THE EVOLUTION OF THOUGHT ON THE AVAILABILITY OF NON-RENEWABLE NATURAL RESOURCES IN THE LONG RUN

by

Wilhelm Pieter Nel

Submitted in accordance with the requirements for the degree of

Master of Commerce

in the subject

Economics

At the

University of South Africa

Supervisor: Prof D Hodge

6 September 2020

DECLARATION

I declare that the work I am submitting for assessment contains no section copied in whole or in part from any other source unless explicitly identified in quotation marks and with detailed and complete referencing.

6 September 2020

(Signature of WP Nel) Date

ACKNOWLEDGEMENTS

I would like to acknowledge the assistance that I have received from my supervisor, Professor Duncan Hodge at Unisa's Department of Economics.

ABSTRACT

There are different views about the availability of non-renewable resources in the long run. Hotelling's (1931) seminal model of exhaustible resources greatly influenced subsequent studies. Hotelling's and related fixed-stock models imply decreasing availability and increasing real prices of non-renewable resources in the long run. However, most of the empirical evidence does not support the prediction of higher real price trends. Hotelling's model has been criticised for ignoring certain factors relevant to the discovery and innovation-driven creation of additional non-renewable reserves. Contrary to Hotelling's fixed-stock assumption, this may expand the total stock of non-renewable resources available for profitable extraction. The main research objective of this study is to address this problem by identifying a broader range of factors to be used when constructing models of the availability of non-renewable resources. This was done by means of an extensive literature survey of both historic and more contemporary thought in this regard. This study shows the evolution of thinking and reasons behind the diversity of views on the availability of non-renewable resources. Thirty core facts were identified and a broad research framework formulated, including policies and methods to mitigate resource depletion and ensure availability both at national and global levels. A key finding is that improvements in various productivity-enhancing technologies have, thus far, delayed the onset of decreased availability and higher real price trends implied by Hotelling's and other fixed-stock models.

NOMENCLATURE

A number of concepts and terms used in this dissertation are defined and/or briefly explained in Appendix A. These words and phrases appear in italics.

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LIST OF ABBREVIATIONS AND ACRONYMS

4IR – 4th Industrial Revolution

ASM – artisanal and small-scale mining

Au, B, Be, C, Ca, Co, Cr, Cu, Fe, K, Li, Mg, N, Ni, P and Zn – Chemical symbols for elements such as gold, boron, beryllium, carbon, calcium, cobalt, chromium, copper, iron, potassium, lithium, magnesium, nitrogen, nickel, phosphorous and zinc as on the periodic table

Availability BOK – “Availability of non-renewable resources in the long run” body of knowledge

BEV – battery electric vehicle

BGR – Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources in Germany)

BOK – body of knowledge

BRI – *Belt and Road Initiative*

CIA – Central Intelligence Agency

CIM – Canadian Institute of Mining, Metallurgy and Petroleum

CLCS – Commission on the Limits of the Continental Shelf

EU – European Union

EV – electric vehicle

FCEV – fuel cell electric vehicle

GDP – gross domestic product

GHGs – green house gases

ICEV – internal combustion engine vehicle

ICMM – International Council on Mining and Metals

ICSG – International Copper Study Group

IGF - Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development

IoU – intensity of use

IoM – Internet of Materials

ISA – International Seabed Authority

JORC Code – Joint Ore Reserves Committee Code

LSM – large scale mining

NEA - Nuclear Energy Agency

OECD – Organisation for Economic Co-operation and Development

OPEC – Organization for the Petroleum Exporting Countries

PERC – Pan European Resources & Reserves Code (for reporting mineral reserves/resources)

PGM – platinum group metal

PV – photovoltaic

R&D – research and development

REE – rare earth element

RFF – Resources for the Future

R/P ratio – Reserves-to-production ratio

SAIMM – Southern African Institute for Mining and Metallurgy

SAMREC – The South African Mineral Resources Committee

SMnNs – seafloor manganese nodules

SWF – sovereign wealth fund

SWP – Stiftung Wissenschaft und Politik (German Institute for International and Security Affairs)

SX-EW – solvent extraction and electrowinning

UN – United Nations

UNCTAD – United Nations Conference on Trade and Development

USGS – United States Geological Survey

WEEE – Waste Electrical and Electronic Equipment

WEF – World Economic Forum

WGC – World Gold Council

WTO – World Trade Organisation

WWI – World War I

WWII – World War II

CHAPTER 1 – INTRODUCTION

1.1 INTRODUCTION

According to Lin et al (2018: 1) global production and consumption required 1,7 Earths in 2014 to replenish the resources used and to absorb the pollution generated. This finding is based on ecological footprint accounting which quantifies the supply and demand of Earth's biocapacity. It is expected that three Planet Earths will be needed by 2050 if the current rate of production and consumption continues (World Economic Forum, 2018: 7). Alexander and Gleeson (2019: 6, 7) believe that the days of capitalism are numbered because it provides an incentive to maximise profits and productivity without limits on a finite planet. Associated with concerns regarding the availability of resources are concerns about demand- and supply-related factors such as population levels; sustainable growth; food, energy, materials and water security; and various manifestations of the problem such as volatile prices. Factors that may worsen the situation, for example, political tensions and hindrances to the free trade of non-renewable resources are also major concerns and are linked to the concept of "political availability". Furthermore, the consumption, production and occurrence of mineral reserves occurs unequally around the world. The last mentioned factor, is linked to "geological availability". The availability of non-renewable resources is multi-dimensional in nature and ranges from the physical to economic and political (See *dimensions of availability* in Annexure A).

Resource scarcity and availability is a recurring theme that is again back with a vengeance (Lee et al, 2012: x; Humphreys, 2013: 1). The impact of humans on Earth is visible, for example, in the appearance of manufactured materials in sediments, the modification of carbon, nitrogen and phosphorous cycles and the occurrence of plastic in isolated and unexpected places in the earth. This, some believe, warrants the recognition of a new geological time unit known as the Anthropocene (Loose, 2019: 12; Waters et al, 2016: ad2622:1). For non-renewable resources, economic *indicator*s such as real price trends do not, however, provide conclusive evidence of increased scarcity. This raises a number of questions which are investigated in this study where the focus is on the availability of non-renewable resources in the long run. Ore bodies comprise one such non-renewable resource where certain chemical elements are found to be concentrated to much higher levels than the average in the earth's crust, through a number of geological processes over very long periods of time.

All resources are scarce or inadequate to various degrees. That is the reason for the existence of the subject of economics, in which the central or main problem is to satisfy human wants and needs with scarce resources (Heilbroner & Thulow, 1975: 3). *Non-renewable resources* (See Annexure A), by definition and their nature, are unable to re-generate in a relevant, human-centric time frame as is the case for renewable resources, and it is therefore argued that orebodies mined today will be depleted and, therefore, not available for future generations. This characteristic creates the expectation that the current and future availability of non-renewable resources is a problem that requires constant attention – a problem that may perhaps become unsolvable at some point in time. Future non-renewable resource availability and adequacy forms part of the debate regarding the achievability of sustainable development which is defined in the Brundtland Report as “development that meets the needs of the present without compromising the ability of the future to meet their own” (World Commission on Environment and Development, 1987: 16).

Cowell et al (1999: 278) raised the following important question about the sustainable use of non-renewable resources: “Can continued extraction of minerals and metals from the earth’s crust be regarded as a legitimate part of sustainable development leading to a sustainable society?” Although matter and energy are very abundant in the universe, only a very small percentage is currently accessible to humanity. Furthermore, only a very small percentage has been concentrated and “processed” by nature in the earth’s crust into a form that makes it currently, economically exploitable. Such anomalies where coal and oil formed and where elements such as tin, silver, gold and uranium occur in much higher concentrations than the average concentrations in the earth’s crust, are scarce and gifts of nature. Figure 1.1 illustrates that current mining tries to exploit the richest concentrations of minerals present in orebodies, in such a way that various types of minerals, and the products manufactured from them, are affordable. As miners improve productivity it becomes possible to mine profitably at lower *grade*s. Skinner (1976) believes that the amount of metal available will increase geometrically down to a *grade* corresponding to the peak of the curve.

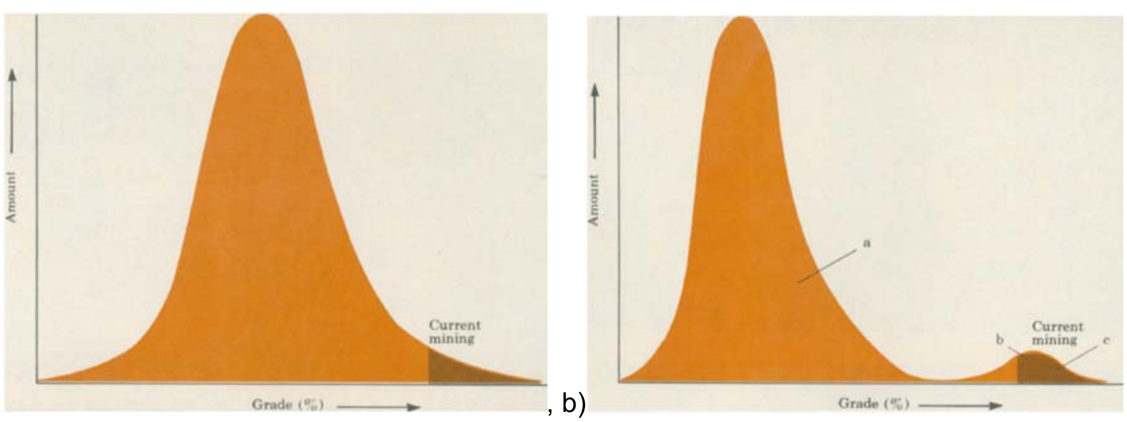
a) 

Figure 1.1. Skinner’s (1976: 263) view on the typical distribution of geochemically a) abundant and b) scarce metals in the earth’s crust

To answer Cowell’s question and by implication the question of how available non-renewable resources are, it is necessary to make sense of different and contrasting views, *paradigm*s and theories, of which some cannot be reconciled with empirical results. According to Brobst (1979: 107) the "diversity of conclusions drawn from studies of resource availability has caused debate and confusion." Tilton (1996: 92, 93) refers, for example, to the "fixed stock" and "opportunity cost" *paradigm*s. Research by Barnett and Morse (1963: 51, 195) contradicts the so-called "scarcity doctrine" constructed by a number of the "Classical Economists". According to the Ricardian model the quality of land and minerals varies from high to low as suggested by Skinner (1976) in the case of minerals – please see Figure 1.1. It is often assumed that if the highest quality is utilised first, the cost of producing mineral commodities will increase as lower quality orebodies are utilised later, giving rise to diminishing returns on capital, energy, labour, chemicals and other inputs employed.

1.2 THE ECONOMICS OF NON-RENEWABLE RESOURCE EXTRACTIVE INDUSTRY

All raw materials used in the manufacturing and construction sectors of the economy have to be either grown or extracted. A renewable raw material such as wood can regrow and restock itself provided that it is not used at a rate faster than it can be replenished. *Non-renewable resources* such as oil, coal, limestone, potash, sand, tin and uranium are depleting natural resources because the reservoirs and deposits from which they are exploited cannot be replaced except for, in a few limited cases, water-transported minerals and geothermal fluid. The amount of minerals in the earth's crust is for all practical purposes finite and can be considered a stock from which mining activities remove a certain quantity whenever exploitation occurs. Renewable resources such as plants and trees regularly receive sunlight, used for photosynthesis, from outside *spaceship earth* (Boulding, 1966: 3) and therefore the earth's energy system is not a closed one. (A brief definition of *spaceship earth* and all other terms in italics can be found in Annexure A.) Renewable resources like fish live in a circular ecosystem where one organism, or its waste, is another's food. From a materials perspective the earth is for all practical purposes a closed system considering the relatively small mass of meteorites entering the system and the fact that *mining in space* has not yet been commercialised.

Non-renewable resources are extracted mostly from the earth's crust, from wells and by means of surface and underground mines and other methods such as dredging and the in situ leaching of various salts and uranium minerals. A small percentage of the total value of all minerals produced per year is currently extracted from the seabed and from below the seafloor. Non-renewable resource commodities are produced by the *extractive industries* such as the mining and petroleum industries, which have certain important characteristics as described, for example, by Halland et al (2015: 2, 3) and Gentry (1988: A25). Such commodities can be classified in different ways, for example as metallic minerals, non-metallic minerals, construction materials and petroleum products. Some of them are extracted from ores and require further processing before they can be used as consumer products or the raw materials required for the manufacturing and construction sectors. Lots of waste is generated when the final product, e.g. 99,95% pure gold, is present in low concentrations in the ore. Ore beneficiation is in some cases capital intensive and may require a lot of energy and chemicals. As a result, the *extractive industries* have a significant environmental impact. Mining may also generate noise, dust and vibrations which may affect communities located close to such operations.

With a few exceptions, construction materials such as sand, gravel and crushed stone are relatively abundant, of low value and locally produced. Although the metallic elements such as tin, chromium, platinum and gold are present almost everywhere in the earth's crust, it is only in certain places where they can be found at much higher concentrations than the average. Nations where such orebodies occur have a competitive advantage in producing and exporting these commodities. Bulky materials such as iron ore and coal are traded across the borders of countries today because of good trade relations, globalisation and the reduction of per unit shipping costs over many decades.

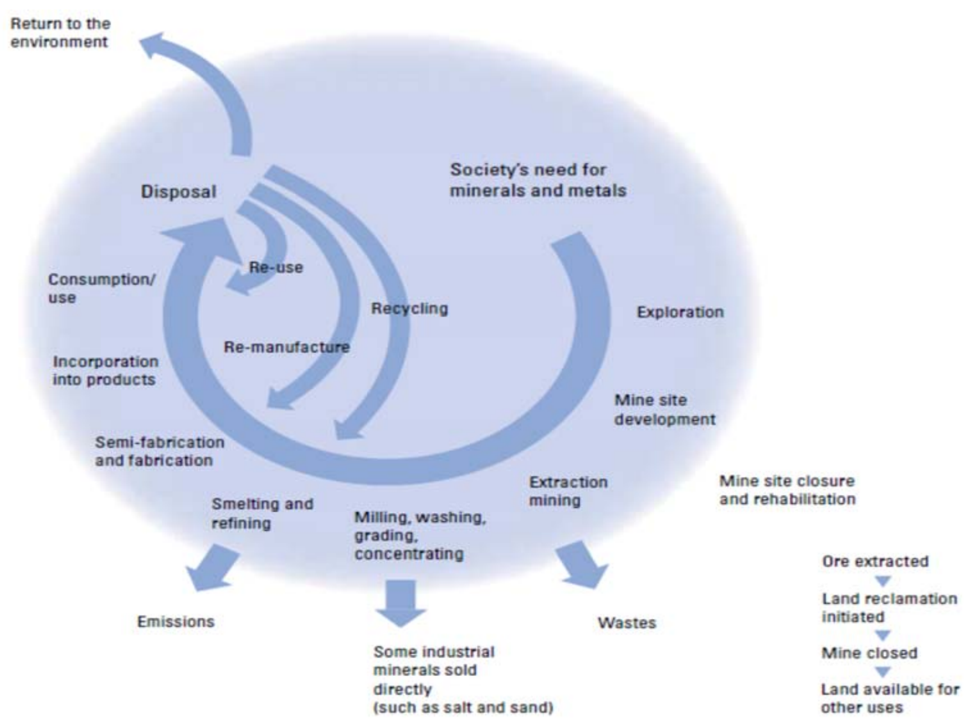


Figure 1.2. The Minerals Cycle (Starke, 2002: 34)

Most of the “easy to find” orebodies have been found and, therefore, the minerals cycle usually starts with exploration as indicated in Figure 1.2. This is followed by mine development, extraction and ore beneficiation until the mineral is ready to be used in a consumer or industrial product. Once a product such as a cellular phone gets to the end of its life, it is possible to extract various non-renewable resources from it. This is called secondary mining or recycling. The secondary production of certain resources that, for example, are not burnt like large quantities of fossil fuels, has increased over the years because of a change in attitude and better ways of recycling. In the *circular economy,* recyclable materials such as metals will be re-used to a large extent. The minerals cycle in Figure 1.2 provides clues as to the framework that should be used when analysing the availability of non-renewable resources. For example, availability can be increased by doing more exploration, increasing investment in the development of mines and through increased recycling. This framework is expanded in the rest of this document to one for the body of knowledge (BOK) related to the availability of non-renewable resources in the long run.

The non-renewability characteristic of mineral resources often leads to the question whether their economics are different from that of other goods and whether it should be dealt with in a special way. Some people think that this characteristic of non-renewable resources will eventually result in the unavailability of such goods in a global economic system where demand almost constantly increases from one year to another.

1.3 AVAILABILITY IN THE LONG RUN

The life of every mine and oil well is limited because of the finiteness of the orebody or oil field that is being exploited. This study is not concerned with the life of a specific mine or oil well but rather the availability of non-renewable resources from all mines or oil wells in a specific country or globally, combined. The time frame considered in this study is very long. Given such a time frame, it is possible to find new orebodies and, therefore, not only current mines are considered but also potential future ones. Events and factors that may impact on availability in the short run are not the focus of this study. Many of the factors that affect the availability of non-renewable resources in the short run at a regional level may not do so in the long run at a global level – labour strikes and the flooding of surface mines because of heavy rain are likely to affect the supply from such mines in the short run only. Microeconomic theory informs that production inputs such as labour, energy and materials can be varied in the short run but not production capacity. In the long run production capacity can also be varied if investors are willing to support new projects (Pindyck & Rubinfeld, 2013: 206).

In this study the focus is broader than that of the micro- or firm-level. Governments sometimes want to know how available a specific mineral commodity is in their countries and how dependent they are on imports. For that reason they may appoint an entity to gather the relevant statistics. In an integrated and interdependent world the level of global reserves is of great importance because perceptions of low availability may result in competition, *resource nationalism* and even war.

For non-renewable resources, four distinct time periods should be considered according to Halland et al (2015: 22), namely the immediate, short term, long term and very long term. Immediate demand can only be provided from inventories. In the long term, supply is limited to the depletion of known deposits and by known technologies. In the very long term it is, however, possible to find new orebodies and to develop technologies that may expand reserves. In the very long term certain developments may take place such as the development of a new substitute for a material that has become scarcer. Over a long period of time, completely new sources can be found. The possibility of seabed and asteroid mining serve as examples.

Over the long to very long term, the demand for specific non-renewable commodities may change. It is, for example, possible for a *dominant design* such as the internal combustion engine, used in vehicles, to be replaced by the electric motor in battery electric vehicles. Such a transition will decrease the demand for crude oil and increase the demand for electric motor and battery materials such as copper, lithium and cobalt. Such developments have the potential to contribute towards the evolution of thought about the availability of non-renewable resources in the long run and are therefore included in this study.

“Long term” availability (as in the title of this study) may refer to a period as long as 70 years or longer. That is the time period that may be required for a new extraction technology to be invented, developed, improved and adopted. *Hydraulic fracturing* (fracking), for example, was used for the first time to stimulate flow of natural gas from the Hugoton field in Kansas in 1947. It only became successful and fairly widely adopted much more recently. The technique is used today to produce large quantities of oil and gas from the U.S.’s large shale oil and gas reserves. In certain mining jurisdictions such as some of the states in Australia, the use of this extraction method is prohibited because of its environmental impact. Today the U.S. is again one of the top oil and gas producers in the world after its conventional oil production peaked in the early 1970s, as predicted by *Hubbert* (1969).

According to Henckens et al (2016: 103), “the extraction rate of a mineral resource is sustainable if it can provide 9 billion people with that mineral for at least 1 000 years, assuming that the per capita use is equally divided over the countries of the world”. This is a very tall order, considering the lives of current global *reserves.* Henckens' definition of sustainable mining is one of many attempts to find such a definition – numerous people simply feel that a non-renewable resource cannot be utilised in a sustainable manner. By using a number such as 1 000 years, Henckens is probably allowing for too much time for significant technological innovations to take place. The large scale mining of a number of minerals from the deep-sea floor will probably take place within the next number of decades, for example. Large scale mining of asteroids and the colonisation of the Moon and Mars will probably also take less time to accomplish.

1.4 AVAILABILITY PARAMETERS, DIMENSIONS AND MEASURES

1.4.1 Availability parameters and measures

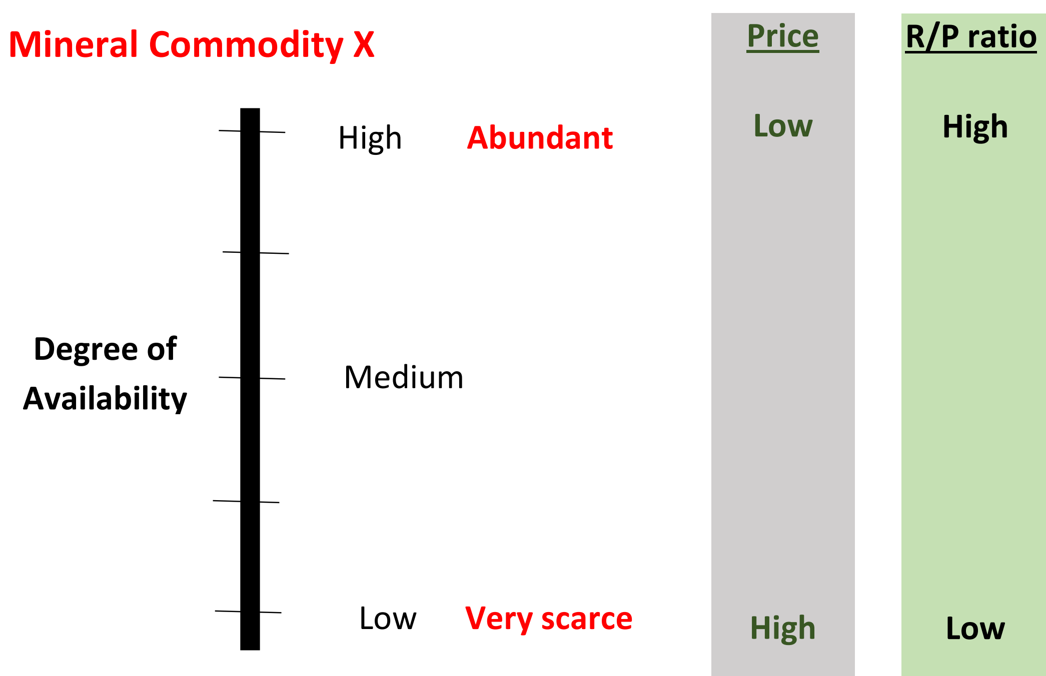


Figure 1.3. Two availability indicators – price and the *R/P ratio*.

Various measures or *indicators* of availability have been developed over time. Price and the *reserve to annual production (R/P) ratio* are shown in Figure 1.3. With regard to price, it is important to note that real price trends over long periods of time are of particular interest for this study where the focus is on availability in the long run. Daily, weekly and monthly market prices could be volatile at times and may be influenced by short-term demand and supply factors such as mine strikes. For various reasons, none of the older *indicators* are considered to be perfect and therefore newer ones have been developed. More information about *indicators* follow in the rest of this document, particularly, Chapter 4.

Availability is a function of various parameters. This can be illustrated by means of the price mechanism which influences the availability of a specific commodity through a feedback loop as illustrated in Figure 1.4.

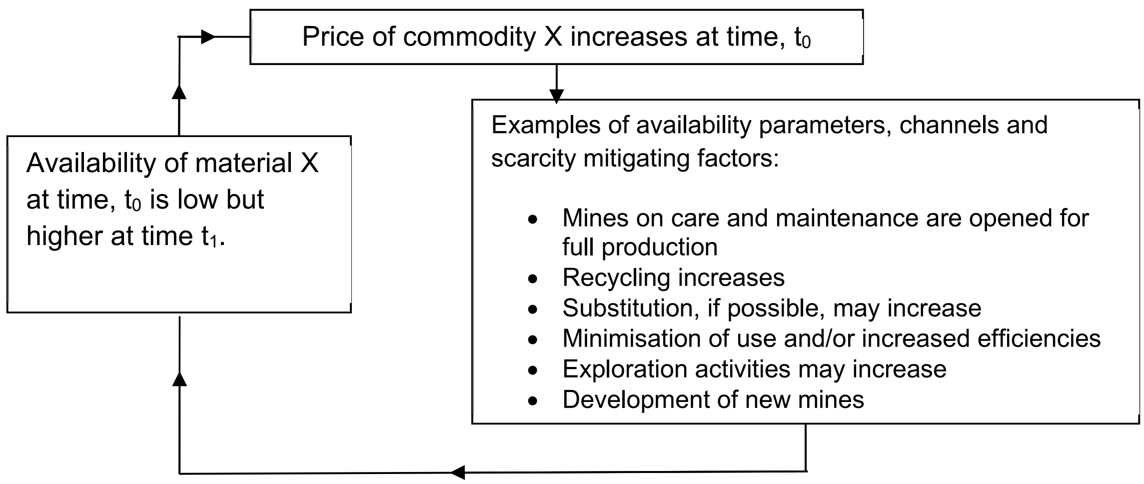


Figure 1.4. The price mechanism and the availability of a specific commodity, X.

As already discussed to some extent, each of the parameters, channels and scarcity mitigating factors has its own time period or window of influence. The lead time for planning and developing a new deep-level mine is long, and it may not significantly contribute to supply while the establishment project is still in progress, especially during the time when shafts are being sunk. Such a project may take many years, assuming that an orebody has already been identified, something which may also take years. In contrast, mitigating factors such as recycling can be increased in a much shorter time horizon. Technology development may take very long.

1.4.2 Dimensions of availability

The availability of non-renewable resources may be perceived to be different at national and global levels. The degree to which governments perceive natural resources to be scarce, critical or strategic may, for example, depend on the degree to which they depend on imports and whether such trade is free of restrictions or not. Such perceptions may influence policies such as to stockpile certain resources or allocate funds for the research and development of substitutes. In order to ensure good decision-making, governments need to know what quantities of resources are available locally, imported, available from only a few sources, which trade flows are most likely to be interrupted, the demand shifts that are likely to occur in the short to medium term future, and so on. According to Lee et al (2012: x) poorly designed and short-sighted policies make things worse.

National or global supply is the aggregate of supply produced by individual mines and firms, each operating in a specific jurisdiction and mining orebodies with specific characteristics such as depth, size, shape and quality that affect their economics. Future availability depends not only on current mines but even more so on finding new orebodies through the exploration process.

Eggert et al (2008: 71) identified five dimensions of primary (mined) mineral commodity availability, namely geological, technical, environmental and social, political and economic. These dimensions are illustrated by the following quote that refers to energy-critical elements: ‘An element may be “energy-critical” for a variety of reasons: It may be intrinsically rare or unevenly distributed in Earth’s crust, poorly concentrated by natural processes, currently unavailable in the U.S., found in concentrations that do not allow for economic extraction, or produced in a small number of countries or in locations subject to political instability.’ (Jaffe et al, 2011).

Geological availability

Geological availability is about the existence and size of the resource while economic availability is about the cost of extraction and processing. The interaction between geology and economics is well illustrated by the *McKelvey diagram* in Annexure A. Only a very small part of the *resource base* can be mined and processed at a profit and, therefore, forms part of *reserves*. Many of the scarcity concerns recorded in the literature are not linked to geological constraints. The case of tin scarcity in ancient Greece and the oil price shocks of the 1970s, discussed in Chapter 2, serve as examples.

Technical availability

Technical availability is about the knowledge, skills and technology required to extract and process a resource and find substitutes for a resource. Technical improvements often result in improved economic availability by means of improved productivity and/or lower costs. Humanity has made great progress in this regard since the days when its only source of iron was of meteoritic nature – it did not know how to extract iron from haematite (iron oxide ore) which is (geologically) abundant in the earth’s crust.

Environmental and social availability

The days when Milton Friedman (1970) propagated that the social responsibility of business was basically to just consider one stakeholder, namely the shareholder, are long gone. In his words: “There is one and only one social responsibility of business – to use its resources and engage in activities designed to increase its profits so long as it stays within the rules of the game, which is to say, engages in open and free competition without deception or fraud.” (Friedman, 1970: 55).

A number of negative externalities are linked to the extraction and processing of ore. Environmental and social availability refers to the ability to extract and process a resource in an environmental and socially acceptable way, also referred to as the “social licence to practise”. Despite most people wanting products, services and infrastructure such as cellular phones, TVs, cars, electricity networks and plumbing, they do not want a mine close to their doorstep from which the raw materials required for such goods are extracted. NIMBY, which stands for “Not in my back yard”, captures this attitude. Cases of extreme community activism are impacting on the availability of mineral commodities and may even result in wastage of exploration investment when orebodies are prevented from being developed into mines (Bennie, 2017; Bloomberg, 2018; Els, 2017; Jasmasmie, 2016; Li, 2016; Sohn, 2017; Tempelhoff, 2017: 7; Tempelhoff, 2018: 11).

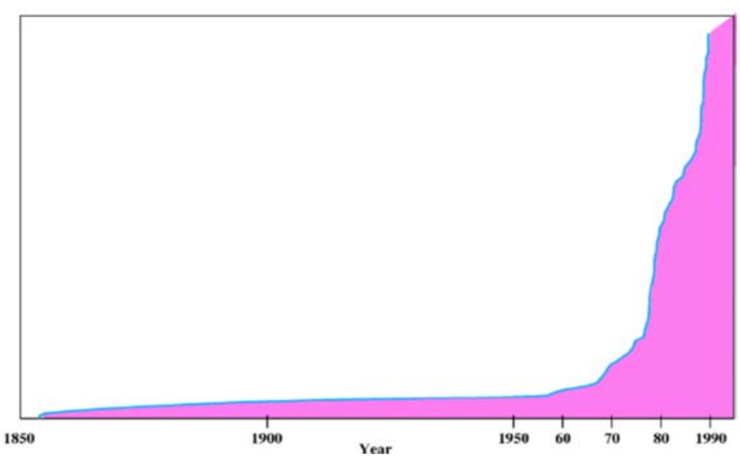


Figure 1.5. The increasing burden of cumulative environmental legislation enacted in Germany (Ayres, 2008: 282)

The environmental impact of the *extractive industry* has become a much bigger problem as the volume of materials increased over time, resulting in twin concerns about both the future availability of non-renewable resources as well as the ability and capacity of the environment to absorb the waste generated. A number of persons, for example Ericsson (2019: 127), think that environmental availability is a bigger problem than physical availability. Furthermore, alternative uses for land may result in conflict between miners, farmers and communities. Many of the externalities associated with mining have been internalised over the years by means of environmental legislation, standards and taxes. Today, some of these externalities are not yet fully reflected in the market prices of mineral commodities, but faults and oversights by companies are at times severely punished – BP was fined a record $20,8 billion for the 2010 Deepwater Horizon oil spill (Grush, 2015).

In many, especially developed, countries environmental compliance has become more onerous. This is shown in Figure 1.5 which illustrates the cumulative number of new pieces of environmental legislation introduced in Germany over time and how it exploded since the late 1960s. The implementation of environmental legislation and controls increases the cost of production and may help to explain why mining activity started to shift to emerging economies decades ago. Certain methods of mineral extraction have a greater impact than others. In the Philippines, for example, nickel production declined by an average 12% per annum from 2016 to 2018 because of a ban on open pit mining (Arnoldi, 9 Sep 2019).

Environmental availability also refers to the impact that goods produced by the *extractive industry* has on society in whatever product they may be imbedded during the life of such a product. The use of asbestos in building materials, brake shoes and other goods has been banned by many governments. This resulted in the destruction of asbestos reserves. Tools such as life cycle assessment are used nowadays to assess the environmental impact of a product or raw material over its whole life cycle. Today, high levels of fossil fuel utilisation globally as well as accumulated carbon dioxide emissions are contributing towards global climate change. There has been a number of calls for a decarbonised economy or zero net emissions of CO_2 (Fay et al, 2015: 2; G7, 2015: 12; Hallegatte et al, 2016: 2).

There is a risk that the infrastructure required to exploit, process and transport fossil fuels to markets may become *stranded assets*. High carbon taxes may result in the non-extraction of some fossil fuel orebodies that might otherwise have been economically viable. Such coal reserves on the balance sheets of coal companies are referred to as *stranded assets* (EY, 2015: 43). Companies such as Shell (2018: 6) and Rio Tinto are taking action to reduce potential *stranded assets*. Certain investors, such as Norway's sovereign wealth fund and the Church of England, are either reducing their investments in such assets or no longer investing in such assets (Biersheuvel, 2017).

Political availability

Political availability refers to the way in which governments influence availability through their policies and actions. The global and regional availability of mineral commodities are influenced by politico-regulatory factors and policies related to ownership, royalties, taxes, mineral legislation, mineral *resource nationalism* (e.g. nationalisation and indigenisation), security of tenure as well as tariffs and other trade restrictions. Such factors influence not only how attractive a specific jurisdiction will be for investors and how viable a specific mine may be, but can actually destroy *reserves* because they influence economic viability and availability. The political *dimension of availability* is manifested in many ways such as fights over the positioning of oil pipelines, the isolation of oil and mineral producing countries (e.g. U.S. restrictions on Iranian oil exports) and the subsidisation of energy to ensure security of supply. Mineral flows from politically unstable countries increase the risk of supply disruptions. During the cold war USSR minerals were largely unavailable to the West. According to Lee et al (2012: xiv), the markets for critical resources have always been political and their opinion is that resource politics will dominate the global agenda in years to come. According to Reichl et al (2018: 17), mine production from politically unstable countries has increased since the year 2000.

One reason for China's involvement in Africa (and other continents), and more lately through the *Belt and Road Initiative* is to ensure the adequate flow of resources to its fast-growing, resource intensive economy. The World Bank referred to China's average growth rate of 9,5% from 1979 to 2018 as "the fastest sustained expansion by a major economy in history" (Congressional Research Service, 2019: 2, 5). The building of islands, equipped with landing strips and other military-related installations, in the South China Sea forms part of this strategy to secure the flow of mineral commodities to China. Some people apply the concept of *Thucydides's Trap* to the shift in economic power away from the U.S. to China. Such thinking is fuelled by the Trump Administration's approach to China as manifested by its trade war and the description of China as a strategic and economic rival by Vice-president Pence. There are signs that the U.S. to China power shift is impacting on the potential availability of non-renewable resources. After starting the Trump-China trade war, the U.S. became concerned that China may use its dominance in *rare earths* and the U.S.'s dependence on them to retaliate. A few years ago China used Japan's dependence on its rare earths to punish Japan after a Chinese fishing boat collided with a Japanese Coast Guard vessel in a disputed territory in the East China Sea (Allison, 2017: 5, 156; Bulbulia, 2019; De Wit, 2015: 2; Turner, 2019).

The Political economy of non-renewable resources is dynamic as illustrated by shifts in the demand and supply of non-renewable resources. In an era of global climate change and decarbonisation, battery electric vehicles are challenging the dominant position of oil and internal combustion engine vehicles (ICEVs). Power produced by solar and wind farms is becoming cheaper and is a threat to fossil fuels. The global fossil fuel system has estimated assets worth

$25 trillion and some of them may become *stranded assets*. Countries which produce the resources that are in demand have geopolitical power. Oil production, for example, occurs in a limited number of geographic locations and its supply and availability has been managed by OPEC for decades. The political availability of oil will become less critical during the next number of decades as energy supply shifts from oligopolistic to more competitive markets. The political power of countries well endowed with oil reserves will decline while others such as China will increase because of its leadership position in the manufacturing and adoption of electric vehicles, batteries, solar (photo voltaic) cells and as producer of *rare earth* metals. Wind and solar radiation is available almost everywhere in the world and will democratize energy supply. The demand for copper, graphite, lithium, cobalt, *rare earth* elements, and others used in batteries, electric vehicles (EVs), solar and wind farms is likely to increase and new dependencies are likely to be created. According to the World Economic Forum (2018: 7) this “energy revolution will reshape the modern world in ways comparable only to the switch from coal to oil a century ago” (Scholten, 2018; Global Commission on the Geopolitics of Energy Transformation, 2019).

The availability of non-renewable resources is an important component of sustainable development. If materials required for the new decarbonised global economy are not available in the long run, it will be a severe blow for humanity’s attempts to achieve sustainability. The dimensions of mineral resource availability can be compared to the three pillars of sustainable development, namely the social, environmental and economic and is an important component of the framework for the “Availability of non-renewable resources” (Brent, 2012: 405).

1.5 THE GROWING DEMAND FOR NON-RENEWABLE RESOURCES: REASON FOR CONCERN?

The demand for non-renewable resources is derived from their various applications in industrial processes as well as raw materials in the manufacture of various consumer goods and the delivery of services. In many instances this demand is indirect. Various characteristics of metals and minerals make them desirable for a variety of applications. Characteristics such as high strength, durability, ferromagnetism, luminescence, the capacity to conduct heat and electricity create demand for various metals. The demand for materials has increased dramatically since the Industrial Revolution and is driven by various factors. Increased global population, affluence, *plutonomy*, the utilisation of materials, product and service innovation, speed of product and service adoption, and diffusion and consumer choice are some of the factors that have resulted in exponential growth in the demand for numerous types of materials. The story of Henry Ford’s plans to increase car ownership is well known. The dramatic increase of car ownership during the

20th century in developed countries such as the U.S., France and Japan (Smil, 2017: 329) clearly illustrates the impact of affluence on the (indirect) demand for non-renewable resources. The growth in demand for mineral commodities in the development of an economic superpower such as the U.S. is illustrated by Table 1.1. At the beginning of the 1900s the total U.S. mineral consumption was less than 100 million tonnes, but by the year 2000 it had increased to more than 3,3 billon tonnes (Casper, 2007: 48; Kesler & Adam, 2015: 1).

Table 1.1 Kilograms of mineral commodity used per capita in the US for the years 1776 and 2005 (Mineral Information Institute, 2005: 44; Casper, 2007: 47)

Commodity used	**Quantity$_{1776}$**	**Quantity$_{2005}$**	**(Q_{2005}/Q_{1776})-fold increase**
Aluminium (bauxite)	0	36	∞
Cement	5	410	32
Clay	45	132	3
Coal	18	3 361	187
Copper	0,5	9	18
Iron ore	9	200	22
Lead	0,9	5	6
Phosphate	0	148	∞
Potash	0,5	20	40
Salt	2	184	138
Sand, gravel & stone	454	9 816	22
Sulphur	0,5	42	84
Zinc	0,2	5	25

According to the International Council on Mining and Metals (ICMM) the demand for metals increases particularly fast once the per capita income of a developing country reaches the level of $5 000 to $10 000 per year (ICMM, 2012: 3). During the 20th century global population almost quadrupled, GDP increased about 18 times and GDP per capita about 4,6 times. In the early 21st century the rapid development of China had a big impact on the demand for minerals and contributed towards the so-called minerals supercycle. (See *commodity supercycle* in Annexure A). The global metal and industrial minerals industry increased in value from USD214 billion in the year 2000 to USD644 billion by 2010 during a time when China experienced high annual growth rates (ICMM, 2012: 5). It is this increase in non-renewable resource growth that got many people worried about its sustainability.

Tilton (2003: 1) described the situation as follows: "Humankind has consumed more aluminium, copper, iron and steel, phosphate rock, diamonds, sulphur, coal, oil, natural gas, and even sand and gravel during the past century than all earlier centuries together … today the world annually produces and consumes nearly all mineral commodities at record rates … The sharp rise in mineral consumption and production has, understandably, raised concerns about the long-run availability of mineral commodities." One of the consequences of the limited availability of non-renewable resources is that many people would expect economic growth to be impacted upon sooner or later. This was emphasised by the alarmist publication, *Limits to growth,* in the 1970s.

In contrast to the pessimists, there are many economists who are not particularly concerned about the long-term availability of mineral resources. Neoclassical economic growth models, for example the Cobb-Douglas and Harrod-Domar models, consider natural resources as less important than the other factors of production. According to Galbraith (2019) "Postwar neoclassical growth theories deliberately ignored resource and environmental limits, disparaged and disdained ecologists, and promised what was effectively impossible: perpetual growth fuelled by unlimited resources, the free disposal of wastes, and never-ending technological progress." The debate between the optimists and pessimists regarding the long-term availability of minerals is at the centre of mineral economics as an academic field. Dasgupta and Heal (1979: 3) describe two divergent views of researchers on the "availability" topic as follows: "Partly in response to this apocalyptic vision is the other reaction to the exhaustible resource problem. This is that there is really no problem." So, why are some economists not concerned about the scarcity problem? One reason is that they trust in markets and the price mechanism. They argue that the prices of resources will rise as they become scarcer. This will incentivise entrepreneurs to search for cheaper substitutes and at the same time serve as a demand rationing mechanism. Thus the new market equilibrium will reflect both an increase in supply and a decrease in demand. According to Maurice and Smithson (1984: xii, xiii), the reaction by producers to higher prices has solved various resource crises over thousands of years. One case in point was the American natural rubber crisis of 1942 when the Japanese captured a large part of the world's supply of natural rubber. Soon thereafter the US replaced natural rubber with synthetic rubber. Milton Friedman (1978: 3) said something similar about the American reaction to the high oil prices in the 1970s: "What we need is an adjustment mechanism that will enable us to adapt to what happens as it develops. And of course, as everybody in this room knows, there is such a system, namely the price mechanism, which successfully steered us over several centuries from wood to coal to whale oil to petroleum to natural gas." Dasgupta and Heal (1979: 3) consider such reliance on markets to solve scarcity problems as overly simplistic. The environmental availability of extractive resources has become a major issue and *Ecological Economics* challenges the neoclassical *paradigm* in many ways.

Tilton (2001: vi) states that, simplistically, the debate is between the pessimists who believe that mineral resources will be depleted and the optimists who believe that humans will, through their creativity, find solutions to the problem. Both Milton Friedman and Herbert Simon, another well-known Nobel laureate, fall into the camp of optimists, while Malthus and Mill fall into the camp of pessimists. Advocates of *weak sustainability* such as John Hartwick (1977: 972) and Robert Solow (1974: 11) argue that ("reproducible") capital ("such as machines") and ("exhaustible") natural resources are substitutes and can therefore be put in the camp of the optimists. In contrast, advocates of *strong sustainability* such as Daly (1997: 261) can be put into the camp of pessimists because they call for the maintenance of natural resources. In his paper, "The economics of resources or the resources of economics", Solow (1974: 11) states: "If it is very easy to substitute other factors for natural resources, then there is in principle no problem. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe." Daly (1997: 261) severely criticises Solow in no uncertain terms as follows: "… natural resources and capital are generally not substitutes but complements … The issue is not substitution between two types of natural resource, rather it is one of substitution of capital for resources, an entirely different matter … Solow's recipe calls for making a cake with only the cook and his kitchen. We do not need flour, eggs, sugar, etc. nor electricity or natural gas, nor even firewood. If we want a bigger cake, the cook simply stirs faster in a bigger bowl and cooks the empty bowl in a bigger oven that somehow heats itself." A number of developments have taken place since. They are discussed in Chapter 4.

Table 1.2. Concerns regarding the availability of specific mineral commodities – a few examples.

Mineral commodity	**Authors**	**Comments**
Cobalt	Hagelüken (2017: 8, 10) Köllner (2018: 25)	It is foreseen that battery electric vehicles (BEVs) may be rapidly adopted resulting in great demand for mineral commodities used in the manufacture of batteries. The diffusion of BEVs could be accelerated by governments in an attempt to combat climate change. Supply is

	Nishiyama & Fujii (1998: 281) Olivetti et al (2017: 229)	concentrated in the DRC, a politically unstable country. Cobalt is obtained mainly as a by-product. Hagelüken (2017) predicts a possible bottleneck in 2030.
Dyspro-sium and other REEs	Campbell (2014) Kooroshy et al (2010) Martin (2010) McLellan et al (2013) Vateva, A., 2012	Dysprosium, like many of the other *rare earth elements* (REEs), is not actually rare geologically, but structurally scarce because China produces the vast majority of such elements. Dysprosium is therefore considered a *critical mineral* by some governments.
Oil	Campbell & Laherrére (1998) Deffeyes (2001) Hubbert (1969)	The availability of oil was a big concern in the past, especially for the U.S. as it became more dependent on imports in the 1970s. Concerns about *peak oil* have declined to some extent during the last number of years as potential viable substitutes for conventional vehicles are emerging, energy generated by photovoltaic cells and wind turbines is becoming more price competitive and because of the commercialisation of *hydraulic fracturing*.

The resource-optimists assume that higher prices would only be a relatively short-term phenomenon from which the economy will recover, although it may send shocks through the global economic system such as in the case of the oil price shocks of the 1970s. Recently, Waughray from the World Economic Forum (2014: 4) stated the following: “Three billion middle-class consumers are expected to enter the global market by 2030, driving unprecedented demand for goods and services. Commodity prices overall rose by almost 150% from 2002 to 2010, erasing the real price declines of the last 100 years. Experts have calculated that without a rethink of how we use materials in our linear ‘take-make-dispose’ economy, elements such as gold, silver, indium, iridium, tungsten and many other vital for industry could be depleted within five to fifty years.” This statement shows that some people do not trust the market’s price mechanism.

So, who is correct, the optimists or the pessimists? Is there a clear answer yet on how long minerals in the earth's crust will last? And how can the differences in opinion be explained? Over the last few decades a vast amount of literature has been published which is not only interesting to study from a historical perspective, but which is also essential to master before a person can contribute to this body of knowledge (BOK) or use it to formulate policies.

In this section it has been illustrated that great uncertainty still exists about the future availability of non-renewable resources and that a debate indeed exists between different researchers regarding the topic. A topic where such a gap in views and understanding exists between experts must certainly be worthwhile studying, as it points to an incomplete body of knowledge.

1.6 MINERAL ECONOMICS

Concerns, questions and debates about the availability of mineral commodities led to the development of mineral economics as an academic discipline after World War II. It is defined by Gordon and Tilton (2008: 4) as follows: "Mineral economics is the academic discipline that conducts research and education on economic and policy issues associated with the discovery, extraction, processing, use, recycling and disposal of mineral commodities." This multidisciplinary discipline applies economic theory to physical goods whose (geological) availability draws on knowledge generated in other academic disciplines such as Economic Geology and whose uses are researched in disciplines such as Materials Science. It is therefore a discipline that various professionals contributed towards over the years. Tilton (1996: 94) ascribes the various and sometimes opposing views regarding the long-term availability of non-renewable resources to the contributions made by economists, engineers, geologists, metallurgists, industrial ecologists and others with different approaches and views.

Although Mineral Economics is only a few decades old it will be shown that concerns about the long-term availability of mineral commodities, and other natural resources, go back much further in time.

Tahvonen (2000: 1), for example, provides a brief historical overview of the debate in a paper whose objective it is to describe how thinking about the scarcity of natural resources has evolved during the last century. As alluded to by Tahvonen, the debate has evolved considerably and a number of manifestations of it are discussed in the literature. One manifestation is the debate on scarcity and economic growth. This debate is in essence about the question of how long natural resources will be available to support future economic growth. The topic of sustainable development is linked to it because of the belief by many people that economic growth will become unsustainable because sooner or later it may be stopped by the finite supplies of resources or the capacity of the ecosystem to absorb harmful pollutants or the loss of biodiversity (Beckerman, 1999: 622).

Knowledge used in Mineral Economics often overlaps with other areas within Economics. For example, the economics of waste disposal also forms part of Environmental and Ecological Economics. (Such waste is generated during extraction processes as well as from non-recycled mineral commodities and burnt gas, oil and coal.) Mineral Economics shares a lot of common ground with Natural Resource Economics because minerals, although non-renewable, are natural resources. The multi-disciplinary nature of Mineral Economics is described by Gordon and Tilton (2008: 5) as follows:

"Mineral economics borrows freely from many, more traditional disciplines, including economics, geology, mining and petroleum engineering, mineral processing, fuel science and technology, and metallurgy."

Contributions as far back as that of Malthus, one of the so-called Classical Economists, illustrate why the question about the availability of resources in the long run is multi-disciplinary in nature. The demand for resources originates from people, their needs, their way of living and their numbers. Malthus focused not only on the demand side of natural resources, however, but also on the supply thereof by pointing to the limitations there are to the production of food by means of limited agricultural land. The production of goods from limited natural resources involves many disciplines, from those studying the earth's crust to various technologies involved in the production process and the affordability thereof. Cassel (1932/1967: 4) thinks economics is at the heart of it all because economics is governed by the principle of scarcity.

Some consider Hotelling to be the father of mineral economics because of his 1930s paper, "The economics of exhaustible resources", which attracted much attention decades later after the oil price shocks of the 1970s. Hotelling predicted increased future non-renewable prices because of his view of a limited, fixed stock of "exhaustible resources" (Hotelling, 1931: 137, 141, 143), their depletion over time and increased future scarcity. The Hotelling rule basically states that under free competition a future non-renewable resource commodity price, p_t would equal the current price, p_0, times a time appreciating number calculated as the base of the natural logarithm to the power of the interest rate, γ (also known as a discount factor when a future value is discounted, for example, to the present), times the time period, t, between the current date and future date at which the price is determined ($p = p_0e^{\gamma t}$, where e is approximately 2,71828). Contrary to this rule, constant to declining (real) price trends (discussed in more detail later) were observed for a number of mineral commodities before 2002. Some of these price trends were to some extent reversed after 2002. These are some of the phenomena that are addressed in this study as indicated by the questions that follow in section 1.7. Hotelling's contribution to the "availability of non-renewable resources" body of knowledge is discussed in Chapter 2.

1.7 PROBLEM STATEMENT, RESEARCH QUESTIONS AND OBJECTIVES

The intention of this research project is to establish how the nature of the body of knowledge regarding the availability of non-renewable resources in the long run has changed over time. In the process, a suitable framework for analysing the "availability" body of knowledge will be developed and the central and universal facts will be determined which should form the basis for greater understanding and future research. An assessment will also be made about whether it is possible to tell from existing knowledge and theory how long various types of non-renewable resources will last. This can be more specifically formulated in the following three main research questions:

<u>Main research question 1</u>: How did the body of knowledge related to the scarcity and availability of non-renewable resources evolve?

<u>Sub-questions</u>

Does the availability of minerals in the short run differ from the long run?

Why did the debate start and how did it evolve from there? What progress has been made over the years?

What are the main ideas that came to the fore over time?

Why are there differences of opinion between different researchers or groups of researchers? How can the differences be explained?

What are the central and universal facts that should be considered when constructing a theory of or model about this body of knowledge? Which views and contributions have withstood the test of time?

<u>Main research question 2</u>: Is it possible to establish from existing knowledge and theory how long non-renewable resources will still be available to support humanity's needs?

<u>Sub-questions</u>

Do real price trends have predictive value?

Why did real price trends before 2002 not indicate increased scarcity as predicted by Hotelling despite decade-long increases in the demand for most mineral commodities? Why is *Hotelling's rule* not working as expected?

Which mitigating factors counter the increased demand for non-renewable resources?

Does the international system of markets and the price system satisfactorily solve the problem of scarcity and sustainability of resources in the long run?

Is international government cooperation and intervention necessary to change market outcomes in this regard?

Which uncertainties and imperfect information makes predictions regarding the future availability of non-renewable resources difficult?

<u>Main research question 3</u>: What questions should future research address?

What likely scope exists to push the boundaries of research?

Four main objectives are focused on during this study. The first objective is to do a thorough literature survey of the evolution and current status of the debate so that at least an overview of the main developments and themes can be provided. A second objective is to appropriately classify and structure information so that greater understanding can be obtained from the vast number of relevant publications. Such a structure will help upcoming researchers to see the big picture and where individual events fit into the broader context. It will help the reader to identify a research programme for research that may contribute towards new knowledge in this field of study. A last objective is to assess the status of whether non-renewable resources is used in a sustainable way or not and the policies required to improve such sustainability.

1.8 RESEARCH METHODOLOGY

According to Blanchard "Macroeconomics is not an exact science but an applied one where ideas, theories and models are constantly evaluated against the facts, and often modified or rejected … Macroeconomics is thus the result of a sustained process of construction, of an interaction between ideas and events. What macroeconomists believe today is the result of an evolutionary process in which they have eliminated those ideas that failed and kept those that appear to explain reality well" (Snowdon & Vane: 5). Much of what Blanchard said applies to the approach followed in this study, where the ideas, theories, models and thoughts of various contributors are studied.

