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Material Flow Analysis of Rare Earth Elements and their Sustainable Use in Australia to Reduce Potential Environmental Impacts

Thesis Submitted by

Mejame **Palle Paul Mejame**

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James Cook University

Townsville, Queensland 4811

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Abstract

Rare earth elements (REEs) are a major constituent of many advanced materials in the information and telecommunication industries, as well as the renewable and energy efficiency sectors. REEs are enablers of speed, performance, durability and low carbon emissions in these industries. They are required in everyday applications because of their unique chemical and physical properties. Given the rise in environmental concerns, demand for REEs, and the limited locations where REEs can be sourced, there is a very high risk of supply disruption. Despite the threat of REE supply disruption and the associated environmental and economic significance, an in-depth examination of the environmental impacts and benefits of sustainable consumption of REE metals systematically and holistically is lacking in Australia, as in many parts of the world, particularly regarding improvement in resource efficiency strategies.

Given these constraints, this study employed a holistic and systematic approach to assessing the sustainability of REEs consumption in Australia. Based on the circular economy (CE) model, a sustainability framework, followed by an implementation strategy to close the material loop and minimise the adverse impacts of resource shortages while achieving maximum environmental benefits, was developed. The CE approach applied two essential circular tools, Material Flow and Life Cycle Impact Analysis, within a sustainable management framework to achieve end-goals. The systems approach enabled the determination of the impact of material resources (REEs) on the environment and people, over time. Components of the systems approach included: (a) an account of the whole life cycle of resources (REEs) consumption; (b) a material flow analysis to connect resource use to environmental impacts through footprints; and (c) the consideration of interactions between people and the environment.

The Material Flow Analysis (MFA) served as an inventory tool to compile and evaluate REEs material resource usage from primary material extraction through to End-of-Life (EoL) while Life Cycle Impact Analysis (LCIA) was used to determine the lifecycle-based environmental impacts of material consumption using characterisation factors obtained from ecoinvent. These potential environmental impacts were measured using three key metrics in a sustainable development framework: materials use, energy demand, and greenhouse gas emissions indicators. IPCC 2013 GWP 100a and CED midpoint impact assessment methods in ecoinvent were used to determine the environmental impacts associated with REEs material use.

To achieve this goal, the study conducted a holistic assessment of primary and secondary material flow consumption of REEs in high-tech applications and the derived environmental impacts. A sustainable management framework based on the CE model was developed, followed by a practical implementation strategy suggesting approaches to reduce the negative impacts to improve resource efficiency at each stage of the material used, from raw material input to EoL. The approach is significant as it would allow the evaluation of existing resource efficiency strategies in REEs and make recommendations to improve sustainability outcomes in Australia. The end goal was to introduce strategies to mitigate and transform resource use in ways that minimise environmental and socioeconomic impacts through enhancing resource efficiency and creating sustainable consumption patterns.

The overall results from material lifecycle flow analysis show that material use of REEs consumption from secondary material inputs would result in significantly lower emissions and cumulative energy demand from the equivalent amounts of REEs generated from primary material inputs. Findings showed that the gross CO_2 emission for using REE primary material input in applications would fall from 2278.3 to 1253.0 kg CO_2-Eq/yr/1kt in the case of secondary material inputs. While the gross total cumulative energy demand potentials for using REEs primary material inputs in applications will decrease from 25674.9 to 14482.7(MJ-Eq./yr./1kt) for a given year (2019). These findings suggest that improvement in the existing pattern of REEs consumption and production would result in a wide range of environmental benefits compared to the current state-of-the-art primary production. The high primary CO_2 emissions and energy consumption calls for the need for the development of recycling technologies and infrastructure. These results are significant as the life cycle material flow report in this study identifies that the current REEs consumption pattern in Australia are highly dependent on primary material inputs, with the main reasons being the low recycling rates of these metals, and the export of EoL products abroad for downstream recycling. It was evident that improvement in sustainable resource consumption practices such as recycling efficiency will improve resource use efficiency.

The material use analysis (MUA) investigation showed that the REEs recycling potential for 2019 was 55.5%. This represents a significant contribution to the overall supply of these metals and a reduction in the dependency on primary material inputs. Major recovery interest for EoL products can, however, be focused on phosphors and magnets, as findings show that these products contain potential sources for secondary material inputs of these metals. It was identified that phosphor and magnet products consume 26% and 27%, respectively, of selected critical REEs in applications in Australia, with the highest demand from Neodymium and Yttrium. Reclaiming REEs from EoL products in the waste stream can significantly contribute to mitigating some of the critical risks faced by the metal industry, such as high supply-risk disruption, and the risks associated with radioactive elements like uranium and thorium and their primary production.

The findings from this study, therefore, underscore the significance of implementing a holistic and systematic approach to evaluating the sustainability of REEs consumption. It was identified that strategic choices for the improvement in REEs material efficiency are heavily dependent on the EoL phases (recycling), which in turn overshadow the opportunities for more sustainable consumption across the entire life cycle of this material. In this study, REEs material consumption viewed from the perspective of a holistic approach provided a plausible scientific picture of the potential impacts of this material consumption in Australia and the priority phases to target for the development of measures to combat or reduce these impacts. The innovative approach of implementing material flow and life cycle impact assessment combined as CE tools for sustainability assessment facilitated an in-depth structural and systematic analysis of the full life cycle of REEs consumption in Australia: from the major companies involved to the total metal reserves, location and extraction, applications, material consumption and environmental impacts, waste disposal and recycling potentials.

As principal contributions, this study has proposed a comprehensive REEs CE framework and practical implementation strategy as a way to close the material loop and improve resource efficiency for these metals. The proposed framework demonstrates a restorative and regenerative system through which the CE manufacturing oriented-strategies (long-lasting application designs to extend product life, through manufacturing for easy-repairs, maintenance, re-use, repurposing, remanufacturing, and refurbishing) can be combined with EoL-oriented strategies (recycling and recovery) to close material and energy loops, keep resources in circulation and achieve sustainable end goals for REEs. The framework underlines that improvement in REEs material efficiency is a combination of a set of strategic CE components in addition to recycling. This study, therefore, hopes to contribute to the understanding of how REEs within the sustainability framework can be implemented to achieve improvements in resource efficiency and decouple economic progress from environmental and resource degradation through CE. It promotes CE as a vital tool in resource management.

The study further calls for an understanding of the strategic economic and political significance of these metals at the global level, and the necessity to put in place parameters to quantify material efficiency which can inform sectors in the system that needs to be improved to reduce impacts. The waste stream containing these metals is a general concern. Waste disposers, recyclers, and other stakeholders must therefore continue to work together to introduce new Designs for the Environment (DfE) and waste management policies for REEs products. The sustainability of REEs can be widely achieved with a broader consideration of environmental, social, economic, and technological aspects of the consumption of these metals.

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List of key acronyms

General

Austrade	Australian Trade and Investment Commission
CE	Circular Economy
CED	Cumulative Energy Demand
DfE	Design for the Environment
DIIS	Department of Industry Innovation and Science and Australia Trade and Investment Commission
EoL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IRP	International Resource Panel
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Analysis
LCM	Life Cycle Management
MFA	Material Flow Analysis
MU	Material Use
OECD	Organisation for Economic Co-operation and Development
REEs	Rare Earth Elements
UNEP	United Nations Environment Programme
USGS	US Geological Survey
WEEE	Waste Electrical and Electronic Equipment
WITS	World Integrated Trade Solution Software

Specific Materials

Ce	Cerium
Dy	Dysprosium
Er	Erbium
Eu	Europium
Gd	Gadolinium
Ho	Holmium
La	Lanthanum
Lu	Lutetium
Nd	Neodymium
Pm	Promethium
Pr	Praseodymium
Sc	Scandium
Sm	Samarium
Tb	Terbium
Tm	Thulium
Y	Ytterbium
Yb	Yttrium

Glossary

Circular economy (CE): A circular economy is an approach to economic growth that aligns with sustainable environmental and socio-economic development (Korhonen et al., 2018). The essence of the circular economy concept is to boost the circularity of resource production and consumption by optimising the entire process and transforming materials during and at the end of their life services into new resources for others (Wang, P. & Kara, 2019). It emphasises the use of renewable energy with maximum efficiency in the use of raw materials for manufacturing processes (Balanay & Halog, 2019). It is a sustainable development strategy that is particularly linked to the Sustainable Development Goal (SDG) 12 of sustainable production and consumption (Reike et al., 2018; United Nations Environment Programme, n.da). It is characterised by a restorative and regenerative system based on sustainability principles: designing out waste and pollution, and keeping products and materials in use (MacArthur, 2017).

Critical materials: Material criticality is regarded as any substance with high supply risk that is important to the growth of modern technology, and for which there are no easy substitutes (Bauer et al., 2010).

Extended Producer Responsibility (EPR): Extended Producer Responsibility refers to a type of stewardship that places primary responsibility on the manufacturer, importer, or seller for the management of End-of-Life (EoL) products (International Resource Panel, 2017). The approach involves a take-back system, where these stakeholders are responsible to collect EoL products from consumers (International Resource Panel, 2017).

Life Cycle: A system approach that looks at all stages of a product system or service, from raw material acquisition to the final disposal (International Organization for Standardization, 2006a).

Life Cycle Assessment (LCA): Life Cycle Assessment referred to as Life Cycle Analysis is a tool to evaluate the environmental impact (input-output) and social performance of products or services along their entire life cycle (International Organization for Standardization, 2006).

Life Cycle Inventory (LCI): The phase of Life Cycle Assessment where data are collected, the systems are modelled, and the LCI results are obtained. (UNEP/SETAC, 2009). It is the second phase of Life Cycle Assessment that involves the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact Assessment (LCIA): The third phase of Life Cycle Assessment involves identifying and evaluating the magnitude and significance of the potential environmental impacts associated with a given environmental resource used throughout the life cycle and identified releases using inventory data (International Organization for Standardization, 2006b; Navarro & Zhao, 2014).

Material Flow Analysis (MFA): Material Flow Analysis is defined as the systematic assessment of flows of inputs and outputs of elements within a system at a given time and place (Brunner & Rechberger, 2003; Brunner & Rechberger, 2016; Environmental Justice Organisation Liabilities and Trade, 2012; John et al., 2016).

Material Consumption: Material consumption refers to the amount of material (in terms of weight) used in an economy (Organisation for Economic Co-operation and Development, 2008). It is the raw material that is consumed during a specific period or an entire production cycle.

Primary materials: Primary raw materials are virgin materials, natural inorganic or organic substances, such as metallic ores, industrial minerals, construction materials or energy fuels, used for the first time (European Commission, 2017).

Recycling: Recycling refers to an action or process of transforming waste into resources for other products (MacArthur, 2017).

Rare earth elements (REEs): Rare earth elements, referred to as Rare earth metals, are a group of 17 metallic elements in the periodic table that are crucial for many emerging high-technology devices and low carbon economy. These include a set of 15 elements in the lanthanide series plus Scandium and Yttrium.

Resource efficiency: Resource efficiency is the process of using the Earth's limited resources sustainably while minimising impacts on the environment (Mudgal et al., 2012).

Sustainable Development: The Brundtland Commission by the United Nations defines sustainability as meeting the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987).

Sustainability (within the framework of mineral resources): Sustainability within the framework of mineral resources is regarded as a state of a dynamic interplay between environment and society (in a broad sense) that ultimately contributes positively to indefinite human development and universal wellbeing whilst not overdrawing on natural resources or irreversibly overburdening the environment (McLellan et al., 2014; McLellan et al., 2013).

Sustainable consumption and production: The use of services and related products, which respond to the basic needs and quality of life, while reducing the use of natural resources and toxic materials, as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardise the needs of future generations (United Nations Environment Programme, 2010).

Secondary materials: Secondary raw materials refer to materials produced from sources other than primary. Secondary raw materials can also be obtained from the recycling of raw (primary) materials, industrial residues etc (European Commission, 2017).

Chapter 1 Introduction to this Thesis

Chapter outline

1.1 Introduction

This thesis focuses on the sustainability of Rare earth elements (REEs) consumption in Australia. A critical mineral with very high supply risk disruption due to high demand and importance in the clean energy sector, its availability in only a few countries, and low recycling rates (Balaram, 2019; Bauer et al., 2010; Bauer et al., 2011; Cai, 2019; Goonan, 2011; Huleatt, 2019; King, 2021; Li et al., 2022; Long et al., 2017; McLellan et al., 2014; Suli et al., 2017; U.S. Geological Survey, 2020; Yuksekdag et al., 2022). This study suggests a holistic and systematic approach based on the circular economy model in the context of sustainable management to examine the sustainability of REEs, a strategy against the adverse impacts of material criticality with societal-wide benefits.

REEs are vital constituents of many advanced materials, especially in the information and telecommunication industries, as well as the renewable and energy efficiency sectors. REEs are used as enablers for speed, performance, durability and low carbon emissions in these industries (Balaram, 2019; Huleatt, 2019). They are heavily required in everyday applications because of their unique chemical and physical properties (Balaram, 2019; Gibson & Parkinson, 2011; Goonan, 2011; Huleatt, 2019; Lynas Rare Earths Ltd, 2021b; Reisman et al., 2013; U.S. Geological Survey, 2020; Van Gosen et al., 2014). In an era of high demand for renewable and energy-efficient technologies to meet global carbon and environmental objectives, demand for REEs is expected to grow continuously (Balaram, 2019; Sarker et al., 2022; Van Gosen et al., 2014).

While the demand for REEs grows, global supply is under threat (Alonso et al., 2012; Balaram, 2019; Cai, 2019; Jowitt et al., 2018; Li et al., 2022; Suli et al., 2017; Yuksekdag et al., 2022; Zaimes et al., 2015). In recent years, this global supply challenge has been accompanied by economic wars between the major consumer countries and strong political tensions, resulting in a rare earth metal war or scramble between the USA and China, for example (Bradsher, 2010; Hornby & Zhang, 2019; Hornby & Sanderson, 2019a; Hornby & Sanderson, 2019b; Snow, 2019). The unforeseen Covid-19 pandemic may serve as a wake-up call, as this has affected many mines, factories and borders exacerbating the supply-demand problems of these critical metals (Akcil et al., 2020). Australia is not immune to these conflicts, experiencing tensions as a major consumer of REEs, with a relatively small contribution to its supply. This is an urgent crisis that needs to be addressed as a reduction in the use of REEs in renewable and energy-efficient technologies such as smart display screens, wind turbines, electric vehicles, solar cells and energy-efficient lighting will adversely affect the development of clean energy technology and the green economic growth (IT and telecommunication generally, automotive, defence, healthcare etc.)

Most previous work on REEs has focused either on the politico-economic conflicts over supply and distribution, or the environmental and social impacts of production and have not holistically examined this problem as a system (Alonso et al., 2012; Drost & Wang, 2016; Gaustad et al., 2011; Jowitt et al., 2018; McLellan et al., 2014; McLellan et al., 2013; Wang, X. et al., 2017). While the sustainability of REEs has been examined in several papers, including in an Australian context (Ali et al., 2017; Haque et al., 2014; Klinger, 2018; McLellan et al., 2014; McLellan et al., 2013), what is lacking is an assessment of the environmental impacts and the benefits of sustainable consumption, systematically and holistically, particularly regarding improvement in resource efficiency strategies (Klinger, 2018). This study proposes a holistic and systematic approach based on the circular economy model to assess the sustainability of REEs in Australia, a strategy to minimise the adverse impacts of resource shortages while achieving maximum environmental and societal-wide benefits. This study uses three key metrics for resource efficiency (Beasley et al., 2014; Klinger, 2018; Mudgal et al., 2012; Organisation for Economic Co-operation and Development, 2015; Science Communication Unit et al., 2012) in a sustainable development framework, namely, materials use, energy demand and greenhouse gas emissions indicators to assess the sustainable use of REEs in Australia. The primary aim is to find advanced strategies to reduce the supply risk impacts of these critical resources and minimise the potential environmental impacts associated with their consumption.

1.2 Location and sources of REEs

1.2.1 The case of Australia: country's total reserve, production, and locations

1.2.1.1 Australia's REEs reserves and production

According to Australian resource reviews of Rare earth elements 2019 and USGS mineral reports 2020, Australia has the world's sixth-largest reserves of REEs and is currently the second-largest producer of REEs after China (Huleatt, 2019; U.S. Geological Survey, 2020), as shown respectively in Table 1.1 and Table 1.2. These reports show that in 2019, Australia produced 10% of these metals, which is an increase compared to the previous years (U.S. Geological Survey, 2020). These supplies came predominantly from Lynas Corporation's Mount Weld mine (now known as Lynas Rare Earths) in Western Australia. Mount Weld is recognised as the sole active mine project in Australia, apart from minor activities from the Browns Range project in the Kimberley region of Western Australia. The total REEs produced in Australia in 2019 was 21 kt, as shown in Table 1.2. Currently, Australia's REE reserves as of 2019 are 3300 kt, which is 3% of global reserves (Table 1.1). However, although the position as the second-largest producer might sound big, compared to the global demand for these metals and China's position, Australia still stands far behind in this industry with an insignificant contribution to global supply.

Countries	**Reserves 2019(kt)**	%
United States	1,400	**1%**
Australia	**3,300**	**3%**
Brazil	22,000	**19%**
Canada	830	**0.7%**
China	44,000	**38%**
Greenland	1,500	**1%**
India	6,900	**6%**
Russia	12,000	**10%**
South Africa	790	**0.7%**
Tanzania	890	**0.8%**
Vietnam	22,000	**19%**
Other countries	310	**0.3%**
World total (rounded)	120,000	100%

Table 1.1: Global reserves of REEs: Australia's position

National figures other than Australia's are rounded up in these reports.

Source: (Huleatt, 2019; U.S. Geological Survey, 2020).

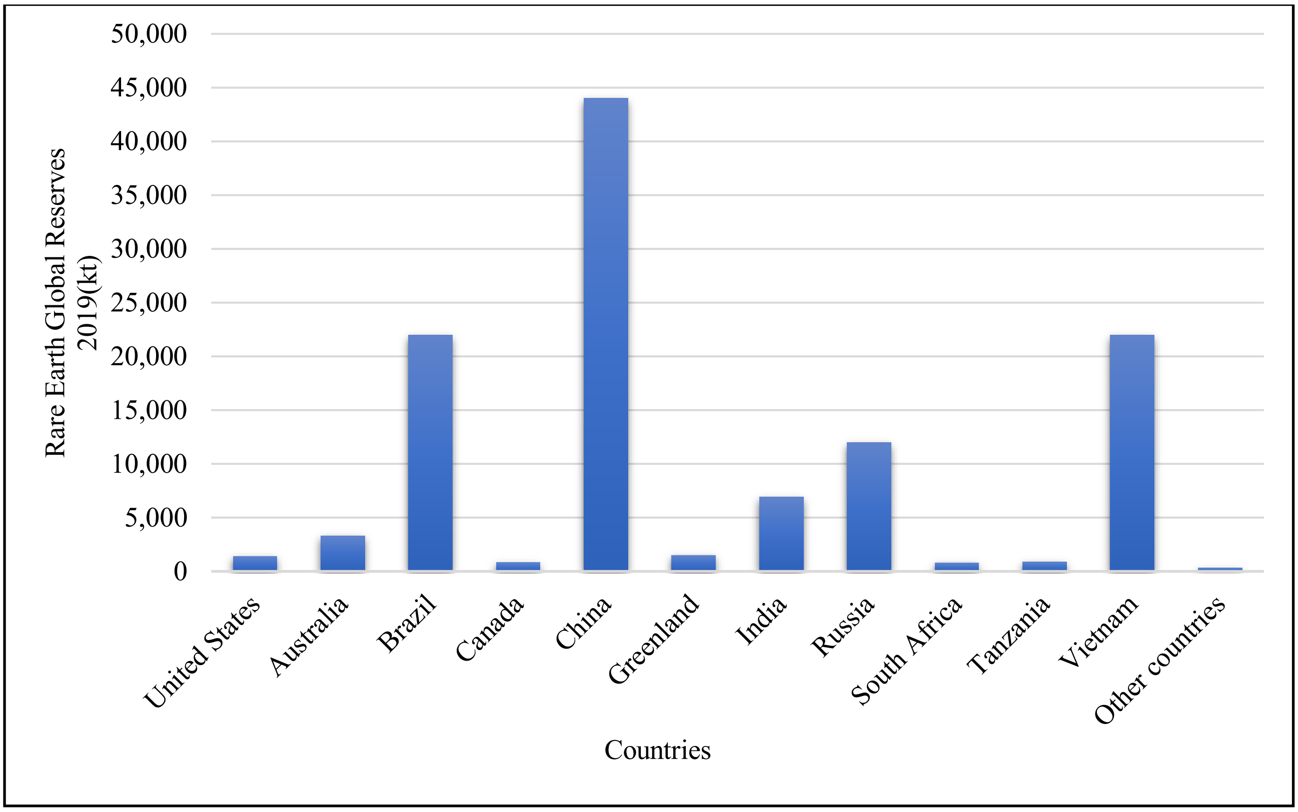


Figure 1.1: Global reserves of Rare earth elements: Australia's position

Input data from USGS, 2020

Countries	REEs annual production (kt)		
	2017	2018	2019
Australia	**19**	**20**	**21**
China	105	120	132
USA	/	15	26
Brazil	1.7	1	1
Russia	2.6	2.6	2.7
Vietnam	0.2	0.4	0.9
India	1.8	1.8	3
Thailand	1.3	1	1.8
Myanmar	N/A	5	22
Malaysia	0.18	0.2	/
Burundi	/	1	0.6
Madagascar	/	/	2
World total (Rounded)	132	170	210

Table 1.2: Global REEs production trends: Australia's position

Source: (Huleatt, 2019; U.S. Geological Survey, 2020). N/A: not available. /: no production in that year.

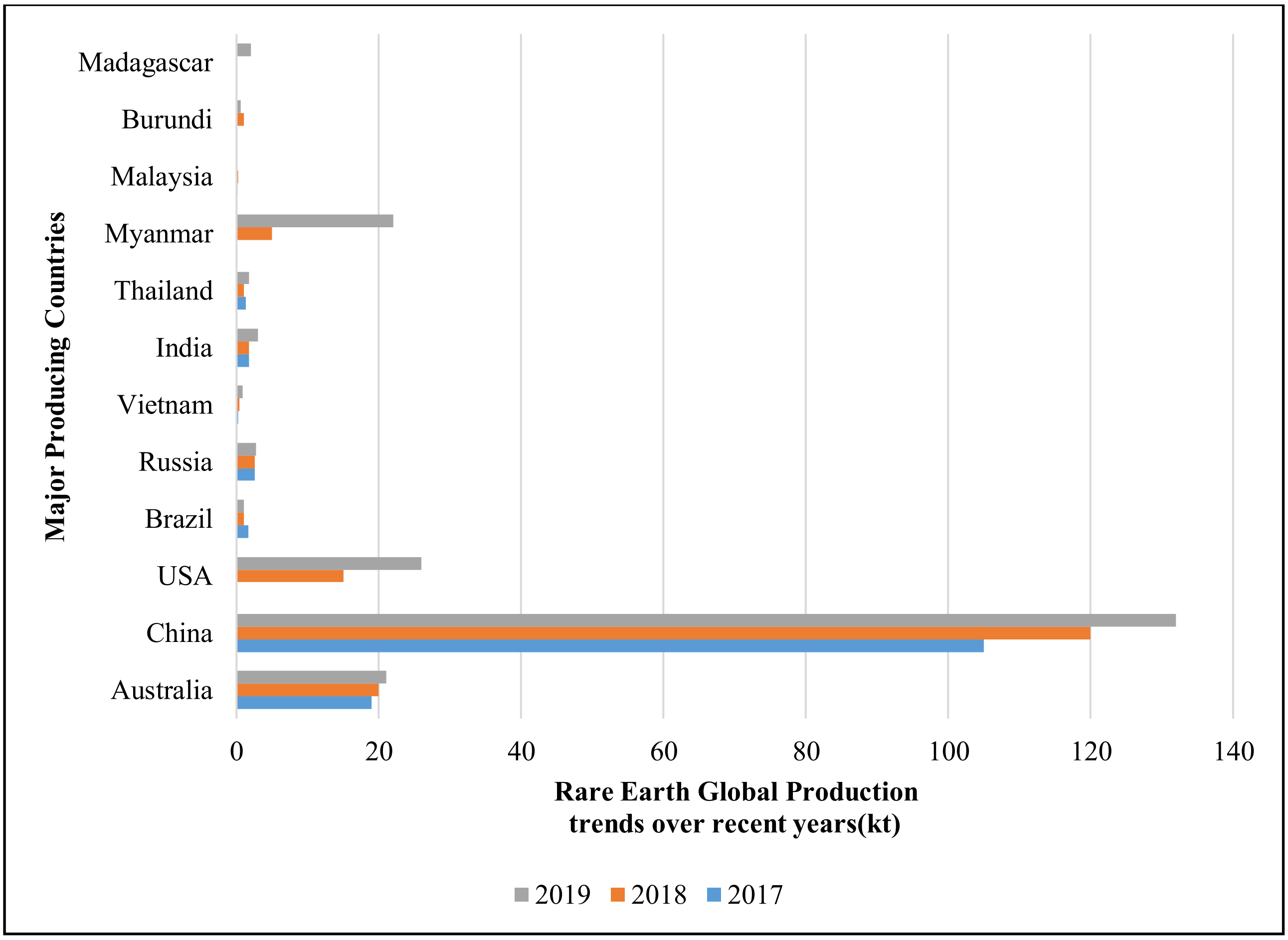


Figure 1.2: Global REEs production trends: Australia's position

Input data from (U.S. Geological Survey, 2020)

While Australia currently holds good potential for the supply of these metals as compared to other countries, this is accompanied by low government investment in these sectors, specifically regarding the weak recovery and recycling of the End-of-Life (EoL) products containing these metals (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; Huleatt, 2019; Miezitis et al., 2011). Recycling is currently focused on a small scale and mostly on magnet scrap (Australia Trade and Investment Commission, 2019; Dulfer et al., 2013). Improvements in resource efficiency (recovery and recycling efficiency) could boost Australia's position in this global challenge. There are significant economic and strategic benefits for Australia if it can secure this market permanently (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019). Table 1.3 shows a list of Australian REEs companies in Australia and other operations abroad.

List of Australia's Rare earth companies	Locations
Alkane Resources Limited	New South Wales, Eastern Australia.
Arafura Resources Limited	Northern Territory, South Australia
Crossland Uranium Mines Limited	Northern Territory, South Australia
Hastings Rare Metals Limited	Western Australia
Lynas Corporation Limited	Western Australia
Northern Minerals	Northern Territory, Western Australia
Peak Resources Ltd	Tanzania (abroad)
Greenland Minerals and Energy Limited	Greenland (abroad)

Table 1.3: List of Australian REE Companies and Locations within and outside
Adapted from Geoscience Australia (Huleatt, 2019)

1.2.1.2 Australia's Rare earth mines and projects

REEs in Australia are associated with igneous, sedimentary, and metamorphic rocks in a wide range of geological environments (Australia Trade and Investment Commission, 2019; Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Miezitis et al., 2011). The production of REEs is mostly sourced from heavy mineral sand deposits (beach, dune, offshore marine, and channel), carbonatite intrusions, (per) alkaline igneous rocks, iron-oxide breccia complexes, calcsilicate rocks (skarns), fluorapatite veins, pegmatites, phosphorites, fluviatile sandstones, unconformity-related uranium deposits, and lignites (Australia Trade and Investment Commission, 2019; Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Miezitis et al., 2011). Carbonatites and alkaline igneous rocks, and secondary placer deposits such as heavy-mineral sand deposits formed by weathering, are the most commercially viable REEs deposits in Australia (Australia Trade and Investment Commission, 2019).

At present, two main projects produce REEs in Australia, with several other projects in the development pipeline (Australia Trade and Investment Commission, 2019; Huleatt, 2019). This includes Lynas's Mount Weld mine and Northern Minerals' Brown Range project. Lynas's Mount Weld mine is the primary REEs producer in Australia. The major REEs produced from this deposit include Lanthanum, Cerium, Praseodymium, Neodymium, Samarium, Europium, Gadolinium, Terbium, Dysprosium and Yttrium (Australia Trade and Investment Commission, 2019). Table 1.4 and Figure 1.3 show a list of Australia's mine projects and REEs deposits respectively.

Mines and Projects name	Location/State	Companies
Mount weld	Western Australia	Lynas Rare Earths Limited
Nolans	Northern Territory	Arafura Resources Limited
Browns Range	Northern WA	Northern Minerals Limited
Dubbo	New South Wales	Australian Strategic Materials Limited
Yangibana	Western Australia	Hastings Technology Metals
Brockman	Western Australia	Hastings Technology Metals
South Darwin	Tasmania	Corona Resources Ltd via a subsidiary entity
Charley creek	Northern Territory	Crossland Strategic Metals Limited
Avonbank	Victoria	Wim Resource Pty Ltd
Mary Kathleen	East of Mount Isa	Hammer Metals Limited
Ravenswood	North Queensland	Stavely Minerals Limited
Narraburra	Central NSW	Paradigm Resources Pty Limited
Tanamai West, Mt Surprise and Mt Ramsay projects	North Queensland	Orion Metals

Table 1.4: Major Australia's REEs mine projects

Adapted from Austrade (Australia Trade and Investment Commission, 2019).

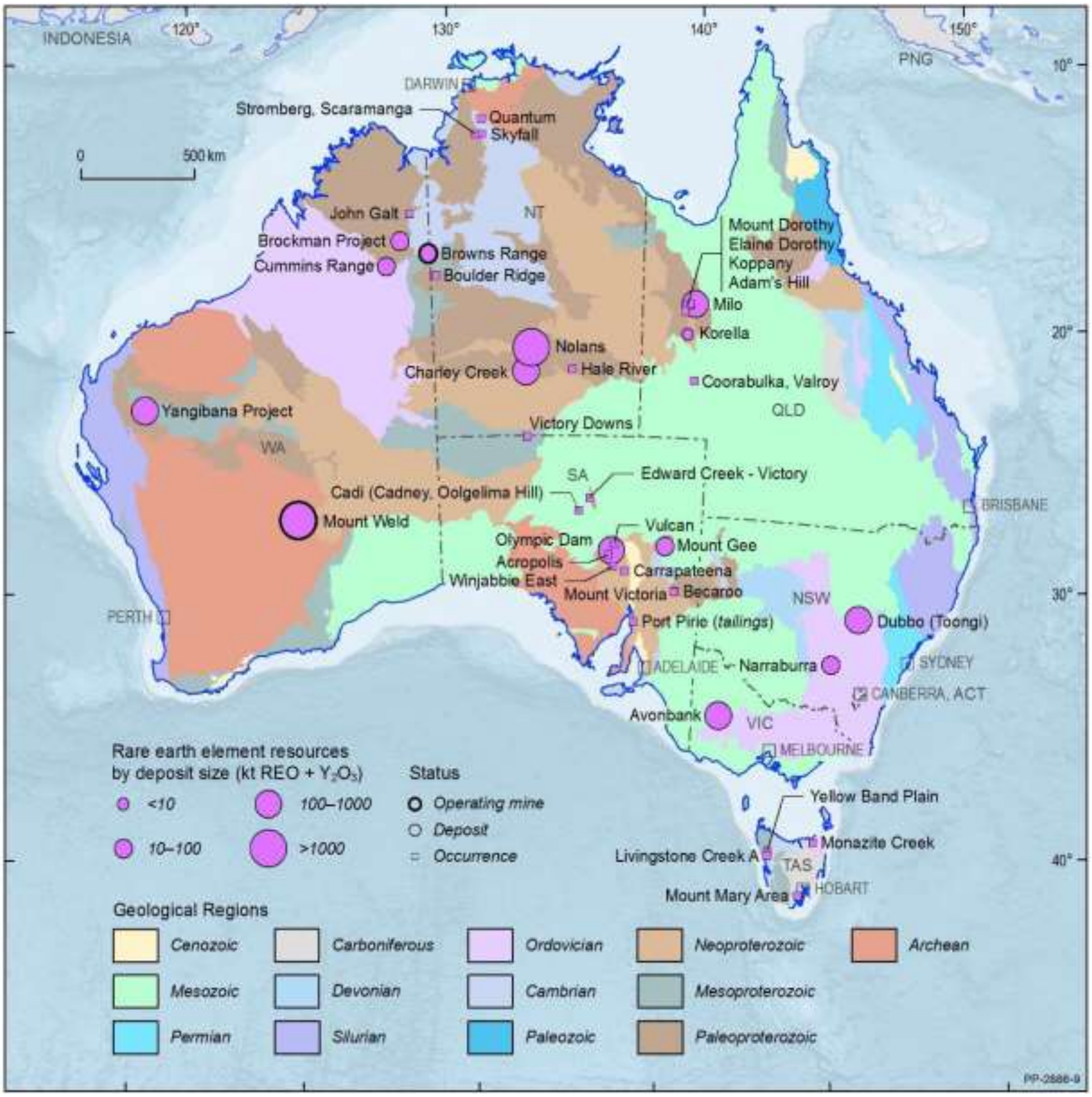


Figure 1.3: Australia's REEs deposits as of 2018

Source: (Huleatt, 2019). This figure shows the current two REEs operating mines (Mt Weld and the Brown's Range), deposits and occurrence and other deposits.

1.2.2 Other parts of the World: Locations, reserves, production and trends

REEs with high economic value and demand are found only in a few countries of the world (Akcil et al., 2020; Balaram, 2019; McLellan et al., 2013). As of December 2019, the global world reserves currently stand at 120,000 kt and the supply at 210 kt (as seen in Table 1.1 and Table 1.2 respectively). As of 2019, China alone holds more than 38% of the world's reserves and controls more than 62% of global supply (as seen in Table 1.1 and Table 1.2 respectively).

Figure 1.1 vividly illustrates China's global reserve dominance. Other major REEs production countries include the United States, Brazil, Russia, Myanmar, Burundi, India, Malaysia, Madagascar, Thailand, and Vietnam (Huleatt, 2019; U.S. Geological Survey, 2020). Over the past decade, China has been the dominant supplier and producer of these metals, maintaining a monopoly over the industry. Figure 1.2 graphically illustrates global REEs production trends (2017, 2018, 2019), Australia's position, and China's dominance over supply.

The supply response to scarcity is therefore bound to be slow, limiting the production of technologies that depend on such mining operations or causing sharp price increases (Bauer et al., 2011). With such a large proportion of these minerals located in just one country, and with China placing supply restrictions on other countries, there is a considerable threat to all major consumer countries (King, 2021). This specific situation, therefore, calls for an urgent implementation of sustainable environmental management techniques for the consumption of these critical resources to minimise not only the current, but also the future, economic and environmental impacts associated with its use. The impact of the 2019 Covid-19 pandemic on the mining industry, such as border closures reducing imports and exports among countries, is a prime example of the need for implementation of sustainability strategies in the consumption of these metals to reduce dependency and supply failures. The current Global REEs mines and advanced exploration projects are shown in Figure 1.4.

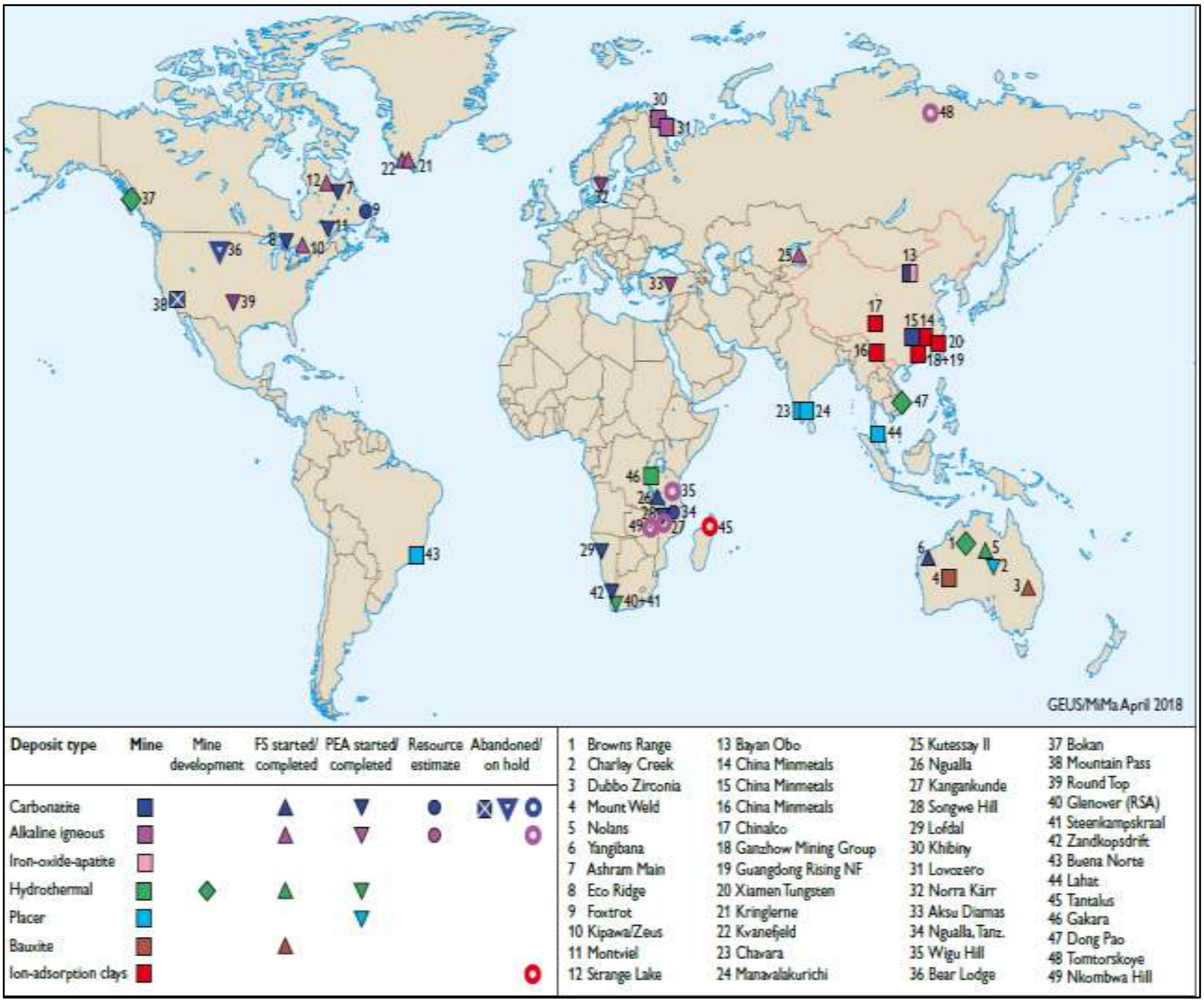


Figure 1.4: Global REEs mines and advanced exploration projects
Source: (Kalvig & Machacek, 2018)

1.3 An overview of the aims and objectives of the study

The main goal of this work is to improve the sustainability of REEs consumption in Australia. This work will provide the basis for the evaluation of existing resource efficiency strategies for REEs and a pathway to improve sustainability outcomes in Australia, and a strategy for global uptake. It will examine the current research landscape of REEs within a sustainability framework, and examine the application and uses of these metals, availability, locations and reserves, and existing governance policies. The objectives of this study are to (1) conduct a holistic and systematic assessment of the material flows of REEs in selected high-tech applications in Australia, by (2) determining the extraction, flows and consumption of selected REEs and their impacts, including their recycling rate, distribution and reserves; and finally, (3) suggesting approaches to minimise negative impacts to improve resource efficiency at each stage from raw material extraction, through use and EoL. In this regard, the study plans to:

- establish circular economy (CE) as a sustainable management tool that has a core goal of eliminating adverse effects of material consumption while attaining greater environmental and societal-wide-benefits;
- develop a framework for REEs material criticality mitigation; and
- generate a practical implementation model to close any material loop and improve efficiency in REEs consumption.

This work aims to evaluate material use and potential environmental impacts from REEs consumption in Australia for resource efficiency improvement. The study will map the existing pattern of material flows of these metals in Australia's waste stream and the associated environmental impacts and define a better scenario via a sustainable management framework where environmental benefits from resource efficiency improvements are maximised.

This study also aims to provide advice to stakeholders, industries, and the government about these materials. This includes analysing data, especially about availability in other parts of Australia, and alerting the government to the significance and importance of these metals in the waste stream to minimise supply risks and environmental burdens. Emphasis will be placed on the importance of their recovery, including the main sectors (phases) to target. Information about the general availability of these metals is essential for the implementation of cost-effective management, sustainable usage, and managing the supply capacity of these metals. The work will further alert the international community to the global economic and potential political consequences of the eventual decline in the supply of these materials. The mishandling of waste products containing these materials is of paramount importance and common interest.

1.4 Content and structure of the thesis

This thesis is structured into 7 chapters. Chapter 1 presents the general introduction and overview of the thesis. This is followed by Chapter 2, where the literature is reviewed. This chapter examines the current research landscape of REEs within a sustainability framework (a description of CE as a sustainable development strategy and its significance to REEs sustainability, a discussion of CE tools for sustainability management through material use and life cycle analysis), the application and uses of REEs, availability, locations and reserves (the case of Australia and other nations), and existing governance policies. This chapter presents the theoretical and conceptual frameworks used to investigate REEs sustainable consumption and production practices in Australia. The chapter includes a discussion of the connection between these concepts, particularly CE, and the methodological approaches used in this study. Chapter 2 ends with clearly identified research gaps and associated research questions that drive the investigation of the thesis.

Chapter 3 presents a general overview of the methodological framework of this thesis. This includes a discussion of the data sources, the analytical approach and CE tools for sustainability assessment.

The results of the investigation of the thesis are presented in two chapters (4 and 5). These chapters discuss the material use and impacts of primary and secondary material consumption of REEs in applications respectively. The second part of Chapter 5 further presents an analysis of the benefits associated with the sustainable management of natural resources from a resource management perspective. These chapters provide a clear pathway that leads to the objectives of this study and the answers to each of the research questions addressed.

Chapter 6 presents a discussion of the findings identified in Chapters 4 and 5. Drawing from these discussions, a comprehensive CE framework for REEs within the sustainable development paradigm for criticality mitigation is developed. As a way forward, this is followed by a conceptual and practical model for the implementation of the comprehensive CE strategy in the REEs industry to close material loops. The chapter provides clear answers to the objectives of this study and to each of the research questions addressed in this thesis.

Conclusions and recommendations are drawn in Chapter 7. The chapter provides an overview of the thesis and key findings, contribution to theory and methods, and implications for policy and practice and future studies. Figure 1.5 below illustrates a schematic presentation of the content and structure of the Thesis.

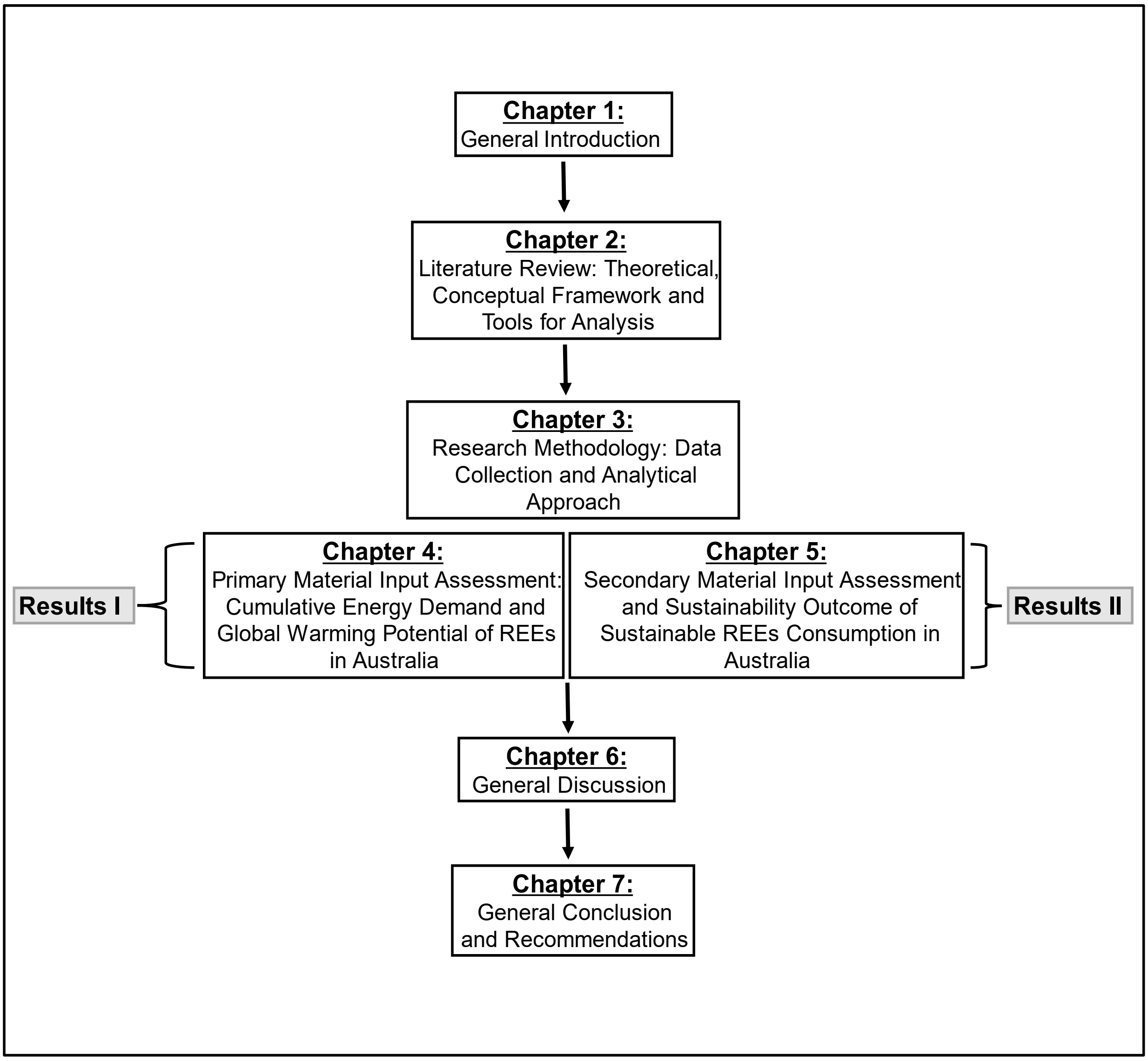


Figure 1.5: Schematic Diagram of Thesis Content and Structure

1.5 Publications arising from the work

From this work, as a further contribution to knowledge, three papers were published or accepted for publication.

The first paper titled '**Circular economy: a sustainable management strategy for Rare earth elements consumption in Australia'** was published in Current Research in Environmental Sustainability Journal, Elsevier (Palle Paul Mejame et al., 2022a). Sections from the thesis published in the article include parts of Chapter 1 (Intro), Chapter 2 (Literature review), Chapter 3 (Methods), Chapter 4 (Results 1), and a part of Chapter 6 (Discussion).

The second paper, titled **'Sustainability of Rare earth elements consumption in a circular economy perspective',** was accepted for a Chemeca 2022 conference proceeding (Palle Paul Mejame et al., 2022b). Sections from the thesis incorporated into the article include a part of Chapter 1 (intro), a part of Chapter 2 (Literature review), Chapter 3 (Methods), Chapter 4 (results 1), Chapter 5 (Results 2), a part of Chapter 6 (Discussion), and a part of Chapter 7(Conclusion and Recommendations).

The third paper was published as a book chapter in Springer Nature titled **'Life Cycle Assessment & Circular Economy'**. The work was published in a book series "Environmental Footprints and Eco-design of Products and Processes". The paper is titled **'Circular economy as a way forward against material criticality: the case of Rare earth elements in the context of sustainable development'** (Palle Paul Mejame et al., 2023). This research paper was awarded the "Circular Economy Award" at the James Cook University 2022 Sustainability Impact 10x program (Impact10X, 2022). Sections from the thesis comprised in the article include a part of Chapter 1 (Intro), a part of Chapter 2 (Literature review), Chapter 3 (Methods), Chapter 4 (Results 1), Chapter 5 (Results 2), a part of Chapter 6 (Discussion), and Chapter 7 (Conclusion and Recommendations).

At the Chemeca 2021 conference, the conference paper titled **"Material flow analysis of Rare earths elements and their sustainable use in Australia to reduce potential environmental impacts"** (Palle Paul Mejame et al., 2021) was awarded the John A. Brodie Medal 2021 Certificate of Merit, Engineers Australia.

