A Historical Perspective of Critical Materials: 1939 to 2006

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Chapter 5

A Historical Perspective of Critical Materials, 1939 to 2006

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The tensions around limits to growth versus tech will fix it are, today, as prominent as ever in the debates around critical materials. Changes in the demand and supply of materials has regularly led to periods of material supply problems. This chapter provides an overview of the development of critical materials from the mid-20th into the early 21st century. The overview begins with, in the U.S., the development of critical materials policy in World War II and the Cold War years, the oil crisis of the 1970s and the subsequent evolution into the early years of the 21st century. Critical materials thinking has been defined through war, the cold war and then concerns over energy availability and environmental impacts. This chapter shows how the historical military-energy framework for assessing critical materials has evolved into critical materials approaches to help address the challenges of energy, materials and the environment in the 21st century.

5.1 Introduction

Over the past 200 years, the period since the industrial revolution, there has been a tension between people who prioritize the power of an economy and people who put the care of the natural environment first. The economists' position is based upon near term models of economic growth, with productivity driven by use of natural resources. The environmentalists' position is

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based upon the stewardship of all living things on earth, across very long term time periods, and implies that human activity will consistently erode finite natural capital to the point of exhaustion (Tahvonen, 2000, Martin & Kemper, 2012).

Whilst the idea of economists versus environmentalists can be seen as too simplistic, in general such adversarial positions are often reasonably valid. The environmentalist has long maintained that as finite resources are depleted at an accelerated rate, with the corresponding environmental degradation, there will come a point of social, economic and environmental collapse. The economist will argue that every date proposed for the forecast collapse is never reached and that constant new technological innovations mean that the exhaustion of resources will never happen and any environmental damage can be mitigated and repaired.

These two positions can be summarized as “limits to growth” versus “tech (technology) will fix it”. Whilst natural resources have not physically ‘run out’ there has, over the past 100 years, been periods of problems with material availability, which have been developed into definitions of critical materials. The actors involved have not been limited to economists and environmentalists and the motivations for developing critical materials thinking vary from situation to situation. One consistent factor in the story of critical materials has been the development of new materials together with new technologies.

The development of new materials is so significant that historians have taken the periods of material change to define ages in human history. This is shown in Fig. 5.1 below, which outlines in general terms the ‘ages’ of materials. The timeline in Fig. 5.1 is not equally spaced because the development and consumption of materials has increased rapidly over the 20th and 21st centuries when compared to past centuries.

From the mid-19th century onwards the field of materials, as a science, has developed rapidly. This evolution was driven by the demands of the industrial age. The development of steam power required new materials, whilst at the same time the availability of plentiful energy, through coal fired steam power, facilitated new technologies, which assisted the discovery, recovery and production of new materials. This industrial demand and scientific development have gone hand in hand, facilitating the introduction of new materials and their transformative effects into society.

The deepening understanding of the periodic table of elements and the corresponding development of new materials, coupled with the evolution

Fig. 5.1. A materials time line. Adapted from Ashby 2016.

of new technologies, has also driven changes in the demand and supply of materials, especially metals.

Changes in the demand and supply of materials have regularly led to periods of material scarcity, or shortage (Tilton, 2003, Johnson, *et al.*,

2007, Ashby, 2013, Ashby *et al.*, 2016). Significant problems in the supply of materials have often arisen during wartime. Conversely, risks concerning the control of material supply have often led to increases in geo-political tensions, and at worst, conflict breaking out. Wars have been won, or lost, due to control, or loss of control, of material supplies. An example of material supplies playing a significant role in the outcome of a war can be seen in World War One (WWI). By 1918, even though the Imperial German Army was still a formidable fighting force in the field, a collapse on the home front led to a rapid German defeat. This political and societal collapse was primarily the result of the severe resource restrictions within Germany. Conversely the Allies were able to overcome unrestricted German U boat action and provide for not only the rapidly growing Allied forces, but the home front too (Eckes, 1979, Stevenson, 2012).