Some of the central and universal facts that will be distilled from the study include so-called *stylised facts* which are defined in the glossary of terminology. Another reason for identifying the correct facts that should shape thinking and be used in models is because Hotelling's model for exhaustible resources has been criticised for not using the correct ones (Cairns, 1994: 778).

The literature survey is an important research method used in this study. Some sources of information call this a library-based or theoretical study. A source on the website of the University of Birmingham (http://www.socscidiss.bham.ac.uk/methodologies.html) explains the nature of such a study as follows: "While all dissertations will include a literature review, it is possible to produce a dissertation that is entirely based on a review of the literature. If you do this, it is important to review the literature from an explicit angle and identify some themes to make the review distinctive." The title, research questions and objectives of this research project indicate the angle from which literature is engaged and relevant sections are identified and analysed. In their paper, "Scholars before researchers". Boote and Beile (2005: 3) state that "a thorough, sophisticated literature review is the foundation and inspiration for substantial, useful research". A fairly extensive literature survey has, therefore, been done to make sense of a complex, sometimes messy and vast body of knowledge that includes seemingly conflicting views.

A three-legged research strategy was followed. The first leg of the strategy was to study the context and history of the problem – how it changed and evolved over time. This approach is in line with that of Hirai (2005: 453), who states that "to understand an author's thought in its philosophical and historical context, it is very important to trace the sources on which he founded his ideas". Chapter 2, where contributions made by the various classical economists and others such as Hotelling are briefly captured, is the result of this first leg of the research strategy, and provides important context.

The second leg of the strategy was to focus on themes because that helps scholars and researchers to deal with vast bodies of knowledge by means of classification and specialisation. In this study a similar approach has been followed by classifying the literature into themes after relevant works were analysed and the findings synthesised. The main macro or overarching themes identified from the literature study are firstly, the evolution of, or history of the body of knowledge (Chapter 2), secondly, the identification of information from which the core facts of the availability body of knowledge can be distilled (Chapters 3 and 5), thirdly, the various solutions that humanity developed over time to mitigate non-renewable resource scarcity problems (Chapter 4) and fourthly, *indicators* that have been developed to measure non-renewable resource availability (Chapter 4).

A critical view is taken of Hotelling's contribution, discussed in Chapter 2, and that of some of his followers. This is done by identifying numerous core facts not addressed by Hotelling. Various links are made between bits of information not previously associated with this body of knowledge.

Many definitions for concepts used in this dissertation, indicated by italics, can be looked up in Annexure A.

1.9 BACKGROUND INFORMATION

1.9.1 A note about non-renewable resources and their classification

The physical quantities of different types of minerals and elements in the crust, the oceans or elsewhere on earth available for exploitation are finite. Orebodies and reservoirs where higher quality concentrations of mineral and non-renewable energy resources occur are even more limited and can be depleted through exploitation. These are not renewed or replenished within a human-centric time scale. In the case of non-renewable energy resources such as coal, oil and gas, they are burned and their ability to do useful work thereafter is lost. Unlike metals, such resources cannot be recycled. If recycled, the lives of recyclable raw materials could be longer than the lives of the products, capital goods or other assets in which they are currently assimilated. Non-renewable resources exist as *stocks* and can be differentiated from *flow resources* such as wind and sunlight. In the case of stock resources, their current use may affect future availability, especially if no recycling takes place. Future availability may therefore depend on *intertemporal choice* and optimisation and linked to the concept of sustainable development.

From an availability perspective, it is probably best to divide non-renewable resources into four groups, namely the energy minerals (e.g. coal, natural gas, oil and uranium), the metallic minerals (e.g. copper, iron, nickel and aluminium), elements and substances required for modern food production (e.g. nitrogen, potash and potassium) and the non-metallic materials which are also known as industrial minerals and rocks. This category includes building materials such as sand, stone and lime used to produce cement.

1.9.2 Renewable and non-renewable energy sources

Figure 1.6 illustrates how reliant humanity was on wood, a renewable energy source, in the 1850s. Coal, a substance with a higher energy content, became more important than wood and was the main energy source for steam engines. Steamships largely replaced sailing ships and caused a shift towards non-renewable energy during the (first) Industrial Revolution. Large supplies of cheap coal were initially available in the UK. Coal is today still an abundant form of energy in countries such as Australia, South Africa and the U.S., and plays an important role in the energy mixes of certain countries. It is a relative cheap form of energy if externalities are excluded. Since the (first) Industrial Revolution, when coal dominated in countries such as England and the U.S., a diversification of energy supply towards the other fossil fuels such as oil and gas has taken place.

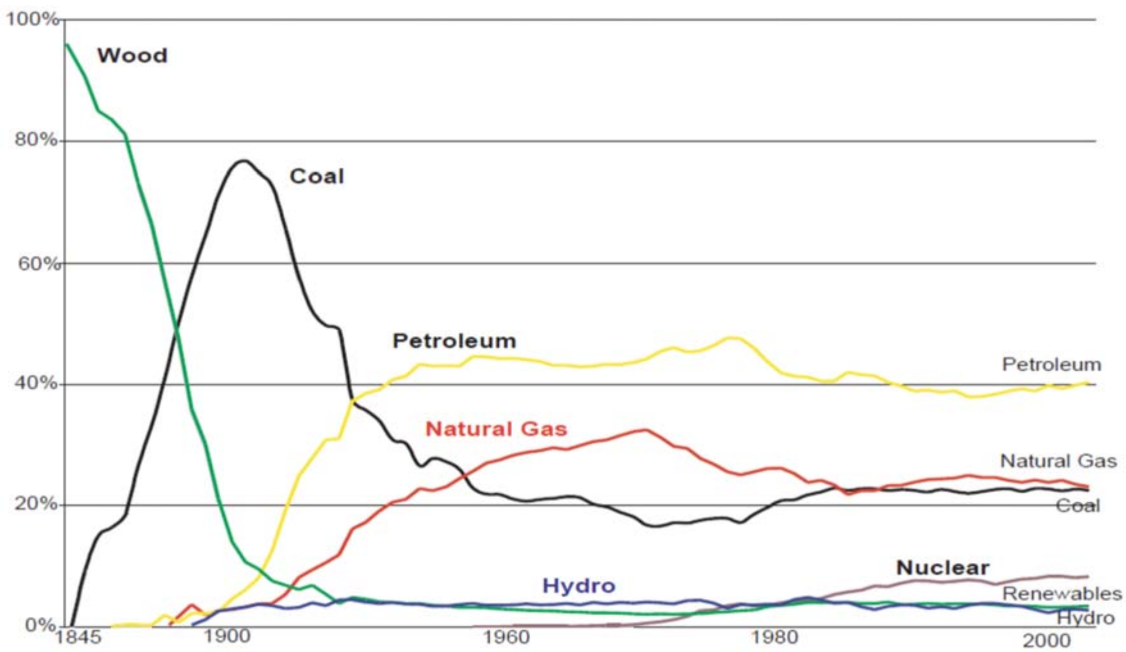


Figure 1.6. Global energy mix, diversification and substitution over time – In 1949 the "Wood" line concerts to include all renewable fuels except hydro power (Mineral Information Institute, 2005: 7)

Henry Ford's success with the mass production of affordable cars and trucks resulted in oil-dependent economies, especially that of the U.S. For a few decades, oil availability and security has been a major area of study, especially after the formation of OPEC, the two oil price shocks in the 1970s and the peaking of U.S. oil production in 1971 as predicted by *Hubbert*. Thereafter the U.S. became more and more dependent on oil imports. As a consequence the security of trade routes from the Persian Gulf to the U.S. became of vital importance, and in his 1980 State of the Union Address President Carter declared that the country would defend shipping routes. The Carter Doctrine illustrated the vulnerability of the U.S. economy to a cut-off of oil imports at the time (Butts, 1993: 3). A number of U.S. presidents after President Carter expressed their desire for the U.S. to regain its energy independence. Today the Strait of Hormuz and the South China Sea are congested and important parts of oil trade routes.

After a number of decades of improvement, *hydraulic fracturing* ("fracking") solved the United States' oil import dependency problem. The technology enables it to exploit its large shale oil and gas reserves. Figure 1.7 shows how fracking assisted the U.S. to "escape" from *peak oil* decades later – the declining production trend experienced after the peak for a number of years was broken. Such incidences where technological innovation resulted in the turn-around of mineral supply after peaking illustrates the importance of technology in mitigating scarcity.

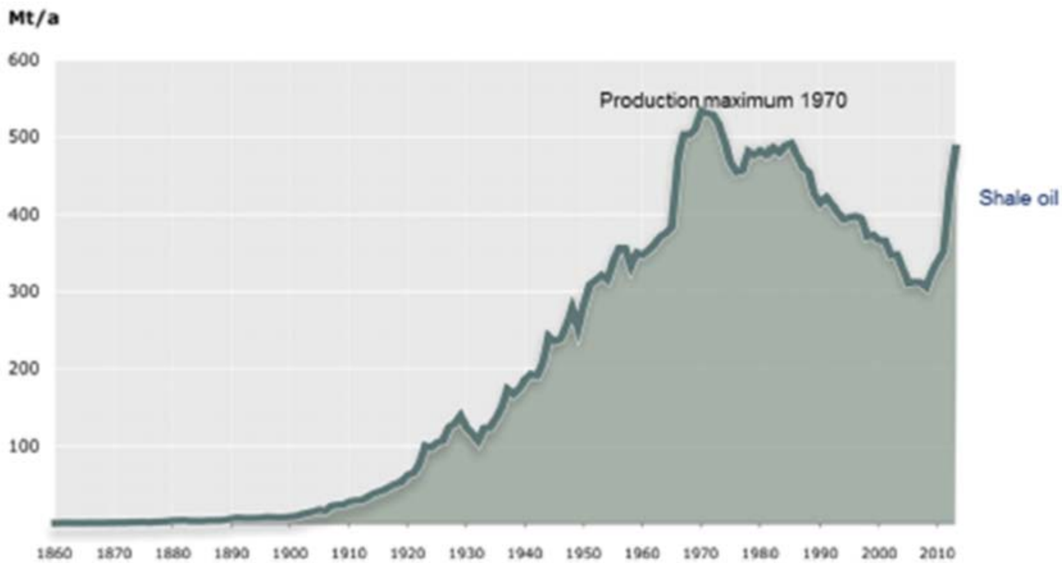


Figure 1.7. Oil production by the USA over time (Wellmer & Scholtz, 2017: 76)

The development of cost-effective electric vehicles, wind turbines and solar farms may dramatically reduce the future demand for fossil fuels. These technologies will be responsible for the decentralising and democratisation of energy and energy generation. A new availability concern is now replacing the old concerns regarding oil availability and dependency, namely that of the availability of metals required for the greener, low-carbon economy. This is discussed in more detail in Chapter 3 (Resourcing the low-carbon economy).

1.9.3 Non-metallic industrial minerals

Another category of minerals, the non-metallic minerals, are generally fairly abundant from a physical perspective and include building materials (e.g. sand, gravel, limestone and cement materials), chemical minerals (e.g. sulphur and salt), ceramics (e.g. clays and feldspar), abrasives (e.g. sandstone and industrial diamonds), insulants (e.g. asbestos and mica), pigments and fillers (e.g. clay, diatome and barite), refractories and fluxes (e.g. clay and magnesia), precious stones and gemstones (Rudawsky, 1986: 31). Industrial minerals such as sand and aggregate (building stone) that are used in huge quantities in the construction sector are generally abundant, of low value and usually have to be sourced locally because transportation cost can be a significant component of the cost of getting it to a specific site where it is needed (Smith, 1789: 246). Some of these, therefore, do not enter international trade. Some of the non-metallic raw materials, for example building materials, require little processing and therefore their impact on the environment per unit mined is generally less than that of metals that must be extracted from various types of ores.

1.9.4 Metals

The third category of minerals are the metallic minerals which are extracted and processed to produce various metals. These elements can be combined to form alloys such as steel, which is extremely important in a modern economy. Iron, manganese, chromium, nickel, molybdenum, cobalt, vanadium, copper, lead, zinc, tin, aluminium, magnesium, titanium, gold, silver and platinum are all metals. One of their characteristics is that they have to be extracted from various types of mineral ores, for example bauxite (aluminium bearing mineral ore), galena (lead sulphide) and hematite (iron oxide). This can at times be energy and water intensive and may require a lot of chemicals, especially in the case of the *rare earth elements* (REEs). Furthermore, these minerals are often in low concentrations present in the mined ore. Gold, for example, often occurs in relatively low concentrations, usually less than 10 grams per tonne – Harmony, a gold mining company mine at an average *grade* of between 5 to 5,6 g/t. This means that a lot of waste material is generated in the extraction process, which affects the environmental and social availability of such metals. Unlike industrial materials, which are often used after little processing, metal ores are often beneficiated until a fairly pure metal is obtained. One positive aspect of metals from an availability perspective is that, in contrast to fossil fuels, they are more durable and can be sourced from both primary (mining) and secondary production, for example recycled consumer goods that have reached the end of their useful lives. The percentage recycling of goods varies widely and depends on a number of factors such as economics and the availability of recycling channels. The recycling of platinum (Standard Bank, 2003: 19-25) used in auto-catalysts is, for example, profitable and a high percentage of lead used in lead-acid batteries is recycled because vehicle owners are able to hand in old batteries when they are replaced. Gordon et al (2006: 1209) refer to three types of metal repositories (or stocks), namely those in: 1) the *lithosphere* (that can potentially be mined), 2) use in products providing services (stock-in-use), 3) waste deposits. Table 1.3 illustrates this more comprehensively. Metals in structures and infrastructure such as pipes, railway lines, bridges and buildings may be locked up for decades before there is an opportunity for the potential recycling thereof.

Table 1.3 Types of metal repositories (or stocks)

Metal in the lithosphere	**Metal in waste deposits**	**Metal in structures and infrastructure that provide certain services**
This is metal that is present in the earth's crust and the upper part of the mantle and that could potentially be mined.	Metal in landfills and in scrapyards where old products have been dumped. Includes e-waste.	Examples: steel in railway lines; copper in electricity transmission and distribution lines; zinc in roof plates; steel in reinforced concrete structures.

Recycling and the *circular economy* are discussed in Chapter 4.

1.9.5 Elements needed for food production

The elements required in modern agriculture and food production are not mutually exclusive to those in the previous three categories. Elements such as Ca, N, K and P are required in large amounts while at least 13 trace elements such as F, Si, V, Cr, Mn, Fe, Co, Cu, Zn, Se, Mo, Sn and Iodine (I) are needed in smaller quantities. There are no substitutes for elements that are required to sustain life. Fortunately, most of them are abundant. Three of these elements, K, N & P, are used in fertilisers. They are obtained from non-renewable resources such as potash and phosphate rock. There are some concerns about the future availability of phosphorous, and a number of studies have been done to estimate its future availability (Goeller & Weinberg, 1976: 684; Wellmer & Scholtz, 2017).

1.10 LITERATURE SURVEY

A number of publications are directly related to this study. Books by Barbier (1989), Barnett & Morse (1963), Dasgupta & Heal (1979), Robinson (1989), Smith (1979) and Tilton, book chapters by Tilton and Guzmán (2016: 205-228) and journal articles by Devarajan & Fisher (1981), Hotelling (1931), Jayasuriya (2015), Neumayer (2000) and Solow (1974) serve as examples. General books on Mineral Economics, Natural Resource Economics and Environmental Economics usually include a chapter or sections that deal with the availability of mineral commodities and other non-renewable resources and are, therefore, also easily identifiable. Journals such as *Resources Policy* and *Mineral Economics* often include relevant articles. Certain relevant literature is less easily identifiable and may appear in a variety of publications as indicated in the list of references. This is probably because of the diversity of contributors and themes related to the availability of non-renewable resources.

1.11 SIGNIFICANCE OF THE STUDY

Sustainable development is a major field of study and research nowadays. The 17 United Nations Sustainable Development Goals for the period 2015 to 2030 have become organising and guidance principles for governments and even other types of organisations. Non-renewable resources are very important for modern society and questions about their availability in the long run, therefore, form part of the sustainable development research programme. This study provides an overview of how thinking about the availability of non-renewable resources has evolved over time so that the latest concerns can be understood in that context. The study provides an appropriate framework and distils the central facts related to this body of knowledge.

For reasons such as sustainability and security of supply, governments and companies have questions about the future availability of non-renewable resources from time to time. One such example is the U.S. National Defense Authorization Act of 2010 which instructs the Government Accountability Office to submit a report on *rare earth* materials in the U.S. Department of Defense supply chain. Shifts in materials demand patterns may occur with the broad adoption of new technological innovations. At times when technological innovations such as battery electric vehicles, fuel cell electric vehicles and the hydrogen economy have the potential to become strong demand drivers for raw materials used in such value chains, questions are usually raised about the availability of such materials (Nel, 2004: 302). Lithium, cobalt, graphite, vanadium, manganese and nickel are used in the manufacture of the newer types of batteries (INN, 2020: 4, 22, 39, 47, 52; Olivetti et al, 2017: 232).

The document should be useful to academics and researchers tasked from time to time to generate information on the future availability of non-renewable resources. Paul Donnovan, a senior economist at UBS, said in 2017 that it was critical to overcome the ongoing *environmental credit crunch,* which is not a “mythical future scenario that academics write papers about” (Udasin, 2017).

1.12 SCOPE AND DELIMITATION

The focus of this study is on mineral resources, mineral commodities and all other non-renewable (secondary) resources at a macro level. The detailed analysis of a specific mineral commodity is avoided by emphasising macro trends and developments over relatively long periods of time even though non-renewable resources such as fossil fuels, especially oil and OPEC's involvement, have a huge history. Both historic as well as more recent, ongoing, developments such as the decarbonisation of the global economy are dealt with. The availability of non-renewable resources is multi-dimensional. This study focuses on the economic availability of non-renewable resources within a framework that also provides for the other *dimensions of availability*.

1.13 THE WAY FORWARD

A historic perspective is provided in the next chapter on the evolution of thinking regarding the availability of non-renewable resources. Starting with some of the earliest recorded concerns and thinking about the availability of renewable resources, Chapter 2 then progresses to also cover contributions by the Classical Economists. The Industrial Revolution and the development of the "New World" (North America) and its oil addiction later on contributed greatly to the availability body of knowledge. Hotelling's famous 1930s paper influenced thinking in the second part of the 1900s while events such as the oil price shocks of the 1970s also hugely influenced the thinking of economists and others. Chapter 2 provides essential background information for what follows in Chapters 3, 4 and 5. In these chapters reference is made numerous times to content provided in Chapter 2. The diversity of opinions found in this chapter shows why there is such great uncertainty about the future availability of non-renewable resources and why it is a worthwhile research topic.

Chapter 3 provides important information and evidence that supports the core facts of the availability body of knowledge proposed in Chapter 5. It illustrates, for example, how the supply and demand of minerals diversified and shifted away from the Western World which is dealt with in Chapter 2. It provides evidence that mineral commodities are not equally scarce or abundant, that the quality of ore resources differs and that the average *grade* of ore bodies mined is declining. This has important implications, of which some are discussed in Chapter 3 and elsewhere. Mineral trade, trade restrictions and their impact on theory related to *resource nationalism* and critical minerals are also dealt with in Chapter 3. Whereas neoclassical economics focuses on the firm as a supplier of goods, the role of artisanal mining is pointed out and its important contribution to the supply of a number of mineral commodities. One of the currently developing trends, namely that of resourcing the low-carbon economy, is one of the latest developments in the body of knowledge on the availability of non-renewable resources.

A number of means exist to mitigate resource scarcity. These are discussed in the first part of Chapter 4 and it is illustrated why these should form part of the framework (proposed in Chapter 5) used to analyse the current and future availability of non-renewable resources. The second part of Chapter 4 focuses on *indicators* of availability. It is argued that no perfect single future-looking *indicator* exists, a major contributor towards the uncertainty regarding the future availability of non-renewable resources. In the last part of the chapter various strategies and policies used by firms and governments to ensure raw material availability are discussed.

Chapter 5, the last chapter, draws upon all the information and evidence provided in the previous chapters to provide two main outcomes. Firstly to propose a framework that can be used when the future availability of non-renewable resources is analysed and secondly to distil a number of core facts that can be used in theory and model building. These point to the fact that Hotelling's models were overly simplistic.

CHAPTER 2 – EARLY THINKING ABOUT THE AVAILABILITY OF NON-RENEWABLE RESOURCES

2.1 INTRODUCTION

This chapter gives a historical perspective on the evolution of thought related to the availability of non-renewable natural resources, especially in the long run. The chapter starts by tracing the very first (non-renewable) resource scarcity problems mentioned in the literature and then follows various developments, mainly chronologically, thereafter. Relevant events (e.g. the Industrial Revolution), institutions (e.g. Conservation Movement) as well as ideas, theories and models by thought leaders such as Ricardo, Jevons, Mills, Cassel, Meadows and Hotelling are discussed briefly. In broad terms, the chapter is chronologically divided into the following three periods: Firstly, "The time of the Alchemists" which ends before the Industrial Revolution; Secondly, the era of the Industrial Revolution; and, thirdly "Scarcity in the 'New World' and the era thereafter. The chapter illustrates not only how thinking about the research topic progressed over time but also that there is more than one view on and interpretation of various issues.

2.2 THE TIME OF THE ALCHEMISTS (from pre-history to about 1735)

At Sterkfontein and Kromdraai in South Africa evidence was found of the earliest use of minerals in the form of stone tools by pre-humans, Homo Habilis, about 1,7 to 2 million years ago (Jourdan et al, 2012: 14). Homo Habilis probably had no knowledge of mineral commodities such as copper, tin and iron. The Bronze and Iron Ages were to follow much later in the development of humanity. The use of copper can be traced back as far as 9 000 B.C., which is relatively recent on a time scale that has to accommodate Homo Habilis. During the Stone Age, humanity developed tools from materials on the earth's crust that were very abundant compared to many of the metals used today.

The way in which humankind dealt with limited natural resources goes at least as far back as 10 000 to 6 000 BC when food shortage had to be solved because of the increased human population of about 10 million. This was solved by two means, an intensified migratory lifestyle after new sources of game by some, and the settling in one place by others through the domestication of animals and the cultivation of plants – the Agricultural Revolution (Common, 1995: 63; Mebratu, 1998: 494, 495). Over time more advanced agriculture developed, more complex divisions of labour and new tools to delve and shape the earth allowed the global population to increase to about 800 million by 1750 (Mebratu, 1998: 495). As humanity discovered more mineral commodities and ways of using it, various products were manufactured from them. Trade in mineral commodities and goods manufactured from them increased.

Another mineral resource scarcity problem was solved circa 1000 BC when the trade routes of ancient Greece were interrupted – the Greeks were cut off from tin, an ingredient of bronze. This caused tin and bronze to become more expensive than iron in Greece, and the Greeks switched to iron as a working metal, thus contributing to the transition from the Bronze to the Iron Age (Maurice and Smithson, 1984: xiii, 102 - 104). This incident is one of the earliest known examples of the use of metal substitutes and can be classified as a regional rather than a global non-renewable resources scarcity problem. It points to a core fact related to the topic of this study, namely that orebodies of the different types of mineral commodities are not homogenously diffused across mining jurisdictions. These core facts are summarised in Chapter 5.

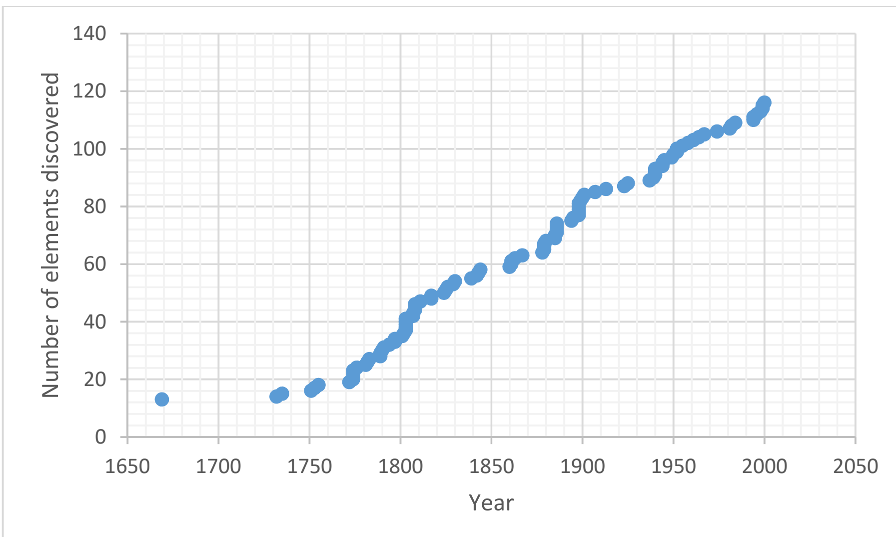


Figure 2.1. The number of elements discovered over time. Sources: https://www.lenntech.com/periodic-chart-elements/discovery-year.htm#ixzz4vwfPuEyF ; http://chemistry.about.com/od/elementfacts/a/timeline-element-discovery.htm

As humanity learned how to differentiate between different types of soil and rock and their building blocks, the chemical elements, it started to learn more about the different and sometimes unique properties of elements, compounds and minerals such as gold, silver, haematite (iron oxide) and copper. Occasionally, metals from outside "*spaceship earth*" entered this semi-closed system in the form of meteorites which were a source of humanity's first iron before it discovered how to extract iron from iron oxide ore. This explains why various ancient civilisations valued iron to be of equal or greater value than gold. Today we know that iron is actually relatively abundant in the earth's crust, with ore typically containing as much as 65% iron oxide, and its price is relatively low in an era where the technology exists to separate it from iron oxide. Figure 2.1 illustrates that the chemical elements known to the ancient world were limited. The bulk of the elements were discovered only after 1735, an era that can be linked to the beginning of chemistry as a modern science. By 1900 the Periodic Table of chemical elements, of which approximately 75% are metals, was essentially complete. Many of the elements were considered laboratory curiosities for quite a while after they were discovered. Metals such as titanium, niobium, molybdenum and zirconium have been used commercially for only the past fifty years. Today humanity uses at least eighty different types of the elements, of which the majority are metals (Starke, 2002: 35).

The era before the emergence of modern chemistry can be described as the "Time of the Alchemists" because Alchemy was the precursor to modern day chemistry. Alchemists believed in transmutation and tried to discover a means of turning base metals such as lead into gold. According to Lange, the work of Robert Boyle in the last part of the 17th century and that of Joseph Black, Joseph Priestly, Henry Cavendish and Antoine Lavoisier in the 18th century contributed towards the evolution of alchemy to what is today known as chemistry (Lange, 1966: 92). Founders of modern scientific methods, Robert Boyle and Sir Isaac Newton, were both practising alchemists, which supports the notion that the lines between alchemy and chemistry are blurred. According to Lange (1966: 92), a small number of metallurgists denounced the practices of alchemists already in the 16th century. In his book, *De la Pirotechnia*, Vannoccio Biringuccio wrote that he did not observe any alchemists who became rich from practising alchemy (Lange, 1966: 92).

The "Alchemy Era" can be linked to the idea of an Alchemy *paradigm* in which some people may not have believed in ultimate physical limits or in the existence of non-renewable resources. For example, there was a fairly general belief that coal was inexhaustible at the time Williams (1789: 132) wrote his book, *The Natural History of the Mineral Kingdom*. One of the reasons for this is because the average citizen did not know at the time how coal deposits were formed. Williams (1789: 132) pointed out, however, that coal could not be inexhaustible because the matter from which it was formed was limited in quantity. The fact that minerals are limited in the earth's crust was not well understood until only a few hundred years ago and it seems that some people believed in their regrowth in the presence of air. The idea that mineral resources regrow as they are extracted was investigated by Robert Boyle. In 1674 he published "*Observations about the growth of metals in their ore exposed to the air*" in which he stated that proof existed for such regrowth. He referred to a number of cases, including that of a tin mine that was refilled in the course of time after it had been emptied by miners (Hirai & Yoshimoto, 2005: 454, 455). It is clear from Agricola's book, *De Re Metallica*, published in 1556 that he knew of this belief in the regrowth of minerals. Agricola, was sceptical of alchemists, and seems to have believed less in the regrowth of minerals than Boyle, although he did not rule it out completely in an era when little was known about the formation of ore bodies. He expressed his beliefs regarding this as follows: “For if they were generated in the air, a thing that rarely happens, …” (Agricola, 1556: XIII, XXVII, 12).

Lange (1966: 95) pointed out that alchemy and chemistry as a science persisted alongside each other, though a number of practical scholars and engineers in the field of metallurgy already doubted transmutation as early as the sixteenth century. With the transmutation of metals by chemical means and the regrowth of orebodies ruled out by modern day chemistry and geology, the idea that mineral ores are non-renewable established itself more widely. Today we know that mineral deposits and ores are non-renewable from a human-centric perspective and timeframe. An orebody cannot be renewed or a new one formed unless a geological time scale is a given.

According to Wennerlind (2003: 234, 235), the failure by alchemists to transmute other materials into gold may have led indirectly to the creation of credit or fiat money. Fiat money, which is a currency declared by a government as legal tender and not backed by a physical commodity, such as gold, is a substitute for such commodities and thus helps to mitigate resource scarcity.

2.3 THE ERA OF THE INDUSTRIAL REVOLUTION (From about 1750 to 1850)

2.3.1 The Industrial Revolution (1750 – 1850), economic growth, consumerism and non-renewable resource needs

The use of primitive materials started as far back as the Stone Age. Over time, other materials were discovered and technologies expanded. At first, such change was slow, but accelerated later on. The accumulation and acceleration of knowledge started to have a profound influence on economic growth and became visible in GDP statistics during the Industrial Revolution, illustrated in Figure 2.2. It was during this era that the gap in economic development, or divergence, started to take place between nations. Economic growth and prosperity characterize this era more than any other preceding era. It is also in this era that humanity became less reliant on renewable energy sources and their related technologies such as the sailing ship and water-wheel and increasingly made use of non-renewable, limited, high-*grade* (concentrated) energy sources such as coal with its associated technologies such as the steam engine. The volume of pig iron produced in England increased from 25 tons in 1720 to two million in 1860 (Revuelta, 2018: 12).

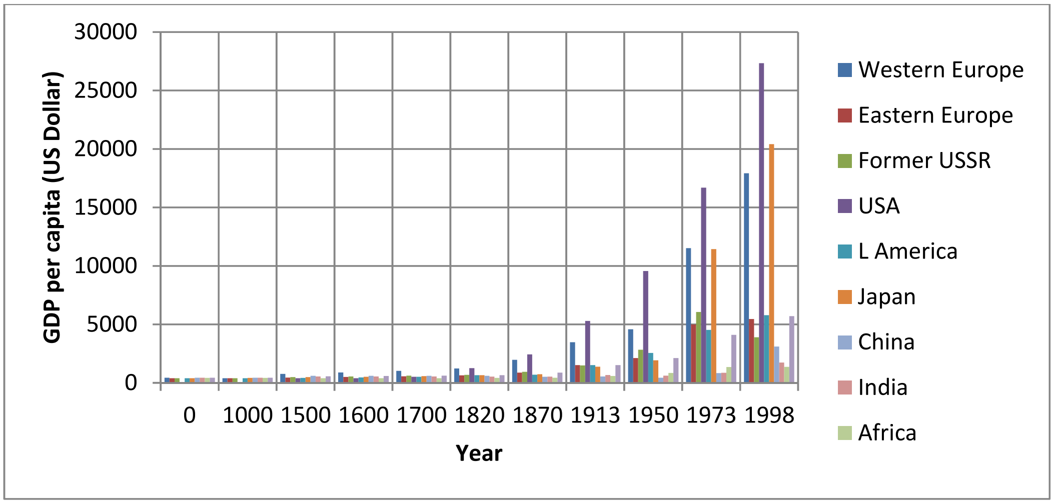


Figure 2.2. GDP per capita over time for a number of countries and regions. Data from Maddison (2006: 264)

The Industrial Revolution (IR) is linked not only to the start of large-scale use of non-renewable resources, but also to the emergence of concerns about their availability and the sustainability of ever-increasing consumption of such resources. The IR is linked not only to the divergence in the level of economic growth between countries but also to higher levels of population and an era characterised by the accelerated use of metals, coal, capital equipment, knowledge of technology, commerce and science, the expansion of human capital, increased productivity and growing consumerism. The quality of life in developed countries today is a direct result of this. Since the Industrial Revolution, the rate of technological innovation has steadily increased. If this marker event had not occurred, there would have been no developed and developing nations, and the subject of development economics would not have existed.

2.3.2 The doctrine of increasing natural resource scarcity

John Williams and a number of the so-called "British Classical Economists" were also concerned about the scarcity of resources. Christensen (1989: 18, 19) argues that "the tools for a reconstruction of a more ecologically based economics may be found in the older classical tradition" rather than the "modern theories". Many of the British economists published their work during the Industrial Revolution during which coal was a very important source of energy. Barnett and Morse (1963: 1, 2) associated the British classical economists with the doctrine that an inherently limited availability of natural resources sets an upper limit to economic growth and welfare and which will result in increasing scarcity. Barnett and Morse state that Malthus, Ricardo and Mill predicted that the scarcity of natural resources would eventually lead to diminishing social returns to economic effort and cessation of economic growth. At the time that the classical economists made their contributions, it had been known for thousands of years that the quality of agricultural land varies (see for example Matthew 13:8). Much later, Smith (1789: 133, 207, 232, 235, 1200) and Ricardo (1821: 2.5, 3.4) linked the amount of rent on land, used for both agriculture and mining, to its quality.

2.3.3 Adam Smith (1723 – 1790)

Smith's second book, *An Inquiry into the Nature and Causes of the Wealth of Nations*, records his views about laissez-faire, the division of labour and the economic laws of a competitive nation. Smith paid a lot of attention to mining although it contributed only about 11 % of the GDP of the Britsh Isles in 1770 (Robinson, 1989: 55). He also paid attention to one important demand driver for natural resources, namely population. Smith (1789: 116) had the following to say about population and subsistence before Malthus: "Every species of animals naturally multiplies to the means of their subsistence, and no species can ever multiply beyond it." Smith (1789: 232, 233) noticed that not all mine land was economically exploitable. Costs may exceed income, not only as a result of the quality of the coal (or orebody) but also because of accessibility to markets. Smith (1789: 290) knew that certain countries had a competitive advantage in the production of metals such as gold and silver, and that trade, therefore, played an important role in the global availability of such minerals.

2.3.4 De Condorcet (1743 – 1794) and Malthus (1766 – 1834)

Malthus made a significant contribution to thinking about "population economics". Population and population growth is one of the big demand-drivers for non-renewable resources today and one of the reasons why many people are concerned about the adequacy of minerals availability and production to meet the needs of a growing global population. Malthus believed that humanity could not continue on the population growth trajectory that it was on. He argued against the growth optimists of his time such as De Condorcet (1743-1794), who made the "idea of progress" a central concern of Enlightenment thought. Like Simon (1981), De Condorcet (1795) believed in human capital and was concerned about the small percentage of people who were adequately educated and developed. He argued that expanding knowledge in the sciences would lead to an ever more just world of individual freedom, material affluence and moral compassion. De Condorcet was concerned about various forms of inequality and the possibility that the human mind may be limited in its understanding of nature (de Condorcet, 1795: 11, 27, 45, 75, 101, 102, 106 107, 109; Tahvonen, 2000: 1).

As a curate in the Anglican Church at the parish of Oakwood, Malthus observed parishioners who stayed in low huts with dirt floors and lived almost entirely on bread. One of Malthus' duties was to record births and deaths at the parish. He was surprised to find that the number of births was higher than the number of deaths. It was probably this situation that led Malthus to write in the first edition of his essay on the "principle of population" the following "postulata": "The power of population is so superior to the power in the earth to produce subsistence for man, that premature death must in some shape or other visit the human race." Malthus continues to build on this postulate by saying that: "Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio" (Avery, 2007: 23; Malthus, 1798: I17, I18, I19 & VII.20, P.2, I.22, II.18). Malthus is widely regarded as the first economist to foresee the limits to growth due to resource scarcity (Mebratu, 1998: 498). The influence of Malthus is still visible today in the literature, for example, Paul Ehrlich's (1968) "*The Population Bomb*". Many people support some of Malthus's ideas, and measures to curb population have become public policy in countries such as China. According to Brue (2000:98), Malthus was accounting for the poverty and misery faced by the poorest of every nation, even today.

Fortunately, Malthus' predictions have proved to be incorrect. Population continued to grow. Cereal yields per hectare are still increasing and food prices have actually declined as a result of improved technology yields (Pindyck & Rubinfeld, 2013: 213). There is a large group of people today that label Malthus as too pessimistic and that criticise him for underestimating the role of innovation (Brue, 2000: 106). Many innovations that have led to more affordable food, new materials, energy, plumbing, sanitation, birth control and clean water have prevented hundreds of millions of people from the type of life that Malthus observed. Julian Simon (1981), an advocate of "human capital", considers humans as the ultimate resource, assuming that they are properly educated and skilled. In the context of numerous problems such as global climate change, it should not be assumed that current and future innovation will be sufficient to ensure quality of life for future generations. Millions of human beings still live in absolute poverty today, not only because of limited resources, but also the uneven distribution thereof.

2.3.5 John Williams (1729 –1797)

In his book, *Natural History of the Mineral Kingdom*, first published in 1789, John Williams included a chapter with the title, *Of the limited quantity of coal of Britain*. The chapter starts with the words: "I have no doubt that the generality of the inhabitants of Great Britain believe that our coal mines are inexhaustible" (Williams, 1810: 184). With these words Williams tried to warn the population of Britain that the coal which had brought so much prosperity would not last forever and that it must not be wasted. Williams refers to how wood was wasted and then replaced by coal and how the experience of the tin miners in Cornwall had shown that the cost of mining increased with depth. Furthermore, not only the continued mining of tin in Cornwall depended on affordable coal used in the engines used to dewater the mines, but it was also important that coal should be cheap and plentiful for Britain's manufacturing industry. (Williams, 1810: 187, 192, 193, 207, 217). Williams (1810: 218) made a strong argument for Britain to stop coal exports, which may today be labelled as *resource nationalism*. Apart from possible concerns about resource dependency and security, such a view is questionable as long as free international trade exists. The concept of comparative advantage, on which free trade is based, was promoted by Ricardo. It is possible that Williams (1810: i), who was older than Ricardo, and a surveyor, may not have been aware of it (Brue, 2000: 126, 127).

The realisation by some thought leaders that mineral resources are limited, non-renewable and therefore exhaustible, is an important milestone in the evolution of the "availability" body of knowledge. It challenged the "pre-modern, renewable resource" *paradigm* associated with Alchemy and pre-modern belief in the "regrowth" of minerals.

2.3.6 Ricardo (1772 – 1823)

In the 1817 publication, "*Principles of political economy and taxation"*, Ricardo made a number of contributions regarding land use for farming and mining. Ricardo (1821: paragraphs 1.14, 1.20, 2.4, 3.4, 13.2, 24.6 & 24.8) knew that just like agricultural land, orebodies also vary in quality. He assumed that both the highest quality land and mineral resources would be worked first and that the result would be diminishing marginal returns as lower quality resources were worked later. Ricardian (or "differential") rent is closely linked to the variation in quality of agricultural land and mineral resources (Brue, 2000: 114-117; Crocker, 1999: 33). Ricardo's "quality" of ore deposits is an economic construct because it depends on physical characteristics such as *grade* ("fertility of mines"), ease of being processed, location relative to transport infrastructure and so on. Ricardo (1821: 2) was aware of the impact of factors such as "skill, ingenuity and instruments" on agricultural production but did not consider the possibility that future technological innovations such as fertilizers could push the production curve upwards (Mebratu, 1998: 499).

2.3.7 Carey (1793 – 1879)

Carey was from the American School of Capitalism, President Lincoln's chief economic advisor and the author of publications such as "*Principles of Political Economy*" (1837), "*The Past, The Present and the Future*" (1847) and "*Principles of Social Science*" (1858). He provides an American perspective which seems to contradict the assumption that the highest quality land and mineral resources would be worked first resulting in diminishing marginal returns when lower quality resources were worked later. He, therefore, did not agree with the Malthus-Ricardian theory that population growth would result in the utilisation of increasingly lower quality land and mineral resources. He was of the opinion that the low fertile lands were cultivated first followed by the more fertile lands. He also argued that the low quality mines were often first brought into production. Furthermore, he stated that tool development also followed this progression from lesser to better quality. He backed these claims ("laws") by referring specifically to how areas within the United States and in other parts of the world developed as the population increased and how materials such as iron or low grade steel was replaced by improved steel. He believed that Ricardo's theory was not universally applicable (Robinson, 1989: 82, 83; Ricardo, 1821: 2.4; Carey, 1858: v).

Carey argued that earlier societies, with little capital, first cultivated the poorest soils which were on high ground and lightly wooded. For them it was the lower cost way to start in a specific area and therefore the rational way to act. Over time, as capital stock and the population density of an area increased, they unlocked the highly fertile soils of the low lands that were heavily wooded and difficult to access. They would then become the lowest cost soils. According to Carey this development sequence and (cost) rank order reversal ensured that agricultural output would grow faster than population and increase the welfare of humankind. In his three major works, Carey also mentions a number of other factors that help to ensure increasing returns to labour over time. They are the development of improved agricultural and mining equipment, the creation and extension of roads and canals that reduced transport costs to the markets, and increasing prospects of association, cooperation and commerce (Robinson, 1989: 83; Carey, 1837: 38; Carey, 1858: 112, 175). It is important to note the ceteris paribus assumption that is at work here. The low lands were heavily wooded and difficult to access. If this had not been the case, then presumably they would have been cultivated first.

In a fashion similar to his argument for agriculture, Carey argued that mining is also subject to historically increasing returns on labour. Mining equipment improves over time and so does the capacity to mine at greater depth. Roads, railroads and canals unlock mines in previously inaccessible locations and, just as in the case of agriculture, change the (cost) rank order of ore deposits (Robinson, 1989: 84, 85; Carey, 1837: 134, 240, 241). Here it is again important to note the hidden ceteris paribus – for a given stock of capital and state of technology, the lower cost orebodies would presumably be mined first.

Robinson (1989: 87) regards Carey's "hypothesis of a natural progression to superior mineral resources" as the most significant part of his work in the context of the development of the economic theory of exhaustible resources. Carey seems to be referring to what is known today as the *positive feedback loop* of investment followed by income and profits, reinvestment, capital accumulation and economic growth and the model of *linkage development*. He definitely points to the important role of infrastructural development in making mineral commodities, especially bulky minerals like coal, iron ore and bauxite (aluminium ore) more available to the market. The landlocked Mmamabula coal field in Botswana is just one example where the absence of a railway line to the coast is limiting the availability of coal globally. Apparent differences between Carey and Ricardo are addressed in Chapter 4 where empirical evidence is provided on declining *grade* trends.

2.3.8 Mill (1806 – 1873)

John Stuart Mill was a well-known classical economist who wrote *Principles of Political Economy*. This work consisted of four books, the first of which was on production. He thought that labour, capital and "natural agents" were required for production. He refers to the last mentioned also as land in its broader sense to include agricultural land, minerals and fisheries (Mill, 1848: I.10.3). Mill (1848: I.8.1) characterised natural resources (called "natural powers") by stating that some were limited while others were unlimited. Along the same lines as Malthus, he stated in Book 1, Chapter 10, entitled *Of the law of the increase of labour*, that labour is abundant because its supply from the population could increase geometrically (Mill, 1848: I.10.6). Mill assumed that capital was fairly abundant because he applied the law of diminishing returns to agriculture and not to manufacturing. He believed that limited land and its limited productiveness were the real barriers to increases in production and that the limited quantity of natural resources on earth could in principle constrain production. He believed, however, that such a global limit had not yet been reached and that it would not be reached soon because a large portion of the earth's surface was still uncultivated at the time he made his observations (Mill, 1848: I.11.25, I.12.1, I.12.2; Brue, 2000: 149, 152; Tahvonen, 2000: 1, 2).

Mill was positive that developments such as the increasing security of property and the growing role of corporations would improve industrial production, but that it would be offset by diminishing returns on agriculture with a *stationary state* as the final outcome (Brue, 2000: 157, 158). Mill believed that not all goods were equally scarce or "limited in quantity". He thought that land in the newly settled countries such as the USA and Australia was practically unlimited in quantity relative to the sizes of their populations. Even in such countries, however, the type of land that was close to markets was limited in quantity. He considered water to be generally unlimited in quantity but that the energy (hydroelectricity and hydropower) that can be generated from it to be limited in quantity. He considered coal and metallic ores to be even more limited than land because he was aware that they were available in only certain locations, and exhaustible. He considered fish to be practically unlimited in quantity but that the supply of Arctic whale, used for oil at the time, did not meet demand, even at high prices. Mill's (1848: I.7.1) opinion about rent on land was that it was a *scarcity rent* which he explained as follows: "The reason why the use of land bears a price is simply the limitation of its quantity."

Mill thought that low quality land would, just like low quality mineral deposits, require higher prices for agricultural products, and minerals. He stated this as follows: "Inferior lands, or lands at a greater distance from the market, of course yield an inferior return, and an increasing demand cannot be supplied from them unless at an augmentation of cost, and therefore of price." (Mill, 1848: I.12.8). Whereas Malthus considered war as one possible solution to overpopulation, Mill considered emigration, colonialization and the importation of corn as some of the solutions (Mill, 1848: I.13.14). Today, high levels of international trade in mineral commodities take place because no single country in the world is completely self-sufficient in terms of mineral production.

Mill agreed with Ricardo that profits would decrease as a result of increased cost of food production for a growing population (Brue, 2000: 157, 158). Today, the global population is much larger and the amounts of various minerals mined are also much greater than in the time when Mill made his contributions. A number of researchers (e.g. "the limits to growth" (Meadows et al, 1972) study for the *Club of Rome*) have since asked whether humankind has reached the point where the earth's limited endowment of minerals will constrain future production and economic growth. The relationship between limited resources and economic growth is one theme related to the "availability" body of knowledge (Tilton, 2001: II-2, 3 & 4; Auty, 2007: 627; Bardi, 2011: 64; Neumayer, 2000: 308).

2.3.9 Marx (1818 – 1883)

Both Marx and the proponents of the Conservation Movement (1890-1920) noticed the rapid exploitation of natural resources in the United States. Marx was aware of the exhaustion of soil and believed that the more the development of a country was based on "large-scale industry", the more rapid will be this "process of destruction" (Marx, 1867: 638). This view of Marx is related to the environmental *dimension of availability*.

Long before John Hartwick and Robert Solow argued that capital, for example the insulation of a building from the outside climate, and natural resources, e.g. coal used to produce the electricity to heat or cool such a building, are substitutes, Marx (1867: 130, 131) thought that labour and carbon could be a substitute for diamonds – "If man succeeded without much labour, in transforming carbon into diamonds, their value might fall below that of bricks." Today, De Beers manufactures *synthetic diamonds* at a cost lower than that of mining (natural) diamonds. Whether natural and *synthetic diamonds* are exactly the same product can be debated because differences can be observed by means of specialised equipment due to natural diamonds having been formed over longer periods.

Marx and Ricardo used labour cost of production as a measure of the "use value" of a commodity. Marx knew that technology, embedded in capital, could increase labour productivity while increased infertility of land could decrease it. Reduced labour-time, required to produce a commodity, decreases both its labour cost and use value while decreased fertility may result in increased prices (Marx, 1867: 53, 129, 145, 665). Thinking related to technology innovation as a force that opposes the effect of declining ore *grade*s is discussed in Chapter 3 of this document.

2.3.10 Jevons (1835 – 1882)

In his book, *The coal question*, Jevons (1866: 20) refers to the book by John Williams, *Natural History of the Mineral Kingdom*, and basically continues with the investigation as to how close Britain was to depleting its coal. Jevons also referred to a number of other sources and quoted extensively from Sir W. Armstrong's address to the British Association at Newcastle in 1863. According to Armstrong, England would cease to be a coal-producing country at some point in time because nations such as the U.S. which possess coal-fields 37 times larger will be working more accessible coal reserves at lower costs and would therefore be more cost-competitive than England. Armstrong was pointing to economic depletion of British coal resources as a result of increased costs. The gradual deepening of mines and increased prices of fuel in Britain made it difficult for its coal industry to compete with coal from the USA (Jevons, 1866: 4, 5, 29).

Like Williams, Jevons (1866: 15) also linked the prosperity that Britain enjoyed during the Industrial Revolution to low coal prices and its abundance. England's manufacturing and commercial greatness was at stake if this did not continue. It is for this reason that Jevons was concerned about high coal prices. He knew that England's prosperity was a relatively recent phenomenon, perhaps an anomaly, and he was concerned that higher coal prices may take the country back to an era of lower growth. Jevons dedicated a chapter to technological innovation in which he pointed out how various technologies developed over time and how they contributed to prosperity. He was of the opinion that the adoption and diffusion of products made from iron depended on cheap iron and coal.

Jevons calculated the rate of increase in coal consumption in the UK to be 3,5% at the time. He then projected future consumption based on the assumption that coal consumption would continue to grow at this rate into the future. Jevons forecasted that the total aggregate consumption of coal over a period of 110 years (1861 – 1970) would be about 102,7 billion tons. He compared this with an estimate by a Mr Edward Hull of the Geological Survey who estimated that Britain had about 83 billion tons of coal up to a depth of 4 000 feet, which was 1 500 feet deeper than the deepest mine of about 2 000 feet at the time. Jevons knew that increased depth of mining would result in higher costs. The conclusion that Jevons drew from this information was that Britain could no longer continue on the current consumption trajectory because it would run out of cheap coal in less than a century and that this would stop the progressive condition in which Britain found itself at the time. Basically Jevons, just like Williams before him, believed that growth at the time was unsustainable and therefore of limited duration (1866: 23, 141, 142). Jevons' predictions turned out to be too negative. In the next chapter it is explained why a number of pessimists, such as Jevons, were proven to be wrong.

Jevons considered not only the supply of coal but also the demand for it. He considered two demand-related factors, namely population growth and (increased) *intensity-of-use*. "Population growth" he probably included because he was aware of Malthus' essay, "*Principle of population*" (Jevons, 1866: 100). This approach of considering both demand and supply is also followed in Chapter 3 of this dissertation. Jevons (1866: 99-101) may have been the first economist who used the concept of *intensity-of-use*, measured in coal used per capita. He claimed that intensity of coal use in the UK, at the time, increased four-fold – "In round numbers, the population has about doubled since the beginning of the century, but the consumption of coal has increased eightfold, and more." Today, declining intensities-of-use are observed for certain mineral commodities in developed countries and therefore declining *intensity-of-use* is briefly discussed in Chapter 4 as one of the possible factors that may mitigate demand.

Jevons (1866: 41, 43, 45, 46) was aware of the various problems related to mining at increasing depths, for example, that temperature increases with depth and that it put a limit to the depth at which miners can work. He was aware that Cornish tin miners could work for only 20 minutes at a time when temperatures were between 110 and 120 degrees Fahrenheit. This impacted negatively on productivity. Increased ventilation of working places could be accomplished only with difficulty and greater cost. The dewatering of mines was another cost item. A short extract from his book where he compares surface mining with underground mining methods follows: "If coal were quarried at the surface, and wheeled straight away, each hewer would scarcely require more than one subsidiary labourer. In a deep mine we find that nearly three subsidiary labourers are required, so that four only accomplish what two would do at the surface, to say nothing of the timber and other materials consumed, and the great capital sunk in the shaft, engines, and works of the deep mine."

Like Ricardo, Jevons was aware of different quality resources. Jevons did not use the concept of *reserves* in his book but knew that lower grade coal could be mined if prices increased. He therefore knew that *reserves* were a dynamic concept that varied with price. He also knew that when only low quality coal was left behind in a mine, prices would have to rise significantly to justify going back after it at a later stage. (Coal) seam thickness is another factor that impacts on the cost and profitability of mining. It is not profitable to mine a thin seam at depth (Jevons, 1866: 47, 48).