<table>
<tr><th>Chapters/Status</th><th colspan="3">Publication output</th><th>Conferences/Awards</th></tr>
<tr><td>Chapters 1-7

- 1) Intro
- 2) Literature Review
- 3) Research Methods
- 4) Results I
- 5) Results II
- 6) General Discussion
- 7) General Conclusion and Recommendations</td><td>❑ Circular economy: a sustainable management strategy for Rare earth elements consumption in Australia</td><td>❑ Sustainability of Rare earth elements consumption in a circular economy perspective</td><td>❑ Circular economy as a way forward against material criticality: the case of Rare earth elements in the context of sustainable development</td><td rowspan="3">- The John A. Brodie Medal 2021 Certificate of Merit Engineers Australia

- The “Circular Economy Award”, James Cook University 2022 Sustainability Impact 10x program

- The Chemeca 2022 Greener, Safer, Cleaner Conference</td></tr>
<tr><td>Chapter sections published</td><td>Chap 1, 2, 3, 4(results I), and 6</td><td>Chap 1, 2, 3, 4(results 1), 5(Results II), 6 and 7</td><td>Chap 1, 2, 3, 4(results I), 5(Results II), 6 and 7</td></tr>
<tr><td>Status</td><td>Published in Current Research in Environmental Sustainability Journal, Elsevier</td><td>Accepted for a Chemeca 2022 conference proceedings Publication</td><td>Published as a book Chapter in Springer Nature titled 'Life Cycle Assessment & Circular Economy’.

The work was published in a book series "Environmental Footprints and Eco-design of Products and Processes".</td></tr>
</table>

Figure 1.6: Publications arising from the work

Chapter 2. Literature Review: Theoretical, Conceptual Framework and Tools for Analysis

Chapter outline

2.1 Introduction

Chapter two provides an overview of previous works on Rare earth elements (REEs). It examines the current research landscape of REEs set within a sustainability framework. This goes further to introduce the major theoretical and conceptual frameworks for the case study that comprises the main focus of this work.

This chapter begins by defining what REEs are, their uses and their significance to the global economy, especially in the transition to a low carbon economy. This is followed by examining the literature about REEs processes, which introduces the way these minerals are being processed and the associated impacts. Literature on REEs sustainability and criticality aspects are also examined, followed by a review of current resource management and sustainable policies governing REEs consumption in Australia and across the world. Major theoretical and conceptual frameworks used to investigate REEs sustainable consumption and production practices are reviewed. This introduces the connection between these concepts and the methodological approaches used in this study. The chapter ends with clearly identified research gaps; associated research questions are proposed which provide the focus for the investigations reported on in subsequent chapters of this thesis.

2.2 Defining REEs

What are REEs? And why are they critical to our current transition to green economic growth and the clean energy sectors?

REEs, which the Japanese have termed the seed of technology and which the US Department of Energy has dubbed the technology metals (Rare Element Resources Ltd, 2016), are a group of 17 metals that comprise the lanthanide series of elements namely: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu) and scandium (Sc) and yttrium (Y). They possess similar physical and chemical properties (Dulfer et al., 2013; Huleatt, 2019; Koltun & Tharumarajah, 2014; Miezitis et al., 2011; Tharumarajah & Koltun, 2011). REEs are key enablers for modern technologies that seek to lower emissions, reduce energy consumption, as well as improve efficiency, performance, speed, durability, and thermal stability (Cai, 2019; Goonan, 2011; Huleatt, 2019; Long et al., 2017; Lynas Rare Earths Ltd, 2021; United State Environmental Protection Agency, 2012; Van Gosen et al., 2014). These metals are also a key component in technologies that seek to make products lighter and smaller (Gibson & Parkinson, 2011; Long et al., 2017; Lynas Rare Earths Ltd, 2021g; Van Gosen et al., 2014). This is facilitated by their unique properties, which can be catalytic, metallurgical, nuclear, electrical, and magnetic, among others (Lynas Rare Earths Ltd, 2021e). Australia, like many other countries, relies on REEs as the backbone of all these technologies cited above.

With REEs facing supply risk, implementing and improving resource efficiency strategies, such as optimisation of recycling efficiency, can recover a high percentage of waste materials in the waste stream (Jowitt et al., 2018). Improving recycling efficiency means waste prevention of potentially useful materials and minimisation of the consumption of virgin materials, thereby reducing material consumption, energy use, and CO_2 emissions.

To further understand why these metals are essential for the growth of the green economy, the following sections will look broadly into (1) the uses of these metals, (2) their significance, (3) their processes, (4) sustainability and REE criticality aspects (5), governance policies regarding these metals, (6) theories and concepts, and (7) their consumption in applications.

2.3 Use of REEs

As mentioned above, the unique properties of these elements have led to their use in most everyday devices. As seen in Figure 2.1 below, the largest-growing markets for REEs are permanent magnets, fuel cracking catalysts, metallurgy and alloys, polishing agents and phosphors, with neodymium, praseodymium, dysprosium, yttrium, and terbium having the greatest exposure to these segments (Statistica, 2019).

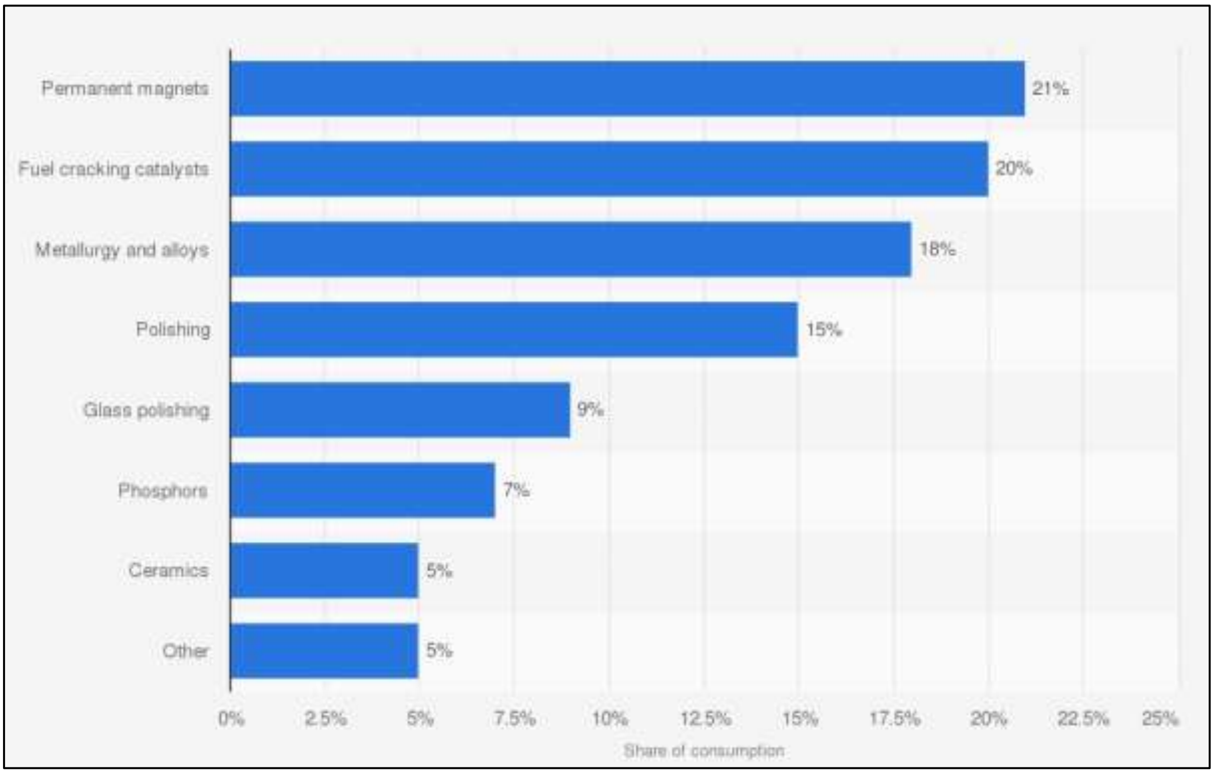


Figure 2.1: Rare Earth Element consumption worldwide by major end-use sectors 2018
Source: (Statistica, 2019)

The deployment of these technologies is predicted to only continue to grow substantially in the years ahead (Van Gosen et al., 2014). For instance, the demand for dysprosium (Dy) may grow by more than 700% and the demand for neodymium (Nd) elements may increase by more than 2600% in the next 25 years (Suli et al., 2017). Currently, in Australia, there is a growing demand for critical metals in the fast-growing clean energy sectors (such as wind turbines and electric vehicles) (Wang & Kara, 2019). The fleet proportion of electric vehicles in Australia, for example, is projected to reach up to 75%-100% by 2050 (Wang & Kara, 2019). Electric vehicles and wind turbines heavily depend on the rare-earth magnets sector. A clear picture of how REEs are being used in modern technology, especially in the green economic sector, can be seen in Figure 2.2. They constitute the major component of hybrid cars. Figure 2.3 further demonstrates other daily devices in which these metals are applied. Table 2.1below shows the leading uses of REEs in modern technologies.

Catalysts: (La, Ce, Nd, Pr, Lu, Y, Sm) - Automotive catalysts petroleum refining, - Fuel catalytic cracking, - Fuel and hybrids, - Diesel fuel additive , - Air pollution controls, - Water filtration, - Hydrogen storage,	Permanent and ceramic magnets: (Nd, Pr, Sm, Dy, Tb, Tm, La, Ce) - **Cars:** hybrids-plug-in and electric vehicles, window motors, screen wipers, starter motors, hybrid batteries, alternators, brakes , - **Electronics** :computer disc drives, data storage, iPods, DVDs, CDs, video recorders, consoles, video cameras, mobile phones speakers, headphones, microphones, ceramic capacitors, - **Wind-, hydro-, and tidal-power turbines** - Electrical motors, refrigeration, generators, cordless power tools, - Medical imaging, - Handheld wireless devices
Phosphors: (Y, Eu, Tb, Gd, Ce, La, Dy, Pr, Sc) - LCD televisions and monitors, - Plasma televisions and displays, - Mobile phone displays, - Energy efficient fluorescent lights, - High-intensity lighting, - LEDs, mercury-vapour lamps, - Phosphors—red (Eu), blue (Eu), and green (Tb)	Polishing powders: (Ce, La, Pr) - Television and computer screens—plasma, - CRT precision optical lenses and electronic components - Silica wafers and chips, - Catalyst for self-cleaning ovens
Glass additives: (Ce, Er, Gd, Tb, La, Nd, Yb, Pm) - CRT screens to stabilise glass from cathode ray - Glass—optical lenses, - Glass for digital cameras, - Tinted glass, - UV-resistant glass, - High-refractive index glass, - Fibre optics	Ceramics: (Dy, Er, Ce, Pr, Nd, Gd, Ho, La) - Colours in ceramics and glass —yellow (Ce), green (Pr), and violet (Nd)
Metallurgy and alloys : (La, Ce ,Pr, Nd, Py, Pm) - Rechargeable NiMH batteries, - Battery electrodes, - Nuclear batteries, - Fuel cells, Steel, - Lighter flints, Super alloys, Aluminium	Others : - Medical equipment :(various REEs) - Fertilizers:(various REEs) - Lasers :(Yb, Y, Dy, Tb, Eu, Sm, Nd, Pr, Gd, Ho, Er) - Defense: (Dy, Tb, Eu ,Sm ,Nd ,Pr , Y, La, Lu, Sc) - Nuclear: (Ce, Er)

Table 2.1: Major uses of REEs in emerging high-technologies

Source: adapted from Geoscience, Australia reports (Huleatt, 2019)

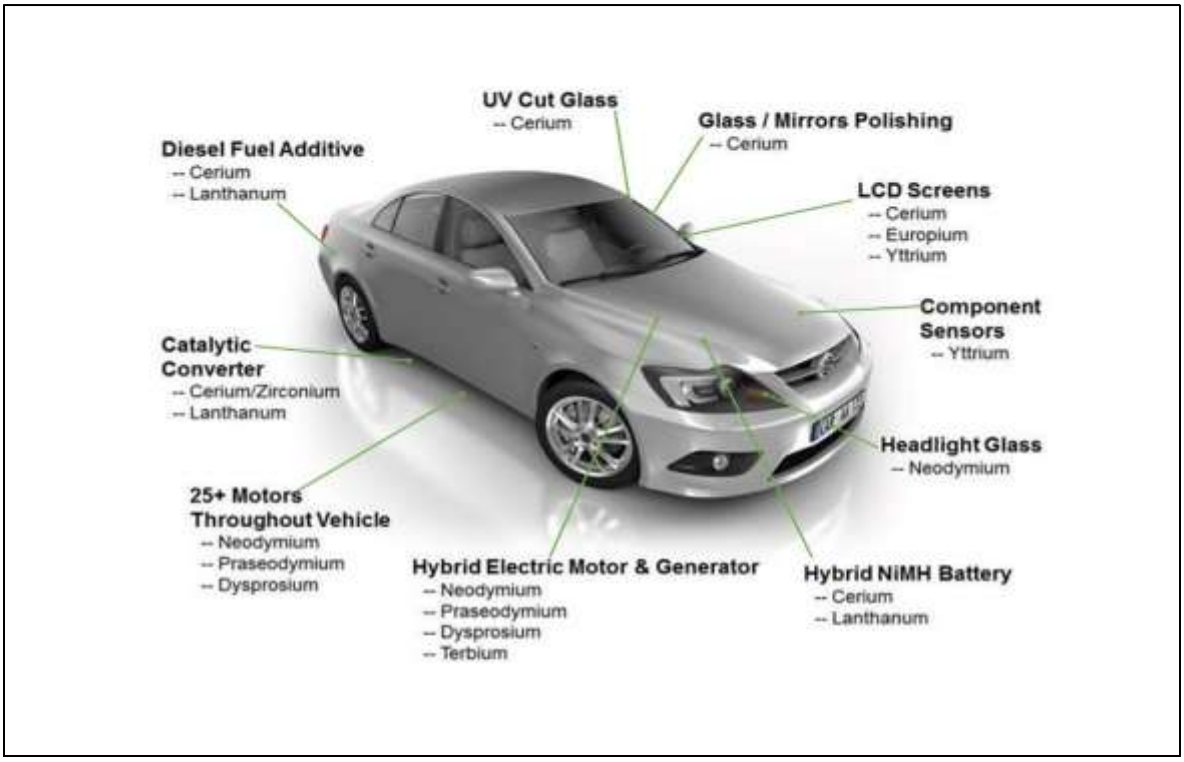


Figure 2.2: Green Cars and REE applications.

Source: (Cullinane, 2019)

Figure 2.3: Example of REEs component devices. Wind turbines, fluorescent bulbs, computers, and mobile devices, disks, hybrid vehicles, high-intensity lighting.

Source**:** (Van Gosen et al., 2014)

2.4 The significance of REEs

Over the past 50 years, new applications for these metals have not slowed (Gibson & Parkinson, 2011). The versatility and specificity of the REEs have given them a level of technological, environmental, and economic importance considerably greater than might be expected from their relative obscurity (Van Gosen et al., 2014). These individual metals have multiple roles in most highly technological devices (Dulfer et al., 2013; European Commission, 2017; Goonan, 2011; Jha, 2014; Van Gosen et al., 2014). The following points below analyse the significance of REEs to different sectors of our society**.**

2.4.1 Green economy and energy efficiency

REEs are essential components for the expanding energy efficiency and renewable energy industries (Bauer et al., 2010; Bauer et al., 2011; European Commission, 2017). This is mainly due to the growing demand for environmental concerns (United State Environmental Protection Agency, 2012). The rapid growth in these industrial sectors could result in heightened global demand for REEs (King, 2021; Zaimes et al., 2015). The significance of REEs in the growth of the above-mentioned sectors can only be broadly understood by subdividing them under the following themes:

Modern Technology: REEs are crucial to the functionality of many modern commercial industries, including medical devices, and national defence applications (Dulfer et al., 2013; United State Environmental Protection Agency, 2012; Van Gosen et al., 2014; Zaimes et al., 2015). The specific optical, magnetic and catalytic properties of REEs have enabled greater efficiency, durability and speed in components within these idustries (Gibson & Parkinson, 2011; Long et al., 2017; Lynas Rare Earths Ltd, 2021f; Van Gosen et al., 2014). The efficiency in current technology, such as computer memory, DVDs, rechargeable batteries, cell phones, catalytic converters, magnets, and fluorescent lighting, among others, are facilitated by the functions of REEs (King, 2021; Long et al., 2017; Van Gosen et al., 2014).

Furthermore, REEs are also the main driving force behind modern technologies that aim to improve the health of the planet, such as wind turbines, electric vehicles, solar cells and energy-efficient lighting (Balaram, 2019; Haque et al., 2014; Huleatt, 2019; Keenan, 2019; Lynas Rare Earths Ltd, 2010; Lynas Rare Earths Ltd, 2021d; McLellan et al., 2013). These clean technologies all depend on components often manufactured with these materials (Bauer et al., 2010; Bauer et al., 2011; European Commission, 2017; Long et al., 2017; Van Gosen et al., 2014). According to Lynas Corporation documents on "rare earth element impact on us", it is reported that in wind turbines, for example, REEs are used to make NdFeB magnets (Lynas Rare Earths Ltd, 2021h). The report outlined that their use in wind turbines enables this technology to provide better electrical yields, reduce maintenance and improve reliability. These metals are essential for hybrid, plug-in hybrid and electric vehicles, a fast-growing sector that contributes to controlling pollution at its point of emission (King, 2021; Lynas Rare Earths Ltd, 2021a; Van Gosen et al., 2014). Additionally, in vehicles more broadly, NdFeB magnets enable substantial weight reduction, contributing to overall energy savings and reduction in CO_2 emissions (Lynas Rare Earths Ltd, 2021). It is worth noting that clean energy sectors are fast-growing, promising areas of interest in Australia (wind turbines and electric vehicles), that will exhibit a growing demand for these critical metals (Wang & Kara, 2019).

Moreover, many applications of REEs are generally known to be characterised by high specificity and high unit value (Gordon et al., 2002; Van Gosen et al., 2014). For instance, fibre-optic telecommunication cables replaced copper wires and cables due to their higher provision of bandwidth (Van Gosen et al., 2014). It is also noted that these cables are only able to transmit signals over long distances because they incorporate periodically spaced lengths of Erbium-doped fibre, which function as laser amplifiers. Despite the high cost of erbium ($700/kg), its use is favoured in these laser repeaters as the metal alone possesses the required optical properties (Gordon et al., 2002; Van Gosen et al., 2014). Furthermore, the high specificity and unit value of REEs metals has completely revolutionised technology (Lynas Rare Earths Ltd, 2021). They have led to more efficient, higher-performance materials, which meet the demand for faster, smaller, and lighter products, as reported by Lynas Rare Earths. Permanent magnet technology, for example, has been significantly advanced by alloys containing Nd, Sm, Gd, Dy, or Pr. This is due to the way that REEs in magnets, which are small, light and very strong, have led to the miniaturisation of numerous electrical and electronic components used in appliances, audio and video equipment, computers, automobiles, communications systems, and military equipment (King, 2021; Lynas Rare Earths Ltd, 2021; Van Gosen et al., 2014).

Sustainability of energy use: Due to these unusual properties, REE applications have brought innovation to the energy sector (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019). Key components of energy-efficient lighting include phosphors containing REEs (Lynas Rare Earths Ltd, 2021c). Specific REEs are used individually or in combination to make phosphor substances that emit luminescence for many types of ray tubes and flat panel displays, in screens that range in size from smartphone displays to stadium scoreboards (Long et al., 2017; Lynas Rare Earths Ltd, 2021; United State Environmental Protection Agency, 2012; Van Gosen et al., 2014). Some REEs are used in energy-efficient compact fluorescent and LED light, which enables fluorescent lamps to use approximately 75% less power to produce the same amount of light as a standard incandescent light bulb (Lynas Rare Earths Ltd, 2021). Yttrium, europium, and terbium phosphors are the red-green-blue phosphors used in many light bulbs, panels, and televisions (Van Gosen et al., 2014). The glass industry is one of the largest consumers of REEs, using them for glass polishing and as additives that provide colour and special optical properties (Gibson & Parkinson, 2011). For instance, Lanthanum makes up as much as 50 percent of digital camera lenses, including cell phone cameras; Lanthanum-based catalysts are also used to refine petroleum (Gordon et al., 2002).

Furthermore, via the miniaturisation of digital technologies, REEs play a significant role in the reduction of energy consumption (European Commission, 2017; Gordon et al., 2002; Lynas Rare Earths Ltd, 2021). This is applicable, but not limited, to music devices, mobile phones, iPods, LCD televisions, camera lenses, PCs, and CD/DVD players (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019). These are all everyday consumer products. For example, in a smart mobile phone, REEs are used to polish the glass surface of the phone (Lynas Rare Earths Ltd, 2021). They are also the main components of the magnets within devices, which enable the phone speakers to provide high-quality sound (Lynas Rare Earths Ltd, 2021).

Additionally, Lynas Corporation reported that REEs play a pivotal role in the automotive industry as they enable energy-efficient electrical motors (Lynas Rare Earths Ltd, 2021). For instance, Cerium-based catalysts are used in automotive catalytic converters (Gordon et al., 2002; King, 2021). Neodymium-iron-boron magnets are the strongest magnets available and are useful when space and weight are limiting factors (Van Gosen et al., 2014). Even so, these magnets are also used in a variety of conventional automotive subsystems, such as power steering, electric windows, power seats, and audio speakers (Gibson & Parkinson, 2011). Another example of energy-efficient technology is rechargeable lanthanum-nickel-hydride (La-Ni-H) batteries built with lanthanum-based alloys as anodes (Van Gosen et al., 2014).

These battery types, when used in hybrid electric cars, contain significant amounts of lanthanum, requiring as much as 10 to 15 kilograms per electric vehicle (Van Gosen et al., 2014). They possess high energy storage capacity (Lynas Rare Earths Ltd, 2021).

2.4.2 Mitigation of climate change

REEs play an important role in greenhouse gas reduction through their unique application in automotive catalytic converters, hybrid vehicles, wind turbines, and energy-efficient compact fluorescent light bulbs (Gordon et al., 2002; Lynas Rare Earths Ltd, 2021). The ongoing development of these applications has brought about important environmental innovations (Gibson & Parkinson, 2011; Gordon et al., 2002). Notably, these applications are considered environmentally friendly and exhibit low toxicity potential (Gordon et al., 2002). These roles can broadly be understood by subdividing them under the following two themes:

REEs applications are environmentally friendly: The growing concern about climate change and the need for energy efficiency technology has led to increased environmental applications of REEs over the past three decades (United State Environmental Protection Agency, 2012). According to an EPA report (United Environmental Protection Agency), environmental applications of REEs are expected to continue as environmental concerns are only growing stronger. For instance, REEs are the main components of petroleum fluid-cracking catalysts and automotive pollution-control catalytic converters (Huleatt, 2019; Van Gosen et al., 2014). The use of REE magnets is essential for reducing the weight of automobiles, and consequently reducing resource inputs (Lynas Rare Earths Ltd, 2021). According to the EPA report, in the USA for example, it is estimated that widespread adoption of new energy-efficient fluorescent lamps (using Y, La, Ce, Eu, Gd, and Tb) for institutional lighting could potentially achieve reductions in the U.S. carbon dioxide emissions equivalent to removing one-third of the automobiles currently on the road (United State Environmental Protection Agency, 2012). The same study reported that large-scale applications of magnetic-refrigeration technology could also significantly reduce energy consumption and CO_2 emissions.

REEs applications have low toxicity potentials. According to the USGS report on "rare earth elements critical for high technology", it was found that in many applications, REEs are advantageous due to their relatively low toxicity (Gordon et al., 2002). As a result, rechargeable lanthanum-nickel-hydride (La-Ni-H) batteries, which are less toxic, are gradually replacing Ni-

Cd batteries in computer and communication applications, and could eventually replace lead-acid batteries in automobiles. Furthermore, La-Ni-H batteries, though considered more expensive, are reported to supply greater energy density, better charge-discharge characteristics, and fewer environmental problems upon disposal or recycling (Gordon et al., 2002).

2.4.3 Defence and military

REEs are a strategy mineral for military technologies (King, 2021; United Nations Environmental Programme-Global Environmental Alert Services, 2011). This is due to the diverse nuclear, metallurgical, chemical, electrical, magnetic, and optical properties of these metals (Gordon et al., 2002). According to King's (2021), report on the uses of REEs, REEs comprise a large part of most military equipment such as radar, cruise missiles, night-vision goggles, precision-guided weapons, communications equipment, GPS equipment, batteries, and other defence electronics (King, 2021). Thus, countries that possess a significant amount of these materials subsequently also possess an enormous advantage. Additionally, the study mentioned that these metals are essential for making very hard alloys used in armoured vehicles and projectiles that shatter upon impact, and although substitutes are available for these metals in diverse applications, they are not found to be as effective as REEs.

2.4.4 Political/economic dominance

REEs have proven to be vital in terms of economic and political dominance (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Dulfer et al., 2013). They are essential, not only for military growth, but also for economic and political dominance (King, 2021). China stands as a clear example of the value of these metals . China's restrictions on the export of their rare earth elements to particular countries over the past several decades has triggered concern among the main consumer countries (Hornby & Zhang, 2019; Hornby & Sanderson, 2019). This has been perceived as an attempt by China to dominate the world economy, gain political power and meet its own domestic needs (Zaimes et al., 2015). This indicates that countries that possess these metals could have significant control over the global economy and political arena (King, 2021).

2.5 Rare earth element processes

The production of REEs consists of six main steps, which include deposit exploration, mining, beneficiation, chemical treatment, separation, refining, and purification (Suli et al., 2017). According to Suli et al. (2017), REEs in their pure state exist in complex rocks, and can only be recovered by employing the beneficiation process. Beneficiation is a process that involves the physical separation of REEs, the purpose of which is to remove undesired impurities or enhance the concentration of the desired product (Suli et al., 2017). The next process is chemical treatment, which is used to leach the REE concentration. In the end, the individual elements can be extracted using hydrometallurgy. After processing, REEs are usually sold as either pure elements or metal oxides to the consumers. A schematic presentation of all these processes can be seen in Figure 2.4 below.

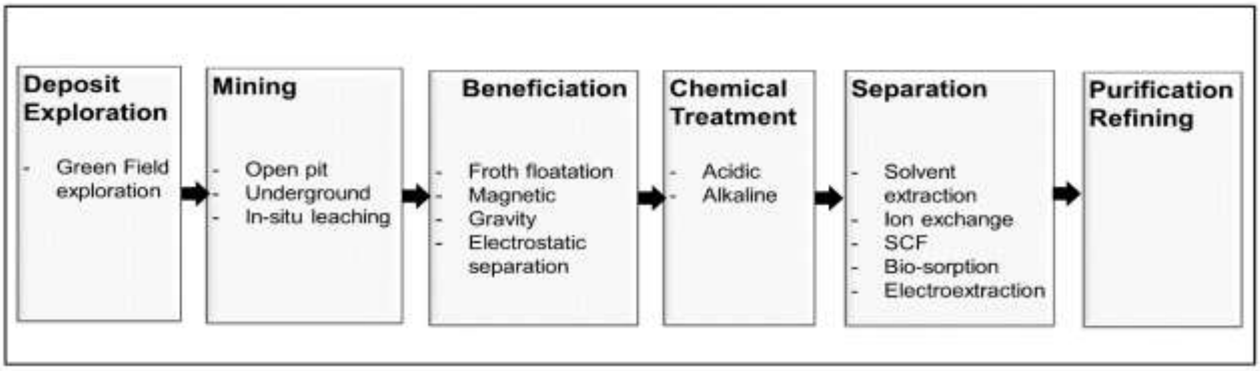


Figure 2.4: Schematic presentation of REEs processing.

Source: (Suli et al., 2017)

Another major REE process also focussed on in this study is the EoL stage. This stands as the basis of this study, as the overall goal is to demonstrate the environmental benefits of improving waste reclamation and recycling efficiency. The EoL process for REEs has been largely neglected in practice. According to the literature, typically only around 1% of REEs are recycled from end products, with the remainder of EoL products going to waste and, thus, removed from the materials cycle (Drost & Wang, 2016; Haque et al., 2014; Jowitt et al., 2018). Technological problems, inefficient collection, and a lack of incentives are primarily responsible for this waste (Drost & Wang, 2016). Notably, Australia exports the majority of its waste, specifically e-waste, for downstream recycling (Islam & Huda, 2019). This particular waste stream contains a significant amount of EoL REEs (Islam & Huda, 2019; Islam & Huda, 2020; Xavier et al., 2021).

2.6 Theoretical and Conceptual Frameworks

This section presents a description of the theoretical and conceptual frameworks underpinning this study: Sustainable development theory, resource efficiency, circular economy (CE) concept and tools for assessment (Material Flow Analysis and Life Cycle Impact Assessment).

2.6.1 Theoretical Framework: Sustainable Development

Sustainable development is the main theory that lies behind the concept of material (REEs) consumption and resource efficiency (United Nations Environment Programme, 2010; United Nations Environment Programme, 2017). By definition, sustainability within the framework of mineral resources is a state of a dynamic interplay between environment and society (in a broad sense), that ultimately contributes positively to indefinite human development and universal wellbeing, whilst not overdrawing on natural resources or irreversibly overburdening the environment (McLellan et al., 2014; McLellan et al., 2013). According to McLellan et al, the term sustainability in mining does not imply that mining can be 'sustained' but rather refers to a mine that is making its proper contribution to societal sustainability. A strong sustainability perspective is necessary to strengthen the concept of sustainable consumption. This means considering the normative dimension of sustainability frameworks including intergenerational equity and geographical inequalities in the distribution of REEs.

One of the ways to achieve resource efficiency in a state that remains within the planetary boundaries is by adopting a systematic perspective (John et al., 2016). This includes assessing the full life cycle of the dynamics of flows and stocks of these materials in the whole system (John et al., 2016; McLellan et al., 2014; Wang & Kara, 2019). This will provide an understanding of these materials, and determine which aspects of the system should be challenged in order to not only reduce resource consumption, but also increase the sustainable and efficient use of these materials, minimise CO_2 pollution and, to a broad extent, regulate human-environmental activities. Within this study, this pattern of looking at REE material flows in the context of a system can be captured under the concept of a circular economy system.

The sustainability framework based on circularity provides a scientifically plausible picture of material consumption, which captures major phases in the material life cycle where strategies can be implemented to achieve sustainability in material criticality (Korhonen et al., 2018). In such a system, the goal is not only to improve the EoL strategies for the consumption of critical materials, but equally the manufacturing-oriented strategies. The EoL strategies should have as the main goal, to turn waste into new products while manufacturing-oriented strategies improve material efficiencies for the consumption of these metals via sustainable circular economy principles (Wang & Kara, 2019). Such practices not only impact waste and recycling, but the entire material life cycle through resource efficiency improvements; in other words, using limited resources sustainably while minimising the associated environmental burdens. Figure 2.5 below summarises the theoretical and conceptual frameworks of this study.

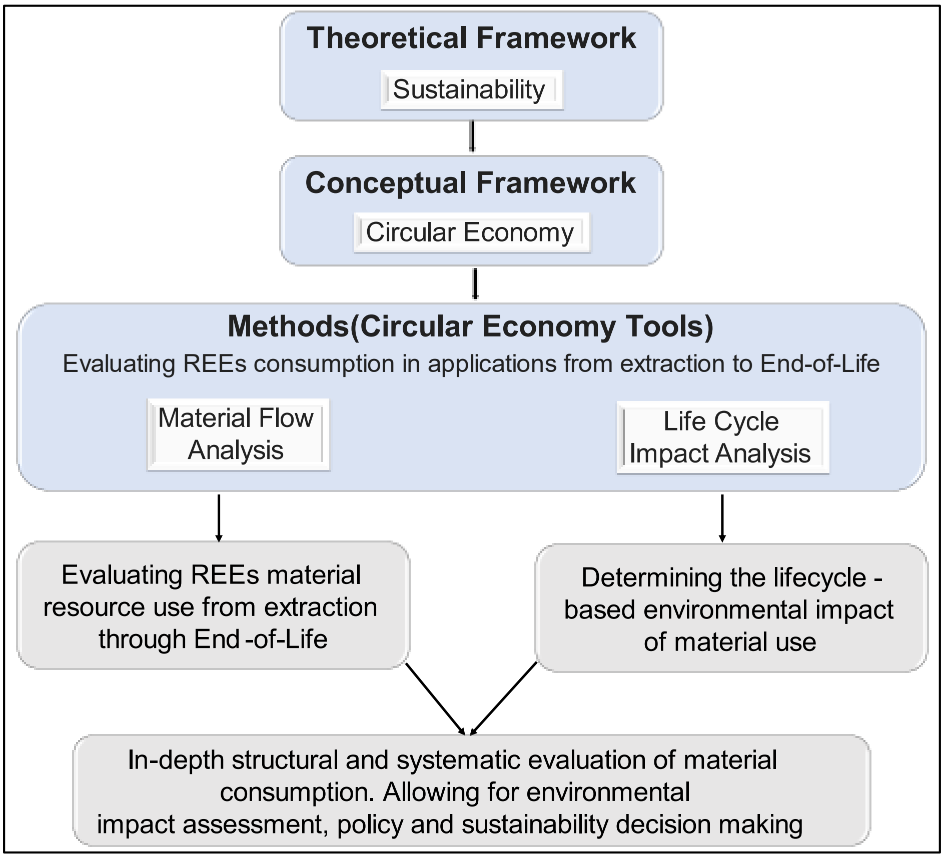


Figure 2.5: Schematic presentation of the research theoretical and conceptual framework.

The next three sections provide an overview of the concepts mentioned in Figure 2.5 above, followed by the combination of CE tools for sustainability management and their inter-relationship, to establish a broad understanding of what they are, how they are being used, and how they will be applied to realise the aims of this research.

2.6.2 Conceptual Frameworks: CE, sustainability management

The material criticality of REEs has attracted global attention, primarily due to their economic viability, strategic importance, and availability in only a few nations with high supply risks. Any efforts toward combatting material criticality must be directed toward material efficiency (John et al., 2016). The sustainability of REEs' criticality can be understood by considering the consumption of these metals from the perspective of sustainable development and its three pillars (environmental, social, and economic), as this provides a background for the implementation of sustainable strategies to achieve material resource efficiencies, while minimising environmental and social burdens. To examine the sustainability of REEs in Australia, the focal point should be on the examination of two broad aspects:

a) Sustainability and REEs criticality
b) REEs and sustainable management policies in Australia

The first aspect follows the widely used sustainable development framework approach on society, the environment, and the economy, while the second is based on the examination of existing strategies and policies governing resource (REEs) consumption in Australia. Both approaches are linked directly to the United Nations (UN) Sustainable Development Goal 12 (SDG 12) of sustainable production and consumption, and provide the background to support CE both as a sustainable development strategy and as a strategy for REEs sustainability. The literature regarding REE was extensively reviewed with a focus on sustainable material consumption and environmental impact reduction in Australia. The literature was classified into various categories such as academic and industrial sources, and global and Australia-focused. The rationale for including the global-Australia classification was to determine the extent to which the literature examined the sustainability of REEs in general, but with a focus on an Australian context.

Overall, this work contributes to advancing the understanding of REEs within the framework of sustainability via the contribution of CE principles. It provides the basis for examination of the consumption pattern of these metals in Australia and an evaluation of existing resource efficiency strategies in REEs, thus, providing a pathway for improving sustainability outcomes in Australia, and a strategy for global uptake. The study aims to demonstrate how the concept of CE in a sustainable development framework context can be implemented to tackle the challenge of REEs resource scarcity with reduced environmental burdens.

2.6.2.1 Sustainability and REEs criticality

When looking at the sustainability of REEs, it is important to take into account the complete life cycle of the material from the extraction, manufacturing, through to waste disposal and recycling (Haque et al., 2014; John et al., 2016; McLellan et al., 2014; McLellan et al., 2013). It is essential to consider all the major stages of material circularity in the system. REEs material criticality has attracted global attention due to the increasing demand for materials and high supply risk. Improving the circularity of material use by turning materials at the end of their service into resources for others is an important component (McLellan et al., 2014). A circular economy is considered by many industrial economies as essential in addressing material criticality (European Commission, 2017; European Commission, 2018; McLellan et al., 2014; Wang & Kara, 2019). It is a driver of sustainable business (Barros et al., 2021) and a solution to resource scarcity and waste reduction, especially if the full life cycle of a material is being considered (John et al., 2016; McLellan et al., 2014). To be able to examine the sustainability of REEs and their criticality, considering the full life cycle of the material (from extraction to recycling), it is necessary to focus on the three main pillars of the sustainable development framework: economy, environment, and social pillars. Additionally, it is necessary to consider the geological and technical characteristics for REEs.

Economy: The sustainability of REEs material criticality from an economic perspective can be examined in terms of the high continuous demand of REEs vs low supply; for example, its importance to clean energy and the inequality in global distribution (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Gordon et al., 2002; King, 2021; McLellan et al., 2014). The rapidly increasing demand for these key materials could hinder the clean energy agenda by outpacing new mining projects, thus leading to supply-demand problems (United Nations Environmental Programme-Global Environmental Alert Services, 2011). Furthermore, these materials generally have very few effective substitutes (King, 2021) and extremely low recovery and recycling rates (Balaram, 2019; Goonan, 2011; King, 2021).

A major problem with these materials is not so much their rarity, but rather their unequal global distribution. REEs are currently available in just a few countries of the world (Huleatt, 2019; McLellan et al., 2014; U.S. Geological Survey, 2020), with a supply monopoly held by a single country. Mines in Australia have only recently become active again due to China's limited exports and supply restrictions, high costs, and associated taxes (King, 2021). The critical nature of these materials and their uses should be a driving force for exploring other reserves in different locations, and incentive to increase mining, expand recycling and develop advanced techniques for the recovery of these materials at the end of their use, increase research into alternatives, and enact further changes in international policy (United Nations Environmental Programme-Global Environmental Alert Services, 2011).

The importance of REEs sustainability can also be well understood when considering the crustal concentration of these metals and the difficulty of extracting them. The similarity in properties and geological deposits of these metals is a major constraint affecting their supply (Gordon et al., 2002; Van Gosen et al., 2014). All17 REEs are found in REE deposits, but their distribution and concentrations vary (Gordon et al., 2002). It is partly due to these distribution and concentration factors that they are referred to as rare, as it is not common to find them in commercially viable concentrations (King, 2021). Mines containing these metals may have proportionally more of one particular type of REE over others, but they will rarely have significant quantities of that REE (Gordon et al., 2002; United Nations Environmental Programme-Global Environmental Alert Services, 2011). These similarities in geochemical properties between REEs and the subsequent processing required to separate them have made mining a costly and complex process (King, 2021). Furthermore, not only do REE-rich minerals need to be concentrated, but the actual elements must be separated from each other, usually as oxide compounds (Gordon et al., 2002). As such, it is extremely difficult to find economically exploitable deposits and simple methods of extraction and separation (Long et al., 2017; Van Gosen et al., 2014). Moreover, the lead times for new mining operations are considerable and can span from 2–10 years (Zaimes et al., 2015).

Socio-environmental aspect: The criticality of sustainability of REEs can also be examined socially regarding aspects that relate to the health of people within society (McLellan et al., 2013). A significant problem with REEs is that not only do these metals have low concentration characteristics, but they are closely associated with radioactive elements (particularly thorium and uranium) (Rim, 2016; Zaimes et al., 2015). Consequently, adequate environmental and health safety mitigation methods must be ensured, which subsequently increases operational costs (United State Environmental Protection Agency, 2012).

The environmental aspect of REE sustainability can be assessed in terms of REE technologies and processes (Drost & Wang, 2016; McLellan et al., 2013). Generally, this aspect has been well examined in terms of REEs technologies and their associations with clean energy. For instance, products that result from REEs are typically considered to be environmentally friendly and low in carbon production. However, a key environmental concern for communities is radioactive elements, such as thorium and uranium, which are often closely associated with REE deposits, and are responsible for issues associated with processing and disposing of waste.

2.6.2.2 REEs and sustainable management policies

To address the global challenge arising from the supply risks of these metals, Australia, as with many industrial economies, has proposed different strategies.

Efforts towards combatting supply risks: As one way to address this global challenge, REEs have been listed as "critical and strategic metals" in Australia, an approach which has been utilised in other industrial economies around the world. Over the last decade, expert panels convened by research institutes and government agencies have highlighted specific REEs as raw materials that are critical to evolving technologies, such as clean-energy applications, high-tech military components, and electronics (Bauer et al., 2010; Bauer et al., 2011; Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; European Commission, 2017; United Nations Environmental Programme-Global Environmental Alert Services, 2011) (see Figure 2.6-2.8). These reports suggest that the supply of REEs faces a significant risk of disruption. Consequently, this expert panel analysis ranks REEs high on the "criticality" factor of raw materials, meaning they are of high technological and economic importance and have high supply-side risk (Bauer et al., 2010; Bauer et al., 2011; Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Dulfer et al., 2013). In Australia, this has already been affirmed by major institutions, such as the Australian Trade and Investment Commission, Department of Industry, Innovation and Science in their collaborative reports with Geoscience Australia (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; Huleatt, 2019). The main goal of these conventions is to promote movement towards the adoption of sustainable management patterns for the consumption of these resources.

Additionally, some governments have taken action to address these potential shortages. In the United States, for example, several bills have been introduced in the House of Representatives to address potential supply issues; the Department of Energy also released a strategy to fill gaps in knowledge about critical materials, and to define actions for overcoming risks, including diversifying the global rare earth supply chain, developing substitute materials and technologies, and seeking ways to recycle, increase efficiency in use, and reuse rare earth minerals (Bauer et al., 2010). Japanese companies have started signing deals with India for the supply of rare earth minerals. In Australia, the government is alerting other stakeholders about the need to explore more sources for REEs and improve their production (Department of Industry Innovation and Science & Australia Trade and Investment Commission, 2019). The US government has also joined forces with Australia and other major consumer countries to develop a sustainable REEs supply chain that is secure and reliable. The US warned the Australian government about the need to boost its production sector of REEs to supplement the cuts from China (Crooks, 2019).

Waste management: In terms of waste management, the recycling rate of REEs is still only around 1% (Drost & Wang, 2016; Haque et al., 2014; Jowitt et al., 2018). At present, the focus of waste management is placed on the recovery of scrap magnets, and regulating policies do not clearly indicate how to improve the waste management system as a whole (Islam & Huda, 2020). The majority of Australia's secondary sources of these metals (EoL products) are found abroad and landfill is still practised. For instance, though WEEE (Waste Electrical and Electronic Equipment also known as e-waste) is said to contain a very high portion of REEs in its waste stream, there is insufficient regulation in Australia to fully manage this waste stream (Islam & Huda, 2019; Islam & Huda, 2020). E-waste in Australia arising from waste television, computers, printers, and IT parts is being managed by the National Television and Computer Recycling Scheme (NTCRS) (Dias et al., 2018). As the name indicates, this current Australian scheme only considers e-waste to include old televisions, computer parts, printers etc (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020).

Under the EU WEEE Directive (European Union, 2012), there are six classified categories of e-waste, with specific targets for collection and recycling rates; this NTCRS scheme falls under only categories 2 and 6 of this directive. There is no policy indication on how to manage the other electric and electronic products found in the EU WEEE Directive (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). The majority of these products end up in landfill and the rest are collected as scrap (Dias et al., 2018; Islam & Huda, 2019). Category 1, 3 and 4 products under the WEEE Directive, for example, comprise a large portion of renewable and green energy products, such as photovoltaic panels, and energy-efficient fluorescent lamps, which significantly utilises REEs. Other products in this category include refrigerators, washing machines, air conditioners, cameras, headphones and earphones, CD players, and shavers and hair-removing appliances, which are currently not regulated in Australia under the NTCRS e-waste management scheme (Dias et al., 2018; Islam & Huda, 2019). Recent studies show that waste solar PV panels are one of the significant e-waste streams in Australia (Mahmoudi et al., 2019; Salim et al., 2019). These are all products that contain a high percentage of magnets (Islam & Huda, 2019). It is worth mentioning again that permanent magnets, for example, constitute the largest portion of REEs consumption, with one of the fastest-growing markets for REEs being rechargeable batteries, and phosphors (found in category 3 and 4 products) (Statistica, 2019).

In summary, the NTCRS-oriented e-waste scheme conducts first-stage recycling operations in Australia and then transports the waste overseas for downstream recycling to developing countries such as China, Indonesia, India and Vietnam (Islam & Huda, 2020). E-waste recoveries from other electronic products (category 1, 3 and 4) are considered as scrap metals with the majority ending up in landfill (Dias et al., 2018; Islam & Huda, 2019). In terms of material circularity, this is a loss and thus an unsustainable practice. Greater focus must be placed on the recovery of secondary materials from waste and optimisation of the whole system to close the loop. In a year, there is an estimated 6 million tonnes of metal content in waste in Australia, which could supplement 50% of annual metal consumption in the country (Corder et al., 2015) constituting an estimated worth of AUD 6 billion if fully recovered (Corder et al., 2015).

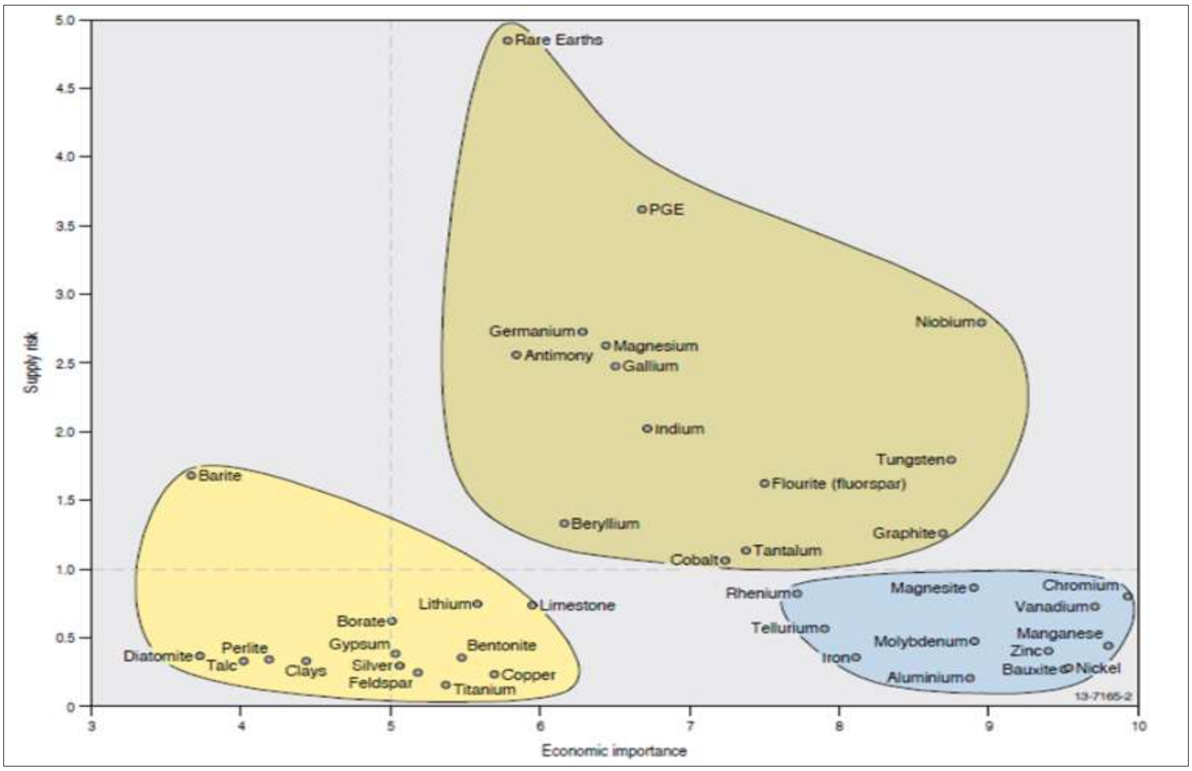


Figure 2.6: Report on the criticality of REEs among other metals

Source: (Bauer et al., 2010; Bauer et al., 2011).

REEs are analysed as the most critical metals among others as shown in Figure 2.6. In this figure, we can see REEs at the top of the matrix for critical metals with the highest supply risk and high economic importance.