This experience in WWI led to nations in the 1930s feeling they were threatened by lack of direct control of their own resources. These nations included Germany, Italy and Japan and were termed the 'have not' nations. Against them were the 'have' nations such as Britain and the U.S. (Eckes, 1979).

Governments have often used criticality assessments to determine the military material stockpiles in response to the risks to material supply. Such an approach can be seen in the late 1930s, when Britain began to hold stock of raw materials for the expected conflict with Germany. The British termed this activity as 'purchasing war reserves of materials' (Postan, 1952). The terms used often change but from the mid-20th and into the 21st century, material scarcity has evolved into the current, widely used, term, critical materials.

This chapter provides an overview of the development of critical materials from the mid-20th into the early 21st century. The overview begins with late 1930s uses of the term 'critical' in the U.S., the development of critical materials activity in the Cold War years, the oil — energy crisis of the 1970s and the subsequent evolution into the late 1990s and into the early years of the 21st century. This chapter will show how the background of critical materials thinking has been defined through war, the cold war and then concerns over energy availability and more recently, environmental impacts. At the same time, rapidly increasing economic growth, fuelled by technological developments, coupled with an increasing global population, has led to ever increasing material demands and corresponding losses due to waste. These demands and wastes have

raised questions over risks to economic growth. Most importantly, the need for a complex range of advanced, complex, technology materials to provide solutions to climate change drive the need for critical materials action.

The tensions around limits to growth versus tech will fix it are, today, as prominent as ever in the debates around critical materials. This chapter shows how the historical military-energy framework for assessing critical materials has evolved into critical materials approaches to help address the challenges of energy, materials and the environment in the 21st century.

5.2 1939 to 1945: the Second World War and Critical Materials

This period can be viewed as one in which concerns over ‘limits to *military* growth’ took precedence, and this gave rise to the first uses of the term ‘critical materials’. One of the first uses of the term ‘critical materials’ was by the U.S. government in the late 1930’s. With a Second World War (WWII) looking increasingly likely, the U.S. government enacted the “*Strategic and Critical Materials Stock Piling Act of 1939*”. This act provided funding to purchase and stockpile strategic and critical materials deemed essential for military production. The list of critical materials was determined by the degree to which the U.S. was import dependent and the risk of a material shortage occurring (Eckes, 1979) (National Academy of Sciences, 2008). Other countries developed similar stockpile strategies in this period, notably Britain, but they did not use the term ‘critical materials’. The approaches taken can be seen as a form of ‘limits to *military* growth’ as all activity was primarily aimed at winning the war.

The material needs were assessed from the material demand arising from the planned requirements of equipment, such as aircraft, ships or vehicles, etc. Also assessed was the potential of domestic material production and the substitutability of a material. The methodology was built upon the experiences of the Allies in World War One (1914–1918), in particular in 1918, when the ability to supply the armies in the field and societies at home became a significant deciding factor in the outcome of the war. In Table 5.1 it can be seen that widely used materials were, in terms of elements, less complex in WWII compared to today.

Table 5.1: The Increasing Diversity of Elements Used in Materials over the Period from WWII to 2016. Table Adapted from Ashby 2016.

Materials	Typical elements in the materials from WWII to 2016	
	WWII	2016
Iron based alloys	Fe, C	Al, Co, Cr, Fe, Mn, Mo, Nb, Ni, Si, Ta, Ti, V, W
Aluminum Alloys	Al, Cu, Si	Al, Be, Ce, Cr, Cu, Fe, Li, Mg, Mn, Si, I, V, Zn, Zr
Nickel Alloys	Ni, Cr	Al, B, Be, C, Co, Cr, Cu, Fe, Mo, Ni, Si, Ta, Ti, W, Zr
Copper alloys	Cu, Sn, Zn	Al, Be, Cd, Co, Cu, Fe, Mn, Nb, R Pb, Si, Sn, Zn
Magnetic materials	Fe, Ni, Si	Al, B, Co, Cr, Cu, Dy, Fe, Nd, Ni, Pt, Si, Sm, V, W

Note: Data from the composition fields of records in the CES EduPack '14 Level 3 database, Granta Design, 2014, (Ashby, *et al.*, 2016).