One of the big contributions by economists such as Ricardo and Jevons is their distinction between economic availability and physical availability. Minerals may be physically present in many places in the earth's crust but may not be economically available unless prices increase and/or costs can be decreased. Humanity's biggest fear should not be that the last barrel of oil or the last tonne of iron ore will be removed from our mines, but rather the cost of exploiting them, because that is what will prevent the poorest from improving their standard of living or more developing countries from becoming developed countries. In the following chapters reasons are provided why real prices did not increase in the long run. The majority of people today strive for improved prosperity. Most people love their relatively comfortable lives and would not like to go back to an era, decades ago, when there was no plumbing, electricity and modern sewage systems. Alex Epstein (2014, 2017) in his video and book, *The moral case for fossil fuels,* points, like a modern Jevons, to the importance of cheap, reliable energy for human prosperity. Epstein's view is that it is difficult to replace cheap coal with another source of cheap energy. Today, the world is experiencing declining prices of renewables and low cost (energy-storage) solutions have been proposed to solve the problem of their intermittency (Nel, 2015).

The *Jevons' paradox* was another important contribution by Jevons. It is briefly discussed in chapter 4.

2.4 SCARCITY IN THE "NEW WORLD" AND THE CONSERVATION MOVEMENT (1890-1920)

The focus in this section is on the experiencing of scarcity in the "New World" which was once regarded as a "wide open" country suitable for people from Britain and elsewhere to migrate to. The Conservation Movement tried to find answers to concerns about scarcity in North America and how to preserve resources for future generations. The United States became a major economic superpower and consumer of non-renewable resources with the result that much of the literature on the "availability of non-renewable resources" was dominated by American responses to events such as the oil price shocks of the 1970s.

Many economists such as Gray (1913: 497), Hotelling (1931: 138), Pigou (1932), Zimmerman (1933: 781), Scott (1955), Krutilla (1967) Barnett and Morse (1963: 72-97), Burton & Kates (1965) and Tilton (1996: 92) referred in their work to the Conservation Movement. This section provides some background information on the Conservation Movement and how proponents of this movement attempted to solve natural resource scarcity. This section also highlights some of the reasons why there were concerns in the United States about the rapid exploitation of non-renewable and other natural resources. Thinking that evolved from that of the Conservation Movement is discussed elsewhere in the chapter.

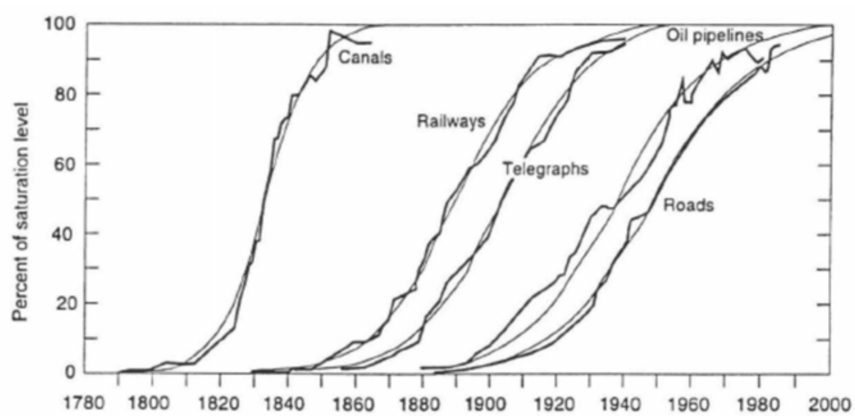


Figure 2.3. The diffusion of infrastructure in the United States. The length of each type of infrastructure was plotted over time as a percentage of its saturation level, e.g. total length of road constructed (Grübler et al, 1999: 261).

Classical economists such as Malthus (1798: III.0, III.7, III.10, IV.2, VI.1, VI.5) and Mill (1848: I.13.14) considered migration and colonialization as possible, partial solutions to the problem of overpopulation in a specific country or area. The migration of many Europeans to North America is fairly well documented. The first settlers experienced abundant resources such as land and wood, but this started to change once they inhabited the whole area – when they reached the "ultimate frontier" (Gray, 1913: 497). The realisation that the United States was filling up with people led to concerns about the future availability of natural resources. Furthermore, many people were shocked by the way industrialisation changed the country over a period of about 50 years. People saw forests disappearing, farms stripped of vegetation and topsoil and water polluted (Barnett & Morse, 1963: 83, 94). The characteristic diffusion S-curves in Figure 2.3 illustrate how various infrastructures diffused in the U.S. Such infrastructure is resource intensive – railways require lots of steel and telegraphs require copper wire. Various technologies and infrastructures co-evolve and co-diffuse, for example oil pipelines, cars and roads are complements. Infrastructures are not only linked to industrialisation but also enable trade and economic growth and can lead to the rapid exploitation of natural resources. This situation probably provided fertile grounds for the Conservation Movement, which was an influential political ideology in the United States between 1890 and 1920.

Burton and Kates (1965: 158, 159) described the Movement as both a crusade and ideology under the leadership of Theodore Roosevelt, Gifford Pinchot and Francis Newlands. President Roosevelt said the following about timber in a speech that he delivered in 1905: "If the present rate of consumption is allowed to continue … a famine in the future is inevitable" (Maurice & Smithson, 1984: xv). Pinchot (1910: 31) said: "Our supplies of iron ore, mineral oil and natural gas are being rapidly depleted, and many of the great fields are already exhausted. Mineral resources such as these when once gone are gone forever." Hotelling provides a summary of the Conservation Movement's beliefs in the first paragraph of his paper, "*The Economics of Exhaustible Resources*". They believed that natural resources were "too cheap" and therefore too rapidly exploited "for the good of future generations" (1931: 138).

The Movement provided fertile ground for Malthusian and Ricardian doctrines of increasing resource scarcity. Proponents of this Movement believed that economic growth had clear physical boundaries which could not be avoided by technological development. They considered the rapid use of non-renewable resources as a major threat to future generations. The movement rejected laissez faire as far as the management of natural resources was concerned and instead tried to provide political leadership. They believed that public policies should guide the conservation and management of scarce natural resources. Their view was that economic competition and monopolies were unwise ways of using natural resources. (Jayasuriya, 2015: 221, 222; Tahvonen, 2000: 2; Barnett & Morse, 1963: 2, 96; Pigou, 1932: I.II.7).

During the Roosevelt administration, the National Conservation Commission was formed in 1908 with the task of producing an inventory of the natural resources in the U.S.A. The Commission was headed by Gifford Pinchot. This was an initial inquiry that was followed by a number of others with a similar focus (Tietenberg, 2006: 316). There were concerns in the USA about the depletion of coal and the capability of industry to provide enough oil for the economy. As a result, the leading oil producing states passed conservation laws (Zimmerman, 1933: 782, 783; Bardi, 2011:

65). Conservation literature stresses losses and waste of mineral commodities because it worsens the scarcity problem. Even if metals are recycled they will eventually be dissipated by corrosion, wear and other loss. The efficient use of resources was also emphasised (Barnett & Morse, 1963: 79, 83).

Dwindling interest in the Conservation Movement can be ascribed, according Zimmerman (1933: 786), to the fact that they were ahead of their time. Some of the ideas of the Conservation Movement survived in one form or another, however. Researchers such as Ise (1925), Scott and Ciracy-Wantrup, for example, devoted themselves to the topic of “Conservation Economics” (Jayasuriya, 2015: 223). Conservation is today still considered as an important part of the solution to achieve the goal of sustainable development. Some of the guidelines that they proposed for the wise usage of resources are still valid. One is that renewable resources should not be utilised beyond their regenerative capacity. Another is that renewable resources should be used instead of non-renewable resources where possible, for example, regenerative hydropower should be used instead of non-renewable resources such as coal, gas and oil as far as possible. Abundant mineral resources should be used before less plentiful ones – for example, iron should be used rather than zinc where substitution is possible because iron is much more abundant in the earth’s crust (Barnett & Morse, 1963: 80, 81).

Infrastructural developments in the United States are illustrated in Figure 2.3. The development of a large economic superpower such as the United States was very resource intensive and many of the well documented lessons learned during that process can today be applied to China. China is a large, fast developing country and an emerging economic superpower. It has been consuming a high percentage of global production of various types of mineral commodities during the past two decades. This phenomenon is the latest example of a *commodity supercycle*. Jevons would not have agreed with the Conservation Movement’s proposal of increasing prices for non-renewable resources as that would make it even more difficult for the developing world to eradicate poverty.

2.5 INTERTEMPORAL ISSUES

2.5.1 The roots of sustainable development

One of the implications of the exhaustibility of non-renewable sources is that orebodies mined today will not be available in the future and therefore choices made now will influence conditions in the future. The optimal extraction of a non-renewable resource such as an orebody is, therefore, important. A number of economists, such as Cassel, Gray and Hotelling paid attention to *intertemporal choice* in their work.

2.5.2 Cassel (1866 – 1945)

Gustav Cassel is known as one of the co-founders of the Swedish School of Economics and for his theory of Purchasing Power Parity. The first edition of Gustav Cassel's "*The Theory of Social Economy*" was already prepared by 1914 but only published in 1918 because of the Great War (Brems, 1986: 21, 25). Robinson (1989: 157) regards certain aspects of Cassel's contribution to the economics of mineral extraction as superior to that of Gray and is surprised that it was not assimilated into the literature dealing with the subject. In it Cassel addressed, among others, mineral economics-related topics such as *intertemporal choice* and he applied neo-classical concepts such as marginal analysis to mineral production. Robinson (1989: 162) thinks that the particular link between the present and future made by Cassel is the first of its nature in the literature dealing with the economics of mineral extraction.

"*The Theory of Social Economy*" shows that Cassel (1932/1967: 276, 277, 296) was aware of the role of substitution, technology, the expansion of land, exploration and the pricing mechanism in solving scarcity problems. He illustrated, for example, how capital and labour can substitute for land by more intensive farming. In the preface to the first edition, Cassel expressed his desire to move away from the old value theory and turn economics into a science by building it up from the beginning on the theory of prices (Cassel, 1932/1967: vii, 4, 6, 291). He (1932/1967: 17, 290, 297) knew how to calculate the net present value (NPV) of the cash flows generated by a mine and differentiated between physical (or geological), economic, technological and political/regulatory availability of mineral commodities. He was aware of the fact that coalfields were irregularly distributed around the globe but plentiful, and that some were so remote and isolated from an infrastructural perspective that mining them would not be a viable economic proposition. He was also aware that some orebodies were not mined because of technical difficulties. He considered most raw materials as economic goods and regarded them as scarce from an economic perspective. Higher prices brought about by taxes and export regulations artificially decreased the availability of mineral commodities (globally) and increases their scarcity. Like the proponents of the Conservation Movement and Hotelling, he was aware that prices influenced the temporal distribution of consumption. He also knew that market structure could affect the current and future availability of mineral commodities. Like Hotelling, he knew that monopoly control over minerals would shift some mineral production towards the future, thus securing more for future generations (Cassel, 1932/1967: 293).

According to Robinson (1989: 160, 167, 168), it is clear from Cassel's analysis (1932/1967: 289-291) that he considered present and future production to be antagonistic and that present production therefore involved a positive but low *user cost*. Although Cassel did not use the term *user cost*, he would probably have allocated a low value to it. This is explained in what follows. According to Cassel (1932/1967: 289, 290), the greatest part of the price of a material such as coal was related to the capital and labour utilized to extract and transport it. A small part of the price was payment for the in situ mineral. This "small part" was related to the scarcity of the available quantities of a natural product such as ore. He argued that although available quantities of natural materials might seem to be plentiful, because they were more than what could be used during a year, a scarcity price could be put on it. He was aware that costs would have to be incurred to increase the production capacity of a mine and that the mine owner would have to compare the advantages and disadvantages of moving some of the extraction to an earlier date (Cassel, 1932/1967: 291).

Cassel (1932/1967: 293) had basically a similar model of a mine in mind that Hotelling had for an individual mine with a limited total mass of mineral. Cassel knew that the optimal useful life of a mine would be shorter, the higher the rate of interest. This was because future cash flows had much smaller present values when discounted at high rates. In order to increase the net present value of a mining venture it may be mined at a faster rate when interest rates were high. Brems (1986: 18-21) constructed a mathematical model based on Cassel's description to illustrate the same result mathematically. It is important to note that unlike Hotelling, Cassel diid not apply his model of an individual mine to that of the whole industry (all mines aggregated). This was because he believed that there was great uncertainty about the future market for a specific mineral commodity because new deposits could be discovered or demand could fall because of the invention of a substitute or a new method of production (1932/1967: 293). It was probably because of these insights and his knowledge of trends in international trade that Cassel attacked, in the daily press, Sweden's policy of imposing a maximum export quota on iron ore produced in the country. He pointed out that one krona now would become more than 130 krona a century hence at an annual compound interest rate of 5%. He also said that unmined ore carried no interest and therefore it was better to extract a tonne of ore now than waiting a century to do so. He advised Sweden to do away with the export quota and let the market decide the optimal depletion of mines (Brems, 1986: 17).

The results of Barnett and Morse's (1963) study would not have surprised Cassel (1932/1967: 297) because he was aware how the introduction of pneumatic drills and the utilisation of water-power for the generation of electricity reduced the costs of mine production (in Sweden). He was also aware of how a relatively cheap and bulky product such as iron ore had become increasingly traded over longer distances, even between continents, as a result of reduced costs of shipping and rail transport. Today it is known that these are important forces behind globalisation. He was also aware of how improvements in metallurgy allowed for the exploitation of poorer ore or ores of inferior quality.

2.5.3 Gray (1881 – 1952)

The American LC Gray contributed towards the development of the economics of mineral extraction in two papers published in 1913 and 1914. Hartwick (2011: 1, 2) described his contribution, in which he extended Ricardian rent theory to intertemporal problems involving both diminishing productivity and exhaustibility, as remarkable. It predates Hotelling's (1931) analysis of intertemporal problems related to exhaustible resources by years. Peterson and Fisher (1977: 692) described his 1914 paper as the first comprehensive theory of the mine.

In his 1913 paper Gray classifies resources according to their level of abundance and scarcity, and labels mineral deposits as exhaustible. As a result of their exhaustibility, the conservation of mineral deposits is important and there is a conflict between present and future use. This "conflict" between present and future, points to the concepts of opportunity cost and *unit cost*. Like Cassel, Gray knows that high interest rates will accelerate the depletion of an ore body and that low interest rates are required for increased conservation. Metals comprises a group of minerals which can, however, be recycled. According to Gray, if everything else stays the same, e.g. prices, then there is an incentive to mine minerals fairly quickly because profits can be invested to earn interest – in situ minerals yield no interest. The Law of Diminishing Productivity may however counter the incentive to turn in situ minerals into profits at a fast rate. A fast rate of mining requires increased application of factors of production (Gray, 1913: 499, 500, 501, 502, 505 & 506; Gray, 1914: 474, 485).

A high production rate at a specific mine requires a lot of production capacity. For a surface mine, it means more equipment and for an underground orebody more shafts and equipment. Gray assumes a fixed stock of in situ ore at mine level. The life of a mine is determined by finding some optimal balance between two economic considerations. That of how much to spend on production capacity given the economic incentive of interest that could be earned on investing net cash flows generated from operations, and negative cash outflows related to creating a certain level of production capacity. (Crabbe, 1983, 203-205; Gray, 1913: 507; Gray, 1914: 474, 485).

2.5.4 Hotelling and "The Economics of Exhaustible Resources" (1931)

Hotelling's paper, "*The economics of exhaustible resources*" has been cited more than 6 500 times according to Google Scholar. This may be one of the reasons why Hotelling is considered by some people to be the father of mineral economics. Greater attention is given to his paper in this study as it stands out as a landmark in the debate for some researchers.

Hotelling provides a classification of natural resources and refers, for example, to forests (and stocks of fish) as semi-replaceable assets because they are only renewable if replaced after having been harvested. That which is used and not replaced is also classified by him as exhaustible, just like "absolutely irreplaceable" assets, for example minerals, which is the focus of his paper (1931: 139, 140). Today the word "exhaustible" is no longer used and much more elaborate systems have been developed for the classification of mineral resources.

Hotelling reacted to the Conservative Movement's demand for the regulation of the exploitation of exhaustible resources and, secondly, proposed an economic theory of exhaustible resources which he believed was an improvement on existing theory (Gaudet, 2007: 1034). The Conservation Movement believed that natural resources were too cheap and exploited too rapidly (Hotelling, 1931: 281, 283). Hotelling wanted to change the "static-equilibrium" economic theory of his time because, according to him, a steady rate of production is a "physical impossibility" as a result of exhaustible, irreplaceable, fixed assets (1931: 139). (It seems that Hotelling did not consider Ricardo's views that resources could be of different *grade*s or qualities and that reserves could be expanded through different means such as higher prices.) The assumption of a fixed resource is central to his model and prediction that the prices of mineral commodities might increase without limit over time as a consequence of continued exploitation. More precisely, Hotelling's rule states that the asset price of an exhaustible resource must grow over time at the rate of interest (Gaudet, 2007: 1037). The optimal use of a limited resource is explained by Hotelling using the mathematics of the calculus of variations to construct a theoretical model in which the social well-being from non-renewable resources is maximised over the long run. He showed that in a market economy, profit-maximising mining firms would extract non-renewable resources at the socially optimal rate (Tahvonen, 2000: 2). Crucially, market prices were assumed to be a good *indicator* of the availability of a mineral resource (Bardi, 2011: 66, Tilton, 2001: II-11, 12).

Hotelling's mathematical model relies on some key assumptions and simplifications, for example that the mineral content of a single mine and all mines, in aggregate, is fully known and limited

(1931: 139). Whereas Mill linked the scarcity of a resource to its price, Hotelling went further to say that the net price of non-renewable resources should increase over time as they are depleted. One of the results produced is the Hotelling rule which states that under free competition, $p = p_0e^{\gamma t}$, where e is a mathematical constant (approximate value: 2,71828) that is the base of the natural logarithm, p is the net price received after paying for the extraction and marketing cost of a mineral commodity, p and p_0 are relative prices at different points in time and γ is the interest rate. Hotelling thus employs the equivalence principle associated with the time value of money theory to argue that a mine owner would be indifferent as to whether p_0 is received now or $p_0e^{\gamma t}$ after a period of time (Hotelling, 1931: 140; 141). Hotelling anticipated rising mineral prices because they are finite and non-renewable.

Hotelling starts with a microeconomic model of an individual mine. He assumes that the mineral reserve of the mine is a constant (limited). Exploitation of the fixed mineral reserve is then optimised between current and future use. Hotelling's assumption of a fixed reserve is, however, questionable. New mining projects are initiated as soon as enough exploration and mine design had been done to determine that a big enough reserve exists to support a business case. Many mines continue to add to their reserves during their lives as new areas become more accessible, resulting in reduced cost of converting resources to reserves. This is referred to as *brown-fields exploration*.

Further explicit and implied assumptions enter the picture when Hoteling changes the micro-model into a macro-model that applies to the whole industry. His macro-model implies that no new orebodies will be found through exploration because the whole industry's reserves are assumed to be fixed. Technological innovations that could reduce costs and increase reserves are ruled out. Hotelling's approach may be criticised for skirting some fundamental questions about the depletion of non-renewable mineral resources: how many mineral reserves are still out there waiting to be discovered; what new technological and scientific discoveries will still be made in the future; how might such discoveries alter mining and exploration costs and lead to new materials that could substitute for existing ones; and so on. Hotelling therefore contradicts one of Zimmerman's (1933) fundamental views regarding the nature of resources, namely that it is dynamic – it can be created and destroyed. (This is discussed later in this chapter).

Hotelling regarded the rate at which a fixed reserve should be exploited over time as central to managing an exhaustible resource. This can be described as the problem of optimal intertemporal allocation of output from a mine, and therefore optimal control theory was used to solve this problem (Robinson, 1989: 5). Hotelling (1931: 137) agreed with the Conservation Movement and thought of exhaustible resources as a fixed stock of which less will remain for future generations the more the current generation consumes – “These products are now too cheap for the good of future generations.” Tilton (1996: 94) refers to such thinking as the fixed stock *paradigm*. Such a view of non-renewable resources is very different from that of Zimmerman, which is discussed next. Hotelling had been praised and followed by many researchers, while others have criticised his views severely. Others tried to improve his initial model by relaxing some of the strong assumptions he made. According to Brätland (2000: 24) “the economics profession generally tends to view the Hotelling Principle as offering the promise of being operational and to have potentially sufficient empirical content to serve as the basis of prescriptive policies for the socially optimal conservation of an exhaustible resource”. Others, such as Pindyck (1978), tried to relax some of the assumptions made by Hotelling in order to make the model more realistic. Researchers such as Bradley (1985) and Banks (2004) are much more critical of Hotelling’s model. In an essay titled, “*Has the ‘Economics of exhaustible resources’ advanced the economics of mining?*”, Bradley (1985) points to certain differences between Hotelling’s theory and observed behaviour in the mining and petroleum industries. Banks (2004: 27) labels Hotelling’s theory of resource exhaustion as an “unrealistic construction” that is “fundamentally irrelevant” in the study of oil and gas economics. He prefers reserve-to-production (R/P) ratios and the research methodology developed by Hubbert (1969).

A number of studies have tested Hotelling’s rule and the general belief that scarce, limited resources should increase in price over time as they are depleted. Many empirical studies did not find strong evidence to support Hotelling’s rule, namely that the prices of minerals should increase over the long term in line with the rate of interest (Gaudet, 2007: 1037). Does this mean that exhaustible resources are not becoming scarcer, or are there other explanations for this phenomenon? The interpretation by a number of economists of such results is that mineral resources are not a scarce commodity from an economic perspective. Friedman (1978: 4), for example, pointed out that the real price of energy declined by 28% between 1950 and 1970 and that this was an indication that oil was not an exhaustible resource from an economic perspective.

Non-renewable resource availability in Hotelling’s model

In the Hotelling world the production quantities during subsequent time periods of a competitive, non-renewable industry decrease so that benefits from the extraction of a fixed reserve are optimised. This extraction path is illustrated in figure 2.4 d) where the reserve is completely depleted at time T (Hartwick & Olewiler, 1998: 282). Resource prices increase accordingly, and rents increase at the rate of interest. Increasing prices are illustrated by the price path in figure 2.4 b). The linear demand curve in part (a) of the figure intersects the vertical axis at price, $\bar{P}$ where the quantity of the resource demanded at such a high level will be zero. This is called the choke price (Hartwick & Olewiler, 1998: 282). At time T, when the choke price is reached, the last part of the fixed stock resource would have been depleted. Figure 2.4 c) is just a line drawn at 45 degrees to the axes. The cumulative quantity of extraction must exhaust the total stock of mineral reserves which is represented by the area under the extraction path. Figure 2.4 illustrates that the availability of a non-renewable resource will decline over time because of the fixed reserve assumption and is the main reason why many researchers have a pessimistic view about future economic growth and sustainability.

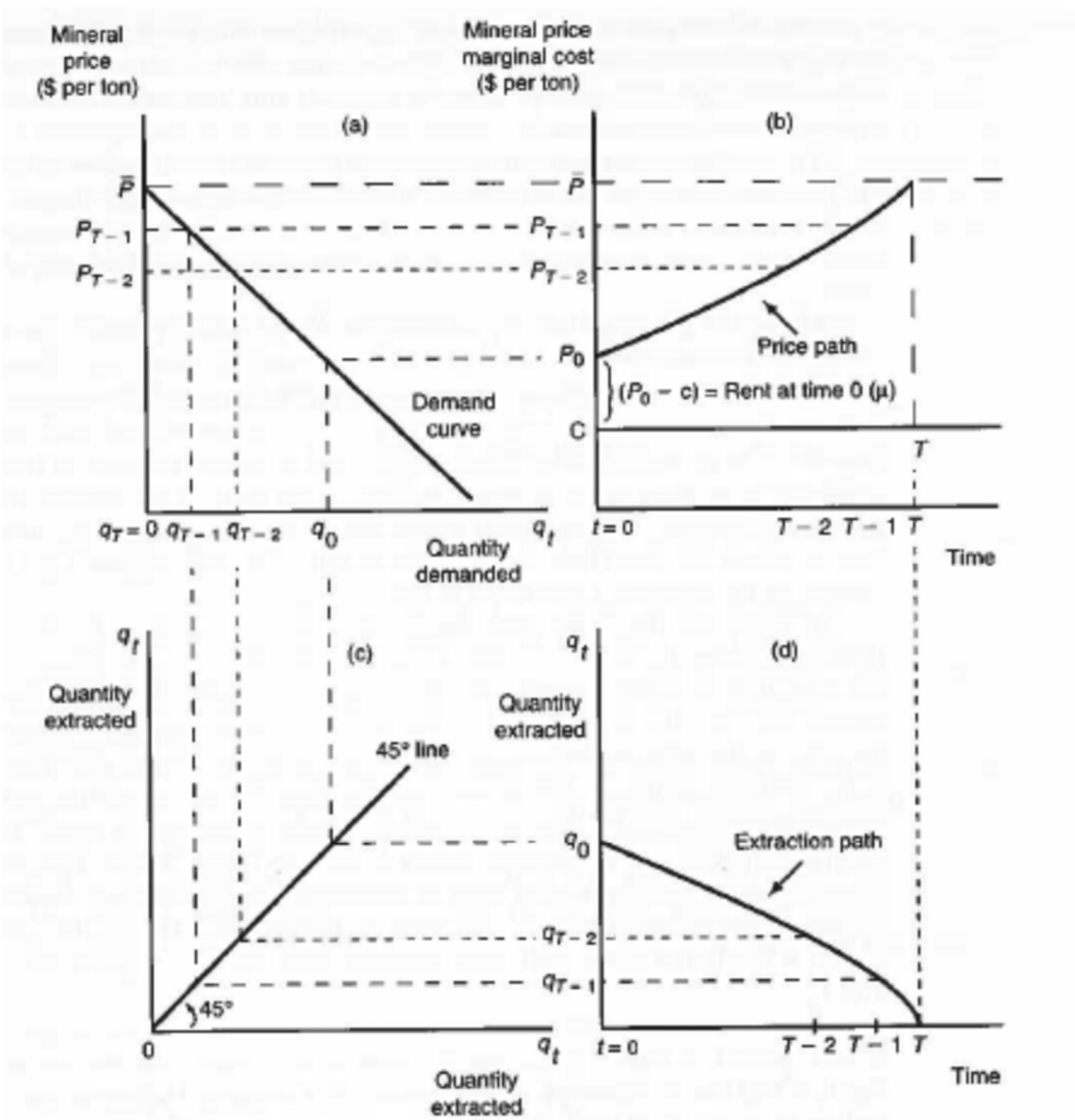


Figure 2.4. Price and extraction paths for a competitive non-renewable industry (Hartwick & Olewiler, 1998: 282)

Hotelling's model, published in 1931, does not provide for non-renewable resource substitution or *backstop technologies*. The concept of a backstop technology relies on the assumption that a substitute is available for a currently used non-renewable resource and is a development that attempts to improve Hotelling's original model. A backstop technology is defined as "a new technology producing a close substitute to an exhaustible resource by using relatively abundant production inputs and rendering the reserves of the exhaustible resource obsolete when the average cost of production of the close substitute falls below the spot price of the exhaustible resource." (Levy, 2000: 1). When the price of a non-renewable resource increases, it creates incentives for a new backstop technology, which may be expensive at first, to be developed. Shale gas and oil, discussed later in this document under section 4.3.9 (unconventional sources), serves as an example of a backstop resource. The exploitation of shale gas and oil reserves are enabled by technological developments referred to as hydraulic fracturing or just fracking but its adoption is prevented in certain jurisdictions by means of legislation because of negative externalities. Wind farms and solar farms can be regarded as another example of a backstop resource enabled by technology that has become much cheaper over the years thanks to significant Chinese production volumes and economies of scale. Adoption of battery electric vehicles or hydrogen fuel cell vehicles as alternatives to petroleum driven vehicles is complex and not only driven by price as suggested by the theory of backstop technology. Range anxiety, relatively long recharging times and insufficiently numbers of recharging stations are still today affecting the adoption of battery electric vehicles in many countries.

The idea of backstop technologies assumes continuous innovation and technological breakthroughs which are by no means guaranteed. The role of technology and substitution is discussed later in this document.

This section does not conclude the discussion and evaluation of Hotelling's paper. The layout of this dissertation is based on a framework that is much broader than that assumed by his model. The rest of this document includes core and *stylised fact*s of the "availability" body of knowledge, many of which were not considered by Hotelling. According to Cairns (1994: 778) the heterogenous nature of non-renewable resources is fundamental to their rate of exploitation. He points to at least three main *stylised fact*s of non-renewable resources that Hotelling ignored.

The next two contributions by Zimmerman (1933) and Barnett and Morse (1963) also challenge Hotelling's work. Zimmerman (1933) gives a more comprehensive definition of a resource while Barnett and Morse (1963) did not observe Hotelling's prediction of increasing prices.

2.5.5 Zimmerman's "Functional Theory of Mineral Resources" (1933)

Zimmerman, a resource economist, proposed the "*Functional Theory of Mineral Resources*" which rejects the notion of fixed resources. According to Zimmerman, it is impossible to know what will be regarded as a resource in the future because this will depend on future human wants which are unknown: "A functional interpretation of resources…makes any static interpretation of a region's resources appear futile; for resources change not only with every change of social objectives, respond to every revision of the standard of living, change with each new alignment of classes and individuals, but also with every change in the state of the arts—institutional as well as technological." (Zimmerman, 1933: 3; Bradley, 2007: 79; Rudawsky, 1986: 2, 3).

According to Zimmerman the following three prerequisites must be met in order for a resource to be created (Rudawsky, 1986: 3):

- Naturally-occurring substances ("neutral stuff") must exist.
- There must be a human demand for these substances; and
- The technology to process these substances and to use them to benefit humanity must exist.

The following three examples illustrate that resources are indeed dynamic, functional concepts as Zimmerman advocated:

- Human effort and accumulated knowledge took very long to unlock the utility offered by uranium. Before uranium was discovered in 1789 and isolated in 1842, it was of no use to humanity. It was therefore just "neutral stuff" according to Zimmerman.
- Asbestos was once used in huge quantities but its use declined as humanity became aware of its negative environmental and health effects.
- The utilisation of fossil fuels such as coal and oil may decline in a few decades as a result of their impact on global climate change and the use of cheaper alternatives .

Some of Zimmerman's ideas are in line with the different *dimensions of availability,* especially politico-institutional and technological availability. The evolution of humanity's energy and materials needs from the stone, bronze and iron ages and from renewables to fossil fuels to nuclear energy and back to renewables is better understood from the perspective of Zimmerman's functional theory.

2.5.6 Barnett and Morse (1963)

The book *Scarcity and Growth: The economics of natural resources availability* by Barnett and Morse (1963) draws on data provided by Potter and Christy (1962) at *Resources for the Future*. In Chapter 8, Barnett and Morse described their methodology and the results obtained from a quantitative test of whether increasing economic scarcity of natural resources took place in the U.S. between 1870 and 1957. During this time, U.S. economic output expanded 20 times and its population increased four-fold. Barnett and Morse deliberately chose a long period to ensure that shorter-term events such as business cycles and wars did not obscure the long-term trends. They found no economic scarcity of natural resources in the U.S. for the period 1870 to 1957, which seems to contradict Hotelling's rule (Barnett & Morse, 1963: vi, ix, 164).

Barnett and Morse analysed U.S. prices and production costs for various resources and concluded that the scarcity of natural resources was not a constraint on economic growth during the period under investigation. The study put the emphasis on real price and production cost trends as *indicators* of increasing or decreasing availability of non-renewable resources. They ascribed their findings to the scarcity mitigating effect of technology.

2.5.7 Limits to Growth (1972)

The alarmist *Limits to Growth* (LTG) report for the *Club of Rome* was published in 1972 by Meadows, Randers and Behrens. The team that produced LTG relied heavily on Jay Forrester's (1968) pioneering work, Principles of Systems, in the field of *System Dynamics,* which was used in their computer model of the world on which various scenarios were run. When the report was written, exponential growth trends for population growth in developing countries, fertiliser utilisation, global industrial production and economic growth in rich countries were observed and expected to continue. In the "standard" world model, scenario variables follow historic values during the period 1900 to 1970 as illustrated in Figure 2.4.

The total world supply of arable land was predicted to run out before the year 2100, even at quadruple the productivity levels achieved in the 1970s. Exponential growth is linked to *positive feedback loops* and used in their computer model which predicted that food production, technology and limited resources would not be able to keep up with such growth and would result in a growth collapse before 2070. This collapse would be the result of physical limits that would be reached in terms of non-renewable resources, agricultural production and excessive pollution. The study predicted that 11 vital mineral commodities, including copper, gold, lead, mercury, natural gas, oil, silver, tin and zinc, would be exhausted before the end of the 20th century. The predicted lifetimes of various mineral commodities were obtained by using a model that considers interrelationships between *grade*s of ore, production costs, new mining technology, the elasticity of consumer demand and substitution of other resources. It was also assumed that technology would not progress sufficiently to compensate for rising costs of discovery, extraction and processing. As a result, prices would start to rise. The model predicted that, at the resource-consumption growth rates at the time, non-renewable resources would become extremely scarce and thus costly by 2070. As long as growth continues exponentially, this will remain the outcome even under optimistic findings of new reserves, technological advances, substitution and recycling.

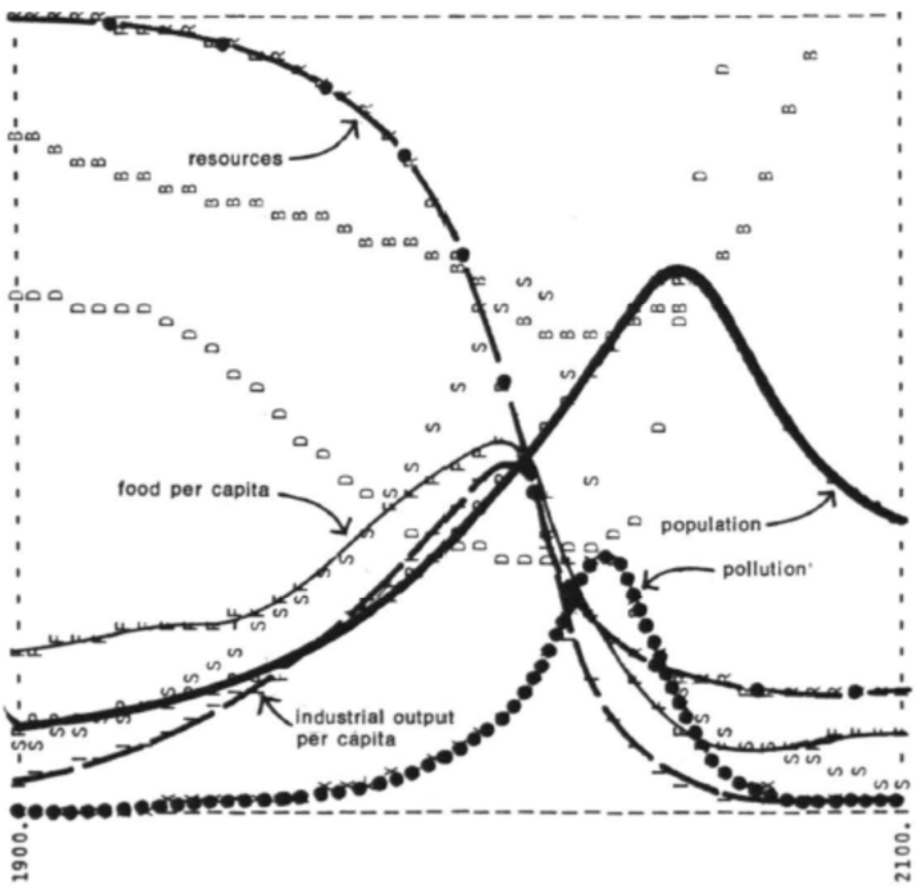


Figure 2.5. Outcome of the "standard" world model (Meadows et al, 1972: 124)

The LTG-team knew that additions would be made to current known reserves through exploration activities, which left them with the problem of how to forecast total future reserves. They illustrated that even at five times the known mineral reserves of 1970s, the life of reserves would not last much longer when utilisation rates were growing exponentially. They correctly remarked that the static *reserve-to-production ratio* was not a good indicator of long-term availability, and introduced the concept of an exponential reserve index.

One of the consequences of the LTG publication was the development of various efficient resource models. Another was fierce criticism of the LTG report by prominent economists such as Robert Solow and Josef Stiglitz (Solow, 1986: 143; Von Hauff, 2016: 101). Beckerman (1972), Nordhaus (1973: 1182), Kay and Mirrlees (1975) also commented on the “Limits to Growth” study. Nordhaus (1973: 1183; 1974: 22) and Stiglitz (1974: 123) showed that changes such as technological progress, factor substitution, population decline and economy of scale would lead to more optimistic results. Some of the factors that mitigate non-renewable resource scarcity are discussed elsewhere in this document. Solow (1974: 78) was of the opinion that “if it is very easy to substitute other factors for natural resources, then there is in principle no problem. The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe.” The dominant neoclassical *paradigm* is based on this optimistic view (Von Hauff, 2016: 101).

The first oil price shock occurred in 1973, one year after the publication of LTG, and fortuitously this helped the report gain credibility in the public’s eyes.

One of the “early” predictions, such that 11 minerals would be exhausted by the end of the 20th century, did not materialise. The study did make a significant contribution, however, to the “sustainable development” debate, including the shift from the “limits to growth” view to a “sustainable development” view by the United Nations. The report’s content is relevant to this study because of the broader “sustainability” context to which it contributed and because it made certain findings about the depletion of mineral resources and “environmental availability”. When unlimited resources are assumed, then economic growth will still stop because of rising pollution under some of their scenarios. The report points to the fact that it is very difficult to make accurate predictions about the future when great uncertainties exist about potential mineral deposits that may still be discovered, the ability of humanity to come up with various innovations and the inadequacy of current *indicators* of mineral resource availability. The predicted finding of rising (long-term) price trends has not been confirmed by the empirical data, as was the case of Hotelling’s prediction of rising prices. Similar to *Hubbert*’s *peak oil theory*, a bell-shaped mineral commodity usage rate was predicted (Fisher, 1995: 245; Meadows et al, 1972: 11, 23, 26, 27, 31, 38, 40, 45, 50, 55, 56, 58, 63, 66, 132).

To date, global economic growth is still continuing with humanity better off compared to the 1970s in terms of global poverty measures. Today global consumption and population are, however, at much higher levels compared to the 1970s when the report was written.

2.5.8 The oil crises of 1973 and 1979

One year after the publication of LTG, oil prices rose about threefold over a very short time and exposed the US economy's dependence on oil. This resulted in numerous commentaries, research programmes (e.g. Partnership for a New Generation of Vehicles & FreedomCAR), foreign policy changes and other attempts to secure oil, reduce the country's energy dependence and break its "oil addiction" habit for decades afterwards. According to Adelman (1997: 13, 30, 31) the price increases had little to do with real global scarcity, however, but rather with cartel behaviour and politics, thus pointing to the "political availability" dimension.

Not only the LTG study gained credibility in the public's eyes as a result of the first oil crisis but also *Hubbert*'s *Peak Oil* Theory. According to Tahvonen (2000: 3, 4), very few American citizens questioned the view that the world was entering a future of increasing scarcity of energy and natural resources as a result of the combined impacts of the LTG study and the first oil price shock. Energy security and independence was on the agendas of a number of American Presidents, from Carter to Obama. In his 1980 State of the Union Address, President Carter, for example, declared the security of the Persian Gulf to be of vital interest to ensure the uninterrupted flow of oil to the US (Butts, 1993: 3). This situation only started to change fairly recently with the successful adoption and diffusion of *hydraulic fracturing* ("fracking") technologies to exploit America's large shale gas reserves on a significant scale.

2.5.9 "Our Common Future"

Intergenerational equity is at the heart of the concept of sustainable development as defined in the Brundtland Commission's 1987 publication, "*Our Common Future*": "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987: 16). As indicated in this chapter, signs of intergenerational equity were already part of the objectives of the Conservation Movement (1890s-1920s) whose advocates were concerned if sufficient natural resources would be left for future generations.

What does sustainable development mean in practical terms? Does it mean that the mining of all non-renewable resources should be halted and that humanity should only use renewable resources and energy? According to the authors of "*Our Common Future*", non-renewable resources may be used but that the rate of depletion should depend on factors such as the criticality of each non-renewable resource, technologies for improving efficiencies, the availability of substitutes and the recycling of materials (World Commission on Environment and Development, 1987: 43). Hicksian sustainability, *weak sustainability*, *strong sustainability* and *Hartwick's rule* are all concepts and constructs that are linked to the umbrella concept of sustainable development. Adherents to "weak sustainability" agree with the leading Brundtland definition that future generations should have similar consumption opportunities and that natural resources can be exhausted if they are replaced by substitutes and human-made capital (Henckens et al, 2016: 102).

Hartwick thinks that a constant level of consumption could be maintained perpetually if all *scarcity rent* is invested in capital. He thinks that that level of investment would be sufficient to assure that the value of the capital stock would not decline and is linked to the concept of *weak sustainability* (Hartwick, 1977: 972; Tietenberg, 2006: 96; Tietenberg & Lewis, 2011: 114). This view is however contested by advocates of *strong sustainability*. Today the goal of achieving sustainable development is driven by many individual organisations, businesses, governments and the United Nations.

2.6 CONCLUSION

This chapter illustrates that thinking about the availability of non-renewable resources has evolved over time. Concerns over the availability of natural resources are very old and have tended to recur whenever there are heavy demands on available resources and the current capacity and infrastructure to meet such demand. It is important to differentiate between events and factors that may affect availability in the short versus long run. Concerns about the availability of non-renewable resources in the long run are driven by population growth, the associated material intensive life style that started during the Industrial Revolution and the exhaustible nature of orebodies. Some of the contributors focused on demand-side concerns while others on supply-side concerns. Some assumed that the stock of resources available for exploitation (*reserves*) is fixed while others knew that resources are not homogenous but of different quality and that improvements in technology could enable the exploitation of lower quality resources. A number of the contributors to the "Availability of non-renewable resources" body of knowledge, for example, Barnett, Morse, Carey, Marx, Zimmerman and Cassel referred to the role of technological innovation to mitigate scarcity. Others such as the "Limits to Growth" group and the "*Peak Oil*" supporters underestimated the role of technological innovation.

The historic part of the body of knowledge about the availability of non-renewable resources can be reflected upon and questions asked about why it evolved in the way it has. Much of the analysis in the rest of this dissertation follows from this foundation. History illustrates that advances in technology, substitution, conservation, recycling and re-use are some of the solutions to the problem of non-renewable resource scarcity. Such factors have to be considered and must form part of the framework when assessing the long-term availability of non-renewable resources. Hotelling's model does not consider exploration, technological solutions and substitution and is thus contradicted by, for example, Barnett and Morse's (1963) empirical findings.

A discussion of the physical, social and economic dimensions of the availability of non-renewable resources continued in this chapter. The availability of non-renewable resources is a complex issue that is much broader than the physical availability thereof. Today, the global population is much higher and the amount of minerals mined much greater than in the time when the classical economists were already concerned about population growth, limited land and possible limitations on economic growth. Furthermore, very high numbers of people are still experiencing absolute poverty. It is, therefore, no wonder that there are still concerns among some people about the adequacy of resources.

CHAPTER 3 - RECENT THINKING ON THE AVAILABILITY OF NON-RENEWABLE RESOURCES

3.1 INTRODUCTION

Chapter 2 gave a historical perspective on thinking about the availability of non-renewable resources. This chapter summarizes more recent research and findings in this regard. The information in this chapter will support some of the core facts and conclusions in Chapter 5. Many of these facts were either unknown or not properly understood when Hotelling wrote his paper on the "*Economics of exhaustible resources*" in the 1930s.

3.2 THE INCREASING ROLE OF EMERGING ECONOMIES

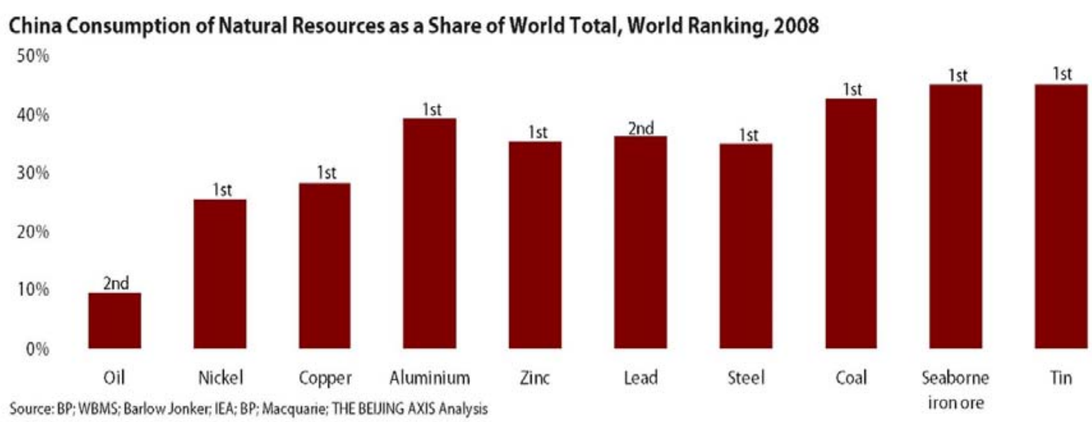


Figure 3.1. China dominates the consumption of non-renewable resources

In the 1950s the U.S. was a fast-growing economic superpower using its mineral reserves at a faster rate than other countries. One solution was to import more and encourage direct foreign investment into developing countries with low-cost resources so that their production capacity could be expanded (President's Materials Policy Commission, 1952: xvii, 60). Today, emerging economies are playing a much greater role in both the production and usage of non-renewable resources. The consumption of copper is a good example of this shift. In 1990 the developed countries used about 69% of global supply. By 2014 this had declined to 28,5% and China alone used 49,8% (Tilton & Guzmán, 2016: 46). Many similar shifts, for various types of mineral commodities, have occurred during the last number of decades. Table 3.1 and Figures 3.1 and 3.2 illustrate how resource-intensive Chinese economic growth is and that the country relies increasingly on imports to make up for the difference between demand and local supply. More examples in the rest of this document help to underline this trend.

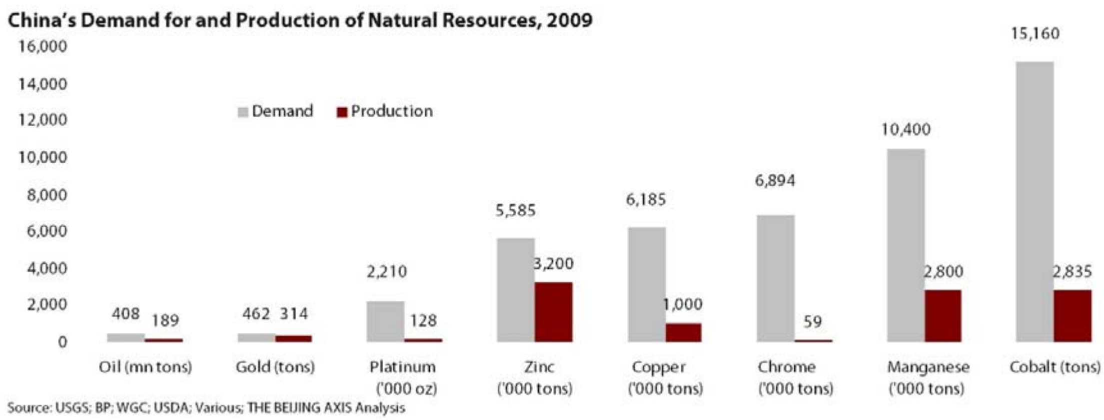


Figure 3.2 The difference between China's demand and local supply

Table 3.1 Increase in resources demanded by China during the period 2002 to 2015 for three metals (UNCTAD, 2016: 14).

Refined materials	**China's consumption volume (thousand tonnes)**		**China's consumption (kg per citizen)**		**China's share of global consumption (%)**	
	2002	**2015**	**2002**	**2015**	**2002**	**2015**
Aluminium	4 115	31 068	3.2	22.7	16.2	54.4
Copper	2 737	11 353	2.1	8.3	18.2	50.2
Nickel	84	964	0.1	0.7	7.1	50.3

The fact that more mineral commodities are mined and refined in developing regions today (illustrated by figures 3.6 and 3.7), compared to a few decades ago, exposes importing countries to greater political and economic risks (Barteková & Kemp, 2016: 153).

3.2.1 Closing the development gap

A number of countries, particularly China and India, are closing the development gap between them and the developed world. By achieving economic growth rates far exceeding those in the developed world, they are catching up like Japan and the Asian Tigers did after World War II. Forecasted growth rates are indicated by Figure 3.3.

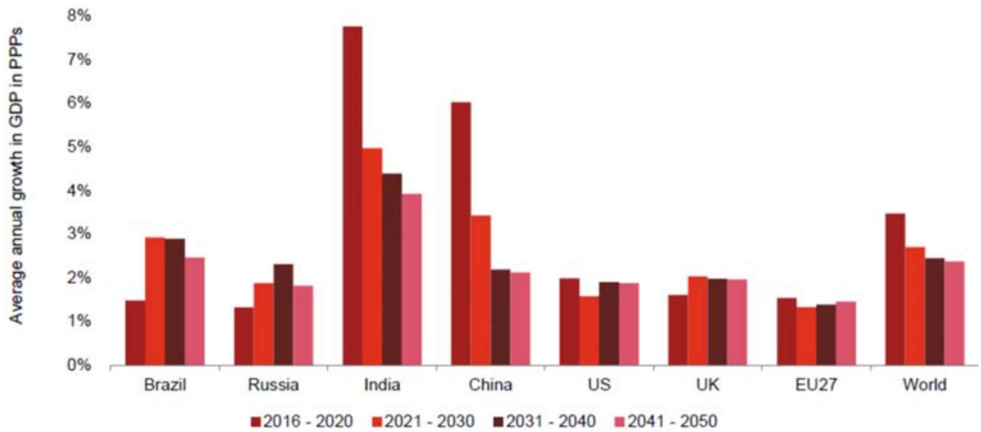


Figure 3.3 Projected growth profiles for a number of large economies (PWC, 2017: 8)

According to PWC (2017), emerging economies will dominate the world's top ten economies by 2050 as indicated by GDP measured in terms of purchasing power parity (PPP). Please see Figure 3.4.

	2016	2050	
China	1	1	China
US	2	2	India
India	3	3	US
Japan	4	4	Indonesia
Germany	5	5	Brazil
Russia	6	6	Russia
Brazil	7	7	Mexico
Indonesia	8	8	Japan
UK	9	9	Germany
France	10	10	UK

E7 economies G7 economies

Figure 3.4 Expected dominant role of emerging markets by 2050 – GDP is measured in terms of purchasing power parity (PWC, 2017: 2)

Dobbs et al (2016: 8, 18) confirm that the centre of gravity of global economic power is currently shifting east and south. This is illustrated by Figure 3.5. Ninety five percent of the world's largest international companies, as listed in the Fortune Global 500, were headquartered in developed countries in the year 2000. It is expected that by 2025, China will be the home of more large companies than either the U.S. or Europe and that more than half of the world's large companies, with revenues of $1 billion or more, will be in emerging markets.

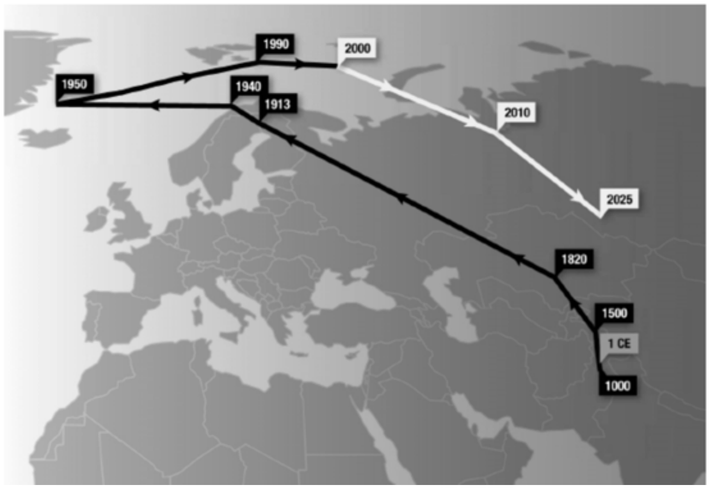


Figure 3.5 Shifts in the economic centre of gravity since 1CE (Dobbs et al, 2016: 18)

According to Dobbs et al (2013: 3), the economic growth of China and India is unprecedented considering that it is happening at a speed about ten times the rate at which average incomes improved during the Industrial Revolution in the United Kingdom and at about 200 times the scale. It is expected that the global car fleet will double to 1,7 billion by 2030 and that by that year almost 600 million people with annual incomes greater than $20 000 a year will be living in emerging markets. This group of people will increase the spending on various types of goods (Dobbs et al, 2016: 75).