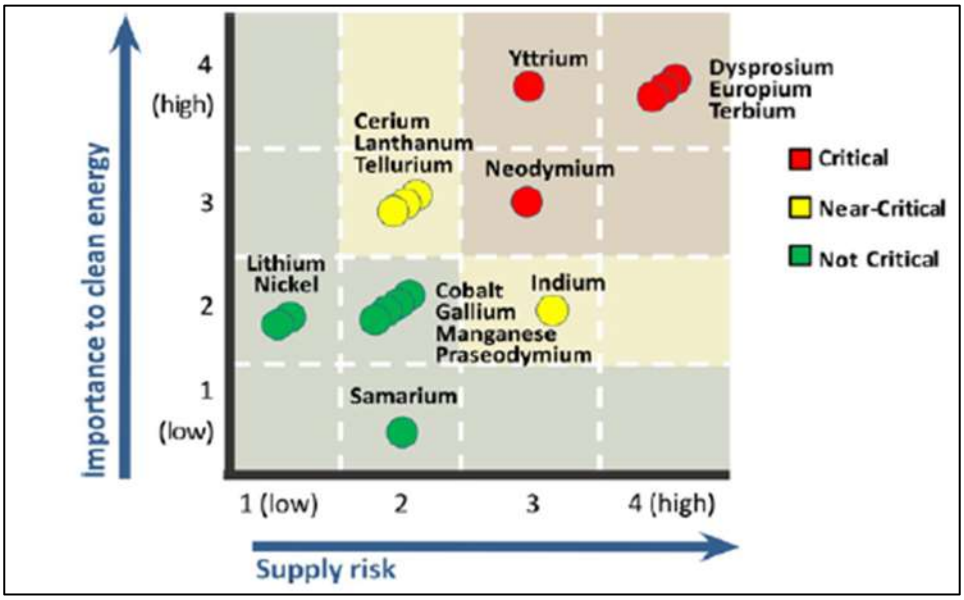


Figure 2.7: Short-Term (0–5 years) Criticality Matrix

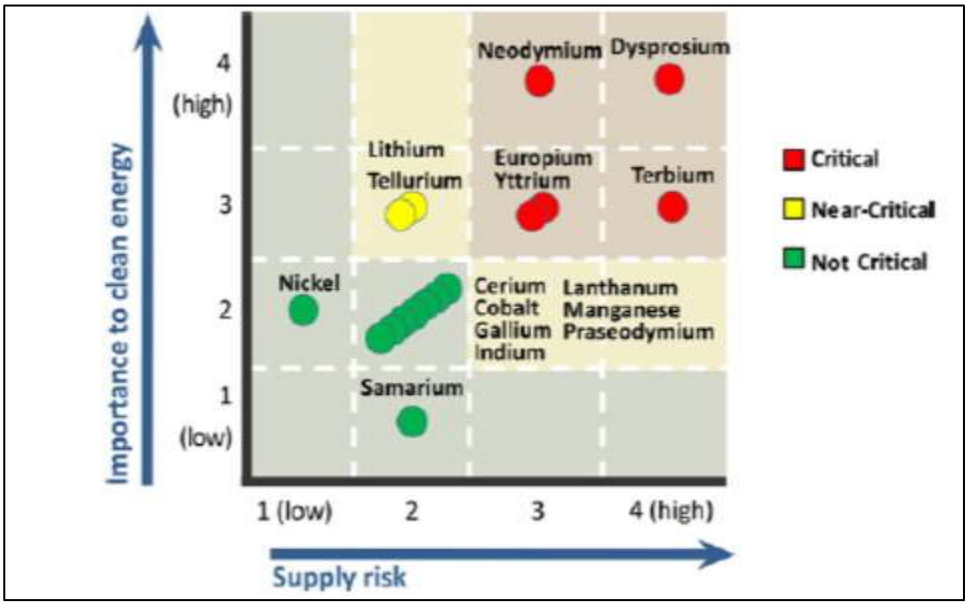


Figure 2.8: Medium-Term (5–15 years) Criticality Matrix

Reports on the most critical REEs in different time frames(Figure 2.7 and 2.8.) Source: (Bauer et al., 2010; Bauer et al., 2011).

Based on economic importance to the green economy growth, and supply risks over a specified timeframe, some REEs are considered more critical than others. In the above Figures, the red dots represent REEs at the top of the criticality matrix. Yttrium, Dysprosium, Europium, and Terbium, for example, top the criticality matrix within the short-term timeframe, while in a medium-term timeframe, Neodymium and Dysprosium are the most critical (Bauer et al., 2010; Bauer et al., 2011).

2.6.2.3 Circular economy as a sustainable development strategy and strategy for REEs sustainability

The following section describes CE as a sustainable development concept, and examines its significance as a sustainable strategy for REEs. It presents REEs consumption in a CE model within the context of sustainable development, and the description of CE principles, their contributions, the importance of circularity and the tools to achieve sustainability for REEs.

a) CE as a sustainable development strategy

Sustainable Development, as defined by the Brundtland Commission, is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland Commission, 1987). The concept emphasises building intragenerational prosperity while simultaneously preserving and conserving life-support systems needed to meet intergenerational needs. The idea of limited natural resources, and the goal to manage those sustainably to meet present and future needs, are stipulated in this definition, with the specific target of achieving sustainable management and efficient use of natural resources by 2030. This also introduces the concepts of weak and strong sustainability, which is very important as both concepts have implications for the degree of conservation, restriction and adjustment in the consumption of natural resources for the wellbeing of the current generation and the generations to come as well. The planetary boundaries specifically serve as a guide for the current generation to adjust their consumption patterns of natural resources to meet the needs of future generations (Balanay & Halog, 2019). Any strategy toward a more sustainable resource use must not only reduce total resource use, but equally keep within the system what is being used (John et al., 2016). In this regard, a strategy and a paradigm for these goals need to be established (Balanay & Halog, 2019; John et al., 2016). Regarding this view, circular economy (CE) has been promoted as an approach that brings forth promising systemic solutions to the global economy and environmental challenges, such as resource scarcity, waste reduction etc (Balanay & Halog, 2019; Wang & Kara, 2019). The connection to Sustainable Development Goals (SDG) is well established within the definition of circular economy and its foundation (Camilleri, 2018).

CE is a concept that complements the SDG (Balanay & Halog, 2019; United Nations Environment Programme, 2010)**.** It is a sustainable development strategy that is particularly linked to SDG goal 12 of sustainable production and consumption (Reike et al., 2018; United Nations Environment Programme, n.d). The objective of SDG goal 12 is to intensify efforts to reduce the use of services and scarce resources to create products, whilst minimising the environmental impacts from the generation of waste and pollution over the life cycle of the services or products so as not to jeopardise the needs of future generations (United Nations Environment Programme, n.db). The CE concept provides a holistic framework to progress towards the United Nations' sustainable consumption and production goal. It is widely regarded as an alternative model to the current strategy (sustainable consumption and production), thereby contributing to sustainable development (Reike et al., 2018; United Nations Environment Programme, 2019). It challenges the current economic take-make-consume-and-dispose patterns of the growth model (linear economy) and moves toward a sustainable future focusing on positive society-wide benefits (Camilleri, 2019; Lieder & Rashid, 2016; MacArthur, 2017; United Nations Environment Programme, n.d). Furthermore, the closed-loop and product-service systems of CE could result in significant efficiencies in sustainable consumption and production of resources through waste management and the responsible use and reuse of materials in business and industry (Camilleri, 2019).

CE is a necessary condition for sustainably maintaining economic growth (United Nations Environment Programme, 2006). Circular economy is an approach to economic growth that aligns with sustainable environmental and economic development (Korhonen et al., 2018). The core concept of CE is to maximise the circularity of resource production and consumption by optimising the whole process and turning materials at the end of their service into new resources for others (Wang & Kara, 2019). It emphasises the use of renewable energy with maximum efficiency in the use of raw materials for manufacturing processes (Balanay & Halog, 2019). This sustainable approach defines CE as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017). In another sense, this closed-loop system can be attained through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling of resources (Geissdoerfer et al., 2017). In sum, the circularity of material flow in the system will enable improvement in resource efficiency through the sustainable consumption and production of resources, whilst minimising the environmental impact (Camilleri, 2018). It is imperative to take a systemic approach to looking at the whole life cycle of product-service systems, raw material inputs, and respective emissions (John et al., 2016). CE, as a regenerative design and closed system, can be considered a sustainable development strategy as it creates economic and environmental value for society (International Resource Panel, 2017; United Nations Environment Programme, 2017; United Nations Environment Programme, 2019). CE is built on conceptualisations revolving around sustainable development goals, particularly sustainable consumption and production (Camilleri, 2019).

CE is based on three main sustainability principles, which are designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (MacArthur, 2017). It is, therefore, a large-scale industrial ecology that aims to minimise environmental footprints through adherence to its principles. Underpinned by the transition to a low carbon economic model, CE reconciles the environment, society and economic prospects for the wellbeing of the current generation as well as the future ones (MacArthur, 2017). Improving the wellbeing of people, while minimising resource consumption and environmental impacts, particularly through enhanced resource efficiency, is the paramount objective of Sustainable Development Goal 12 (sustainable production and consumption), and linked to the entire Sustainable Development Framework (International Resource Panel, 2017). The Sustainable Development Goal 12 entails decoupling prosperity from finite resource consumption, in other words, the consumption of goods and services without dependency on the extraction of virgin materials, resulting in a closed loop that will prevent waste generation (International Resource Panel, 2017; MacArthur, 2017; Sauvé et al., 2016a). To achieve such decoupling, the current linear material flows through the economy must pass into circular use through intelligent design of products, blending standardisation, reuse, recycling remanufacturing, development of efficient and inclusive infrastructure systems, and a focus on delivering services, rather than material products (International Resource Panel, 2017).

The concept of CE builds on a collection of sustainability concepts (Balanay & Halog, 2019; Camilleri, 2018; Korhonen et al., 2018; Manickam & Duraisamy, 2019). However, while some of these approaches have made important sustainability science contributions, the connection to the popular concept of CE is a complex one (Korhonen et al., 2018). Sustainability concepts embedded in CE include cradle-to-cradle, eco-effectiveness, eco-efficiency, industrial ecology, ecological economics, cleaner production, life cycle thinking, green economy, eco-design, and extended producer responsibility. CE is also governed by the major waste management strategies for the sustainable development concept of the '3Rs', namely Reduce, Reuse, and Recycle (Manickam & Duraisamy, 2019). These related sustainability concepts and approaches have contributed to achieving relative, but not absolute, decoupling of natural resource use and environmental impact from economic growth (Reike et al., 2018).

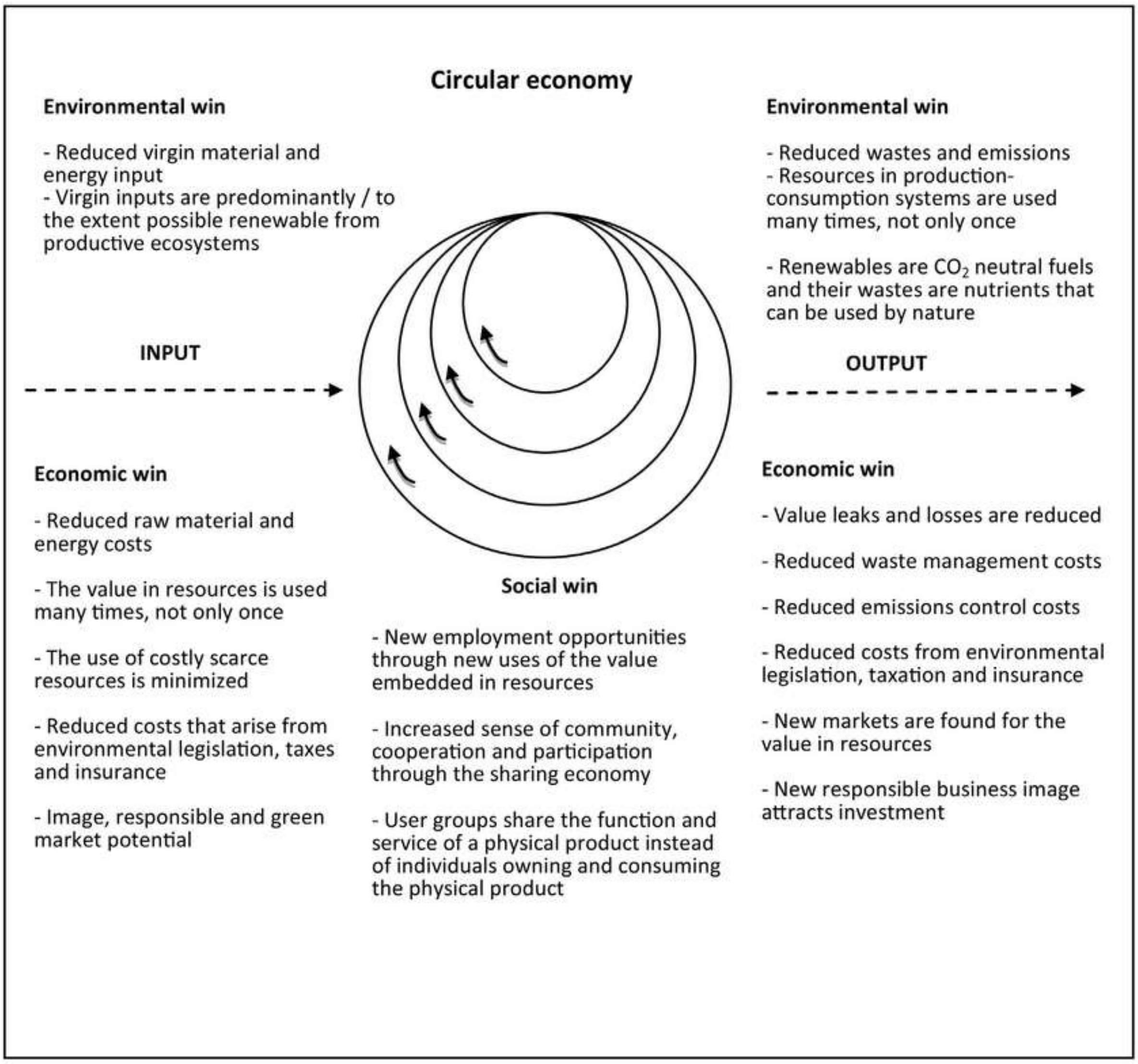


Figure 2.9: CE for sustainable development.

Source: (Korhonen et al., 2018).

Figure 2.9 shows the win-win potential of CE. This paper suggests that a successful CE contributes to all three dimensions of sustainable development (economic, environmental and social dimensions), also known as the triple-bottom-line framework – a holistic framework that is lacking for Australia's REEs sustainability studies (Klinger, 2018).

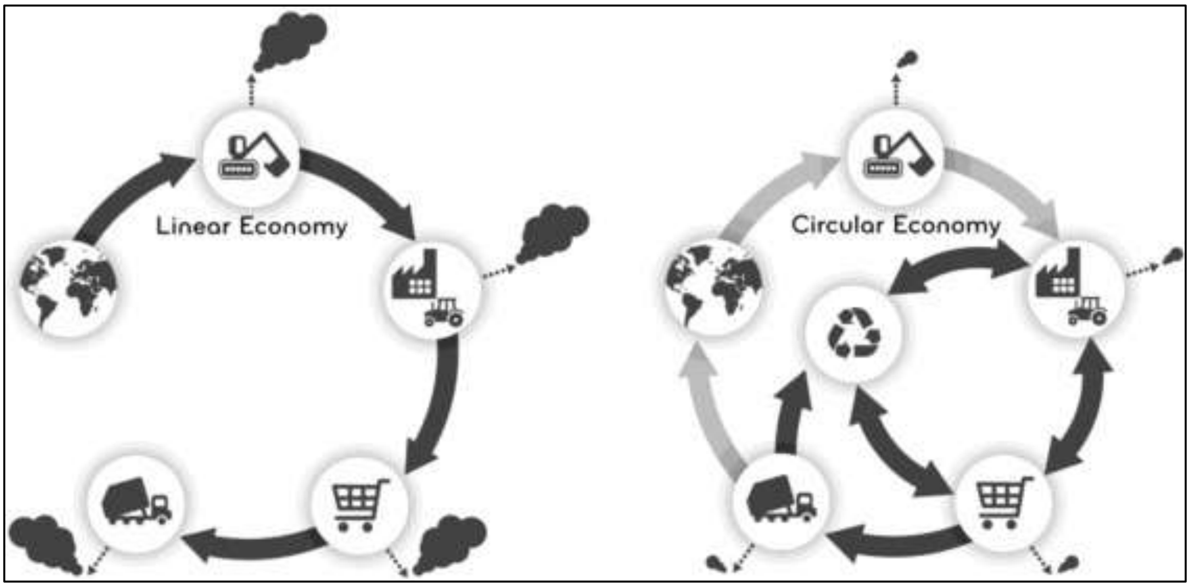


Figure 2.10: An illustration of a linear vs a circular economy system
(Sauvé et al., 2016b).

Figure 2.10 illustrates a model in which the economy takes place in a loop where the planet plays an important role in providing natural resources and absorbing waste and pollution. Provided the planet's carrying capacity is not overshot, the model holds. The linear economy (left) disregards the environmental impacts of resource consumption and waste disposal, leading to increased levels of virgin resource extraction, pollution, and waste. The linear economy ignores feedback processes as it is a take-make-waste extractive industrial model, where impacts are placed on the environment. On the contrary, CE (right), accounts for the impact of resource consumption and waste on the environment and is a more sustainable approach. CE operates in a closed-loop system, where resources move along circularly within a closed system.

b) CE as a sustainable management strategy for REEs

CE, by definition, is an economic system with the main goal being the elimination of waste and the continuous extraction of resources (Domenech, 2014; European commission, 2018; Geissdoerfer et al., 2017). In other words, it is considered a restorative system in which resource consumption and waste, emissions, and energy output are reduced by gradually closing, and decreasing material and energy loops (Geissdoerfer et al., 2017). Ce is a vital strategy for the sustainable management of REEs consumption to combat supply risk and reduce impacts as it considers both environmental and socio-economic gains simultaneously.

CE includes the design for long-life, reuse, renovation, repurposing, sharing, easy repairing, remanufacturing, recovery, and recycling of waste to establish a closed-loop system, reducing material consumption and production of waste and pollution (European commission, 2018). CE redefines growth, focusing on positive society-wide benefits (MacArthur, 2017). Its main principles, to be demonstrated in this study, include designing out waste and pollution, maintaining products and resources in use, and restoring natural systems (MacArthur, 2017).

In sum, CE aims to enhance resource efficiency via the optimisation of the use of virgin resources and the maximum reduction of pollution and waste at each phase, focusing on positive society-wide outcomes (Sauvé et al., 2016) It is a model that aims to decouple economic progress from resource limitations in a way that introduces innovation throughout the whole value chain (International Resource Panel, 2017). To achieve this goal, Material Flow Analysis and Life Cycle Impact Assessment are considered the most relevant CE tools to assess environmental sustainability (Balanay & Halog, 2019).

2.6.2.4 CE tools for sustainability management: Material Flow Analysis and Life Cycle Assessment as tools for sustainability assessment

Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA) are the principal tools used in this study for the sustainability assessment of REEs in Australia. To carry out an in-depth structural and systematic sustainability assessment of REEs consumption, it is important to consider the whole life cycle of the material, from extraction through to waste disposal and recycling (Haque et al., 2014; John et al., 2016; McLellan et al., 2014; McLellan et al., 2013). This framework captures the main phases where resource efficiency strategies can be implemented to achieve sustainable consumption of these critical metals (John et al., 2016). The following section will give an outline of an overview of these CE tools (MFA, LCIA).

A. An overview of Material Flow Analysis (MFA)

MFA has become a widely accepted tool for assessing environmental sustainability, waste, energy use, GHG emissions, and resource management through a better understanding of the circular flows of material (John et al., 2016). MFA is defined as the systematic assessment of the flows of element inputs and outputs within a system in a given time and place (Brunner & Rechberger, 2003; Brunner & Rechberger, 2016; Environmental Justice Organisation Liabilities and Trade, 2012; John et al., 2016). MFA aims to delineate material flows and stocks, reduce system complexity while maintaining a basis for decision-making, assess relevant flows and stocks quantitatively, check mass balance, sensitivities, and uncertainties, and present system results in a reproducible, understandable, transparent fashion (John et al., 2016). Understanding the flows of materials is essential to managing them, and provides a basis to identify and take into account the externalities throughout a product's value chain and in the broader context of human-environmental interactions (John et al., 2016).

Material flow analysis can be applied at different scales depending on the specific needs of the study or area of interest (Balanay & Halog, 2019). An MFA can be carried out on a regional or global level, which generally involves quantifying material efficiency over a geographic area (Pincetl, 2012). An MFA can also be conducted at the industrial level. This type of study is mostly concerned with material flows within an industry, where it is used to improve production levels and efficiency of energy flows, recycling rate, and reduction of major costs, among others. MFA can be used to quantify the material flows within the system and use LCA to assess the environmental burdens. MFA and LCA can also be combined for flow and impact analysis. It is a key tool in industrial ecology and serves as the basis for material flow management (Pincetl, 2012). The various applications of MFA means that it is widely applied in the fields of environmental management and engineering, resource, and waste management (Brunner & Rechberger, 2003).

- **Basic principles and concepts that guide the MFA model**

MFA relies on two key principles: the systems approach and mass balance approach (Brunner & Rechberger, 2003). The Mass Balance Approach studies the balances between metals, goods, substances, and water, among others, and energy flows via the economy and the environment at a local or global scale. Fundamental to this is the basic principle of conservation of matter, where input is equal to output plus any change in stock expressed in kg/year, tonnes/year or kg/capita/year (Brunner & Rechberger, 2003). The concept is that materials come from the environment used by people and all end processes come back into the environment. MFA also applies the law of thermodynamics.

MFA can be modelled for an industrial plant or a region of the world depending on the area of study interest. A system boundary is identified showing process flows and stocks of materials found within these processes (Brunner & Rechberger, 2003). All movements that occur between the system and its environment take place through the flows and system boundary.

MFA is a modelling process that contains five main steps (Brunner & Rechberger, 2003; John et al., 2016) :

a. Identification of the relevant material flows
b. System analysis (selection of the relevant matter, processes, indicator substances and system boundaries)
c. Quantification of mass flows of matter and indicator substances
d. Discovery of major leakages in any given system
e. Discovery of new problems and schematic representation, interpretation of the results. This study on REEs entails a systematic approach.

- **History of MFA overview**

MFA is not a new field of interest. Conservation of matter as a concept has been in use in some degree since the time of ancient Greece. This concept was later used in modern chemistry (Brunner & Rechberger, 2003), from which moved to Chemical Engineering and then to Environmental Science. Many contributions have been made to MFA by Theodor Weyl (Lederer & Kral, 2015). Notable developments in MFA methodology were undertaken during the 1980s-90s. Brunner and Rechberger (2003), van der Voet et al. (2002), Friedrich Schmidt-Bleek and UNEP (specifically under the UNEP Resource Panel) (International Resource Panel-UNEP, 2018) have been credited as the drivers of this methodological development. Over the past few years, UNEP Resource Panel has gathered experts and researchers on multiple occasions to analyse concepts and findings, and disseminate these concepts and findings to policymakers and stakeholders.

MFA has been widely used across many disciplines and has been adopted and used at different scales of studies. In terms of REEs MFA study, the past few years have seen an increase in studies which employ this model, due to rising concerns over the criticality of these metals. Denmark (Habib et al., 2014), China, Japan, the United States, and Europe (Du & Graedel, 2011a; Du & Graedel, 2011b; Du & Graedel, 2011c; Habib et al., 2014; Rademaker et al., 2013), as well as the EU (Schüler et al., 2011; European Union & Risk and Policy Analysts Limited, 2014; Guyonnet et al., 2013; Guyonnet et al., 2015) stand as key examples of countries and regions where MFA models have been adopted and used for different purposes, with a focus on the estimation of material availability and recycling technologies.

- **Strengths and Weaknesses of MFA**

The strength of MFA lies in its usefulness in the development of environmental policy for managing hazardous substances, the evaluation of product environmental impact, the provision of environmental performance data, the derivation of sustainability indicators, and the possibility to develop material flow accounts for use in official statistics for resource management, environmental, trade and economic and technological policies (Balanay & Halog, 2019; Brunner & Rechberger, 2003; International Resource Panel, 2017; John et al., 2016; Kaufman, 2012; United Nations Environment Programme, 2016). MFA can serve as a decision-making tool to evaluate and improve the effectiveness of measures, and to design efficient management strategies, to optimise sustainability in supply chains (Zaghdaoui et al., 2017).

The most notable weakness of MFA is its dependency on adequate and accurate data (Balanay & Halog, 2019).

B. Life Cycle Assessment principle and framework overview for environmental management

Life Cycle Assessment (LCA), also referred to as life cycle analysis is an environmental assessment and management tool for industrial systems (Curran, 2008). According to EPA (the United States Environmental Protection Agency), LCA is a technique and method for assessing the environmental aspects and potential impacts associated with the overall stages of a product, process or service (Curran, 2006). It is a holistic view of environmental interactions that covers a range of activities throughout a product's life cycle, from raw material acquisition (Cradle) through product manufacture, use, EoL treatment, recycling (cradle-to-cradle) or final disposal (cradle-to-grave)(Curran, 2006; Curran, 2008; International Organization for Standardization, 2006). LCA is recognised as the most comprehensive approach to quantifying the environmental sustainability of a product or process, but there are limited studies associated with REEs consumption (Navarro & Zhao, 2014). The few LCA studies on REEs focus primarily on REEs production and the environmental impacts (Ikhlayel, 2017; Koltun & Tharumarajah, 2014; Zaimes et al., 2015), and REEs recoveries (Sprecher et al., 2014).

- **Origin and Development of LCA**

The early 1960s marked the beginning of LCA (Curran, 2006). Its origin was ignited by concerns over the limitation of raw materials and energy use, which had created interest in the search for means to cumulatively account for resource use and the possibility to account for future material supplies and use (Curran, 2008). In the United States in 1969, the Coca-Cola Company initiated research to compare beverage containers to determine which container had the minimum releases on the environment and was least affected by the supply of natural resources (Amahmoud et al., 2022; Curran, 2006; Guinée et al., 2011). This study laid the foundation for the current methods of life cycle inventory analysis. It quantified the raw materials and fuels used, and the environmental loadings from the manufacturing processes for each container – ostensibly, the origin of the life cycle inventory study. By the 1970s, other companies in America and Europe had carried out similar comparative life-cycle inventory analyses (Amahmoud et al., 2022; Curran, 2006).

The 1970s saw growth in the standard research methodology or protocol to conduct these studies. This came about due to pressures from growing public interest groups encouraging industry to ensure the accuracy of information in the public domain. The oil crisis around this period further helped to amplify the situation. At this time in the United States, the process of quantifying the resource use and environmental releases of products became known as 'resource and environmental profile analysis' (REPA). In Europe, they called it 'Eco-balance (Amahmoud et al., 2022).

However, from 1975 through the early 1980s, interest in these studies weakened. This was largely due to the fading influence of the oil crisis, and environmental concerns being shifted to issues of hazardous waste and household waste (Curran, 2006). The methodology, however, slowly continued to improve as the European LCA practitioners developed approaches which paralleled those being used in the United States.

By 1988, as solid waste grew to become a worldwide issue, LCA again emerged as a tool for analysing environmental problems (Curran, 2006). As time went by, the interest in all areas affecting resources and the environment continued, prompting further developments in the improvement of the LCA methodology. These comprehensive studies moved from inventory to impact assessment, bringing LCA methodology to another point of evolution.

In 1991, concerns over the inappropriate use of LCAs by product manufacturers to make broad marketing claims, and increased pressure from other environmental Organizations, led to the development of the LCA standards in the International Standards Organization (ISO) 14000 series (1997–2002) (International Organization for Standardization, 2006). The ISO series provides principles and guidelines for evaluating the environmental impacts of products using LCA – the latest version was updated in 2006. Following the introduction of the ISO series, the Life Cycle Initiative was launched in 2002. This was an international partnership spearheaded by the joint initiative of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) (Guinée et al., 2011). The goal of this initiative was to put life cycle thinking into practice and to improve the supporting tools through better data and indicators. Three programs resulted from this initiative: the Life Cycle Management (LCM) program, which aimed to stimulate awareness and improve decision-maker and stakeholder opinions via the production of standardised information materials, international training and forums; the Life Cycle Inventory program, which aimed to improve worldwide access to transparent, high-quality life-cycle data by hosting and facilitating expert groups whose work results in web-based information systems; and the Life Cycle Impact Assessment program, with the initiative to hike the quality and global reach of life-cycle indicators by encouraging interaction among experts wide world whose work results in a set of universally recognised recommendations(Curran, 2006).

- **Purpose and goals of LCA**

Performing an LCA can assist several actions as follows:

a) Identify opportunities to improve the environmental performance of products at various points in their life cycle i.e., from raw material acquisition through production, use, EoL treatment, recycling and final disposal.
b) Analyse the environmental impacts associated with a product/service or process at each stage of their life and inform decision-makers, stakeholders, and government organisations of an acceptable plan of action, for instance strategic planning, priority setting, product or process design or redesign etc.
c) Develop relevant indicators of environmental performance, including measurement techniques. This includes the quantification of environmental releases for each stage of a product or service life cycle.

d) Enable quantification of the environmental sustainability of a product or process. LCA provides an in-depth systematic evaluation of a product, process or service to enable an evaluation of the material consumption of the given item and the overall environmental impacts associated with its consumption.

- **Conducting an LCA**

LCA involves compiling an inventory of inputs and outputs of a product system, then evaluating the potential environmental impacts and interpreting the results to help decision-makers make more informed decisions (Curran, 2006; International Organization for Standardization, 2006). A typical procedure involves four phases:

a) Scope of study and definition phase

The scope of the LCA study and its goals are defined, including the system boundary of the LCA. The level of detail of these elements depends on the subject and the intended use of the study. Therefore, the scope and system boundary of LCA can differ considerably depending on the goal of a particular LCA.

b) The inventory analysis phase

The creation of the Life Cycle Inventory (LCI) involves the compilation and quantification of inputs and outputs for a product throughout its life cycle. The data collected needs to meet the goals of the study. In this case, the REEs consumption at the EoL products using material flow analysis complements the inventory phase. It will quantify REEs consumption in Australia from raw material acquisition to product manufacture and the EoL phase.

c) The impact assessment phase

Life Cycle Impact Assessment (LCIA) involves identifying and evaluating the magnitude and significance of potential environmental impacts associated with a given environmental resource and identified releases using inventory data (International Organization for Standardization, 2006; Navarro & Zhao, 2014; Palle Paul Mejame et al., 2016; Palle Paul Mejame et al., 2020). LCIA is generally performed through classification (i.e., associating inventory data with environmental impact categories) and the characterisation factors from established LCIA methodologies. Examples of established LCIA methodologies include CED (Cumulative Energy Demand), IPCC 2013 GWP 100a (from Intergovernmental Panel on Climate Change), CML (Institute of Environmental Sciences), Eco-indicator 99, ReCiPe and TRACI, which are used to classify environmental impacts into different categories such as global warming, energy use and resource depletion potentials, human health risks, acidification, etc. (Curran, 2006; Curran, 2008; International Organization for Standardization, 2006). The category indicator results can be further normalised, grouped, and weighted to derive a single score of environmental performance. LCIA can be performed using either midpoint or endpoint characterisation factors. Midpoint impact assessment models reflect the relative potential of the stressors at a common midpoint within the cause-effect chain, for instance, global warming potential, while the endpoint reflects the stressor at the endpoint (e.g., damage caused by GHG in terms of flooding, extinction of species etc.) (Curran, 2006; Curran, 2008; Navarro & Zhao, 2014). In this study, environmental impacts from REEs consumption will be assessed using a midpoint. The Heavy Metal Weighting/characterisation factors for life cycle impact-based assessment methodologies will be derived from the eco-invent database using Sima Pro software as a reference point. IPCC 2013 GWP 100a and Cumulative Energy Demand comprise the LCIA methodologies used in this study (see details in the analytical approach section 3.3, Chapter 3).

d) **Interpretation phase**

The final phase of LCA involves analysing and evaluating the findings of the inventory analysis, or impact assessment, in line with the defined goal and scope. This is followed by reaching conclusions, and recommendations and providing input into decision-making.

- **Limitations of an LCA**

Conducting an LCA can be very time-consuming and resource-demanding. Gathering data is typically problematic, and this greatly influences the accuracy and outcome of the research (Curran, 2006). However, there has been gradual progress in this domain, and most LCA-inventory tools can run sensitivity and/or uncertainty analyses. Another increasingly recommended approach to data gathering problems is the integration of LCA indicators with other sustainability assessment tools, such as material flow analysis (as will be applied in this study), life cycle costing etc. In this study, material flow analysis (MFA) is performed in place of the life cycle inventory assessment, with well-determined material flows (import and export of REEs, the material consumption in applications etc). A well-determined material flow minimises the data-gathering issues associated with LCA and improves the robustness of criticality assessments (Laner & Rechberger, 2016). The MFA tool quantifies the inputs and outputs within a system and identifies sources, uses, losses and gaps in the entire material cycle (Brunner & Rechberger, 2016). Integrating LCA indicators with the material flow tool provides the analysis of the material life cycle, allowing for environmental impact assessment, policy and sustainability decision-making (Palle Paul Mejame et al., 2022). Combining these tools offers the potential for consistency and reliable decision support in environmental/resource management (Laner & Rechberger, 2016).

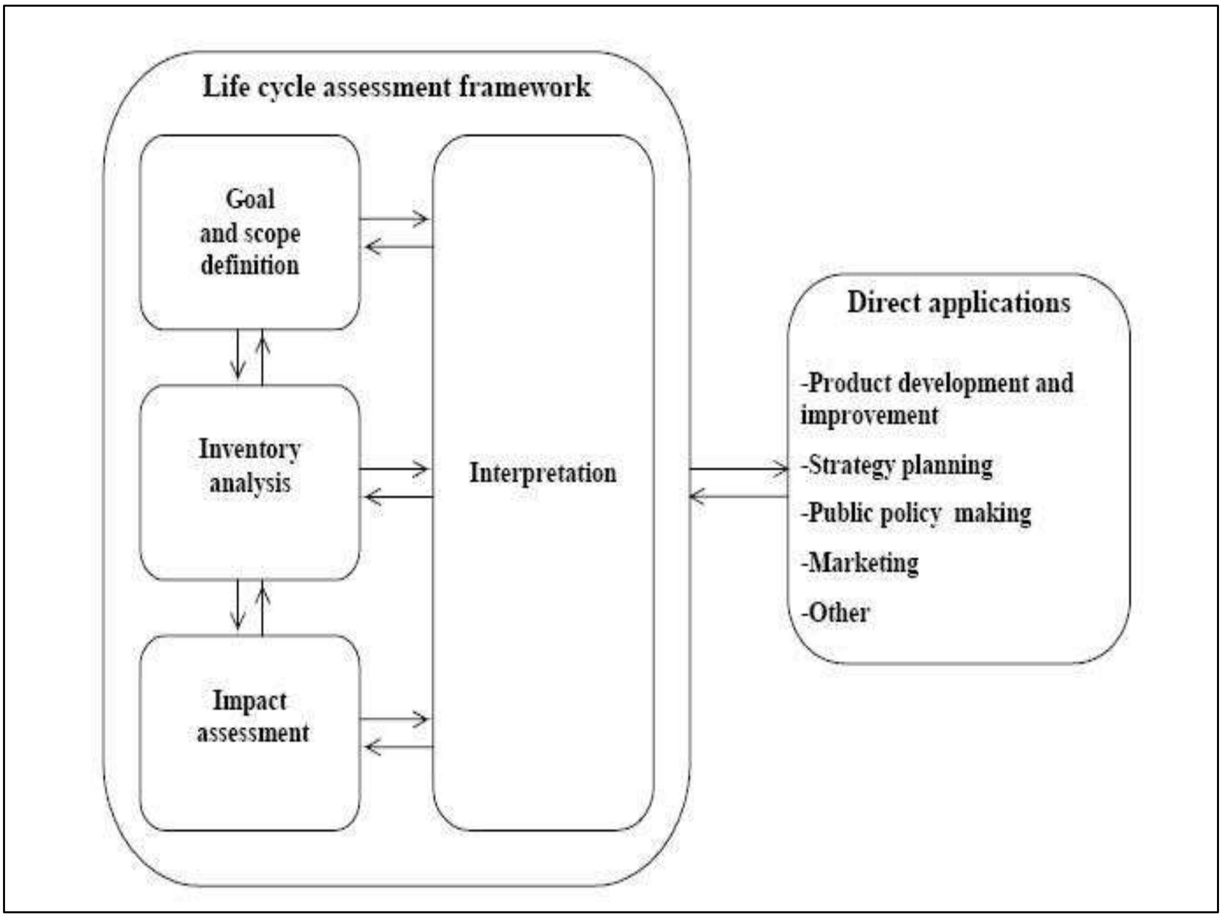


Figure 2.11: Phases of an LCA according to ISO 14040 (1997)

2.7 Literature examining REEs consumption in applications (primary material input assessment)

The measurement of material consumption is the central focus of the material flow analysis concept (Organisation for Economic Co-operation and Development, 2008). Knowing REEs material consumption in applications crucial; it provides the basis to examine the total amount of a particular material used directly in the economy over a given period. This information is paramount as it can then be used to estimate secondary material availability. Material consumption in a single country is defined as the amount of material (in terms of weight) used in an economy, i.e., materials extracted or harvested in the country, plus materials and products imported, minus material and products exported (Organisation for Economic Co-operation and Development, 2008). The materials refer to metals, non-metallic minerals (construction minerals, industrial minerals), biomass (wood, food) and fossil energy carriers. Du & Graedel (2011) relied on data from the US Geological Survey (USGS) regarding mine production and the proportions of individual REEs in the mined ores to estimate the flow of individual REEs into the global economy (Du & Graedel, 2011). Guyonnet et al (2013), using MFA, estimated the flow of individual REEs in Europe by considering import and export statistics from EUROSTAT, REEs consumption in each market sector and the proportions of REEs distribution in the applications manufactured by these sectors (Guyonnet et al., 2013). This approach was used on the basis that Eu-27 consumption of REEs is an open system, as there is no mining activity for REEs in Europe and the economy depends solely on imports. Another similar approach by Goonan (2011) uses REEs consumption in the market sectors in combination with distribution usage in applications to approximate worldwide REEs consumption by end-use sector (Goonan, 2011). The Methodology chapter provides more details on how these approaches were adopted to measure REEs material consumption in Australia.

2.8 Summary: research gaps and questions

Most previous works on REEs have focused either on the politico-economic conflicts over supply and distribution, or the environmental and social impacts of its production, and have not holistically examined this problem as a system (Alonso et al., 2012; Drost & Wang, 2016; Gaustad et al., 2011; Jowitt et al., 2018; McLellan et al., 2014; McLellan et al., 2013; Wang et al., 2017). While the sustainability of REEs has been examined in several papers, including in Australia (Ali et al., 2017; Haque et al., 2014; Klinger, 2018; McLellan et al., 2014; McLellan et al., 2013) assessment of the environmental impacts and the benefits of sustainable consumption in a holistic manner is lacking, particularly regarding improvement in resource efficiency strategies (Klinger, 2018). As such, this study intends to propose a holistic and systematic approach based on the CE model to assess the sustainability of REEs in Australia and to develop a strategy to minimise the adverse impacts of resource shortages, while achieving maximum environmental benefits. This study uses three key metrics to evaluate resource efficiency (Beasley et al., 2014; Mudgal et al., 2012; Organisation for Economic Co-operation and Development, 2015; Science Communication Unit et al., 2012; United Nations Environment Programme, 2010) namely materials use, energy demand and greenhouse gas emissions indicators in a sustainable management framework to assess the sustainable use of REEs in Australia. The main aim is to find efficient strategies to reduce the supply risk impacts of these critical resources and minimise the potential environmental impacts associated with their consumption.

Research Questions

a) How sustainable are current strategies for REEs consumption in Australia? What are the key indicators and how they can be assessed?

b) How might the sustainability of REE consumption in Australia be enhanced?

To answer these questions, the study will employ Material Flow Analysis and Life Cycle Impact Assessment to examine the existing pattern of consumption of REEs, the resource efficiency strategies, and policies governing the REEs industry in Australia, and find strategies to improve the sustainability of REEs consumption in Australia to close the material loop.

Chapter 3: Research Methodology

Chapter Outline

3.1 Introduction

A holistic and systematic approach based on a circular economy (CE) model was used to assess the sustainability of REEs in Australia. Components of the systems approach included (a) an account of the life cycle of resources (REEs) used, (b) a material flow analysis to connect resource use to environmental impacts (through footprints), and (c) the consideration of interactions between humans and the environment. The circular economy model as a systems approach aimed at zero waste and an in-depth understanding of the full circulation of REEs materials, from resource extraction, through manufacturing, and reuse to EoL disposal, and environmental burdens. To achieve this goal, the study applied Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA) tools within a sustainable management framework to quantify and assess the flows and determine the impacts of REEs consumption in Australia. This provides an understanding of the potential environmental impacts associated with the use of these critical natural resources and the benefits of resource efficiency.

Certain REEs were targeted as a case study throughout the course of this investigation. MFA was used to quantify and examine REEs material resource usage from extraction through to EoL, while LCIA served as the tool to determine the lifecycle-based environmental impact of the material using characterisation factors obtained from ecoinvent. This information is significant as a background for environmental impacts assessment, policy and decision-making for socio-economic benefits.

The potential environmental impacts were assessed using three key metrics in a sustainable development framework - materials use, energy demand, and greenhouse gas emissions - indicators to evaluate REEs material resource use. Other resource use indicators include land use and water, which are beyond the scope of this study. Using these metrics (material use, energy demand and greenhouse emissions), a material resource (REEs) use assessment, and the derived environmental impact and impact reduction, were modelled into three steps:

- Firstly, the study examined the existing sustainability patterns governing REEs consumption in Australia and the associated environmental impact using IPCC 2013 GWP 100a and CED midpoint impact assessment methods.
- Secondly, to improve the sustainability outcome of REEs in Australia, the study applied CE strategies to assess the secondary material inputs of these metals and the derived environmental impacts using the same impact methods mentioned above. This step aimed to promote CE as a sustainable management strategy that can be used to

achieve improvements in resource efficiency and decouple natural resource use from economic progress.

- The final step involved an assessment of the environmental benefits associated with sustainable consumption and production patterns through life cycle environmental impact reduction. The aim of the final step was to highlight the differences between primary and secondary material consumption patterns through system comparison.

The end goal of this approach was to evaluate existing resource efficiency strategies for REEs and make recommendations to improve sustainability outcomes in Australia, find potential mitigation approaches to transform resource use in ways that minimise environmental impacts, and improve society-wellbeing through the enhancement of resource efficiency strategies via sustainable production and consumption patterns. Figure 3.1 below presents a general overview of the methodological framework of this study.

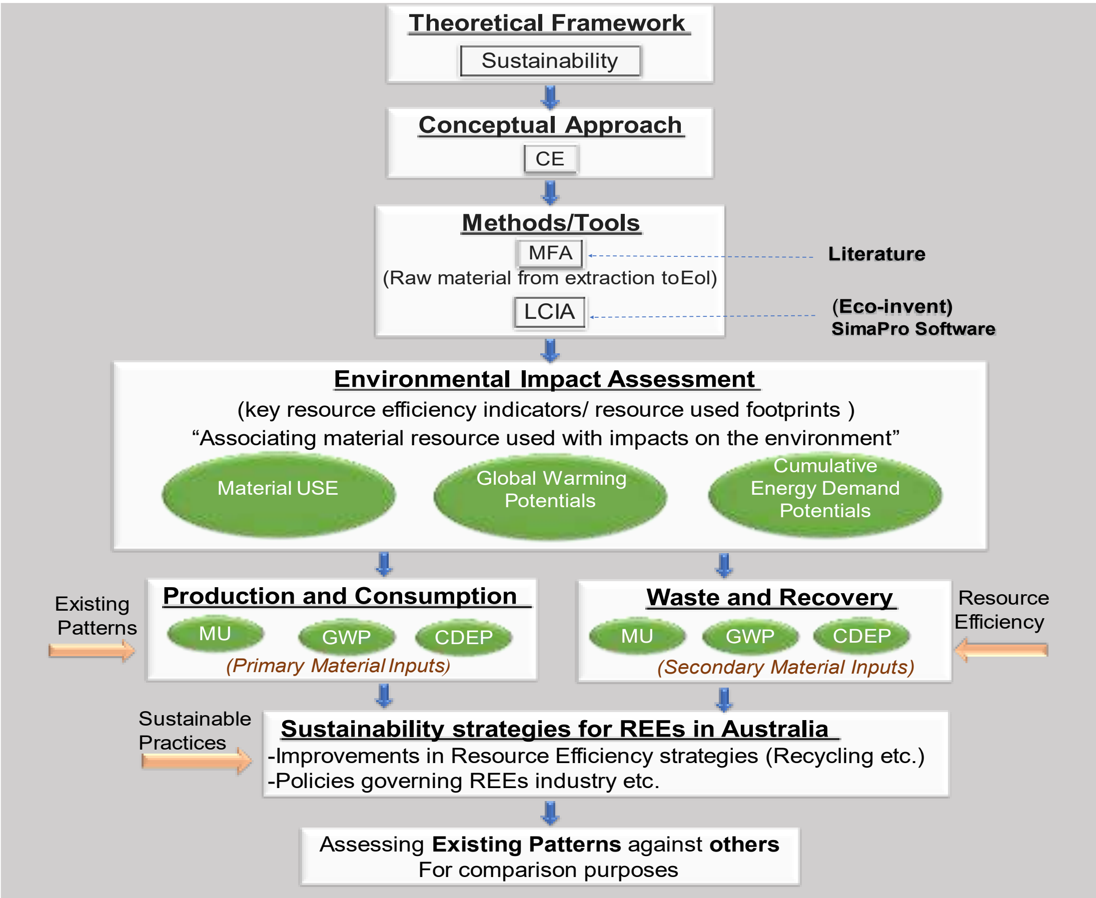


Figure 3.1: General overview of the methodological framework showing the theoretical and conceptual approach, tools and expected outcomes.[1]

[1] Note. CE: Circular Economy, MFA: Material Flow Analysis, LCIA: Life cycle Impact Assessment, MU: Material use, GWP: Global Warming Potentials, CDEP: Cumulative Energy Demand Potentials.

Figure 3.1 illustrates MFA as a tool used to compile REEs data (material resource use) from extraction through to EoL, while LCIA is the tool to determine the impact of this resource use on the environment. The green bubbles represent resource use and environmental indicators identified in this study for material use life cycle environmental impact analysis.

3.2 Data Sources

First, desktop research was conducted to gather information about the current reserves, production, consumption, applications, and recovery rates of REEs in Australia, as well as the Life Cycle Impact Assessment methods that can be applied to REEs. Data were sourced from the literature, including academic papers, company annual reports and governmental reports. Life cycle impact assessment methodologies (IPCC 2013 GWP 100a, CED) were identified and the characterisation factors for impact assessment of REEs material use in ecoinvent. Table 3.1 below presents data sources, types, and a summary of uses.

CE tools	Data content	A brief definition of analytical data purpose for this study	Databases/Sources 2017-2019 (2019 as the base year)	Links
MFA	REEs reserves	This information serves as part of the inventory data to help understand the whole system of resource use and what decision-making policy to direct towards sustainable production and consumption	Geoscience Australia database	https://www.ga.gov.au/data-pubs
			US. Geological Survey data	https://www.usgs.gov/centers/national-minerals-information-center/international-minerals-statistics-and-information
	REEs production/Import and export	The information serves as part of the inventory data to assess total material primary material inputs for life cycle impact analysis	Geoscience Australia database	https://www.ga.gov.au/data-pubs
			USGS Geological Survey database	https://www.usgs.gov/centers/national-minerals-information-center/international-minerals-statistics-and-information
			British Geological Survey database	https://www.bgs.ac.uk/geological-data/
		It helps to illustrate which areas to target to reduce impacts in the production process and where to implement strategies to enhance resource efficiency	UNEP/International Resource Panel Material use database that covers almost 191 countries since 1970	https://www.resourcepanel.org/global-material-flows-database
			WITS export/import database	https://wits.worldbank.org/Default.aspx?lang=en
	REEs applications	The information serves as part of the inventory data to identify REEs end-use sectors	Geoscience Australia annual resource reports, Rare-Earth Australia annual publications and reports, Academic papers from literature review, Australia REEs companies' annual reports and publications	References in text
	REEs consumption in applications	This information serves as part of the inventory data to determine total material consumption in applications and the potential impacts using LCIA	Academic papers from literature review, Australian REEs companies' annual reports and publications	References in text
		It helps to illustrate which areas to target to reduce impacts in manufacturing processes and where to implement strategies to enhance resource efficiency		
	REEs recycling rate	This information serves as inventory data that helps to examine the existing consumption pattern of these resources and provides a platform where policies can be implemented to enhance sustainable consumption and production	Academic papers from literature review, Australian REEs companies' annual reports and publications	References in text
LCIA	Life cycle Impact Assessment methodologies (IPCC 2013 GWP 100a, CED)	They serve as a weighting factor in LCIA to determine the environmental impacts of REEs consumption	Eco-invent database, Version 3.7.1	https://ecoinvent.org/
		This helps to locate the impacts and target the areas where improvements can be made to increase environmental and societal benefits		
	Software-Sima Pro	Serves as a source for Eco-invent		

Table 3.1: List of main data sources: data types and a summary of the purpose of this study

Data were sourced from Australian and international institutions that have established databases for raw materials, such as Geoscience Australia, Lynas Corporation annual reports, UNEP International Resource Panel (IRP), and US Geological Survey (USGS) among others (Huleatt, 2019; International Resource Panel-UNEP, 2018; Lynas Rare Earths Ltd, 2010; U.S. Geological Survey, 2020). The collection of this data set enabled the assessment of REEs material flows (using MFA), from extraction through to the EoL of REEs. These flows served as the input (inventory data) to determine the environmental impacts derived from the consumption of these metals.