5.3 Cold War Material Stockpiles, the 1950s and 1960s

Concerns over ‘limits to *military* growth’ continued in the global materials chaos of the immediate post WWII period, which meant the U.S. continued their wartime critical materials stockpiling policy. By the late 1940s geo-political tensions began to dominate, with western governments’ concerns over the expansion of communism leading to the Cold War. This resulted in the U.S. intensifying their material stockpile actions. The U.S. planning frame was based on a scenario of a 3 year industrial/military mobilization period followed by a 5 year conventional (non-nuclear) war, a scenario based on the experience of WWII.

In 1950 the Cold War turned hot with the outbreak of the Korean War. The U.S. stockpiling budget increased to \$2.9 billion in just 6 months. By end of 1952 the material stockpile value was \$4.02 billion and by 1956 it was \$10.9 billion (National Academy of Sciences, 2008).

During this period the U.S. set up the President’s Material Policy Commission, which was tasked to assess if global resources could meet future U.S. demand. The subsequent report, called the ‘Paley report’, predicted significant shortages based on estimations of future resource use, essentially concerns over ‘limits to *military* growth’. The report proposed a range of technology innovations, exploiting domestic reserves and continued stockpiling to overcome material constraint problems, effectively proposing a ‘tech will fix it’ solution (Paley, 1952). Figure 5.2 shows a figure from the Paley report demonstrating the increase of material quantities over a seven-year period. The P-80 aircraft shown was the

NEW WEAPONS USE MORE MATERIALS

Fig. 5.2. The increase in quantity of materials over a seven-year period (Paley, 1952).

U.S.'s first jet fighter and the F-94C was a later derivative of that same aircraft.

By the mid-1950s the Soviet Union had developed their own nuclear arsenal, including the much more powerful hydrogen bomb. This led military planners to consider material requirements in the event of a nuclear war. They decided that this scenario would mean the war would last only three years and therefore in 1958 it was decided to dispose of a portion of the critical materials stock. The reason was that a nuclear war was assumed to need less material as the fighting would not last as long. In the early 1960s the critical materials stockpile was further reduced by nearly \$3.4 billion, from a figure of \$7.7 billion (National Academy of Sciences, 2008).

As the global economy grew through the 1960s, the material demand increased accordingly, which in turn placed a strain on material supply. As a result, U.S. industry, which supplied the military, was experiencing material supply problems, so the government released critical material stocks into the U.S. economy, to help overcome material shortages.

5.4 Critical Materials, the Energy Crisis and Rising Environmental Concerns through the 1970's

In the 1970s, the U.S. approach to critical materials was further developed and other limits to growth factors came into play. Conflict in the Middle East led to a global oil crisis in 1973, with the U.S. and the Netherlands both

experiencing a total Middle Eastern oil embargo. Through the 1970s the prices of materials continued to rise due to continued economic growth in Japan, North America, and Europe. From 1947 to 1971, raw materials prices had increased 21%. From 1971 to 1973 prices increased by 46% (Eckes, 1979).

In parallel with the energy and materials challenges, Donella H. Meadows and colleagues, based in MIT, published their 1972 book, *The Limits to Growth*, where they forecast dramatic population collapse due to exhaustion of resources resulting from rising demand from a growing global population (Meadows *et al.*, 1972).

In 1976 the U.S. re-introduced the requirement for civilian industrial material needs to be considered alongside military production needs, when considering the materials stockpile (National Academy of Sciences, 2008).