In 2005, Rogoff (www.project-syndicate.org) remarked on this trend and its impact on consumption and commodity prices as follows: "The world is not about to run out of commodities. Instead, what is happening is that the integration of 2,5 billion people (China and India alone) into the global economy is producing a demand shift that is likely to put far more upward pressure on commodity prices than any technological gains are likely to offset. So, for at least the next 50 to 75 years, or perhaps until humans start mining on Mars some time in coming centuries, prices for many natural resources are headed up."

3.2.2 A shift in mineral supply

Not only demand but also supply is shifting. Figure 3.6 shows that Europe's contribution towards global mining peaked between 1850 and 1870. It was during this period when Jevons (1866: 20) wrote "*The Coal Question*". The so-called (first) *Scramble for Africa* followed in the latter part of the 19th century when a number of European countries occupied, divided and colonised African territory. One of the reasons was to access African natural resources. The figure also shows the rapid growth of mine production in the United States between 1890 and 1920, the period during which the Conservation Movement was most active in the United States.

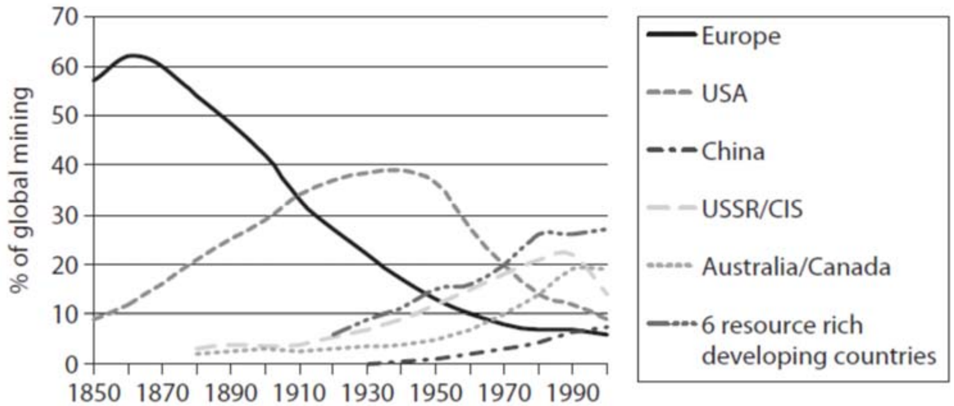


Figure 3.6 Locus of mine production through time (World Bank, 2011: 3; ICMM, 2012: 4)

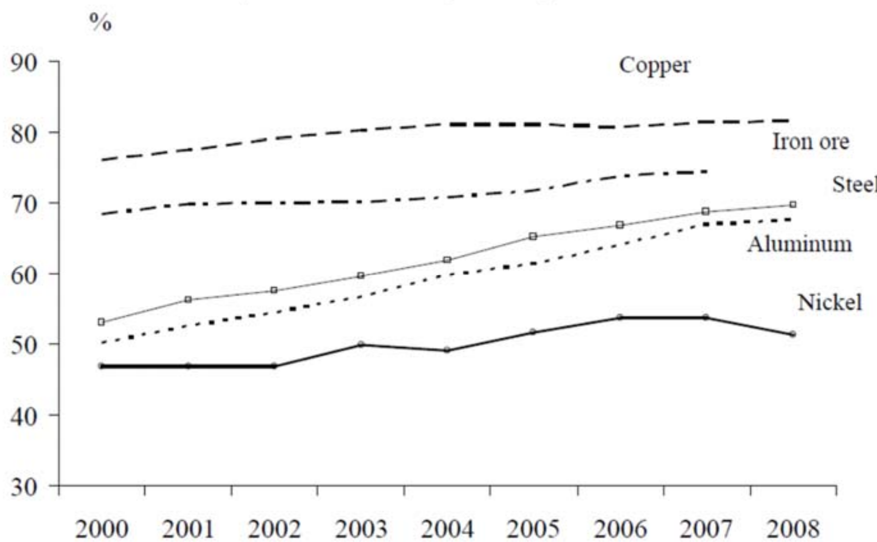


Figure 3.7 Emerging economies' contribution towards global mineral commodity production (Humphreys, 2009: 1)

Both Figures 3.6 and 3.7 show that emerging economies have become important producers of minerals. Although emerging economies account for about 75% of the world's total land surface, they underperformed in the past, in terms of minerals production, according to Humphreys (2009:

2). This he ascribed to a number of reasons ranging from inadequate geological knowledge, poor infrastructure, inconsistent and ineffective government policies and a lack of capital. The lowering of unit shipping costs, one of the contributors towards globalisation, made the transportation of even bulky commodities such as iron ore and coal over long distances increasingly viable. Other reasons for the shift in supply, such as competitive advantage in the production of mineral commodities, is discussed later.

One of the manifestations of this shift in production is increased pressure to collect high public revenues through rents from the *extractive industries* (UNCTAD, 2014: xiii). This is associated with the concept of *resource nationalism*.

In summary, section 3.3. focuses on two factors that have opposite effects on global mineral availability. Firstly, mineral supply today is more geographically diverse, which results in greater supply. In contrast, the development of emerging economies has contributed to much greater demand for a variety of mineral commodities, which tends to decrease availability.

3.3 THE RELATIVE SCARCITY OF NON-RENEWABLE RESOURCES

Just as it is important to differentiate between renewable and non-renewable resources, it is also important to compare the scarcities of different non-renewable resources. Although the reasons for such differences are studied in the physical sciences and fall outside the scope of this study, they have consequences for the economics of availability. In Chapter 2 it was pointed out, for example, that the Conservation Movement promoted the idea that abundant resources should be used to a larger extent than those that are scarcer. Figure 3.8 shows, for example, that tin (Sn) and copper (Cu), two main ingredients of bronze, are less abundant in the earth's crust than iron (Fe) which became more important later in humanity's cultural evolution, during the Iron Age.

Most non-renewable resources minerals are currently exploited from the earth's crust, and Figure 3.8 therefore provides an indication of their relative physical abundance. The crustal abundances of those elements that are at very low concentrations are categorized as "geochemically scarce". Eight elements are very abundant and account for 98.5% of the crust. They are listed in Table 3.2. Table 3.3 illustrates the relative crustal abundances of a few selected elements, most of which are much scarcer than the eight listed in Table 3.2. The mineral *resource base* can be estimated by using the crustal abundances of the elements, also called *Clarke* values. It is important to note that the average crust is in most cases not mined. Only *reserves,* which is a small percentage of the *resource base*, are mined. *Reserves* are often parts of the crust where the concentration of an element is much higher than its average value in the crust. Various geological processes concentrated minerals during the planet's existence. The extent to which such natural concentration has taken place is referred to as the natural *enrichment factor*. Concentrations that are high enough to be mined profitably are referred to as *reserves*.

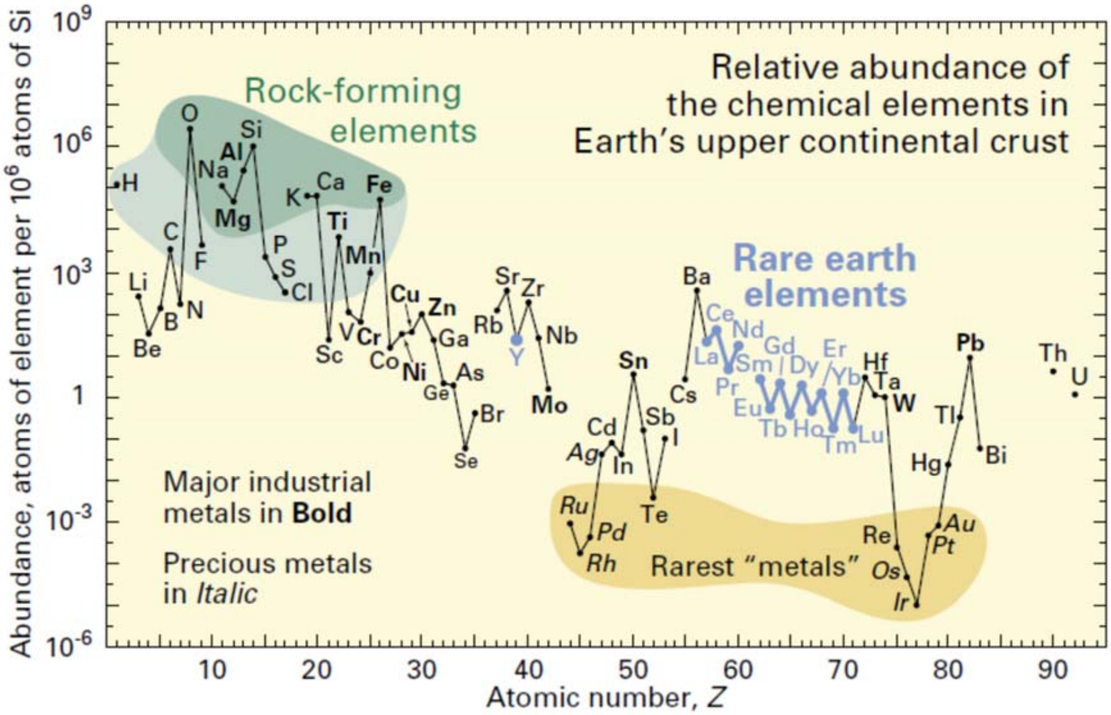


Figure 3.8 The relative abundance of the chemical elements in the Earth's upper continental crust relative to one million atoms of silicon (Si). Major industrial metals are labelled in bold, precious metals in italic. The rarest elements are the six platinum group elements plus gold (Au), rhenium (Re) and tellurium (Te). (Haxel et al, 2002: 3).

Table 3.2 The eight most abundant elements in the Earth's crust (by mass) - http://www.windows.ucar.edu/tour/link=/earth/geology/crust_elements.html&edu=high

Element	**Crustal abundance (by mass)**
Oxygen (O)	46,6%
Silicon (Si)	27,7%
Aluminium (Al)	8.1%
Iron (Fe)	5.0%
Calcium (Ca)	3.6%
Sodium (Na)	2.8%
Potassium (K)	2.6%
Magnesium (Mg)	2.1%

Table 3.3 The crustal abundances of a few selected elements (Henckens et al, 2014: 3)

Element	**Average upper crustal abundance (ppm)**	**Relative crustal abundance compared to that of gold**	**Typical minimum grades at which it is mined from naturally enriched zones (ore deposits)**	**Typical natural *enrichment factors***
Geochemically abundant elements				
Aluminium (Al)	8.0% or 80 000 ppm	44 000 000	32% or 320 000 ppm	4
Titanium	4,1% or 4100 ppm	2 280 000	10% or 100 000 ppm	20
Iron (Fe)	3,5% or 3500 ppm	1 900 000	25% (> 60% at Sishen and Australian iron ore mines)	7
Geochemically scarce elements				
Zinc	71	39 000	40 000 ppm or 4%	600
Nickel	44	25 000	10 000 ppm or 1%	200
Copper	25	14 000	5 000 ppm or 0,5%	200
Lead	17	9 000	40 000	2 000
Tin	5,5	3 000	50 000 ppm or 5%	9 000
Gold	0,0018	1	4 ppm or 4 g/t or 4 x 10^{-4} %	2 000

The 2nd last column of Table 3.3 shows that the concentration or *grades* of orebodies that are economically viable to mine, are higher for the geochemically abundant elements. The last column of Table 3.3 shows *enrichment factors* for various types of mineral commodities. An *enrichment factor* of 2 000 for gold means basically that only once its average concentration is 2000 times the average level of that in the crust (0,0018 ppm) will it become a *reserve* that can be mined at a profit (2 000 x 0,0018 ppm = 3,6 ppm = 3,6g/t).

Various types of geological processes are responsible for the above average concentrations of minerals and are studied in the field of Economic Geology. It is not foreseen that the average, unenriched, crust will be used as a source for such elements because efficiency improvements roughly equal to the various *enrichment factor*s would be required to ensure profitability. Just as nature provides many services, such as fresh air and clean water to humanity for free, it also does so in the form of orebodies which are rare gifts of nature. In his paper, "*A second iron age ahead?*", Skinner (1976) proposes that humanity will have to use abundant resources such as iron rather than less abundant ones.

The *enrichment factor*s provided in Table 3.3 are just general *indicators*. Ore deposits exploited by large scale, industrialised mining (LSM), as opposed to those exploited by artisanal and small-scale mining, are usually fairly large in order to achieve economy of scale effects, and therefore lower *grade*s can be mined at a profit. Generally, the deeper and smaller the ore body, the higher the *grade* required for profitable exploitation. A study done by S&P Market Intelligence found that the average *grade* of surface gold mines were 1,05 g/t compared to 3,25 g/t for underground gold mines (Slater, 2020).

The fact that there are large differences in the abundance of various types of minerals in the earth's crust raises the question of whether we should be equally concerned about the availability of all types of mineral commodities.

3.4 THE VARYING QUALITY OF RESOURCES: NON-HOMOGENOUS OREBODIES

Orebodies differ one from another. They differ in terms of average quality, average *grade*, depth below surface, shape, size, presence of by-products and distance to market, to name just a few factors. Figure A.11 in Annexure A illustrates for example how grades may vary from one point to another within an orebody. Different mining methods, ranging from surface to deep-level underground and from small-scale to large-scale, is one of the consequences of the diverse nature of orebodies. These differences may result in different cost structures of mines where such orebodies are extracted. In figure 3.9 the cost of mining a specific commodity, for example, copper is shown on the vertical axis as Cost A, B and M. The symbols A to P represent different mines and Cost A is the cost of mining the commodity at mine A. The supply curve for an individual commodity may have a shape similar to that in Figure 3.9 if it reflects all the costs of the mines in the world where such a commodity is produced. The heterogenous nature of non-renewable resources was ignored by Hotelling (1931: 139, 141) at both an industry (macro) and firm (micro) level. Unlike Ricardo, he assumed that the quality of resources was homogenous (Cairns, 1994: 778). One of the implications of a (gold, platinum, iron ore or any other mineral) industry cost curve shaped like that in Figure 3.9 is that reserves will increase when prices increase. Hotelling assumed that reserves are fixed. Mine P, in Figure 3.9, is probably on care and maintenance or will probably soon be put on care and maintenance if prices do not increase or if management cannot decrease its cost structure.

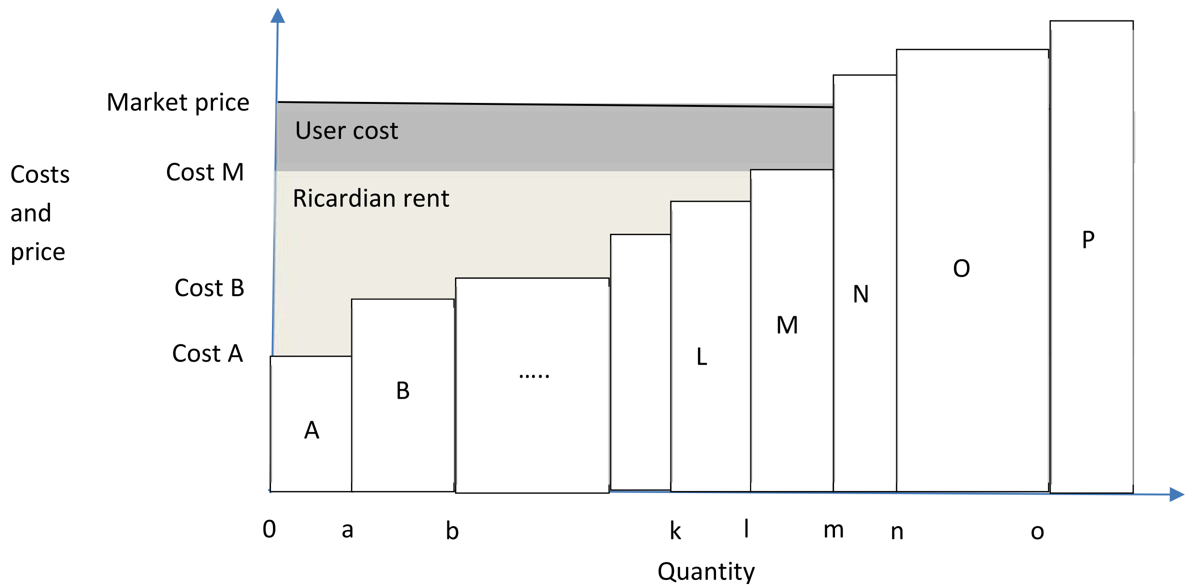


Figure 3.9 A *stylised* cost curve for a specific commodity where 0a, ab, lm and mn depict the quantity of mineral produced by four mines (Tilton, 2001, III-20)

At the micro or firm level it is also important to note that the *grade* of a single orebody or the quality of coal in a seam may vary. This is illustrated by both figure 3.10 and Figure A.10 in Annexure A. Orebodies have a higher average *grade* than that in the rest of the earth's crust. The earth probably started with a molten, relatively homogeneous crust about 4.5 billion years ago but the continental crust evolved into a heterogeneous crust through magmatic, sedimentary and metamorphic processes that led to segregation and local concentration of elements, resulting in natural enrichment which can be measured as *grade*s and expressed as *enrichment factor*s listed in Table 3.3 (Gocht et al, 1988: 10; Henckens et al, 2014: 3). The result of these geological processes is that the *grade* throughout an orebody often varies. This was observed in diamond-bearing Kimberlite pipes early in the South African mining history where diggers who worked equally hard in their respective claims had large differences in net wealth (Nel, 2018: 848). Figure 3.10 provides an example of the *grade*-tonnage curve at a specific mine and points to the non-homogenous nature of orebodies.

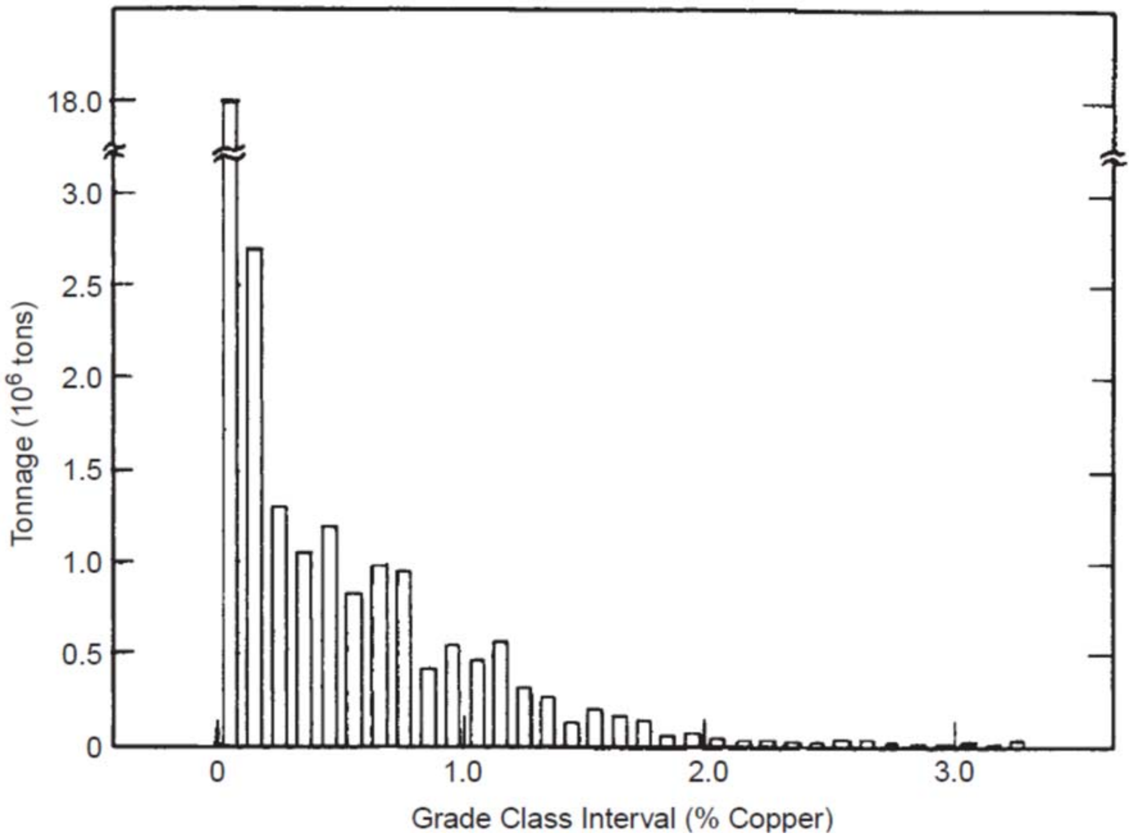


Figure 3.10 Tonnage versus grade class interval for the Silver Bell oxide pit (Hustrulid et al, 2013: 507)

An important implication of the shape of the *grade*-tonnage curve in Figure 3.10 is that the reserve of a specific mine can be increased if the commodity price increases and everything else remains the same. Reserves can also be increased if the mine's cost structure is decreased by means of improved technology. According to Halland et al (2015: 15) the economics of an orebody may be sensitive to changes in prices, costs, fiscal policy and technology because of the heterogeneity of orebodies. The heterogenous nature of orebodies with its consequences were overlooked by Hotelling (1931).

3.5 LOW GRADE RESOURCES ARE MORE ABUNDANT

The whole continental crust of the earth forms the biggest part of the *resource base* from which minerals could potentially be mined. This is an enormous resource, but at very low average *grade* compared to that of the ore deposits as indicated in Table 3.3. The ore deposits (or reserves) are a much smaller part of the *reserve base*. An important implication of this is that if it became possible to mine lower *grade* ores profitably, then more reserves would be created. Lasky's results, known as *Lasky's Law*, suggest that as *grade* declines arithmetically, tonnage goes up geometrically. This seems to hold, however, only for relatively high *grade*s close to ore *grade*s. This fact, that low *grade* resources are more abundant, provides an important mechanism or channel through which technological innovation could create more reserves and thereby increase availability.

It is important to note, however, that environmental availability may decline as lower *grade* reserves are mined. This may counter efforts to increase reserves in such a way. Negative externalities related to the mining of lower *grade*s, such as increased negative environmental impact, are discussed in the next section.

3.6 THE AVERAGE GRADES OF OREBODIES ARE DECLINING

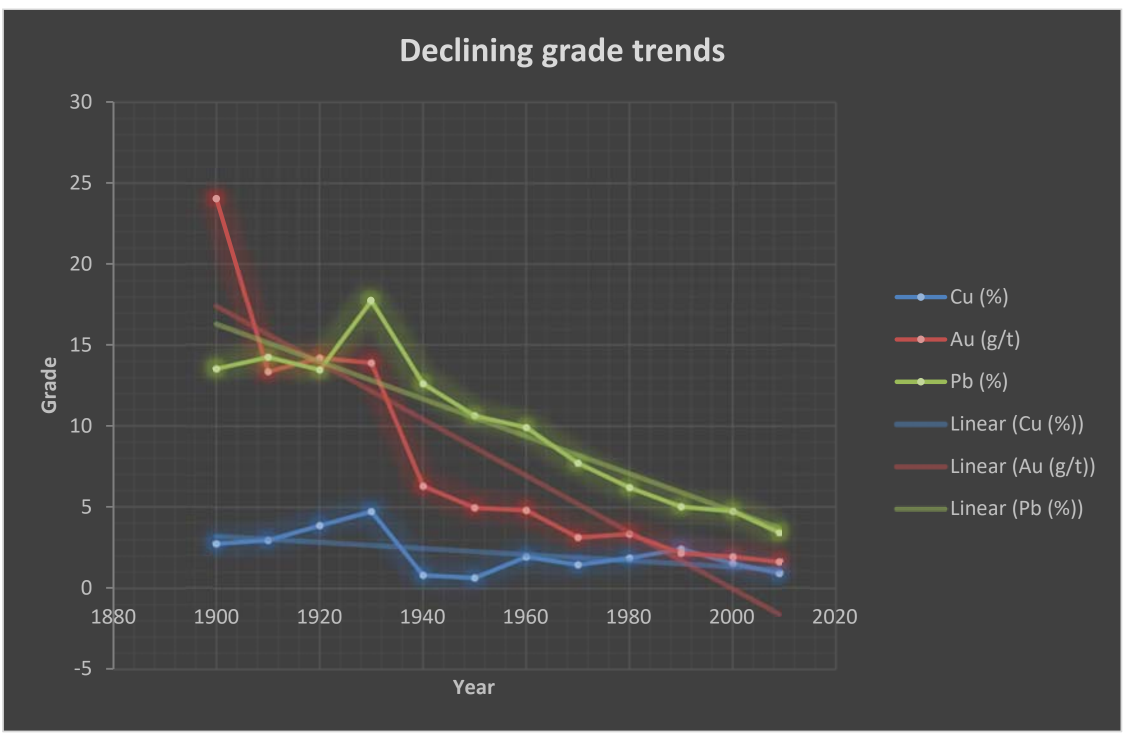


Figure 3.11 Average ore grades of copper, gold and lead mined in Australia over time. Here it measures the metal as a percentage of the ore from which it is extracted (Eggert, 2016: 478; Mudd, 2009: 111).

Declining ore *grade*s have an impact on both economic and environmental availability. Lower-quality ores require more capital and labour to produce the same output as previously if everything else, such as processes used and the level of technology, stays the same. According to Steen and Borg (2002: 402, 411) humanity would be in serious trouble long before ore *grade*s approached levels equal to those of the average *grade* of the earth's crust as indicated by the *Clarke values*, especially in the case of geochemically scarce minerals whose average concentrations in the earth's crust are very low. Lower *grade* areas were less enriched by the various geological mechanisms involved in orebody formation. Declining *grade*s have huge implications, not only for processing costs and energy usage but also waste generation. Comminution, the reduction of broken rock to smaller particle sizes by means of processes such as crushing and grinding, may be consuming 2-3 % of the world's total energy consumption (Batterham, 2011: 138). When lower *grade*s are mined, more rock volumes have to be processed just to get the same quantity of final product produced by a smaller volume of higher *grade* ore. More chemicals are used and more waste, often in the form of tailings, is produced.

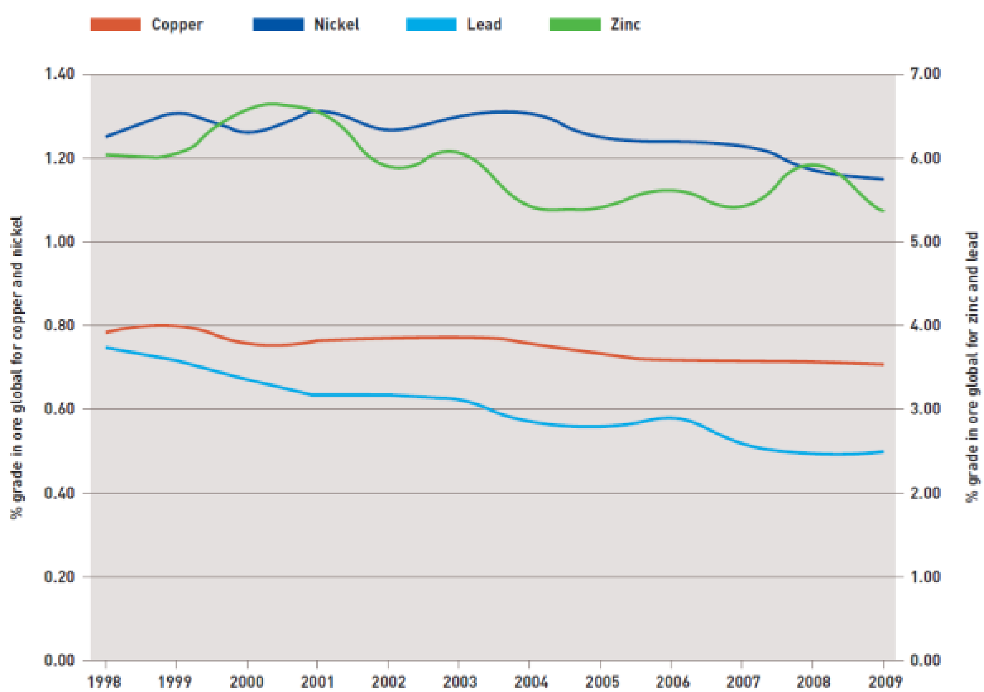


Figure 3.12 Declining ore grades for four mineral commodities (ICMM, 2012: 15)

Improvements in technology not only enable the profitable mining of lower *grade* orebodies that may not have been profitable previously but also enable the re-mining of low *grade* areas of a mineral resource that was previously unpayable. At New Vaal Colliery, high quality coal was mined from 1931 to 1969 by means of underground mining methods. Later, the rest of the lower-*grade* coal seams were mined by means of *draglines* from the surface (Laybourne and Watts, 1990: 187). Another example is the reprocessing of mine dumps at old South African gold mines by companies such as DRD Gold. The company uses flotation fine-grind circuits to extract gold from tailings that were processed and dumped decades ago (Greve, 2015)

As a result of continued technological improvements, declining ore *grade*s have not yet resulted in lesser economic availability. It seems that higher long-term prices, discussed elsewhere, have not yet been required to compensate for declining *grade*s and quality.

3.7 THE COMPARATIVE ADVANTAGE OF NATIONS, INTERNATIONAL TRADE AND GLOBAL NON-RENEWABLE RESOURCE MARKETS

Mining jurisdictions have different natural resource endowments. Platinum and chrome are good examples of mineral commodities that are unequally distributed in the earth’s crust – South Africa produced between 70 and 80% of the world’s known platinum and 49% of global chromium in 2016, but has little oil. Whether a specific jurisdiction has a competitive advantage with regard to the production of a specific type of non-renewable resource depends on geology and good quality orebodies, but also on a number of other factors related to the various *dimensions of availability*. One of the implications of such comparative advantages, namely the shift of supply to emerging markets, has already been discussed. More information follows in this section.

Global *rare earth* mineral production had been dominated for years by China. This is not because such deposits are not present in other parts of the world. In addition to favourable geology, low labour costs and low regulatory costs, China’s production of *rare earth* elements (REEs) has increased since the late 1970s to such an extent that it supplied between 95 and 97% of global production for the period 2002 to 2013. Radioactive material is often present in tailings (waste) when *rare earth* minerals are processed. Companies operating in countries with stricter regulations regarding the treatment of such waste may therefore have a competitive disadvantage in the production of rare earths (Biedermann, 2014:276-277, 284; De Wit, 2015:2; He, 2014:236; He, 2018:3; Tse 2011:4).

Some countries have a competitive advantage in both the mining and processing of certain mineral commodities. Beneficiation of ore is often energy intensive and steep price increases of electricity in the past few years combined with unreliable supply thereof is a big blow to the traditional view that South Africa should beneficiate more of its mineral resources locally. Much of its chromium and manganese ores are currently beneficiated by China.

Factors like economies of scale, support from government and again lower regulatory costs provided China with the competitive advantage needed to close Britain's steel making industry – the place where it all began during the Industrial Revolution. During a recent period of less than two years, China manufactured more steel than Britain has over many years since the height of the Industrial Revolution in 1870. In 2018 China produced almost a billion tonnes of steel – something that took Britain about a century. Despite tremendous productivity increases, the UK steel making industry could not make a profit and had to close down (Island FM, 2019).

If a simple product such as the incandescent light bulb, invented by Thomas Edison, is manufactured in the USA, some of the raw materials (e.g. manganese, tungsten and copper) have to be imported because they cannot be produced cost competitively locally (Mineral Information Institute, 2005: 2). This necessitates trade between countries. When such trade is not occurring freely, for whatever reason, it decreases the availability of such resources in certain parts of the world. Figure 3.13 illustrates global copper trade flows and the importance of international trade in mineral commodities.

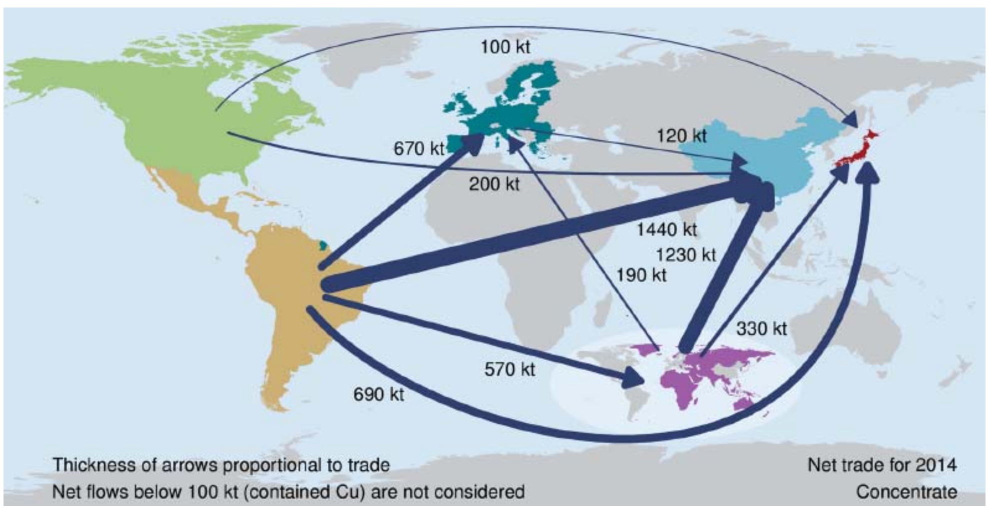


Figure 3.13 International trade in copper concentrate in the year 2014 (Expinoza & Soulier, 2016: 50)

A few centuries ago only high value goods were traded. Some time between 1750 and 1850, trade in bulk goods took off as shipping unit costs declined. Globalisation gained much momentum in the 1820s (O'Rourke et al, 2002: 24). This increased the supply and availability of a broad range of non-renewable resources in most countries.

3.7.1 Towards global non-renewable resource markets

In ancient history only high-priced items such as gold and silver were transported over long distances. Bulky lower-cost commodities such as coal and iron were only traded locally and regionally. This started to change with globalisation and the lowering of transportation costs to such an extent that even lower quality coal is today cost-effectively transported between continents, for example from South Africa to India. This resulted in the creation of international markets for such commodities and increased the global availability of many mineral commodities.

The evolution of ship design and the associated lowering of shipping costs was only one factor that influenced the global availability of mineral commodities. Another important factor is global politics. After World War II trade in the Western world was becoming well established. Because of the Cold War and the Western world's isolation of the Soviet Union, it traded mostly with other communist countries. The Soviet Union was a large and mineral-rich part of the world.

It was possible for the West to isolate the Soviet Union in the 1950s because the GDP of Western Europe and its Western Offshoots, which include the U.S. and Australia ,was about 57% of the global GDP while that of the former USSR was just below 10% of the global economy GDP in 1950 (Maddison, 2006: 612). Today, Germany is unified and the economy of modern Russia more integrated with that of Western Europe and the rest of the world. According to Tilton and Guzmán (2016: 55), the movement of the Soviet Union and China away from centrally planned economies has resulted in a "tremendous geographic expansion for many mineral commodity markets", which enhanced competition. Large volumes of low-priced palladium came onto the market, for example, after the collapse of the Soviet Union in 1991. The Soviet Union was a major producer of palladium and had significant stockpiles that seem to have lasted many years (Information about stockpile volumes is unavailable but it seems that in addition to the VW scandal, the current high price of palladium may also be due to depleted or dwindling stockpiles). Palladium and platinum are partial substitutes for one another in the exhaust systems of vehicles (Creamer, 2020).

In a few years' time more European countries may have the choice between Russian, American, Norwegian and Eastern-Mediterranean gas if existing and planned pipelines and liquid natural gas (LNG) terminals are expanded and built and a unified EU energy market is created (Quinn, 2018).

3.7.2 Trade wars and the break-down of the World Trade Organisation

Under the Trump administration the multi-decades-long view of China as a strategic partner of the U.S. has changed to one of "strategic adversary". One option considered by the Trump Administration is to use Cold War isolationist-type strategies against China. U.S. alliance partners such as Australia, Japan and Singapore are, however, not willing to choose between the U.S. and China according to Graham Allison, author of the *Thucydides's Trap* (Allison, 2017; Wei, 2018). The *Thucydides's Trap* phenomenon provides an explanation for the US-China trade war. An isolation strategy might not be very effective because China is much more powerful than the Soviet Union was during the Cold War, its economy is becoming more integrated with the rest of the world through the Belt and Road Initiative, and Australia exports a large part of its minerals to China. It would also be difficult for the U.S. to decouple its economy from that of China (Allison, 2017; Wei, 2018). It is in the interest of nations, especially those who are net importers of mineral commodities, to have better integrated global mineral markets to ensure lower prices, improved security of supply and improved availability.

The actions of the Trump Administration, including that of turning away from the World Trade Organisation (WTO), may have certain consequences (Martin, 2019). China may, for example, stop supplying the U.S. with Rare Earth elements which are much needed by the U.S.'s military and high-tech industries. More information is provided elsewhere in this document.

3.8 MINERAL RESOURCE NATIONALISM AND CRITICAL MINERALS

In the past governments and especially military strategists were concerned about the availability of resources that would become scarcer if trade were to be interrupted. During the Late Bronze Age, tin, an important ingredient of bronze, was of strategic importance because bronze weapons were essential for maintaining the balance of power between the competing empires at the time (Bell, 2009: 180). Many other examples exist of the strategic use of raw materials, especially during wars, ranging from the attempted blocking of German imports of nitrates and petroleum by Britain during the two World Wars to the withholding of chromium exports by the Soviet Union to the U.S. during the Korean War (Russett, 1984: 481; U.S. CIA, 1983: 1, 12). More recently, Chinese *rare earth resource nationalism* and industrial policy has put the spotlight again on *strategic* and *critical minerals*. The U.S. National Science and Technology Council (2016: ix) defines *critical minerals* as "those that have a supply chain that is vulnerable to disruption and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence."

Multiple dependencies exist between nations. "The United States relies on imports for more than 90% of its supply of the majority of Energy Cricital Elements (APS/MRS, 2011: 28). Large manufacturing countries like Japan, the U.S. and Germany import significant amounts of mineral commodities and, therefore, have a particular interest in knowing how reliable the supply of such mineral commodities is. Trade reductions or stoppages will result in local and/or regional unavailability of the affected resources and impact negatively on such economies.

3.8.1 Value chains and Chinese rare earth resource nationalism: Leveraging resource dependency

Numerous value chains depend on the availability of non-renewable raw materials. Where sources of such resources are diversified across geographical locations, the availability of such raw materials is often not the weakest link in such value chains. This was for example illustrated by the USA and Israeli governments who disrupted the Iranian nuclear weapons programme by targeting their uranium enrichment facility with the Stuxnet worm (Zetter, 2014). The Americans and Israelis did not prevent the Iranians from obtaining unenriched uranium which can be easily obtained from various sources. They targeted another part of the value chain.

In some cases minerals, and/or the know-how to beneficiate them, are geographically concentrated. Currently, only a few organisations have the know-how to convert rare earth ores, which usually consist of a combination of rare earth minerals, into separate rare earth elements or their oxides. China positioned itself strategically to dominate this value chain, that goes as far as the manufacturing of permanent magnets from Neodynium, a rare earth element. Such magnets are used in wind turbines and certain electric cars.

As a result of favourable geology, low labour costs and low regulatory costs, Chinese production of *rare earth* elements (REEs) has increased since the late 1970s to such an extent that it supplied between 95 and 97% of global production during the period 2002 to 2013. The industrial demand for REEs, measured in tonnage, is relatively small, but they are essential in high-technology applications such as cellular phones, hybrid vehicles, fibre optic cables, displays and defence equipment. In 2005 China introduced export quotas on REEs, which they reduced sharply from 2010. In that year they stopped exporting REEs to Japan and Germany altogether. As a result, the prices of REEs increased about three-fold in 2011. In reaction to these events, the U.S., EU and Japan filed a complaint with the World Trade Organization (WTO) which found China's reasons of conservation and environmental protection to be unsubstantiated and to be rather related to industrial policy. The Bundesverband der Deutschen Industry interpreted China's actions as an attempt to force German and other foreign companies to relocate to China and help develop their high-tech industry to advance at a faster pace. Hao and Liu (2011: 1) regard this as a "misinterpretation of China's export controls" on Rare Earth Elements (Biedermann, 2014: 276-277, 284; De Wit, 2015, 2; He, 2014: 236, He, 2018: 3; Tse, 2011: 4).

3.8.2 Critical minerals needed for batteries

If battery electric vehicles replace conventional internal combustion engine vehicles to a large extent over the coming years and decades, the demand for commodities such as lithium, cobalt, graphite, manganese and nickel may increase substantially because they are important ingredients of batteries. The price of cobalt increased threefold in the recent past because of the relatively fast adoption of all sorts of battery-driven smart devices. A quarter of the world's cobalt production is currently used in smartphones. Apple, a producer of various electronic devices such as smartphones, is probably concerned about the availability of cobalt because the company recently decided to buy it directly from producers (Farchy, J. & Gurman, M. 2018). This seems to be an unusual step for a company which is a battery user but not a battery manufacturer. One of the reasons why countries such as the U.S. have cobalt on their list of *critical minerals* is because the DRC dominates the production of cobalt. Furthermore, the DRC is politically unstable, and a significant percentage of cobalt is produced by artisanal miners and child labour. Civil war in the DRC resulted in decreased and unreliable supply of minerals such as cobalt during the period 1995 to 2002. Figure 3.14 shows that the demand for cobalt increased at a faster rate than the formation of new reserves for the period 2005 to 2015 – consequently reserve life (the reserve to annual production (R/P) ratio) declined to only a few years. In 2016, 54,69% of global cobalt production was from the DRC (Reichl, 2018: 136). In the same year 69,27% of global graphite was produced by China (Reichl, 2018: 160). There are concerns that China is trying to increase its dominance in materials required for electric vehicles just as it did with rare earths. Perhaps it is just wise of China to do so because it is the world's largest electric vehicle manufacturer.

The status of the *R/P ratios* of a few battery materials is shown in figure 3.14. For lithium and graphite the global reserve lives have increased while it declined for cobalt during the period from 2005 to 2015. As a result there is a shift towards the use of the *NMC811* battery where nickel substitutes to a larger extend for Cobalt. The R/P ratio, discussed in chapter 4, is not an *indicator* of political tensions and availability and, therefore, a different *indicator* is required to indicate supply risk related to geopolitics and other relevant factors. This raises the question of how so-called *critical minerals* can be identified and is discussed next.

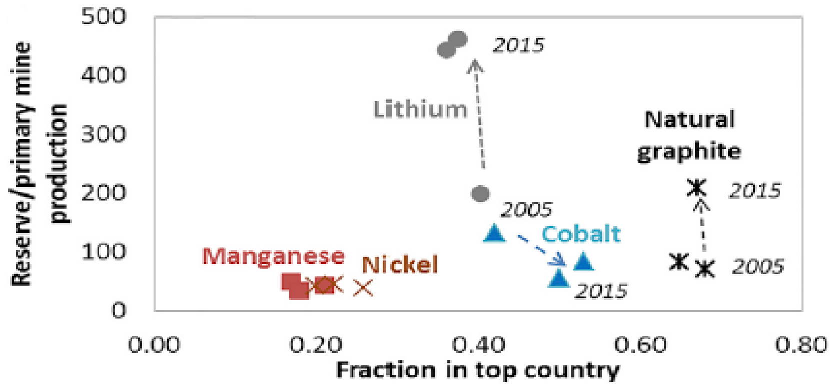


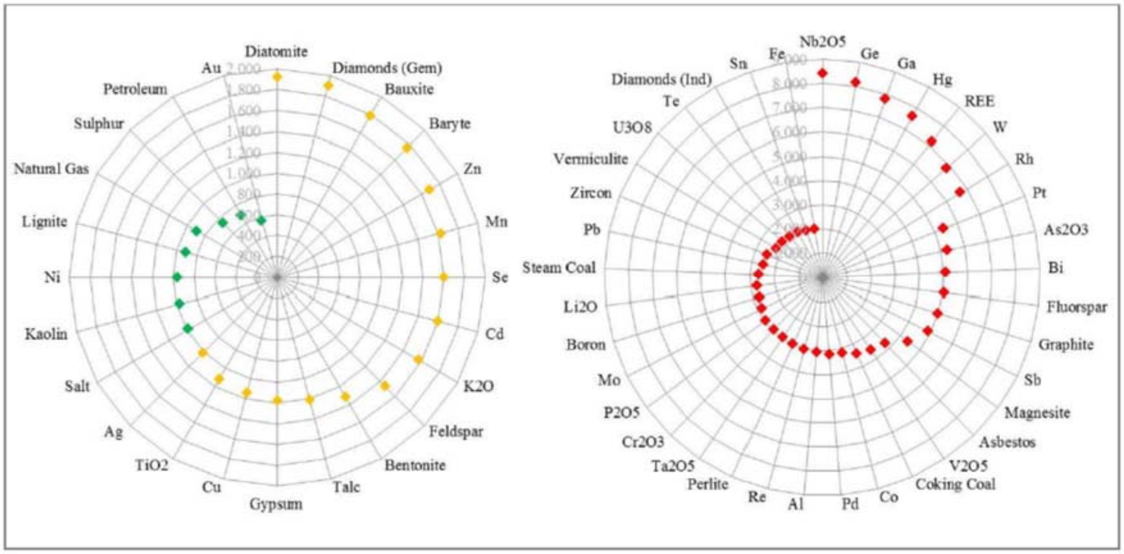
Figure 3.14 The *R/P ratios* of a few materials used in Li-Ion battery production for the years 2005, 2010 and 2015 as well as the fraction produced from the biggest producing country (Olivetti et al, 2017: 232)

3.8.3 Indicators of mineral criticality

Various *indicators* have been developed for mineral criticality. Factors such as high import reliance, concentration of supply and limited domestic capability are considered when determining if a specific mineral is critical at a specific point in time for a specific country or region. Some of the methods designed to indicate criticality make use of formulas to calculate indices which may be difficult to interpret. Certain methods go further than others to also include, for example, the environmental and technological *dimensions of availability*. The goal for developing an *indicator* or doing a "criticality" study should be to provide an early warning of potential problems to come so that they can be addressed timeously through the introduction of appropriate policies and action, discussed in chapter 4. Criticality *indicator* design and theory development is one area within the "Availability of non-renewable resources" body of knowledge that is still evolving as measured by the growth in published papers (Achzet & Helbig, 2013: 436-447; Brown, 2018: 202; Eggert et al, 2008: 28, 31; Graedel et al, 2012: 1064-1066; McCullough & Nassar, 2017: 258-259; Speirs et al, 2013: 5).

The *Herfindahl-Hirschman Index* (HHI), which is often used to measure market concentration, is also used to measure the market share of a minerals producing country (Ferguson & Ferguson, 1994: 41; Nassar et al, 2015: 5, Reichl, 2018: 13).

In 2016, Brazil produced 91,476% of global niobiumoxide (Nb_2O_5) and China 82,29% of global tungsten (W) resulting in HHIs of 8 368 ($91{,}476^2$) and 6 772 ($82{,}29^2$), respectively, as indicated in Figure 3.15. In the same year China also produced 54% of global aluminium (Al), 67,6% of antimony (Sb), 68% of bismuth (Bi), 88% of gallium (Ga), 90% of germanium (Ge) and 84% of *rare earth*s concentrate. One of the consequences of the geographical concentration of mineral commodities is that importing countries are dependent on a single or few major producers. In some cases such dependence is so high that such minerals are classified as *critical minerals*. Many *critical mineral indicator*s include the HHI (Brutschin & Jewell, 2018: 322; Reichl, 2018: 139 – 147; Russett, 1984: 482).



(Country Concentration ◇ low, ◇ moderate) *(Country Concentration ◇ high)*

Figure 3.15 The concentration of producer countries for various mineral commodities (Reichl, 2018: 16)

The U.S. National Science and Technology Council's (2016: ix) Mineral Criticality Screening Tool is an early warning screening tool that uses a two-stage approach. Stage one is *indicator* based, and a single value for potential criticality (C) is determined on a 0-to-1 scale. 0,3 and 0,335 were proposed as threshold values above which a mineral should be considered as potentially critical. A threshold value of 0,335 is believed to be an acceptable value when applied to historic data for *rare earth elements*. At such a threshold value, *rare earth* elements would have been identified as critical as early as 2001, a few years before China introduced export quotas on them.

3.9 SUPPLY BY ARTISANAL AND SMALL-SCALE MINING

Mainstream, neoclassical economic theory focuses on the firm as the economic unit that produces various types of goods. So did Hotelling (1931: 143, 146, 170). Today resource economists are no longer overlooking artisanal mining (Saldarriaga-Isaza et al, 2013: 224). Although all early mining was *artisanal and small-scale* in nature, most of it became more formalised, consolidated and industrialised over time in developed countries. Nel (2018: 845-852) provided proof that mining had to be consolidated at the early kimberlite diamond mines in South Africa when artisanal and small-scale miners started to mine kimberlite pipes at greater depths. The resultant large producer solved safety and productivity problems caused by the lack of coordination and cooperation between numerous diggers working claims next to one another in the same large orebody. In such orebodies, large scale, well-planned, capital-intensive mining is the most cost-effective way to mine.

Most artisanal mining does not take place, however, at the deeper levels of large massive ore deposits unless such miners are able to access infrastructure such as shafts that were produced by large scale miners. The number of people involved in artisanal and small-scale mining (ASM), mostly in developing countries, has increased over the past number of years to about 40.5 million compared to 7 million for industrial mining. Artisanal and small-scale miners produced the significant percentages of 26, 25 and 25 of the world's tantalum, tin and gold production, respectively, in 2011 and therefore the ASM-sector should be acknowledged for its contribution to global supply and availability (ICMM, 2012: 8). Furthermore, new opportunities are arising for the ASM sector in evolving mining ecosystems (Nel, 2018: 846). This shows that ASM are very important because of their contribution towards the supply and improved availability of various types of minerals.

One advantage of artisanal and small-scale mining is that much smaller orebodies can be mined than what large scale mining would be able to mine profitably. The overhead costs of artisanal miners are lower. Such miners often operate in poor countries with high levels of unemployment, and due to their skills they do not have many opportunities elsewhere in the economy to earn money (IGF, 2017: 50). Some are subsistence miners who just manage to eke out a living. In such cases the cost of labour as well as production costs are very low. Such miners are motivated not only by prices but also by the opportunity to earn a living within economies such as Zimbabwe and South Africa where not enough jobs are created in the formal sector. Illegal artisanal miners are often at the bottom of the food chain and do not always receive market prices for the ore, concentrated ore or processed product that they mine – they are sometimes exploited by the dealers higher up the value chain (Groot, 2019). One report regards ASM as an "economic refuge" and "safety net" (World Bank, 2019: 9, 10).

Some of the characteristics of artisanal miners are shared by informal waste collectors and recyclers in the streets of our cities, many of whom can be described as secondary, subsistence, urban miners.

Large scale mining (LSM), which produces the bulk of many types of minerals, is very capital intensive, has high fixed costs and long pre-production periods up to at least 12 years, and is the main focus of this study (Gentry, 1988: A25). Informal secondary mining (recycling & urban mining) is briefly discussed in Chapter 4 as a method of mitigating resource scarcity.

3.10 BY-PRODUCTS AND STRUCTURAL SCARICTY

Two or more elements are often found to be concentrated in orebodies. For example, the SA Witwatersrand orebodies contain both gold and uranium, and a number of South African gold mines had operating uranium plants a few decades ago. Orebodies that contain a variety of minerals enable the mining of by-products which otherwise may have been uneconomical to mine. Figure 3.16 illustrates how the extraction of certain elements depends on the mining of other, primary elements. The cost of mining as well as part of the processing costs, for example the crushing and milling of the ore, of by-products are paid for by the income generated from sales of the primary product. A problem associated with mineral commodities that are extracted as by-products only, is that it increases uncertainty about their future supply (Ashby, 2015: 7).

Indium (In), for which the demand has increased substantially over the past few of decades (by 1 675% from 1975 to 2012), is a good example of such an element. Over the same period the production of Zinc (Zn), from which the vast majority of indium is recovered, increased by 231% only (Nassar et al, 2015: 7). The recovery efficiencies of indium from zinc ore had to be improved. Fortunately, that solved the problem in the near term. This type of scarcity is structural in nature (Gunn & Buccholz, 2010: 10). Germanium is another example of "an element that is constrained in its availability because it is not appreciably concentrated by geological processes. While not particularly scarce (it is 20 times more abundant than silver), it rarely forms minerals in which it is a principal component, and is produced primarily as a by-product of zinc extraction." (Jaffe et al, 2011).