The USGS is the most common database source for minerals internationally. The report includes sections on government policies and programs, environmental issues, trade and production data, industry structure and ownership, commodity sector developments, infrastructure, and a summary outlook (U.S. Geological Survey, 2020). The annual publication on mineral commodities, published 2020, provided timely statistical data on REEs production and reserves in Australia for the year 2019. The same data source was cited in Australian Resource Reviews: Rare earth elements 2019 by Geoscience Australia (Huleatt, 2019). As seen in Table 3.1, this data served as part of the inventory data for primary material input for life cycle impact analysis.

WITS is software with databases developed by World Bank in collaboration with the United Nations Conference on Trade and Development (UNCTAD) and other organisations such as the International Trade Center (ITC), United Nations Statistical Division (UNSD) and the World Trade Organization (WTO). The WITS software databases allow users to access and retrieve information on trade and tariffs. The UNSD Commodity Trade (UN Comtrade) database like the WTO's Integrated Data Base (IDB) contains merchandise trade exports and imports by detailed commodity and partner country data. WITS permits users to browse the country profile section to obtain exports, imports and tariff statistics for countries, along with relevant development data. The export and import data of Australia’s REEs from WITS served as part of the inventory data for primary material inputs for cycle impact analysis as seen in Table 3.1.

Sima Pro is a professional tool to collect, analyse and monitor the sustainability performance data of products and services (PRé Consultants, 2010). The software can be used for sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators. Sima Pro allows users to see the entire supply network of a product and provides total insight into databases and unit processes. SimaPro software version 9.1.1 was used in this study to access the life cycle assessment database ecoinvent, which was used for the life cycle assessment impact for this study. Sima Pro has the capability to conduct LCA studies in the software using existing databases, or export the LCIA data into other third-party tools to conduct the analysis. The LCIA data (IPCC 2013 GWP 100a and CED) for this study obtained from the existing ecoinvent database in Sima Pro were exported to Microsoft Excel software to facilitate simulations and the use of aggregated Life Cycle Inventory (LCI) dataset from the material flow mentioned above to perform Life Cycle Impact Assessment.

Ecoinvent is a world leading LCI database that contains different LCIA datasets that can be accessed via third-party reseller software such as Sima Pro or directly from the database (Wernet et al., 2016). Ecoinvent is used in a range of environmental studies including Life Cycle Assessment (LCA) studies, Design for Environmental or Carbon Footprinting applications (Arshi et al., 2018; Haque et al., 2014; Koltun & Tharumarajah, 2014; Navarro & Zhao, 2014; Sprecher et al., 2014; Zaimes et al., 2015). Ecoinvent uses established LCIA methodologies that include IPCC 2013 GWP 100a (from Intergovernmental Panel on Climate Change), CED (Cumulative Energy Demand), CML (Institute of Environmental Sciences), Eco-indicator 99, ReCiPe and TRACI. These methodologies are used to classify environmental impacts into different categories such as global warming, energy use and resource depletion potentials, human health risks, acidification, etc. (Curran, 2006; Curran, 2008; International Organization for Standardization, 2006).

IPCC 2013 GWP 100a and CED in ecoinvent version 3.7.1 were the LCIA methodologies used in this study to determine the environmental impact of REEs material consumption in Australia (for global warming and cumulative energy demand potentials respectively). These are both standard established LCIA methodologies for impact assessment (Arshi et al., 2018; Haque et al., 2014; Koltun & Tharumarajah, 2014; Navarro & Zhao, 2014; Sprecher et al., 2014; Zaimes et al., 2015). The LCIA dataset (IPCC 2013 GWP 100a and CED) starts with REEs concentrates leaving the gate of the producing entity, ready for distribution to using entities; in other words, from the cradle, including all upstream activities. It includes estimates for average transport requirements from producing to using the entity (Wernet et al., 2016). More details are provided in section 3.3.2 on how these LCIA methodologies in ecoinvent were applied to determine environmental impacts associated with REEs material use in Australia.

3.3 Analytical approach: Material use and Life cycle impact assessment of REEs consumption in Australia

Three metrics were used to identify the environmental impacts associated with REEs consumption: material use, greenhouse gas emissions and energy demand. The system boundary was divided into four stages: (a) production, (b) consumption of REEs in applications (c) waste and (d) recovery in Australia (see Figure 2). These four main stages represent two main categories: primary and secondary material inputs. Primary material inputs indicate virgin sources into the system, while secondary material inputs include waste and recoveries, as illustrated on the system boundary material flowsheet (See Figure 3.2).

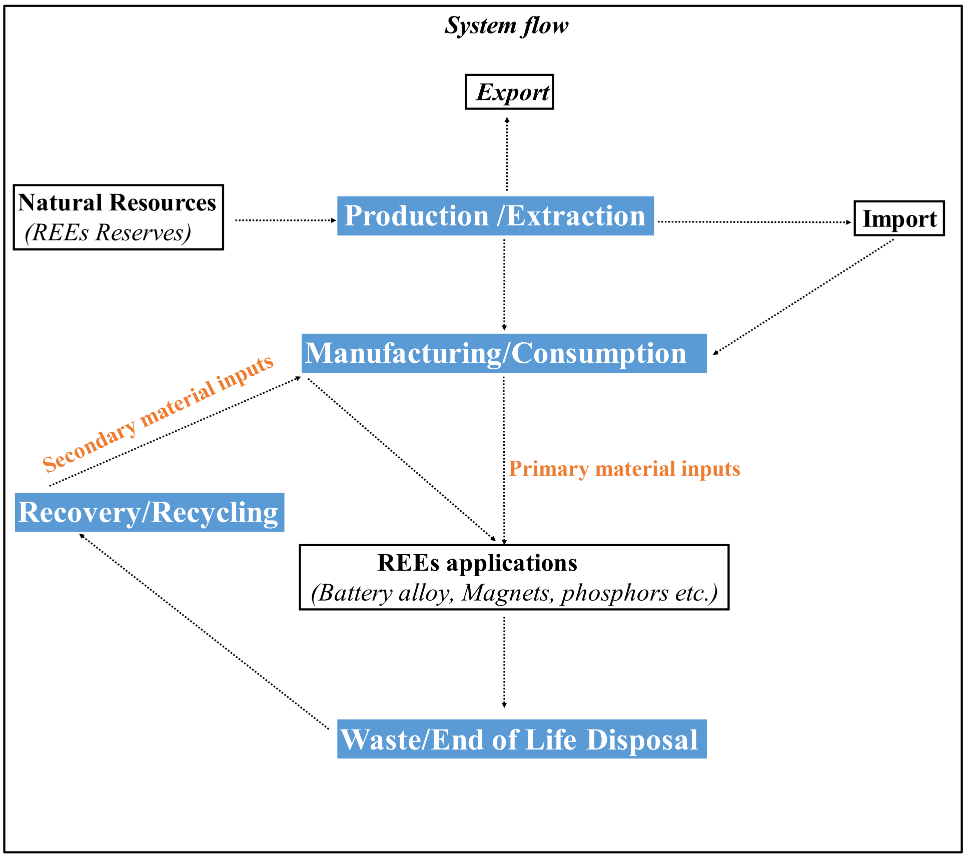


Figure 3.2: System boundary flowsheet

First, the years 2017, 2018 and 2019 were selected as the timeframe for the development of patterns to compare trends in REEs consumption and the applications over recent years. To proceed, as a case study, this research used 2019 as the base year because it contained the most up-to-date information at the time of the study. Moreover, the following two years saw significant economic disruption in all parts of the globe as a result of restrictions imposed due to the COVID-19 pandemic. However, the same simulation can be run for any given year to assess material use and the associated environmental impact, as the goal of this study was to develop a sustainable management framework that can be used to assess resource use and impact over a given period. The functional unit for this study was 1 kilotonne REE.

In this research, five REEs – Neodymium (Nd), Dysprosium (Dy), Europium (Eu), Yttrium(Y), Terbium (Tr) – were selected based on their economic viability, criticality index, and supply risk; in the medium term, the selected REEs are more critical in terms of supply risks, economic importance in green economic growth (higher demand in applications), and availability in other parts of the globe (Bauer et al., 2010; Bauer et al., 2011; European Commission, 2017). Figure 3.3 below provides a schematic summary of the analytical approach used in this study.

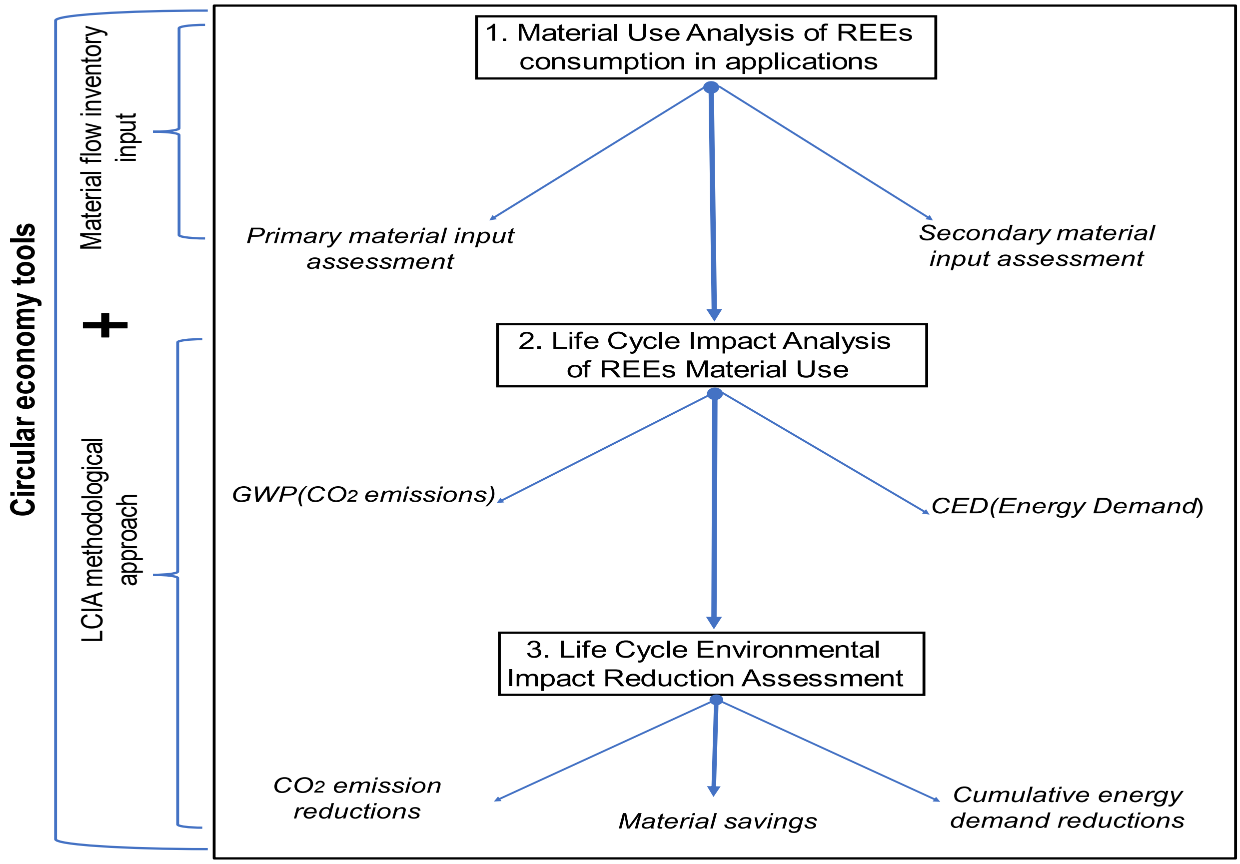


Figure 3.3: Schematic presentation of the analytical framework for material use and life cycle impact assessment of REEs consumption in Australia. [2]

[2] *(Metric 1) _Material use analysis of REEs consumption in applications was analysed in terms of primary and secondary material inputs. (Metric 2-3) _The results served as life cycle inventory inputs to determine the environmental impacts of REEs consumption using IPCC 2013 GWP 100a and CED impact assessment methodologies derived from ecoinvent detailed in sections (3.3.1-3.3.3) below.*

3.3.1 Material Use Analysis

Material use assessment measures the material consumption of a given resource in an economy across the entire supply chain (Organisation for Economic Co-operation and Development, 2008). It was used in this study to assess both primary and secondary material consumption of REEs in applications across Australia, as exemplified in sections 3.3.1.1 and 3.3.1.2 respectively. The pattern in which materials are used in production and consumption in a system reflects on the waste flows and emissions that are an unavoidable consequence of the material cycle (International Resource Panel, 2017). Material use assessment is an essential aspect of sustainable resource management as it can be used to provide information on the environmental impacts across the entire material cycle of a resource (covering aspects such as energy use, air pollution, resource depletion, human health, etc.), and it is a good tool for evidence-based policymaking (International Resource Panel, 2017). Key studies that have applied material use to assess resource consumption include Beasley et al. (2014), Behrens et al. (2015), Ekins et al. (2017), Grimes et al. (2008), International Resource Panel (2017), International Resource Panel (2018), International Resource Panel (2019), Mudgal et al. (2012), Organisation for Economic Co-operation and Development (2008), Organisation for Economic Co-operation and Development (2015).

To evaluate the material use of REEs in applications for a given period, information from metal consumption in applications and the recovery rate were used. The information enabled the analysis of the metal recovery rate from EoL products and the recycling efficiency of REEs (see section 3.3.2).

3.3.1.1 Step 1: Assessment of REEs Consumption in applications (primary material inputs)

The measurement of material consumption is the central focus of the material flow analysis concept (Organisation for Economic Co-operation and Development, 2008). REEs material consumption in applications shows the total amount of material used in the economy over a given period, which was used to estimate secondary material availability. Material consumption in any given country is defined as the net amount of material (by weight) used in an economy, i.e., materials extracted in the country, plus materials and products imported, minus material and products exported (Organisation for Economic Co-operation and Development, 2008).

In this study, the consumption of selected rare earth elements (REEs) in Australia was estimated by first calculating the proportions of these elements found in different applications. These proportions were derived from a study by Binnemans et al. (2013). The annual mine production of REEs in Australia was then obtained from the USGS and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020). Finaly, export and import statistics were obtained from the WITS database (WITS, 2019).

- REEs primary material consumption in application =
  (Material extracted + Import- Export * Material consumption % estimate in applications)

The percentage of individual REEs consumption distribution in applications has been used in several studies (Binnemans et al., 2013; Goonan, 2011; Guyonnet et al., 2015; Jordens et al., 2013) to estimate REEs consumption.

3.3.1.2 Step 2: Assessment of REEs secondary material consumption in applications (recycling potentials)

Recycling potential is defined as the amount of an embodied element that could be returned to material streams (in the form of refined metal and contained in reused parts) where its properties are utilised again functionally (Xu et al., 2019). In this study, the term recycling potential will be used interchangeably with secondary material input. The estimated recycling potential is calculated by multiplication of the EoL Recycling Rate (EoLRR) with estimated REEs old scrap i.e., material content in EoL products available for recycling (Binnemans et al., 2013; Norgate, 2013). This approach is feasible for this study as the EoLRR refers to the efficiency with which materials in EoL products are collected, pre-treated, and recycled (International Resource Panel, 2011). The EoLRR is strongly influenced by the least efficient step in the recycling chain, which is typically the initial collection activity, as is the case in Australia. The EoLRR of a metal is determined by considering its consumption and the efficiency of its recovery, which depends on factors such as technological advancement, or waste collection systems.

The EoLRR approach is significant as it compares the quantity of metal acquired from recycling with the amount theoretically available at the end of the life of products. The rate depends on the efficiency of the metal collection (collection system), the efficiency of the recycling process and technology (International Resource Panel, 2011). EoLRR results from the multiplication of the collection rate and the recycling process efficiency rate (Binnemans et al., 2013; International Resource Panel, 2011; Norgate, 2013). The EoLRR for REEs for this study was calculated as shown below, adopted from International Resource Panel (2011); a similar approach has been used by IRP (2011), Norgate (2013) and Binnemans et al (2013) to estimate the global EoLRR for REEs.

$$\mathbf{EoLRR}\boldsymbol{i} = \mathrm{CR}i\ (\%) * \mathrm{RPE}i(\%)$$

Where:

- **EoLRRi** = EoL recycling rate of a given metal i
- **CRi** = Collection rate (Gross consumption) of a given metal i
- **RPEi** = Recycling process efficiency also known as recovery efficiency rate of a given metal i

Two main assumptions using EoLRR were applied:

a) As a desirable sustainable scenario, all material at EoL should be returned to the system 100%. This assumption underlines the key concept in the CE model, which emphasises a regenerative, closed-loop system, and which also implies a complete recirculation of material within the system (i.e., zero-waste system) – nothing should be considered waste.

b) The recycling processing efficiency was considered 55%. The recycling processing efficiency rate was based on the current recycling technology or e-wastes in Australia, since the majority of EoL products containing REEs are found in the e-waste stream (Dias et al., 2018; Islam & Huda, 2019). The current recycling process efficiency for e-waste in Australia is limited to first-stage recycling, which entails the dismantling, shredding and sorting of electronic devices into parts and materials, such as glass, metals, plastics, batteries, and printed circuit boards (Dias et al., 2018; Islam & Huda, 2019). The separated recyclables are exported to specialised facilities, usually abroad, for downstream recycling (Dias et al., 2018; Islam & Huda, 2019). Though recycling process efficiency can be high it can never reach 100% due to thermodynamics and other limitations (Castro et al., 2004; International Resource Panel, 2011).

3.3.2 Life cycle impact assessment of material use

3.3.2.1 Global Warming Potential (GWP) Assessment

The life cycle impact assessment of material use was performed in terms of Global Warming Potential (GWP) using IPCC 2013 GWP 100a methods. The GWP was used to assess CO_2 emissions potential from primary and secondary material consumption of REEs in applications. CO_2 emission weighting factors were derived from IPCC 2013 GWP 100a in ecoinvent from primary material inputs. REEs primary and secondary material consumption in applications were used to determine CO_2 potentials from secondary material inputs. The information from the CO_2 emission potential assessment is significant to analyse recycling emission reduction potential (RERP) (see section 3.3.3.1).

- **CO_2 emission potential assessment**

The environmental impacts associated with the primary and secondary material consumption of REEs in applications were analysed in terms of CO_2 emissions potential. The impacts associated with these metals were evaluated in terms of impact categories. The impact of global warming potential was determined by accumulating the emissions of all greenhouse gases, each expressed in metric tonnes of carbon dioxide equivalents (tonne CO_2-eq) calculated from their relative global warming potential (GWP).

Emission potential for the primary material and secondary material inputs were determined by multiplying the characterisation factors derived from the IPPC 2013 mid-point impact assessment methods in eco-invent with the various individual material consumption inputs respectively as summarised in the life cycle formula below:

$$\mathbf{EP}\boldsymbol{i} = \mathrm{M}i * \mathrm{Wf}i$$

Where:

- **EPi** = CO_2 emission potential of metal i
- **Mi** = Metal i consumed in application(inputs)
- **WFi** = LCIA weighing or characterisation factor for metal i

The production stage accounts for the emissions associated with the extraction of a particular REE. This includes emissions from the mining or extraction, processing and transportation of the material inputs. The consumption stage accounts for the emissions associated with the use of the material or transformation into a usable product. The EoL stage includes materials recycled, and so accounts for CO_2 emission from the recovery of secondary material. By closing the loop, we considered recycling as the only EoL option. The goal is to eliminate landfill processes as much as possible by implementing material circularity (CE). If this is achieved, not only will CO_2 emissions decline but energy and materials can be saved and recovered.

3.3.2.2 Cumulative Energy Demand Potential Assessment (CEDP)

The CEDP assessment metric aims to assess and compare the energy used during primary material and secondary material inputs of selected REEs in product production. The cumulative energy demand characterisation factor derived from the CED mid-point impact assessment methods in Eco-invent combined with selected REEs mine production, consumption and recycled data was used to determine energy demand potentials from primary and secondary material inputs. The result is significant to determine Cumulative Energy Demand Reduction Potentials using simple mathematical approaches (See section 3.3.3.2). This, in turn, also provided the basis to evaluate the benefits associated with recycling efficiency as a CE strategy for sustainable development.

- **Energy Demand Potential Assessment**

In this study, the method to calculate energy demand was based on the CED mid-point impact assessment methods through characterisation factors derived from Eco-invent. CED is based on non-renewable, fossil characterisation factors. The impact of the Cumulative Energy Demand was determined by summing up all the gross energy demand, each expressed in metric tonnes of gigajoule equivalents (GJ-eq./yr./1kilotonne), calculated from their cumulative energy demand potential (CEDP).

Energy demand potential from primary material and secondary material inputs were determined by multiplying the characterisation factor by the various individual material inputs respectively. This life cycle formula is summarised below:

$$CEDP_i = M_i * Wf_i$$

Where:

- **CEDPi** = Cumulative Energy Demand Potential of metal i
- **Mi** = Metal i consumed in application(inputs)
- **WFi** = Weighing or characterisation factor for metal i

This method describes a production stage that includes the energy use associated with the extraction of a particular material. This includes energy used from the mining or extraction, processing, and transportation of the material inputs. The use stage accounts for the energy required to use the material or transform it into a usable product, and the EoL stage includes energy used from material recycled.

3.3.3 Life cycle environmental impact reduction analysis

3.3.3.1 Recycling Emission Reduction Potential Assessment (RERP)

The benefits associated with resource efficiency strategies such as recycling include material and energy savings and the reduction of greenhouse gas emissions (Camilleri, 2018; Camilleri, 2019; International Resource Panel, 2017; United Nations Environment Programme, 2019) such as CO_2, the component considered in this study. GHG emission reduction factors have been designed to encourage recycling in line with climate change policies and are generally based on relative emission reduction benefits (United State Environmental Protection Agency, 2011b). GHG emission benefits from recycling are determined by comparing virgin material manufacturing with recycled material (Grimes et al., 2008; United State Environmental Protection Agency, 2011). The life-cycle approach is used to express avoided emissions from manufacturing using recyclables, the use of raw materials in the manufacturing process, transportation emissions, and recycling efficiency. For this study, the recycling emission reduction potential for REEs material use was determined using the following life cycle approach adapted from EPA (2011). The original approach intended to include Transportation emission reduction potential, which was omitted in this study due to a lack of avaialble data on nationwide waste transportation routes of EoL products containing these metals.

$$\textbf{RERP} = (\text{Ms Virgin} - \text{Ms recycled}) * \text{RE}$$

Source; adapted and modified from EPA, (2011)

Where:

- **RERP** = Recycling Emission Reduction Potential
- **Ms virgin =** emissions associated with using a (%) of input for manufacturing the material (kt CO_2-eq. of material)
- **Ms recycled =** emissions associated with using a given (%) of recycled material (kt CO_2-eq. of material)
- **RE =** Recycling Efficiency

Improving the recycling efficiency of REEs for sustainable consumption is an important aspect of this study. Recycling materials are not fully recovered at a recycling facility (United State Environmental Protection Agency, 2011). To be able to account for collection and use inefficiencies, a material-specific recycling efficiency factor needs to be applied to the recycling emission reduction potential (United State Environmental Protection Agency, 2011). Recycling Efficiency (RE) equals the fraction of gross material demand from tonnes of recycled material (United State Environmental Protection Agency, 2011). RE was determined using the following method:

$$\textbf{RE} = \frac{\text{Recycling today}}{\text{Gross demand today}}$$

Where:

- **Recyclin today=** Current levels of supply from recycling
- **Gross today =** Current gross metal demand

In summary, RE measures the efficiency of collecting, pre-treating and recycling EoL metal as well as new scrap (United State Environmental Protection Agency, 2011). It shows the efficiency of the collection and recycling process throughout the life cycle of metals and the technological efficiency used. It provides a good indication of the total losses at a global level (United State Environmental Protection Agency, 2011).

3.3.3.2 Recycling Energy Demand Reduction Potential (REDRP)Assessment

This method quantifies the material-specific cumulative energy demand potential reduction benefits associated with recycling and incorporates avoided energy use from manufacturing using recyclables, the use of raw materials in the manufacturing process, and recycling efficiency. The formula was adapted from United State Environmental Protection Agency, (2011) method for estimating Green House Gas emission reduction from recycling. The original method quantified avoided emissions from manufacturing using recyclables, the use of raw materials in the manufacturing process, and recycling efficiency.

$$\textbf{REDRP} = (\text{Ms Virgin} - \text{Ms recycled}) * \text{RE}$$

Where:

- Recycling Energy Demand Reduction Potential (REDRP)
- Ms virgin = energy used associated with using a given amount (%) of input for manufacturing the material (GJ-eq./yr./1kilotonne of material)
- Ms recycled= energy used associated with using a given amount (%) of recycled materials (GJ-eq./yr./kilotonne of material)
- RE= Recycling Efficiency

In summary, the goal of this investigation, to be presented in the upcoming chapters, is to assess the existing resource efficiency strategies in REEs and make recommendations to improve sustainability outcomes in Australia. To identify sustainable mitigation and implementation strategies that can be used to improve this current pattern of REEs consumption in Australia in a way that reduces pressures on the environment and climate while promoting human and economic growth.

Chapter 4 (Results 1): Primary Material Input Assessment: Cumulative Energy Demand and Global Warming Potential of REEs in Australia

Chapter outline

4.1 Introduction

This chapter is the first describing the results of a holistic and systemic approach to examining the existing sustainability patterns of consumption of REEs in Australia, and their environmental impacts. A material flow analysis (MFA) was combined with a life cycle impact assessment (LCIA) to evaluate and determine the impacts associated with these economic activities. This provided the grounds to quantify and assess the flows and consumption of REEs in the various end-use sectors. These are two popular circular economy (CE) tools commonly used in sustainability and environmental impact assessment. In this study, the MFA was used to compile and analyse data about REEs, from raw material through to end-of-life (EoL), while LCIA was used to analyse the material life cycle, allowing for environmental impact assessment, and policy and sustainability decision-making. In other words, MFA serves as the tool for recording materials and energy flow entering and leaving the system, thus representing the perfect life cycle inventory (LCI) for an impact assessment.

To link material resource use and the associated impacts, the environmental life cycle impact assessment was carried out using three key sustainability metrics: Material Use, Global Warming Potential and Cumulative Energy Demand. This is an approach also known in sustainability studies as Drivers-Pressures-State-Impacts-Response (DPSIR) (International Resource Panel, 2017). The result of this analysis will identify which areas in the entire REEs life cycle need to be targeted to improve consumption and production in Australia, in a way that reduces pressures on the environment and climate change. The goal is to connect economic activities to impacts on the environment, as a whole, with the end goal to promote society's response to target these driving forces to reduce impacts (International Resource Panel, 2017). See Figure 4.1 for a summary of the entire material life cycle flow for REEs, depicting existing trends of REEs consumption and production patterns in Australia.

REEs are the most important group of critical minerals, as indicated on the material criticality sheet described in Figure 2.6. However, some are considered more critically important than others (Bauer et al., 2011; Binnemans et al., 2013). To raise focus on specific minerals that are of greater concern to green economic growth and sustainability, five out of the seventeen REEs were selected using the identified critical material matrix described in Figure 2.7 and Figure 2.8. The critical material index initiative was a response to address the criticality aspect of certain metals and their importance to green economy growth developed by expert panels, government agencies and international research institutes (Bauer et al., 2010; Bauer et al., 2011; European Commission, 2017).

Before moving to the main results, firstly, this study will look at the existing consumption and production patterns of REEs in Australia over three years 2017, 2018 and 2019. This pattern will provide the basis to compare trends in REEs use and application. The main results will be divided into three main sections: (1) material use assessment of the selected critical REEs over a given year, which examines the consumption of primary material inputs in the economy, (2) Global Warming Potential of the selected critical REEs, which examines CO_2 emissions resulting from the primary material consumption and (3) finally Cumulative Energy Demand Potential of selected critical REEs, which reveals the environmental impact of energy consumption associated with the primary material used.

4.2 Existing consumption and production patterns of REEs in Australia

4.2.1 REEs consumption and production pattern: Life cycle material flows

Figure 4.1 below presents a general overview of the existing consumption and production patterns of REEs in Australia.

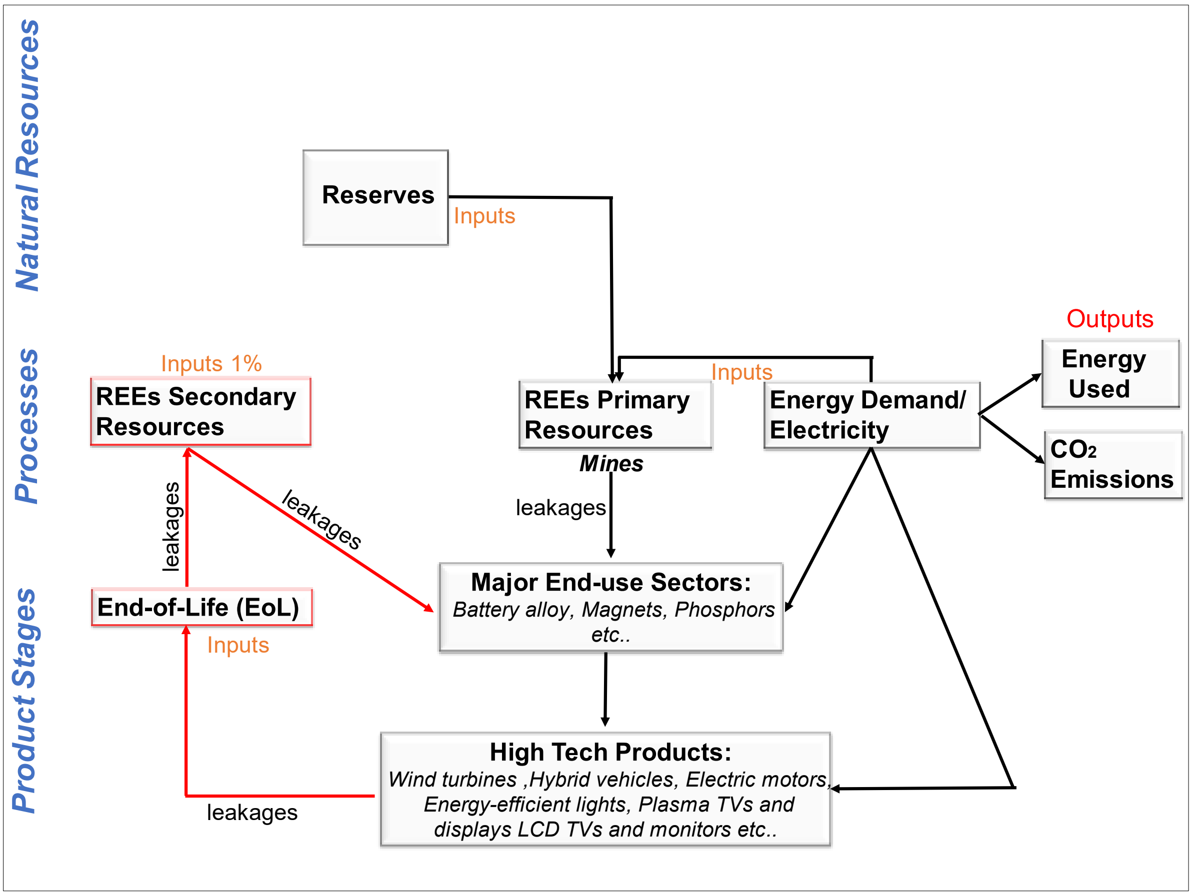


Figure 4.1: Summary of the whole REEs material life-cycle flow system.

Note: Leakages refer to a loss of materials through the export of EoL products abroad or in the landfill; inputs refer to the introduction of materials into the system directly from primary material sources (e.g., mines) or secondary (e.g., recycling, mining wastes/by-products). Outputs refer to impacts on the environment associated with the various economic activities (inputs). Red arrows indicate the phases of the life cycle material flows with significant sustainability attention. The black arrows are the existing trends or patterns of life cycle material flows of REEs consumption in Australia.

Recycling (input from secondary materials) is currently limited to 1%, mostly from magnet scrap (Australia Trade and Investment Commission, 2019; Haque et al., 2014). This means that the system is highly dependent on primary materials. The major aim of this chapter is to measure economic activities (inputs) and examine the impacts (outputs) associated with these activities.

The life cycle material analysis of the existing production and consumption pattern of REEs in Australia is characterised by what the Ellen MacArthur Foundation (2017) deems as the traditional, 'take-make-waste extractive industrial model'. Based on this analysis, as illustrated in Figure 4.1, the consumption of REEs is based on primary material sources with little to no input from secondary sources. Australia, similar to the rest of the world, currently has a very low recycling potential of REEs from EoL products (Drost & Wang, 2016; Haque et al., 2014; Jowitt et al., 2018).

4.2.2 Trends in critical REEs consumption and application

The trend of REE consumption in applications is presented in the table below. The years 2017, 2018 and 2019 were chosen as the timeframe to enable an analysis of REEs consumption in applications in Australia over a different period.

Critical REEs consumption distribution estimates 2017						
Application	Nd	Dy	Eu	Y	Tb	Gross consumption
Magnets	13.2	1.0	-	-	0.04	14.2
Battery Alloy	1.9	-	-	-	-	1.9
Metallurgy	3.1	-	-	-	-	3.1
Auto Catalysts	0.6	-	-	-	-	0.6
Glass Additives	0.6	-	-	0.4		1.0
Phosphors	-	-	0.9	13.1	0.9	15.0
Ceramics	2.3	-	-	10.1		12.4
Others	2.9	-	-	3.6		6.5
Gross consumption	**24.5**	**1.0**	**0.9**	**27.2**	**0.9**	**54.5**
Critical REEs consumption distribution estimates 2018						
Application	Nd	Dy	Eu	Y	Tb	Gross consumption
Magnets	13.9	1.0	-	-	0.04	14.9
Battery Alloy	2.0	-	-	-	-	2.0
Metallurgy	3.3	-	-	-	-	3.3
Auto Catalysts	0.6	-	-	-	-	0.6
Glass Additives	0.6	-	-	0.4	-	1.0
Phosphors	-	-	1.0	13.8	0.9	15.7
Ceramics	2.4	-	-	10.6	-	13.0
Others	3.0	-	-	3.8	-	6.8
Gross consumption	**25.8**	**1.0**	**1.0**	**28.6**	**1.0**	**57.3**
Critical REEs consumption distribution estimates 2019						
Application	Nd	Dy	Eu	Y	Tb	Gross consumption
Magnets	14.7	1.1	-	-	0.04	15.8
Battery Alloy	2.1	-	-	-	-	2.1
Metallurgy	3.5	-	-	-	-	3.5
Auto Catalysts	0.6	-	-	-	-	0.6
Glass Additives	0.6	-	-	0.4	-	1.1
Phosphors	-	-	1.0	14.6	1.0	16.6
Ceramics	2.5	-	-	11.2	-	13.7
Others	3.2	-	-	4.0	-	7.2
Gross consumption	**27.2**	**1.1**	**1.0**	**30.3**	**1.0**	**60.6**

Table 4.1: Australia's critical REEs consumption distribution estimates 2017, 2018, 2019(kt)

Note: Data based on a combination of sources, including estimates of the proportions of REEs used in different applications (Binnemans et al., 2013), annual mine production data from the USGS and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020), and export and import statistics from the WITS database (WITS, 2019). See section 3.3.1 in the research methodology chapter for more detail about the analytical approach. The dash (-) represents no metal consumption in that end-use sector/application. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

Overall, results show a trend of a continuous increase in the consumption of critical REEs in Australia from 2017 to 2019 (54.5, 57.3 to 60.6 kt respectively as seen in Table 4.1 above). The critical metal with the highest demand in applications over these years was Yttrium followed by Neodymium, by Dysprosium, as illustrated in Figure 4.2 below. Terbium and Europium show a similar pattern of consumption over this period. Thus, it is fair to say that demand for critical REEs has increased yearly.

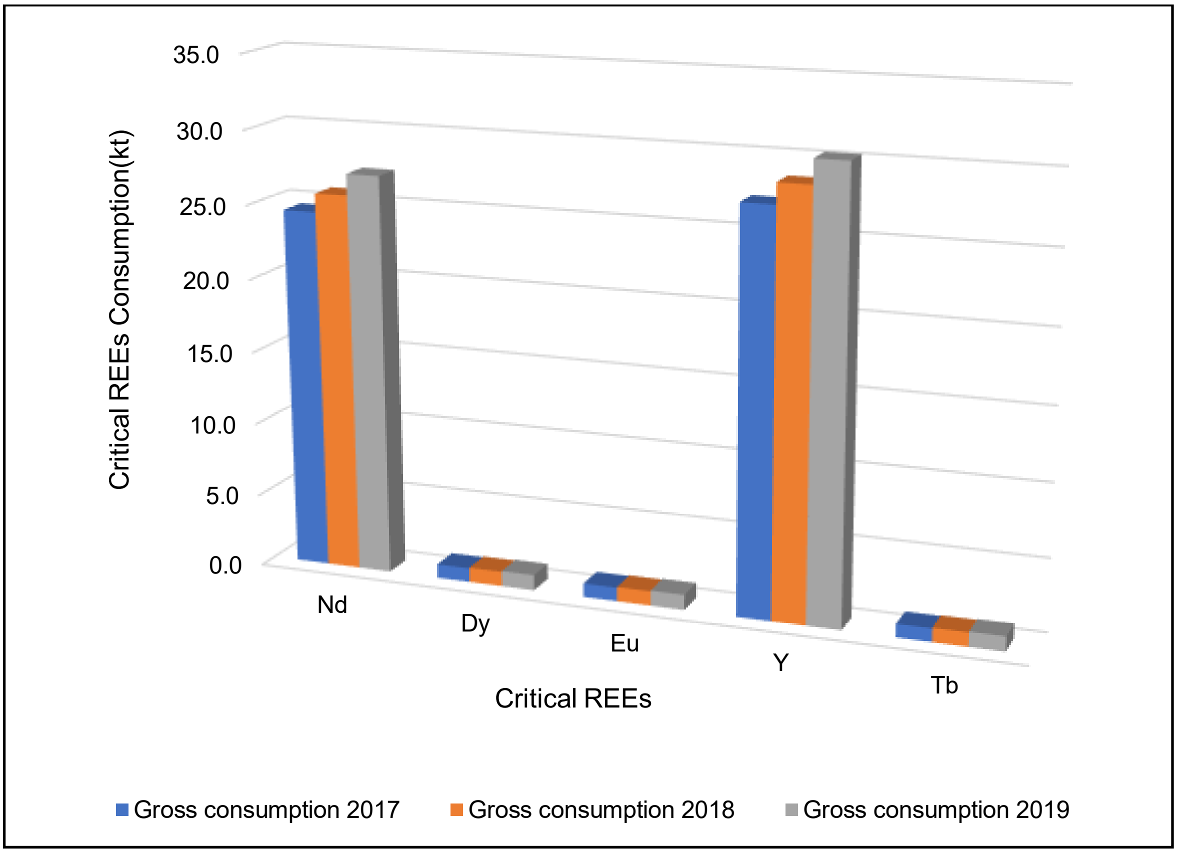


Figure 4.2: Comparison of individual critical REEs consumption in Australia over the timeframe 2017- 2019 (kt)

In terms of REEs consumption per application over these years, overall, the results show continuous growth. Phosphors, for instance, showed evidence of the highest consumption of these metals over this period. This is followed by magnets with the same continuous growth trend. In line with this are ceramics, metallurgy, battery, glass additives and autocatalysts respectively as illustrated in Figure 4.3 below.

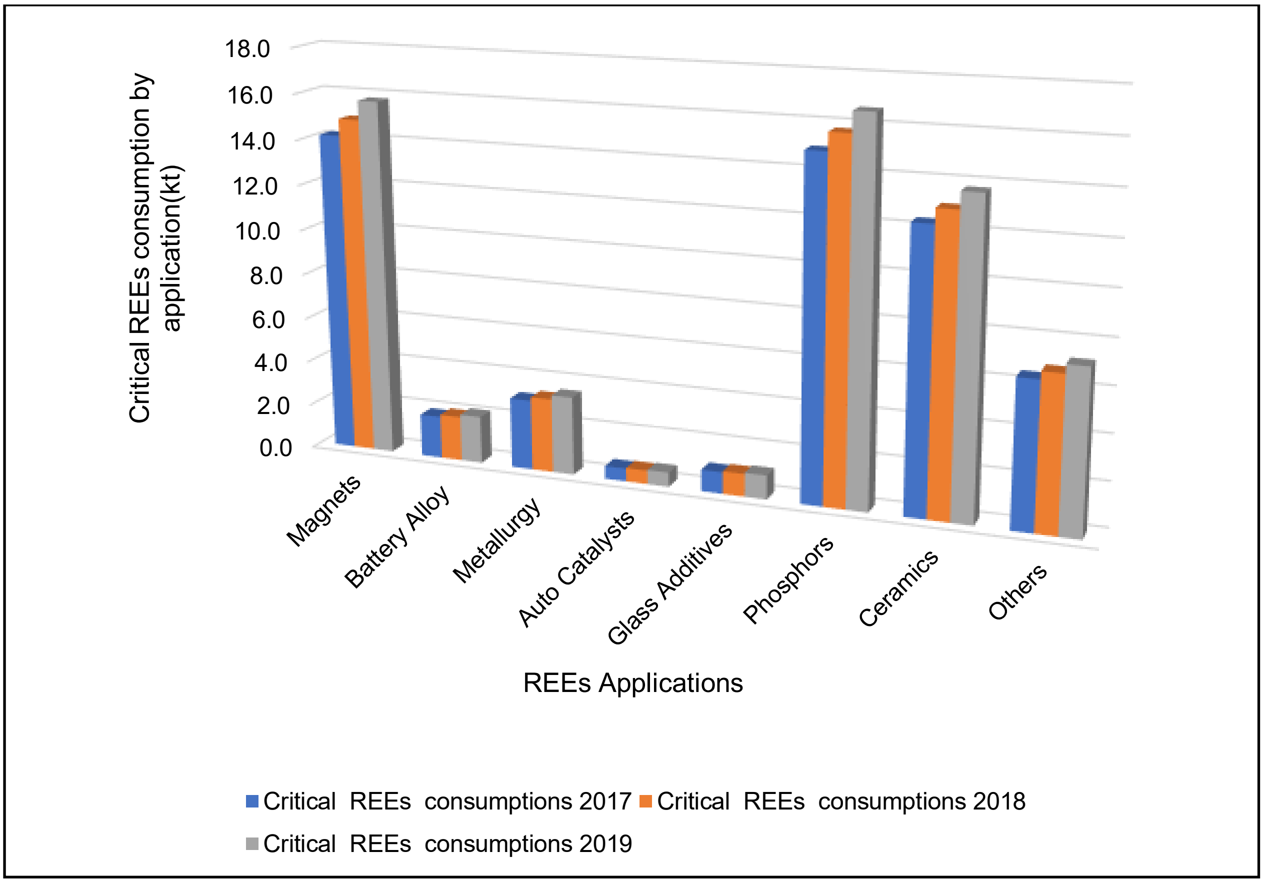


Figure 4.3: Comparison of REEs consumption by application over a timeframe 2017-2019 (kt).

4.2.3 Trends in clean energy consumption of REEs

Overall, results show that there is a continuously growing trend in the demand for REEs in the clean energy sector. Low emission energy usage shows evidence of higher demand for REEs in applications over these years, as seen in Table 4.2 and Figure 4.4 below. The demand comes particularly from La, Nd, Ce in battery alloy and Eu, Tb, Y, Ce, Gd in phosphors. For Low emissions energy production, in total, the demand comes from Nd, Dy and Pr in magnets.

Clean Energy sectors	REEs applications	REEs	Estimated consumption 2017 (kt)	Estimated consumption 2018 (kt)	Estimated consumption 2019 (kt)	Major High Tech-use examples
Low-emissions energy production	Magnets	Nd, Dy, Pr	18.6	19.6	20.7	Wind turbines, hybrid vehicles etc
Low-emissions energy usage	Battery alloy	La, Nd, Ce	17.7	18.7	19.7	Hybrid vehicle batteries, hydrogen absorption alloys for rechargeable batteries
	Phosphors	Eu, Tb, Y, La, Ce, Gd,	19.0	20.0	21.1	Energy-efficient lights Plasma TVs and displays LCD TVs and monitors etc

Table 4.2: Trends in Australia's Rare earth elements consumption in the clean ener y sectors (2017, 2018, 2019) kt.

Note: Data based on a combination of sources, including estimates of the proportions of REEs used in different applications (Binnemans et al., 2013), annual mine production data from the USGS and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020), and export and import statistics from the WITS database (WITS, 2019). See section 3.3.1 for more detail about the analytical approach. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y(Yttrium), Tb (Terbium), Pr (Praseodymium), La (Lanthanum), Ce (Cerium), Gd (Gadolinium).

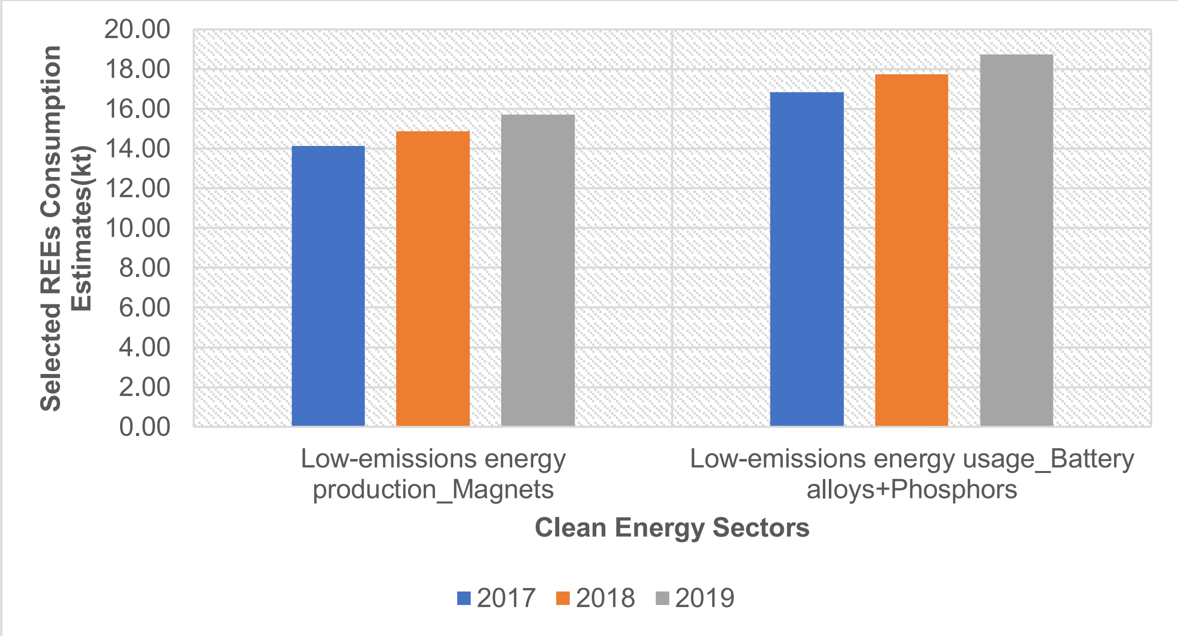


Figure 4.4: Trends in Australia's Rare earth elements consumption in the clean energy sectors (2017, 2018, 2019) kt

4.3 Material use analysis of REEs consumption in Australia and the associated environmental impact

The analysis below presents results from the assessment of selected critical Rare earth elements consumption estimates in Australia using primary material inputs and the associated environmental impacts from these activities. The first section looks at the material consumption of these elements in applications, while the other two sections look at the impacts associated with these activities. As a case study, the year 2019 was chosen as the base year for this analysis because it contains the most updated data and information at the time of the study. However, using this approach, the same simulation can be run for any given year to assess material use and the associated environmental impact. The goal is to develop a sustainable management framework that can be used to assess resource use and impact over a given period.

4.3.1 Material Use (MU) Assessment Results:

4.3.1.1 Assessment of critical REEs consumption in applications using primary material inputs

Results for the estimated consumption of selected REEs by applications in 2019 are presented in Table 4.3. The consumption of selected REEs in Australia was estimated based on the individual estimates of the proportions of these elements found in applications derived from (Binnemans et al., 2013) as well as Australia's REEs annual mine production data from USGS and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020), and export and import statistics from WITS database (WITS, 2019) (details in research methodology chapter, section 3.3.1).