In 1977 the U.S. Congress published the proceeding of a conference entitled *Engineering implications of chronic materials scarcity: ... Engineering Foundation Research Conference on National Materials Policy*. This was part of a conference series on the topic (Huddle and Promisel, 1977). This publication demonstrates the more complex and comprehensive approach the U.S. was developing towards critical materials. This approach laid the foundations of the critical materials approaches in the 21st century.

An example of this approach can be seen in Fig. 5.3, where material substitution analysis is conducted. This highlights areas of policymaker focus.

What was not a focus for the critical materials approach in the 1970s were materials used in low carbon renewable energies, materials used in digital technologies or the growing materials demands of emerging economies such as China and India. These considerations would come to the fore in the late 20th and early 21st century.

5.5 Critical Materials and Energy Nexus in the 1970s

In parallel with the policy focus concerning wider engineering applications for critical materials, the USA developed policies to ensure that energy independence could be achieved over a 15 year period, up to 1990. The assessment of the non-fuel minerals needed for the planned transition was led by the U.S. Geological survey (USGS). The USGS developed the Minerals for Energy Production (MEP) program (Albers *et al.*, 1976).

The MEP program aimed to determine first the materials and quantities needed to achieve full energy independence. The program had a focus

Fig. 5.3. Engineering implications of chronic materials scarcity report.

on seeking to ensure as much of the key materials as possible would come from U.S. primary mining. In addition, the program sought to understand the foreign dependence and determine any possible alternatives, including material substitution.

Importantly the MEP program sought to understand the 'most stressed materials' and ensure, if possible, the domestic U.S. materials primary supply. The term 'most stressed' would by the late 1990s become 'critical materials'. Of note is the 1976 report by Albers, *et al.*, which does not use the term scarcity. The position of the authors of the report was that if sufficient investment and attention were to be given to exploiting primary resources, the prospect of scarcity or 'running out' would not arise.

The MEP program aimed to use early computer databases for materials stocks and flows and to use this database to understand materials 'stresses' as the U.S. developed total energy independence. The use of computers was seen as essential to manage the complexity of materials needs as part of the energy independence transition.

The report was divided into two parts; Part I covered demand and Part II supply. Part I of the report lists 31 materials essential for technologies to provide energy supply. The energy generation technologies listed cover fossil and non-fossil energy generation from coal and oil, plus nuclear as well as wind and solar. Part II of the report highlights the fact that materials independence cannot be reached and imports of some materials will always be needed. The report's Part II highlights the need for imports of, for example; cobalt, manganese, niobium, aluminum, nickel and tungsten. The report also highlights that the U.S. materials stockpile has been used extensively to address shortages in some materials.

The report does not highlight concerns about any environmental impacts of either increased material production or of increased burning of fossil fuels. Climate change concerns were not a widespread policy issue at this time. Nor were there any health and safety issues raised concerning the expected increased use of asbestos and other hazardous materials.

The conclusions of the report begin by making the statement that energy generation is essential and must always have first call on materials. The authors proposed that supply shortages could occur for other sectors as the energy sector material demand increased. The report does however highlight that there was extreme uncertainty with the supply and demand data they had available and to address this estimations were used. Interestingly, the rare earths were assessed, but not for energy production, and the USA was deemed to be self-sufficient. This position on rare earths

Fig. 5.4. Global rare earth element production (1 kt = 10^6 kg) from 1950 through 2000.

Source: Haxel, *et al.*, USGS, 2002.

can be seen in Fig. 5.4, where later work by the U.S. Geological Survey in 2002 shows the period up to 1976 and beyond.

The report's conclusions highlight that for many materials significant increases in domestic supply would be needed to reach energy independence by 1990. The releases of the material stockpiles were only buying time and would not be a long term solution. The report ends with an urgent call for action to understand the scope and scale of the materials problems. The authors voice deep concern at the lack of understanding of the problems of supplying industry with the materials needed to ensure energy independence by 1990. They highlight how quickly the situation of an oil embargo impacted the U.S. and that on the topic of materials there was widespread complacency.