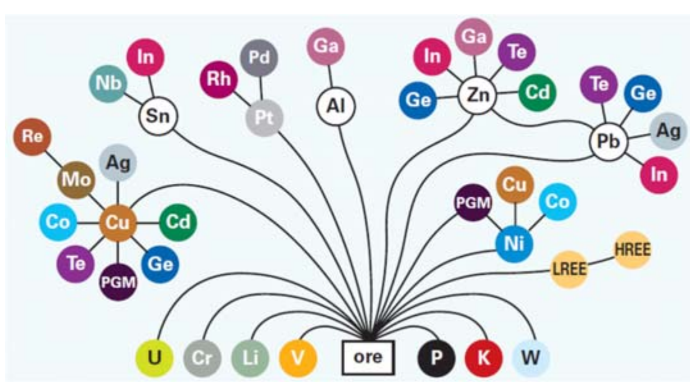


Figure 3.16 Chemical elements not directly linked to the "ore" block are produced as co- or by-products (Zepf et al, 2014: 14)

3.11 RECURRING CONCERNS, BUSINESS CYCLES, AND SUPERCYCLES

Non-renewable resource demand and supply are not constant in the long run. Neither do demand and supply grow at a constant rate. They are subject to regular booms and busts and changing market conditions. Primary demand is influenced by economic growth, the intensity of materials use, recycling and so forth. Economic growth is cyclical in nature. In the short run, mine supply can be influenced by natural disasters, labour unrest, high rainfall at surface mines and the breakdown of critical equipment and infrastructure. Business cycles influence investment patterns and vice versa. The above-mentioned are just some of the factors and phenomena that fuel "recurring concerns" about the availability of non-renewable resources observed by Krautkraemer (2005: 5).

A number of the so-called classical economists were concerned about the declining quality of agricultural land, declining mineral *grade*s, diminishing marginal returns, and as a consequence of that, the sustainability of future economic growth. The relationship between the availability of resources and economic growth was subsequently addressed in a number of publications such as *Scarcity and growth* (1963), *Limits to growth* (1972), *Scarcity and Growth Reconsidered* (1979) and *Limits to growth revisited* (2011).

The average global economic growth rate of almost 5% experienced from 1950 to 1975 declined because of the recession triggered by the first oil price shock in the 1970s followed by tight monetary policies in the 1980s and the shrinkage of the communist economies in the 1990s after the collapse of the Soviet Union. This left the minerals industry with a lot of overcapacity (Humphreys, 2015: 13). Furthermore, metal consumption stagnated during the period because of factors such as the greater contribution of services towards the GDPs of developed countries. This resulted in deteriorating *intensity-of-use* (Tilton, 1989: 265). Economic growth seemed to be decoupled from mineral raw materials. However, during the last (2002/3 – 2013/14) price *supercycle*, concerns about the availability of non-renewable resources resurfaced. Figure 3.17 shows both the declining price trend for copper since the early 1970s as well as the start of the price cycle.

Researchers found price supercycles in both combined renewable and non-renewable as well as in non-renewable commodity price data. Many concerns about the long run availability of non-renewable resources seem to overlap with such cycles. This is illustrated in Table 3.4 (Cuddington & Jerrett 2008; Erten & Ocampo, 2013; Jacks, 2013; Jerrett & Cuddington, 2008; Radetzki, 2006).

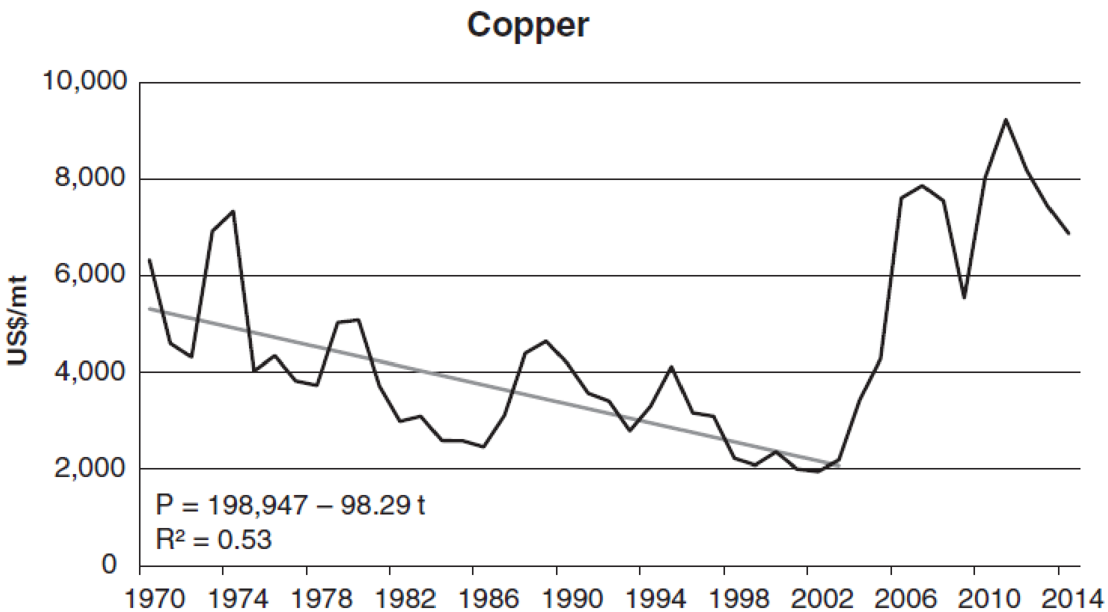


Figure 3.17 Average annual real price for copper from 1970 to 2014 in 2014 dollars per metric tonne (Tilton & Guzmán, 2016: 94).

Table 3.4 Four commodity price supercycles identified from 1865 to 2010 (Erten & Ocampo, 2013: 14, 19, 20, 26)

Super cycles (peaks) and probable cause. [metal cycles]	**Evidence of concerns regarding scarcity and availability**
1894-1932 (1917). [1885-1921]	Corresponds with the period during which the U.S. Conservation Movement was very active because of concerns over the country's resource use.
1) 1932-1971 (1951) "Post-war reconstruction in Europe augmented by the economic emergence of Japan". 2) Massive inventory build-up in response to the Korean War which started in 1950 and ended in 1953 (Radetzki, 2006: 56) [1921-1945]	Appointment of the U.S. President's Materials Policy Commission. A comprehensive report was published in 1952.
1971-1999 (1973). "OPEC's market management" and other causes (Radetzki, 2006: 56, 59). [1945-1999].	Oil price supercycle. Much debate and many publications about the role of OPEC and the impact of high oil prices on the economy.
(2010). Mineral prices are driven by the rapid pace of industrialisation and urbanisation in China, India and other emerging economies. [From 1999 and ongoing at the time of publication.]	Renewed interest in supercycles and *critical mineral*s. Concerns in Europe about the availability of mineral commodities. The *circular economy* is adopted as a means to alleviate materials scarcity.

Since the early 1990s China's economic growth was around the 10% level but the size of its economy was not yet such to have a clearly noticeable influence on the minerals markets. After continued fast growth, its share of global base metal consumption reached about 50% by 2013. The accompanied price supercycle which was clearly visible by 2005 came as a surprise to many and because of the characteristic production capacity lag, massive new production capacity was only in place by 2013.

Evidence in this section suggests that concerns about the availability of non-renewable resources may increase and decrease during a business cycle and supercycle.

3.12 PAST AND CURRENT DEMAND SHIFTS

Shifts in raw material demand are briefly discussed in this section. Such shifts are driven by factors such as disruptive technologies, the emergence of *dominant designs*, economic development, urbanisation and, more recently, global warming and climate change. The last mentioned is referred to in the literature in a number of ways, such as the need for a decarbonised or low-carbon economy. Demand shifts may cause availability concerns when new types of raw materials are required or if raw materials are required in greater quantities than before. Demand shifts are likely to put pressure on existing mine production and processing capacity.

3.12.1 Raw material shifts from the Stone, Bronze and Iron ages to the Fourth Industrial Revolution

The demand for bronze as a dominant material during the so-called Bronze Age had to change in a world with increasing appetite for raw materials. The dominance of the internal combustion engine over steam- and battery-driven vehicles in the early history of cars soon created an enormous demand for oil, which still dominates road transport today. The rise of OPEC is considered to be one of the key transformations of the 20th Century. Together with the two oil price shocks of the 1970s, it is linked to economic recessions, US-Middle East power relations, oil dependency and military strategy, and it had a major impact on the discipline called the "International Political Economy of Energy and Natural Resources". Oil availability and security became a major focus of study, and much has been written about it, especially after the formation of OPEC, the two oil price shocks in the 1970s and the peaking of U.S. oil production, after which the country became more and more dependent on oil imports.

Today we experience the beginnings of a change away from a fossil-based economy to a decarbonised economy. Furthermore, the emerging raw material needs of the so-called Fourth Industrial Revolution may yet again be responsible for raw material demand shifts in the years and decades to come.

3.12.2 Resourcing the greener, low-carbon economy and energy transition

Some people consider planetary warming to be the biggest existential crisis facing humanity today (Planting, 2019). More and more people are experiencing the effects of global warming and climate change, and fewer have doubts about it. According to a Statista survey (2019), 71% of the adults in India, 69% in Spain, 48% in France and 38% in the U.S. believe that humans are mainly responsible for Climate Change. According to Ian Dunlop, chairman of Safe Climate Australia and a former chairman of the Australian Coal Association, a two-degrees Celsius increase in the average global temperature is at the boundary of extremely dangerous climate change. Three degrees represents extreme social chaos, while we are heading for four degrees according to Dunlop (Planting, 2019; Videos by Ian Dunlop). Many citizens worldwide demand action on Climate Change, but the fossil fuel economy is well entrenched and the Trump Administration started the procedure to withdraw the U.S., the biggest carbon admitter, from the *Paris Agreement on Climate Change* despite calls for a *Green New Deal*. Diverse opinions and the unfolding of many opposing events make predictions about the future use of fossil fuels very difficult. There are two important drivers behind the change towards the low-carbon economy. The one is to introduce remedies to lower carbon emissions and the other is the declining cost of renewable energy. Both support the transition to the low-carbon economy, also referred to as "green economy", "energy transition" and "energiewende" in Germany.

Electricity generation and global transport contribute significantly towards global GHG emissions, and decarbonisation efforts should therefore focus on these sectors of the economy (Hunt et al, 2013: 1; Paun et al, 2019: 8). The economics of renewable energy technologies, such as wind turbines and photovoltaic cells, have improved significantly over the past few decades. Today they are cost competitive and their cost curves illustrate declining trends (Energy Transitions Commission, 2017: 15, 54; IRENA, 2018: 17). These technologies have expanded the different options in the energy sphere significantly and provide solutions to the problem of global warming and climate change. Together with energy storage technologies (e.g. battery and pumped storage) they would be able to completely substitute for fossil fuels. A few countries have made significant and rapid progress towards the decarbonisation of their economies. In the UK, where the Industrial Revolution and mass utilisation of coal started and about 80% of electricity was produced from fossil fuels only ten years ago, more electricity was generated from renewables in the third quarter of 2019 than fossil fuels (Ambrose, 2019). The UK has decreased its carbon intensity by 35% over the past ten years (PWC, 2019). In fossil fuel rich countries, such as the U.S., Australia, Russia, Saudi Arabia, Poland and the Czech Republic, the transition to a low-carbon economy will probably not be as fast and may even be contested (Ocelík et al, 2019; Planting, 2019). Höhne et al (2020: 27) pointed out that remedies to lower GHG emissions will have to be accelerated because of the increasing gap between what nations pledged in the 2010 Cancun Agreement, the 2015 Paris Agreement and what has actually materialised.

Currently, battery electric vehicles (BEVs) are adopted much faster and to a much greater extent than fuel cell electric vehicles (FCEVs). FCEVs together with the hydrogen economy have a number of advantages, however. Intermittent renewable energy can be stored as hydrogen when not immediately needed. A number of initiatives are in place to promote fuel cell use and the hydrogen economy. For example, China, the world's biggest electric vehicle producer, is in its latest five-year plan shifting its focus from BEVs to FCEVs (Creamer, 21 Aug 2019).

Many people are concerned about the cost of solving the climate change problem. Projections on both the costs of global climate change as well as the benefits of finding solutions are available. A study by Burke et al (2018: 549) claims that there is a 60% chance that accumulated global benefits will exceed $20 trillion under certain conditions and Lewis (2019: 3) thinks that mobility provided by a combination of wind and solar-energy projects and battery electric vehicles (BEVs) is affordable. Using the concept of Energy Return on Capital Invested (EROCI), he showed that oil at a price of $60 cannot compete with this type of low-carbon mobility. According to him the key is to understand that wind and solar projects deliver their energy over a 25-year operating life. To get the same mobility from petrol as from new renewables combined with BEVs over the next 25 years would cost 6 to 7 times more than the renewable option. According to Lewis, the oil industry has never before in its history faced this type of threat to its business model. BEVs powered by solar and wind farms no longer provide a backstop technology – they may push the price of oil much lower once low-carbon mobility has diffused to a larger extent.

Goods such as wind and solar farms are mineral and metal intensive, and the materials that they are composed of are in some cases different from conventional technologies. The amount of copper required by an electric vehicle (EV) is, for example, about four times greater than for an internal combustion engine vehicle (ICEV). Wind and solar use about six times more copper than coal-fired power generation (US Dept of State, 2019). Lithium, cobalt, nickel and manganese are important for the manufacture of batteries used in BEVs. Various forecasts have been made based on assumptions and scenarios. The models of Watari et al (2019: 91) indicate total material requirement flow increases associated with mineral production of 200 to 900% and 350 to 700% in the electricity and transport sectors respectively for the period up to 2050. According to Glencore, the deployment of 140 million EVs by 2030 will require more copper, nickel and cobalt – 3 million, 1,3 million and 263 000 tonnes per year, respectively (Bloomberg, 2019). The United States acknowledges the fact that the transition to the low-carbon economy will increase the demand for certain minerals to such an extent that special measures will have to be taken to ensure future supply. The *Green New Deal* is based on "gargantuan renewable energy projects" which will require massive amounts of non-renewable resources such as copper and battery minerals (Franzen, 2019). According to the U.S. Dept of State (2019) the “demand for critical energy minerals could increase almost 1 000 percent by 2050”. Argus expects the demand for lithium to increase 5,4-fold from 50 000 tonnes in 2018 to 270 000 tonnes by 2030 (Seddon, 2019). This and other forecasts for nickel and cobalt are summarised in Table 3.5 below where they can be compared with the much lower growth rate forecasted for oil.

Table 3.5 Forecasted data for three important battery metals compared with a fossil fuel (Creamer, 11 March 2019; Seddon, 2019).

Metals and energy	**Actual demand in 2018**	**Estimated demand in 2030 [2024]**	**Average annually compounded growth rates**
Lithium	50 000 tonnes	270 000 tonnes	15,1%
Cobalt	100 000 tonnes	300 000 tonnes	9,6%
Nickel	2,3 million tonnes	4,6 million tonnes	6,0%
Oil	99,2 m barrels/ day	[106,4 m barrels/day]	1,2%

Despite current relative low levels of adoption and diffusion of wind turbines, solar cells and EVs, there is much support for them and a lot pressure on companies to reduce their usage of fossil fuels. France has, for example, indicated that it will stop the sale of petrol and diesel vehicles by 2040 while the UK has pledged that half of all new cars will be hybrid or electric by 2030. BP now stands for beyond petroleum, Glencore announced the capping of coal production, South 32 is divesting from its coal assets, Russia has sold off parts of Rosneft, Saudi Arabia wants to diversify its economy away from oil by selling (privatising) parts of Aramco, and various shareholders, investors and investment funds no longer invest in fossil fuel stocks and production capacity, to mention just a few examples (Bloomberg, 2016: 7; Boehling, 2019: 51; Fickling, 2019; Goldthau et al, 2018: 1, 3; Jordans, 2019; Naidoo, 2019; Schwartz, 2016; The Economist, 2017: 13).

Numerous wind and solar farms have been constructed over the years and, therefore, the materials and quantities needed to manufacture and construct them are well established (IRENA, 2017: 11, 13). Many non-renewable resources, for example steel are used in the construction of wind turbines and wind farms. This shows that although wind and sunlight are generally referred to as a renewable energy, their *energy pathway*s are not renewable. The same applies to solar (PV) cells and solar farms. This is why Sverdrup and Ragnarsdottir (2014: 148), define photovoltaic (PV) technology as *semi-renewable*. Although PV cells use solar energy, which is renewable, the cells are made of materials that are non-renewable and of which some are classified as *critical materials*. The energy company, BP, commissioned a study to get more information on how different *energy pathway*s may be impacted by the availability of materials (Zepf et al, 2014).

Previous concerns about the availability and affordability of oil are now being replaced by concerns about the future availability of materials required to manufacture wind turbines, PV cells and devices to store energy produced from intermittent energy sources such as sunlight and wind. Such devices are more material-intensive than coal-, gas- and oil-fired power stations (Arrobas et al, 2017: 19). It is predicted that fossil fuels will become abundant once renewable resources of energy are well adopted (WEF, 2018: 12). Zepf et al (2014: 5) identified 60 metallic elements involved in *energy pathway*s and McLellan et al (2016: 1, 9) selected a number of *critical mineral*s required for energy efficient devices and clean energy technologies.

This may significantly increase demand for materials from which wind farms, PV plants and electric vehicles are constructed if it becomes necessary to significantly accelerate the adoption of renewable *energy pathway*s as a result of global climate change. If storage capacity, like battery storage, is added to wind farms and PV plants to compensate for the intermittency problem of such variable sources of electricity production, then even more materials will be required. Currently there is a scramble by various companies to get their hands on battery materials such as lithium and cobalt (Rathi, 2018; Reichl, 2018: 7; Reuters, 12/12/2018).

To summarise, we are in a world where numerous energy options are available ranging from non-renewable to renewable sources. Declining renewable energy costs are increasing its competitive advantage. One problem, however, is that the *energy pathway*s of so-called renewable energies are not renewable. The “availability of energy” problem has shifted to some extent to a concern about the availability of materials from which renewable energy devices are manufactured, given a scenario in which its implementation has to be fast-tracked. For this reason the focus of this study is more on materials rather than non-renewable forms of energy.

3.13 CONCLUSION

Emerging economies, especially China, have influenced the demand and supply of mineral commodities significantly over the past few years. The natural sciences provide clear evidence that the concentrations of different metal types in the earth’s crust vary significantly in some cases from one another – some are more abundant than others. Orebodies are not homogeneous – the quality and *grade* of minerals inside an orebody may differ from one point to another. The average *grade* of one orebody may differ from another. This contributing factor gives rise to orebodies with different costs and an associated cost curve for each mineral commodity at a specific point in time. Low *grade* resources are more abundant, and the average *grade* of orebodies is declining. Some countries have a comparative advantage in the production of certain mineral commodities. Other nations cannot compete with them and may import such commodities from them, resulting in mineral dependency. Mineral dependency could create problems when mineral *resource nationalism* arises. Such occurrences have stimulated research into the area of critical minerals.

Mineral commodities are supplied by both large scale industrial mining firms as well as by artisanal and small scale miners. Artisanal mining plays an important role in the supply of a few commodities. The cost of producing certain mineral commodities is currently relatively low because they are produced as by-products. Prices will have to increase significantly if future demand increases to levels where such commodities can no longer be produced as by-products only. Mineral prices are cyclical. High prices at the peak of cycles are associated with recurring concerns about the availability of non-renewable resources. Mineral demand shifts have occurred in the past during transitions such as that from the Bronze to the Iron Age. Today, the beginning stages of a shift to a low-carbon, greener economy are expected to result in similar mineral demand shifts.

In Chapter 5 this information is used to identify the core facts related to the "availability" body of knowledge.

CHAPTER 4 - THE MEASUREMENT AND MITIGATION OF NON-RENEWABLE RESOURCE SCARCITY

4.1 INTRODUCTION

In this chapter, three main topics are discussed. Firstly, *indicators of resource availability* such as real price trends are discussed. The focus is on how effective and efficient various *indicators* are in measuring availability. The second main topic discussed in the chapter is the methods that are used to mitigate non-renewable resource scarcity and availability. Of interest is how effectively a broad range of methods may affect the availability of non-renewable resources now and in the future. One of the goals of company strategies and government policies is to mitigate scarcity and to ensure the availability of critical and strategic raw materials for a nation's manufacturing industry and military. Policy making is, therefore, the third main topic discussed in this chapter.

4.2 MEASURING THE AVAILABILITY OF NON-RENEWABLE RESOURCES

4.2.1 An introduction to scarcity and availability indicators

If it was possible to design measures that could accurately indicate the availability of various types of renewable and non-renewable resources at various times into the future, then uncertainty would disappear and debates about the future availability of resources would quieten down. The use of *indicators* such as real price trends and reserve-to-annual production (*R/P*) ratios are attempts to generate information about the past, current and future availability of non-renewable resources. *Overshoot day* indicates, for example, that shortfalls already exist in terms of the utilization of natural resources and that the *environmental credit crunch* is underway. None of the current *indicators* are perfect, however. Cost and price trends do not reflect all externalities, for example. Consequently, various *indicators* have been proposed and analysed over the years, ranging from real user costs to elasticities of substitution, the *resource base*, real marginal costs of extraction and processing, real product price, rental rate, reserves, *reserve-to-production ratio (R/P ratio)* and unit costs. Less conventional *indicators* such as *peak mineral production* can also be added to the list. *Indicators* of critical or strategic minerals indicate national availability and supply risk and are discussed in Chapter 3. (Barnett & Morse, 1963: 164; Brown & Field, 1978:

229; Campbell & Laherrére, 1998; Cleveland & Stern, 1999: 89; Fisher, 1979: 253; Johnson et al (1980); Singer and Menzi (2010); Tilton, 2003: 19, 21, 26).

Ideal *indicators* must meet criteria such as ease of computability and the ability to look forward and serve as a warning of scarcity. The lack of certain information, for example about quantities of undiscovered non-renewable resources and the future effects of undiscovered technologies, are unknown or at best imperfect and complicate the development of the perfect *indicator*. According to Tietenberg (2006: 320) foresight is an important criterion for an ideal scarcity *indicator*. This points to the ability of an *indicator* to forewarn and provide humanity time to respond. Foresight is, however, a challenging criterion of which most *indicators* fall short. For example, extraction costs depend on the quality of resources currently being used rather than those which will be used in the future (Tilton, 2003: 30).

Various advantages and disadvantages of *indicators* are discussed in the literature. It is clear that no superior metric has yet been designed. Of all the *indicators* invented and tested over the years, reserve-to-production (R/P) ratios and real price trends are still being used. They are briefly discussed.

4.2.2 The reserve-to-production ratio

The *R/P ratio* is the ratio of (global) reserves to annual (global) production and provides the life of (global) reserves in years. It is also referred to as the “reserve-to-use” ratio or “burn” ratio. The United States Geological Survey regards *reserves* as that part of the reserve base that could be economically extracted at the time of determination (USGS, 2016: 197). At a micro, firm or orebody level, that term can also be defined as that store of natural raw material upon which a profitable enterprise might be built. It is usually required of mining companies to declare their reserves, especially if they are listed on stock exchanges. It is also in their interest to do so if they wish to attract investments. The reserves of a specific mine divided by its annual production gives an indication of the mine’s life. Mineral reserves are dynamic because they can be depleted through mining and new reserves may be found through exploration activities. Furthermore, reserves will increase when prices increase and/or costs are reduced because most orebodies contain ores of a variety of *grade*s ranging from lower to higher *grade*s. Technological innovation that enables the profitable mining of formerly uneconomical low *grade* resources change such ores into reserves (Lasky 1945: 471, 474).

Mining companies adjust their reserves from time to time. Some mines may not even know the full extent of their ore reserves at the time they start mining because not all mining companies will explore a (large and/or dispersed) orebody fully before a mine is established. It may be too expensive to do extensive drilling of the whole resource, especially if it extends to deep levels as in the case of a kimberlite pipe. Most companies start a mine as soon as a big enough part of the orebody had been confirmed as reserve. It is cheaper to explore deeper parts of the orebody by drilling holes from inside a pit or underground mine once it has reached a certain depth. Existing mines often expand their reserves as they do further (brownfield) exploration concurrent with extraction. This may result in the addition of new sections, (sub) shafts, declines and/or neighbouring pits.

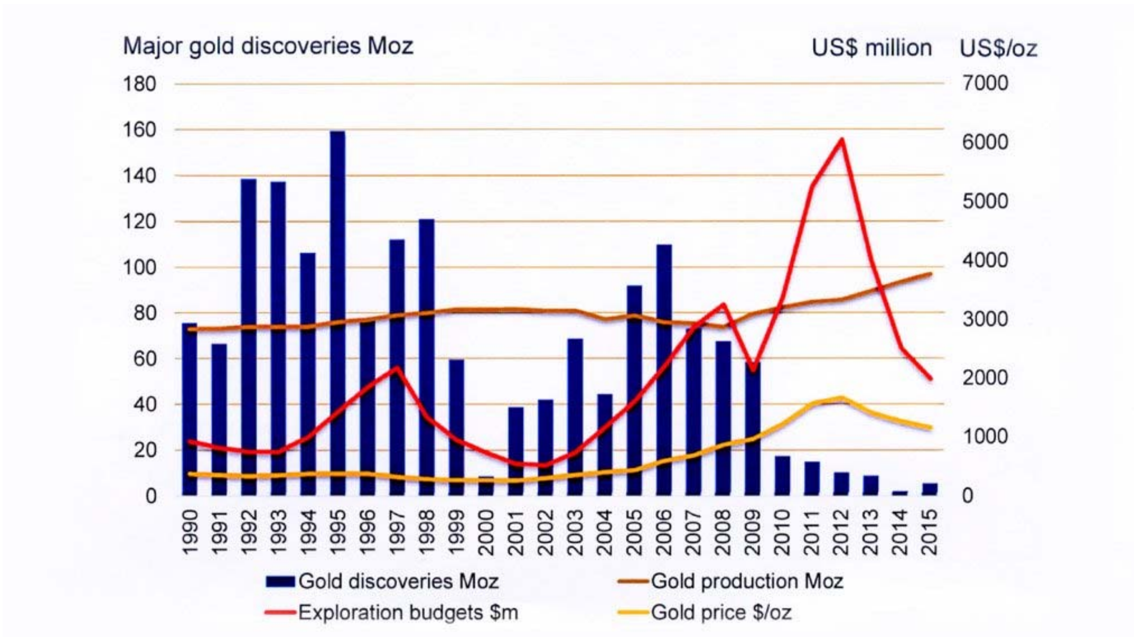


Figure 4.1 Annual additions to gold reserves vs annual production for the period 1990 to 2015 - provided by Randgold to Creamer Media (Creamer, 2016)

Reserves decrease as they are mined and increase when exploration activities are successful in finding profitable orebodies. If everything else stays the same, *R/P ratio*s decline over time when more reserves are mined per annum than what is added by means of new discoveries. This may raise concerns if it becomes a trend that continues for a number of years. Such concerns may at some point in time be observed in the working of the price mechanism and exploration budgets. This is illustrated in Figure 4.1.

Table 4.1 World production and R/P ratios for various minerals in 1970 and 1990. The 1970 R/P ratios are from the Limits to Growth study. (Ekins, 2000 :20)

Mineral commodity	World production (million tonnes)		R/P ratios at different points in time (measured in years)	
	1970	1990	1970	1990
Copper	8,56	8,81	36	36
Aluminium	75	109	100	200
Lead	3,5	3,37	26	21
Mercury	8,7	5,8	13	22
Nickel	0,81	0,94	150	52
Tin	0,25	0,22	17	27
Zinc	5,35	7,33	23	20

Similar to determining the life of an individual mine, the global life of reserves can be easily calculated by dividing global reserves for a specific mineral commodity by the global annual production. The reserves in Table 4.1 are the aggregate of all exploration and mining companies' individual reserves for a specific mineral commodity and this, therefore, provides a macro view. Decades ago global *R/P ratio*s alarmed a number of researchers. They did not understand the dynamic nature of both reserves and *R/P ratio*s and thought they indicated that a number of minerals would be depleted within a few years' time. Once *R/P ratio*s had been calculated for a number of years, an interesting phenomenon was observed, namely that *R/P ratio*s did not decline significantly due to depletion by mine production. *R/P ratio*s actually increased in some cases as was the case with oil by 1978. Compare the *R/P ratio*s of 1970 and 1990 in Table 4.1. Friedman (1978: 3, 4) described this phenomenon as follows: "In the 1920s there was a great uproar about the fact that the total volume of reserves of petroleum would only last ten or twenty years. Today the total volume of known reserves is higher than it has ever been … What's true in the case of oil is true in the case of all of these natural resources. Invention, discovery, innovation have enabled us to discover substitutes for natural resources. It has enabled us to learn how to use them more efficiency, to recycle them."

The *R/P ratio* has certain advantages and disadvantages as an availability *indicator*. It is relatively easy to calculate and data is readily available. Its "forward looking" capacity is limited, however, by the degree to which investments are made to create reserves. It is important to calculate it from time to time. It has been found that individual mining companies have little incentive to expand their exploration activities once they have reserves that are sufficient for about 30 years of mining.

Expected future economic growth in consumption reduces *R/P ratio*s rapidly when it goes hand-in-hand with growth in annual commodity production. This is shown in Table 4.2 for commodity production growth rates of 0, 2 and 5 percent. A static, no-production-growth *R/P ratio* (as in column 4 of Table 4.2) of say 50 years for a specific mineral commodity may actually not provide much of a buffer if such a commodity is needed for the manufacturing of a new product that is fast and widely adopted by the market. Commodities used in the batteries of electric vehicles and in solar and wind farms may experience significant increases in demand if the transition to a low-carbon economy takes place quite rapidly.

Table 4.2 Life expectancies of global reserves (Tilton, 2003: 21)

Mineral Commodity[a]	*1999 Reserves*[b]	*1997–1999 Average Annual Primary Production*[b]	*Life Expectancy in Years, at Three Growth Rates in Primary Production*[c]			*Average Annual Growth in Production, 1975–1999 (percent)*
			0%	*2%*	*5%*	
Coal	9.9×10^{11}	4.6×10^{9}	216	84	49	1.1
Crude oil	1.0×10^{12}	2.4×10^{10}	44	31	23	0.8
Natural gas	5.1×10^{15}	8.1×10^{13}	64	41	29	2.9
Aluminum	2.5×10^{10}	1.2×10^{8}	202	81	48	2.9
Copper	3.4×10^{8}	1.2×10^{7}	28	22	18	3.4
Iron	7.4×10^{13}	5.6×10^{8}	132	65	41	0.5
Lead	6.4×10^{7}	3.1×10^{6}	21	17	14	–0.5
Nickel	4.6×10^{7}	1.1×10^{6}	41	30	22	1.6
Silver	2.8×10^{5}	1.6×10^{4}	17	15	13	3.0
Tin	8.0×10^{6}	2.1×10^{5}	37	28	21	–0.5
Zinc	1.9×10^{8}	7.8×10^{6}	25	20	16	1.9

4.2.3 Real prices over time

Price theory and price determination in the short term is dealt with by universities in the curricula of Microeconomics. Despite certain shortcomings, many economists believe that prices are still generally among the best *indicators* of short-term imbalances between the demand and supply of a product. Prices are not only an *indicator*, but high prices are also believed to be the quickest cure of shortages of products and services. From there comes the saying that the best solution to a high price is an even higher price because that will incentivize entrepreneurs to make use of such opportunities. Price controls, externalities and taxes may, however, prevent markets from providing correct responses to scarcity (Tietenberg, 2006: 316).

Microeconomic theory informs that in a competitive market a firm should choose its output at a level where its marginal cost equals the market price (Pindyck & Rubinfeld, 2013: 287). In the case of non-renewable resources, the situation is slightly more complicated because *user cost* (*scarcity rent*) must also be considered. According to Slade (1982: 123) and Tilton (2003: 14), price reflects user cost as well as extraction and processing cost. Nor do all these extractive industries operate competitively.

Mineral commodity prices can be very volatile and can double or halve within a period of one to two years (President's Materials Policy Commission, 1952: 83; Tilton & Guzmán, 2016: 93). As a result of the usually long lead times to find new ore reserves and design and develop mines, it is difficult to balance supply and demand in the short run. Mineral price volatility is influenced by factors such as the price elasticity of demand, income elasticity of demand, the prices of substitutes and production disruptions where production is geographically concentrated. It is known that mineral commodity prices are sensitive to business cycles because most materials are used in capital equipment, construction, transportation and consumer goods. When the global economy is booming, the demand for such goods tends to expand even more rapidly, but they also suffer more severely when the global economy is in recession. In the long run, consumers have more time to respond to price changes and, therefore, long-run price elasticity of demand is relatively greater than that in the short run (Tilton & Guzmán, 2016: 27, 28).

Before humanity discovered a method to extract iron from ores in the crust, iron oxide meteors were the only source of iron, and therefore iron was very scarce despite the fact that iron oxide is a very abundant component of the earth's crust. The same applies to aluminium, which was once considered to be a precious metal. The two examples illustrate that price is not only an *indicator* of geological but also of technological availability.

Concerning the long run, the *Prebisch-Singer hypothesis* claims that the prices of primary renewable and non-renewable commodities decline relative to the price of manufactured goods, with an associated deterioration of the terms of trade of primary-product-based economies (Cuddington et al, 2007: 104). In contrast, in Hotelling's original model, which does not make provision for the discovery of new mineral reserves, substitution, recycling and efficiency improvements, the prices of non-renewable resources are expected to increase over time as they are depleted. Solow (1974: 2) agrees with Hotelling. He regards non-renewable resources as capital assets in the ground that must appreciate in value.

Various theoretical and empirical studies had been done and Hotelling's rule could not be confirmed by Barnett and Morse (1963: 210), Barnett (1979: 186) and Smith (1979: 426). La Nauze and

Schodde (2004: 2) found a long-term declining trend in real metal prices for the period 1800-2000 as illustrated in Figure 4.2, which seems to support the *Prebisch-Singer hypothesis*. Nordhaus (1974: 24), found declining prices for 11 mineral commodities relative to the cost of labour during the period 1900 to 1970. Figure 4.3 shows that although the annual consumption of copper has increased about a hundredfold since the 1880s, its (real) price has not changed in a similar way, suggesting that copper has not become significantly scarcer. The volatility visible in Figure 4.3 and the phenomena of price *supercycles* suggest that only long-term trends should be considered, and suggest that a reason why the findings of empirical studies sometimes differ may be because data over different time periods are used.

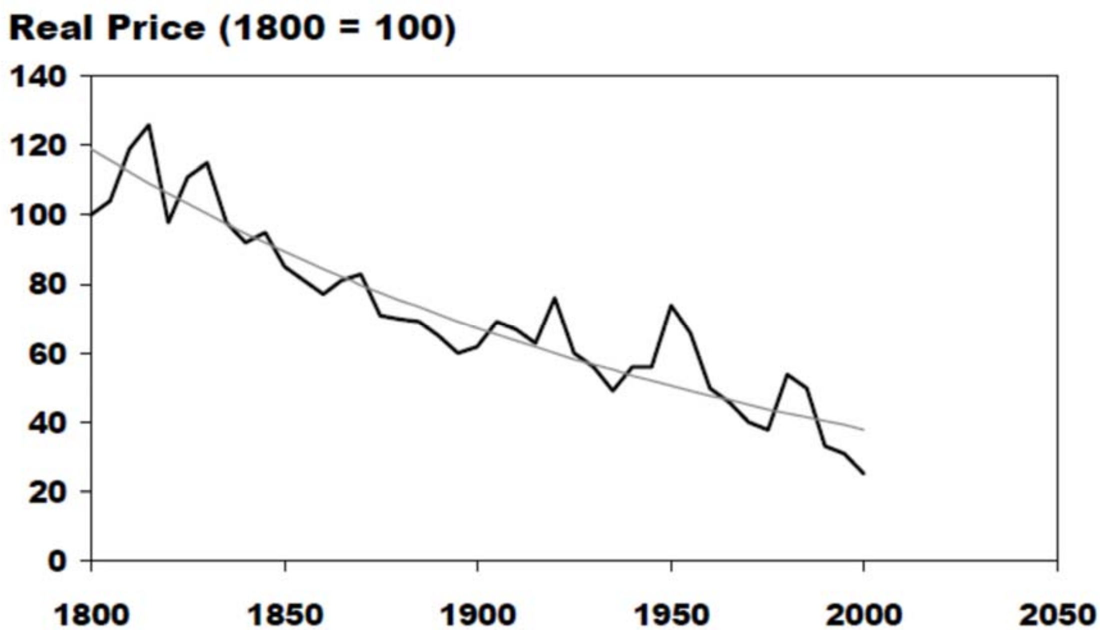


Figure 4.2 Long term trends in real metal prices: 1800-2000 (La Nauze & Schodde, 2004: 2)

In Pindyck's (1978: 842) price model, he assumed that the "fixed reserve base" proposed by Hotelling, can be increased by means of exploration. He proposed a U-shaped price profile because production will increase with the discovery of new non-renewable reserves and later decline as both exploration activity and discovery rates decline. Slade (1982: 130-136) investigated the possibility that prices might first decline but then increase later to form an inverted U-shaped pattern. She found some evidence of such quadratic shapes for a number of mineral commodities. Heal (1981: 338) also found a quadratic U-shaped pattern for prices over the period 1870 to 1973. Slade (1982: 136) and Tilton (2001: IV-28) illustrated that such a pattern can be obtained when user costs increase over time, as predicted by Hotelling – please see Figure 4.4. Over time production costs will increase if technological and efficiency improvements do not adequately compensate for exploitation at deeper levels and at lower *grade*s. Slade (1982: 136) suggested that different mineral commodities are in different phases of their life cycles. Whether their price paths have a falling, stable or rising path at a specific point in time just depends on the phase in their life cycle they are in. Tin, which has been used since ancient times and whose ore *grade*s are declining, is showing a rising price trend.

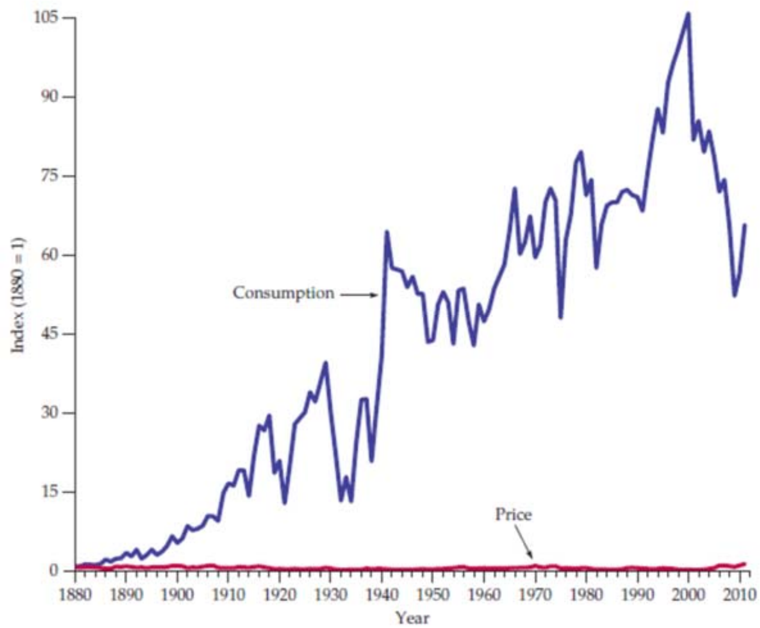


Figure 4.3 The annual consumption and real price of copper over time both shown as indices (Pindyck & Rubinfeld, 2013: 30)

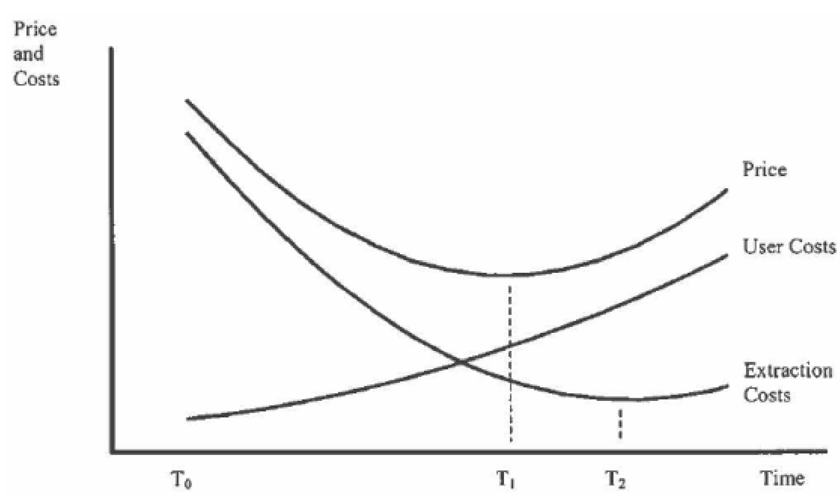


Figure 4.4 Hypothesized trends in user costs, production costs and prices for mineral commodities (Tilton, 2001: IV-27, Slade, 1982: 125)

The accuracy of inflators is a factor that may impact on the accuracy of real prices as *indicators* of scarcity in the long run. Svedberg and Tilton (2003: 21) think that the US CPI and other standard

deflators overestimate inflation by 0,9 to 2,0 per cent. In the case of copper this may call the downward trend of copper prices over a period of 130 years into question.
One of the latest, comprehensive studies on long-term price trends was done by Cuddington and Nülle (2014: 224). They investigated the price trends of more than 100 minerals over fairly long periods back to the late 19th or early 20th century for long-run trends by using low-frequency band-pass filters. Cuddington and Nülle concluded that there is no "general tendency" in the negative or positive direction of long-run mineral commodity price trends and, therefore, their findings do not support the *Prebisch-Singer hypothesis.* According to them the topic of whether mineral resources are becoming scarcer or not is far from being exhausted (Cuddinton & Nülle, 2014: 237).

No *indicator* is perfect, and a number of faults can be found with price as an *indicator* of long-term availability. Prices can be distorted by monopolies and cartels, and therefore real price trends must be interpreted within a broader context. If a cartel such as OPEC pushes oil prices higher and the cost of production stays unaltered, then cost trends may be a better *indicator* of scarcity (if such data is readily available). Many oil price changes in the past and today can be explained by political turmoil and decisions made by OPEC. The steep oil price increases in 1973 and 1979 are ascribed to an Arab embargo and the dethroning of Iran's Shah. Cartelization in the 1970s can explain changes in uranium and bauxite prices of that era. According to Pyndyck (2012: 587) some of the price fluctuations observed in the minerals industry have nothing to do with mineral depletion but are rather the result of market structure and other factors.

Another problem with using price to indicate future availability is that future markets are incomplete, and price determination in future markets is mostly based on incomplete information (Campbell & Laherére, 1998: 78; Snowdon & Vane, 2005: 17). It is also uncertain how future prices will be influenced by future technological innovations.

4.3 MITIGATING SCARCITY

A wide variety of methods and techniques for mitigating non-renewable resource scarcity have been developed over the ages since the ancient Greeks experienced a shortage of tin. Such methods range from the exploitation of lower-*grade* resources and the more productive utilisation of resources in manufacturing processes, to the substitution of more-abundant for less-abundant resources. The substitution of iron for bronze and the subsequent transition from the Bronze to the Iron Age serves as a well-known example of scarcity mitigation and a mineral demand shift. Technological innovation is key to many of the methods for mitigating scarcity.

The development of larger mining equipment for surface mines enables economy of scale, increased exploitation productivity and the cost-effective mining of lower-*grade* resources. Technological innovation such as *hydraulic fracturing* (fracking) is key to the exploitation of and creation of shale oil and gas reserves which were previously considered to be of too low quality. Improved technologies also increase the productivity of exploration and may result in the discovery of new reserves. Technological breakthroughs may create the next generation of non-renewable *reserves* on the seabed, the moon and asteroids. Without such breakthroughs, humanity may in future slide back to living standards associated with pre-modern times.

Mitigation methods such as the miniaturization of consumer products or components, the utilisation of nano-materials and structural changes of economies towards services, which is often less materials and capital intensive, usually contribute towards the so-called dematerialisation and "de-coupling of economic growth" trends, resulting in less materials being used per unit of GDP generated. A scarcity mitigation tool such as recycling, also called secondary production, does not reduce the overall need for raw materials but alleviates the demand for primary, mine or oil well production. Some of the resource mitigating methods may have led to the optimism seen in the neoclassical literature regarding the challenge of *sustainability*. One view is that *intergenerational equity* can be achieved through the substitution of non-renewable natural resources by capital. For example, capital goods such as wind and solar farms can substitute for coal used to generate electricity. The combined impact of various scarcity mitigating measures has reduced upward pressure on non-renewable resource prices despite increased demand over time (Barnett & Morse, 1963: v, 7, 127, 164, 229; Rosenberg, 1973: 111, 116; Kamien & Schwartz, 1978: 179; Von Hauff, 2016: 100).

In terms of demand and supply dynamics, mitigating measures either introduce greater supply (e.g. exploration), shift demand to another resource (e.g. substitution) or decrease demand for a specific resource by means of recycling, re-use and wealth taxes. This may result in reduced *intensity-of-use* (IoU). A few examples of both demand and supply-side factors are listed in Table 4.3. These are discussed in greater detail in this section (4.3).

Table 4.3 Factors and forces involved in the mitigation of non-renewable resource scarcity.

Demand side factors	Reducing population growth (e.g. China's now abolished one-child policy)
	Increase efficiency of materials usage in manufacturing
	Lower living standards in the developed world
	Reduced energy and material intensities
Primary supply side factors	Finding substitutes for non-renewable resources

	Finding new orebodies by means of exploration
Secondary supply side factors	Urban mining / Recycling / *Circular economy*

4.3.1 Exploration

The number of new ore deposits found as well as discovery success rates are related to the level of exploration spending, the geological availability of minerals, the status of exploration technology, and exploration productivity. Without exploration, reserves will diminish as they are depleted by mining, assuming that all else, for example, mineral prices and costs, remains constant. The depletion of reserves results in lower reserve-to-annual production *(R/P) ratios.*

Expenditure on greenfields exploration is a high-risk type of investment considering that about one in 500 exploration projects proceed to mine development, according to Colin Rice, founder of an exploration company (Hancock, 2018: 10). Stevens (2010: 5) and De Wit et al (2016: 199) agree that the odds of finding an economic mineral deposit are very low. The purpose of Canadian *flow-through shares* is to reduce the exploration risk for investors. This mechanism is responsible for greater global availability of mineral commodities.

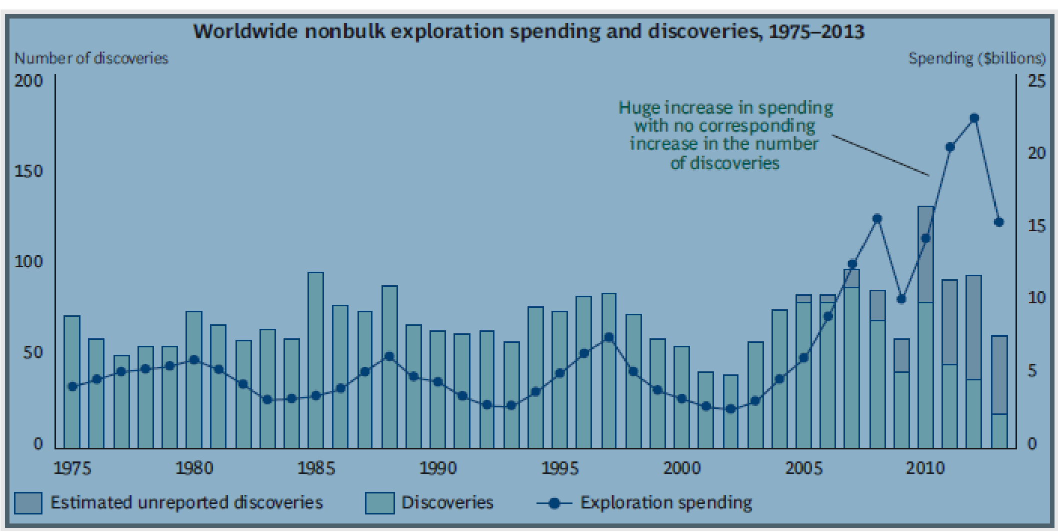


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Figure 4.5 Exploration spending and discoveries (Koch et al, 2015: 4)

Greenfields mine development could lag initial prospecting by as much as 15 to 19 years. Exploration expenditure is often cyclical because it is affected by mineral prices, which are cyclical. Price levels influence the free cash flow of mining companies and the expected profitability of new discoveries (Starke, 2002: 36). According to Jayasuriya (2015: 226), a firm would undertake exploration until the marginal discovery cost equals the marginal scarcity rent received from a unit of the resource sold. This mechanism should encourage exploration as long as population and income growth contribute to higher mineral demand and increase marginal *user cost*.

An important perspective on exploration is that once mining companies have enough reserves to last about 20 to 30 years, there is less incentive to spend money on exploration if reserves created in the process will only be used and generate returns in a few decades' time (Meinert et al, 2016: 3; Tilton, 2003: 20). The lives (*R/P ratios*) of mines in terms of measured reserves may, therefore, generally not be expected to be much higher than 30 years. From a sustainability perspective, one would like to see much higher global *R/P ratio*s (longer lives, measured in years), but that is not going to happen because exploration is expensive and risky.

Information from a few sources suggests that returns on exploration spending, measured in terms of discoveries, have decreased over the past number of years as indicated in Figure 4.5. According to Schodde (2017: 14, 31), it is too early to tell whether the drop in discovery rate is "real" or "apparent" (WEF, 2014: 23). Obtaining good information on the type, quantity, quality, location and depth of remaining resources in the earth's crust is very expensive. The lack of such information is one reason why the debate about the availability of non-renewable resources in the long run is likely to continue into the future.

4.3.2 Technological innovation

Technological innovation plays an important role in both the increasing (indirect) demand as well as the supply of mineral commodities. Devices such as smartphones and GPS devices have informed consumers today of needs that many did not even imagine they had a few decades ago. Various economists, for example Schumpeter (1987: 648 & 995), Marx (1885: 73, 349, 351) and Solow (1957: 320), pointed to technological innovation and change as potential sources of economic growth, although this is difficult to model and quantify as illustrated by the *Solow residual*.

In some cases, innovation can also alleviate the scarcity of a specific non-renewable resource. This was pointed out by Barnett and Morse (1963: v, 7, 127, 229), who ascribed the fact that an index of mineral prices did not increase significantly over many decades to factors such as technological innovation and substitution. The approach followed in this section is to illustrate by means of a few examples how technological innovation, its adoption and diffusion could influence the cost of mining, mineral prices and the availability of various mineral commodities.

Innovation manifests itself in different forms and can, therefore, be classified in various ways which are not necessarily mutually exclusive. It is possible to differentiate between organisational and technological innovation but also between incremental, radical and transformative innovation. Research and Development may result in process, product or other forms of innovation. For the purposes of this study it is useful to refer to innovation which helps to create new reserves. This may be accomplished in many ways and through different channels. The improvement of exploration, extraction and processing productivity and efficiencies reduce exploration, mining and mineral processing costs and allow for cost-effective mining. It is possible to compile a very long list of various technologies that have contributed towards the increasing supply of mineral commodities, but only a few significant and notable examples are mentioned here. Pumping technology is required at many surface and underground mines because water tables can be found at shallow depths. This enables mining at much greater depths, together with improvements in hoisting technologies, mine ventilation and cooling. Improvements in processing technologies enable the profitable re-processing of low *grade*, previously unprofitable, tailings. The invention of explosives improved rock breaking productivity tremendously – something that was very much needed to enable today's large production volumes.

It is not only technological innovation in the area of mining and extraction that reduces upward pressure on the prices of mineral commodities, but also innovation in areas such as materials technology, miniaturization and digitisation. Many examples exist of new materials that have been developed and the use of resources that are more abundant (Rosenberg, 1973: 116; Kamien & Schwartz, 1978: 179). Innovation may also enable a higher degree of recycling.