Applications	Critical REEs consumption distribution estimates (kt)					Gross consumption
	Nd	Dy	Eu	Y	Tb	
Magnets	14.7	1.1	-	-	0.04	15.8
Battery Alloy	2.1	-	-	-	-	2.1
Metallurgy	3.5	-	-	-	-	3.5
Auto Catalysts	0.6	-	-	-	-	0.6
Glass Additives	0.6	-	-	0.4	-	1.1
Phosphors	-	-	1.0	14.6	1.0	16.6
Ceramics	2.5	-	-	11.2	-	13.7
Others	3.2	-	-	4.0	-	7.2
Gross consumption	27.2	1.1	1.0	30.3	1.0	60.6

Table 4.3: Critical REEs consumption by application in 2019(kt)

Note: The dash (-) represents no metal consumption in that end-use sector/application. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

a) Analysis of individual critical REEs consumption in applications

The highest consumption stems from Yttrium (30.3kt), followed by Neodymium (27.2 kt). Yttrium alone makes up about 50% of the total critical metal consumption (as seen in Table 4.3 and illustrated in Figure 4.5). Neodymium consumption is 45% of the total consumption. Europium and Dysprosium both show similar consumption patterns (2%). Terbium has the smallest consumption in applications. Figure 4.5 below illustrates the consumption distribution of individual critical REES in Applications.

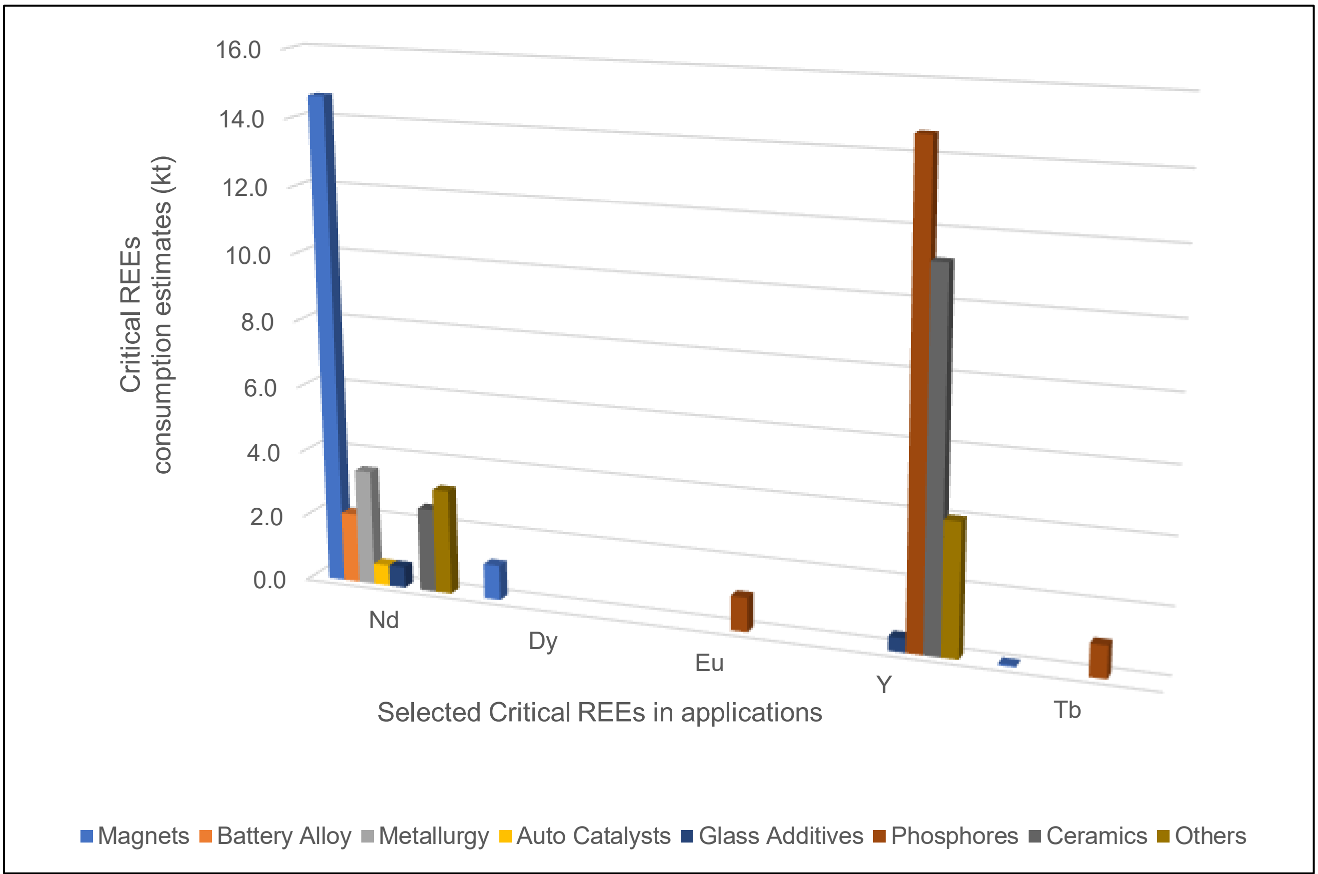


Figure 4.5: Selected critical REEs consumption distribution estimates 2019 (kt)

b) Analysis of individual application consumption of critical REEs

It is worth noting that phosphors and magnets show the highest evidence of critical REEs material consumption estimate with 16.6 and 15.8kt each, which is 27% and 26% respectively, followed by ceramics (23%) (as seen in Table 4.3 and illustrated in Figure 4.5). Yttrium (Y), Europium (Eu) and Terbium (Tb) are the main critical materials used in phosphors with significant contributions coming from Yttrium. Neodymium, Dysprosium, and Terbium account for the main material used in magnets, with a significant contribution from Neodymium. The main materials used in ceramics are Neodymium (Nd) and Yttrium (Y), with significant contributions from Yttrium. Other applications with significant consumption of critical REEs materials include metallurgy (6%), battery alloy (3%), glass additives (2%) and autocatalyst (1%).

4.3.2 Global Warming Potential (GWP) Assessment Results

This section examines CO_2 emission potential in Australia associated with the consumption of critical REEs in applications using primary material inputs.

4.3.2.1 CO_2 emission potential assessment of critical REEs consumption in applications using primary material inputs

The estimated gross CO_2 emissions associated with the consumption of REEs by end-users in Australia for the year 2019 is 2278.3 kg CO_2-eq/yr/1kt, and is shown in Table 4.4 below, which indicates the estimated CO_2 emission potential from the consumption of REEs in applications, Australia 2019.

Application	Estimated CO_2 emissions potentials by application (kg CO_2-eq/yr/1kt)					Gross CO_2 emissions
	Nd	**Dy**	**Eu**	**Y**	**Tb**	
Magnets	745.2	1.3	-	-	0.13	746.6
Battery Alloy	107.4	-	-	-	-	107.4
Metallurgy	177.2	-	-	-	-	177.2
Auto Catalysts	32.2	-	-	-	-	32.2
Glass Additives	32.2	-	-	12.4	-	44.6
Phosphors	-	-	1.0	429.5	3.0	433.5
Ceramics	128.9	-		328.9	-	457.8
Others	161.1	-	-	117.9	-	279.0
Gross CO_2 emissions	1384.2	1.3	1.0	888.7	3.1	2278.3

Table 4.4: Estimated CO_2 emission potentials from REEs consumption in applications (kg CO_2-eq/yr/1kt) based on the IPCC 2013 assessment method on GWP 100a from ecoinvent

Note: The dash (-) sign represents no metal consumption in the end-use sector/applications. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

In terms of individual material consumption by applications, the highest CO_2 emissions stem from the consumption of Neodymium (1384.2 kg CO_2-eq/yr/1kt) in magnets, ceramics, metallurgy, battery alloy, glass additives and autocatalyst respectively. This is followed by Yttrium (888.7 kg CO_2-eq/yr/1kt), used in phosphors, ceramics, glass additives, and others. Other critical metals like Terbium (Tb), Dysprosium (Dy), and Europium (Eu) show evidence of relatively lower emission contributions of 3.1, 1.3 and 1.0 kg CO_2-eq/yr/1kt respectively, as seen in Table 4.4 and illustrated in Figure 4.6 below. The results show impact levels from two directions: impacts from the use of the individual critical materials in applications, and a comparison of impacts between the individual applications themselves. This is good in terms of decision-making and policymaking, as it can be used by policymakers to monitor specific materials and applications simultaneously when planning for impact reductions.

In terms of individual applications, magnets have the highest gross CO_2 emission potential (746.6 kgCO_2-eq/yr/1kt), followed by ceramics (457.8 kgCO_2-eq/yr./1kt), phosphors (433.5 kg CO_2-eq/yr/1kt), metallurgy (177.2kt), the grouping 'other' (279.0 kg CO_2-eq/yr/1kt) battery alloy (107.4 kg CO_2-eq/yr/1kt), glass additives (44.6 kg CO_2-eq/yr/1kt) and autocatalyst (32.2 kg CO_2-eq/yr/1kt) respectively as seen in Table 4.4 and illustrated in Figure 4.6.

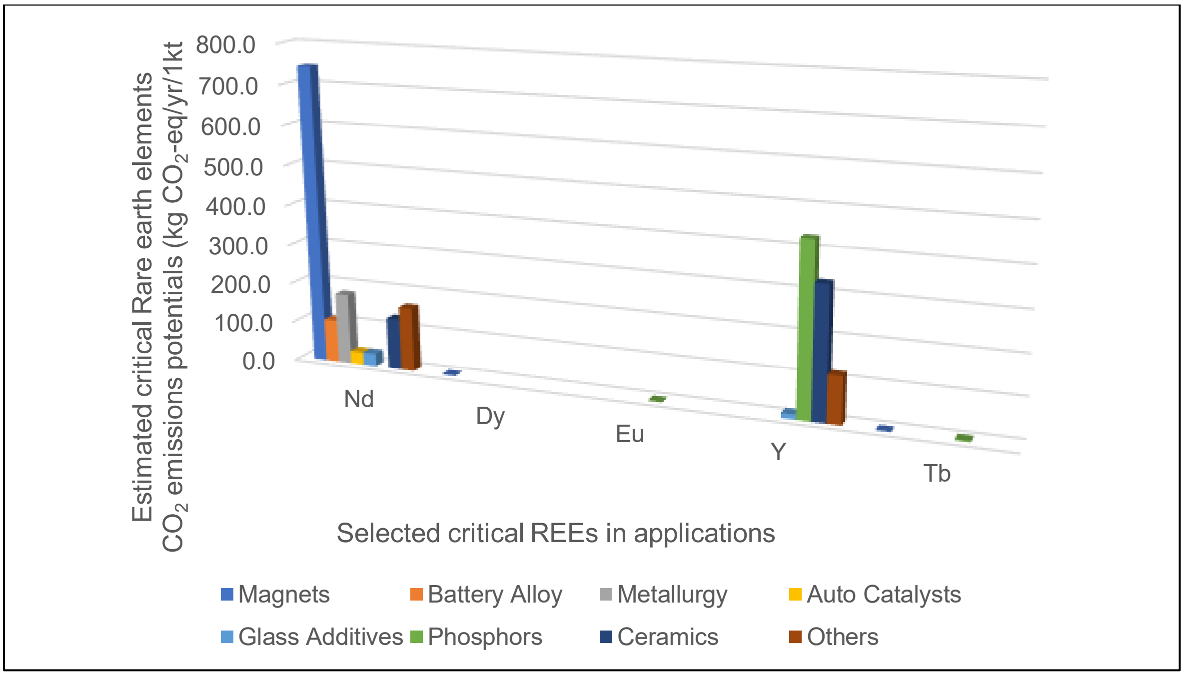


Figure 4.6: Estimated CO_2 emission potentials from REEs consumption in applications 2019 (kg CO_2-eq/yr/1kt) based on the IPCC 2013 assessment method on GWP 100a from ecoinvent

4.3.3 Cumulative Energy Demand Potential (CEDP) Assessment Results:

This section examines the Cumulative Energy Demand Potentials in Australia associated with the consumption of critical REEs in applications using primary material inputs.

4.3.3.1 CEDP of critical rare earth metal consumption in applications using primary material inputs

Table 4.5 shows the estimated Cumulative Energy Demand Potential associated with critical REEs material consumption from applications in Australia for the year 2019. Gross cumulative energy consumption was estimated to be 25674.9 MJ-Eq./yr./1kt.

Applications	Estimated REEs Cumulative Energy Demand Potentials in 2019 (MJ-Eq./yr./1kt)					Gross CEDP
	Nd	Dy	Eu	Y	Tb	
Magnets	8659.4	14.8	-	-	1.5	8675.6
Battery Alloy	590.5	-	-	-	-	590.5
Metallurgy	2058.8	-	-	-	-	2058.8
Auto Catalysts	374.3	-	-	-	-	374.3
Glass Additives	374.3	-	-	142.3	-	516.6
Phosphores	-	-	12.6	4922.0	34.3	4968.9
Ceramics	1497.3	-	-	3769.8	-	5267.1
Others	1871.6	-	-	1351.4	-	3223.0
Gross CEDP	15426.2	14.8	12.6	10185.5	35.8	25674.9

Table 4.5: Estimated Cumulative Energy Demand Potentials from critical REEs consumption in Applications 2019 (MJ-Eq./yr./1kt) based on the Cumulative Energy Demand assessment method on non-renewable energy resources, fossil characterisation factors from ecoinvent

Note: The dash (-) sign represents no metal consumption in that end-use sector/application. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

In terms of individual material consumption by applications, Neodymium and Yttrium have the highest energy consumption (15426.2 and 10185.5 MJ-Eq./yr./1kt respectively (see Table

4.5 and Figure 4.7). A reason for this may be the higher demand for these critical metals in applications generally as compared to the others. The applications accounting for energy consumption for Neodymium are magnets, metallurgy, ceramics, battery alloys glass additives and auto-catalysts. For Yttrium, the highest contribution comes from phosphors, followed by ceramics, the grouping 'other' and glass additives respectively. Energy consumption associated with terbium (35.8 MJ-Eq./yr./1kt), Dysprosium (14.8 MJ-Eq./yr./1kt) and Europium (12.6 5 MJ-Eq./yr./1kt) were small in comparison to Neodymium and Yttrium.

In terms of comparison between the individual applications for the consumption of these critical materials, magnets and phosphors are of major concern due to their higher environmental impact potential than the others. The Cumulative Energy Demand Potential for magnets and phosphors were 8675.6 and 4968.9 (MJ-Eq./yr./1kt) respectively. This was followed by ceramics, metallurgy, the grouping 'other', battery alloy, glass additives, and auto-catalyst respectively as illustrated in Figure 4.7 below.

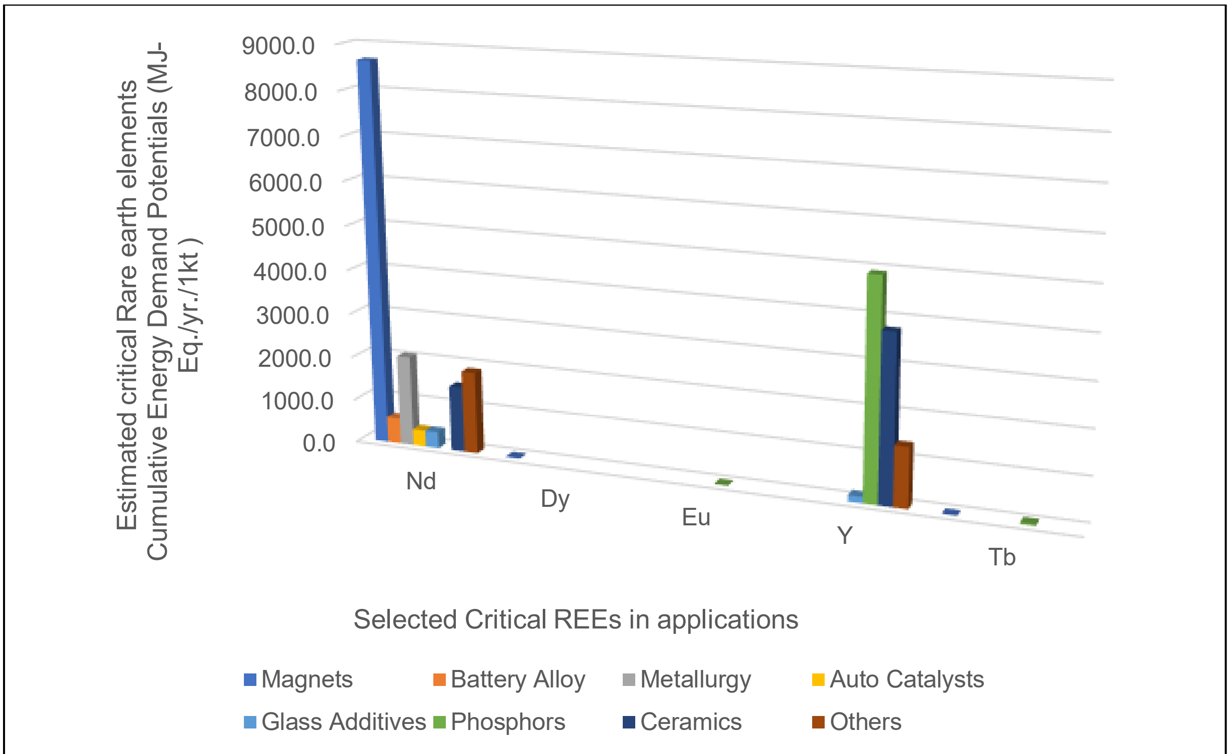


Figure 4.7: Estimated Cumulative Energy Demand Potentials from critical REEs consumption in Applications 2019 (MJ-Eq./yr./1kt based on the Cumulative Energy Demand assessment method on non-renewable energy resources, fossil characterisation factors from ecoinvent.

The results from this study can be used to provide valuable information needed, not only for manufacturers (consumers), but to waste disposers, recyclers, and policymakers to establish Design-for-Environment (DfE) and waste management policies for EoL products containing these metals. This sustainable framework approach can be adopted to estimate resource use and the associated environmental impact over any period and place to measure the environmental sustainability of resource consumption.

Chapter 5(Results 2): Secondary Material Input Assessment and Sustainability Outcome of Sustainable REEs Consumption in Australia

Chapter outline

5.1 Introduction

The previous results chapter modelled a primary material resource use assessment of REEs using three identified metrics (material use, greenhouse gas emissions and energy demand). The existing sustainability pattern governing REEs consumption in Australia was examined and the derived environmental impacts. To improve the sustainability outcome of REEs in Australia, circular economy (CE) strategies were applied to assess secondary material inputs of these metals and the derived environmental impacts. As such, this second chapter describes the results of a holistic and systematic approach to examining secondary REEs material consumption in applications and the associated environmental impacts. The chapter aims to highlight CE as a sustainable management strategy that should be implemented to achieve improvement in REEs resource efficiencies in Australia.

A material flow analysis (MFA) was combined with a life cycle impact assessment (LCIA) to compile and assess the impacts derived from secondary material consumption. Several sustainable management factors were considered. This includes CE strategies of resource efficiencies such as zero waste initiatives and a closed-loop system. Zero waste for instance aims to achieve complete recirculation of materials within the system and the improvement of the recycling process efficiency. The closed-loop system focuses on a sustainable circular system where materials are used efficiently and as many times as possible. Recycling as a CE strategy serves as an important strategy to strengthen the sustainable management of natural resources (Xu et al., 2019).

The first part of the results will look at REEs recycling potential in Australia over a given period, which examines the consumption of secondary material inputs in the economy. The other parts will look at the derived environmental impacts from the consumption of these secondary materials: CO_2 emissions resulting from the secondary material consumption and the Cumulative Energy Demand Potential.

The aim of this results section is to highlight the differences between primary (virgin) and secondary material (recycling) consumption patterns through system comparison and the benefits of such. The benefits of recycling, as opposed to virgin material use, will be examined in the last section of this chapter.

5.2 Recycling potential assessment and associated environmental impact

The analysis below presents the results of the recycling potentials of selected critical REEs consumption estimates in Australia using secondary material inputs and the derived environmental impacts in a given year (2019). This first section looks at the recycling potential from REEs consumption in applications over a given period and the next two following sections (5.2.2 and 5.2.3) look at the impacts derived from these activities.

5.2.1 Assessment of critical REEs secondary material consumption in applications (Recycling potentials)

Results for the estimated secondary material inputs for selected REEs are presented below in Table 5.1. The secondary material inputs or recycling potentials were estimated using the EoL recycling rate (EoLRR) and REEs old scrap, that is material content in EoL products available for recycling (Binnemans et al., 2013). The EoL recycling rate is calculated from the multiplication of the collection rate and the recycling process efficiency rate (Binnemans et al., 2013; International Resource Panel, 2011; Norgate, 2013). (Details were provided in the research methodology chapter).

Applications	**REEs recycling potential (kt)**					**Gross Consumption**
	Nd	Dy	Eu	Y	Tb	
Magnets	8.1	0.6	-	-	0.02	8.7
Battery Alloy	1.2	-	-	-	-	1.2
Metallurgy	1.9	-	-	-	-	1.9
Auto Catalysts	0.3	-	-	-	-	0.3
Glass Additives	0.3	-	-	0.2	-	0.6
Phosphors	-	-	0.6	8	0.5	9.1
Ceramics	1.4	-	-	6.2	-	7.6
Others	1.7	-	-	2.2	-	4
Gross consumption	15	0.6	0.6	16.6	0.6	33.3

Table 5.1: Estimated critical REEs recycling potentials from applications in a given year (2019 in kt)

Note: The dash (-) represents no metal consumption in that end-use sector/application. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

5.2.1.1 Analysis of recycling potential from individual REEs

In terms of recycling potential from individual REEs, Yttrium (16.6 kt) and Neodymium (15kt) were recorded as metals with the highest gross recycling potential, with 50% and 45% consumption of these critical metals in applications respectively, as seen in Table 5.1 and illustrated in Figure 5.1 below. Dysprosium (in magnets), Europium (in phosphors) and Terbium (in phosphors) all recorded similar recycling potential patterns.

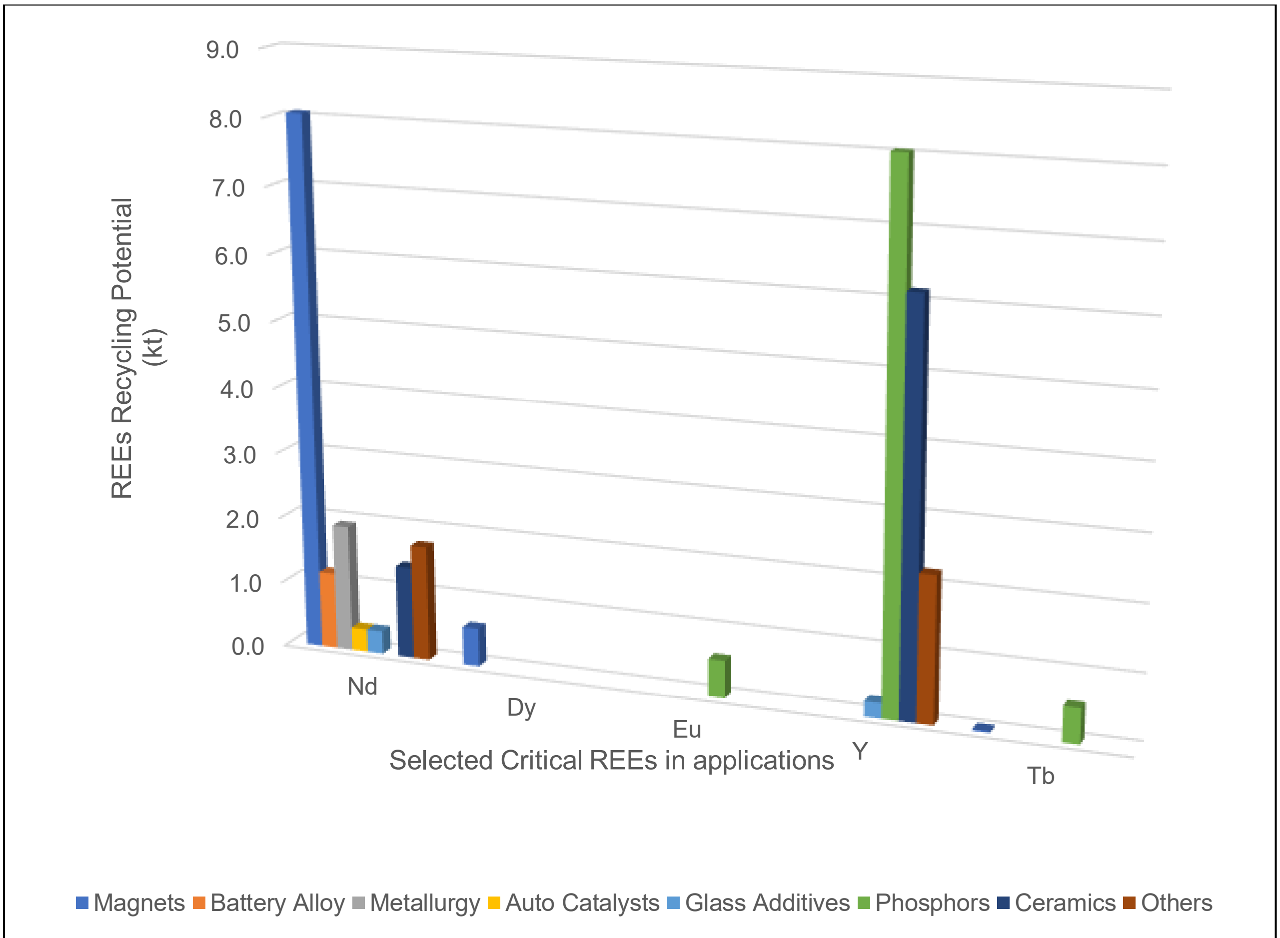


Figure 5.1: Recycling potentials of critical REEs in a given year (2019 in kt).

5.2.1.2 Analysis of recycling potentials from individual applications

In terms of recycling potential from individual REEs applications, results show phosphors (9.1kt) and magnets (8.7kt) have high gross recycling potential for recovery as compared to the other applications. They made up 27% and 26% of gross recycling potential respectively as seen in Table 5.1 and illustrated in Figure 5.1. This was followed by ceramics (23%), metallurgy (6%), glass additives (2%) and auto-catalysts (1%). The results suggest that improvements in the recycling rates in phosphors, magnets and ceramics would make secondary material inputs a significant contribution to overall REE supply and make REEs much more sustainable.

5.2.2 Global Warming Potential assessment results

This section examines CO_2 emission potentials associated with the consumption of critical REEs in applications using secondary material inputs.

5.2.2.1 CO_2 emission potentials assessment of secondary material inputs

Overall, the gross CO_2 emissions potential determined from the consumption of secondary material inputs in a given year (2019) were estimated to be 1253.0 (kg CO_2-eq/yr/1kt) as shown in Table 5.2 below.

Applications	**CO_2 emissions potentials from REEs recycling (kg CO_2-eq/yr/1kt)**					**Gross CO_2 Emissions**
	Nd	Dy	Eu	Y	Tb	
Magnets	409.9	0.7	-	-	0.07	410.7
Battery Alloy	59.1	-	-	-	-	59.1
Metallurgy	97.4	-	-	-	-	97.4
Auto Catalysts	17.7	-	-	-	-	17.7
Glass Additives	17.7	-	-	6.8	-	24.5
Phosphors	-	-	0.6	236.2	1.6	238.4
Ceramics	70.9	-	-	180.9	-	251.8
Others	88.6	-	-	64.9	-	153.4
Gross CO_2 Emissions	761.3	0.7	0.6	488.8	1.7	1253.0

Table 5.2: Estimated CO_2 emissions potential from secondary material consumption in a given year (2019 kg CO_2-eq/yr/1kt) based on the IPCC 2013 assessment method on GWP 100a from ecoinvent

Note: the dash (-) sign represents no metal consumption in the end-use sector/applications. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

In terms of individual material consumption by application, the highest CO_2 emission is derived from the consumption of Neodymium (761.3 kg CO_2-eq/yr/1kt) in magnets, metallurgy, ceramics, battery alloy, auto-catalysts and glass additives respectively as shown in Table 5.2

and illustrated in Figure 5.2. The metal with the second-highest derived CO_2 emission potential was Yttrium (488.8 kg CO_2-eq/yr/1kt) used in phosphors, ceramics, and glass additives. These emissions were relatively higher when compared to other critical metals like Terbium (1.7 kg CO_2-eq/yr/1kt), Dysprosium (0.7 kg CO_2-eq/yr/1kt), and Europium (0.6 kg CO_2-eq/yr/1kt)

Regarding individual applications, magnets have the highest gross CO_2 emission potential (410.7 kg CO_2-eq/yr/1kt) as shown in Table 5.2 and illustrated in Figure 5.2 below. This is followed by ceramics (251.8 kg CO_2-eq/yr/1kt), phosphors (238.4 kg CO_2-eq/yr/1kt), metallurgy (97.4 kg CO_2-eq/yr/1kt), battery alloy (59.1 kg CO_2-eq/yr/1kt), glass additives (24.5 kg CO_2-Eq/yr/1kt) and auto-catalysts (17.7 kg CO_2-eq/yr/1kt) respectively.

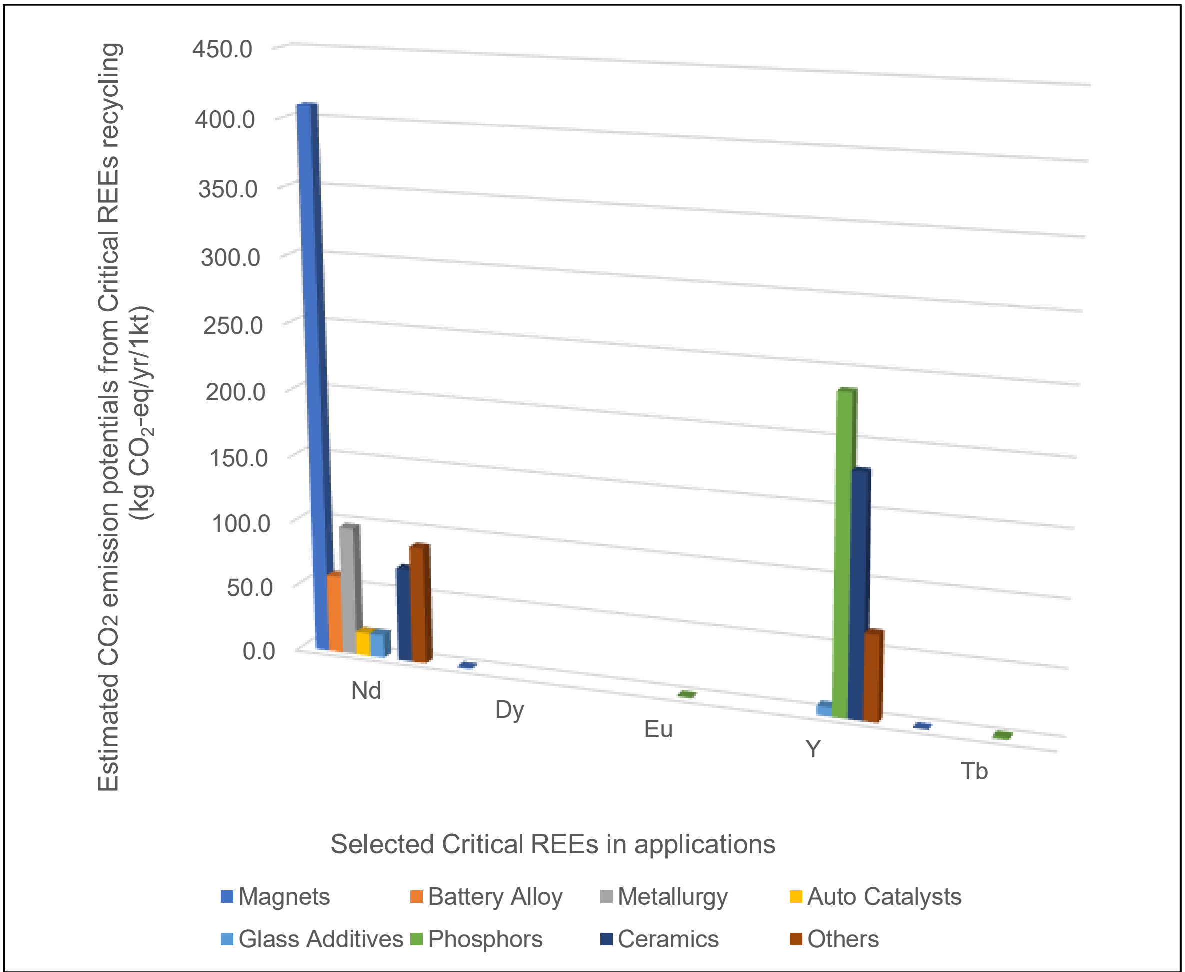


Figure 5.2: Estimated CO_2 emissions potentials from secondary material consumption in a given year (2019 kg CO_2-eq/yr/1kt) based on the IPCC 2013 assessment method on GWP 100a from ecoinvent

5.2.3 Cumulative Energy Demand Potential assessment results

This section examines the Cumulative Energy Demand Potential associated with the consumption of critical REEs in applications using secondary material inputs.

5.2.3.1 Cumulative Energy Demand Potential assessment of secondary material inputs

Table 5.3 shows an estimated Cumulative Energy Demand potential (CEDP) derived from the consumption of secondary material inputs. The gross CO_2 emission potential was estimated to be 14482.7 MJ-Eq./yr./1kt in a given year (2019)

Applications	Cumulative energy demand potentials from REEs recycling (MJ-Eq./yr./1kt)					Gross CEDP
	Nd	Dy	Eu	Y	Tb	
Magnets	4762.7	8.1	-	-	0.8	4771.6
Battery Alloy	686.3	-	-	-	-	686.3
Metallurgy	1132.3	-	-	-	-	1132.3
Auto Catalysts	205.9	-	-	-	-	205.9
Glass Additives	205.9	-	-	78.2		284.1
Phosphors	-	-	6.9	2707.1	18.9	2732.9
Ceramics	823.5	-	-	2073.4	-	2896.9
Others	1029.4	-	-	743.3	-	1772.7
Gross CEDP	8845.9	8.1	6.9	5602.0	19.7	14482.7

Table 5.3: Estimated Cumulative Energy Demand Potential from secondary material consumption in a given year (2019 MJ-Eq./yr./1kt) based on the Cumulative Energy Demand assessment method on non-renewable energy resources, fossil characterisation factors from ecoinvent.

Note: The dash (-) sign represents no metal consumption in that end-use sector/application. Nd (Neodymium), Dy (Dysprosium), Eu (Europium), Y (Yttrium), Tb (Terbium).

Concerning individual material consumption in applications, Neodymium has the highest energy consumption (8845.9 MJ-Eq./yr./1kt). The energy consumption is derived from magnets, metallurgy, ceramics, battery alloys, glass additives and auto-catalysts respectively as shown in Table 5.3 and illustrated in Figure 5.3. This is followed by Yttrium (5602.0 MJ-Eq./yr./1kt) with the main contribution deriving from phosphors, followed by ceramics and glass additives respectively. Energy consumption associated with Terbium (19.7 MJ-Eq./yr./1kt), Dysprosium (8.1 MJ-Eq./yr./1kt) and Europium (6.9 MJ-Eq./yr./1kt) were small in comparison to Neodymium and Yttrium.

With individual applications, magnets posed the highest environmental impact potential resulting from high cumulative energy potentials 4771.6 MJ-Eq./yr./1kt) as seen in Table 5.3 and illustrated in Figure 5.3. This is followed by ceramics (2896.9 MJ-Eq./yr./1kt), phosphors (2732.9 MJ-Eq./yr./1kt), battery alloys (686.3 MJ-Eq./yr./1kt), glass additives (284.1 MJ-Eq./yr./1kt) and auto-catalyst (205.9 MJ-Eq./yr./1kt) respectively.

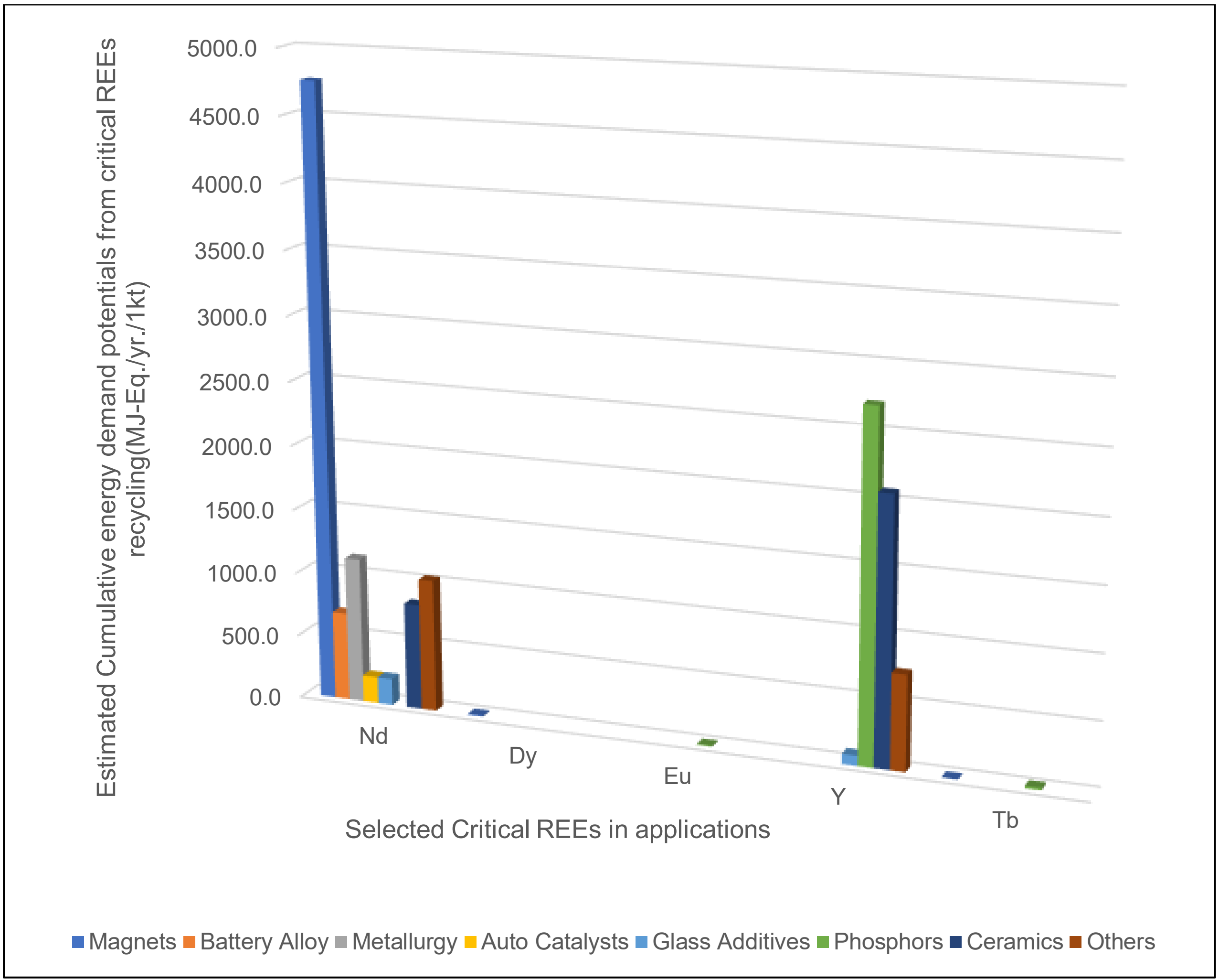


Figure 5.3: Estimated Cumulative Energy Demand Potential from secondary material consumption in a given year (2019 MJ-Eq./yr./1kt) based on the Cumulative Energy Demand assessment method on non-renewable energy resources, fossil characterisation factors from ecoinvent.

The overall results show an implementation of sustainable consumption strategies in REEs consumption in Australia over a given period and the derived environmental impacts. The results provide empirical evidence that can be used to highlight the differences between primary and secondary material consumption patterns of REEs through system comparison and the significant environmental benefits from such. This framework can be used over any given period to monitor material consumption and resource-saving activities as analysed in the following section 5.3.

5.3 Assessment of the environmental benefits derived from sustainability practices

This section aims to evaluate the environmental benefits associated with sustainable consumption and production of REEs in terms of material use and resource efficiency practices to mitigate supply risk, climate change and energy consumption. It aims to identify savings that can be made by using recyclables as opposed to virgin materials. The first section (5.3.1) looks at material savings estimates from recycling, while the other sections (5.3.2 and 5.3.3) look at global warming and cumulative energy demand potential reductions.

5.3.1 Material saving analysis

Results from an assessment and comparison of critical REEs material consumption from primary (virgin) and secondary (recycling) material inputs are presented in Table 5.4 and Table 5.5. The main objective was to evaluate the environmental benefits of recycling in terms of material savings/avoided mine production. Gross material savings were estimated to be 33kt for a given year (2019).

5.3.1.1 Analysing material savings from individual metals

Results show Yttrium (16.6 kt) and Neodymium (15 kt) as the metals with the highest environmental benefits in terms of material savings in comparison to other metals as seen in Table 5.4 below.

Critical Rare earth elements	Nd	Dy	Eu	Y	Tb	**Gross Total**
Gross consumption from primary material	27.2	1.1	1	30.3	1	**60.6**
Gross consumption from secondary material	15	0.6	0.6	16.6	0.6	**33.3**

Table 5.4: Comparing primary and secondary inputs in terms of individual REEs consumption in application in a given year (2019 kt)

5.3.1.2 Analysis of material saving from individual applications

Regarding material savings from individual applications, phosphors (9.1 kt) and magnets (8.7 kt) show products with greater material savings in comparison to the other applications as seen in Table 5.5 below.

Applications	**Gross consumption from primary material inputs**	**Gross consumption from secondary material inputs**
Magnets	15.8	8.7
Battery Alloy	2.1	1.2
Metallurgy	3.5	1.9
Auto Catalysts	0.6	0.3
Glass Additives	1.1	0.6
Phosphors	16.6	9.1
Ceramics	13.7	7.6
Others	7.2	4
Gross consumption	60.6	33.3

Table 5.5: Comparing primary and secondary inputs in terms of material consumption by individual REEs application

5.3.2 Environmental benefits from recycling in terms of Global Warming Reduction Potentials

This section examines the Global Warming Reduction Potential associated with recycling. GHG emission benefits from recycling are determined by comparing virgin material inputs with recycled material (Grimes et al., 2008; United State Environmental Protection Agency, 2011a).

5.3.2.1 Recycling Emission Reduction Potentials assessment

Table 5.6 shows the estimated CO_2 emission reduction potential. This method quantifies the material-specific GHG emission reduction benefits associated with recycling. The gross CO_2 emission reduction potential was estimated to be 1589.1 kg CO_2-eq/yr/1kt.

Applications	REEs estimated Recycling Emission Reduction Potentials (CO_2 emissions avoided) (kg CO_2-eq/yr/1kt)					Gross CO_2 emissions avoided
	Nd	Dy	Eu	Y	Tb	
Magnets	519.8	0.9	-	-	0.09	520.8
Battery Alloys	74.9	-	-	-	-	74.9
Metallurgy	123.6	-	-	-	-	123.6
Auto Catalysts	22.5	-	-	-	-	22.5
Glass Additives	22.5	-	-	8.7	-	31.1
Phosphors	-	-	0.7	299.5	2.1	302.3
Ceramics	89.9	-	-	229.4	-	319.3
Others	112.3	-	-	82.2	-	194.6
Gross CO_2 emissions avoided	965.5	0.9	0.7	619.9	2.2	**1589.1**

Table 5.6: Estimated Recycling Emission Reduction Potential in a given Year (2019 kg CO_2-eq/yr/1kt)

In terms of individual critical Rare earth elements, Figure 5.4 illustrates a comparison between primary and secondary material consumption CO_2 emission potential, and the avoided emissions from recycling activities. Neodymium (965.5 kg CO_2-Eq/yr/1kt) and Yttrium (619.9 kg CO_2-eq/yr/1kt) have the highest gross CO_2 emission potentials in comparison to the other metals.

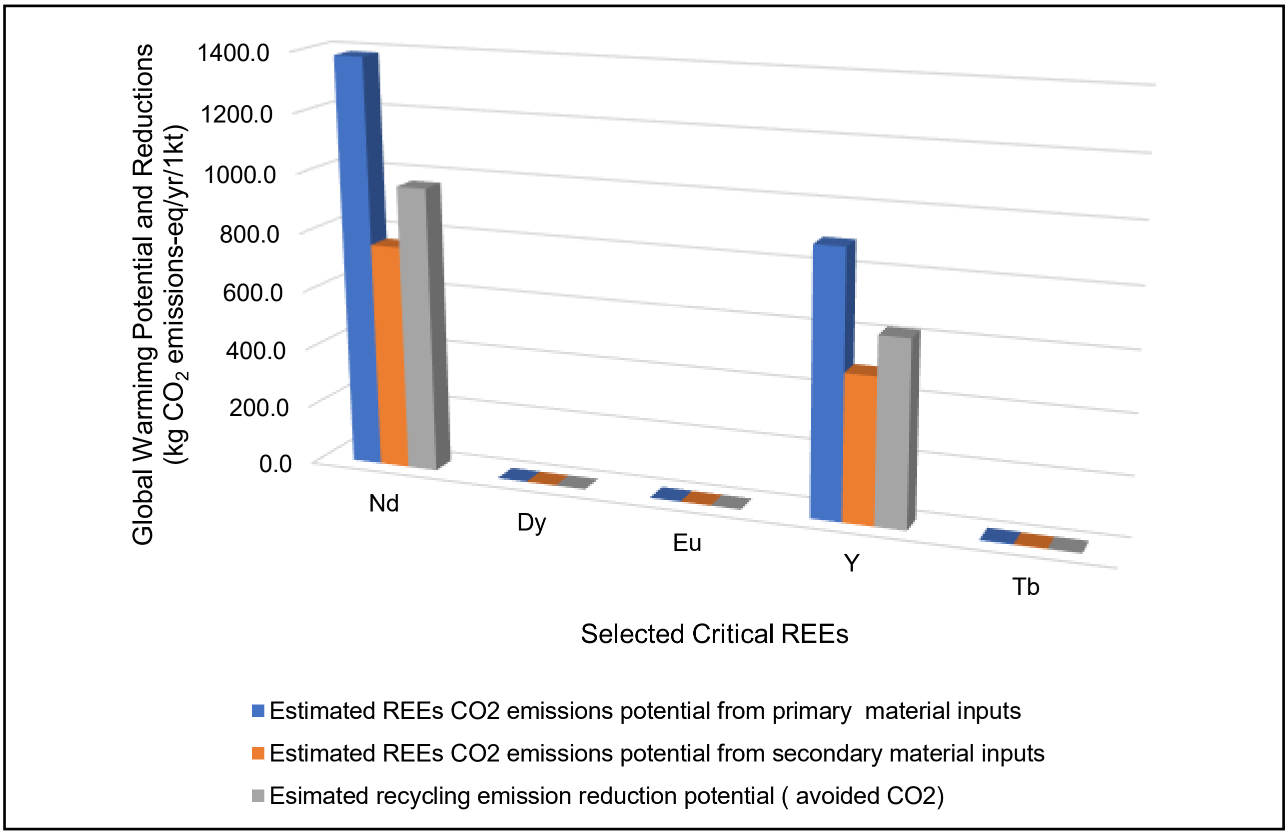


Figure 5.4: Global Warming Potential and Reductions from individual metals in a given year (2019 kg CO_2-eq/yr/1kt)

In terms of product analysis, results show higher CO_2 emission reduction potential associated with magnets, phosphors and ceramics in comparison to the other metals as illustrated in Figure 5.5.