The solutions proposed were mainly around new geological assessments to ensure supply. Again the urgency of this work was stressed as any delay would reduce the U.S.'s flexibility to meet new challenges. There was scant mention of secondary materials supply via recycling or of reuse of materials, as part of a resource efficient approach. The authors felt confident the U.S. could become both energy independent and significantly more materials independent by 1990. They warned against reliance on 'crash programs', or quick fixes, as the lead times for geology and mining programs can be up to 20 years (Albers *et al.*, 1976).

5.6 Technology Materials and Tackling Climate Change in the late 20th and early 21st century — the Critical Materials Agenda Emerges

As Fig. 5.4 shows, the hopes and calls for urgent action of the Albers, *et al.*, 1976 report were far from realized through the 1980s. In turn, the technology revolutions of the digital age and economic globalization had not been envisaged. The challenges to the planet of man-made climate change were also not understood in the 1976 report.

From the 1980s onwards it was felt by U.S. policy makers that global markets would ensure a supply of energy and non-energy materials. Essentially this represented a ‘tech + global economy will fix it’ approach. This situation started to change from the late 1990s onwards with the rise of new technologies, globalized economic growth, increasing levels of waste, concerns over energy & climate, resource nationalism, and shifts in geopolitics, which have combined to drive the need for the development of a more sophisticated approach to critical materials. This development has ensured that around 2006, *critical materials* had become a distinct field.

The growth of new technologies has made the critical materials challenge even more complex. The number of elements needed in modern

Source: T. McManus, Intel Corp., 2006

Fig. 5.5. An Intel corp. internal image of the growing complexity of elements in electronic chips. McManus, Intel Corp., 2006.

Table 5.2: The Shift from Material Scarcity towards Current Understanding of Critical Material Approaches (Peck, 2016).

Title	Author	Term	Descriptor
1. Depletion and the Long-run Availability of Mineral Commodities 2001	Tilton J E, Report published by IIED for WBCSD, Washington D.C, USA	Mineral commodities depletion	Mineral resource availability Mineral depletion Shortages and scarcity = opposite of availability Excess of demand over supply Declining availability
2. On Borrowed Time? Assessing the Threat of Mineral Depletion 2003	Tilton J E, RFF Press, Washington, D.C. USA	Mineral depletion	Mineral resource availability Mineral depletion Shortages and scarcity = opposite of availability Excess of demand over supply Declining availability
3. Scarcity and Growth in the New Millennium: Summary 2004	R. David Simpson, Michael A. Toman, and Robert U. Ayres Discussion Paper 04-01 Resources for the Future, USA	Scarcity New Scarcity	Resource limits to growth
4. Minerals, critical minerals, and the U.S. Economy, 2008	Eggert R. G. <i>et al.</i> , Minerals, Critical Minerals, and the U.S. Economy, National Research Council, USA	Critical minerals; Critical materials	The two dimensions of criticality are: 1. importance in use; 2. availability
5. Methodology of Metal Criticality Determination, 2009	Thomas E. Graedel, <i>et al.</i> , Yale University, USA	Metal criticality	A critical metal involves three dimensions: 1. supply risk; 2. environmental implications; 3. vulnerability to supply restriction

societies covers much of the periodic table. As an example Fig. 5.5 shows that between the 1980s and the 2000s electronic chip manufacture required 49 more elements as complexity increased.

The U.S. policy of holding large strategic material stockpiles came to an end in 1992. Between 1993–2005 the stockpile was reduced by 75%.

Politically, the view was that markets could always supply what was needed (Abraham, 2015). Whilst this is a further example of the ‘tech + global economy will fix it’ approach, concerns persisted over the rate of material use, increasing complexity and global dependence. This shift is highlighted in examples of literature from 2001 to 2009, which is shown in Table 5.2.