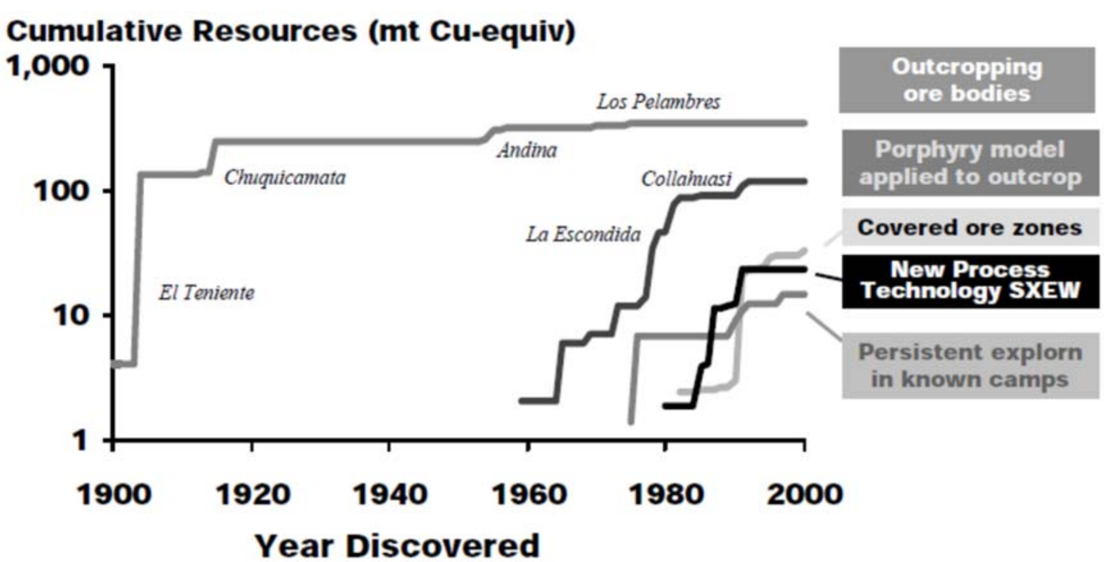

Figure 4.6 Cumulative copper resources in Chile using different exploration, mining and processing technologies (La Nauze & Schodde, 2004: 6)

An example of how newer technology enabled the mining of a new class of copper orebodies is that of the solvent extraction electro-winning (SX-EW) process for copper oxide ore. Figure 4.6 illustrates how this technology enabled the re-invigoration of copper mining in Chile. Advantages in the block caving mining method resulted in a further 70% reduction in the capital cost per tonne mined, thus expanding the reserves.

Rosenberg (1973: 111) thinks technological change is in the long run the most powerful mechanism through which a market economy responds to shifting patterns of resource scarcity. There are limits, however, to research and development budgets and the rate of innovation. Technological innovation could, therefore, be overrated by some as the saviour of humanity. According to Bartos (2007: 149), mining is not comparable to high tech manufacturing with its 9,5% annual growth in productivity improvement but more comparable to general manufacturing with lower productivity improvements of between 2,5 and 3%. It is difficult to predict whether research and development spending will result in continued technological innovation in the long run. Persons with views on the nature of its continued influence into the future are often divided into two groups, technology optimists and pessimists.

4.3.3 Economies of scale

According to Pindyck and Rubinfeld (2013, 255, 256), economies of scale is a "situation in which output can be doubled for less than a doubling of cost". This can be achieved in a number of ways.

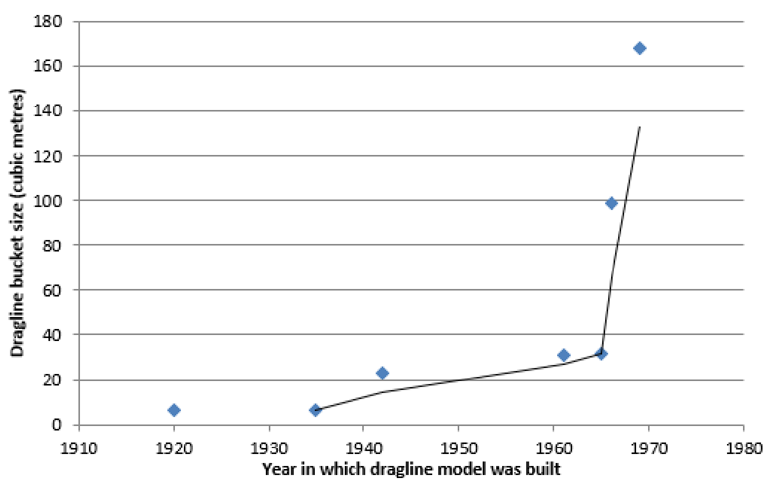

Figure 4.7 Dragline bucket sizes over time (Data set can be obtained from WP Nel at wnel@unisa.ac.za or wilhelmpnel@gmail.com)

One way in which economies of scale are achieved by an individual mine (or plant) with certain fixed or overhead costs is to produce (or process) more units, which results in lower long-term average or unit costs. The scaling-up of operations may or may not go hand-in-hand with enabling technological innovation. Forms of innovation other than technological innovation, such as organisational innovation, specifically the invention of the firm, played an important role in the upscaling of mining operations. Thousands of years ago mining activity started as artisanal mining and then progressed through organisational innovation such as division of work and specialisation to industrialised, large scale mining (LSM). This allowed for economies of scale, the profitable mining at deeper levels and of lower-*grade* orebodies. The ability to increase all the factor inputs in their most efficient proportions over the long run is an important source of industry-wide economies of scale.

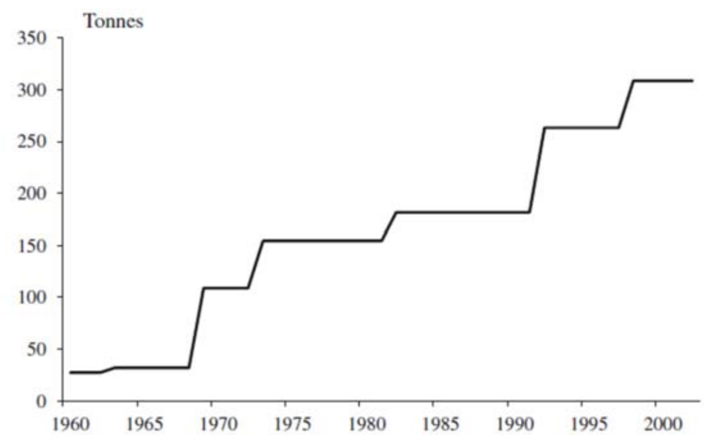

Figure 4.8 Surface mine truck capacity over time (Humphreys, 2013: 7)

Surface mining lends itself better to large equipment such as large trucks, loaders, shovels and draglines that can handle many more tonnes per load or scoop compared to a few decades ago. Figures 4.7 and 4.8 illustrate how dragline bucket sizes and mine truck capacity increased over time, enabling the large scale mining of massive low-*grade* orebodies. There are concerns, however, that further economies of scale may not continue as in the recent past. According to Humphreys (2013: 6), the next 30 years may not bring the same eleven-fold increase in truck capacity experienced from the 1960s to the 1990s. Bartos (2007: 155) points out that although haul truck size has increased by more than 1 000 % during a period of 45 years since 1960, unit costs decreased by only 72% during the same period. Tannant & Regensburg (2001: 3, 9, 71) explained that economies of scale is the driving force behind the increase in truck sizes. However, larger trucks are longer and broader and thus have longer turning radii. This means that surface mine roads which are usually 3,5 to 4 times the width of the biggest truck using them have to be made broader than what was previously the case and will cost more to construct and maintain. Broader roads may result in higher stripping costs and/or loss of ore. Furthermore, larger trucks also require better roads. Increases in truck size may, therefore, not indefinitely continue to lower unit transportation and total mining costs, given the diminishing returns entailed.

4.3.4 Mine productivity

Technological improvements often go hand-in-hand with increases in productivity. Figure 4.9 shows, for example, how improved hauling technology increased productivity at the early kimberlite diamond mines in South Africa. Today most hard rock is still broken by drilling holes into the rock, filling the holes with explosives and detonating them. Improvement in drilling rates is, therefore, another example of how productity has been increased over the years in the minerals industry as a result of better drills and drill rigs. Please see Figure 4.10.

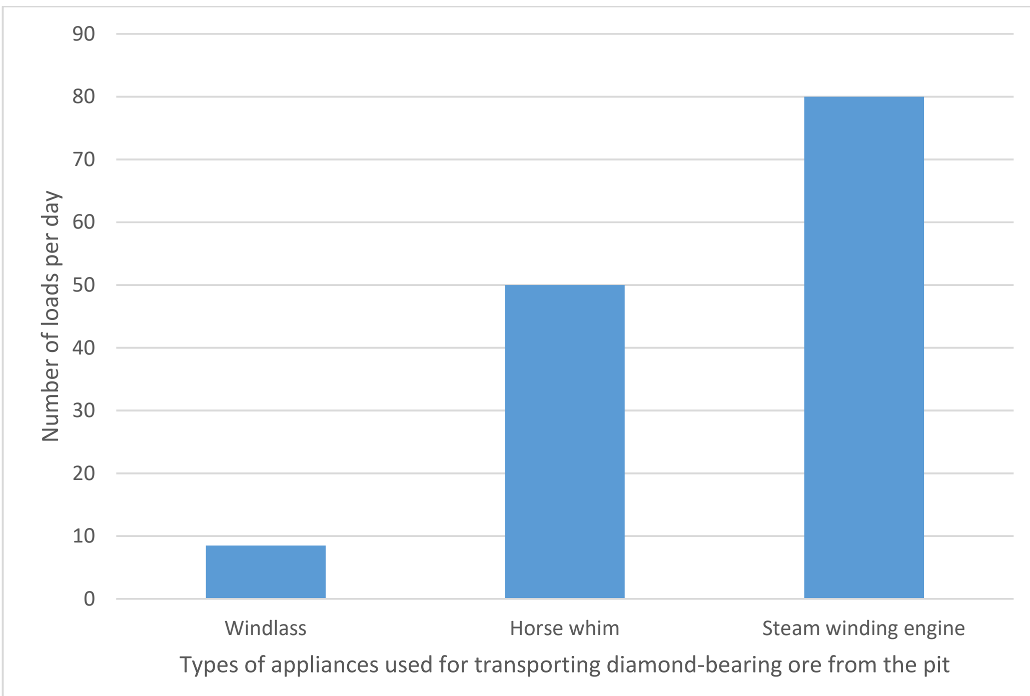

Figure 4.9 The evolution of hauling technology and associated improvement in productivity at the Kimberley Diamond Mine (Turrell, 1987: 12)

All is not well with mining productivity, however. Lower productivity and higher costs can be expected as surface and underground mines increase in depth over the next number of decades unless compensated for by improved technologies and/or better work arrangements. Deeper mines mean longer travelling distances for workers and consumables to stopes (workings) – at some deep level mines workers have to go down three shafts. For every km increase in depth, rock temperatures increase 9 to 12 degrees centigrade as workers get slightly closer, and a little less isolated, from the heat inside the earth. This has to be compensated for by creating an artificial environment, at high cost, in order to achieve reasonable levels of worker productivity. McKinsey (Flesher, 2018: 2) and PwC (2014: 2) measured dramatically declined mine productivity from 2004 to 2012. Ernst and Young (EY) identify low productivity as the number one risk for mining companies in their 2014-2015 report titled “Business risks facing mining and metals”.

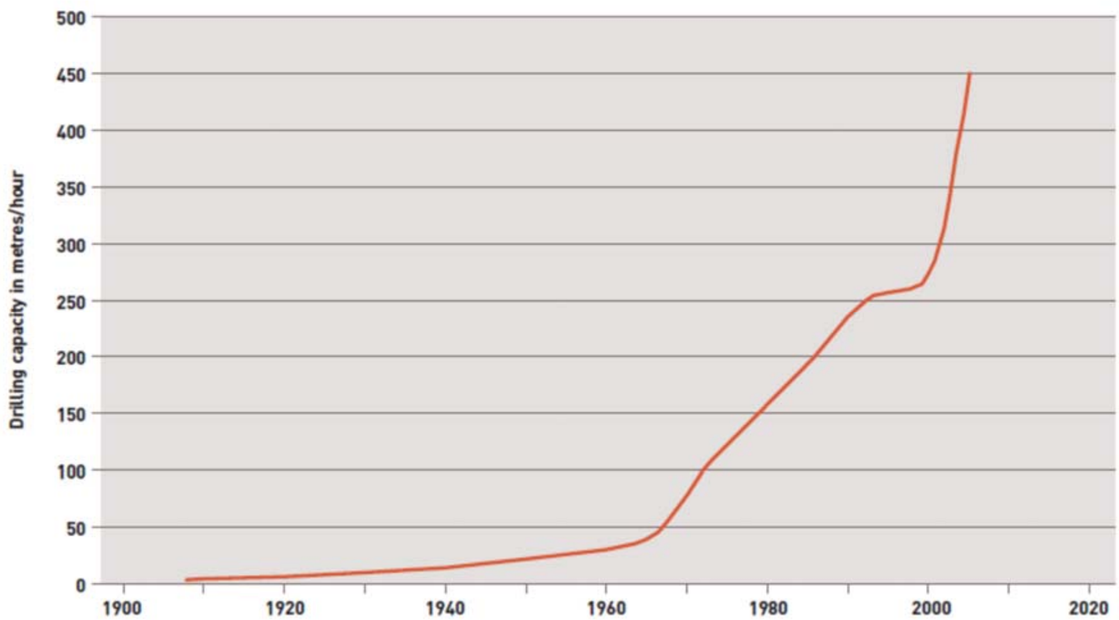

Figure 4.10 Increases in rock drilling efficiency over time (ICMM, 2012: 10)

4.3.5 Substitution

Most mineral commodities are intermediate goods and therefore their demand is often indirect in nature. Consumers value the quality and functionality of final consumer products and are often not particularly concerned about the raw materials they are made of. People requiring a house may not be extremely concerned about whether wood, stone, bricks or concrete is used in its construction, and often different materials are used in different parts of the world based on availability and price. Similarly, an electric vehicle can either use a copper rotor cage or Neodymium Iron Boron traction motor (Widmer et al, 2015: 5). Heat, energy, electricity and hydrogen, an energy carrier, can be produced by various means ranging from fossil fuels to using renewable energy sources such as solar, wind and biomass. This means that a high degree of substitution between energy sources is technically possible. The energy mixes of different countries and regions often depend on what is available and cost-effective, locally.

Whenever a specific resource becomes scarcer and more expensive relative to another which could serve as a potential substitute, this creates an opportunity for optimisation. Thousands of substitutes exist, some better than others. Certain substitutes may perform better than the materials that they replaced – one example is optic fibres which can carry much more data than copper wire (Radetzki, 2008: 123). Numerous economists and researchers are optimistic about the role that substitution plays in the mitigation of scarce resources (Casper, 2007: 143; Friedman,1978: 3; Goeller & Weinberg, 1976: 683, 685; Lele and Bhardwaj, 2014: 21, 23, 25, 27, 30, 31, 33, 37, 39, 44, 47, 49, 51, 108-110; Maurice & Smithson, 1984: xii, xiii; Messner, 2002: 264; Solow, 1974: 11; and Tilton et al, 2018: 56). Graedel et al (2015: 6298) illustrated that substitutes do not exist for all applications of all the elements. There is, for example, no substitute for chromium in stainless steel production and cobalt is not easily substituted (Lele and Bhardwaj: 2014: 27, 30). There are no substitutes for the major uses of magnesium, manganese, yttrium and dysprosium (Graedel et al, 2015: 6298).

The substitution of more for less abundant resources contributed significantly to the general availability of resources and helped control prices to avoid rises according to *Hotelling's Rule*. The extent to which substitution will continue into the future depends on future breakthroughs in disciplines such as materials science, and is unknown.

4.3.6 Urban mining, recycling, circular economy, re-use and dissipation

A number of means of ameliorating non-renewable resource scarcity such as urban mining, recycling and the *circular economy* form a source of secondary supply and thus reduce the quantities required from primary production, i.e. mining. Durable materials such as metals have a high potential for a sustainable closed loop economy. The quality of metals may, however, reduce over time during recycling and re-use. Although the laws of thermodynamics and the economics of recycling prevent 100% recovery (Solow, 1974: 2), much potential for increased recycling exists because of current, generally low recycling rates.

Huge quantities of metals and other mineral commodities are locked up in infrastructure, industrial and consumer goods. In some countries, a culture of reusing products and materials is being fostered. There are plans to improve the re-use and recycling of products and the materials they contain by means of Fourth Industrial Revolution (IR)-type technologies such as the *Internet of Materials* (WEF, 2018: 11).

4.3.6.1 Urban mining

Tuppen (25 May 2014) forecasted that *urban mining* will exceed extractive mining by 2052 because it will become more economically attractive to recover and recycle than to dig and refine. Tuppen thinks that this change will be driven by the increasing scarcity of naturally occurring ores, high societal stocks of common elements such as iron and aluminium and increasing processing costs associated with ore refining. According to Tuppen there are already more than 14 billion tonnes of steel and 200 million tonnes of copper locked up in current infrastructure. These will be further increased in, especially, emerging economies as urbanisation continues to increase. The greater concentration of people in cities does not only influence the demand for mineral commodities but also creates an opportunity for humanity to design better ways of recycling valuable raw materials.

4.3.6.2 Recycling, re-use and dissipation

Probably most of the gold ever produced by humanity is still in use because of its high value. Of all copper ever mined it is probable that about 85% may still be in use. Other metals and alloys such as lead, aluminium, nickel and stainless steel are also suitable for recycling and re-use. The recycling rates of materials provided in Table 4.4 differ significantly. The level of recycling of a specific mineral commodity depends on whether it retains its chemical form when re-used and whether it is economical to recycle it. Some materials may, however, be locked up in food and beverage cans for days to months, consumer goods like motor cars and capital goods such as mining equipment for years or in infrastructure such as buildings, railways, bridges and pipelines for decades. Scrap generated for example in factories during manufacturing processes can however be recycled fairly quickly by reintroducing it into smelting furnaces. The recycling of certain materials may be physically difficult and not economically viable – the recycling of antimony from flame retardant material is, for example, practically impossible (Lele and Bhardwaj, 2014: 18).

Table 4.4 The recycling of materials (Casper, 2007: 147; The Economist, 1 Apr 2017: 65; WGC, 2018: 9)

Materials recycled	**% recycled**		**Materials recycled**	**% recycled**
Aluminium	50% in the USA		Lead	65% in the USA
Antimony	43% in the USA		Magnesium metal	24% in the USA
Building materials	28% in Britain in 2014		Mercury	16% in the USA
Chromium	26% in the USA		Nickel	30% in the USA
Cobalt	25% in the USA		Platinum group metals	67% in the USA
Copper	24% in the USA		Selenium	20% in the USA
Gold	60% in the USA		Silver	49% in the USA
Gold	25 to 30% globally		Tin	35% in the USA
Glass	75% in Europe by 2025		Tungsten	33% in the USA
Iron and steel scrap	100% in the USA		Zinc	29% in the USA

In addition to conserving non-renewable and other materials, a big advantage of recycling durable materials such as metals is that the remelt energy required to put such recycled metal back into productive use is less than the energy needed to reduce and refine ores. For magnesium, aluminium, scrap steel and titanium it is respectively 1.5, 5, 25 and 30 percent of the energy required to win the metal from ore (Goeller & Weinberg, 1976: 686; Starke, 2002: 41). In such cases recycling is economical. Plastics produced from oil or coal can also be recycled and re-used to some degree.

A lot of materials are lost by means of a process called dissipation which can be defined as the loss of materials from recycling routes which happens when the cost of reclaiming is too high relative to the benefit derived. Dissipation occurs, for example, when metals are used in small quantities in devices, such as autocatalysts where a portion is lost in the exhaust stream or when added to fuels (Zepf, 2014: 14). Mobile phones provide another example of dissipation (Reller et al, 2009). Certain scarce materials such as indium used in mobile phones may be dissipated because of a lack of recycling channels worldwide and poor economics. Some metals are present in such small quantities in mobile phones (called spice metals) that the incentive to recycle may be low.

Despite increasing efforts to improve recycling rates in especially First World countries, new virgin metal will have to be provided from primary sources for as long as the global population continues to grow and recycling channels are inadequate (Starke, 2002: 41, 42). Just as for the *circular economy*, discussed next, recycling could help countries which are currently importing certain mineral commodities, to reduce such dependency. The U.S.A., for example, does not have its own bauxite (aluminium ore) and is therefore dependent on other countries for importing whatever they cannot produce themselves by means of recycling (Casper, 2007: 146, 147).

4.3.6.3 The Circular Economy

The *Circular Economy* is also referred to as the closed-loop economy and can be described as a regenerative industrial system (Nguyen et al, 2014: 2; von Gleich et al, 2006). According to Lovins (2016: 84) the *circular economy* was introduced in the 1970s by Walter Sahel and became the basis of Chinese development policy at the 11th Party Congress. Europe is also eager to adopt recycling and the *circular economy* to a larger extent. Recycling forms an essential component of the *circular economy*. The *circular economy* involves much more than just recycling, however, because further value is added to products instead of downgrading them as is the case for recycling. For example, one of Renault's plants remanufactures automotive engines, transmissions, injection pumps and other components for resale. The plant's remanufacturing operations use 80 percent less energy about 90 percent less water and generate 70 percent less oil and detergent waste as a plant with similar outputs. Creative thinking and developments in the area of the *circular economy* hold potential to decouple economic growth from resource constraints to a larger degree than what is the case today and it seems to be good for both society and business with projections that $1 trillion can be gained from it (Burger, 2017: 22; Nguyen et al, 2014: 1, 2).

4.3.6.4 Minituarization

The power of miniaturization to save materials can be explained by the evolution of the transistor and the first valve radios. The first processor produced by Texas Instruments in 1974 contained 727 transistors per $1mm^2$. Today the transistor count has increased to more than 250 million transistors per $1mm^2$ (Source: https://en.wikipedia.org/wiki/Transistor_count). Such miniaturisation enabled the evolution of the first bulky valve radios and mainframe computers to much smaller models such as the Sony Walkman and modern desktop computers with more computing power. Nanotechnology enables the depositing of an active ingredient which is just a few layers of atoms thick. Recycling may however be uneconomical because of the small quantities used.

4.3.6.5 Digitisation

Digitisation is a good example of dematerialisation. The idea of the so-called paperless office is to save resources. The digitisation of photos seems to be a good example of how the consumption of resources such as silver halide and other chemicals can be reduced as people switch from analog photography, which peaked in the year 2000, to digital photography, resulting in more photos being taken every 2 minutes nowadays than in all of the 19th Century (Brynjolfsson & McAfee, 2014: 80). It can be argued however that one result was the proliferation of digital cameras, now also incorporated into smartphones. The minituarisation and reduction in cost of digital cameras resulted in their widespread diffusion to more than 2,5 billion people today (Brynjolfsson & McAfee, 2014: 80). This caused a shift in the demand for materials used in the production of physical photos to that used to make digital cameras and the storage devices on which the trillions of digital photos are stored.

E-commerce, e-learning and e-banking require less physical infrastructure than physical bricks and mortar stores, universities and banks. They still require some physical infrastructure, however, such as fibre-optic or copper cable and so on. As in the previous example of photography, such technological disruptions may therefore shift the demand from one type of resource, for example concrete, to another. Overall the impact on materials demand may decline, however.

4.3.7 Efficient resource use and Jevons' paradox

Increases in the efficient use of energy and materials is an obvious way of reducing non-renewable resource use if everything else stays constant. Efficiency increases may, however, result in lower prices and greater demand for the products in which such non-renewable products are used. The greater demand by consumers for electricity due to lower prices will increase, indirectly, the demand for coal used in the generation of electricity. This phenomenon is known as *Jevons' paradox*. Alcott (2005: 10) uses the example of how a more fuel-efficient car makes more driving affordable and increases the demand for cars. Fuel and cars are complementary goods. The phenomenon is called rebound, feedback, take-back, snap back or re-spending.

4.3.8 Intensity-of-use and dematerialisation

The decline of the weight of the materials used in products over time is often called dematerialisation. Absolute, or strong, dematerialisation refers to the situation when the total material input to an economy decreases in absolute terms as is the case for Japan, because Japan increasingly focused on nonmaterial goods such as tourism, leisure activities, and financial services and on the consumption of value added goods that contain a lot of technology and design rather than raw materials (Herman et al, 1990: 333). Relative, or weak, dematerialisation refers to the situation where *intensity-of-use* decreases. This means that the ratio between material input and GDP falls over time. This can be achieved when the growth in resource use is slower than economic growth (Behrens et al, 2007: 445). Dematerialisation can be achieved by increasing material efficiencies, miniaturisation and digitisation, and may be associated with structural changes in the economy of a specific country as shown in Figure 4.11. Ride-sharing offered by companies such as Uber and Lyft, which optimizes routes and carpooling arrangements, reduces the number of vehicles on the road and is an example of both dematerialisation and increased efficiency. Many examples exist where the ownership of assets is replaced by the renting of assets, thus replacing ownership with services such as renting. (Woetzel et al, 2017; Burger, 2017: 22).

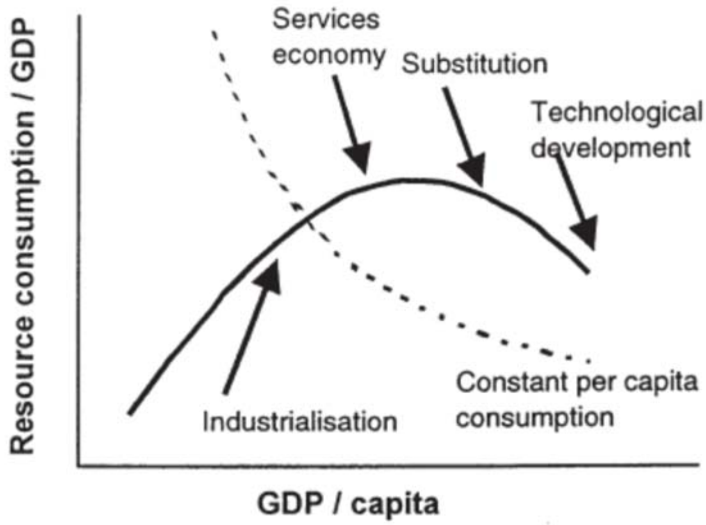

Figure 4.11 The *Intensity-of-use hypothesis* (Malenbaum, 1978: 18; Van Vuuren et al, 1999: 242)

Intensity of energy, metal or resource use (IoU) can be defined as metal or resource use per unit GDP. IoU has been determined for various countries and materials and for some follows an inverse U-shape as hypothesized by Malenbaum (1978: 18). Please see Figures 4.11 and 4.12. The inverted U-shape can be explained by factors such as urbanisation, structural changes in the economy of a country, government policies, shifts in demographics, materials substitution and new technologies. Agriculture and services are associated with low IoU while manufacturing and construction are linked with high IoU (Van Vuuren et al, 1999: 241; Starke, 2002: 48). Government policies to expand services sector activities, for example, to encourage the expansion of the tourism sector should reduce the materials required per unit of GDP generated because it is less materials intensive compared to manufacturing. Population growth increases the total demand for non-renewable resources if everything else stays the same. Non-renewable resource use is unequal and the quantity demanded per capita from developed countries such as the USA and Australia are higher than for low-income countries. If affluence increase to a wider percentage of the population of a country (or globally), then raw material use per capita will increase if everything else remain the same.

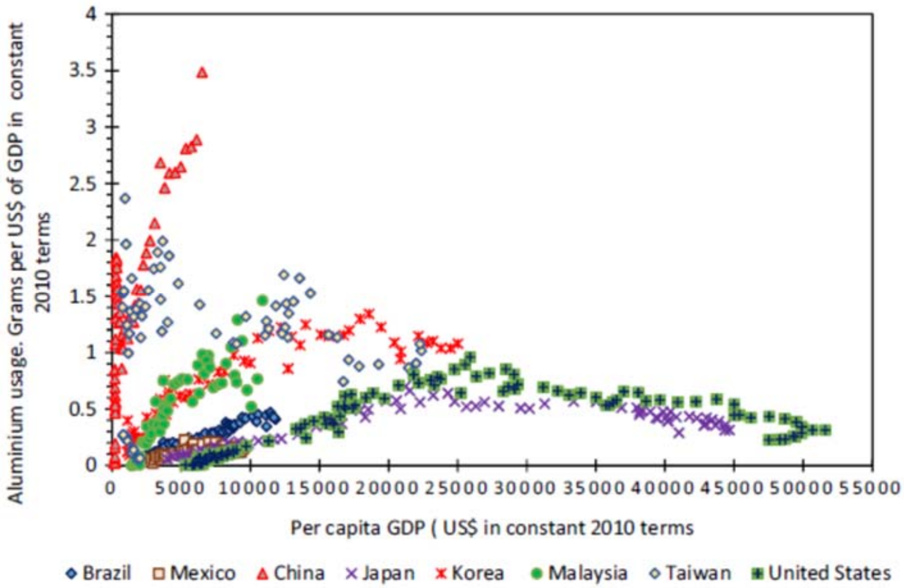

Figure 4.12 Primary aluminium usage in various countries as per capita GDP increased over time (Crowson, 2018: 63)

Figure 4.12, which includes both developed and developing nations, seems to confirm the *Intensity-of-use* hypothesis for a number of countries as far as aluminium is concerned. Crowson (2018: 68) warns that per capita GDP is only one factor that influences the development of materials usage and it is therefore difficult to use the *intensity-of-use* hypothesis to predict, for example, where the graph for China, which is closely watched by large mining companies, will go. China has taken the first steps towards a service economy but still has a long way to go (Hsu, 2017).

4.3.9 Unconventional sources: Shale, sea-bed, arctic, asteroid and lunar mining

4.3.9.1 Shale oil and gas

Oil tar sands and various shale deposits are low-quality, unconventional sources of oil and gas whose exploitation is economic at the right price and enabled through technological innovation. *Hydraulic fracturing* (fracking), which has been developed and refined over a number of decades, has proven itself as a technology that can unlock gas and oil from shale deposits which are abundant in certain parts of the world. Although the cost of production is higher up the cost curve compared to some conventional sources of oil and gas in Saudi Arabia and Russia, it contributes towards total production when prices are higher than the cost of production (The Economist, 7 Feb 2018). *Hydraulic fracturing* has put the US back on the map as the world's largest oil producer.

4.3.9.2 Seabed resources

The seabed and the earth below it is becoming an important source of oil and minerals. About 30% of crude oil is already exploited from offshore and De Beers has been mining alluvial diamonds from the seabed for many years. Exploitation of the oceanic crust is still at very low levels relative to that of the continental crust. Various studies point to huge resources such as polymetallic nodules on the seabed, *rare earth*s from seafloor sediment, sulphide deposits near hydrothermal vents along the mid-ocean ridges and metal-rich crusts on seamounts. Companies such as DeepGreen are far advanced with their seabed mining plans. The International Copper Study Group (ICSG), which reports on copper mines and plants, is of the opinion that copper will be mined from the seabed very soon (Arnoldi, 2019; Cathles, 2015: 312, 314; Heffernanl, 2019: 467; ICSG, 2013: 161; Kato et al, 2011: 535; Manning, 2016).

The Law of the Sea gives coastal states the right to establish exclusive economic zones up to 200 nautical miles from the coast or to the continental margin depending on which is the furthest (Howard, 2009: vii). Beyond that is the international seabed where exploration and exploitation licenses are awarded by the International Seabed Authority (ISA). The ISA has to date issued only 29 exploration licences for the exploration of the international seabed, covering an area of about one million square kilometres. It is foreseen that the oceans would be divided up like land and industrialised in the future. A number of countries, for example, New Zealand and Portugal are expanding their maritime influences (Economist, 10 Nov 2018: 75; Greenpeace, 2019: 6; Garibli & Neftchi, 2020; Monch & Lahl, 2018; Neftchi, 2020).

Deep sea-bed mining at four kilometres has a very small chance of competing with other interests, such as fishing. This differentiates deep sea-bed mining from many other forms of mining where there is often competition between farming, community and mining interests. One of the advantages of mining nodules off the ocean floor is that it does not require infrastructure like mine shafts and other expensive excavations. Investment in equipment such as ships and sea crawlers is however required. Various types of remote controlled equipment are currently being developed and tested. There are strong indications that certain parts of the seabed have the potential to be mined profitably (Cathles, 2015: 313, Economist, 2018: 75). Volkmann et al (2019: 15) did a study on the economic viability of the exploitation of seafloor manganese nodules (SMnNs). Their study is limited in scope and illustrated that better models, data and more detailed studies are required. There is a good match between the content of *polymetallic nodules* found on the seafloor and materials typically required for the manufacture of batteries whose demand may increase significantly with the transition to a low-carbon economy. A mining code was expected to be in place by 2020 for the international seabed by when commercial mining will become legally possible (Heffernan, 2019: 466).

4.3.9.3 The Arctic

The Arctic, which includes the Arctic Ocean and parts of Alaska, Finland, Greenland, Iceland, Canada, Norway, Russia and Sweden, contains significant oil, natural gas and other mineral resources. Commercial interest in this area has increased because climate change is opening up new shipping routes as well as parts of Greenland that were previously under ice (McPherson, 2015: 25). Greenland, an autonomous Danish dependent territory with limited self-governing powers, houses reserves of various minerals such as uranium and *rare earth elements*. A memorandum of understanding for the cooperation on development of Greenland's mineral sector exists between the U.S. and Greenland since June 2019. Under this agreement the US military has conducted an aerial survey of Greenland to assess its mineral potential. Later in 2019 the U.S. approached Denmark with a proposition to purchase Greenland. This was declined (DW News, 2019).

Various countries are trying to expand their exclusive economic zones to distances further than 200 nautical miles from their coasts. This they do by gathering data to prove to the Commission on the Limits of the Continental Shelf that their continental margin is further away from the coast than 200 nautical miles. If successful, this could expand the mineral endowments of a country significantly (Howard, 2009: vii; Monch & Lahl, 2018). In 2007 the Russians used a small submarine to plant a rust-free titanium flag on the seafloor below the geographic North Pole in order to claim the territory. Canada and the U.S. rejected this claim. China would also like to have a piece of the Arctic pie. It calls itself a "near Arctic" power and is busy with a "Polar Silk Road" which forms part of the *Belt and Road Initiative* (Wong, 2018). The Arctic Council was established in 1996 to deal with issues related to countries that border the Arctic Ocean. Canada, Denmark (through Greenland) and Russia all lay claim to the Lomonosov Ridge which stretches through the Arctic Ocean to the North Pole (Garibli, 2020; McPherson, 2015: 7, 8, 24).

4.3.9.4 Mining in outer space

The large-scale commercial mining of asteroids and the moon is probably much less likely in the near future, although there are resources out there that are of value. There are water, oxygen, metals and other materials on some of the asteroids, moons and planets in the solar system. In the future moon rock may be mined for water, oxygen and helium-3. The moon also contains aluminium, chromium, iron, magnesium, manganese, titanium and so on. Helium-3 can be used to fuel fusion reactors whose commercialization is still a few years to decades away. John Lewis studied Amun, a near-earth asteroid, and concluded that the monetary value of Amun's platinum group metals is more than $6 trillion, its iron and nickel might be worth $8 trillion and its cobalt deposits $6 trillion. The European Space Agency recently announced its intention to mine moon rock for oxygen and water by 2025. Doing so for future lunar and other missions may be viable given the high payload costs of taking any resources from Earth into space. Japan was the first nation to collect subsurface materials from an asteroid (Lies, 2020). Transporting any resources from space to Earth is currently very costly and it is, therefore, unlikely to be done on a massive scale in the near future. It is questionable whether any of the vast sources of non-renewable materials in the solar system, excluding those found on Earth, meet the requirements for classification as a *reserve* (Barbee et al, 2018: 37; Casper, 2007: 156-158; Christian, 2019; Howell, 20 Apr 2018; Ingebretsen, 2001: 34-39; Reuters, 2019, Robitzski, 2019).

4.3.10 Concluding remarks on mitigating factors

Despite the various scarcity mitigating factors discussed, Figure 4.13 shows that the growth in mined (primary) mineral use increased faster than the average global growth for the period 1994 to 2013. The median value for primary production growth was greater than that of global GDP growth. Demand for elements such as yttrium, *cobalt* and indium is growing fast. They are all on the U.S. 2018 list of *critical minerals*. The growth in mercury, a poisonous substance, is less than that of the growth in GDP.

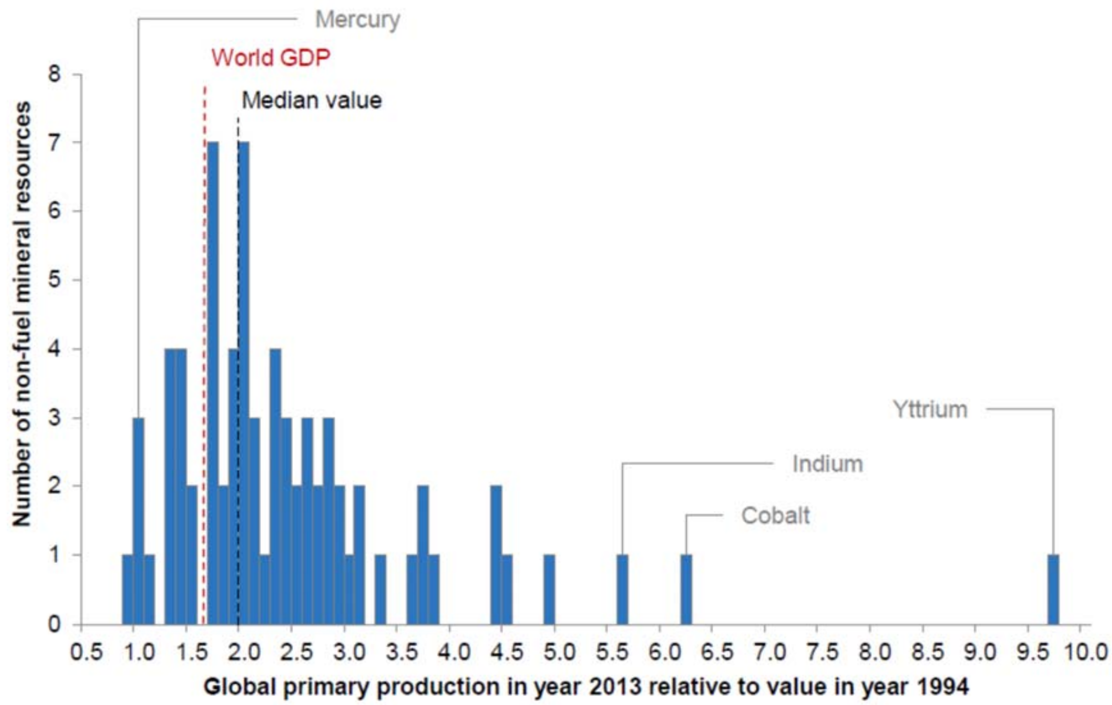

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Figure 4.13 Global primary production growth from 1994 to 2013 for 73 non-fuel mineral resources (U.S. National Science and Technology Council, 2016: 2)

4.4 POLICIES FOR MANAGING THE AVAILABILITY OF NON-RENEWABLE RESOURCES

Countries and jurisdictions have different resource endowments and needs. National policies to alleviate scarcity in the short to long term may, therefore, be diverse as illustrated in Table 4.5. Such policies may range from encouraging exploration by means of *flow-through shares* in Canada to the stockpiling of oil and other commodities in case of supply interruptions. Countries may also expand their territories through war, peaceful annexation and other means in order to access resources. Part of Africa was for example divided up between a number of European countries, and colonised. This is commonly referred to as the *Scramble for Africa* and the title of a book by Pakenham (1991). Large parts of the U.S.A. were purchased from other countries. Recently President Trump's administration tried to buy Greenland from Denmark. This was also attempted by President Truman a few decades ago (DW News, 2019; VisualPolitik EN, 2019; Vox, 2017).

Much information is publicly available about the materials policies of the United States, which experienced shortages of certain materials during World War II and which consequently led to the establishment of the Strategic and Critical Materials Stock Piling Act of 1946 (Huddle, 1976: 654). As predicted by *Hubbert*, the U.S. became more and more reliant on oil imports after domestic conventional oil production peaked in the 1970s. This influenced American foreign and military policy for decades afterwards. The narrow Straits of Hormuz and Malacca are for example strategic parts of global oil and natural gas shipping lanes with respectively 19 and 16 million barrels per day being shipped through them. Since the 1970s the true cost of oil to the U.S. must have been significantly higher than market prices, negative externalities aside, considering the cost of securing its availability to American consumers by heavy spending on the military and maintaining diplomatic relations related to keeping these supply routes open. In a similar fashion, China's involvement in the South China Sea has to do with the security of supply routes and as a potential source of seabed minerals. One reason for China's *Belt and Road Initiative* (BRI) is to establish and strengthen a number of trade routes to ensure security of supply and trade continuation when one or more are cut off for whatever reason. The European Union also has a number of strategies to ensure supply security. Its Raw Materials Initiative focuses for example on primary production, recycling and substitution (Global Commission on the Geopolitics of Energy Transformation, 2019: 56,57; Lovik et al, 2018: 9; Parthemore, 2011: 13).

Table 4.5 Examples of policies for the alleviation of scarcity, improving security of supply and/or decreasing resource dependency.

Type of policy	**Examples**
Encouragement of exploration and investment with the aim to increase reserves and increase mine production capacity.	• Canadian *flow-through shares* encourage investment in exploration through tax incentives. • Improvement of investor information regarding exploration results through reporting codes so that scandals like *Bre-X* can be minimised and investment encouraged. This can be done through the various codes, guidelines and standards for reporting mineral reserves and resources such as the Australian JORK code (Noppe, 2020).
Recycling, re-use and urban mining	*Circular Economy* – supported by for example the EU. This reduces the demand for primary mining.
Substitution	R&D spending with the goal to develop substitutes (Russett, 1984: 482).
Trade agreements between importers and suppliers.	Numerous examples exist of such agreements. One example is the Commerce and Navigation Treaty of 1911 that existed between the U.S. and Japan. Between 1911 and 1939 the U.S. was a major supplier of strategic materials such as ores and petroleum to Japan (Reyes, 2013: 1).

Funding/co-funding and ownership/co-ownership of mines in other countries.	• Iran has a 15% share of the Rössing Uranium mine in Namibia. • Swedish steelworks tried to open chromium (used to manufacture stainless steel) mines in Turkey during the interwar era because they were concerned about the British Empire's dominance of such supplies (Vikström, 2017: xii). • Germany entered into a partnership with Bolivia on the development of its lithium reserves. This makes Germany less dependent on Asian markets for this raw material that is used in battery electric cars (Reuters, 12/12/2018). • Although only 9,5% of lithium is produced in China, Tianqi Lithium, a Chinese company, through its shareholding in Chilean and Australian companies, controls almost half of the global production (Rathi, 2018; Reichl, 2018: 7).
Autarky, import tariffs or the development of high-cost domestic mines and plants to ensure security of supply.	Although autarky is not generally practised, governments are sensitive to becoming too dependent on imports for security of supply reasons (Russett, 1984: 481). Tariffs will ensure that high-cost mines and plants needed in times of war can continue to be operated during times of peace. Sasol was developed in the RSA to reduce dependency on imported oil.
Stockpiling	The National Defense Stock Piling Act. 50 of the U.S. mandates the procurement, maintenance and management of the national defence stockpile. Tantalum and Niobuim are stockpiled by the U.S. Military (Parthemore, 2011: 14). Stockpiles act as buffers which means that demand does not have to be immediately balanced by primary (mine) supply.
Research and Development related to the development of unconventional resources	The Blue Mining Project, which investigates deep sea nodule mining, received funding from the European Commission (Volkmann et al, 2018: 1). Japan is interested in deep-sea *rare earth* mud deposits in the Ogasawara area because that may help them to reduce supply risk (Motoori et al, 2018: 560).
Preventing the blocking of trade routes and stoppage of exports.	The establishment of an American Rapid Deployment Force (Russett, 1984: 481). Many countries, including China, has military bases in Djibouti. The small country is on the Bab el-Mandeb Strait, which is a gateway to the Suez Canal. The

	canal is one of the world's busiest shipping routes (Oladipo, 2015).
Lowering of regulatory requirements.	Should critical shortages occur globally or in countries that depend on others for imported raw materials then the lowering of regulatory requirements is one possible solution. The Mountain Pass *rare earth* mine in California is an example of a mine whose cost competitiveness will improve if the environmental policy framework in the U.S. was less onerous (Campbell, 2014: 22).
Encourage foreign direct investment by protecting the interests of investors.	Investors are scared of expropriation and mine nationalisation and may therefore underinvest in the development of mines and associated infrastructure in certain countries. Governments can through investment treaties protect the rights of investors (President Materials Policy Commission, 1952: 68).
Expansion of territory / *resource nationalism* / regime change / resource conflicts and wars	Japan is a resource poor country. It initiated a plan in the 1890s to attain economic control of the Asia-Pacific region and free itself from Western economic domination. The plan was to allow the flow of raw materials from Asia to Japan where it was converted into manufactured goods for the Chinese market (Maechling, 2000: 41; Reyes, 2013: 1). The British Anglo-Iranian Oil company essentially had a monopoly over Iranian oil until 1951 when the Iranian parliament passed legislation for the nationalisation of the country's oil industry. In 1953 the CIA and MI6 orchestrated a coup in Iran and replaced the democratically elected Prime Minister, Muhammad Mussadeq, with the authoritarian regime of Mohammad Reza Shah Pahlavi (Cavendish, 2001; Sachs, 2019; Stone & Kuznick, 2013: 342-346).

*R/P ratio*s can be calculated at firm level (to determine the life of mine), country level (to determine the life of reserves in a specific country or at global level. Low and declining country *R/P ratio*s for specific commodities in certain countries may indicate that more of it will have to be imported unless local exploration levels are increased and new deposits are found. Figure 4.14 shows China's low *R/P ratio*s for a number of mineral commodities. The Government of

China must have been aware of this many years ago and empowered and encouraged a number of domestic state-owned and private companies to actively pursue mining deals throughout the world. Since this strategy, known as “Two Resources, Two Markets”, was launched in 2006, Africa quickly became a desirable region for China and Hong Kong-based companies in pursuit of mining deals (Basov, 2015).

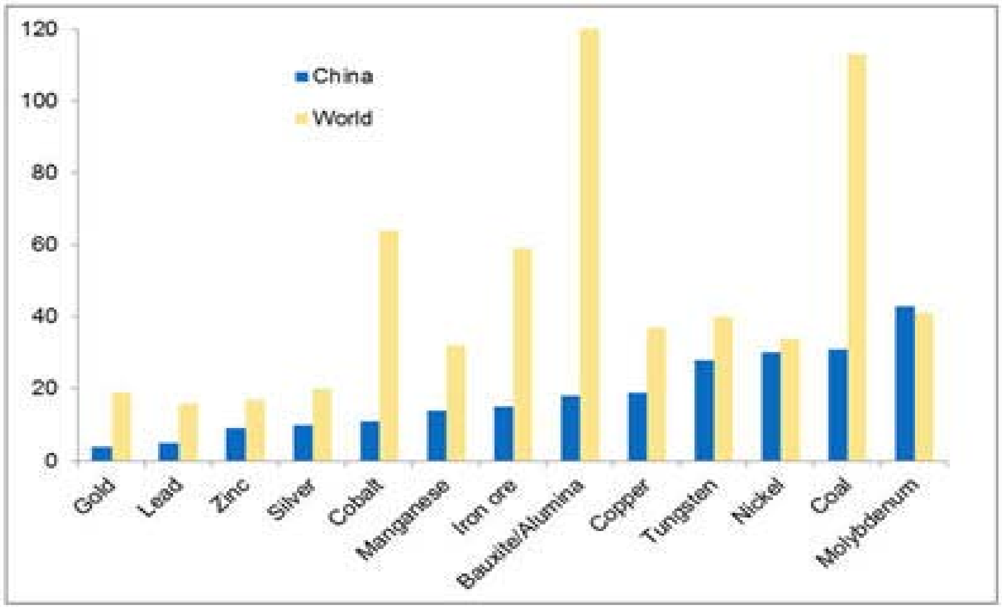

Figure 4.14 Chinese versus global R/P ratios (Basov, 2015)

Chinese battery firm GEM has a three-pronged strategy for sourcing cobalt and ensuring its availability as a raw material. It buys cobalt from a large supplier, Glencore, stockpiles cobalt, and obtains it from recycling / urban mining (Reuters, 14/12/2018).

4.5 CONCLUSION

The three main topics discussed in this chapter form an important part of the “availability” body of knowledge. The first topic is that of measuring the availability of non-renewable resources. Many such *indicators* have been investigated over the years. It is clear that no superior availability *indicator* exists. The advantages, disadvantages and limitations of two such *indicators*, namely the *R/P ratio* and real price trends, are well understood today and are still used. The wide variety of scarcity mitigating methods implemented by firms and governments explain largely why real prices of non-renewable resources have not generally increased despite enormous increases in production volumes over many decades, and is the second main topic discussed. A number of forces that traditionally countered resource scarcity, for example economies of scale, low-cost energy and the opening of new mineral provinces, may be waning. Secondary supply may also never replace primary production because of the nature of the economics of recycling, dissipation and factors that still continue to drive demand to higher levels. Technological innovation is key to many of the methods for mitigating scarcity. Technological progress played a major role in improving productivity and the dramatic lowering of the cost of extraction and processing of non-renewable resources amidst huge increases in raw materials demanded. The third important topic discussed in this chapter is about various scarcity mitigation policies and strategies. It illustrates that governments and companies are concerned about the availability of certain resources and possible supply disruptions.

CHAPTER 5 - CONCLUSION

5.1 INTRODUCTION

The chapter is structured roughly along guidelines provided by Hofstee (2006: 155-163). He suggests that the last chapter of a dissertation may include four main sections, namely a summary of findings, conclusions, a summary of contributions and suggestions for further research. The first section of this chapter summarises the relevant research on the availability of non-renewable resources as it evolved over time. That is followed by a proposed framework for the identification of information from the literature that is relevant to the “availability” body of knowledge. The framework can also be used when the future availability of a specific non-renewable resource is analysed to ensure that all factors are considered in such a study.

The equivalent of Hofstee’s “contributions” section is a section on core facts that were identified from the literature. Such facts are essential ingredients of the “availability body of knowledge”, and the criteria that they should meet are described in this chapter – please see section 5.4. In this chapter, value is added to information provided in the first four chapters, and a number of core facts, distilled from information provided in Chapters 1 to 4, are listed, and their implications briefly explained. The core facts, some of which are *stylised fact*s, are much more comprehensive than those used in Hotelling’s models, underlining the shortcomings of his model and findings. (Please see the glossary for the definition of *stylised fact*.) The core facts are proposed as the main characteristics of the Availability of Non-renewable Resources body of knowledge, and explain a number of phenomena observed historically.

The chapter is concluded with suggestions for further research.

5.2 SUMMARY OF FINDINGS

5.2.1 Introduction

In Chapter 1 it was pointed out that humanity has become very reliant on non-renewable resources for sustaining a high living standard. Concerns about the availability of non-renewable resources surface periodically because of record high demand, supply risk, business and supercycles, resource conflicts and wars, rapid economic development and transitions where the demand for certain minerals or groups of minerals increases significantly, causing structural changes in metal demand. Demand is driven by factors such as population growth, consumerism, materialism, increased affluence, urbanisation, globalisation and economic development. The reason for the existence of Mineral Economics as an academic field has its roots in concerns about the availability of non-renewable resources during and after World War II. The reason for this study is to construct a body of knowledge from the literature that deals with the evolution of the topic over time and which can explain and address the problem of recurring concerns about the current and future availability of non-renewable resources.

5.2.2 Historic perspective

Chapter 2 illustrates that the availability body of knowledge has a long and colourful history which starts with the scarcity of tin in Ancient Greece. That event contributed towards the transition from the Bronze to the Iron Age. The transition caused a structural change in the amount of mineral commodities demanded, especially for tin, copper and iron.

An important milestone is that the whole Periodic Table became known to humanity only a few decades ago. All the elements are now available, to be used and researched. We also now know in which average concentrations the elements are available in the earth's crust and, therefore, the size of the minerals *resource base*.