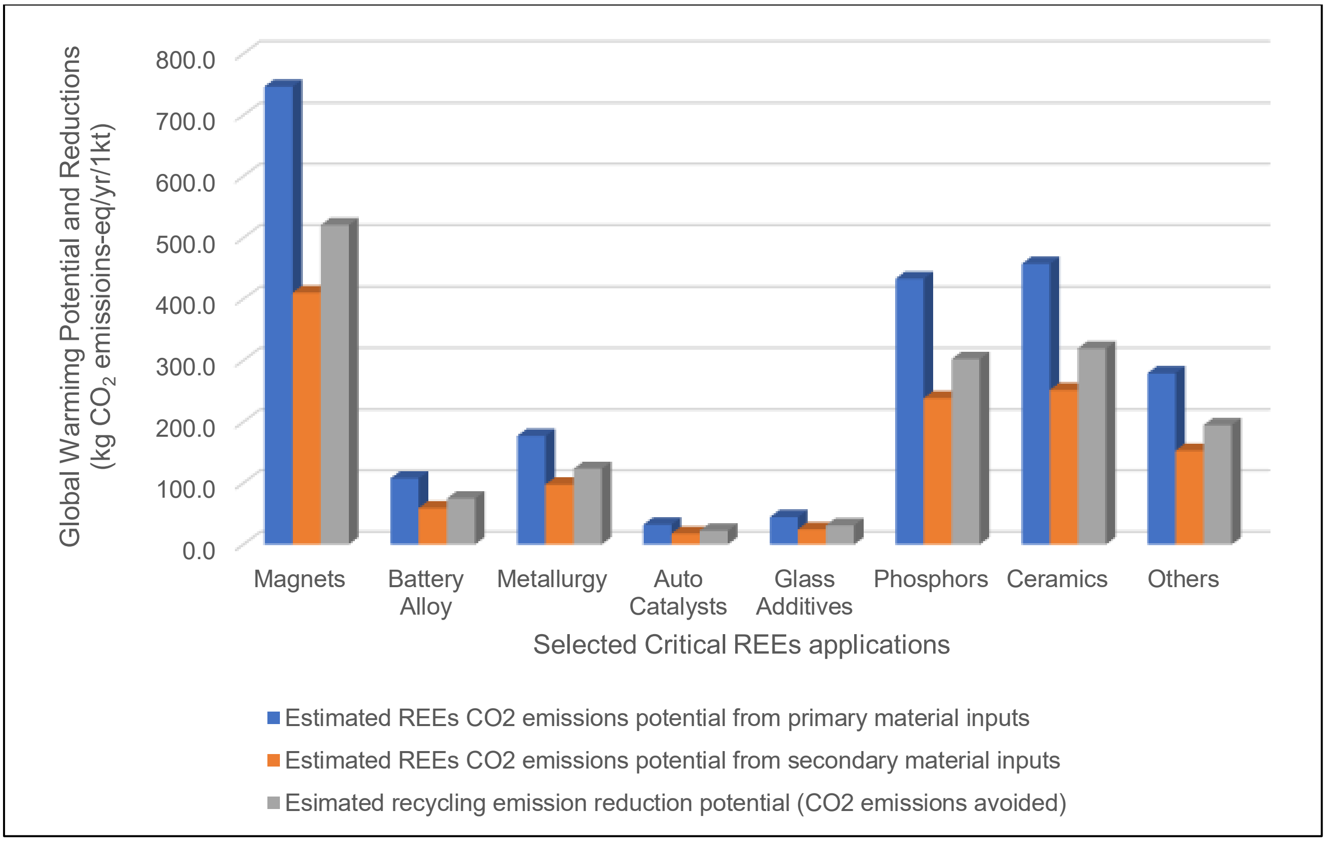


Figure 5.5: Global Warming Potential and Reductions by REEs applications in a given year (2019 kg CO_2-Eq/yr/1kt)

5.3.3 Environmental benefits from recycling in terms of Cumulative Energy Demand Reductions Potential

5.3.3.1 Cumulative Energy Demand Reduction Potential assessment

Table 5.7 shows the environmental benefits of recycling in terms of Cumulative Energy Demand Potentials Reductions. The gross Cumulative Energy Demand Potential Reductions (avoided Energy usage) were estimated to be 17709.4 MJ-Eq./yr./1kt

Applications	Estimated Cumulative Energy Demand Potential Reductions (avoided Energy usage) (MJ-Eq./yr./1kt)					Gross CEDP (avoided)
	Nd	Dy	Eu	Y	Tb	
Magnets	6039.9	10.3	-	-	1	6051.3
Battery Alloy	213.1	-	-	-	-	213.1
Metallurgy	1436	-	-	-	-	1436
Auto Catalysts	261.09	-	-	-	-	261.1
Glass Additives	261.1	-	-	99.2	-	360.3
Phosphors	-	-	8.8	3433.1	23.9	3465.8
Ceramics	1044.4	-	-	2629.4	-	3673.8
Others	1305.5	-	-	942.6	-	2248.1
Gross CEDP (avoided)	**10561**	**10.3**	**8.8**	**7104.4**	**25**	**17709.4**

Table 5.7: Estimated Cumulative Energy Demand Potential Reductions (avoided Energy usage) for a given year (2019 MJ-Eq./yr./1kt)

Regarding individual material analysis, Neodymium (10561.0 MJ-Eq./yr./1kt) and yttrium (7104.4 MJ-Eq./yr./1kt) have higher energy demand reduction potential associated with recycling activities as illustrated in Figure 5.6.

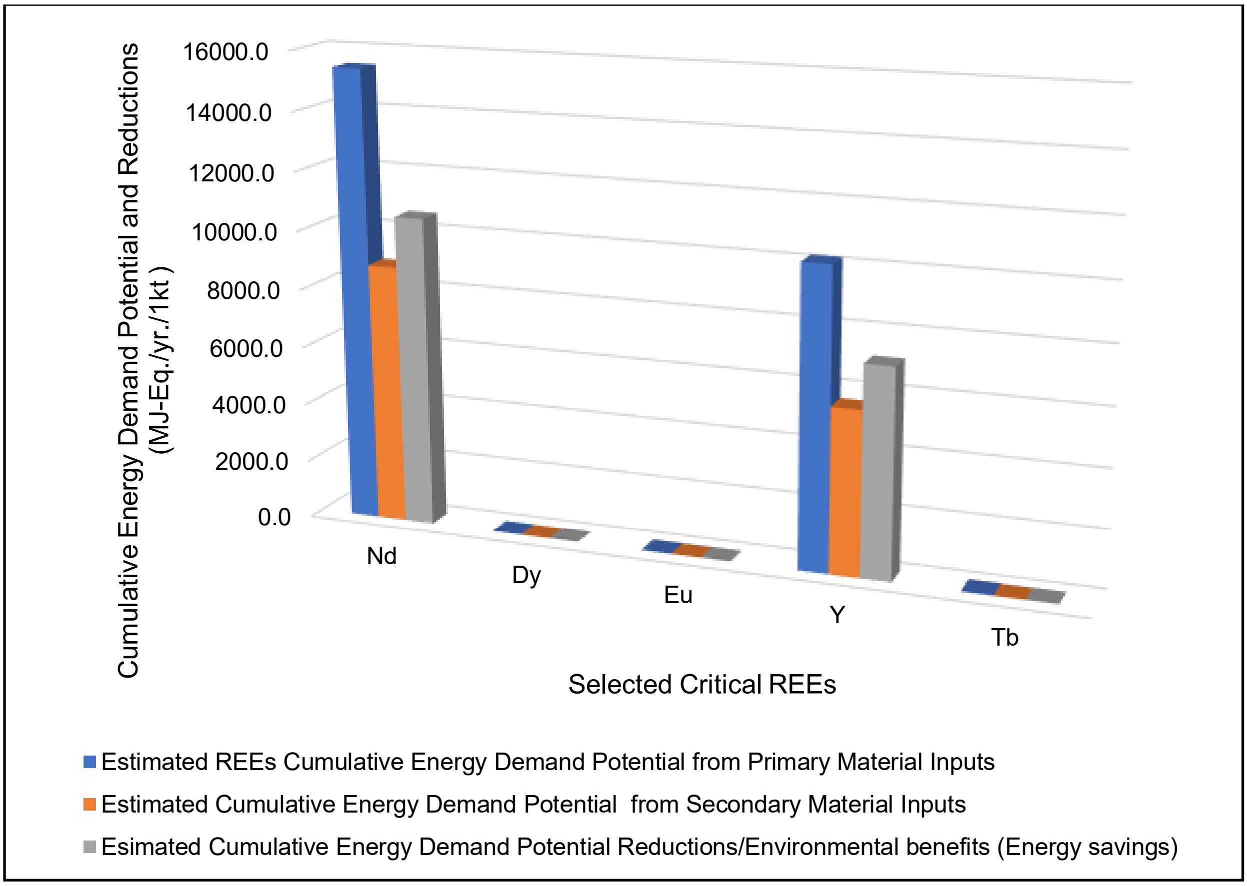


Figure 5.6: Cumulative Energy Demand Potential and reductions for individual metals in a given year (2019 MJ-Eq./yr./1kt)

Regarding applications, secondary material consumption in applications such as magnets, ceramics and phosphors results in a significant increase in energy savings as illustrated in Figure 5.7.

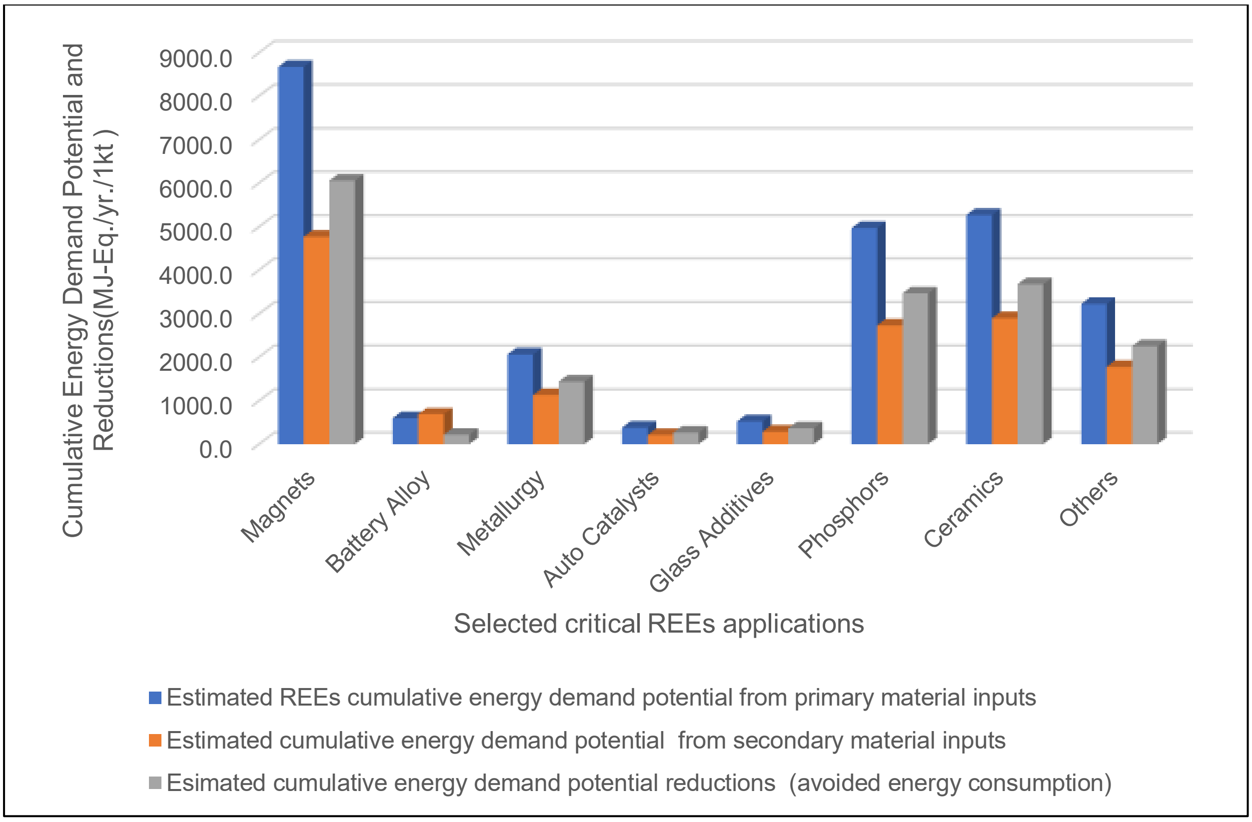


Figure 5.7:Cumulative Energy Demand Potential and Reductions by REEs applications in a given year (2019 MJ-Eq./yr./1kt)

Together these results provide important insights into the sustainable management strategies of REEs in Australia and the derived environmental benefits that will be thoroughly discussed in the subsequent chapter.

Chapter 6: General Discussion

Chapter outline

6.1 Introduction

This thesis proposes a holistic and systematic approach based on the circular economy (CE) model to assess the sustainability of REEs (in Australia as a case study), a strategy to minimise the adverse impacts of resource shortages, while achieving maximum environmental benefits. It introduces a novel framework for REEs within the sustainability paradigm and the holistic view of the contribution of CE to the sustainability of REEs consumption in Australia. This chapter discusses the results of the two previous chapters, 4 and 5. It provides clear answers to the objective of this study and for each of the research questions addressed in Chapter 1: a) How sustainable are current strategies for REEs consumption in Australia? What are the key indicators and how they can be assessed? b) How might the sustainability of REE consumption in Australia be enhanced?

Chapters 4 and 5 demonstrate the application of CE tools (MFA, LCIA) for sustainability management. First, Chapter 4 presented the primary material resource use assessment of REEs using three identified metrics (Material use, Greenhouse Gas Emissions and Energy Demand) within a sustainability framework to investigate the existing sustainability pattern governing REEs consumption in Australia and the derived environmental impacts. Second, Chapter 5, using CE strategies of sustainability, assessed secondary material inputs of these metals and the associated environmental impacts. Chapter 5 ended with an analysis of the environmental benefits associated with the sustainable management of natural resources specifically recycling. The purpose of this last section is to promote CE as a sustainable management strategy that can be used to achieve improvements in REEs resource efficiency and decouple natural resource use from economic prosperity. It highlights the differences between primary and secondary material consumption of REEs and the derived environmental impacts through system comparison. Decoupling REEs economic growth from environmental and resource degradation, and creating a circular economy through reuse, recycling, and remanufacturing, are key strategies for reducing both GHG emissions and other environmental and resource pressures (International Resource Panel, 2017).

Following this line of thought, this chapter first considers the discussion of the findings identified in Chapters 4 and 5. Drawing from these discussions, a comprehensive CE framework for REEs within the sustainable development paradigm for criticality mitigation is suggested in section 6.3.1. This is followed by a practical implementation strategy as a way forward to close the material loop and enhance the sustainability of REEs consumption in Australia in section 6.3.2.

6.2 Discussion of empirical findings

A holistic and systematic approach based on a CE model was used to assess the sustainability of REEs in Australia as a case study. Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA) tools were applied together to quantify and assess the flows and the impacts of REEs consumption in Australia. The research objective was to evaluate the material consumption of REEs, to find efficient strategies to reduce the supply risk impacts of these critical resources and minimise the potential environmental impacts associated with their consumption. The project has as its main goal to introduce CE as a sustainability model against the fight for REEs material criticality mitigation. The discussion is organised into 3 major sections (6.2.1, 6.2.2 and 6.2.3 respectively) drawing on the findings presented in Chapters 4 and 5.

6.2.1 Primary material input and life cycle impact analysis

A sustainable framework approach was developed to estimate resource use and the associated environmental impact over a given period to evaluate the environmental sustainability of REEs consumption in Australia. The framework combined material flow analysis (MFA) and life cycle impact assessment (LCIA) to measure and assess the impacts associated with these economic activities.

The first part of this section will analyse findings from examining the existing sustainability pattern governing REEs consumption in Australia over the time frame of 2017-2019. The other sections (6.2.1.2, 6.2.1.3, and 6.2.1.4) will discuss the main findings from primary material use and life cycle impact analysis respectively.

6.2.1.1 Existing consumption and production pattern of REEs in Australia

Overall results from life cycle material flow suggest that the REEs consumption pattern in Australia is highly dependent on primary material inputs (as illustrated in Figure 1, chapter 4). This is due to the low recycling rate of these metals from their EoL products (Drost & Wang, 2016; Haque et al., 2014; Jowitt et al., 2018), and the loss of material through the export of EoL products abroad (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). This type of production and consumption pattern describes what MacArthur (2017) termed a take-make-waste extractive industrial model (MacArthur, 2017; Sauvé et al., 2016) that needs to be replaced with a regenerative design and closed system known as circular economy (International Resource Panel, 2011; International Resource Panel, 2017; MacArthur, 2017; Sauvé et al., 2016; United Nations Environment Programme, 2019)

An analysis of REEs consumption over recent years (2017-2019) in Australia indicates a continuous increase in the demand for these metals in applications. This was not surprising as literature reports the same patterns in the demand for REEs previously, as well as globally (Balaram, 2019; Huleatt, 2019; Jowitt et al., 2018; Mudd et al., 2019; U.S. Geological Survey, 2020; Wang et al., 2017). Some metals, however, are shown to be of concern due to their higher demands in applications. This includes Yttrium and Neodymium, which are at the top of the ladder for critical metals. Previous studies on the consumption of REEs have equally identified Yttrium and Neodymium to be of great concern due to higher demands in applications globally (Binnemans et al., 2013; Guyonnet et al., 2015). Regarding applications with higher demands for these metals over time, the overall findings from this study (Chap 4, section 4.2) indicate that more focus should be placed on phosphors and magnets where the majority of these REEs are consumed, and material use efficiency strategies can most effectively be implemented to mitigate supply risks and reduce environmental burdens.

Another important finding was from the clean energy consumption sectors over the same time frame as above. The findings indicate a continuously growing trend in the demand for REEs in this sector. Australia, like many other countries around the world, largely depends on REEs to transition to a low-carbon economy (Binnemans et al., 2013; Sprecher et al., 2014; United Nations Environmental Programme-Global Environmental Alert Services, 2011; Zaimes et al., 2015). This likely explains why most of Australia's REEs are used in the low emission energy production (magnets for wind turbines, electric motors, hybrid vehicles) and low emission energy usage industry (phosphors) (chapter 4, Table 4.2). These results are important for Australia, as the management of critical metals has attracted attention from the Australian government (Wang & Kara, 2019). There is a growing demand for critical metals in the fast-growing promising clean energy sectors (such as in wind turbines and electric vehicles) (Wang & Kara, 2019). The fleet proportion of electric vehicles in Australia, for example, is projected to reach up to 75%-100% by 2050 (Wang & Kara, 2019). Electric vehicles and wind turbines heavily depend on the rare-earth magnets sector. The demand for Neodymium for example is expected to rise to more than 2600% in the next 25 years (Alonso et al., 2012).

The following sections present findings from the assessment of selected critical REEs consumption estimates in Australia using primary material inputs and the associated environmental impacts from these activities. The section demonstrates a sustainable management approach that can be used to assess resource use and impact over a given period.

6.2.1.2 Material use analysis (MUA)

The consumption of selected REEs in applications was estimated based on individual estimates of the proportions of these elements found in applications, derived from Binnemans et al., (2013), Australia's REEs annual mine production from the US Geological Survey (USGS) and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020), and export and import statistics from the WITS (World Integrated Trade Solution) database (WITS, 2019).

The overall consumption of REEs in Australia was estimated to be 60.6 kt in 2019. An analysis of individual critical REEs consumption in applications suggested Yttrium and Neodymium are the metals of highest concern. These critical metals made up 50% and 45%, respectively, of selected critical metal consumption in applications, in contrast to the other metals assessed (as discussed in Chapter 4). A possible explanation for this is the higher demand for these metals in applications. This also concurs with previous studies, which have suggested that these metals, and especially Neodymium, constitute some of the REEs most highly demanded in applications (Binnemans et al., 2013; Guyonnet et al., 2015; Jowitt et al., 2018). Alonso et al. (2013), have further suggested that with the dependency of electric vehicles and wind turbines on the REEs magnets sector, the demand for Dysprosium may increase by more than 700%, and the demand for Neodymium elements may increase by more than 2600% in the next 25 years (Alonso et al., 2012). These estimates, while preliminary, identify metals that rank highly on the list for criticality, and where more sustainable actions can be directed to help combat supply risk.

In terms of the individual applications compared, the findings from this study demonstrate that phosphors and magnets have a higher consumption of REEs when compared to the other applications found in the analysis. Both make up 27% and 26% respectively of the estimated consumption of the selected critical REEs, as compared to 2% or 1% from glass additives and auto-catalysts respectively. These results further support the notion that magnets and phosphors are the applications with the highest demand for REEs, and the reasons for the current emphasis on recycling from these sectors, as observed in the literature (Australia Trade and Investment Commission, 2019; Binnemans et al., 2013; Haque et al., 2014; Jowitt et al., 2018; Suli et al., 2017). These findings can be helpful to policymakers and stakeholders from the recycling industry when making decisions for the management of EoL products containing REEs.

6.2.1.3 Material use life cycle impact analysis in terms of Global Warming Potential (GWP)

The environmental impact derived from primary REEs consumption in applications in terms of CO_2 emission potential was evaluated. The overall results indicate a high potential CO_2 emission (2278.3 kg CO_2-eq/yr/1kt) associated with the primary consumption of REEs in applications in a given year (2019). The results provide distinct levels of the impact associated with the individual metals and applications. For instance, in terms of individual metal consumption in applications, Neodymium in magnets shows higher CO_2 emissions (1384.2 kg CO_2-eq/yr/1kt) in a year (2019) in comparison to the other metals. This is followed by Yttrium in phosphors(888.7 kg CO_2-eq/yr/1kt). A possible influence on this comparative allocation could be energy and material used (as they differ per REEs group), and the mass concentration of the individual REEs when calculating the share of the environmental impacts, which are higher for Neodymium and Yttrium compared to others.

In terms of environmental impacts derived from the individual REEs applications, the current findings associate magnets, followed by ceramics and phosphors, with greater environmental burdens, as the CO_2 emission potentials within this group were higher. It should be noted that magnets, ceramics and phosphors are also the applications with the highest consumption of the selected critical metals. The overall findings indicate how much environmental burden is generated from REEs primary material inputs in applications, which can be a good tool to assess against burdens from REEs from secondary material inputs for decision-making and policy development in the battle to achieve emission reductions (see section 6.2.3 of this chapter).

6.2.1.4 Material use life cycle impact analysis in terms of Cumulative Energy Demand Potential (CEDP)

The findings show the gross cumulative energy demand to be 25674.9 MJ-Eq./yr./1kt for primary REEs material consumption in applications. Neodymium and Yttrium are shown to have the highest environmental impacts derived from consumption in applications possibly for reasons cited in section 6.2.1.3 above.

The results also show a clear distinction in the distribution of impacts derived from individual applications. Applications like magnets and phosphors show a significant level of impact in comparison to other selected critical REEs applications. These results suggest that decision-makers should focus their attention on developing policies and other means (e.g., technologies) to reduce the cumulative energy consumption and environmental emissions from the use of REEs, for example, developing more energy efficiency magnets and phosphors in the use of Neodymium and Yttrium. According to the International Resource Panel (IRP), the main goal of sustainable resource management should be to connect economic activities to impacts on the environment as a whole, with end goals to target these driving forces and reduce impacts (International Resource Panel, 2017). These estimates equally provide parameters that can be used to assess CEDP in primary REEs material inputs in applications against secondary material inputs (as seen in section 6.2.3.1,c).

6.2.2 Secondary material input and life cycle impact analysis

A holistic and systematic approach was applied to examining secondary material input for REEs consumption in applications and the associated environmental impacts. The objective was to emphasise the need for sustainable strategies in REEs consumption. The first section (6.2.2.1) will discuss findings from recycling potentials (secondary material input), while the remaining sections (6.2.2.2 and 6.2.2.3) focus on the environmental impacts that can be derived from secondary material input consumption.

6.2.2.1 Recycling potential

Results show that sustainable resource consumption practices, like recycling efficiency, will improve resource use efficiency. Improvements in recycling can help to reduce material shortages as it will serve as a new source of inputs ("surface mines") back into the system. The material use analysis (MUA) showed REEs recycling potential to be 55.5% for the year 2019, a significant contribution to the overall supply of these metals. This suggests that improvement in recycling efficiency can significantly add to the supply of REEs and reduce dependency on primary material inputs. This finding broadly supports the work of other studies in this area, which have suggested that REE recycling has the potential to offset a significant part of primary REE extraction in the future (Binnemans et al., 2013; Du & Graedel, 2011; Guyonnet et al., 2015; Sprecher et al., 2014; Zaimes et al., 2015).

Furthermore, when individual REEs are compared (Table 5.1, Chap 5), the results reveal Yttrium (50%) and Neodymium (45%) to have the highest recycling potential. This finding has important implications for decision-makers and policy developers to target specific metals with greater secondary material input. From the same perspective, an analysis of the individual applications clearly shows that phosphors (27%) and magnets (26%) have a higher gross recycling potential in comparison to the other applications. These findings suggest specific applications where policies can be directed towards increasing secondary material inputs from the waste stream to offset primary REE extraction. This finding also aligns with earlier observations, which showed that phosphors and magnets provide a significant source of secondary material input from REEs (Binnemans et al., 2013; Guyonnet et al., 2015; Jowitt et al., 2018; Zaimes et al., 2015).

6.2.2.2 Global Warming Potential (GWP)

Findings show gross CO_2 emission potential derived from secondary material input from applications in a given year (2019) to be 1253.0 (kg CO_2-eq/yr/1kt). These findings are important as the results can be used to compare the environmental impact derived from primary and secondary material inputs of REEs in applications (as seen in section 6.2.3). This will help to highlight the benefits of recycling, as opposed to virgin material use. The findings also report the individual metals with the highest CO_2 emission potential from secondary material inputs. This was the case of Neodymium (761.3 kg CO2-eq/yr/1kt) in magnets, metallurgy, ceramics, battery alloy and auto-catalyst, and Yttrium (488.8 kg CO_2-eq/yr/1kt) in phosphors, ceramics, and glass additives. This finding, while preliminary, equally identifies metals for which policies can be directed towards reducing CO_2 emissions. Regarding individual applications, the same focus can be directed to magnets, ceramics and phosphors. A logical explanation for this high CO_2 emission potential could be related to the higher demand for these applications, especially in the clean energy sectors.

6.2.2.3 Cumulative Energy Demand (CEDP)

An analysis of the cumulative energy demand potentials derived from REEs secondary material consumption in applications suggests a gross estimate of 14482.7 MJ-Eq./yr./1kt in a given year (2019).

One of the aims of this study was to demonstrate a scenario to highlight the difference between primary (virgin) and secondary (recycling) material input, and to show major environmental gains that can be achieved through increased recycling. This is analysed below in section 6.2.3 in terms of material savings and environmental impact reductions from a resource management perspective.

6.2.3 Comparing primary and secondary material inputs

One of the primary objectives of this study is to highlight the difference between primary (virgin) and secondary (waste recoveries, recycling) material inputs of REEs consumption in applications. From a resource perspective, the study is interested in the extent to which primary material and derived environmental impacts can be avoided by using secondary material inputs. The goal is to demonstrate the benefits from secondary material consumption of REEs, as opposed to primary, and to establish CE strategies of resource efficiencies as important sustainable management practices for REEs in Australia, to demonstrate the significance and benefits of improving resource efficiency (waste recoveries, recycling etc). The study compares the CO_2 emission and energy consumption derived from the use of primary material with those of recycling (secondary material) and demonstrates the major reductions in environmental impacts that can be achieved through increased recycling. The first part (a) looks at findings from material savings in terms of primary and secondary inputs of REEs material consumption in applications, while the other two parts b) and c) look at environmental impacts in terms of impact reductions respectively.

6.2.3.1 Sustainability benefits from improvement in resource efficiencies (recycling), from a resource management perspective

a) Material saving analysis

Eco-environmental benefits: Overall results suggest that improvement in recycling efficiency strategies can significantly add to the supply of REEs and reduce dependency on primary material inputs. The results indicate total REEs recycling potential to be 54.5% in 2019 (as seen in Table 5.4 and Table 5.5, Chap 5). This estimation suggests that secondary material inputs of REEs can be a significant source of material to complement the virgin material inputs and combat supply risks. Further, every kilogram of a material that is successfully recycled and regained reduces the need to mine an extra kilo from virgin sources (International Resource Panel, 2011) and thereby reduces energy usage and environmental pollution (avoided impact from mining) (Balaram, 2019; Eckelman & Chertow, 2009); this is demonstratedin section b) and c) below regarding CO_2 and cumulative energy demand reduction potential from secondary material inputs respectively. Previous studies suggest that recycling has the potential to offset a major part of primary REE extraction in the future (Balaram, 2019; Binnemans et al., 2013; Guyonnet et al., 2015; Sprecher et al., 2014; Zaimes et al., 2015). As such, waste products containing these materials should be regarded as "surface mines" that need to be exploited rather than waste materials ready to be discarded (International Resource Panel, 2011). Findings from previous studies noted that WEEE (Waste Electrical and Electronic Equipment also known as e-waste) contains a very high portion of REEs in its waste stream, but there is insufficient regulation in Australia to fully manage this waste stream (Islam & Huda, 2019; Islam & Huda, 2020). Currently, focus is placed more on magnet scrap recovery, with no regulating policies for improving the whole waste management system (Islam & Huda, 2020). For instance, the current NTCRS (National Television and Computer Recycling) oriented e-waste scheme conducts first-stage recycling operations (collection and sorting) in Australia and then transports the waste overseas for downstream recycling to developing countries while recovered/sorted products from other electronic products (category 1, 3 and 4) are considered as garbage, with the majority ending up in landfill (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). In terms of material circularity, this is a loss, and is an unsustainable practice that requires stricter regulations to enforce the recovery of these materials from waste. Moreover, Corder et al (2015) reports that in a year, there is an estimated 6 million tonnes of metal content in waste in Australia, which could supplement 50% of annual metal consumption in the country (Corder et al., 2015), constituting an estimated worth of AUD 6 billion if fully recovered (Corder et al., 2015).

The overall results also show material savings in terms of individual applications and metals (as seen in Table 5.4 and Table 5.5, Chap 5). Regarding applications, findings show material savings to be highest with phosphors (26%) and magnets (27%) respectively, with the main demand from Neodymium and Yttrium among the selected critical metals. This should be due to the higher demand for these applications in the clean energy sectors. This also explains why the literature indicates that recycling and recovery of REEs from EoL products in waste containing these metals is highly focused on magnet scrap, and recovery of phosphors (Arshi et al., 2018; Balaram, 2019; Binnemans et al., 2013; Guyonnet et al., 2015; Jowitt et al., 2018; Navarro & Zhao, 2014; Sprecher et al., 2014; Suli et al., 2017; Zaimes et al., 2015). These are indicative of areas for policies to support product design for recycling, where the reuse and recovery of the materials can be reinforced to improve resource efficiencies. Increasing the recycling of REEs in the waste stream can contribute to overcoming some of the critical issues faced by these metals, such as supply risk and the environmental burdens associated with primary material inputs (Jowitt et al., 2018).

Socio-environmental benefits: Furthermore, REE recyclates do not contain radioactive thorium and uranium, as opposed to the primary mined REEs ores (Binnemans et al., 2013). It is possible, therefore, that radioactive tailing stockpiles and mining health problems can partially be avoided with recycling (Balaram, 2019; Eckelman & Chertow, 2009). Although recycling alone should not be regarded as a solution to the entire REEs problem (supply shortages, environmental burdens etc.), these figures from recycling potential should be a strong incentive for an increase in efforts to reclaim these materials as they show that there are significant amounts of REEs in the waste stream.

b) CO_2 emission reduction potential

GHG emission benefits from recycling were determined by comparing virgin material inputs with recycled material (Grimes et al., 2008; United State Environmental Protection Agency, 2011). This method quantifies the material-specific GHG emission reduction benefits associated with recycling. The overall result indicates a gross CO_2 emission reduction potential of 1589.1 kg CO_2-eq/yr/1kt (REE) for a given year (2019). Overall, the results show that secondary material inputs of REEs consumption in applications will result in lowered CO_2 emission potential when compared to primary material inputs and, subsequently, extensive savings of carbon dioxide equivalence.

The analysis shows that the gross CO_2 emission for using REE primary material input in applications will fall from 2278.3 to 1253.0 kg CO_2-eq/yr/1kt in the case of secondary material inputs. This will lead to a reduction of 1589.1 kg CO_2-eq/yr/1kt. Applications with the highest consumption of these metals such as magnets, phosphors, and ceramics are the sectors with the maximum reduction potential. This reflects their higher demand and importance in the clean energy sector in comparison to other metals (see Chapter 4, Table 4.2).

This finding, while preliminary, suggests that a shift from primary material dependency will not only lead to material savings (as seen in section a) above), but equally to global warming reduction potential via thousands of kg CO_2-eq/yr/1kt emissions avoided. This finding fortifies the notion that improvement in resource efficiency strategies (EoL collection rate,) and recycling process efficiency (technological), can help to reduce overall environmental burdens (Binnemans et al., 2013; Eckelman & Chertow, 2009; International Resource Panel, 2011). This outcome supports one of the objectives of this study, which was to demonstrate the importance of recycling input, as opposed to virgin material input, for REEs consumption in applications. These results further reinforce the notion that the substitution of primary materials with secondary material input and environmentally-friendly recycling techniques is expected to contribute strongly to reducing the global ecological footprint of REEs consumed in the world (Arshi et al., 2018; Binnemans et al., 2013). Other studies equally reported that the environmental benefits of substituting virgin material inputs with secondary materials could result in significant carbon dioxide savings (Eckelman & Chertow, 2009; Grimes et al., 2008).

c) Cumulative Energy Demand Reduction Potentials

Analysis of cumulative energy demand reduction potential (CEDP) suggests an overall reduction of environmental burdens in terms of cumulative energy consumption. The results indicate a gross cumulative energy demand reduction potential (avoided energy usage) of 17709.4 MJ-Eq./yr./1kt for a given year (2019). The results show material-specific CEDP reduction benefits associated with recycling. It includes the avoided energy use from manufacturing using secondary material inputs, the use of raw materials in the manufacturing process, and recycling efficiency.

The results indicate that the gross total CEDP for using REEs primary material inputs in applications decreases from 25674.9 to 14482.7 (MJ-Eq./yr./1kt) for the given year (2019). This results in an estimate of 17709.4 (MJ-Eq./yr./1kt) energy savings for the given year (2019). This reinforces the conclusion reached by Eckelman and Chertow (2009) who reported that, in general, the processing of secondary materials requires less energy and results in less pollution than the production of equivalent quantities of virgin material (Eckelman & Chertow, 2009). Chapman and colleagues at the UK Open University established this as early as the 1970s (Chapman, 1975). Furthermore, findings indicate that individual REEs such as Neodymium and Yttrium will have higher energy demand reduction potential associated with recycling activities. These are REEs with the highest demand in the clean energy sector, mostly consumed in applications such as magnets and phosphors. These are also the applications with the highest energy demand reduction potentials associated with recycling activities. In combination, these findings can help support researchers, industry and policymakers when looking into specific materials and applications for DfE (Design for Environment) to mitigate environmental impacts often caused by mining.

It is expected that improvement in the EoL recycling rate for REEs will result in diverse environmental benefits, coinciding with the transition to a low-carbon CE and greatly improved working environments, compared to the current state-of-the-art primary production (Balaram, 2019; Binnemans et al., 2013). This is also because, in general, the use of secondary materials for production has less associated life cycle impact than the use of primary (virgin) materials, as secondary materials are already partially refined and have embedded in them much of the needed material and energy (Eckelman & Chertow, 2009).

6.3 A comprehensive CE framework for Criticality Mitigation. Moving towards circularity

This section aims to further discuss the impact of and strategies for integrating REEs within the sustainable development framework from a CE perspective, as an approach for REEs material criticality mitigation. The section starts by proposing a novel framework for REEs within a sustainability paradigm and a holistic view of the contribution of CE to the sustainability of REEs consumption.

To establish CE as a sustainability strategy for REEs within the framework of sustainable development, a comprehensive REEs CE framework for material criticality mitigation was developed. The proposed framework demonstrates a CE concept of REEs integrated within the sustainable development framework, as a way toward material circulation and sustainable REEs management. This framework underlines sustainability in REEs material consumption from a CE approach, which contributes to the three main pillars of sustainable development. Any efforts toward combating REEs material criticality must involve a systematic perspective that harmonises the socio-economic and environmental prosperity of the use of these metals, as illustrated in Figure 6.1 below. The proposed scheme underlines two major points of interest to consider when examining or integrating REEs into the sustainable development framework from a CE perspective: (1), sustainability and REEs material criticality(section 6.3.1); 2) REEs and sustainability management strategies in Australia(section 6.3.2).

The first approach follows the widely used triple bottom line theory of the sustainable development framework concept of economy, environment and society as an integrated system. The proposed framework suggests that economic prosperity must occur in harmony with social and environmental growth. In other words, a closer look at those aspects that affect sustainability in REEs environmentally, economically, and socially is a prerequisite to successfully establishing a sustainable REEs future. This involves the examination of material criticality and sustainable strategies to reduce impacts. The environmental pillar addresses the sustainable mining and processing of REEs to reduce virgin material consumption, and to avoid and minimise environmental burdens. The economic pillar looks at the efficient use of REEs in products and EoL to minimise waste and mitigate material criticality, while the social pillar addresses people and sustainability actions to REEs use. This involves the capacity and willingness for people to contribute to sustainability goals, such as the reuse and recycling of materials, or actions taken to avoid and minimise society-wide impacts and maintain community health.

The second approach focuses on the analysis of existing strategies and policies that govern the consumption of REEs in Australia. It focuses on integrating the implementation of CE principles with REEs material resource management in the context of sustainable development (see Figure 6.3). It involves strategies for mitigating REEs supply risks and waste management approaches to reduce material loss and environmental impacts, as demonstrated in Figure 6.3. It underlines that sustainability in REEs consumptions is a combination of a set of strategic CE components in addition to recycling. This is particularly important as the improvement in recycling techniques alone is not adequate in attaining sustainability in REEs, especially in the short term. This is partly due to the majority of products with significant REEs content, such as wind turbines and electric vehicles, having a long-life expectancy. Consquently, the quantity of EoL products available to be recuperated to complement virgin material input is limited in the short term (Jowitt et al., 2018; Rademaker et al., 2013; Zaimes et al., 2015). Sustainability in REEs against material criticality must, therefore, be regarded not only as a one-way strategy that solely relies on advancement in recycling technologies but as a holistic system that needs systematic improvement. REEs consumption viewed from a CE perspective contributes to all the pillars of sustainability in the short and long-term.

These two approaches are directly related to the responsible consumption and production of the United Nations (UN) Sustainable Development Goal 12 (SDG 12), and are significant to establish grounds to reinforce CE, both as a sustainable development strategy and as a strategy for sustainability in REEs.

6.3.1 REEs within the framework of sustainability (Sustainability and REEs criticality)

Improvements in sustainable resource consumption practices such as material efficiency, reuse, repairs, design for long-life, and recycling efficiency are promising strategies to improve REEs resource use efficiency. However, this cannot be achieved without a broader consideration of the environmental, social, economic, geological and technical aspects of the consumption of these metals. The sustainability and criticality of REEs can be understood by critically considering the consumption of these metals from the perspective of sustainable development and its three pillars (environmental, social, economic), including the geological and technical aspects of REEs. An understanding of REEs consumption within the framework of sustainability provides a background for the implementation of CE strategies to achieve material resource efficiencies by closing material loops and minimising environmental and social impact. When examining the sustainability of REEs, it is paramount to consider the full life cycle of the material (from extraction, manufacturing through to waste disposal and recycling). Another perspective of resource consumption and availability is the impact on the environment and people, and economic prosperity (as illustrated in Figure 6.1).

Over the last decade, REEs material criticality has gained global attention, primarily due to their economic viability, isolated availability in only a few nations and high supply risk. As an important concept, CE aims to improve material use by transforming materials during and at the end of their life services into resources for others (MacArthur, 2017; McLellan et al., 2014). CE is, therefore, seen by many industrialists and stakeholders as a vital tool in addressing material criticality (McLellan et al., 2014; Wang, P. & Kara, 2019). As such, it is a promising solution to resource scarcity, waste minimisation and material criticality mitigation, especially if a complete life cycle of the material is involved (Gaustad et al., 2018; John et al., 2016; McLellan et al., 2014; Wang & Kara, 2019). Figure 6.1 below suggests a comprehensive CE scheme for criticality mitigation, positioning REEs within a sustainable development framework developed from (Korhonen et al., 2018).

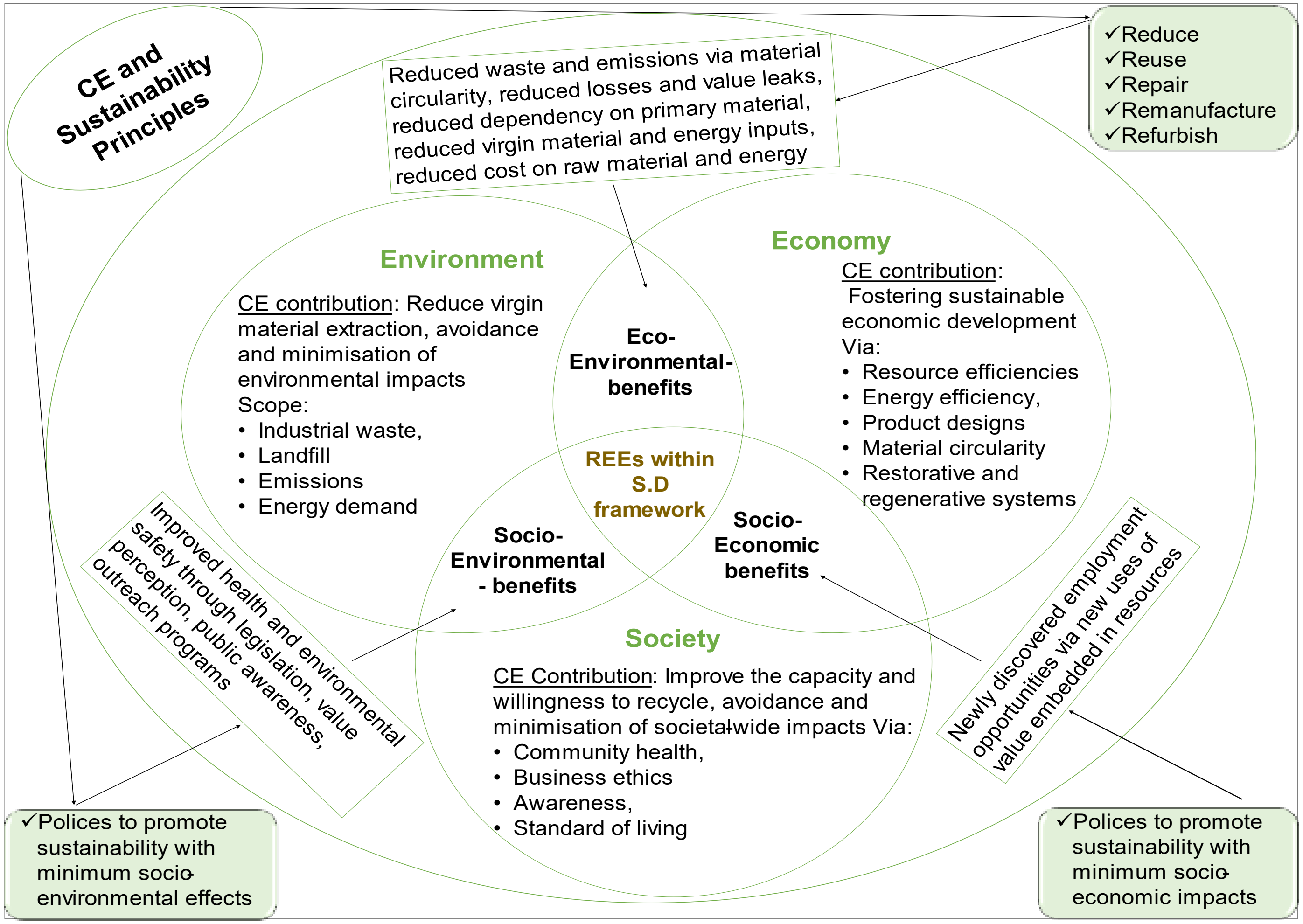


Figure 6.1: A comprehensive CE framework. Moving towards circularity: REEs within the framework of sustainable development[3]

[3] REEs within the framework of sustainable development. The work suggests that sustainability in REEs consumption from a CE perspective contributes to all the three pillars of sustainable development (Economics, Environmental and social). We must understand the existing pattern of REEs consumption to build a sustainable REEs future. Doing so requires a closer look at those aspects affecting sustainability in REEs environmentally, social, and economic.

Economy: The economic aspect of REEs examined within a sustainability framework provides a background for the examination of the material criticality, its economic viability, continuous increase in demand vs low supply, its importance to clean energy and inequality in global distribution. The increasing growing demand for these critical materials could disrupt the transition to a low carbon economy by outpacing new mining projects, thus leading to supply risk issues (United Nations Environmental Programme-Global Environmental Alert Services, 2011). These materials are considered to have few effective substitutes (King, 2021), and currently face low recovery and recycling rates as well (Goonan, 2011); further there is unequal global distribution of these materials. China controls most of the world's supply and demand (Balaram, 2019; Goonan, 2011; McLellan et al., 2014). Mines in Australia and other parts of the world are only becoming active again due to China's limited exports, the supply restrictions placed on REEs, high cost of materials, and taxes (King, 2021). The strategic and economic importance of these metals, and their critical nature, should not only be a driving force in the exploration of other reserves in different parts of the earth and increased mining, but also a reason for expansion in sustainability strategies for the consumption and production of these metals. Such expansions include the development of advanced environmentally-friendly techniques for the recovery of these materials at the end of their use to minimise waste and subsequent environmental impacts, product designs to increase longevity, restorative and regenerative systems, sustainable business models, research into alternatives, and more changes in international policy (United Nations Environmental Programme-Global Environmental Alert Services, 2011).

Socio-environmental aspects: When looking at the social aspect of REEs within a sustainability framework, it is paramount to consider those components relating to the physical and psychological wellbeing of people within society (McLellan et al., 2013). Another major problem with REEs is the association with radioactive elements (particularly thorium and uranium) during mining (Rim, 2016; Zaimes et al., 2015). This generally inflates operation costs as it requires strict environmental and health safety mitigation methods to be operational (United State Environmental Protection Agency, 2012). This aspect of REEs sustainability is a key socio-environmental component of concern to the community. However, REEs recyclates are considered not to contain radioactive thorium and uranium, as opposed to virgin mined REEs ores (Binnemans et al., 2013). It is possible, therefore, that radioactive tailing stockpiles and mining health problems can be partially avoided through recycling (Balaram, 2019; Eckelman & Chertow, 2009), a CE contribution toward resource efficiency and sustainable consumption. Thus, environmentally-friendly recycling technologies, community awareness, and business ethics can be considered essential CE pathways toward the sustainability of REEs consumption.

The current and future economic, environmental and social challenges of REEs are interlinked and must be addressed through an integrated approach as described in the REEs CE framework in Figure 6.1 above. The following section looks at a practical example of CE as a tool for REEs management and the implementation strategies as a way forward to mitigate material criticality by closing material loops and improving resource efficiency.

6.3.2 REEs and Sustainability Strategies (a conceptual and practical model from a CE perspective)

Based on the discussion of the empirical findings from this research project, this study presents below a conceptual and practical model to act as a framework to help practitioners and stakeholders in the REEs industry with the CE strategy implementation process. A novel proposal is presented, providing a background for a complete understanding of REEs consumption from a CE context and a way forward to close the material loop and improve REEs material efficiency.

6.3.2.1 Sustainable Management Framework and Mitigation Strategies for REEs (SMF-MSR) in Australia in a CE Perspective: A material consumption minimisation and waste prevention approach

One of the major goals of this study was to introduce a novel framework for sustainable consumption of REEs in Australia, and by extension to other countries, from a CE perspective, to demonstrate the importance of improving recycling rates and resource efficiency strategies. To that end, this section provides an answer to how the sustainability of REEs consumption in Australia can be enhanced based on circularity. Based on resource efficiency road map strategies (as seen in Figure 6.1), for waste to be managed as a (valuable) resource, in the CE, waste generation must be minimised while recovery must be optimised, such that landfill is only available to non-recyclable materials (Mudgal et al., 2012). Therefore, to achieve maximum REEs resource efficiency in Australia, we must eliminate any unsustainable practices in material resource consumption and the production system. Here resource efficiency refers to using the Earth's limited resources sustainably while minimising impacts on the environment (Mudgal et al., 2012). The main goal of CE as a sustainable management strategy is to use natural resources and design products in a way that extracted raw materials are used efficiently and as many times as possible, as illustrated in Figure 6.2 below, a sustainable management CE model.