The European Union (EU), USA, Japan, and other countries, came together at times to collaboratively develop their critical materials approaches. Their thinking not only saw material criticality in military terms but also from economic and geo-political aspects, taking energy and environmental concerns into account.

The full involvement of the EU in addressing critical materials was an important step in the history of critical materials. The EU consulted other nations, especially the U.S., to help them develop their own distinctive European critical materials strategy.

A key important realization began in the early 21st century as it was recognized that geologists & miners could not alone provide all the solutions to critical materials. Conversely some sustainability thinkers and actors realized that geologists & miners are essential to understanding critical materials and finding solutions. The age of multi-disciplinary thinking along the entire materials value chain had begun.

5.7 Conclusion

This chapter shows that the development of approaches towards critical materials began during times of geo-political tensions and conflict in the 20th century. Actions around material criticality were significant throughout the 1940s, 1950s and 1960s, mainly focused on the stockpiling of materials deemed essential to military equipment production. The main driver was concerns over ‘limits to military growth’ because of concerns over the availability of materials, driven by geo-political concerns and conflicts.

The development of more contemporary critical materials approaches began in the 1970s, with the combined effects of limits to growth concerns and with the energy/oil crisis. At the same time, materials supply/price problems served to intensify action. Low carbon renewable energies, advanced technology materials or emerging economies requirements were not a feature of critical materials thinking at this time. The solutions proposed to material criticality in the 1970s built upon previous decades, with calls to increase understanding of domestic primary resources, increase exploitation of those resources, increase understanding of the stock

flows of materials, seek greater economic control, and stockpile where needed. This represents a 'tech will fix it' approach which has remained in place.

Through the 1980s, 1990s and into the 2000s continued growth in overall material demand was coupled with the emergence of new technologies which resulted in a much more varied palette of elements and materials emerging. The approach of governments in this period was that globalised materials markets would supply the materials needed and also stabilise prices if they spiked. Most of the policy proposals of the 1970s were forgotten as markets in the post-Cold War era opened up.

As the 21st century began it was starting to become clear that revised methodologies to assess critical materials were needed and by 2006 the development of these approaches was well underway. The work of the past decades has been revised and many of the historic policy recommendations restated. One significant difference of the 2006 approach compared to the past was that of the environment. The limits to growth frame has been adjusted to focus on the effects of pollution and climate change. By 2006 data was beginning to show that the tech will fix it approaches to tackling climate change (low carbon energy and mobility, etc.) will require significant increases in materials, which in turn will increase challenges in materials criticality.

The tensions around 'limits to growth' versus 'tech will fix it' are a feature in discussions concerning critical materials. The 'running out' or 'mineral exhaustion' concerns of finite materials are referred to, but this thinking, over the near term, relies on technologies not changing. However, technology does constantly change. At the same time rapidly increasing material consumption, plus the corresponding waste and energy/pollution drives a revised 'limits to growth' framework. The tensions are often contradictory and positions along national political lines as well as geo-political tensions are often firmly taken.

Some features from the reports arising out of the energy–materials crisis of the 1970s are consistent. Time is urgent, but the world moves at a slow pace and manages somehow. Risks are high and increasing but then they either disappear or shift and multiply. Energy requirements and technology changes in energy generation are essential but never taken seriously enough. The need for much improved material demand–supply data is urgently needed but never fully developed. The market meets needs and manages each crisis but concerns linger, sometimes it seems more by luck than judgement. 'Wolf' has been cried often but the wolf never really came,

whilst at the same time knowledge that the wolf is nearby in the forest increases.

A sensible way forwards is to recognize the importance of both ‘limits to growth’ together with ‘tech will fix it’ thinking and collaboratively seek to find solutions across the entire materials value chain, be they critical or not. As so often, we have faced similar challenges in the past, and an improved understanding of our history could help us.

