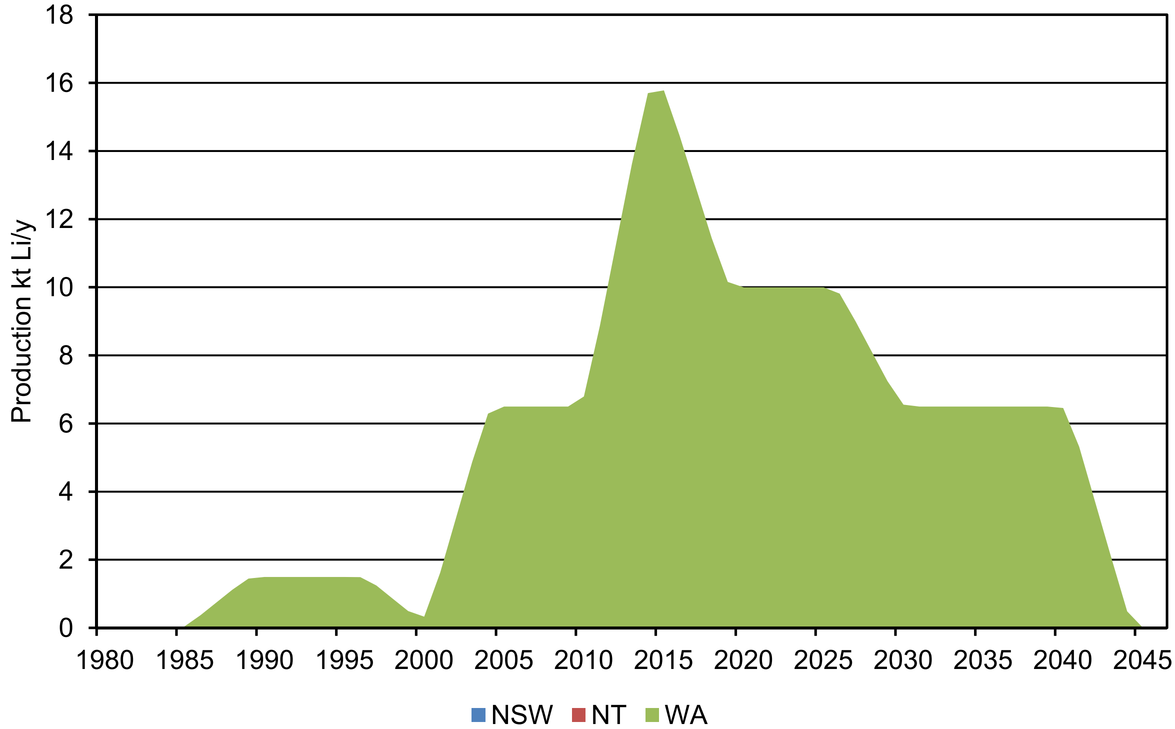


Figure 5. Projected peak lithium production for Australia by state (Ultimately Recoverable Resource estimate from [17]).



The peak years for the various minerals are presented in Table 1, showing lithium, gold and copper as the nearest and then iron and coal. While coal production is projected to have sufficient resources to continue past 2200, the rest of the commodities have production peak within the next forty years, with significant economic and social implication s for Australia.

Table 1. Summary of projected peak years.

Type	Peak Year	Max Producation	Units
Coal	2060	1.1	Gt/year
Copper	2024	1.2	Mt Cu/year
Gold	2021	420	t Au/year
Iron	2039	850	Mt Fe Ore/year
Lithium	2015	15.8	kt Li/year

3.2. Comparing Availability, Addiction, Alternatives

The previous section presented the results using the GeRS-DeMo. Peak modeling has also been undertaken by other authors for copper [8], iron [18], lithium [13] and phosphorus [19]. To supplement the quantitative cross-commodity analysis, an initial qualitative analysis (also including phosphorous) of the factors affecting the impact of peak minerals for Australia in given Table 2 (adapted from [20]).

The first point to note from this cross-comparison is the varying global influence of both geological (iron), social/environmental (coal), geopolitical factors (phosphorus) and technological factors (gold) on availability. From the perspective of Australia—production is likely to be closer to a peak for gold and iron than coal. This opens the question of what resource sustainability is from several angles:

(i) Are the resources available at an acceptable economic, social and environmental cost to meet national needs?
(ii) Where exported to meet international demand—how are both the metals and monies derived from mining and minerals processing used?
(iii) Are the global end-uses of metal being used within ethical supply chains to meet basic human needs or discretionary desires, and are they being used efficiently (taking account of dematerialization) in uses that help add to the stocks of natural, manufactured, financial, human and social capital?
(iv) Are the monies derived from mining used to underpin the long term prosperity and sustainability of the nation—is such use in line with weak or strong sustainability?

By analyzing the nature of the addiction and alternatives across commodities, one can gain an insight into how disruptive peak minerals could be for the commodity, and for linked sectors. For example, using current infrastructure and technology, coal is essential in both electricity and steelmaking. Uptake of alternative energy such as wind or solar could thus displace coal and also shift steel-making to focus more on the Electric Arc Furnace route instead of the coal (coke)-using blast furnace, itself precipitating and increased focus on recycling.