The Industrial Revolution played a big role in the development of the West, increased the demand for commodities such as coal and iron, and gave rise to concerns regarding the future availability of coal in England amidst increases in population and industrialisation. During this era, well-known classic economists such as Adam Smith, Malthus, Ricardo, Mill, Marx and Jevons produced various publications of which portions are relevant to the "availability" body of knowledge.

Perceived scarcity in Great Britain made way for migration to and abundance in the "New World" and the development of its railways, telegraphs, roads, electrical networks and cities. After a relatively short period of rapid development, concerns arose about the future availability of various types of raw materials in what is today the United States. Such concerns were identified and solutions were proposed by the Conservation Movement.

During and after the Conservation Movement, various contributions were made by economists such as Cassel, Gray and Hotelling to literature related to the economics of non-renewable resources. Hotelling's 1933 paper, "*The Economics of Exhaustible Resources*", is probably the most-referenced paper related to the "availability of non-renewable resources" body of knowledge. Hotelling expected increased future scarcity and higher real prices for non-renewable resources. With a fixed stock of non-renewable resources, the optimal use and allocation of resources become very important issues. Trade-offs between current and future usage put the spotlight on intergenerational equity, which is associated with the concept of Sustainable Development.

After World War II the Paley Commission was formed to address availability concerns in the United States. The oil price shocks of the 1970s revived non-renewable resource concerns and studies such as "Limits to Growth" focused on the availability of various types of non-renewable resources. Increased dependence on Middle East oil and the politics of energy security shows that non-renewable resource availability has a political dimension in addition to the geological and economic dimensions.

5.2.3 Developments during the past few decades

Most of the recent developments in the "non-renewable resource availability body of knowledge" are described in Chapters 3 and 4. Fast economic growth after WWII, the rebuilding of countries such as Germany whose infrastructure was destroyed during the war, and the establishment of the U.S. as an economic superpower meant that the demand for mineral commodities continued to be dominated by the West. More recently, rapid economic growth in countries such as India and especially China has shifted the demand for minerals to emerging economies. Like the U.S. in the 1950s, China has more recently implemented policies to ensure sufficient non-renewable resources for businesses and consumers in the country. The international shipping and trade of mineral commodities has increased enormously since the Industrial Revolution as a result of lower unit shipping and transportation costs, and is associated with the concept of globalisation. This enabled emerging economies, which have a competitive advantage in the production of various types of non-renewable resources, to become important suppliers. In some cases a few countries dominate the supply of mineral commodities. This has increased mineral dependence by importing nations and stimulated research to address questions regarding when a mineral is critical and/or strategic to the economy and military of a specific country.

5.2.4 Further contributions towards the Availability body of knowledge

A few topics and other key points related to the ”availability” body of knowledge are briefly mentioned here. More detail and further discussion follows in sections 5.3 and 5.4.

Orebodies are not homogeneous – the quality and *grade* of minerals inside an orebody may differ from one point to another. The average *grade* of one orebody usually differs from that of another. This and other factors result in orebodies with different associated costs and a cost curve for each mineral commodity. Low-*grade* resources are more abundant, and the average *grade* of orebodies is declining.

Mineral commodities are supplied by both large-scale industrial mining firms as well as by artisanal and small-scale miners. Artisanal mining plays an important role in the supply of a few commodities.

The cost of producing certain mineral commodities is currently relatively low because they are produced as by-products. Prices will have to increase significantly if future demand increases to levels where such commodities can no longer be produced as by-products.

The Barnett and Morse study in the 1960s, which is discussed in Chapter 2, was the first of many to determine whether commodity production costs and prices are actually increasing. This topic has since been extensively researched and diversified into attempts to find various *indicators* of scarcity and availability. Of all the *indicators* discussed in Chapter 4 that have been investigated over the years, the *R/P ratio* and real price trends are well understood and still used today. Some of the studies conducted on price trends could not detect any significant upward or downward trends despite massive production increases. This is contrary to Hotelling’s expectations (discussed in Chapter 2) of price increases and Ricardo’s expectations regarding diminishing marginal returns assuming that the best quality resources are exploited first. The observed long-term price trends are explained by the wide variety of scarcity mitigating methods (discussed in section 4.2) implemented by firms. Such methods and forces include, for example, economies of scale, the opening of new mineral provinces through successful exploration, and technological innovation. These facts illustrate that many important aspects related to the availability body of knowledge are overlooked when thinking is shaped by the Hotelling-influenced fixed stock *paradigm*. Cairns (1994), among others, criticised Hotelling’s model on the economics of exhaustible resources for not using the correct *stylised fact*s. This raises the question about which framework and core facts must be used when modelling non-renewable resource availability. This is discussed in sections 5.3 and 5.4.

Orebodies, or places where minerals are highly concentrated, are anomalies and not equally distributed, resulting in demand-supply imbalances between numerous countries for one or more types of mineral commodities. This necessitates trade and can result in angst, or worse, when supplier nations practise one or other form of mineral resource nationalism. Over the years various governments introduced a range of policies to alleviate scarcity and reduce supply risk associated with mineral dependency. Such policies, implemented by importing countries, range from recycling to stockpiling and investing in research to find possible substitutes. Such measures form part of the framework to be used when evaluating the availability of a specific type of non-renewable resource.

At times of high mineral demand, the growth life of reserves may be rapidly reduced because the denominator in the reserves divided by annual production equation increases year-on-year. One such transition is currently underway, namely the transition to the low-carbon economy. This transition has the potential to rapidly increase the demand for materials used in renewable and low-carbon technologies. An associated, but lagging, transition is that to the Hydrogen Economy. Much uncertainty surrounds such transitions. One uncertainty is the rate at which they may take place. That depends on how rapidly technologies such as wind farms, solar farms, electric and hydrogen fuel cell vehicles are adopted, and this makes it difficult for mining and exploration firms to match demand with supply. The process of finding an orebody suitable for large scale-mining and development take many years and requires a lot of capital.

5.3 TOWARDS A FRAMEWORK FOR ANALYSING THE FUTURE AVAILABILITY OF NON-RENEWABLE RESOURCES

A physical framework provides a supporting structure around which something can be built, while a framework used to plan, decide or analyse can be defined as a system of rules, ideas or beliefs. One function of a framework is to provide structure and boundaries. A good framework should ensure that all relevant aspects are considered when a study is done. In the context used in this document, a framework helps to define the main content and boundaries of the body of knowledge to be considered when researching a specific question.

One outcome of and contribution made by this study is a framework for the body of knowledge on the long-term availability of non-renewable resources. Such a framework assists persons to identify sections of the literature that are relevant to the body of knowledge. One criterion for such a framework is that solutions and understanding of various historical and current issues should be found within it. The framework includes, for example, the d*imensions of availability* which range from the physical to economic. All such dimensions must be considered when the current and future availability of a specific and/or all non-renewable commodities are analysed. The framework provides for scarcity mitigation measures, the global versus national availability of non-renewable resources, primary as well as secondary supply, a historical context, unconventional sources, the role of technology in creating new reserves, and efficiency and productivity improvements. Scarcity mitigating measures discussed in this document range from recycling to stockpiling and investing in research to find possible substitutes. The core facts in section 5.4 also form part of this framework and can be used for theory- and model-building and to gain understanding about the "availability" body of knowledge.

Chapters 1 to 4 illustrate that many factors have to be considered when analysing the availability of non-renewable resources in the long run. The relevant body of knowledge was built up from the literature in order to answer the questions listed in Chapter 1. This body of knowledge includes many factors, aspects and dimensions, from the potential future supply of non-renewable resources to economic and environmental factors that may determine whether a resource may become a reserve and, therefore, extractable or not. Quite a broad and complex framework is required to capture all of this. Figure 5.1 is an attempt to illustrate just a few aspects of such a framework.

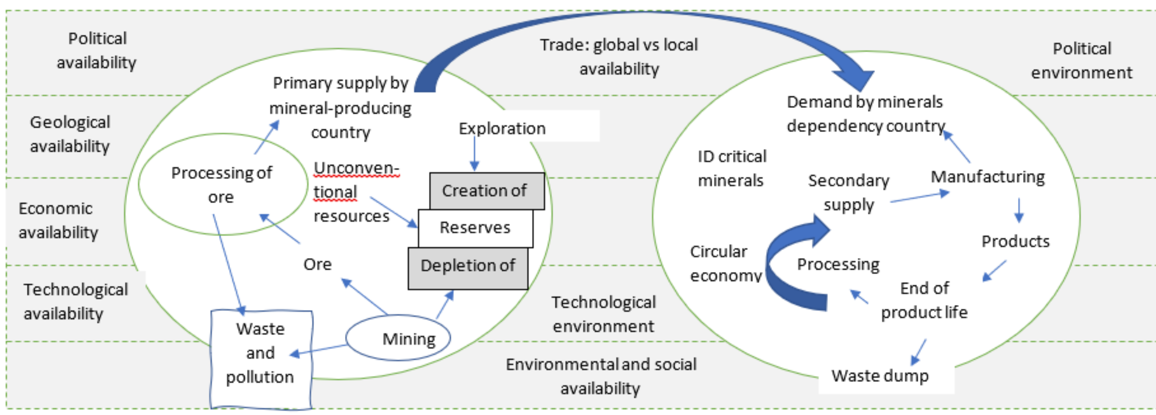

Figure 5.1 Partial illustration of a framework for the analysis of the "Future availability of non-renewable resources" body of knowledge.

Figure 5.1 shows that there may be a difference between the national and global availability of a mineral commodity depending on the security of shipping routes and international trade relations. Both are linked to the political availability of non-renewable resources. The various other dimensions of (primary) availability are captured, especially the impact of mining and ore processing on the environment. Some indication of how new reserves may be created, i.e. exploration, as well as depleted, are provided. Many of the other ways in which scarcity can potentially be mitigated are not captured in the figure. Availability *indicators* are also not addressed. The figure points out that not only primary but also secondary supply should be considered. Figure 5.1 does not show the dualistic structure of the industry, namely the contribution by both ASM and LSM to mineral production. If a study is done on the availability of commodities such as gold, tantalum and tin, where artisanal miners are significant producers, the focus should be not only on large scale mining because that will result in an inaccurate current and future availability picture. Many key aspects of the framework are listed in the table of contents and contents of this document. Some are, however, omitted in Figure 5.1 to prevent it from becoming too information dense and busy.

The framework includes policy measures undertaken by various nations to secure supply and protect their economic interests, and points to the fact that the price mechanism is not always solely relied upon. The raw material needs of humanity are dynamic, influenced by factors such as technological disruption and, lately, global climate change. A decarbonised global economy requires, for example, non-renewable resources in different quantities than is currently the situation for the fossil-based economy. Such demand shifts create uncertainty on availability and necessitate the re-evaluation of frameworks, theory, historic thinking and models.

One of the goals of the core facts in section 5.4 is to augment what has already been stated, in order for users to obtain a good understanding of the main characteristics of the availability of non-renewable resources body of knowledge.

5.4 THE CORE FACTS

5.4.1 Criteria, nature and characteristics

In the previous chapters evidence was provided to support and motivate the identification and formulation of core facts related to the availability of non-renewable resources. Such facts must meet certain criteria. They must carry a lot of weight and help to explain the nature of the body of knowledge that they represent. It should be possible to explain observed phenomena from such facts. Core facts must have various implications and consequences to be of importance. They should be useful for theory- and model-building. If they are incorporated into a model, they should create the expectation that the explanatory and/or predictive capacity of the model or theory will be an improvement over that which Hoteling formulated in his famous paper published in 1931.

The body of knowledge under investigation has a long history which is still today influencing theory, research, *paradigm*s and debates. This has to be reflected in the core facts. The core facts should also attempt to capture the fact that it is a dynamic body of knowledge influenced by various demand and supply shifts over time, such as the transition from the Stone to the Bronze and Iron Ages. Currently, the beginnings of the transition to a low-carbon economy driven by global climate change and competitive renewable energy costs are already discernable, and new availability concerns are emerging. This transition is associated with shifts in mineral demand patterns, some of which are already underway.

According to Von Mises (1949: 55), there are no constant relations in Economics. Prices change dynamically to balance supply and demand, and mineral reserves change as costs and prices change although the *grade*s at different points in an orebody stay the same as nature deposited and formed them there. In contrast to the situation in Economics, the natural sciences contain many constants such as Avogadro's number, the speed of light in a vacuum and the average concentration of different elements in the earth's crust.

In the next section, 5.4.2, the core facts are listed and discussed. Some of these facts are *stylised facts* and of a generalised nature. Some are based on the natural sciences, while others are based on the social sciences and some on a combination of the two. The facts should be interpreted and used with caution because some may change over time.

5.4.2 The core facts

5.4.2.1 The demand and supply of non-renewable resources have increased tremendously over the past few decades.

Significant increases in the demand and supply of various natural resources are empirical facts supported by data. The explanation for increased demand is to be found in various drivers, such as population growth, increased urbanisation, affluence, materialism and the fact that countermeasures such as increased materials efficiency and recycling are not sufficient. This core fact is a generalisation because there are a few exceptions – the demand for asbestos has declined, for example. In a few decades' time the demand for fossil fuels may also decline.

The so-called *stationary state economy* (defined in glossary) of the classical economists has to date not been observed. To the contrary, significant growth of the global economy, its reliance on non-renewable resources and the growth of such raw materials production capacity has been observed. This trend may continue as long as population growth continues and as the average wealth per capita increases.

5.4.2.2 Availability has various dimensions in addition to the economic and geological.

Various historic events that influenced the evolution of thought regarding the availability of non-renewable resources can be explained by the *dimensions of availability*. For example, the shortage of oil in the U.S. in the 1970s and more recently of *rare earths* in countries such as Japan is not because there was a global physical, shortage but rather because of politics and trade restrictions.

Compared to a few decades ago, the environmental and social *dimensions of availability* have become major forces impacting on the availability of non-renewable resources in general. These forces may become even more important in the future if the human impact on the natural environment continues with further population growth, affluence and declining ore *grade*s in what some people perceive to be an already overcrowded earth.

5.4.2.3 The per capita use of many types of non-renewable resources has increased dramatically in the developed countries since the (first) Industrial Revolution.

The Industrial Revolution is an event that is associated with the development of the Western world as well as greater per capita use of non-renewable energy and materials. Development in countries such as Japan and the Asian Tigers, for example, South Korea and Singapore, has caught up with that in the West. Emerging markets such as China are also in the process of closing the development gap between them and the developed world. The development of infrastructure required by urbanisation, electricity generation and delivery, and modern transportation is very resource intensive. Over the last number of decades the developed nations have, generally, contributed much more to waste generation and the amount of greenhouse gases (GHGs) in the earth's atmosphere. Considering the "polluter must pay" principle raises the question of who has to "foot the bill" for the decarbonisation of the global economy.

5.4.2.4 Reserves and reserve to production (R/P) ratios are dynamic.

The *resource base* as calculated from the *Clarke* values (defined in glossary) of the elements (also called crustal abundances of elements) is a constant. It is something that is static and determined from knowledge of the natural sciences. Reserves are that portion of the *resource base* where certain elements or materials exist at a higher concentration or better quality and can be mined profitably. Reserves are, therefore, determined by geology, economic and other factors such as technological innovation and include productivity improvements, economy of scale and price levels. Economic relations are dynamic and, therefore, reserves as well as reserve to annual production (R/P) ratios are dynamic. In the past, a number of persons incorrectly forecasted the future availability of resources because they based such forecasts on the assumption that reserves and *R/P ratio*s are static. Despite the shortcomings of *R/P ratio*s as an *indicator* of availability, they are easy calculable and do provide a worst-case indication of future availability.

5.4.2.5 Almost all the naturally occurring chemical elements are used today.

Today all the elements in the Periodic Table are known and many more of the elements and their various combinations in alloys are used, compared to a few decades ago. Some of them had been known to humanity for hundreds of years while others were only discovered much more recently. Some applications of the naturally occurring elements have, therefore, only been discovered more recently. As materials science and technology develop, more opportunities for substituting abundant materials for scarcer ones are discovered. Certain industrial materials used today were not used a few hundred years ago but are today essential ingredients in various products and infrastructure. An immature industrial material such as lithium is an example of a material that has relatively recently become a battery raw material used in lithium-ion batteries. Hydrogen, an important ingredient of sea and fresh water molecules, is one of the most abundant elements on earth and the most abundant in the universe. It may become widely used as an energy carrier in a hydrogen economy. As a result of advances in materials science, there is today a greater possibility of replacing one element or material with another because of this greater diversity of known materials. One implication is that price signals can be better responded to.

5.4.2.6 Abundant resources but much more limited reserves.

Although matter and energy are abundant in the universe, only a very small percentage is currently accessible to humanity because of existing technological and economic limitations. Only a very small percentage have been concentrated and “processed” by nature in the earth’s crust into a form that is of sufficient quality to make it economically exploitable. *Reserves* will probably always be much smaller than the *resource base*. This follows from evidence provided in this document regarding *enrichment factors*. Please see Table 3.3.

5.4.2.7 Certain elements are much scarcer in the earth’s crust.

The crustal abundances of elements can be used to calculate the *resource base* and give an indication of the relative abundance and scarcity of the different elements in the earth's crust. It shows for example that an element such as iron is much more abundant than tin in the earth's crust. Iron is a geochemically abundant element and there are no concerns about its geological availability, despite very high levels of usage. Other important geochemically abundant elements are silicon, magnesium, titanium and aluminium. Concerns about the future availability of non-renewable resources are much more likely to occur in the areas of the geochemically scarce elements such as platinum, zinc, nickel, gold and so on. Lists of *critical minerals* determined by countries such as the USA, UK, Germany and Japan as well as the European Union confirm this. The reserves of geochemically scarce elements are more likely to be limited because of a much smaller *resource base*.

5.4.2.8 A number of non-renewable resources are under-utilised.

Despite record-high utilisation of non-renewable resources such as iron and copper, there are examples of non-renewable resources that are under-utilised relative to their crustal abundance and *resources bases*. During the Bronze Age, tin was, for example, utilised to a greater degree than iron, which is much more abundant. The transition from the Bronze to the Iron Age, made possible by technological innovation, was a step in the right direction – it ensured greater materials sustainability. Such shifts were advocated by the Conservation Movement decades ago, as discussed in Chapter 2 – they promoted the idea that abundant resources should be used to a larger extent than less abundant resources. An element such as thorium is currently underutilised compared to uranium. Thorium is between three and five times as abundant as uranium (NEA and IAEA, 2016: 38).

5.4.2.9 The production volumes of mineral commodities that are extracted as by-products, only, are economically restricted by the volumes at which the primary elements are mined.

Many ores contain multiple elements. For such ores, sales of the primary element pay for extraction and some, or all, of the processing costs. In Chapter 3 Germanium and Indium are briefly discussed as examples of elements that are structurally scarce by-products. Their supply is economically restricted by the volumes of primary elements that are mined. Prices of such scarce by-products will have to increase significantly before they can be mined economically as primary elements. The (economic) availability of such elements is a concern as long as suitable substitutes are not available.

5.4.2.10 The average grades of ore bodies are declining.

This *stylised fact* is a generalisation of historical trends observed and illustrates that mineral resources of a lower physical and geological quality have been mined profitably over time. The observation raises a number of important questions. For example: Are ore *grade*s declining because of increased scarcity or are mined ore *grade*s declining because miners are managing to mine profitably at lower *grade*s?

The core fact should be interpreted together with another, namely that researchers such as Cuddington and Nülle (discussed in Chapter 4) concluded that there is no general tendency in the negative or positive direction of long-run mineral commodity price trends. These two facts combined can at least be partially explained because of improvements in mining and ore processing technologies and some of the other scarcity mitigating factors mentioned in this document.

This core fact does not imply that all orebodies as yet undiscovered will have lower *grade*s than the average *grade*s currently being mined – information about future mineral discoveries is unknown. It is likely, however, that the average *grade* mined in the future may be equal or lower than that mined currently because it can be done profitably, especially if productivity improvements and new innovations continue to support that.

5.4.2.11 The availability of minerals increases when the mining and processing of lower grade ores can be done profitably and in an environmentally acceptable way.

Currently many low-*grade* resources do not form part of reserves because of poor economics and/or because of unacceptable environmental impact. Low *grade* resources are more abundant than high *grade* resources. This is supported by, for example, Skinner's (1976: 263) view on the typical distribution of geochemically abundant and scarce metals in the earth's crust as well as Lasky's results, known as *Lasky's Law* which suggests that as *grade* declines arithmetically, tonnage probably increases geometrically. Lasky's results may only hold for relatively high *grade*s close to ore *grade*s. To confirm such relationships beyond any doubt for the earth's crust in totality would cost billions of dollars. Skinner's view and *Lasky's Law* have important implications. Firstly, they help to explain why non-renewable resource prices have not increased dramatically as demand expanded over the past 250 years. Secondly, if humanity could continue to mine at lower *grade*s than before, profitably, without price increases, then there is much hope for the future availability of non-renewable resources. Currently reserves form a small part of the *resource base*. If the average unenriched crust of the earth could be mined profitably, reserves would be enormous because the whole *resource base* would become reserves. The enormous amount of energy and chemicals that would be required to mine and process such low *grade*s means that this is extremely unlikely to ever become feasible from both an economic and environmental perspective.

5.4.2.12 <u>The recycling of mature industrial metals is a significant secondary source of supply.</u>

Compared to fossil fuels that are burnt and some industrial minerals, metals can be recycled and reused relatively successfully. Gold, copper, silver, lead, tin and antimony followed later by iron are metals that have been used by humanity for thousands of years. They are mature industrial metals that have already been recycled thousands of years ago. The majority of the other metals have only been discovered and used less than 300 years ago.

Compared to the mature industrial metals, there are much less immature metals locked up in consumer products and urban infrastructure because of their much more recent use. Lithium is an example of an immature metal for which the demand may increase significantly.

5.4.2.13 <u>Numerous methods exist to mitigate non-renewable resource scarcity.</u>

Reserves are depleted by means of mining, but various methods and channels exist through which reserves can be created. New reserves could be discovered through successful exploration. The demand for a specific type of non-renewable resource could be decreased if it is substituted by another resource. The demand for mined (primary) non-renewable material could be decreased by replacing primary supply with secondary supply such as the recycling of materials embedded in products that have reached the end of their lives. Technological innovation is a powerful tool in the creation of new reserves. These methods help to explain why prices did not increase dramatically like production volumes over time.

5.4.2.14 <u>Real mineral prices did not increase during the period 1870 – 2002.</u>

As a result of the physical depletion of mineral resources and more stringent government environmental regulations, prices should have increased if everything else stayed the same. It has been shown, however, by a number of studies that real mineral prices did not increase during the period 1870 to 2002 – they decreased or stayed flat. A number of researchers do not agree with this entirely – some of them focused on shorter time periods and others question whether correct inflation deflators were used. Many explanations exist for this *stylised fact* such as productivity increases that compensated for declining *grade*s. Another is the creation of new reserves by means of technological innovation. Investment in exploration expenditure and the discovery of new orebodies added new reserves despite existing reserves being depleted by mining. Despite many past predictions to the contrary, the mining industry has managed to satisfy growing global demand. But what about the future? A number of people have doubts about the forward-looking ability of prices. One reason is the lack of long-term future contracts.

5.4.2.15 There is no single ideal indicator for measuring mineral availability in the long run.

Numerous *indicators*, in addition to real price trends and *R/P ratio*s, have been investigated in the past in an attempt to find *indicators* that meet various criteria. Such criteria include ease of obtaining data required to determine the value of the *indicator*. Another important characteristic is whether an *indicator* is sufficiently forward looking to provide sufficient warning, timeously. Many of the *indicators* investigated in the past are not commonly used and most researchers nowadays refer to price trends and *R/P ratio*s despite their shortcomings.

5.4.2.16 Mineral commodities are not homogenously diffused across nations.

Not all mining jurisdictions are equally well endowed with all types of mineral commodities. Competitive advantages in the production, beneficiation and marketing of a specific mineral commodity is obtained through means such as favourable geology, good quality ore bodies, low labour costs, low regulatory costs, cheap electricity and low source-to-market transportation costs. *Rare earth* concentrates from the Mountain Pass Mine in California are, for example, processed in China where environmental regulations are less strict and electricity costs are lower. In Chapters 1 to 4 a number of examples are provided why elements such as *rare earth*s and platinum are produced in only a few jurisdictions. Implications are that such mineral commodities are available in certain jurisdictions while other jurisdictions are highly dependent on imports. Trade restrictions lessen the availability of non-renewable resources in areas that rely on imports. It is therefore possible to have different levels of availability in different parts of the world because of politics and trade restrictions. Mineral commodity dependency is an important factor in the identification of *critical minerals*.

5.4.2.17 <u>Transportation infrastructure and low international shipping costs together with free trade ensure the availability of all non-renewable resources in all jurisdictions.</u>

Many decades ago only high-value items were transported between continents because of high shipping costs. Globalisation, free trade, low shipping costs and infrastructure such as harbours and railway lines enable greater availability of non-renewable resources globally. One implication of low international shipping costs is that bulky materials such as various ores and concentrates can be transported to and beneficiated at locations where it can be done at lower cost, for example jurisdictions where the cost of electricity is low. Mining and smelting are known to be energy-intensive and countries with low energy costs have a competitive advantage in the beneficiation of ores and concentrates. The Chinese *Belt and Road Initiative* includes the development of infrastructure required to transport ore, concentrate and mineral commodities from various parts of the world to China where they are required for the country's development.

5.4.2.18 <u>Developing economies are influential w.r.t. mineral demand, supply and trade.</u>

More mineral commodities are mined and refined in developing regions today, compared to a few decades ago. This exposes importing countries to greater political and economic risks. Most artisanal and small-scale mining (ASM) takes place in developing countries and some of it is illegal, raising various concerns such as the use of child labour and inadequate environmental management.

Currently, China dominates both the supply and demand for mineral commodities. Its consumption has increased rapidly during the past few years. Some of the ores and concentrates do not originate from China but are imported and processed there. It is forecasted that emerging markets will in future become even more important because of economic growth and power as illustrated by their changing GDP-rankings.

5.4.2.19 <u>Mining and minerals processing productivity has increased significantly over many decades as a result of technological and other forms of innovation.</u>

Mining is not considered to be a high-tech industry. Numerous technological and other innovations have however occurred over the years. Faster drilling rates and larger equipment at surface mines resulted in increased productivity, for example. There is, however, no guarantee that productivity increases, driven by technological innovation, will continue into the future. Radical breakthrough innovation is very difficult to predict but it may be reasonable to expect small incremental innovation to continue as long as money is made available for research and development activities at equipment suppliers, mines, universities and other types of organisations involved in mining research. An important implication of increased productivity is that it lowered the real cost of breaking, transporting and processing ore.

5.4.2.20 Both large-scale industrial mining as well as artisanal and small-scale mining activities contribute towards the primary supply and availability of mineral commodities.

The dualistic supply structure of the minerals industry has various important implications. ASM has a competitive advantage with regards to the mining of small orebodies close to the surface. LSM, on the other hand, often mines large orebodies and obtains economy of scale by various means such as the use of large equipment and is, therefore, capital intensive. It is important to note that artisanal and small-scale mining contributes significantly to the global supply of mineral commodities. Secondly, artisanal mining produces concentrates and final products at low (labour) cost because minimum wage legislation may not apply. Informal miners do not produce audited annual financial statements and do not report on *indicators* such as reserves and life of mine. In most cases it is not measured and estimated and, therefore, the actual level of global reserves may be understated, especially for those minerals mined in significant quantities by artisanal miners.

5.4.2.21 Technological innovation has created new reserves.

Many examples exist where new metallurgical processes enabled the extraction of mineral commodities from ore-types from which it was not previously possible. The extraction of copper from porphyry ores by means of the solvent extraction and electro winning (SXEW) is an excellent example. In some cases, such orebodies were considered to be of low quality. An important implication of this is that new reserves were created while the demand for metals such as copper increased dramatically over the past few decades. Technological innovation has also enabled the emergence of large-scale industrial mining (LSM). LSM enjoys economy of scale which results in lower unit costs and the mining of lower *grade* deposits.

5.4.2.22 The availability of metals required for the low-carbon economy is currently a bigger concern than the future availability of fossil fuels.

Humanity has experienced a number of energy transitions. Each time it broadened its menu of options ranging from wood to whale oil, coal, petroleum, natural gas and nuclear. During the Industrial Revolution and since then there has been a shift away from renewables such as wood, whale oil and the use of wind to power sailing ships driven by factors such as increased population, deforestation, the utilisation of denser sources of energy such as coal and oil, and technological innovation such as the invention of the steam and internal combustion engines.

In the 1970s oil security and availability became a major issue in the U.S. as the country became more reliant on imported oil when its own oil production peaked in the early 1970s as predicted by *Hubbert*. This continued to be the situation until fairly recently before extensive oil shale gas and oil exploitation commenced in the U.S. The availability of fossil fuels has been a major concern over the past few decades and influenced global politics significantly. This is, however, expected to change over the next few decades.

The transition to a low-carbon economy is driven by the need to replace carbon-intensive industries and products with ones that will have much fewer or no carbon emissions and is driven by concerns regarding global climate change. Currently, the focus is on moving away from fossil-fuel electricity generation and transportation. At the moment, beginning stages of this transition the impact on mineral demand is already discernable – the demand for lithium and cobalt used in battery electric vehicles has increased. Once significant progress has been made there will be a significant reduction in global coal, oil and gas use. Further investment in this area is currently not popular among investors and some of the existing infrastructure and reserves may become *stranded assets*.

Solutions for global warming and climate change require a new set of raw materials. The transition to a low-carbon economy is expected to be very metals intensive and has already raised concerns about the future availability of a number of raw materials. Along with the minerals supercycle caused by massive Chinese mineral demand, this may very well become one of the megatrends of the 21st century from a minerals availability perspective.

5.4.2.23 The democratisation of energy.

Energy supplies are likely to be democratised over the next few decades and this will probably result in the increased availability of all forms of energy. After decades of Middle Eastern oil dependency, the U.S. has become energy self-sufficient after successfully establishing a shale oil and gas sector. This and the increased adoption and diffusion of renewables has started to reduce OPEC's power and is likely to cause increased democratisation of energy over the next few decades.

The transition to a low-carbon economy driven by climate change and cheaper renewables accentuates the multi-dimensional nature of non-renewable resource availability. Huge coal reserves may be left stranded in countries such as the U.S. and therefore it is not geological availability that may be the cause of declining coal usage in decades to come but rather concerns about environmental issues, specifically climate change (assuming that carbon capture and sequestration do not become cost-competitive solutions).

Energy storage goes hand-in-hand with intermittent renewables. One method of storing electrical energy generated by renewables is to create hydrogen by means of electrolysis. The greater and faster adoption of hydrogen as an energy carrier, and hydrogen-driven fuel cell vehicles (FCVs), will boost the democratisation of energy. It may also lower the demand for battery materials because low-temperature fuel cells used in FCVs rely on metals such as platinum.

Unlocking the oil and gas reserves of the Arctic as well as the opening of the Northern Sea Route as a result of global warming will add to the democratisation of the global energy situation. In the past, the power of OPEC and threats to high-volume oil shipping lanes via the Suez and Panama Canals and Strait of Hormuz added to global security concerns and tensions from time to time.

5.4.2.24 <u>There is great uncertainty about the location and quantity of undiscovered reserves.</u>

Exploration is a very risky undertaking – the chances of finding new reserves are very small. Exploration budgets are limited and obtaining information about new reserves is very costly. Consequently, information about the likely location and quantity of undiscovered reserves is limited. It is, therefore, not possible to determine if, of all potential resources, discovered and undiscovered, the best quality ones have already been mined.

This core fact helps to explain why there is a debate about the future availability of mineral commodities – imperfect information fuels the debate.

5.4.2.25 <u>There is great uncertainty about future innovation, its level of adoption and rate of diffusion.</u>

Innovation affects both the demand and supply of non-renewable resources. From the invention of explosives to the design of large mining equipment, mining and processing-related innovation contributed significantly to the creation of new mineral reserves. Research and development (R&D) spending is a pre-requisite for innovation but provides no guarantee that it will result in new innovations and knowledge that can help to offset the higher costs of mining declining *grade*s and/or at deeper levels. The long-term supply of mineral commodities at affordable prices is, therefore, not guaranteed.

5.4.2.26 Substitutes do not exist for all applications of all the elements.

Substitutes play an important role in mitigating resource scarcity. It enables demand shifts from fewer to more abundant resources. Substitution, therefore, contributed significantly to the general availability of resources and is, therefore, one mechanism (or channel) that prevented prices from increasing according to *Hotelling's Rule* and makes the price of the backstop technology impossible to predict. A number of materials exist that can conduct electricity or heat. Various means of transportation can be used to get to work and houses can be constructed by means of a variety of materials. This points to the fact that hundreds of substitutes exist for certain products, services and raw materials. For certain applications there are however no substitutes, or good substitutes. This is discussed in section 4.3.5 of chapter 4. Graedel et al (2015: 6298) produced a method that provides a concise *indicator* of substitutability by focusing on the substitute performance of the Period Table of Elements. Their method ranks the chemical elements on a scale from 0 to 100 where 0 indicates that exemplary substitutes exist for all major uses of an element while a rating of 100 indicates that no substitute exists for any of the major uses of an element. Dysprosium, one of the rare earth elements, is an example of an element for which no substitutes exist. Please see Figure 5.2.

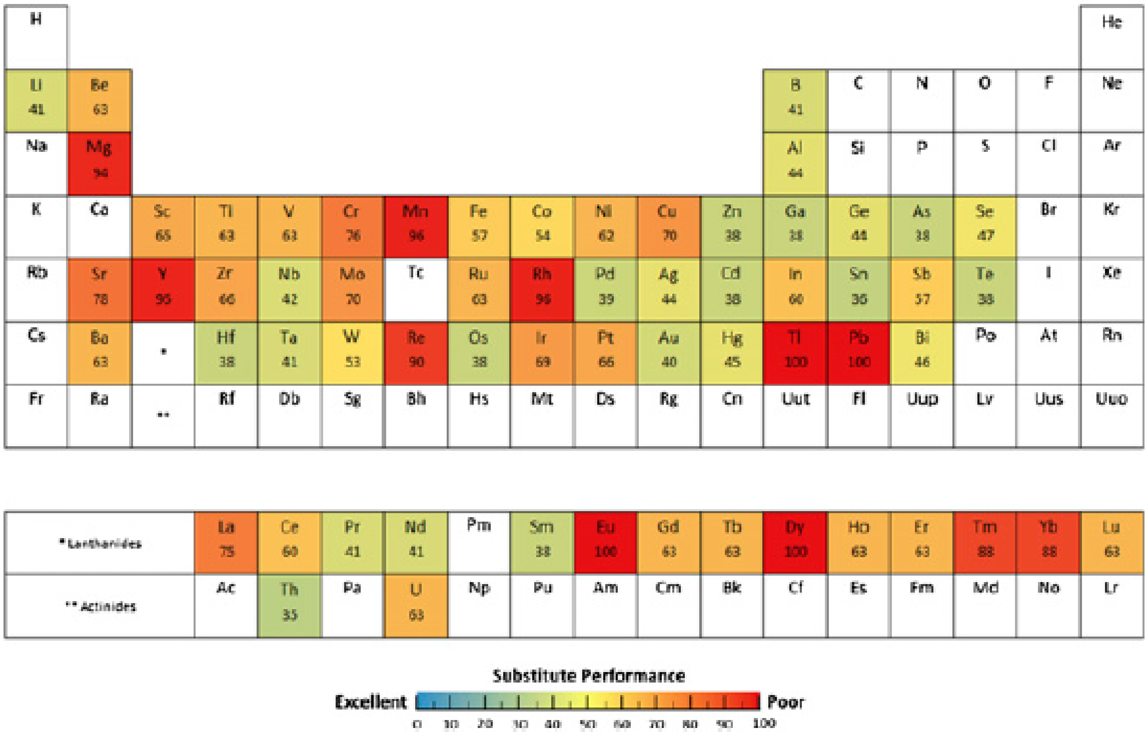

Figure 5.2 The periodic table of substitute performance by Graedel et al (2015: 6298).

5.4.2.27 <u>Mineral resource nationalism often impacts negatively on global availability.</u>

Various forms of mineral *resource nationalism* exist. Mineral *resource nationalism* such as the excessive taxing of mining companies increases the costs of producing raw materials. More extreme forms of mineral *resource nationalism* such as the nationalisation of mines impact negatively on production and availability when states fail to manage state owned enterprises (SoEs) successfully.

5.4.2.28 <u>There is an ongoing effort for new territories to be exploited for their mineral wealth and to develop the next generation of reserves.</u>

The effort to find new territories that can be exploited for their mineral wealth is continuing. The focus lately is on the seabed and the Arctic. Such efforts, if successful, will ensure that the next generation of reserves will be created so that non-renewable resources will be available in the future. Efforts by nations with coastlines to extend their economic zones to the limit of the continental shelf and attempts by the U.S. to purchase Greenland from Denmark serve as examples.

5.4.2.29 Strategic and critical minerals often have an influence on geopolitics.

Many nations are dependent on minerals which may be concentrated in only a few countries in the world. One means of ensuring access to a mineral of which sufficient quantities are not produced locally is to establish and maintain good diplomatic relations with supplying countries. The case of how oil-addicted America's politics were influenced by their oil dependency is well documented. The U.S. has been an ally of Saudi Arabia for decades because of the country's position as a dominant producer of oil.

5.4.2.30 There are attempts from time to time by countries to reduce their reliance on mineral producing countries.

In Chapter 4 a number of government policies are listed. Some of those are aimed at reducing import reliance when minerals are produced by one or a small number of countries and when such minerals are of a strategic or critical nature. The European Union, Japan, Germany and the USA have developed ways of identifying critical minerals. A list of critical minerals can help a country to develop policies to ensure the availability of such minerals in the short, medium and longer terms. Such policies may range from the stockpiling and the increased recycling of end-of-life products that contain such mineral commodities, to the introduction of research and development programmes to find substitutes. Another policy is that of the diversification of supply. One of the latest examples is that of the U.S. which wants to diversify its imports of rare earth elements by entering into agreements with Australia and Canada on the supply of rare earth elements.

Evaluations of whether a specific mineral is critical to a specific jurisdiction have to be done regularly because the type of raw materials required for manufacturing processes changes over time. Sources of supply may also change over long periods of time.

5.5 CONCLUSION: HOTELLING'S MODEL AND THE FIXED STOCK PARADIGM IS TOO SIMPLISTIC

Taking Hotelling's 1930's paper as the benchmark, it is clear that the Availability of Non-renewable Resources body of knowledge has since developed considerably. As explained in Chapter 2, Hotelling focused basically on one *stylised fact*, namely fixed non-renewable resources, and did not consider factors that may mitigate resource scarcity. Hotelling focused on price as the *indicator* of scarcity. Since then, numerous *indicators* have been proposed and investigated to determine their usefulness. In this study, these developments are pointed out and a set of core facts distilled from available literature. The framework proposed in this document together with the core facts explain past events, create clear boundaries for the relevant body of knowledge, and illustrate that the fixed stock *paradigm* is a simplistic way of looking at and dealing with the body of knowledge. A broader and more sophisticated body of knowledge is presented in this document. The conclusion can therefore be drawn that Hotelling's model and the fixed stock *paradigm* is overly simplistic. It cannot be used to analyse future non-renewable resource availability or make predictions regarding it. The core facts illustrate that the availability body of knowledge is fairly complex. One great shortcoming of Hotelling's model is that it does not provide for technological innovation. In light of this, it should not be surprising that Hotelling's rule has not been supported by real price trends over a number of decades.

The shift of supply to emerging markets and the associated diversification of supply is another factor that has countered increased scarcity. The result of this shift and globalisation is that a much larger part of the earth's land surface is now available through better transportation infrastructure and investment to contribute towards global supply. Globalisation with its associated lowering of shipping costs as well as the end of the Cold War resulted in better integrated global mineral markets which may ensure greater competition, lower prices, improved security of supply and improved availability if everything else stays the same.

Furthermore, as already discussed, a number of factors have increased reserves and countered the depletion of reserves caused by mining. Factors ranging from improvements brought about by technological innovation to the contributions by both ASM and LSM may also be responsible for observed price trends.

Phelps' (2019) view is that because of imperfect knowledge, there is no basis for treating decision-makers as having correct models with which to make decisions. Imperfect knowledge about future ore discoveries and innovation explain diverse opinions regarding the future availability of non-renewable resources, and support Phelps' view.

A number of the core facts documented here emerged over time and were not yet known at the time when Hotelling wrote his famous paper. Past trends may not necessarily continue into the future. Furthermore, new trends may emerge and, therefore, the core facts identified by this study must be revisited in the future.

5.6 SUGGESTIONS FOR FURTHER RESEARCH

5.6.1 Contribution of the artisanal and small scale mining sector to future supply and availability

The influence of the ASM sector on current and future mineral commodity availability has not yet been exhaustively researched. The dynamic nature of an evolving mining ecosystem together with the fact that more than 6 000 abandoned mines exist in South Africa alone provides much scope for the activities of zama-zamas (illegal miners) to be increased, especially if high levels of unemployment continue or worsen (for example as a result of COVID-19) and government fails to develop and implement policies to create a conducive environment for the creation of more jobs in the formal sector.

5.6.2 Forecasting the diffusion of infrastructure required by the energy transition

The rate at which new solar and wind farms, battery electric vehicles, hydrogen fuel cell electric vehicles and the hydrogen economy is implemented exerts a huge influence on the future demand and availability of various types of non-renewable resources. The correct forecasting of the future diffusion of such goods will help miners to better plan the roll-out of new production capacity of the raw materials required. If such information is produced by the users of raw materials, and not independently, there may be an incentive for them to overstate future diffusion statistics. That may create overcapacity of raw materials and possible lower prices.

5.6.3 The impact of deteriorating U.S.-China relations on non-renewable resource trade

The rivalry between China and the U.S. is described by some as a techno-economic war and explained by, for example, the *Thucydides's Trap* phenomenon. On the one side there is ambitious China which, through its Made in China 2025 Strategy, wants to control 90% of the top next generation industries and technologies such as biotech, artificial intelligence (AI) and robotics. It is accused by the U.S. of stealing intellectual property and sourcing technological know-how in ways that will help it to quickly catch up. In the area of 5G-cellular network technology, China is already a technology leader. Trump-Administration advisors and government officials can be divided into so-called “globalists” and “nationalists”. Numerous Americans want to maintain their technological leadership in a number of industries and technologies. One possible strategy considered is to decouple the American economy from that of the Chinese, a type of Cold-War strategy. By using national security emergency powers vested in the U.S. Dept of Defence, the U.S. introduced tariffs on steel and aluminium imports. The U.S. is aware of its mineral commodity dependency in areas such as rare earth elements, and is working on policies to reduce it. The Chinese are putting various plans in place to dominate supply chains, for example that of electric vehicles, to ensure that sufficient raw materials will be available in such potentially high-growth areas. In this environment the literature and research on critical and strategic minerals is very relevant. Cold War thinking is not limited to Republicans and may not disappear if the Democrats win the 2020 elections (Frontline PBS, 2019; Arnoldi, 2020).

The Trump administration’s trade war against China raises a number of questions. A few follow:

1) What was the cost of the trade war to the US and Chinese economies, respectively? Which economy lost most?
2) What type of retaliatory measures could China take if the trade war is continued by the next US administration? How damaging would such measures be to both economies?
3) An example of a retaliatory measure that China may take in future is to prohibit the sales of rare earth commodities, and related beneficiated products, to the US military complex. What would the consequences of that be for the US economy and national security?

5.7 FINAL WORDS

All the research questions in Chapter 1 (section 1.7) have been addressed in this document.

The 17 United Nations Sustainable Development Goals for the period 2015 to 2030 have become organising and guidance principles for governments. To end poverty will require economic growth and development. That is still coupled to non-renewable resources, especially for economies where the services sector is a small component of the economy. There is a strong possibility that growth in mineral demand will continue over the next few decades. The result may be temporary or long-term real price increases if it is not compensated for by one or more mitigating factors.

Trade wars may take place from time to time in the future and will complicate the security of mineral supply and affect availability in certain jurisdictions if mineral dependency is used as a weapon. Opposition to mining may increase further as the world becomes more and more crowded unless radical new ways of mining are adopted, for example, increased underground mining, processing and storage of tailings underground and sea-bed mining, assuming that this would be less invasive.

An important outcome of this study is a list of core facts distilled from available literature. These facts illustrate that many factors related to the availability body of knowledge are overlooked when thinking is shaped by the fixed stock paradigm.

As long as sufficient investments are made in exploration and technological innovation to find and create reserves, there is a chance that future demand for non-renewable resources will be met. The current investments being made in seabed exploration and equipment development provide humanity with one such option and this is, therefore, a very important development.

When speculating about likely future developments in the Availability body of knowledge, it is likely that the internalisation of externalities will continue for as long as global population growth continues and humanity's impact on global ecosystems increases. Carbon subsidies will probably decrease over the next few years and carbon taxes or other instruments to keep carbon emissions in check will probably increase. These will probably have important implications for the type of non-renewable resources required in the future.

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APPENDIX A: GLOSSARY OF TERMINOLOGY

Please note: This glossary includes explanations of terminology that are used in the dissertation. Such words are indicated by italics.

Artisanal and small-scale mining (ASM) – Generally understood to be mining that is more labour rather than capital intensive and that takes place on a smaller scale than industrial mining. Many other definitions exist, for example: "Broadly speaking, artisanal and small-scale mining refers to mining by individuals, groups, families or cooperatives with minimal or no mechanisation, often in the informal (illegal) sector of the market" (Hentschel et al, 2002: 3).

"A backstop technology is defined as a new technology producing a close substitute to an exhaustible resource by using relatively abundant production inputs and rendering the reserves of the exhaustible resource obsolete when the average cost of production of the close substitute falls below the spot price of the exhaustible resource." (Levy, 2000: 1)

Battery materials – The lithium-ion battery is expected to dominate battery technology for the next number of years. Of the five main types of lithium-ion batteries, those that use less cobalt (for example the *NMC811*), is expected to dominate in the near future (Seddon, 2019).

Belt and road initiative (BRI) – Also called the "One Belt, One Road" (OBOR) or "old Silk Road". "An investment initiative involving infrastructure, education, construction, roads and railways, the motor industry, real estate and energy. It spans more than 68 countries in Asia, Europe, Oceania and Africa. … it is an estimated $4-trillion to $8-trillion project that if successful, will benefit 65% of the world's population (Ratshitanga, 2018: 9). The initiative may stimulate future mineral commodity demand, depending on how quickly the various infrastructural and other projects associated with the initiative are rolled out. Mr John Bolton, the former U.S. National Security Advisor, described China's BRI as "a plan to develop a series of trade routes leading to and from China with the ultimate goal of advancing China's global dominance" (Mora, 2018). The size of this ambitious initiative is illustrated in Figure A.1 where it is compared with the Marshall Plan.

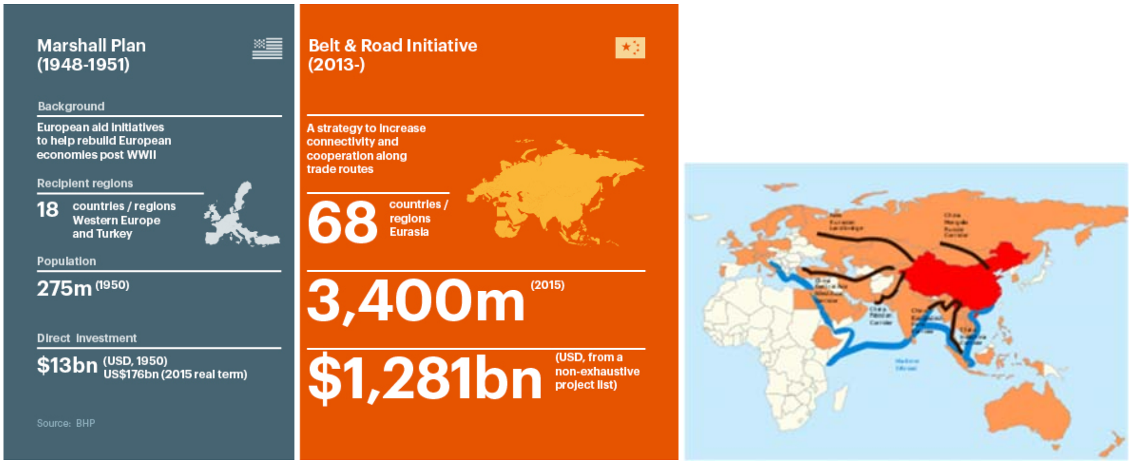

Figure A.1 The corridors (right) and a comparison with the Marshall Plan (BHP, Sep 2017; https://en.wikipedia.org/wiki/Belt_and_Road_Initiative)

Bre-X scandal – Between 1995 and 1997, Canada-based junior mining company Bre-X swindled investors out of billions of dollars by alleging that it had discovered the largest gold resource in the world at Busang, on the Indonesian Island of Borneo. It was subsequently discovered that the original ore samples on which the evaluation of the mineral resource at Busang was based, were salted with gold dust, was believed to have been shaven off gold jewellery. Originally a penny stock, Bre-X's stock price peaked at C$ 286.50 which resulted in a growth rate of about 100 000% in only three years. The reputation of the Canadian exploration sector was damaged in the process. The Bre-X scandal focused the spotlight on the need for reporting codes and standards (Le Roux, 2006). See *Codes, guidelines and standards for reporting mineral reserves and resources*.

Brownfield exploration, also known as near-mine exploration, refers to areas where mineral deposits were previously discovered. See: *Greenfield exploration*. Reference: undervaluedequity.com/mineral-exploration-companies-greenfield-exploration-vs-brownfield-exploration/

Circular economy – “an industrial system that is restorative or regenerative by intention and design” (WEF, 2014: 13). “A global economic model that decouples economic growth and development from the consumption of finite resources. Circular economy systems keep products in use for as long as possible, allow for the recycling of end products, and eliminate waste” (Whitmee et al, 2015: 1975). The intention of the circular business model is to replace the “take-make-use-dispose” business model.

Clarke – The world-wide average crustal abundance is called the Clarke. It was named after Frank Wigglesworth Clarke who, in 1889, undertook the first study to determine the composition of igneous rocks and the concentration of various chemical elements in the earth’s crust. Clarke values can be expressed in % or ppm. Clarke values of 0,0025% (or 25 ppm) and 0,0065% (or 65 ppm) respectively for copper and zinc mean that the average concentration of copper and zinc in the earth’s crust is

0,0025% and 0,0065% (Wedepohl, 1995: 1220). Copper and zinc are, therefore, called geochemically scarce elements. Aluminium, titanium and iron have much higher Clarke values and are, therefore, called geochemically abundant elements/metals. It would be very costly to mine and process the average crust of the earth in order to obtain copper and zinc from it. Orebodies containing copper and zinc have been significantly enriched by geological processes as indicated by *enrichment factors*.

Club of Rome – (Website address: http://www.clubofrome.org) A think-tank consisting of about 150 scientists, business people and politicians from various countries. They try to promote understanding of the global challenges facing humanity, while proposing solutions through scientific analysis, communication and advocacy. The organisation was formed in Italy in 1968. According to Bardi (2014: vii) their work focus on a different set of values required to change economic theory and practice and safeguard resources. "The Limits to Growth" was the first report to the Club of Rome (Dobrotă & Vierita, 2010: 85; Planting, 2019).

Cobalt – Element number 27 on the periodic table. Cobalt has various applications and is an important ingredient in certain types of batteries. Cobalt prices tripled recently for a while because of the expected increase in demand of electric vehicles. Currently, many electric car batteries use lithium, graphite, nickel, cobalt and manganese. The growth in cobalt production increased significantly the last number of years. Cobalt is on the United States' 2018-list for *critical minerals*. See *polymetallic nodules*.

Codes, guidelines and standards for reporting mineral reserves and resources – Various reporting codes such as SAMREC in South Africa, YORC in Australia and PERC in Europe, guidelines like the SME in the U.S., standards such as the NI 43-101 (Canadian Institute of Mining, Metallurgy and Petroleum, 2011) and certification codes (e.g. Comision Minera in Chile) were developed and updated after the Poseidon Bubble and *Bre-X* scandal in the 1960s and 1997. The codes, guidelines and standards incorporate a mineral-classification methodology that enables investors to have greater confidence in what is reported by exploration and mining companies, thus reducing investment risk and improving the climate for investment. See *McKelvey diagram*.