References

1. Abraham, D. S. (2015). *The elements of power: Gadgets, guns, and the struggle for a sustainable future in the Rare Metal Age*. New Haven, Connecticut, USA: Yale University Press.
2. Albers, J.P., Bawiec, W.J., Rooney, L.F., Goudarzi, G.H., and Shaffer, G.L. (1976). *Demand and supply of nonfuel minerals and materials for the United States energy industry, 1975-90 — a preliminary report*. Washington D.C., USA: United States Geological Survey.
3. Ashby, M.F. (2013). *Materials and the environment — eco-informed materials choice* (2nd ed.). Waltham, Massachusetts, USA: Butterworth-Heinemann.
4. Ashby, M.F., Balas, D.F., and Coral, J.S. (2016). *Materials and sustainable development*. Waltham, Massachusetts, USA: Butterworth-Heinemann.
5. Eckes, A.E. (1979). *The United States and the global struggle for minerals*. Austin, Texas, USA: University of Texas Press.
6. National Research Council. (2008). *Minerals, critical minerals, and the U.S. economy*. Washington D.C., USA: National Research Council.
7. Graedel, T. (2009). Defining critical materials. In R. Bleischwitz, P.J. Welfens, and Z. Zhang (Eds.), *Sustainable growth and resource productivity — economic and global policy issues*. Sheffield, UK: Greenleaf Publishing.
8. Haxel, G.B., Hedrick, J.B., and Orris, G.J. (2002). *Rare earth elements — critical resources for high technology*. Reston, Virginia, US: United States Geological Survey. Retrieved from <https://pubs.usgs.gov/fs/2002/fs087-02/>.
9. Huddle, F.P. and Promisel, H.E. (Eds.). (1977). *Engineering implications of chronic materials scarcity*. Washington D.C., USA: US Government Printing Office.
10. Johnson, J., Harper, E. M., Lifset, R., and Graedel, T. E. (2007). Dining at the periodic table: Metals concentrations as they relate to recycling. *Environmental Science and Technology*, 41(5), 1759–1765.
11. Martin, R.L. and Kemper, A. (2012, April). Saving the planet: a tale of two strategies. *Harvard Business Review*. p. 49.
12. Meadows, D.H., Meadows, D.L., Randers, J., and Behrens, W.W. III. (1972). *The limits to growth: A report for The Club of Rome’s project on the predicament of mankind*. Washington D.C., USA: Universe Books.
13. McManus T. (2006). *Internal report*. Santa Clara, California, USA: Intel. In Graedel, T.E. (2006). *Determining the criticality of materials*. [PowerPoint presentation].

14. National Academy of Sciences. (2008). *Managing materials for a twenty-first century military*. Washington D.C., USA: National Academy of Sciences.
15. Paley, W.S. (1952). *Resources for freedom*. Washington D.C., USA: The President's Materials Commission.
16. Peck, D.P., Bakker, C.A., Kandachar, P.V., and de Rijk, T. (2017). Product policy and material scarcity challenges : The essential role of government in the past and lessons for today. Amsterdam, the Netherlands: IOS Press.
17. Postan, M.M. (1952). *British war production*. London, UK: Her Majesty's Stationery Office.
18. Simpson, R.D., Toman, M.A., and Ayres, R.U. (2004). *Scarcity and growth in the new millennium: Summary*. Washington D.C., USA: Resources For The Future.
19. Stevenson, D. (2012). *With our backs to the wall: Victory and defeat in 1918*. London, UK: Penguin Books.
20. Tahvonen, O. (2000). Economic sustainability and scarcity of natural resources: A brief historical review. Washington D.C., USA: Resources For The Future.
21. Tilton J.E. (2003). *On borrowed time? Assessing the threat of mineral depletion*. Washington D.C., USA: Routledge.
22. Tilton J.E. (2001). *Depletion and the long-run availability of mineral commodities*. Washington D.C., USA: International Institute for Environment and Development.