Table 2. Qualitative evaluation of issues for three-criteria framework to characterize peak minerals.

Commodity	Availability	Addiction	Alternatives	Issue for Australia
Coal	• Worldwide, coal will peak before gas • Australia: availability will be constrained not only from physical scarcity, also farm land conflict	• Uses link heavily with other sectors: electricity, steel, cement • Future use will be affected by carbon taxes and CCS viability	• For electricity, energy efficiency and cleaner energy are alternatives • As a reductant (e.g., steel making) biomass has potential	• Australia derives over 50% of export revenues from mining; Coal and Iron ore exports dominate • Coal also dominates Australia's electricity mix.
Copper	• Cu Sulfides dominate; Cu oxides unprofitable • Expansion of Olympic Dam mine dominates	• Uses are diverse (wires, pipes, electronics)	• Electricity: Al can sub. • Pipes: Plastic subs. • Recycling an important alternative to mining	• Australia makes more money from export of mining software than export of refined copper [21]
Gold	• Volatile: Historical peaks in Australia affected by (i) ore discoveries; (ii) technology (CIP); (iii) policy/gold std. • World stocks above ground (122,000 t) greater than below ground (100,000 t) [22].	• Uses are predominantly jewellery then bullion • Getting 2 g of gold for a wedding ring requires 10 t or ore (at 0.2 g/t) *versus* 10 kg of mobile phone scrap at 200 g/t Au. [23]	• Are there other ways to provide the societal value or services derived from gold jewellery and bullion?	• Australia is number 2 global producer of gold, what underpins future competitiveness—"Brand Australia Gold", *i.e.* being a supplier of gold with good environmental/social credentials (*cf.* Responsible Jewellery Council).
Iron/Steel	• Australia and Brazil are dominant iron exporters • Aus production increasing, decades of availability, but impurities increasing	• Transport distances to market are an increasing factor in costs to meet addiction • Uses are rising and long lasting in structures	• Recycling is active but can be increased (for example, in China) • What role may timber play in future structures	• How can we ensure metals and monies from iron ore exports underpin long term benefit in iron-mining regions of Australia (Pilbara) and nationally?
Lithium	• Australia largest hardrock supplier of Li • Global competition from South American brines	• Small but growing market in batteries—demand depends on uptake of electric vehicles and alternative battery technologies not using lithium	• Alternatives to dig and sell business model. Is there a useful role for a product-service system leasing lithium across mines; battery suppliers and electric vehicles?	• Developing cost-effective technology for converting lithium from hardrock to carbonate (more readily derived from brines) for use in batteries will underpin competitiveness
Phosphorous	• Global peak predicted around 2030. Geopolitical issues—China; Western Sahara. Australia could expand mainland production somewhat, but Christmas Island mine closing	• Use in fertilisers/food growing as a result of population growth and more meat and dairy in diets of emerging nations	• No alternative to P needed in our diet. • Potential for supply chain efficiencies and recycling urine and excreta in cities	• As a country with P deficient soils and intensive agriculture, Australia must work to ensure this global issue is adequately addressed

With respect to meeting demand through alternatives to terrestrial ore mining, the role of recycling should be examined closely along with strategies for dematerialization (see for example [24] comparing the environmental impacts associated with terrestrial copper mining, recycling and reduced demand due to dematerialization). When exploring other options such as ocean resources or substituting aluminum or plastic for copper in wires and pipes—close attention should be paid to the potential for burden shifting. For example, exploiting ocean resources for copper may open up new resources, however, there are significant local environmental impacts and stakeholder concerns about the approach [25] which would need to be compared against mining lower grade terrestrial ores. In the case of substituting aluminium for copper in wires, the energy source used to make aluminum which would affect its relative performance, as would the final use. Here it is imperative that life cycle thinking is included in the analysis together with new ways of understanding value along the supply chain.

For example, using the case of Lithium, Australia has significant terrestrial hard rock (spodumene) resources and development of a low-cost technology for converting the lithium to carbonate for use in batteries could further open this global market. However how much money can be made only from the "dig and sell" model? How might a new business model using a linked product-service system add value by providing Brand Australia lithium to more sustainable supply chains through batteries and electric vehicles coupled to clean energy [20]. Such initiatives require a focus on production and use as well as the ultimate benefit provided to society through the use of the mineral and how this can be expanded, not only through new technology, but policy and practices.

4. Conclusions

This paper has utilized the Geologic Resource Supply-Demand Model to project future production across five key commodities. It found significant heterogeneity across commodities with respect to peak production. The quantitative analysis was coupled with a qualitative analysis using the peak minerals framework of availability, addiction and alternatives to characterize criticality issues. Factors contributing to the onset of peak minerals will also be affected by social and environmental constraints (for example, coal mining—land use conflict in Australia) as well as geological, technological and demand factors. The three criteria assessment of peak minerals is an important analysis framework for understanding the potential impact of peak minerals and framing a response consistent with sustainable resource management. Future research will explore the role of technology and policy in responding to this challenge.

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