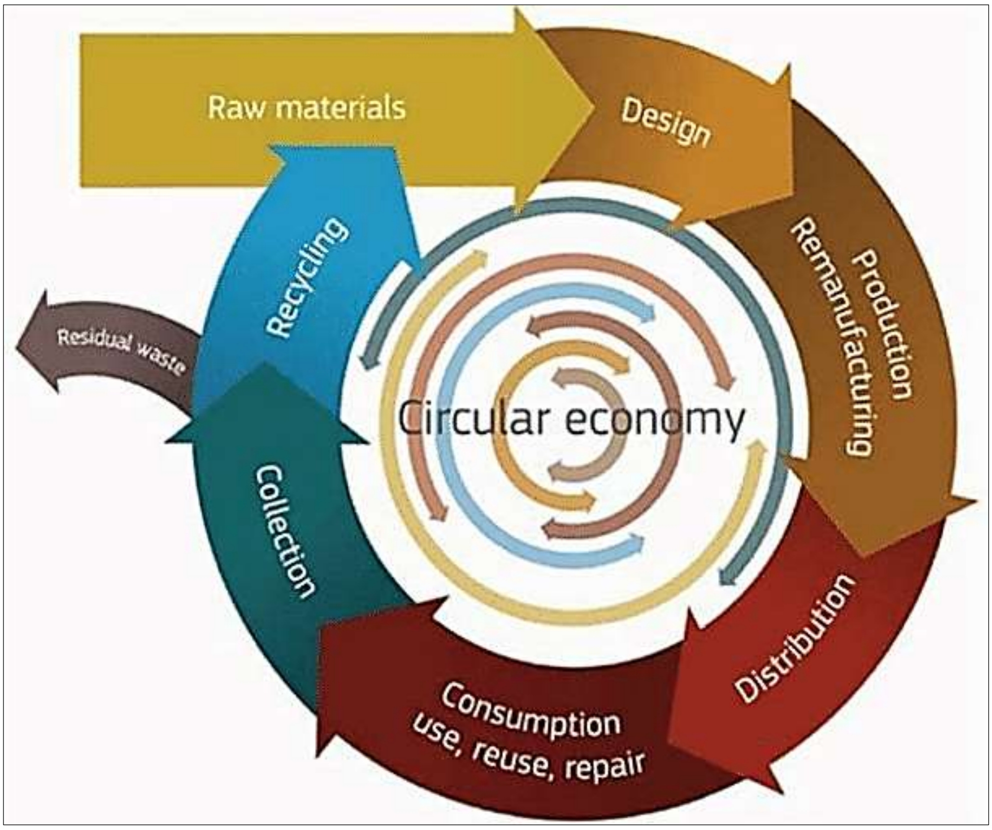


Figure 6.2: Circular economy, a sustainable management model for resource production and consumption.
Source: (European Commission, 2014)

Enhancing recycling efficiency alone, however, is not sufficient to achieve sustainability in the REEs industry without considering the implied economic and socio-environmental effects of the consumption of these metals (as analysed in Chapter 4 result I), particularly while REEs consumption in applications are heavily associated with environmental burdens such as CO_2 emissions and cumulative energy demand. A complete system refinement is necessary, from raw material through manufacturing and EoL treatments, without omitting any stage (see Figure 6.3). Targeting the weakest links in the chain provides the best opportunity for improving the recycling rate for these metals, which in turn can help reduce the overall environmental impact of the metals' supply. Currently, in Australia, examples of the weakest link, as previously mentioned, include waste collection and recycling infrastructure development, and the lack of sustainable policies regulating this sector (Islam & Huda, 2020). As a sustainable CE strategy, more focus needs to be placed on the recovery of secondary materials from waste and the enhancement of the whole system to close the loop and reduce dependency on virgin material sourcing. As seen in the material saving analysis results (section 6.2.3.1, a), improvement in recycling efficiency strategies has the potential to significantly contribute to REEs supply.

The crucial goal of the CE framework, as adopted in this study, is to introduce sustainable mitigation strategies and policies that would improve the current pattern of resource consumption and waste management in Australia in a way that reduces pressures on the limited resource of REEs and climate change, while promoting human and economic development. Implementation of a holistic and systematic strategy via CE is essential to REEs material efficiency from raw material through use and EoL policies for waste management. A sustainable management framework based on the CE model is significant for identifying the areas where strategies can be implemented to achieve sustainable consumption of these critical metals. Figure 6.3 suggests a conceptual and practical framework to help practitioners and stakeholders in the REEs industry with the implementation of CE strategy to close the material loop, improve resource efficiency and achieve sustainability in REEs, a framework based on the CE "R" principles and material consumption minimisation and waste prevention approach. As such, the CE model as a regenerative system with its R's principles: Reduce; Reuse; Repair; Refurbish; Recycle all embodied under the umbrella term Re-thinking, is proposed to close material loops and keep resources in circulation. Re-thinking evolves life cycle material flow strategies. It is a whole process of reflecting on every action of material consumption to reduce waste and increase material use efficiency (MacArthur, 2017).

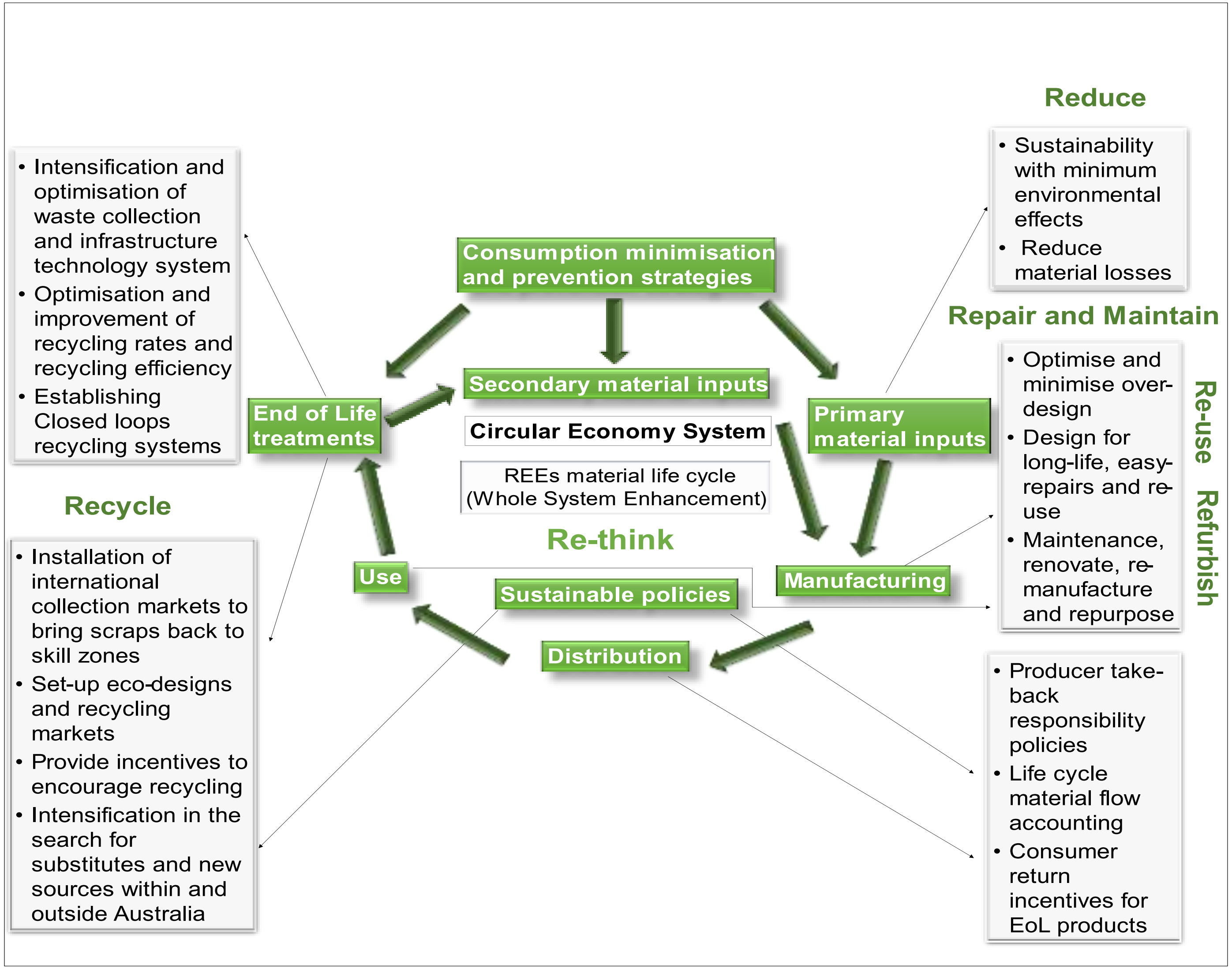


Figure 6.3: Sustainable Management Framework and Mitigation Strategies for REEs (SMF-MSR) in Australia from a CE perspective. A material consumption minimisation and waste prevention approach.

Adapted from the CE Model (European Commission, 2014)

A holistic and systematic CE model necessary to support REEs material efficiency from a material life cycle perspective (from raw material through use and EoL) is demonstrated in Figure 6.3. The approach underlines vital strategies to determine the potential for various REEs waste streams for recovery, including major phases where strategies can be implemented to close material loops and achieve sustainable consumption of these critical metals. Results (as seen in Chapter 5, section 5.2, Table 5.1) show that improvement in recycling efficiency can significantly add to offset virgin material input.

The framework suggests that apart from the focus on improving EoL strategies (collection, recycling) for the consumption of these critical metals, the different components within the CE model, such as the manufacturing-orientated strategies (reduced, long-lasting design, maintenance, and repair, renovate, remanufacturing and refurbish.) offer further potential to improve the sustainability of REEs consumption. In essence, while the EoL strategies are implemented with the main aim of turning waste into resources for new products (recycling), the manufacturing-oriented strategies are implemented to improve the sustainable use of materials via life cycle engineering strategies, with a specific emphasis on product design such as design for durability, intense use, reuse, remanufacture, and design for easy reuse and recyclability (Wang & Kara, 2019). In this regard, emphasis is not only placed on recycling, but equally on the need to tackle the consumption aspect of these metals. From this perspective, resource efficiency, as a CE strategy, can be viewed not as a one-way strategy that depends on recycling efficiency but rather as a holistic system that requires efficiency and constant rethinking. Looking at material consumption from the perspective of a holistic system is significant as this provides a plausible picture of potential consequences, priority areas, and the development of measures to mitigate or reduce any negative impact (Wagner, 2002). It provides an important tool, which helps to rethink consumption habits employed. Below are some mitigation strategies based on a combination of CE principles and resource management practices that can be implemented to enhance sustainable consumption of REEs in Australia, and minimise consumption to manage supply risks, waste prevention and environmental impacts (as suggested in Figure 6.3):

- **REEs sustainable consumption mitigation strategies based on circularity**

a) Collection, recycling (EoL CE-oriented approaches)

As identified in the literature review, although REEs from pre-consumer scrap, industrial residues and EoL products containing REEs are potential sources to supplement shortages in

REEs supply and mitigate supply risks, the EoL recycling rate of REEs is generally low (less than 1%) (Binnemans et al., 2013; Dang et al., 2021; Favot & Massarutto, 2019; Guyonnet et al., 2015; Sprecher et al., 2014; Zaimes et al., 2015). The main reasons are due to the inefficient collection, technological problems, low yields plus the cost and, notably, a lack of incentives (Balaram, 2019; Binnemans et al., 2013; Du & Graedel, 2011; Du & Graedel, 2011). As observed in Figure 6.3, a sustainable management framework for REEs, an increase in EoL recycling rates can only be attained through drastic improvement of the aforementioned factors that affect recycling efficiencies (Balaram, 2019; Binnemans et al., 2013; Goonan, 2011). To do so, improvement of the whole system (**Rethinking**) is a necessity and requires targeting the weakest links in the entire chain (United Nations Environmental Programme-Global Environmental Alert Services, 2011). The perception that EoL products are waste needs to shift to a perspective that EoL products are resources in order to promote the effective collection and proper treatment of these materials and enforce legislation.

For instance, the first step in waste recycling, the collection phase, can be greatly improved by setting up international and local collection points and markets to bring scrap back to skill zones. This can be done in conjunction with the development of economic designs and recycling markets that make it easier to collect and recover EoL products containing these metals. This study has found that phosphors and magnets have the highest concentration of these metals, so they should be targeted specifically. Other measures that can be taken include introducing mandatory producer take-back policies and providing incentives for consumers and recyclers (see Figure 6.3). Extended Producer Responsibility (EPR), for example, is a type of stewardship that places primary responsibility on the manufacturer, importer, or seller for the management of EoL products (International Resource Panel, 2017). The EPR approach involves a take-back system, where these stakeholders are responsible for collecting EoL products from consumers (International Resource Panel, 2017). With the majority of EoL applications that contain REEs ending up in less developed countries for downstream recycling (Islam & Huda, 2019; Islam & Huda, 2020), an implementation of the above-mentioned CE EoL strategies can help to close the material loop by bringing materials back into circulation, reducing losses and eliminating export of scrap to unskilled zones. Compulsory producer take-back strategies would place the burden of EoL REEs product collection on the producers, while incentives for consumers could facilitate the return of EoL products to service points or recycling markets. Sustainable management of waste products containing these metals can help to improve the environment by reducing more demands from virgin sources, as well as the associated environmental impacts (as seen in section 6.2.3 of this chapter) including minimisation of waste.

Moreover, optimisation of the recycling phase can improve the EoL recycling rate and recycling efficiencies. EoL recycling rates compare the quantity of metal acquired from recycling with the amount theoretically available at the end of the life of products (Binnemans et al., 2013; Du & Graedel, 2011; International Resource Panel, 2011). This rate depends on the efficiency of the metal collection (collection system) and the recycling process efficiency and technology (extraction of metals from EoL products) (Binnemans et al., 2013; International Resource Panel, 2011). Improvements in the waste collection system, legal enforcement governing the recycling section (incentives to recyclers, for instance), and environmentally-friendly technology (recycling process efficiency) can have a drastic impact on EoL recycling rates (Binnemans et al., 2013; Goonan, 2011). The findings in this study (as demonstrated in Chapter 5, section 5.2, Table 5.1) show that improvements in sustainable resource consumption practices such as recycling efficiency can advance recycling rates and add significantly to the overall supply of REEs and minimise overall primary material consumption inputs.

Previous studies have suggested that REEs can be recycled efficiently through the development of environmentally-friendly and holistically sound recycling flow sheets, together with dismantling, sorting, pre-processing, and pyro-, hydro- and/or electrometallurgical processing steps to recover REEs in the waste stream (Binnemans et al., 2013; Guyonnet et al., 2015). The current focus on magnet scrap recovery business structures can be replaced with these high-tech recycling and environmentally-friendly technologies, as suggested by Binnemans (2013) (Binnemans et al., 2013; Guyonnet et al., 2015). Efficient recycling of REEs can significantly increase the quantity of materials in the global market (Du & Graedel, 2011; Zaimes et al., 2015) and reduce dependency on primary material use. It can provide both economic and environmental benefits in terms of addressing resource scarcity, in addition to resource conservation and environmental impact reductions from avoided mining. Corder et al reported an estimated 6 million tonnes of metal content in Australia's waste stream, and an estimated AUD 2 billion a year potential for "wealth from metal waste", consisting of the value lost with landfill and export of waste abroad for downstream recycling (Corder et al., 2015).

Many of these applications, however, such as mobile phones, only contain small proportions of REEs (Balaram, 2019; Du & Graedel, 2011; Navarro & Zhao, 2014). This, combined with the complexity of their use, and difficulties in extracting and recovering the constituent within the EoL products, makes recycling costly and energy-intensive and, therefore, from the recycler's point of view, not economically feasible (Du & Graedel, 2011; Jowitt et al., 2018; Navarro & Zhao, 2014; Zaimes et al., 2015). For recycling to be feasible on a commercial scale, many of these technical and economic constraints must be overcome (Jowitt et al., 2018; Zaimes et al., 2015). According to the US Geological Survey (USGS), recycling of REEs is possible if government legislation can mandate recycling, or if elevated REEs costs make REE recycling economically feasible (Goonan, 2011). As such, although recycling can contribute positively to offsetting the demand for primary materials, this alone cannot be the solution to REEs supply risk (Zaimes et al., 2015). Improvement in the whole system is necessary, from raw material extraction through to manufacturing and EoL treatments, without omitting any stage (as suggested in Figure 6.3). As demonstrated in this study, CE as a holistic and systematic management tool can provide the necessary framework for system optimisation.

b) Reduced, long-lasting design, maintenance, and repair, renovate, remanufacturing and refurbish (Manufacturing-oriented CE approaches)

The manufacturing-oriented approaches of the CE model offer other options to complement the EoL-oriented strategies for sustainability in REEs consumption and close the material loop. As outlined in Figure 6.3, in a closed-loop system, long-lasting design, maintenance, and repair, reuse, remanufacturing, and refurbishing of REEs resources become important tools for efficient material use and waste prevention (Geissdoerfer et al., 2017). A REE element in an object that lasts a year is much less sustainable than a REE element in something that functions for 10 years through long-lasting designs that allow for easy repairs, re-use and recovery of materials. The increased demand for REEs in applications, and their importance in the growth of the green economy, military and health technologies, as well as their availability in just a few nations, are the leading causes of its criticality. Any measure aiming to minimise the material demand for REEs is essential for material criticality mitigations. Although recycling is promoted as a resource efficiency strategy with the potential to contribute significantly to primary material input (as seen in chapter 5, section 5.2 result), the impact on REEs demand reduction can be quite minimal in a short-term frame, as many of these applications have a long-life expectancy (such as wind turbines, electric vehicles) and usually with a small proportion of REEs concentration (for instance, mobile phones, computer disc drives). As such, recycling is a less efficient option, due to the limited amount of EoL products available for recovery as substitutes for primary material inputs (Jowitt et al., 2018; Rademaker et al., 2013;

Zaimes et al., 2015). In this regard, the implementation of CE manufacturing-oriented strategies forwaste prevention offers the most environmental and economic benefits in terms of material efficiencies, waste prevention and supply risk mitigations, complementing the EoL-oriented CE strategies.

One of the core principles of CE is to bring back materials used in the system with maximum waste elimination through material use efficiency strategies. CE manufacturing-oriented strategies can help achieve sustainability in REEs consumption through long-lasting application designs that extend product longevity through manufacturing for easy-repairs, reuse, remanufacturing and refurbishing, renovating, and repurposing. This would not only help to increase material efficiency but would also help minimise waste generation through less material consumption and longer use, as well as reduce overall associated environmental burdens.

c) Life cycle material flow accounting

A sustainable CE, however, cannot be achieved without an accounting system, as this is pivotal for a sustainable economy. Life cycle material flow accounting is essential to provide in-depth structural and systematic information on the whole life cycle of REEs consumption. Establishing a life cycle material flow accounting system can drastically impact material efficiency and sustainable consumption of REEs in Australia. Material flow accounting systems would facilitate the availability of data and in-depth knowledge of REEs material availability across the nation. It is important to determine the production, consumption and circulation, export and imports of these materials, as well as recycling information and potential waste streams for material recovery. Material flow accounting for critical materials can help to reduce impacts by providing information necessary to develop strategies for sustainable use of resources across the entire economy. As such, this study serves to demonstrate the significance and need for material flow accounting as a pivotal policy and decision-making tool to improve resource management to achieve sustainable end goals. Figure 4.1, chapter 4, illustrated a life cycle material flow of REEs and identified sectors (leakages) that need to be improved to achieve resource efficiency in Australia. Figure 6.4 below demonstrates a further analysis of the impact and strategies for improving those leakages to achieve sustainability in REEs.

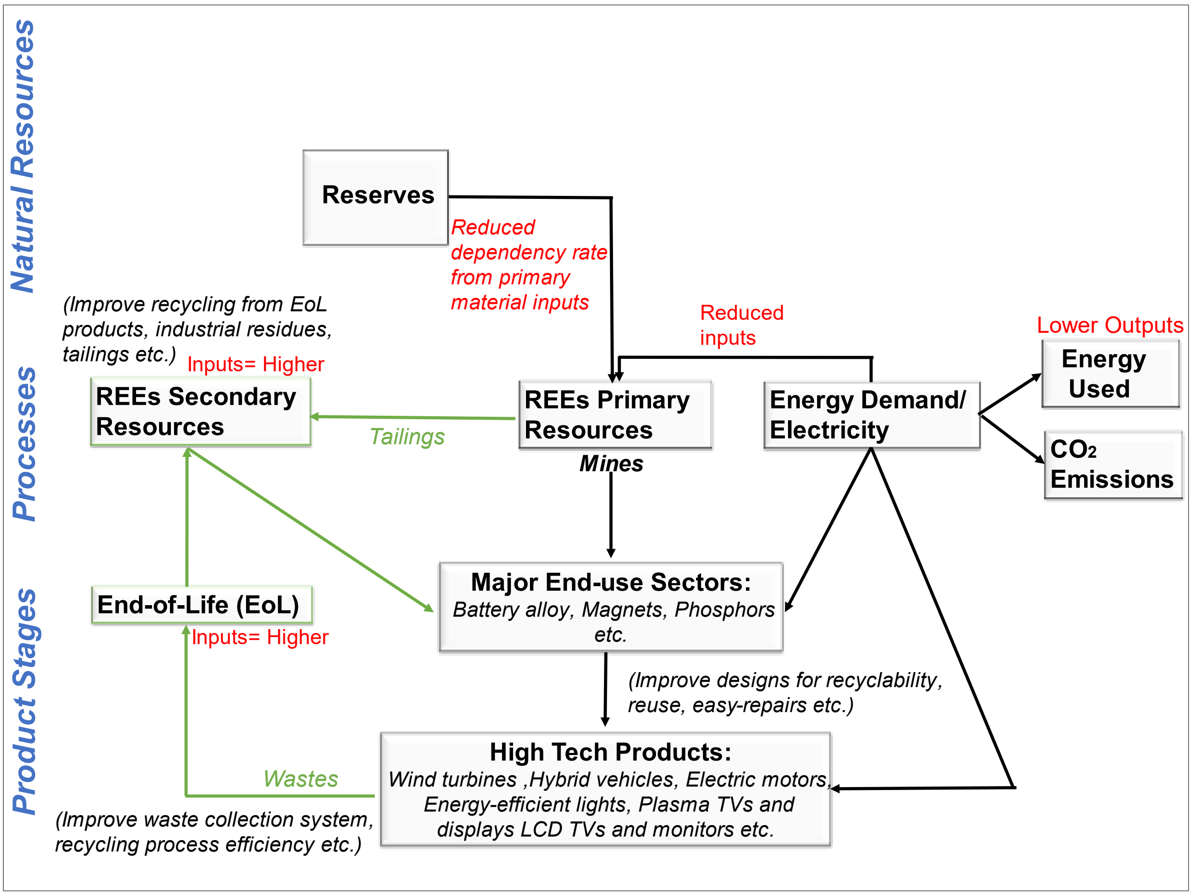


Figure 6.4: REEs material life cycle flow system: a resource efficiency scenario

Note. Black arrows are the existing trends or patterns of the life cycle material flow of REEs consumption in Australia; for instance, where material consumption is highly dependent on primary material inputs i.e., a linear economy also known as a take-make-waste extractive industrial system. The green arrows are the inputs from a resource efficiency route; they represent secondary material inputs that can complement primary material demand and reduce dependency on virgin demand sources, and the subsequent associated environmental and social burdens. The figure, as a whole, illustrates a resource efficiency system from a circular perspective, where the outputs from EoL products are valuable resources for new products. To promote the effective collection and proper treatment of these materials and enforce legislation, the concept of EoL products as waste needs to change to resources.

To achieve resource efficiency, a holistic perspective must be implemented. The findings presented in this study underline the implication of evaluating REEs consumption using a holistic and systematic approach. This incorporates evaluating the full lifecycle of the material circularity, and any changes in the flow. This in-depth and structural knowledge of these material consumption patterns provides a better understanding of the product lifecycle to facilitate decision-making to tackle those sectors in the system that needs immediate attention (as emphasised in Chapter 4, Figure 4.1, and furtherly analysed in Figure 6.4 above). This study provides a novel approach to demonstrating how CE tools, such as MFA and LCIA combined, can be instrumental in sustainability assessment. This includes providing grounds for the modelling of a sustainable management framework and mitigation strategies (SMF-MSR) for the consumption of these metals in Australia. Thus, an understanding of the interactions between humans and their surroundings, such as production and consumption processes, is paramount to implementing strategies to improve sustainability in resource use (OECD,2008).

In summary, a comprehensive REEs CE framework for material criticality mitigation, and a conceptual and practical implementation model to close the material loop and improve resource efficiency is proposed as a solution to help tackle the challenge of REEs resource scarcity, material use and associated environmental impacts. REEs CE framework is demonstrated as a sustainable management strategy to better highlight the concept of resource efficiency and close the loop in the material cycle for REEs. It uses holistic approaches for the evaluation of the entire supply chain of REEs material use, facilitating the examination of every single stage in this cycle providing optimisation of the whole system.

Drawing from this discussion, this study seeks to make three novel contributions: contribution to the empirical literature, contribution to theory and methods, and implications for policy and practice as shall be discussed in detail with other recommendations in the next chapter.

Chapter 7: Conclusion and Recommendations

Chapter outline

7.1 Introduction

The primary purpose of this study was to examine the sustainable consumption of Rare earth elements (REEs) to reduce potential environmental impacts with Australia as a case study. The study aimed to improve the sustainability of the consumption of REEs in Australia, including improving resource efficiency strategies such as waste recovery and recycling. REEs are vital constituents of many technologies in the clean energy sectors, such as information and telecommunications, and are heavily required in these applications. With the growth of the clean energy sector to meet global environmental concerns, REEs are facing a high supply disruption. The research objective was to evaluate the material consumption of these metals in applications and to find efficient strategies to reduce the supply risk impacts of these critical resources, while minimising the potential environmental impacts associated with their consumption. To do so, the study used circular economy (CE) as a scientifically plausible tool for a sustainable management strategy that aims to reduce the negative impacts of REEs resource consumption while achieving environmental and society-wide wellbeing. To achieve this goal, this study (1) conducted a holistic assessment of material flow consumption of REEs in high-tech applications and the associated environmental impacts, (2) determined their extraction, flows, reserves, and distribution, including their recycling potentials and rate, and (3) suggested approaches to reduce negative impacts to improve resource efficiency at each stage of the material use, from raw material input to End-of-Life (EoL). As a way forward, a comprehensive REEs CE framework for material criticality was developed, followed by a proposed practical implementation strategy to close the material loop and improve resource efficiency. This thesis makes three novel contributions: contribution to the empirical literature, contribution to theory and methods, and implications for policy and practice.

This chapter begins with an overview of the thesis and key findings. This is followed by the contribution of the thesis, the limitations, recommendations for further studies, and a concluding statement.

7.2 Overview of the thesis and key findings

REEs face high demand in applications due to their unique chemical and physical properties and their importance in green economic growth, especially in technologies looking to reduce emissions, minimise energy consumption, facilitates miniaturisation, as well as improve efficiency, performance, speed, durability, and thermal stability (Balaram, 2019; Cai, 2019; Gibson & Parkinson, 2011; Goonan, 2011; Huleatt, 2019; Lynas Rare Earths Ltd, 2021; Reisman et al., 2013; U.S. Geological Survey, 2020; Van Gosen et al., 2014). The growing demand for these metals, and need for a low carbon economy to meet environmental demands, is accompanied by high-risk supply issues. REEs are found in just a few countries of the world and global supply is monopolised by one nation, China (Balaram, 2019; Huleatt, 2019; U.S. Geological Survey, 2020). Despite the major concerns about the growing demand and limited availability, and the absence of effective substitutes, the recycling rate of REEs is less than 1% in Australia, which is similar to other parts of the world (Balaram, 2019; Drost & Wang, 2016; Haque et al., 2014; Jowitt et al., 2018; U.S. Geological Survey, 2020). While Australia appears to have the potential for these metals, when compared to some other nations (as seen in Table 1.1, chapter 1), this is accompanied by low government investment in these sectors, specifically with regard to the weak recovery and recycling of EoL products containing these metals.

Despite this threat of REEs supply insecurity, and the possibility of hindering the transition to a low carbon economy, while the sustainability of REEs has been examined in multiple papers, including in Australia, the assessment of the environmental impacts and the benefits of sustainable consumption systematically and holistically are lacking, particularly regarding improvements in resource efficiency strategies. This leaves a significant gap in knowledge for future work in the area. Previous studies have focused on the politico-economic conflicts over the supply and distribution of these metals, or the environmental and social impacts of its production, and have not holistically examined this problem as a system. As such, the goal of this study has been to propose a holistic and systematic approach based on the CE model to assess the sustainability of REEs with Australia as a case study, and to propose a strategy to minimise the adverse impacts of resource shortages while achieving maximum environmental benefits. In this respect, three vital indicators of resource efficiency elements were identified (materials use, energy demand, and greenhouse gas emissions) in a sustainable management framework to assess the sustainable consumption of REEs in Australia, with the main goal to introduce advanced strategies to reduce the supply risk impacts of these critical resources and minimise the potential environmental impacts associated with their consumption. The analytical framework was principally adapted from the CE model, which introduced one of the innovative components of this study (implementation of CE tools) to examine REEs material consumption to meet the research objective.

Using Material flow and Life cycle analysis methodologies as CE tools for sustainability assessment, this study was able to evaluate material consumption of these metals and the associated environmental impacts. Material flow analysis (MFA) was used to compile and analyse data about REEs, from raw material to material use through to EoL, while Life cycle impact assessment (LCIA) was used to analyse the material life cycle, allowing for environmental impact assessment, policy, and sustainability decision-making. To narrow down the focus, five REEs based on their criticality index and importance were selected and analysed using 2019 as the base year for its most up-to-date data at the time of the study.

The results of this study were presented in two chapters. To investigate the existing sustainability pattern governing REEs consumption in Australia, chapter 4 (data analysis results I) presented an assessment of primary material inputs of REEs consumption in applications and the derived environmental impacts using the above-mentioned identified sustainability metrics. To demonstrate the significance of sustainability, specifically recycling, chapter 5 (data analysis results II), assessed the secondary material inputs of REEs consumption in applications, that is, recycling potential and the derived environmental impacts. The chapter concluded with an analysis of the benefits associated with the sustainable management of natural resources specifically recycling with the main goal to determine the advantages of secondary material inputs over primary from a resource management perspective. It promotes CE principles as a sustainable management strategy that can be used to improve REEs' resource efficiencies, decouples natural resource use from economic progress, and hence combat supply shortages. Findings from the data analysis in Chapter 4 provide answers to the research question on "How sustainable are current strategies for REEs consumption in Australia, the key indicators and how they can be assessed", while Chapter 5 responds to the question of "How the sustainability of REE consumption in Australia can be enhanced". As a response, a comprehensive CE framework for REEs within the sustainable development paradigm was developed, followed by a practical implementation strategy to close the material loop and improve REEs' material use efficiencies in Australia.

The overall results from the life cycle material flow report show the REEs consumption pattern in Australia to be highly dependent on primary material inputs, attributable to low recycling rates of these metals, and the export of EoL products abroad for downstream recycling. Findings indicate a continuously growing trend in the demand for these metals, especially in the clean energy sectors. Improvement in the sustainable consumption of these metals should, therefore, be essential. A life cycle material flow of critical material use analysis suggests that Neodymium and Yttrium make up 45% and 50% respectively of selected critical metal consumption in the application, compared to the other REEs. The findings also suggest that magnets and phosphors are the applications with the highest demand for these selected critical metals. It should be noted these are all applications used in the clean energy sectors for low-emissions energy production and low-emissions energy usage. It is reported that, with the dependency of electric vehicles and wind turbines on the rare-earth magnets sector, the demand for Neodymium, for example, may increase by more than 2600% in the next 25 years (Alonso et al., 2012). Looking at the rise in environmental concerns and the subsequent demand for REEs, as well as limited sourcing locations, a sustainable management strategy to help address the adverse impacts of resource (REEs) shortages while achieving maximum environmental benefits should be a necessity, as indicated in this study (chapter 6, section 6.3).

Furthermore, it was evident that improvements in sustainable resource consumption practices, such as recycling efficiency, will improve resource use efficiency. The material use analysis (MUA) conducted in this study showed REEs recycling potential to be 55.5% for the year 2019, which would account for a significant contribution to the overall supply of these metals. This suggests that improvements in recycling efficiency strategies can significantly increase the supply of REEs and reduce dependency on primary material inputs.

The study has also identified that the overall REEs consumption of secondary material inputs in applications will similarly result in lower emission and cumulative energy demand potentials than REEs generated for primary material inputs. One of the major objectives of this study was to highlight the importance of secondary material inputs (waste recovery, recycling) for consumption in applications over primary (virgin) materials generation. From a resource perspective, this study was concerned with the extent to which primary material and associated environmental impacts can be avoided by using secondary material inputs in applications. The results from this investigation showed that the gross CO_2 emissions for using REE primary material input in applications will fall from 2278.3 to 1253.0 kg CO_2-eq/yr/1kt in the case of secondary material inputs. This will lead to an emission reduction of 1589.1 kg CO_2-eq/yr/1kt. These findings, therefore, suggest that a shift from primary material dependency will not only lead to material savings, but will also have direct benefits to reducing global warming through avoided CO_2 emissions.

In the case of Cumulative Energy Demand Potential (CEDP), the research has shown that the gross total CEDP for using REEs primary material inputs in applications will decrease from 25674.9 to 14482.7(MJ-Eq./yr./1kt) for a given year (2019). This means an estimate of 17709.4 (MJ-Eq./yr./1kt) energy savings over this period. In sum, improvements in the sustainable consumption and production of REEs is expected to result in a wide range of environmental benefits compared to the current state-of-the-art primary production. The high primary CO_2 emissions and energy consumption call for the development of recycling technologies and infrastructures.

In terms of individual applications, recovery interest for EoL products could focus on phosphors and magnets, as findings show that these products contain potential sources for secondary material inputs of these metals. It was identified these products consume 26% and 27% respectively of selected critical REEs in applications, with the highest demand from Neodymium and Yttrium. Regaining REEs from EoL products in the waste stream can significantly contribute to managing some of the issues associated with these metals, such as supply disruption, and radioactive elements like uranium and thorium being associated with primary production. (Jowitt et al., 2018). Moreover, according to Arshi et al. (2018), recycling of magnets produces a significantly lower impact compared to the primary material inputs (Arshi et al., 2018). The process of manual dismantling, for example, provides a maximum environmental benefit as it drastically reduces the amount of wasted neodymium (Arshi et al., 2018).

Although EoL products containing REEs have been discussed as potential sources to supplement shortages in REEs and reduce the high supply risk problem, recycling alone cannot be regarded as a solution to the entire REEs problem, as demonstrated in the REEs CE material criticality mitigation framework (Figure 6.2, chapter 6). Improvements in recycling efficiency cannot be achieved without broader consideration of the implied economic and environmental effects of the consumption of these metals, as indicated in Chapter 6, section 6.3.1. A holistic and systematic strategy via CE is essential to REEs material efficiency, from raw material through to use, and EoL policies for waste management. The sustainable management framework, based on the CE model (as presented in chapter 6, section 6.3.2.1), suggested various phases where the CE sustainability strategies against material criticality can be implemented to achieve sustainable consumption of these critical metals in Australia, closing the material loops and improving resource efficiency.

The proposed framework underlines that sustainability in REEs consumption from a CE perspective contributes to all three pillars of sustainable development (Economic, Environmental and Social). The framework combines the following major sustainability aspects of CE contributions: waste-environmental via avoidance and minimisation of environmental and societal-wide impact, sustainable economic growth via the restorative and regenerative system, and material circularity. The framework suggests that apart from the focus on improving EoL strategies (collection, recycling) for the consumption of these critical metals, the different components within the CE model, such as the manufacturing-orientated strategies, offer further potential to improve the sustainability of REEs consumption in Australia. In this regard, emphasis is not only placed on recycling, but also on the need to address consumption. The CE approach in this regard will serve not only as a one-way strategy that depends on recycling efficiency, but rather as a holistic system that requires efficiency.

The findings identified in this study underline the significance of evaluating REEs consumption using a holistic and systematic approach. It was evident that REEs material consumption viewed from the perspective of a holistic system provides a plausible picture of potential consequences, priority areas, and the development of measures to mitigate or reduce any negative impact (as seen in the discussion chapter, section 6.3). The implementation of a material flow analysis (MFA), combined with a Life Cycle Impact Analysis (LCIA) as tools for circularity, provided an in-depth structural and systematic analysis of the whole life cycle of REEs consumption from raw material acquisition through to manufacturing, waste disposal and recycling, and environmental impacts. As such, the CE model as presented in this study, through restorative and regenerative systems facilitated by manufacturing oriented-strategies (long-lasting designs of applications by extending product life), through manufacturing for easy repairs, maintenance, re-use, repurpose, remanufacturing, refurbishing, and through Eol oriented strategies (recovery and recycling principles), can be implemented to close material and energy loops and keep resources in circulation.

7.3 Contribution of the Thesis

This study has established a valuable foundation for understanding the sustainable consumption of REEs to reduce environmental impacts (including socio-economic impacts) using the CE model as a sustainable management strategy with Australia as a case study, though the outcomes could be used more broadly. This thesis makes several novel contributions to the development of knowledge (theory and methods), and the existing body of research in this area, which is considered below. The main contributions include: a novel comprehensive CE framework for REEs set within the sustainable development paradigm for criticality mitigation and a practical implementation strategy to close the material loop and enhance the sustainability of REEs consumption in Australia.

7.3.1 Contribution to the empirical literature

This study contributes to empirical literature as observations from previous studies reveal limited academic research covering the REEs industry in Australia, especially regarding resource consumption, material flows and sustainable strategies to improve resource efficiency. Specifically, it adds to growing literature on REEs and their sustainable use to reduce potential environmental impacts. It provides insight into how CE can be perceived as a scientifically plausible tool of a sustainable management strategy to help address the adverse impacts of resource shortages while achieving maximum environmental benefits.

This study also contributes to understanding REEs within the framework of sustainability and CE, as it provides a model for the examination of consumption patterns of these metals in Australia and an evaluation of existing resource efficiency strategies in REEs, thus, providing a pathway to improve sustainability outcomes in Australia. Moreover, previous studies have focused either on the politico-economic conflicts over REEs supply and distribution, or the environmental and social impacts of their production. The sustainability problem has not been holistically examined as a system (Alonso et al., 2012; Drost & Wang, 2016; Gaustad et al., 2011; Jowitt et al., 2018; McLellan et al., 2014; McLellan et al., 2013; Wang et al., 2017). In particular, this study introduces a holistic and systematic approach adapted from the CE model to assess the sustainability of REEs in Australia, a strategy to minimise the adverse impacts of resource shortages while achieving maximum environmental and societal-wide benefits. The work proposes a comprehensive CE framework for REEs within the sustainable development paradigm for criticality mitigation and a practical implementation strategy to close the material loop to enhance the sustainability of REEs consumption in Australia. The findings from REEs materials used through life cycle material flow analysis, for instance, add to the body of knowledge on the overall impacts associated with critical REEs consumption and the supply risk. According to IRP (International Resource Panel) (2017), material use analysis is an essential aspect of sustainable resource management as it provides information on environmental impacts across the entire material cycle of a resource (International Resource Panel, 2017). This includes resource depletion, pollution (as seen in this study), changes in the ecosystem and human health. These are essential for evidence-based policymaking (International Resource Panel, 2017).

The study also contributes to understanding the significance of material flow accounting in assessing REEs material consumption within the Australian economy, as it provides grounds for the examination of the full circulation of these metals within the economy. This includes analysing data about REEs reserves and availability across the nation, the existing production and consumption pattern, the availability in the waste stream through recycling potential and the significance and extent of their recovery. An account of the general availability of these metals is essential for the implementation of cost-effective management, sustainable usage, and management of the supply capacity of these metals. Furthermore, material flow accounting of REEs also serves as a medium for environmental impact assessment, policy and sustainability decision-making. The findings from the recycling potential of REEs add to the body of literature on the recycling of REEs and the importance of resource efficiency strategies to achieve sustainable end-goals where supply risks are mitigated with reduced environmental burdens.

This study contributes to the understanding of the environmental impacts associated with the consumption of REEs through key sustainability metrics including material use, energy demand and associated greenhouse gas emissions. Specifically, this adds to the expanding literature on the combination of life cycle assessment impact tools to assess the environmental impacts derived from REEs consumption.

The study also makes an empirical contribution to the literature on REEs in general, as it adds to the expanding literature further evidence of the importance of these metals, their critical nature and the need to improve resource efficiency to combat supply risks while reducing impacts. The study highlights the inequality in the distribution and production of these metals, their current low recycling rates and the prevalence of politico-economic conflicts and dominance among nations. Furthermore, this study adds to the literature a novel approach to understanding REEs within a CE and sustainability context.

7.3.2 Contribution to Theory and Method

With regard to theoretical contribution, this study contributes to the understanding of related constructs that have not been examined in-depth in previous studies on the sustainable consumption of REEs. As such, helping to establish a better understanding of REEs within a sustainable management framework from a CE perspective is the key theoretical contribution of this research. In this regard, findings from this study reinforce the need for CE, a sustainable management model that aims to provide systemic solutions to global economic and environmental challenges such as resource scarcity or waste reduction (Balanay & Halog, 2019; Wang & Kara, 2019). In this study, the CE concept was adapted to develop a sustainable management framework for REEs (SMF-MSR) in a holistic system that supports the successful transition from a linear to a circular economy. The framework provided many potential components within this model for the improvement of sustainable consumption of REEs in Australia. This includes:

1) the implementation of a life cycle material flow accounting system, 2) the CE EoL and manufacturing-oriented approaches for the reuse, sharing, repair, refurbishment, remanufacturing and recycling of Eol REEs materials to create a closed-loop system, minimising the use of resource inputs and the creation of waste and pollution, including carbon emissions. Conversely, the existing pattern of REEs consumption, with 99% of EoL products ending as waste or in landfill, is characterised by what is described as a take-make-waste system (MacArthur, 2017; Sauvé et al., 2016); this is a system that is considered unsustainable and must be replaced with a more holistic, circular and regenerative system.

This study also contributes to methodology and theory by introducing a novel approach to the process by which CE, a sustainable management model with multiple concepts and tools, can be applied holistically and systematically to assess the sustainability of REEs consumption. It addresses calls to understand how REEs can be implemented within the CE framework of sustainability to achieve resource efficiencies and minimise environmental impacts. In this view, findings from this study strengthen the need for implementing CE and its strategic tools like MFA and LCIA for an in-depth structural and systematic analysis of the whole life cycle of REEs consumption from resource extraction through to manufacturing, waste disposal and recycling, and environmental impacts (John et al., 2016; McLellan et al., 2014). Most previous work on REEs has failed to examine this problem as a system (Alonso et al., 2012; Drost & Wang, 2016; Gaustad et al., 2011; Jowitt et al., 2018; McLellan et al., 2014; McLellan et al., 2013; Wang et al., 2017). Therefore, as a contribution, this study introduces a holistic and systematic approach where MFA and LCIA are combined to provide a sustainable framework of REEs consumption in Australia, as an extension of a strategy for global uptake.

7.3.3 Implications for Policy and Practice

The findings of this study have several policy and practical implications for industrial stakeholders, decision-makers and policymakers, recycling industries, entrepreneurs, and business development managers. Previous studies on REEs involved primary research on the politico-economic conflicts of the supply and distribution or the socio-environmental burdens of its production while failing to examine the problem holistically. This study introduced a novel framework for REEs set within the sustainability paradigm, describing a holistic view of the contribution of CE to the sustainability of REEs consumption, and a practical implementation strategy as a way forward to close the material loop and improve material efficiency. This is a perspective mostly neglected in previous studies.

The overall results from this study can be used to provide valuable information needed not only for manufacturers but for waste disposers, recyclers, and policymakers to establish DfE (Design for Environment) and waste management policy for EoL products containing these metals. The sustainable management framework approach using CE tools (MFA, LCIA) can be adopted to estimate resource use and the associated environmental impact over any period and location to evaluate the environmental sustainability of resource consumption and impact reductions (see Chapter 3 for analytical framework). A material flow study combined with life cycle analysis (as demonstrated in Chapter 3) will provide an understanding of a fully integrated and logically sound flowsheet of the whole material life cycle of material consumption (John et al., 2016; McLellan et al., 2014). This can connect resource use to impacts on the environment, economy and society (as demonstrated through the REEs CE framework in Chapter 6). The framework captures the main phases where CE strategies of a regenerative and restorative system, through its long-lasting design, maintenance, repair, recovery, and repurposing, can be implemented to achieve sustainable end goals such as identifying particular processes for more efficient material use.

As an implication for policy and practice, this study also contributes to providing several important insights including quantifying the environmental impacts derived from primary and secondary material consumption of REEs using key resource efficiency and environmental impact metrics. These metrics, such as Material Use, Energy Demand and Global Warming Potential can identify metals and products with higher recycling potential, where policymakers can focus on reducing dependency on virgin material consumption. According to Navarro & Zhao (2014), life cycle environmental impact assessment (LCIA) is recognised as the most comprehensive approach to quantifying the environmental sustainability of a product or process as it depicts the full environmental impact of a product over its entire lifecycle, from raw material extraction, through manufacturing, reuse to waste and disposal (Navarro & Zhao, 2014). In this regard, LCIA can enable practitioners to perform environmental assessments through the quantification of environmental effects (Curran, 2006).

Furthermore, through material flow analysis, this work also provides in-depth information on the flows of these metals by identifying major REEs producers in Australia, the locations and reserves of these metals, their consumption in Eol products, recycling rates, and export and import figures. In this study, major REEs applications were identified, including critical REEs with the highest demand in applications. Next, metals with the highest recycling potential, including the applications, were analysed. Metals and applications with the highest environmental impact from the consumption of both primary and secondary materials were also identified. This is because information about the general availability and consumption of REEs is essential for the implementation of cost-effective management, sustainable usage, and management of supply capacity. As reported by John et al. (2016), understanding the flows of REEs is a prerequisite to managing them and helps identify, and account for, the externalities of a product in the broader context of human-environmental interactions (John et al., 2016). This information can further be incorporated with metallurgical and sustainability reports to provide a complete understanding of the environmental sustainability of the ever-growing REEs and metals industry (Zaimes et al., 2015).

The work will equally aid Government, and major stakeholder decision-makers to make decisions and regulate policies on what part of the economy to tackle, to reduce not only resource consumption, but also to increase the sustainable and efficient use of these materials, minimise CO_2 pollution and create new jobs. Furthermore, this will assist in estimating the scale and possible consequences of the mishandling of waste products containing these materials. In summary, this work provides a practical understanding of the benefits of resource efficiency improvements and sustainable consumption patterns.

This study further alerts both the local and the international community to the potential global economic and political consequences of the eventual decline in the supply of these metals, and the need to establish parameters to quantify material efficiency, which can identify areas in which improvements can be made to minimise waste. While the number of these studies (MFA) applied to Australia is minimal, these findings reinforce the need for life cycle material flow accounting of REEs to improve the robustness of criticality assessments, as material flow analysis is fundamental in understanding policy options for demand, supply, use and recycling (Mudd et al., 2019).

7.3.3.1 Contributions of CE as a tool for REEs sustainability management in Australia (Recycling and manufacturing-oriented strategies)

This study adds value by setting the concept of REEs criticality and CE principles within the same context, an approach mostly overlooked by the current body of literature. This study presents a comprehensive framework for REEs material criticality mitigation and practical implementation strategies, as a way forward to material circulation and sustainable REEs management (see Figure 6.1 and 6.3 respectively in Chapter 6). This framework suggests that sustainability in REEs consumption from a CE approach contributes to all three pillars of sustainable development (Economic, Environment and Social). In other words, to build a sustainable REEs future, we must take into consideration those aspects impacting the sustainability of REEs environmentally and socio-economically to understand the existing pattern of their consumption.

A holistic and systematic CE model is necessary to support REEs material efficiency from a material life cycle perspective (from raw material through use and to EoL) as presented in Figure 6.3 (Chapter 6). The framework demonstrates approaches to determine the potential for various REEs waste streams for recovery, and phases where strategies can be implemented to improve sustainability in REEs consumption. The approach considers that apart from the sole focus on improving EoL strategies (collection and recycling) for the consumption of REEs in Australia, the other components within the CE framework, such as the manufacturing-oriented strategies are instrumental to achieving sustainability in REEs consumption (namely, long-lasting design, maintenance, and repair, reuse, remanufacturing, and refurbishing of REEs resources to close the material loop). EoL CE strategies (such as recycling, for example) are generally implemented with the sole goal of transforming wastes into resources for new products. As such, recycling is proving to be a less efficient option at this time (short-term frame) due to the limited amount of EoL products available to be recovered as substitutes for primary material inputs (Jowitt et al., 2018; Rademaker et al., 2013; Zaimes et al., 2015). The manufacturing CE strategies, on the other hand, are designed to improve the sustainable use of materials via life cycles engineering techniques, such as design for durability, and design for easy reuse and recyclability (Wang & Kara, 2019). This strategy complements waste prevention and supply risk mitigations as shown in Figure 7.1. The Figure shows CE strategies (collection, recycling combined with manufacturing strategies) as a way forward for REEs material criticality mitigation.