Commodity (price) supercycle – Cycle that occurred between 2003 and 2015 according to Woetzel et al (2017: vi). The Economist's commodity price index is the longest running global commodity index and is currently made up of the 25 most traded commodities other than gold and oil. The effect of implied American inflation is removed so that a good understanding of the real commodity cycle can be obtained. Real commodity price data gathered by The Economist since 1887 shows four cycles with troughs in years 1931, 1971 and 2002 and peaks in years 1917, 1951, 1980 and 2011. The 1917-peak is linked to the demand for iron and food during WWI and the end of the first wave of globalisation. The supply of food during WWI was limited and the extraction of minerals was in some cases interrupted. WWII caused a rise in prices of about 66% in real terms. The rebuilding after the war ignited the rise of commodity prices. The period after WWII is characterised by both high population and economic growth (Krausmann et al, 2009: 2692). The trough of 1971 was stopped by growing global trade and the oil crisis. The price of gold peaked in 1980 and that of oil in 1981. The 2011 peak occurred after a decade of massive growth in China and other developing countries which created a huge demand for commodities (Schüssler, 2016). The supercycle is characterised by double-digit annual price increases since the early 2000s (Nyquist et al, 2016: 2).

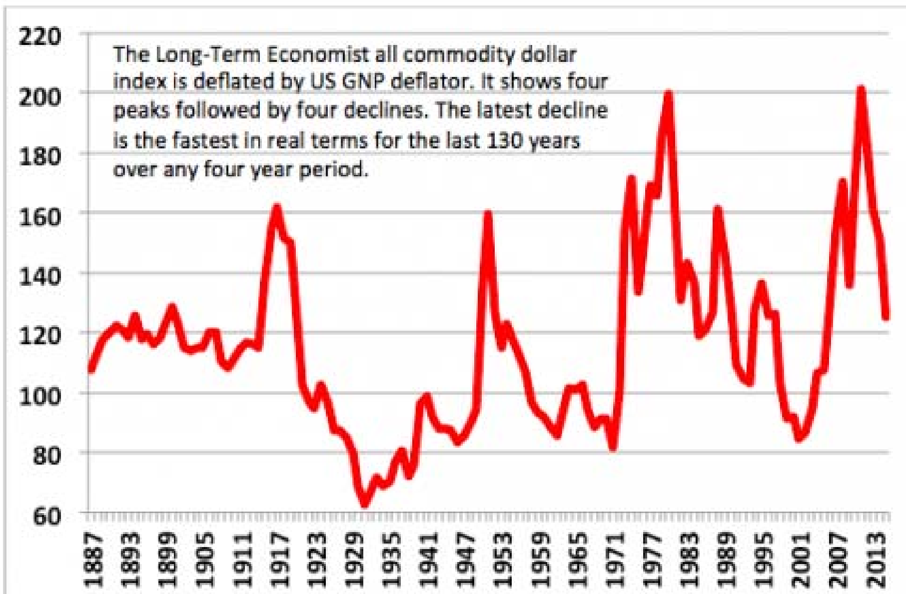

Figure A.2 Commodity price index (Schüssler, 2016 – original source: The Economist)

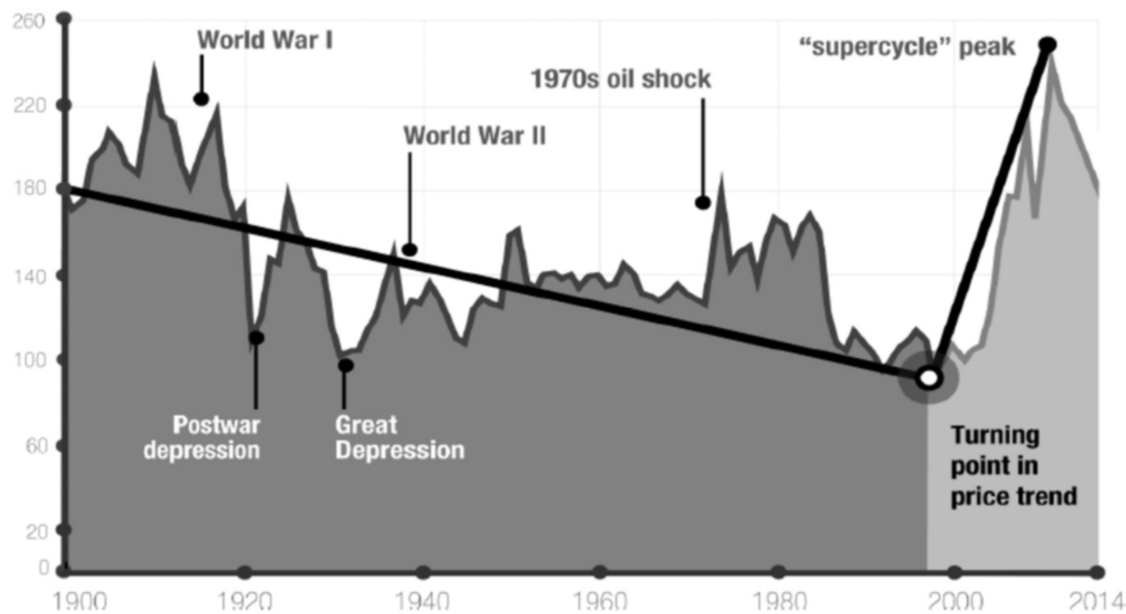

Figure A.3 McKinsey Global Institute commodity price index based on the arithmetic average of four commodity indexes: food, agricultural raw materials, metals and energy – average of 1999 to 2001 = 100 (Sources: http://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/a-new-era-for-commodities; Dobbs et al, 2016: 89)

The average price of different types of commodities has roughly doubled for the 13-year period since 2000 (Dobbs et al, 2016: 87; Dobbs et al, 2013: ii) Cuddington and Jerett (2008) did research on supercycles.

Cost curve – An example of a minerals commodity cost curve is illustrated in Figure A.4 below.

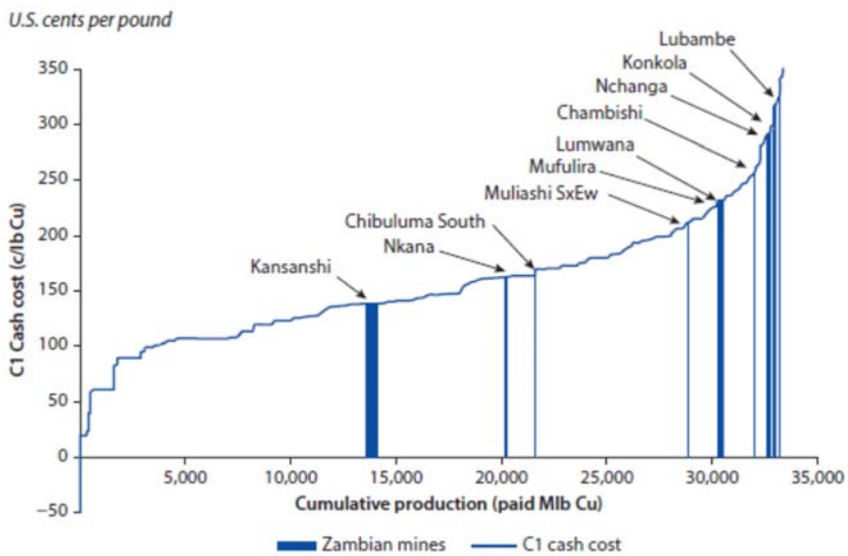

Figure A.4 The cost curve for copper mine production in Zambia (Halland et al, 2015: 19)

The cash cost of different Zambian copper mines were plotted in Figure A.4. Kansanshi mine is a lower-cost supplier (relative to Lubambe).

Critical mineral – A mineral that has "a supply chain that is vulnerable to disruption and that serve an essential function in the manufacture of a product, the absence of which would cause significant economic or security consequence." (U.S. National Science and Technology Council, 2016: ix). See *strategic material*.

Dematerialisation – Absolute dematerialisation refers to the situation when the total material input to an economy decreases in absolute terms. This is also referred to as "strong materialisation" (Behrens et al, 2007: 445). Relative dematerialisation and "de-coupling of economic growth" refers to a situation when less materials are being used per unit of GDP generated resulting in decreasing *intensity-of-use*.

Dimensions of the availability of primary (mined) mineral commodities (Eggert et al, 2008: 71)

1) Geological - existence of resource.
2) Technical - ability to extract and process.
3) Environmental and social – ability to extract and process the resource in an environmentally and socially acceptable way. This is linked to the concept "license to practice".
4) Political – the way in which governments influence availability through their strategies, policies and actions.
5) Economic – cost and affordability.

Dominant design – A product design that is adopted by the majority of producers, one that is a 'de facto' standard (Nel, 2012: 486).Today Windows is the dominant operating system for personal computers. Currently the internal combustion engine is used in most cars.

Dragline - A large excavation machine used in surface mining to remove overburden (layers of rock and soil) covering a coal seam.

Figure A.5 Picture of a dragline

Ecological economics – It is an interdisciplinary field that uses economics and ecology to address the central problem of sustainability. It focuses on the interdependence of economic and environmental systems and regards the economic system as part of the larger system that is Planet Earth. The work of Kenneth Boulding, Nicholas Gerogescu-Roegen and William Kap inspired the development of Ecological Economics. Ecological Economics is characterised by its preservation of environmental systems, the complementarity of natural resources (e.g. unpolluted air and water) and capital and the advancement of a post-growth society which is referred to by Daly as a steady-state or balanced economy. It is associated with the concept of *strong sustainability* (Daly, 2007: 117; Perman et al, 2003: 8; Von Hauff et al, 2016: 100, 101).

Energy pathway – "A practical route from energy source to a useful application of energy" (Zepf et al, 2014: 28). The concept of "energy pathway" is used to explain that although energy sources such as wind, wave and the sun are renewable the devices, e.g. wind turbines and PV cells, used to harvest such energy is not renewable because they are constructed from non-renewable resources. This is indicated by figures A.6 and A.7.

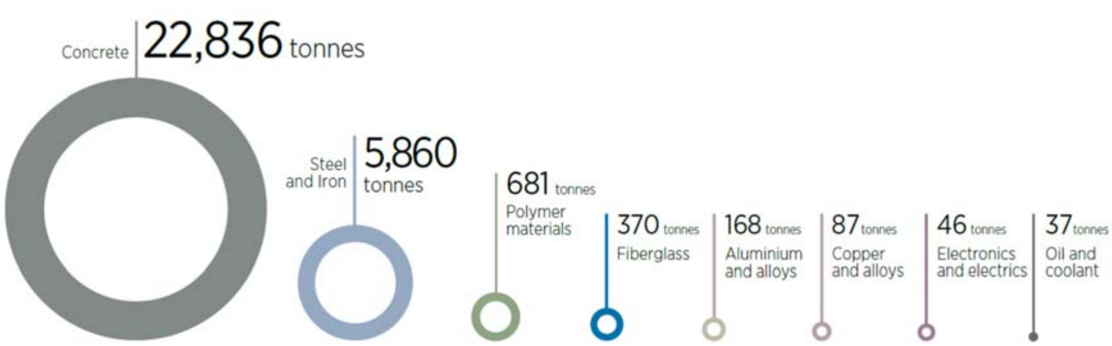

Figure A.6 Materials needed to develop a 50 MW wind farm. (IRENA, 2017: 11)

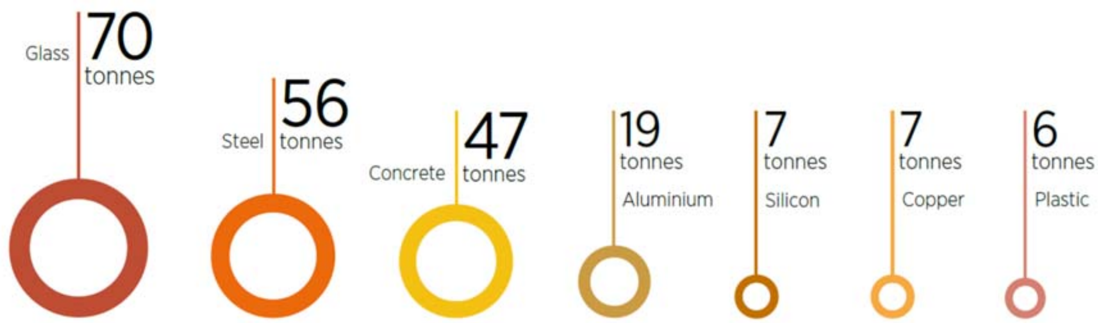

Figure A.7 Materials needed to develop a 1 MW silicon-based solar PV plant (IRENA, 2017: 13)

Energy Transitions Commission – Launched in 2015 by Royal Dutch Shell and multiple partners with the purpose of investigating and informing how the world can shift to a low-carbon economy.

Enrichment factor – “The degree of natural concentration (above Clarke value) required to be labelled as “ore”, varies from X (for Fe, Al) to XX000 (for Hg, Sb)” (Mookherjee & Panigrahi, 1994: 3). Henckens et al (2014: 3) provides typical enrichment factors for different types of elements.

Environmental credit crunch – A credit crunch can be defined as the sudden, sharp reduction in the availability of money or credit from banks or other lenders. Paul Donnovan, a senior economist at UBS, explains the phrase *environmental credit crunch* as follows: “the consumption of environmentally finite resources or the overconsumption of environmentally renewable resources is something that creates credit”. According to him, people are lowering their future standard of living in order to have a better standard of living today, which is just another way of defining non-sustainable development (Udasin, 2017). See *overshoot day* which is a measure of the *environmental credit crunch*.

Evolution of drills and drill rigs

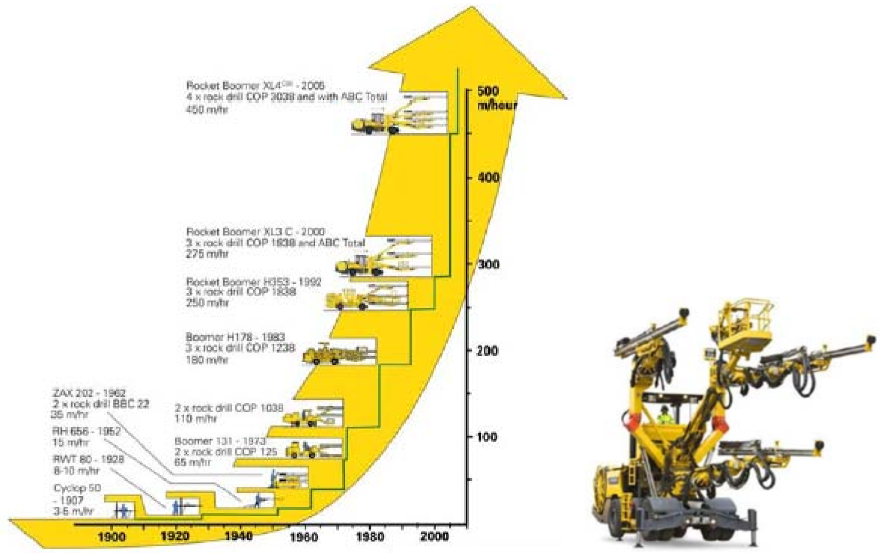

Figure A.8 The evolution of drills and drill rigs and associated increases in drilling rates (van Wageningen, 2017: 11)

Extractive Industry – Any concern involved in the exploration for or the extraction and usage of non-renewable natural resources. Examples: mining, dredging, quarrying, crude oil and natural gas processes and industries.

Feedback loop – see *positive feedback loop*.

Flow-through shares – A financial innovation introduced in the late 1980s in Canada that has helped to generate billions of dollars for mining exploration, contributed towards the development of numerous mines and is an important stimulant of Canada's well-developed junior mining industry. A junior mining company which does not generate income, and therefore cannot deduct exploration expenses from income, can in terms of Canada's Income Tax Act transfer exploration expenses to individual investors who can then apply it against personal incomes (Haselback, 2013).

Flow/flux resource – Solar radiation, wind, tides and naturally flowing water are examples of flow resources (Perman et al, 2003: 11). Solar radiation will exist for at least another 6 billion years and whatever is used today by means of solar geysers or photovoltaic (PV) cells will not reduce the amount of radiation that the earth will receive from the sun in the future. When some of this radiation is converted by means of a PV cell into electricity and stored in, for example a battery, then the amount of electrical energy stored in the battery becomes a *stock resource*.

Grade – The concentration of a mineral or metal in ore. A grade of 5 g/t of gold means that every tonne of ore contains 5 grammes of gold.

Greenfield exploration relies on the predictive power of ore genesis models to find mineral deposits in previously unexplored areas or in areas where they are not already known to exist. See: *Brownfield exploration*. Reference: undervaluedequity.com/mineral-exploration-companies-greenfield-exploration-vs-brownfield-exploration/

Green New Deal – The so-called "Green New Deal" includes the words "New Deal" which refers to U.S. President Franklin Roosevelt's bold package of reforms that was introduced as a response to the Great Depression of the 1930s. The idea is that the Green New Deal should be on the global scale and embrace a "wider and greener vision" (Barbier, 2010: 832).

Hartwick's Rule – John Hartwick thinks that a constant level of consumption could be maintained perpetually if all *scarcity rent* is invested in capital. That level of investment would be sufficient to assure that the value of the capital stock would not decline and is linked to the concept of *weak sustainability*. Solow developed Hartwick's Rule into the so-called "constant capital rule" (Hartwick, 1977: 972; Tietenberg, 2006: 96; Tietenberg & Lewis, 2011: 114). See: *intergenerational equity*.

Herfindahl-Hirschman Index (HHI) – The Herfindahl-Hirschman Index (HHI) is a commonly accepted measure of market concentration. It can be expressed as a number from close to 0 to 10 000, when market share is expressed as a percentage, or 0 to 1 if market share is expressed as a fraction. (The latter is used when the *supply risk indicator* of a specific mineral is calculated.) The HHI is calculated by squaring the market share of each firm competing in a market and then summing the resulting numbers; HHI = $\sum_{i=1}^{n} S_i^2$; where S_i^2 is the square of the market share of the i^{th} firm and n is the number of firms in the market. The U.S. Department of Justice uses the HHI for evaluating potential mergers issues and considers a market with an i) HHI below 1 500 as unconcentrated, ii) HHI between 1 500 and 2 500 as moderately concentrated and iii) above 2 500 as highly concentrated. An HHI value close to 0 indicates a large number of equal-sized firms and 10 000 a monopoly or a highly concentrated market. The HHI index can be used to identify *critical minerals* by using the market share of a country instead of a company (Ferguson & Ferguson, 1994: 41; Nassar et al, 2015: 5; Reichl, 2018: 13).

Hotelling rent (scarcity rent) – "That portion of the value of a mineral deposit attributed to the limited physical availability of the resource. Hotelling rent is a scarcity premium, unrelated to differences in quality among different mineral deposits. It is sometimes called scarcity rent … it is that portion of the price at which a mineral is sold in the market place that is due to physical scarcity" (Eggert, 2001: 47). "The opportunity cost of producing one more unit today instead of in the future" (Halland et al, 2015: 19). See *scarcity rent* and *user cost*.

Hubbert, M.K. – Hubbert, a geologist, was employed by Shell. He was concerned about the enormous increases in oil, coal, lignite and use of other energy resources globally and in the U.S. He correctly predicted the timing of the conventional oil peak for the U.S (Dahl, 2004: 20; Hubbert, 1969: 161, 162; Sverdrup & Ragnarsdottir, 2014: 151, 152). His technique for predicting such a peak became known as *Peak Oil*.

(economic) Indicator – A statistic about an (economic) activity or condition. Also referred to as measures.

Hydraulic fracturing ("fracking")

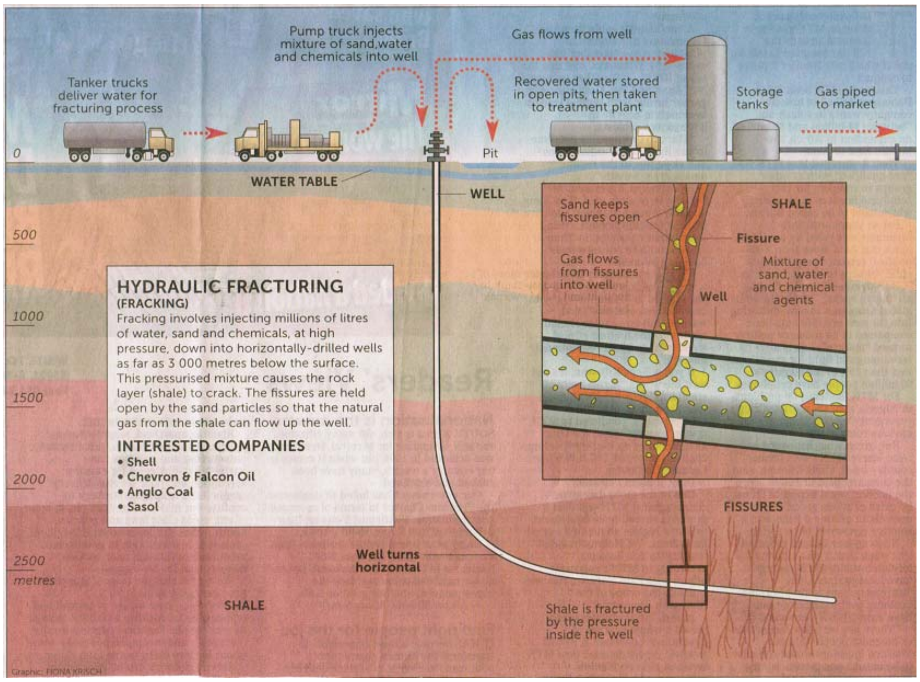

Figure A.9. The hydraulic fracturing process (Prinsloo, 2013: 7)

<u>Indicators of resource availability</u> – Many indicators of resource availability have been proposed over the years. None is perfect and each has its advantages and disadvantages. Different criteria can be used to evaluate such indicators, for example, whether it is forward looking or not and if it easy to calculate or determine the value of the indicator. Some authors differentiate between physical and economic indicators. Examples of indicators: elasticities of substitution, peak production, real price, real marginal costs of extraction and processing, real user costs, rents, *reserves*, *reserve to production ratio (R/P ratio)*, *resource base*, and unit costs (Tilton, 2003: 19, 21, 26; Fisher, 1979: 253; Cleveland & Stern, 1999: 89; Campbell & Laherrére, 1998).

<u>Intensity-of-use</u> (IoU) - The amount of material used per unit of output. Malenbaum did an extensive study on how intensity-of-use may impact on the demand for raw materials. See: *Relative dematerialisation*.

<u>Intensity-of-use hypothesis</u> (also knows as the material Kuznets Curve) – There is an inverted U-shaped relationship between the amount of material used per unit of output and the level of economic development, as reflected in gross domestic product per capita.

<u>Intergenerational equity</u> – Future generations should not be disadvantaged by current generations – they should not be worse off than current generations. The concept is key to the Brundtland Commission's definition of Sustainable Development and is a goal that is shared by both *Neoclassical* and *Ecological Economics*. It raises the important question of what are current

generations' fair share of non-renewable resources. The means of achieving intergenerational equity is for neoclassical economics through the preservation of capital stock (*weak sustainability**) while Ecological Economics promotes *strong sustainability* – the preservation of natural capital for future generations. See: *Hartwick Rule*.

Internet of Materials (IoM) – "A decentralized data system connection data on different products and materials through standardized communication protocols" (WEF, 2018: 11).

Intertemporal choice – Sometimes choices at one time influence the possibilities available at other points in time. Economic agents then have to make choices about what to do and how much to do at various points in time. A consumer may for example postpone consumption by saving more today or a supplier has to compare costs and benefits of producing today with that in the future. Some economists think that intertemporal decision making applies when a depletable stock such as an oil well is exploited. Oil pumped today from a specific reservoir will not be available for future production. Some economists believe that present and future uses of the in situ mineral in an individual mine are necessarily antagonistic (Pindyck & Rubinfeld, 2013: 584; Robinson, 1989: 21, 33). See *intergenerational equity*.

Jevons' paradox – Jevons believed that improved technology-driven efficiency, for example of machines that do mechanical work, actually increases the overall consumption of coal, iron and other resources (Alcott, 2005: 9).

Lasky's Law – There is an inverse relationship between ore grade and the size of deposits (Lasky, 1950; Bardi, 2013: 2).

Linkage development – Information about linkage development is available from:

- Morris, M., Kaplinsky, R. & Kaplan, D. 2012. "One thing leads to another" – Commodities, linkages and industrial development. *Resources Policy* 37, pp. 408-416.

- Morris, M., Kaplinsky, R. & Kaplan, D. 2012. *One thing leads to another: Promoting Industrialisation by Making the Most of the Commodity Boom in Sub-Saharan Africa*. ISBN 978-1-4717-8188-9.

McKelvey diagram – See *Codes, guidelines and standards for reporting mineral reserves and resources.*

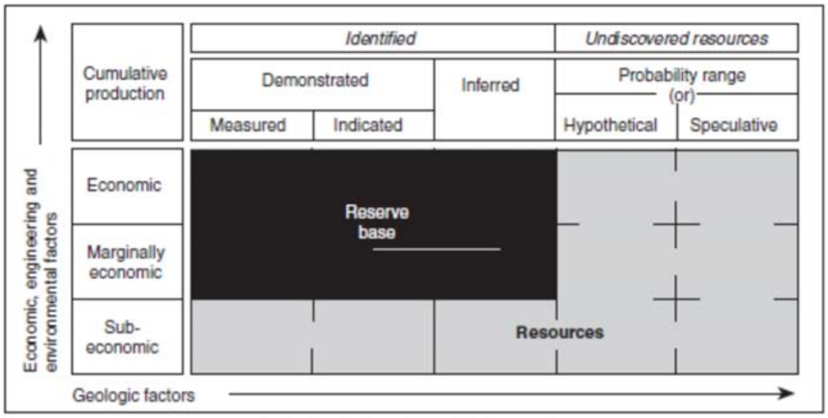

Figure A.10 A modernised McKelvey diagram, used by the USGS for the classification of mineral resources (Kesler & Adam, 2015: 3)

Mineral – “A naturally occurring inorganic element or compound having an orderly internal structure and characteristic chemical composition, crystal form, and physical properties.” (Stevens, 2010: 308). At least 5 477 minerals are known (Chen, 2019).

Mining in space – The exploitation of raw materials from the Earth’s moon and asteroids which may include near-Earth objects.

Model - A model is “an ordered set of assumptions about a complex system … an attempt to understand some aspect of the infinitely varied world by selecting from perceptions and past experience a set of general observations applicable to the problem at hand” (Meadows et al, 1972: 21).

NMC811 – A newer type of lithium-ion battery used in BEVs since about 2018. It contains 80% nickel (Ni), 10% cobalt (Co) and 10% magnesium (Mg). One of the older types of lithium-ion batteries uses equal amounts of Ni, Co and Mg. In the NMC811, Ni substitutes to some extend for Co. The reduced cobalt content is to address availability concerns and cut cost. The increased nickel improves energy density. Cobalt remains an important ingredient, however, because of its properties to ensure thermal stability (Seddon, 2019).

Non-homogenous orebodies – Figure A.10, below, illustrates how grades may vary from one point to another within an orebody.

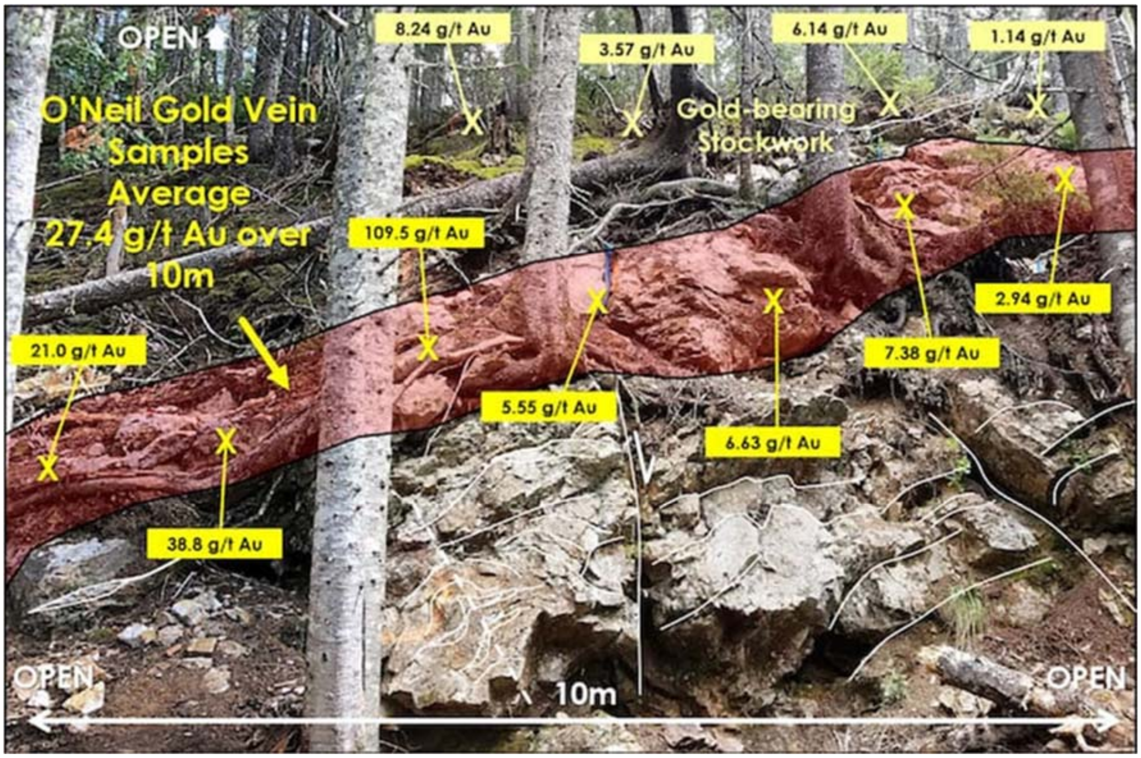

Figure A.11 The concentration of silver (Au), determined from samples, vary throughout the outcrop of the O'Neil Gold Vein (Puma Exploration, 2020: 2).

Non-renewable resource – Definition 1: Resources such as minerals and fossil fuels that exist in a finite quantity on the earth and that has no natural regeneration process within a relevant time scale. Definition 2: "Non-renewable resources can be considered as a stock that has a regeneration rate of zero over a relatively long period" (Lujala, 2003: 7).

Ore deposit – A mineral deposit where the elements within the mineral can be extracted economically. Such a deposit is usually fairly large and concentrated (Bardi, 2013: 1). The concentration (or grades) of minerals in such ore deposits are usually much higher than in the average crust of the earth.

Overshoot day – (Earth's overshoot day) – That day of the year when the demand by the global population exceeds the earth's sustainable supply in terms of cropland, fish stocks, the use of forests for timber processing and its capability of "coping" with carbon emissions. The Global Footprint Network calculates overshoot day to make people aware of its enormous consumption of natural, renewable resources (Howard: 2015). The table below illustrates a trend of increased, global, renewable natural resource consumption. See *environmental credit crunch*.

Table A.1. Overshoot days for the years 1987, 2009 and 2017 (www.footprintnetwork.org/our-earth/earth-overshoot-day; https://en.m.wikipedia.org/wiki/Earth_Overshoot_Day)

Year	Overshoot day
2017	2 August
2009	25 September
1987	19 December

Paradigm – “Universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners” (Kuhn, 1996: x). A non-neutral intellectual scaffolding for holding information together and informing researchers (Turton: 2018).

Paris Agreement on Climate Change – A resolution of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change which was held in Paris in 2015. It came into force on 4 November 2016. The intention of this resolution is to keep average increases in global warming below 2 degrees Celsius compared to pre-industrial levels.

Peak Mineral theory – Hubbert’s *peak oil* theory, also referred to as a *paradigm*, had been applied to various other mineral commodities such as the production of global copper (Kerr, 2014: 723) and coal (Burchardt et al, 2020), South African gold (Hartnady, 2009), South African coal (Hartnady, 2010), phosphorus (Mórrígan, T., 2010), whale oil (Bardi, 2014: 144) and rock phosphate in Nauru and the U.S. (Bardi, 2014: 165). In South Africa gold output per annum has decreased from about 1 000 tons per year in the 1970s to less than 200 tons today (Hartnady, 2009: 329). Hodge (s.a.: 14) provides reasons for this decline. At current price levels and state of technology the large amounts of gold at depths between 4,5 and 5,5 km might not be mined. Other authors who refer to peak minerals include Wellmer & Scholtz (2017).

Peak Oil – The point at which global production of oil will peak and thereafter diminish. *Hubbert* published an oil production curve and technique for estimating the total volume of oil to be produced by a single well in the 1950s. Such a pattern indicates the increase in oil production from a well, the peak production rate and decline with the emptying of the reservoir. Since then such production (from individual wells) had been aggregated at state, national and global levels. Colin Campbell, an oil geologist, founded the Association for the Study of Peak Oil (ASPO) in 2001. (Bardi, 2014: 143-170; Dahl, 2004: 20; Deffeyes, 2001; Hubbert, 1969: 161, 162; Sverdrup & Ragnarsdottir, 2014: 151, 152)

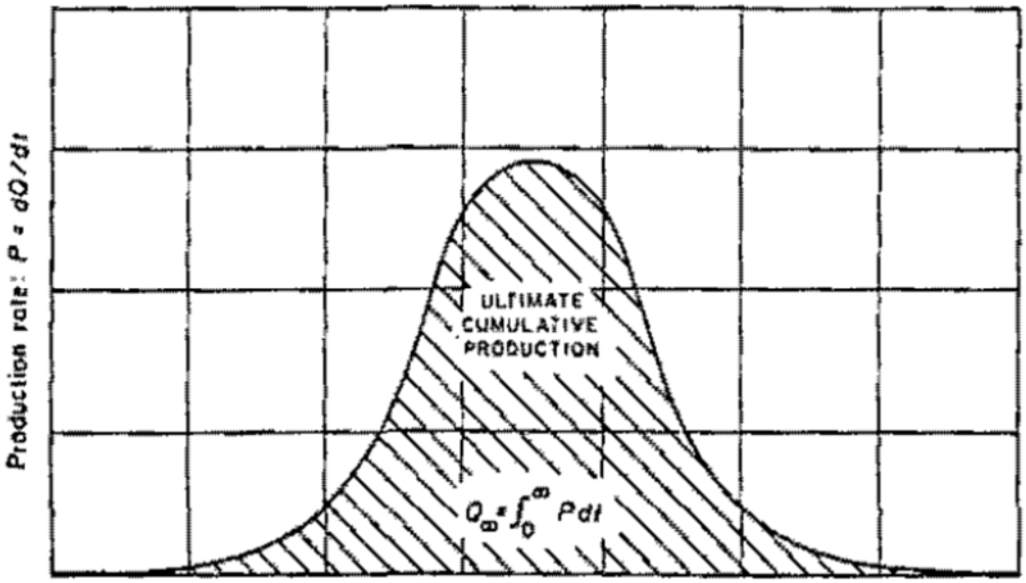

Figure A.12 Production levels from an exhaustible resource over time. The area under the curve is the ultimate cumulative production from such a resource over its life (Hubbert, 1969: 168)

Plutonomy – "An economic system in which a small group, the ultra-wealthy, accounts for a large share of total consumption" (Galbraith, 2019).

Polymetallic nodules – Analysis of seabed polymetallic nodules has shown that they contain high concentrations of manganese, nickel, copper and *cobalt*. See *seabed mineral deposits.*

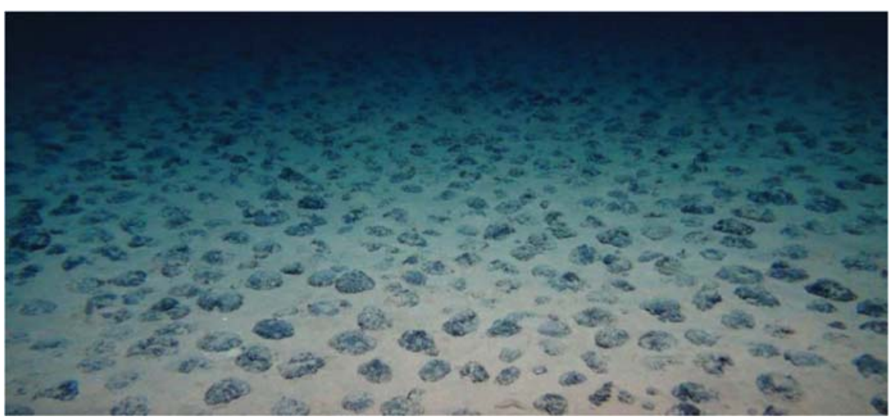

Figure A.13 Picture of polymetallic nodules on the seafloor in the Eastern Pacific's Clarion-Clipperton Zone (CCZ) at a depth of about 4 500m (Cuyvers et al, 2018: 7)

Positive feedback loop – A cross-disciplinary phenomena where secondary effects tend to reinforce the basic trend. Example for economics: Capital accumulation and economic growth – new investment generates greater output and profits which can again be used to fund additional investment thus reinforcing economic growth. Example for climate change: Methane is a stronger greenhouse gas than carbon dioxide. The rise of planetary temperature could trigger the release of methane currently trapped in permafrost thus increasing the amount of methane in the atmosphere which would increase temperatures further (Tietenberg, 2006: 6).

Prebisch-Singer hypothesis – According to this hypothesis the price of primary, renewable and non-renewable commodities declines relative to the price of manufactured goods with an associated deterioration of the terms of trade of primary-product-based economies (Cuddington et al, 2007: 104).

Figure A.14 The commodities-manufactures terms of trade (Morris et al, 2012: 20)

Primary supply of minerals – The mining of minerals. See *secondary supply of metals*.

Rare earth elements (REEs) – A list of 17 elements which, in order of atomic numbers, starts with scandium, with atomic number of 21, followed by yttrium, with atomic number 39, and the 15 elements of the lanthanide series starting with lanthanum (atomic number: 57) and ending with lutetium (atomic number: 71). Sixteen of the seventeen rare earth elements are actually relatively abundant when their average concentration in the earth's continental crust is compared with that of gold (Wedepohl, 1995: 1220). A number of these elements usually occur together and were called "rare" because nineteenth-century chemists struggled to separate them from each other (Wall, 2014: 312). The industrial demand for REEs is relatively small as measured in tonnage but they are essential in high-technology applications such as smart phones, hybrid vehicles and in defence equipment. China is a dominant supplier of REEs, accounting for about 97% of the current supply (Massari & Ruberti, 2013: 36, 37). See *critical minerals, Herfindahl-Hirschman index* and *strategic minerals*.

Relative dematerialisation (or "weak dematerialisation") – The decrease in the *intensity-of-use*. This means that the ratio between material input and GDP falls over time. This can be achieved when the growth in resource use is slower than economic growth (Behrens et al, 2007: 445).

Reserves – That part of the *resource* that can be profitably exploited at current prices and costs. Reserves increase through various means, for example, through successful exploration and when prices increase and/or costs decrease. When prices increase a slightly lower grade/quality resource will become profitable. According to Crowson (1998: 62) reserves is "that portion of the resource that has been more precisely measured and which is, or might be, available for production over a specific time period". As a result of contributions over the last number of decades by people, such as McKelvey, reserves and resources are today classified into various subcategories such as measured reserves. See *Codes, guidelines and standards for reporting mineral reserves and resources* and *McKelvey diagram* in this glossary.

Reserves-to-production ratio (R/P ratio) – An indicator of resource availability at a specific point in time. It is an indicator of the remaining amount of a non-renewable resource, expressed in years. R stands for total reserves at a specific point in time while P is the annual production. Reserves of a specific mineral commodity are divided by annual production to get a measurement of the "life of reserves" measured in years. R/P ratios are usually calculated using national or global reserves and production in order to obtain the global or national R/P ratio for the world or a specific country – when done for a specific mine then it is known as "Life of mine". Declining global R/P ratios may result in mineral availability concerns. Annual additions to reserves versus annual production from reserves will change reserves and therefore impact on the R/P ratio.

Table A.2 R/P ratios for oil, coal and gas (Meadows et al, 1992: 68)

ANNUAL PRODUCTION AND RESERVE/PRODUCTION RATIOS FOR OIL, COAL, AND GAS, 1970 AND 1989

Fuel	*1970 production (per year)*	*1970 R/P (years)*	*1989 production (per year)*	*1989 R/P (years)*
Oil	16.7 billion barrels	31	21.4 billion barrels	41
Coal	2.2 billion tons	2300	5.2 billion tons	326 (hard coal) 434 (soft coal)
Gas	30 trillion cu. ft.	38	68 trillion cu. ft.	60

According to Meadows et al (1992: 67, 68) 450 billion barrels of oil, 90 billion tons of coal and 1 100 trillion cubic metres of natural gas were consumed between 1970 and 1990. During that period new deposits of oil and gas were discovered, in excess of what was consumed, and, therefore, their R/P ratios increased as indicated in Table A.2.

Resource – "A concentration of minerals of economic interest with the potential for eventual economic extraction" (Halland et al, 2015: 15).

Resource base – It includes all minerals and fuels on and in the earth's crust, regardless of concentration (Rudawsky, 1986: 6). The resource base is a physical measure that does not depend, like reserves, on concentration and the level of prices and technological innovation. Some people calculate the resource base from the *Clarke* values. One method is to multiply the Clarke value of a specific element, measured in grams per metric tonne, with the total mass (24 x 10^{18}), measured in tonnes, of the earth's crust (Tilton, 2003: 22, 23).

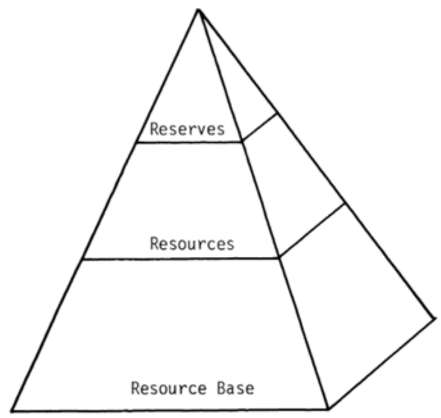

Figure A.15 The relationship between reserves, resources and resource base (Rudawsky, 1986: 6)

Resource Nationalism – A concept that is at times used to describe the desire of the people and governments of resource-rich countries to derive more economic benefit from their natural resources and the desire to exercise greater control over the country's natural resource sectors. The forms in which this intention is manifested vary widely, ranging from the outright nationalisation of private sector companies to statutory indigenisation programmes. Limited nationalisation where the state holds equity in a privately run company, state-owned mining companies, resource rent and progressive taxation mechanisms, restrictions on foreign ownership of mining assets, export controls and developmental state models are all examples of ways and means in which governments try to achieve their objectives of benefiting from the minerals industry (Solomon, 2012: 73; Humphreys, 2015: 6).

Scarcity rent – "Producer's surplus that persists in long-run equilibrium due to fixed supply or increasing costs" (Tietenberg & Lewis, 2011: 631). See *Hotelling rent* and *user cost*.

Scramble for Africa – A metaphor that refers to the occupation, division and colonisation of African territory by a number of Western European powers in the latter part of the 19th century and earlier part of the 20th century. By 1870 about 10 percent of Africa was under European control. This expanded to almost 90 percent by 1914. At the Berlin West Africa Conference of 1884-1885, a number of European nations decided not to fight among themselves for parts of Africa but to divide it up between them. The presence of raw materials such as copper, lead, gold, diamonds and tin needed by European industry is one of a number of reasons provided for European colonisation (Brooke-Smith, 1987: 1, 62; Harlow & Carter, 2003: 8, 209, 211, 423, 424; Pakenham, 1991: 18, 19, 21, 30, 33, 151, 361, 600; Press, 2017: 2, 5, 7, 65, 135, 140, 227, 246). Alex Vines of Chatham House refers to the new scramble for Africa and Basov (2015) to "The Chinese scramble to mine Africa" (The Economist, 2019: 18).

Secondary supply of metals – The supply of metals by recycling and re-use – not from mining. Compare with *primary supply of minerals*.

Semi-renewable energy – Some researchers, for example Sverdrup and Ragnarsdottir (2014: 148) define photovoltaic (PV) technology as semi-renewable. Although PV cells use solar energy which is renewable, the cells are made of certain materials that are non-renewable. The availability of such energy therefore depends on the availability of the materials used in the manufacturing of the devices.

Solow residual – The economist, Robert Solow discovered that not all economic growth could be accounted for by growth in labour and capital inputs. He concluded that the unaccounted (residual) growth was due to technological innovation (Snowdon & Vane, 2005: 325; Solow, 1957: 320).

Spaceship earth – Boulding (1966: 3) referred to Planet Earth in this way to emphasize its limitations as a source of materials and a repository of waste.

Stationary state economy – "… a real condition toward which the economy was tending as increased population, diminishing returns, and increasing land rents squeezed profits to zero. Population would be held constant by subsistence wages and a high death rate. Capital stock would be held constant by a lack of inducement to invest … " (Daly, 2007: 117).

Stock resource – The minerals in the earth's crust is an example of a stock resource (Perman et al, 2003: 11) because it is limited in quantity. Exploitation is the process through which withdrawal takes place from such a stock resource. Withdrawal from a stock resource today means that less will be available for future exploitation.

Stranded assets – "Assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities". Environmentally stranded assets refers to the idea that all the proven coal reserves on the balance sheets of coal companies could not be used because of efforts to avoid catastrophic global climate change (EY, 2015: 43).

Strategic material / mineral – The concept is often used in the context of the military, for example, to refer to specific materials or minerals that are required by the military industrial complexes of countries (Butts, 1993: iii; Lele and Bhardwaj, 2014: 2). See *critical minerals*.

Strong sustainability – Daly's (2007) strong sustainability criterion calls for the maintenance of natural capital. It is based on the belief that natural and physical capital are complements and not substitutes. The ozone layer is an example of natural capital that provides essential ecological services that cannot be easily substituted for. Strong sustainability is associated with *Ecological Economics*. See *weak sustainability*.

Stylised fact – A term that was introduced by the economist Nickolas Kaldor in the context of a debate on economic growth theory. According to him "the theorist, in choosing a particular theoretical approach, ought to start off with a summary of the facts which he regards as relevant to his problem. Since facts, as recorded by statisticians, are always subject to numerous snags and qualifications, and for that reason are incapable of being accurately summarized, the theorist, in my view, should be free to start off with a **'stylized' view of the facts** – i.e. concentrate on broad tendencies, ignoring individual detail, and proceed on the 'as if' method, i.e. construct a hypothesis that could account for these 'stylized' facts, without necessarily committing himself on the historical accuracy, or sufficiency, of the facts or tendencies thus summarized." (Kaldor, 1961: 178). Snowdon and Vane (2005: 305) define stylized facts as "the broad regularities that have been identified in the statistical property of economic time series". It is also defined as "a simplified presentation of an empirical finding", a "broad generalization that summarizes some complicated statistical calculations, which although essentially true may have inaccuracies in the detail."

(price) Super cycles – Decades-long above-trend movements in price. Of long duration – probably 20- to 70-year cycles (Erten & Ocampo, 2013: 14; Jacks, 2013: 10; Jerrett & Cuddington, 2008: 188).

Supply risk indicator (R) – Supply risk is indicated as a number between 0 and 1. It is determined for a specific element or mineral periodically, usually annually. Minerals that are produced in only a few countries have high R-values, closer to 1.

Synthetic diamond – High-pressure high-temperature (HPHT) and chemical vapour deposition (CVD) were the first two methods used to produce synthetic diamonds. The HPHT process is capital and energy intensive because it requires high temperatures and pressures and expensive equipment. About 1 kiloJoule of energy is required per carat (Martineau & McGuinness, 2018: Slide 19).

System dynamics – Jay Forrester, the inventor of system dynamics, used it to uncover the real causes of cyclicality in industry and to explain why low-cost housing has failed to renew inner-city neighbourhoods. System dynamics was used to generate the findings of the "Limits to Growth" report. The System Dynamics National Model identified *feedback loops* that cause the economic long waves (or Kondratieff cycles) that are 45 to 65 years in duration. "System dynamics can organize descriptive information, retain the richness of real processes, build on the experiential knowledge of managers and reveal the dynamic behaviours that follow from different policy choices". System dynamics uses cause-and-effect thinking and *feedback loops* and deals with how things change through time (McKinsey, 1995: 4, 13, 14, 15).

Thucydides's Trap – A situation that may arise when a rising power threatens to displace a ruling power and/or causes fear in an established power which escalates towards war. A few such power shifts have occurred in the past and in only four out of sixteen ruling versus rising power cases was war avoided. For example, in the case of Portugal (ruling global and trade power) and Spain (rising power) in the late 15th century there was no war. In the case of the Dutch Republic (ruling global empire with sea and trade power) and England (rising power) in the mid- to late 17th century there was war (Allison, 2017: 5, Appendix 1).

Urban mining – The reclaiming of compounds and elements from products and buildings when they have reached the end of their useful (first) life (Van der Merwe: 2017).

Figure A.16 Urban mining - the exploitation of landfill-gas (Baker & Letsoela, 2017: 8, 10)

User cost (scarcity rent) – The user cost of production of an exhaustible resource means that selling a unit today will make it unavailable for production and sale in the future. The user cost increases over time as the ore deposit or ore well reaches full depletion. That is because the resource in the ground becomes scarcer and the opportunity cost of depleting another unit becomes higher.

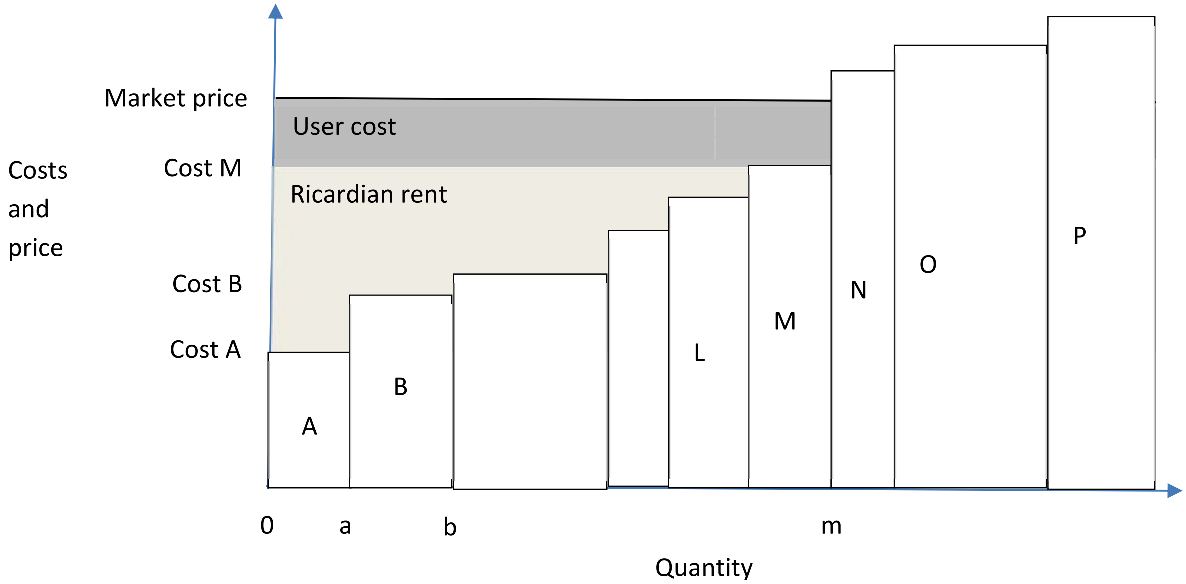

Figure A.15 Relationship between market price, production costs, user costs and Ricardian Rent (Tilton, 2003: 27)

Weak sustainability – In contrast to *strong sustainability*, the advocates of weak sustainability argue that capital and ("non-renewable") natural resources are substitutes. This means that decreases in natural capital, such as non-renewable resources, over time will not be problematic if balanced by increases in ("reproducible") capital such as machines. Example: When buildings are well insulated from external temperatures then less coal is used, by coal-fired power stations, to produce the electricity required to heat or cool such buildings. Diamonds can also be produced by using carbon, capital and energy – it does not have to be produced inside the earth (See *synthetic diamonds*). In this example capital substitutes to some extend for natural diamonds. Hartwick (1977: 972) and Anderson (2010: 188-190) think that capital can substitute for non-renewable natural resources. Weak sustainability is linked to the neoclassical view of dealing with scarcity. See *Hartwick's Rule.*