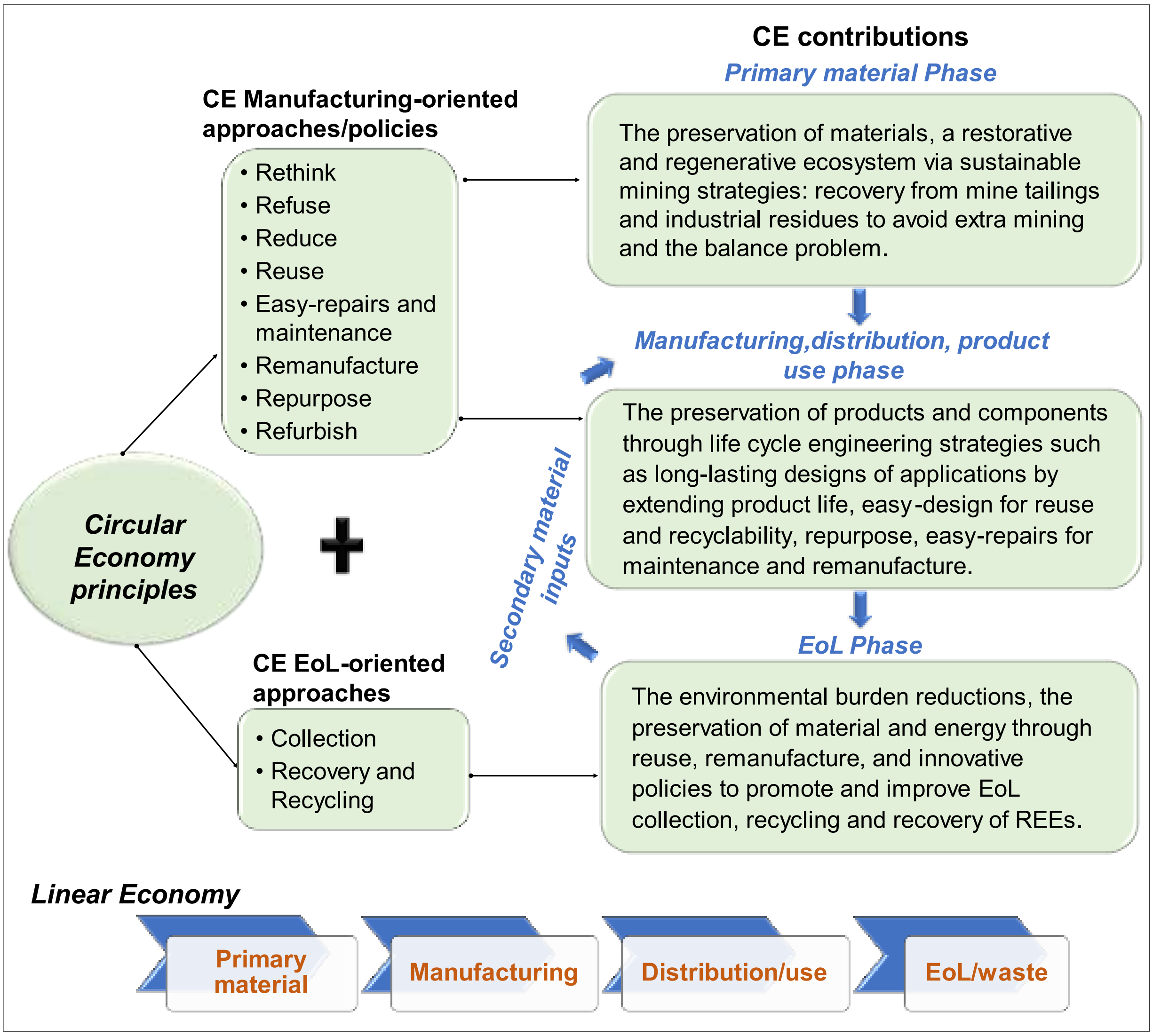


Figure 7.1: CE strategies as a way forward for REEs material criticality mitigation

The improvement in REEs material efficiency is a combination of a set of strategic CE components in addition to recycling as elaborated below.

Efforts to improve the recycling of REEs should be focused on improving policies to promote EoL metal collection and sorting, and should encourage product designers to take recycling more seriously during the design process (CE manufacturing-oriented strategies). For example, as discussed in Chapter 6 (REEs CE framework for criticality mitigation), and further analysed below, the collection phase, which is regarded as a key mechanism for improving metal recycling can be improved by:

- Establishing local and international collection points and markets in Australia, and establishing eco-designs and recycling structures to recall EoL products, reduce losses and eliminate exports to developing countries or unskilled zones.
- Making amendments to the Australian waste framework directives. For instance, the current Australian waste scheme (National Television and Computer Recycling Scheme (NTCRS) only considers old televisions, computer parts, and printers as e-waste (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). These are just categories 2 and 6 of the WEEE (Waste Electrical and Electronic Equipment) Directive (e-waste) (European Union, 2012). No other regulations exist for managing waste products found in the other WEEE Directive categories (1,3, 4 and 5) (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). Most of these products end up in landfill and the rest is collected as scrap (Dias et al., 2018; Islam & Huda, 2019). These Categories (1, 3 and 4) constitute a large portion of renewable and green energy products, such as photovoltaic panels, and energy-efficient fluorescent lamps, which contain high amounts of REEs. Other examples include headphones, refrigerators, CD players, cameras, washing machines, air, conditioners, which currently are not regulated under the Australia NTCRS e-waste management scheme (Dias et al., 2018; Islam & Huda, 2019). Recent studies show that EoL solar PV panels are major e-waste streams in Australia (Salim et al., 2019). These are all products that contain a high percentage of magnets (Islam & Huda, 2019). Permanent magnets, for example, constitute the largest portion of REEs consumption, with one of the fastest-growing markets for REEs being rechargeable batteries, and phosphors found in Category 3 and 4 products (Statistica, 2019).

- Incentivise the market for secondary materials (recycling of EoL products, pre-consumer products, tailings and industrial residues) by imposing fiscal levers or by enforcing a minimum quantity of secondary materials to be used to produce new products. For example, the implementation of compulsory producer take-back policies (such as the extended producer responsivity approach, a take-back system where EoL products are in the hands of the producers), as well as consumer and recycler incentives.

Recycling can also be improved with an innovative and environmentally-friendly recycling system (long-term solutions). According to investigations led by researchers in Belgium, Netherlands, France, UK and France, efficiency in dismantling (products designed for easier disassembly and reuse), sorting, pre-processing, and pyro-, hydro- and/or electrometallurgical processing methods, combined with environmentally-friendly and holistically sound recycling system, can drastically improve recycling and recovery of REEs in the waste stream (Binnemans et al., 2013; Guyonnet et al., 2015). These researchers have reported that the current focus on magnet scrap recovery business structures can be replaced with high-tech recycling and environmentally-friendly technologies (Binnemans et al., 2013; Guyonnet et al., 2015).

Environmental accountability (data information) is another significant CE strategy that supports sustainability in REEs. The CE framework, through its life cycle environmental accounting tools (material flow analysis and life cycle impact assessment), contributes to addressing the challenge of REEs recycling via the material life cycle accounting strategy. This is significant as in-depth structural and systematic information on the life cycle of REEs material use is paramount to understanding material consumption and implementation of sustainable strategies to improve material efficiency. Life cycle assessment strategies, for instance, are beneficial for technically sound and transparent assessments of metal recycling (Norgate, 2013). From a life cycle viewpoint, the benefits derived from metal recycling can be assessed in an approach that enables appropriate comparisons with other product systems or materials that do not have recycling loops (Norgate, 2013). Information from life cycle material flow accounting serves as a pivotal tool to tackle those phases in the material life cycle (like recycling) that need attention. Linking life cycle assessment and material flow analysis provides an analytical framework for a comprehensive assessment of material use and impact, raw material availability, and metal availability in the waste stream, as demonstrated in this study. Thus, CE within a sustainability framework contributes to tackling the challenge of REEs resource scarcity to reduce environmental burdens.

One of the principal goals of CE is to grasp material recycling and to harmonise socio-economic and environmental prosperity in a closed-loop system where resources are conserved and reintroduced into the life cycle at the EoL (Figure 6.2, chapter 6). The recycling of REEs in waste streams can help solve the balance problem (Binnemans et al., 2013). REEs are found together in geological deposits. The mining of critical REEs, for example Neodymium, generates an excess of the more abundant REEs, such as Lanthanum and Cerium, causing what is known as the balance problem in the supply and demand market (Binnemans et al., 2013). As such, the recycling of Neodymium will reduce the extraction of this critical metal, leading to less overproduction of REEs, like Lanthanum and Cerium, for which demand is lower (Binnemans et al., 2013). To avert excess surpluses of certain metals, the market demands for the different REEs need to equate the natural abundance ratios of these elements, as surpluses will lead to imbalances in the REEs market. Lowering the volume of REEs extracted cannot solve the overproduction (surpluses), as this can cause a shortage of less abundant (critical) REEs that are in high demand (Binnemans et al., 2013).

In summary, CE contributes to the sustainability of REEs through its regenerative, restorative and preservation strategies, a tool for short-term and long-term goals in combatting REEs supply risk. For example:

- In the raw material phase: the preservation of materials through a restorative and regenerative ecosystem achieved via sustainable mining strategies, for instance, recovery from mine tailings and industrial residues to avoid extra mining and the balance problem.
- At the manufacturing and product use phase: the preservation of products and components through life cycle engineering strategies such as long-lasting designs of applications by extending product life, easy-design for reuse and recyclability, repurpose, easy-repairs for maintenance and remanufacture.
- In the EoL phase: the preservation of material and energy through reuse, remanufacture, and innovative policies to promote and improve EoL collection, recycling and recovery of REEs.

Successful implementation of CE strategies to close the material loop requires rethinking at every stage in the entire REEs material lifecycle process: rethinking in the raw material use phase via implementation of sustainable mining strategies; rethinking in the manufacturing and product design phase to facilitate reuse, remanufacturing and recyclability at the EoL phase; and rethinking at the EoL phase via innovative policies to improve on the collection and REEs recycling.

7.4 Recommendations

7.4.1 General Limitations and Future Research Avenues

One major limitation of this study is the limited material flow accounting information. MFA studies depend on adequate data (Balanay & Halog, 2019). Material flow data for REEs consumption in Australia by various end-users, for example, seems to be absent in literature. As such, this was a major constraint in the data collection process. However, this was circumvented by adapting popular methods used by other authors to estimate REEs material consumption in the economy (Binnemans et al., 2013; Goonan, 2011; Guyonnet et al., 2013; Guyonnet et al., 2015; Jordens et al., 2013). Further work is therefore needed to establish databases for material flow accounting of critical natural resources like REEs. This is paramount for a sustainable economy of REEs, as more in-depth knowledge is vital for directing approaches to measuring material consumption, recycling, and more efficient use of REEs. A thorough understanding of the interactions between society and the environment, such as production and consumption processes, is essential to developing strategies for more sustainable resource use (Organisation for Economic Co-operation and Development, 2008). To that end, this study serves to demonstrate the significance of life cycle material flow accounting as a relevant decision-making tool for improving resource management in order to achieve sustainability goals.

Another major limitation of this study is that that the selected critical metals for the study were analysed over a single year (2019). This was done on the basis that this year had the most available data at the time of study; moreover, the goal of the research was to introduce a sustainability framework that can be used to evaluate resource use and impact over any given period. Additionally, the following two years (after 2019) were influenced by economic disruptions due to restrictions arising from the COVID-19 pandemic. Further studies, therefore, can examine the sustainable consumption of these critical REEs elements over a particular time frame. Of importance is the assessment of the estimated secondary material available for recycling in a long-term frame and the derived economic and environmental impacts as illustrated in this study. Knowledge about the availability of these metals from secondary materials could promote the development of sustainable and environmentally-friendly recycling technologies for recovery and environmental impact reductions.

In this current study, five REEs were selected for analysis due to their higher criticality index, importance to the green economy, and supply disruption in a short time frame. Similarly, the framework of the study could be extended to the other REEs metals. Further research should be extended to single REEs metals to narrow down the investigation to this specific element with an increasing research focus. In this way, more focus could be placed on analysis of individual metals for material efficiency and sustainable consumption. For instance, studies on the recycling efficiency of an individual critical metal can be beneficial to the balance problem. Successful recycling of critical REEs, for example Neodymium, can reduce the oversupply of more abundant REEs like lanthanum, which need to be extracted in the mining process (REEs are all found together in one deposit) (Binnemans et al., 2013). Excess supplies of less-required REEs create an imbalance in the supply-demand ratio of REEs, offsetting the market value and natural balance (Binnemans et al., 2013). While this research focuses on sustainable REEs consumption in Australia to reduce environmental impacts, the framework of the study could also be extended to investigate the potential implication of the model in other countries. The framework can also be adapted to other industries to investigate sustainable material consumption for resource efficiency.

Future investigations could also extend the developed CE framework to account for the methods of social life cycle assessment and economic life cycle analysis, in line with the triple dimensions of sustainability or within the context of life cycle sustainability analysis. Social life cycle assessment tools are used to examine the potential impacts associated with the use of a product in its whole life cycle, but from the social perspective only (Yang et al., 2020). The developed CE framework could be extended to account for the methods of social life cycle assessment and economic life cycle analysis using the triple dimension of sustainability as applied in this study (**Figure 6.1**).

Additionally, data uncertainties in LCA and MFA are important aspects, especially in industrial ecology. In this study, to improve the robustness of criticality assessments, an integrated approach was applied, whereby Material Flow Analysis was performed in place of Life Cycle

Inventory assessment with well-determined material flows (import and export of REEs, the material consumption in applications etc). A well-determined material flow minimises the data-gathering problem in LCA and improves the robustness of criticality assessments (Laner & Rechberger, 2016). The MFA tool was used to quantify the inputs and outputs of the metal within the economic system, and identify sources, uses, losses and gaps in the entire material cycle. Integrating LCA indicators with the material flow tool enabled the analysis of the material life cycle of REEs, allowing for environmental impact assessment, and mitigation strategies to minimise impact and combat material criticality by closing material loops and improve resource efficiency. Combining these tools offers the potential for consistency and reliable decision-making support in environmental/resource management (Laner & Rechberger, 2016). As with this study, future studies could explore and incorporate other quantitative/computational modelling and analysis available in other fields to improve data acquisition and strengthen the robustness of results. In the field of industrial ecology, for example, there is a growing number of techniques to test robustness (sensitivity analysis, for example), to improve data acquisition, including more comprehensive frameworks to determine quality data presentation etc. The extent to which this might provide an answer to material criticality especially in life cycle material flow accounting should be further explored.

WEEE (Waste Electrical and Electronic Equipment known also as E-waste) is considered a vital source of waste containing REEs (Islam & Huda, 2019; Islam & Huda, 2020). Further research is therefore needed to examine secondary material potential from waste electric and electronic equipment in Australia. Most of Australia's e-waste is currently exported to underdeveloped nations for downstream recycling (Islam & Huda, 2019; Islam & Huda, 2020). For Australia, the classification of WEEE under the NTCRS (National Television and Computer Recycling) scheme is limited to categories 2 and 6 of the EU WEE Directive, and thus, the majority of remaining EoL products are considered garbage and end in landfill (Dias et al., 2018; Islam & Huda, 2019; Islam & Huda, 2020). It is worth noting that these EoL products in the neglected categories (1, 3 and 4) make up a large portion of renewable and green energy products containing high usage of REEs; these photovoltaic panels, and energy-efficient fluorescent lamps, which currently are not regulated in Australia under the NTCRS waste program (Dias et al., 2018; Islam & Huda, 2019). An extension of the WEEE Directive regarding EoL products in these other neglected categories is another area of concern.

Tailings and industrial residues are equally considered potential sources of secondary materials that could supplement the primary extraction of REEs (Binnemans et al., 2013; Du & Graedel, 2011; Haque et al., 2014; Mudd et al., 2019). REEs tailing dumps in Australia are not new in literature, with several reports examining heap deposits (Haque et al., 2014; Huleatt, 2019; Miezitis et al., 2011; Mudd et al., 2019). The tailings heap at Olympic Dam, for example, was reported to be a potentially significant source of REEs (Haque et al., 2014). This is an area of research that is far beyond the scope of this study but presents an area for further investigation. Extractions from tailings are important not only because they could supplement primary material consumption, but because they present less environmental burden (Binnemans et al., 2013). Radioactive elements, such as uranium and thorium, are common byproducts associated with the extraction of primary REEs materials, as are other toxic elements that are dangerous to human health and chemical liquids that are destructive to surrounding environments (water, soil, groundwater), all of which could be avoided (Balaram, 2019; Binnemans et al., 2013; Eckelman & Chertow, 2009). The extent to which this might provide an answer to the criticality of these metals should be further explored. The REEs extraction and impact on human health around these mining zones in Australia could also be a potential area of further exploration to complement this study. In this way, other resource use indicators, such as land use and water, can be introduced to further investigate the impact on human health.

Finally, the overall literature reveals a lack of academic research covering the REEs industry in Australia, and as such, it is recommend that more collaboration should occur between industry and academia to understand the sustainability of these metals, the global economy, and the potential political consequences of the eventual decline in its supply. The mishandling of waste products containing REEs is of paramount importance. The literature reports low incentives, poor collection, and recycling technologies as some major reasons for the current low recycling of REEs (Balaram, 2019; Binnemans et al., 2013; Du & Graedel, 2011; Du & Graedel, 2011). These are potential topics that can be further explored to measure the extent to which this might provide an answer to the criticality of these metals. REEs within the framework of sustainability as indicated in this study provide potential areas for future research.

7.5 Concluding comments

This study has put forward core knowledge on REEs and sustainable consumption to minimise environmental impact through the implementation of CE as a sustainable management strategy. The study identified several areas for improvement in the development of knowledge and the existing body of research in this area and provides a foundation for future research. It contributes to understanding REEs within the framework of sustainability as it provides the grounds for examination of the consumption pattern of these metals in Australia, and grounds for evaluating the existing resource efficiency strategies in REEs. Thus, it introduces ways to improve sustainability outcomes of these metals in Australia and contributes to a strategy for global uptake.

This study demonstrated how the concept of CE within a sustainability framework can contribute to tackling the challenge of REEs resource scarcity to reduce environmental burdens. A comprehensive CE framework for material criticality was developed and a practical implementation strategy was suggested to close the material loop. Overall, the study presents a case that improvements in sustainable resource consumption practices, like recycling efficiency, are promising strategies for improving REEs resource use efficiency. CE being a restorative and regenerative system through its design-for-long-life, easy repairs and reuse, maintenance, renovate, remanufacture, repurpose, recovery and recycling principles can be used to close material and energy loops and keep resources in circulation. However, although recycling is a promising option for mitigating REEs supply issues and reducing overall environmental burdens associated with the production and consumption of these metals, it is not a solution, especially in the short term as many of the emerging technologies that rely on REEs, such as wind turbines and electric vehicles, have a long life span and are not yet ready to be recycled, in addition to the large timeframe required to establish recycling infrastructure. The sustainability of REEs must therefore be achieved with a broader consideration of the environmental, socio-economic, and technological aspects of the consumption of these metals. This involves a combination of CE EoL and manufacturing-oriented strategies. Environmentally-friendly mining and virgin material processing, efficient material use and resources along the supply chain, intelligent product designs and standardisation, and the prolonged lifespan of applications using REEs are some of the efficient approaches that can be used to boost the environmental performance of products and services that rely on REEs (Zaimes et al., 2015).

This study demonstrates sustainability approaches for identifying policy priorities for material consumption and impact reduction. It highlights the importance of these metals, their critical nature, and the need to improve resource efficiency to combat supply risks while reducing impacts. In this regard, priority should be given to the design of longer-lasting magnets and phosphors; the repair or refurbishment of EoL products, and improvement in their collection rate. This study adds value by setting REEs within the framework of CE and sustainability, a novel strategy for resource efficiency, an approach neglected by the current body of literature. The proposed framework suggests the need for a comprehensive CE scheme for REEs in a sustainable development context for criticality mitigation and a practical implementation strategy to close the material loop and enhance the sustainability of REEs consumption. The three pillars of sustainable development (economic, environmental, social) go hand in hand, such that any development towards implementation of CE and improvement in resource efficiency must consider this systematic perspective.

The work equally informs policy and decision-makers of the strategic economic and political importance of these metals in the global milieu, and the need to establish parameters to quantify material efficiency, which can identify sectors within the system that need improvements to minimise waste and close material loops. This study, therefore, addresses the need to understand how REEs can be used within the framework of sustainability to achieve resource efficiencies and minimise environmental and social impacts. It strengthens the need for the implementation of CE as a strategic tool in resource management. Waste disposers, recyclers, and other stakeholders must continue to address Design for the Environment (DfE) and waste management policy for EoL products containing these metals.

References

Akcil, A., Sun, Z., & Panda, S. (2020). COVID-19 disruptions to tech-metals supply are a wake-up call. *Nature, 587*(7834), 365-367. https://doi.org/10.1038/d41586-020-03190-8

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M. A., Kinnaird, J., Littleboy, A., Meinert, L. D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., & Yakovleva, N. (2017). Mineral supply for sustainable development requires resource governance. *Nature, 543*(7645), 367-372. https://doi.org/10.1038/nature21359

Alonso, E., Sherman Andrew, M., Wallington Timothy, J., Everson Mark, P., Field Frank, R., Roth Richard, & Kirchain Randolph, E. (2012). Evaluating rare earth element availability: A case with revolutionary demand from clean technologies. *Environmental Science & Technology, 46*(6), 3406-3414. https://doi.org/10.1021/es203518d

Amahmoud, A., Attar, M. M. E., & Meleishy, A. (2022). The evolution of life cycle assessment approach: A review of past and future prospects. *IOP Conference Series: Earth and Environmental Science, 992*(1), 012002. 10.1088/1755-1315/992/1/012002

Arshi, P. S., Vahidi, E., & Zhao, F. (2018). Behind the scenes of clean energy: The environmental footprint of Rare earth products. *ACS Sustainable Chemistry & Engineering, 6*(3), 3311-3320. https://doi.org/10.1021/acssuschemeng.7b03484

Australia Trade and Investment Commission. (2019). *Australian critical minerals prospectus.* Commonwealth of Australia. https://www.austrade.gov.au/search.aspx?ModuleID=8367&keywords=AUSTRALIAN%20CRITICAL%20MINERALS%20PROSPECTUS&multiSite=False

Balanay, R., & Halog, A. (2019). 3 - Tools for circular economy: Review and some potential applications for the Philippine textile industry. In S. S. Muthu (Ed.), *Circular Economy in Textiles and Apparel* (1st ed., pp. 49-75). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102630-4.00003-0

Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers, 10*(4), 1285-1303. https://doi.org/10.1016/j.gsf.2018.12.005

Barros, M. V., Salvador, R., do Prado, G. F., de Francisco, A. C., & Piekarski, C. M. (2021). Circular economy as a driver to sustainable businesses. *Cleaner Environmental Systems, 2*, 100006. 10.1016/j.cesys.2020.100006

Bauer, D., Diamond, D., Li, J., McKittrick, M., Sandalow, D., & Telleen, P. (2011). *Critical materials strategy. US Department of Energy. Washington DC.* Retrieved from https://www.energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

Bauer, D., Sandalow, D., Diamond, D., Li, J., McKittrick, M., & Telleen, P. (2010). *Critical materials strategy. US Department of Energy. Washington DC.* .https://doi.org/10.2172/1000846 https://www.energy.gov/sites/prod/files/piprod/documents/cms_dec_17_full_web.pdf

Beasley, J., Georgeson, R., Arditi, S., & Barczak, P. (2014). *Advancing resource efficiency in Europe: Indicators and waste policy scenarios to deliver a resource-efficient and sustainable Europe.* European Environmental Bureau. https://makeresourcescount.eu/wp-content/uploads/2014/11/FINAL_Advancing-Resource-Efficiency-in-Europe_PUBL.pdf

Behrens, A., Taranic, I., & Rizos, V. (2015). *CEPS working documents: Resource efficiency indicators for policy-making.* CEPS Publication. https://www.ceps.eu/ceps-publications/resource-efficiency-indicators-policy-making/

Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., & Buchert, M. (2013). Recycling of rare earths: a critical review. *Journal of Cleaner Production, 51*, 1-22. https://doi.org/10.1016/j.jclepro.2012.12.037

Bradsher, K. (2010, November 10). China still bans rare earth to Japan. *The New York Times* https://www.nytimes.com/2010/11/11/business/global/11rare.html

Brundtland Commission. (1987). *Report of the world commission on Environment and development: Our common future.* Oxford University Press. http://www.un-documents.net/our-common-future.pdf

Brunner, P. H., & Rechberger, H. (2003). *Practical handbook of material flow analysis* (1st ed.). CRC Press. https://doi.org/10.1201/9780203507209

Brunner, P. H., & Rechberger, H. (2016). *Handbook of material flow analysis: For environmental, resource, and waste engineers* (2nd ed.). CRC Press. https://doi.org/10.1201/9781315313450

Cai, S. (2019, May 30). Companies like Apple that depend on rare earth metals have nowhere to turn. *Barron's (Online)* https://www.barrons.com/articles/stocks-exposed-rare-earths-metals-51559164960

Camilleri, M. A. (2018). Closing the loop for resource efficiency, sustainable consumption and production: A critical review of the circular economy. *International Journal of Sustainable Development, 21*(1-4), 1-17. https://ssrn.com/abstract=3119575

Camilleri, M. A. (2019). The circular economy's closed loop and product service systems for sustainable development: A review and appraisal. *Sustainable Development, 27*(3), 530-536. https://doi.org/10.1002/sd.1909

Castro, M. B. G., Remmerswaal, J. A. M., Reuter, M. A., & Boin, U. J. M. (2004). A thermodynamic approach to the compatibility of materials combinations for recycling. *Resources, Conservation and Recycling, 43*(1), 1-19. 10.1016/j.resconrec.2004.04.011

Chapman, P. (1975). *Fuel's paradise*. Penguin Books. https://doi.org/www.econis.eu/PPNSET?PPN=190229535

Corder, G. D., Golev, A., & Giurco, D. (2015). “Wealth from metal waste”: Translating global knowledge on industrial ecology to metals recycling in Australia. *Minerals Engineering, 76*, 2-9. https://doi.org/10.1016/j.mineng.2014.11.004

Crooks, E. (2019, Jun 11). US, Canada and Australia join forces to tackle metal shortage risk. *Financial Times* https://www.ft.com/content/4863fff2-8bea-11e9-a1c1-51bf8f989972

Cullinane, D. (2019, September 11). Rare earth stocks on the ASX: The ultimate guide. https://smallcaps.com.au/rare-earth-stocks-asx-ultimate-guide/

Curran, M. A. (2006). *Life cycle assessment: principles and practice.* Cincinnati, OH: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1000L86.PDF?Dockey=P1000L86.PDF

Curran, M. A. (2008). Life cycle assessment. In S. E. Jørgensen, & B. D. Fath (Eds.), *Encyclopedia of Ecology* (2nd ed., pp. 2168-2174). Academic Press. https://doi.org/10.1016/B978-008045405-4.00629-7

Dang, D. H., Thompson, K. A., Ma, L., Nguyen, H. Q., Luu, S. T., Duong, M. T. N., & Kernaghan, A. (2021). Toward the circular economy of rare earth elements: A review of abundance, extraction, applications, and environmental impacts. *Archives of Environmental Contamination and Toxicology, 81*(4), 521-530. 10.1007/s00244-021-00867-7

Department of Industry Innovation and Science, & Australia Trade and Investment Commission. (2019). *Au i ’ critical minerals strategy.* Commonwealth of Australia 2019. https://www.industry.gov.au/sites/default/files/2019-03/australias-critical-minerals-strategy-2019.pdf

Dias, P., Bernardes, A. M., & Huda, N. (2018). Waste electrical and electronic equipment (WEEE) management: An analysis on the Australian e-waste recycling scheme. *Journal of Cleaner Production, 197*, 750-764. https://doi.org/10.1016/j.jclepro.2018.06.161

Domenech, T. (2014). *Explainer: What is a circular economy?* The Conversation. Retrieved Dec 27, 2019, from http://theconversation.com/explainer-what-is-a-circular-economy-29666

Drost, D., & Wang, R. (2016). Rare earth element criticality and sustainable management. Paper presented at the *Proceedings of the 2015 4th International Conference on Sensors, Measurement and Intelligent Materials,* Shenzhen, China. 914-919. https://dx.doi.org/10.2991/icsmim-15.2016.168

Du, X., & Graedel, T. E. (2011a). Uncovering the global life cycles of the rare earth elements. *Scientific Reports, 1*, 145. 10.1038/srep00145

Du, X., & Graedel, T. E. (2011b). Global rare earth in-use Stocks in NdFeB permanent magnets. *Journal of Industrial Ecology, 15*(6), 836-843. 10.1111/j.1530-9290.2011.00362.x

Du, X., & Graedel, T. E. (2011c). Global in-use stocks of the rare earth elements: A first estimate. *Environmental Science & Technology, 45*(9), 4096-4101. https://doi.org/10.1021/es102836s

Dulfer, H., Senior, A. B., Thorne, J. P., Mernagh, T. P., Huston, D. L., & Skirrow, R. G. (2013). *Critical commodities for a high-tech world: Australia's potential to supply global demand.* Commonwealth of Australia. https://www.ga.gov.au/data-pubs/data-and-publications-search/publications/critical-commodities-for-a-high-tech-world

Eckelman, M. J., & Chertow, M. R. (2009). Quantifying life cycle environmental benefits from the reuse of industrial materials in Pennsylvania. *Environmental Science & Technology, 43*(7), 2550-2556. https://doi.org/10.1021/es802345a

Ekins, P., Hughes, N., Bringezu, S., Clarke, C., Fischer-Kowalski, M., Graedel, T., Hajer, M., Hashimoto, S., Hatfield-Dodds, S., Havlik, P., Hertwich, E., Ingram, J., Kruit, K., Milligan, B., Moriguchi, Y., Nas, r. N., Newth, D., Obersteiner, M., Ramaswami, A., Westhoek, H. (2017). *UNEP (2017) Resource efficiency: Potential and economic implications.* A report of the International Resource Panel.

Environmental Justice Organisation Liabilities and Trade. (2012). *Material flow analysis.* EJOLT. Retrieved Sep 9, 2019, from http://www.ejolt.org/2012/11/material-flow-analysis/

European Commission. (2014). *Towards a circular economy: A zero waste programme for Europe.* https://eur-lex.europa.eu/resource.html?uri=cellar:aa88c66d-4553-11e4-a0cb-01aa75ed71a1.0022.03/DOC_1&format=PDF

European Commission. (2017). *Critical raw materials and the circular economy: background report.* Publications Office of the European Union. http://dx.doi.org/10.2760/378123

European Commission. (2017). *Study on the review of the list of critical raw materials critical assessment: Final report.* Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1

European Commission. (2018). *Report on critical raw materials and the circular economy.* Publications Office of the European Union. http://op.europa.eu/en/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1/language-en/format-PDF

European Union. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). *Official Journal of the European Union, 197*, 38-71. http://data.europa.eu/eli/dir/2012/19/oj

European Union, & Risk and Policy Analysis Limited. (2014). *Study on data needs for a full raw materials flow analysis: final report.* Publications Office of the European Union. https://publications.europa.eu/en/publication-detail/-/publication/10ed5c27-edec-43de-8e6f-9676e9308af5

Favot, M., & Massarutto, A. (2019). Rare-earth elements in the circular economy: The case of yttrium. *Journal of Environmental Management, 240*, 504-510. 10.1016/j.jenvman.2019.04.002

Gaustad, G., Krystofik, M., Bustamante, M., & Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. *Resources, Conservation and Recycling, 135*, 24-33. 10.1016/j.resconrec.2017.08.002

Gaustad, G., Olivetti, E., & Kirchain, R. (2011). Toward sustainable material usage: Evaluating the importance of market motivated agency in modelling material flows. *Environmental Science & Technology, 45*(9), 4110-4117. https://doi.org/10.1021/es103508u

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gibson, M., & Parkinson, I. (2011). *Once ignored on the periodic table, don't ignore them now: A Rare Earth Element Industry Overview.* Canadian Imperial Bank of Commerce World Markets Inc.

Goonan, T. G. (2011). *Rare earth elements- end use and recyclability: U.S. geological survey scientific investigations report.* (No. 5094). U.S. Geological Survey. https://doi.org/10.3133/sir20115094

Gordon, B. H., James, B. H., & Greta, J. O. (2002). *Rare earth elements—critical resources for high technology.* U.S. Geological Survey. https://pubs.usgs.gov/fs/2002/fs087-02/

Grimes, S., Donaldson, J., & Cebrian Gomez, G. (2008). *Report on the environmental benefits of recycling.* Brussels, Belgium: Bureau of International Recycling. https://www.mgg-recycling.com/wp-content/uploads/2013/06/BIR_CO2_report.pdf

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology, 45*(1), 90-96. 10.1021/es101316v

Guyonnet, D., Dubois, D., Escalon, V., Fargier, H., Rollat, A., Shuster, R., Ahmed, S. S., Tuduri, J., & Zylberman, W. (2013). Material flow analysis for identifying rare earth element recycling potentials in the EU-27. Paper presented at the *Fourteenth International Waste Management and Landfill Symposium, Sep 2013,* Cagliari, Italy. 10 p. http://dx.doi.org/10.13140/2.1.3672.3844

Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., Vaxelaire, S., Dubois, D., & Fargier, H. (2015). Material flow analysis applied to rare earth elements in Europe. *Journal of Cleaner Production, 107*, 215-228. https://doi.org/10.1016/j.jclepro.2015.04.123

Habib, K., Schibye, P. K., Vestbø, A. P., Dall, O., & Wenzel, H. (2014). Material flow analysis of NdFeB magnets for Denmark: A comprehensive waste flow sampling and analysis approach. *Environmental Science & Technology, 48*(20), 12229-12237. 10.1021/es501975y

Haque, N., Hughes, A., Lim, S., & Vernon, C. (2014). Rare earth elements: Overview of mining, mineralogy, uses, sustainability and environmental impact. *Resources, 3*(4), 614-635. https://doi.org/10.3390/resources3040614

Hornby, L., & Sanderson, H. (2019a, June 4). Beijing's rare plan to hit back: Used in smartphones, electric vehicles and wind turbines, rare earths are at the centre of the trade war. *Financial Times* https://www.ft.com/content/3cd18372-85e0-11e9-a028-86cea8523dc2

Hornby, L., & Sanderson, H. (2019b, June 3). Rare earths: Beijing threatens a new front in the trade war. *Financial Times* https://www.ft.com/content/3cd18372-85e0-11e9-a028-86cea8523dc2

Hornby, L., & Zhang, A. (2019, May 28). China's state planner suggests using rare earths in US trade war. *Financial Times* https://www.ft.com/content/a0125e6a-8168-11e9-b592-5fe435b57a3b

Huleatt, M. B. (2019). *Australian resource reviews: Rare earth elements 2019.* Geoscience Australia, Canberra. http://dx.doi.org/10.11636/9781925848441

Ikhlayel, M. (2017). Evaluation of the environmental impacts of rare earth elements production. *International Journal of Environmental Studies, 74*(6), 939-957. https://doi.org/10.1080/00207233.2017.1341737

Impact10X. (2022). *JCU Sustainability Impact 10x program.* https://jcu.brightidea.com/Impact10X

International Organization for Standardization. (2006a). *ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework.* Retrieved 6/22/2015 2015, from http://www.iso.org/iso/catalogue_detail?csnumber=37456

International Organization for Standardization. (2006b). *ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines.* Retrieved 6/22/2015 2015, from http://www.iso.org/iso/catalogue_detail?csnumber=38498

International Resource Panel. (2011). *Recycling rates of metals - International resource panel-UNEP: A status report.* Retrieved 2019, from https://www.resourcepanel.org/reports/recycling-rates-metals

International Resource Panel. (2017). *UNEP International Resource Panel: Assessing Global Resource Use. A systems approach to resource efficiency and pollution reduction.* UN Environment Programme. https://www.resourcepanel.org/reports/assessing-global-resource-use

International Resource Panel. (2018). *Resource efficiency for sustainable development: Key messages for Group of 20.* Nairobi, Kenya: United Nations Environmental Program.

International Resource Panel. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want.* Nairobi, Kenya: United Nations Environment Programme.

International Resource Panel-UNEP. (2018). *UNEP_International resource panel: Global material flows database.* UN Environment Programme-Global Material Flows Database. Retrieved Feb 4, 2020, from https://www.resourcepanel.org/global-material-flows-database

Islam, M. T., & Huda, N. (2019). E-waste in Australia: Generation estimation and untapped material recovery and revenue potential. *Journal of Cleaner Production, 237*, 117787. https://doi.org/10.1016/j.jclepro.2019.117787

Islam, M. T., & Huda, N. (2020). Reshaping WEEE management in Australia: An investigation on the untapped WEEE products. *Journal of Cleaner Production, 250*, 119496. https://doi.org/10.1016/j.jclepro.2019.119496

Jha, A. R. (2014). *Rare earth materials: Properties and applications* (1st ed.). CRC Press. https://doi.org/10.1201/b17045

John, B., Möller, A., & Weiser, A. (2016). Sustainable development and material flow. In H. Heinrichs, P. Martens, G. Michelsen & A. Wiek (Eds.), *Sustainability Science: An Introduction* (1st ed., pp. 219-230). Springer Netherlands. https://doi.org/10.1007/978-94-017-7242-6_18

Jordens, A., Cheng, Y. P., & Waters, K. E. (2013). A review of the beneficiation of rare earth element bearing minerals. *Minerals Engineering, 41*, 97-114. https://doi.org/10.1016/j.mineng.2012.10.017

Jowitt, S. M., Werner, T. T., Weng, Z., & Mudd, G. M. (2018). Recycling of the rare earth elements. *Current Opinion in Green and Sustainable Chemistry, 13*, 1-7. https://doi.org/10.1016/j.cogsc.2018.02.008

Kalvig, P., & Machacek, E. (2018). Examining the rare-earth elements (REE) supply–demand balance for future global wind power scenarios. *GEUS. Geological Survey of Denmark and Greenland Bulletin, 41*, 87-90. https://doi.org/10.34194/geusb.v41.4350

Kaufman, S. M. (2012). 3 - Quantifying sustainability: industrial ecology, materials flow and life cycle analysis. In F. Zeman (Ed.), *Metropolitan Sustainability* (1st ed., pp. 40-54). Woodhead Publishing. https://doi.org/10.1533/9780857096463.1.40

Keenan, J. (2019, Technology trends drive mining's future. *Canadian Mining Journal, 140*, 5. http://www.canadianminingjournal.com/features/technology-trends-drive-minings-future/

King, H. M. (2021). REE - Rare earth elements and their uses. *Geology and Earth Science News and Information,* https://geology.com/articles/rare-earth-elements/

Klinger, J. M. (2018). Rare earth elements: Development, sustainability and policy issues. *The Extractive Industries and Society, 5*(1), 1-7. https://doi.org/10.1016/j.exis.2017.12.016

Koltun, P., & Tharumarajah, R. (2014). Life cycle impact of rare earth elements. *ISRN Metallurgy, 2014*, 1-10. https://doi.org/10.1155/2014/907536

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its limitations. *Ecological Economics, 143*, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Laner, D., & Rechberger, H. (2016). Material Flow Analysis. In M. Finkbeiner (Ed.), *Special Types of Life Cycle Assessment* (pp. 293-332). Springer Netherlands. https://doi.org/10.1007/978-94-017-7610-3_7

Lederer, J., & Kral, U. (2015). Theodor Weyl: A pioneer of urban metabolism studies. *Journal of Industrial Ecology, 19*(5), 695-702. 10.1111/jiec.12320

Li, F., Wang, P., Chen, W., Chen, W., Wen, B., & Dai, T. (2022). Exploring recycling potential of rare, scarce, and scattered metals: Present status and future directions. *Sustainable Production and Consumption, 30*, 988-1000. 10.1016/j.spc.2022.01.018

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production, 115*, 36-51. 10.1016/j.jclepro.2015.12.042

Long, K. R., Van Gosen, B. S., Verplanck, P. L., Seal, R. R., & Gambogi, J. (2017). *Rare-earth elements: Chapter O of critical mineral resources of the United States—economic and Environmental Geology and Prospects for future supply.* Reston, Virginia: U.S. Geological Survey. https://doi.org/10.3133/pp1802O

Lynas Rare Earths Ltd. (2010). Rare earths, we can touch them every day. *Lynas Presentation at the JP Morgan Australia Corporate Access Days, New York, 27e28 September,*

Lynas Rare Earths Ltd. (2021a). *Auto Catalysts.* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-are-rare-earths-used/auto-catalysts/

Lynas Rare Earths Ltd. (2021b). *Digital Technologies.* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-are-rare-earths-used/digital-technologies/

Lynas Rare Earths Ltd. (2021c). *Energy Efficiency.* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-are-rare-earths-used/energy-efficiency/

Lynas Rare Earths Ltd. (2021d). *How are rare earths used?* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-are-rare-earths-used/

Lynas Rare Earths Ltd. (2021e). *How do rare earths impact us?* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-do-rare-earths-impact-us/

Lynas Rare Earths Ltd. (2021f). *Products.* Lynas Corporation. Retrieved Sep 6, 2019, from https://www.lynascorp.com/products/

Lynas Rare Earths Ltd. (2021g). *What are rare earths?* Lynas Corporation. Retrieved Sep 9, 2019, from https://www.lynascorp.com/products/what-are-rare-earths/

Lynas Rare Earths Ltd. (2021h). *Wind Turbines.* Lynas Corporation. Retrieved Oct 24, 2019, from https://www.lynascorp.com/products/how-are-rare-earths-used/wind-turbines/

MacArthur, E. (2017). *What is a Circular Economy?* Ellen MacArthur Foundation. Retrieved Dec 27, 2019, from https://www.ellenmacarthurfoundation.org/circular-economy/concept

Mahmoudi, S., Huda, N., Alavi, Z., Islam, M. T., & Behnia, M. (2019). End-of-life photovoltaic modules: A systematic quantitative literature review. *Resources, Conservation and Recycling, 146*, 1-16. https://doi.org/10.1016/j.resconrec.2019.03.018

Manickam, P., & Duraisamy, G. (2019). 4 - 3Rs and circular economy. In S. S. Muthu (Ed.), *Circular Economy in Textiles and Apparel* (1st ed., pp. 77-93). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102630-4.00004-2

McLellan, B. C., Corder, G. D., & Ali, S. H. (2013). Sustainability of rare earths—An overview of the state of knowledge. *Minerals, 3*(3), 304-317. https://doi.org/10.3390/min3030304

McLellan, B. C., Corder, G. D., Golev, A., & Ali, S. H. (2014). Sustainability of the rare earths industry. *Procedia Environmental Sciences, 20*, 280-287. https://doi.org/10.1016/j.proenv.2014.03.035

Miezitis, Y., Jaireth, S., & Hoatson, D. M. (2011). *The major rare-earth-element deposits of Australia: geological setting, exploration, and resources.* Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/71820

Mudd, G., Werner, T., Weng, Z., Yellishetty, M., Yaun, Y., McAlpine, S., Skirrow, R., & Czarnota, K. (2019). *Critical minerals in Australia: a review of opportunities and research needs.* Geoscience Australia. http://dx.doi.org/10.11636/Record.2018.051

Mudgal, S., Tan, A., Lockwood, S., Eisenmenger, N., Fischer-Kowalski, M., Giljum, S., & Brucker, M. (2012). *Assessment of resource efficiency indicators and targets. Final report prepared for the European Commission, DG Environment.* BIO Intelligence Service, Institute for Social Ecology and Sustainable Europe Research Institute. https://doi.org/10.2779/5453

Navarro, J., & Zhao, F. (2014). Life-cycle assessment of the production of rare earth elements for energy applications: A review. *Frontiers in Energy Research, 2*, 1-17. https://doi.org/10.3389/fenrg.2014.00045

Norgate, T. (2013). *Metal recycling: The need for a life cycle approach.* CSIRO. 10.4225/08/584d94ce5f6ae

Organisation for Economic Co-operation and Development. (2008). *Measuring Material flows and resources productivity: The OECD guide.* (No. 1). OECD Publishing. http://www.oecd.org/environment/indicators-modelling-outlooks/MFA-Guide.pdf

Organisation for Economic Co-operation and Development. (2015). *Material Resources, Productivity and the Environment.* OECD Publishing. https://doi.org/10.1787/9789264190504-en

Palle Paul Mejame, M., Jung, D., Lee, H., Lee, D. S., & Lim, S. (2020). Effect of technological developments for smartphone lithium battery on metal-derived resource depletion and toxicity potentials. *Resources, Conservation and Recycling, 158*, 104797. https://doi.org/10.1016/j.resconrec.2020.104797

Palle Paul Mejame, M., Kim, Y. M., Lee, D. S., & Lim, S. (2016). Effect of technology development on potential environmental impacts from heavy metals in waste smartphones. *Journal of Material Cycles and Waste Management, 20*(1), 100-109. https://doi.org/10.1007/s10163-016-0548-2

Palle Paul Mejame, M., King, D., He, Y., & Banhalmi-Zakar, Z. (2021). Material flow analysis of rare earth elements and their sustainable use in Australia to reduce potential environmental impacts. Paper presented at the *Chemeca 2021: Advance, Disrupt and Sustai,* Barton, ACT. https://search.informit.org/doi/10.3316/informit.117083923822847

Palle Paul Mejame, M., King, D., He, Y., & Banhalmi-zakar, Z. (2022a). Circular economy: A sustainable management strategy for rare earth elements consumption in Australia. *Current Research in Environmental Sustainability, 4*, 100157. https://doi.org/10.1016/j.crsust.2022.100157

Palle Paul Mejame, M., King, D., He, Y., & Banhalmi-Zakar, Z. (2022b). Sustainability of rare earth elements consumption in a circular economy perspective [Manuscript accepted for publication]. Paper presented at the *Chemeca 2022: Greener, Safer, Cleaner Incorporating Hazards Australasia * Melbourne, Convention Centre.

Palle Paul Mejame, M., King, D., & He, Y. (2023). Circular Economy as a Way Forward Against Material Criticality: The Case of Rare Earth Elements in the Context of Sustainable Development. In: Muthu, S.S. (eds) Life Cycle Assessment & Circular Economy. Environmental Footprints and Eco-design of Products and Processes. Springer, Cham. https://doi.org/10.1007/978-3-031-33982-0_3Pincetl, S. (2012). 1 - A living city: using urban metabolism analysis to view cities as life forms. In F. Zeman (Ed.), *Metropolitan Sustainability* (1st ed., pp. 3-25). Woodhead Publishing. https://doi.org/10.1533/9780857096463.1.3

PRé Consultants. (2010). Simapro Version 9.1.1.

Rademaker, J. H., Kleijn, R., & Yang, Y. (2013). Recycling as a strategy against rare earth element criticality: A systemic evaluation of the potential yield of NdFeB magnet recycling. *Environmental Science & Technology, 47*(18), 10129-10136. https://doi.org/10.1021/es305007w

Rare Element Resources Ltd. (2016). *Rare Earth Elements.* https://www.rareelementresources.com/rare-earth-elements#.Y5VmIHZByHt

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? — Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling, 135*, 246-264. https://doi.org/10.1016/j.resconrec.2017.08.027

Reisman, D., R. WEBER, J. MCKERNAN, & C. Northeim. (2013). *Rare earth elements: A review of production, processing, recycling, and associated environmental issues.* Washington, DC: U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=251706&Lab=NRMRL

Rim, K. (2016). Effects of rare earth elements on the environment and human health: A literature review. *Toxicology and Environmental Health Sciences, 8*(3), 189-200. https://doi.org/10.1007/s13530-016-0276-y

Salim, H. K., Stewart, R. A., Sahin, O., & Dudley, M. (2019). End-of-life management of solar photovoltaic and battery energy storage systems: A stakeholder survey in Australia. *Resources, Conservation and Recycling, 150*, 104444. https://doi.org/10.1016/j.resconrec.2019.104444

Sarker, S. K., Haque, N., Bhuiyan, M., Bruckard, W., & Pramanik, B. K. (2022). Recovery of strategically important critical minerals from mine tailings. *Journal of Environmental Chemical Engineering, 10*(3), 107622. 10.1016/j.jece.2022.107622

Sauvé, S., Bernard, S., & Sloan, P. (2016a). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development, 17*, 48-56. https://doi.org/10.1016/j.envdev.2015.09.002

Sauvé, S., Bernard, S., & Sloan, P. (2016b). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development, 17*, 48-56. https://doi.org/10.1016/j.envdev.2015.09.002

Science Communication Unit, University of the West of England, & Bristol. (2012). *Science for environment policy in-depth report: Resource efficiency indicators report produced for the European Commission DG Environment.* Publications Office of the European Union. https://ec.europa.eu/environment/integration/research/newsalert/pdf/IR4_en.pdf

Schüler, D., Buchert, M., Liu, R., Dittrich, S., & Merz, C. (2011). *Study on rare earths and their Recycling: Final report for the Greens/EFA Group in the European Parliament.* 79017 Freiburg. Germany: Öko-Institut e.V. http://www.ressourcenfieber.eu/publications/reports/Rare%20earths%20study_Oeko-Institut_Jan%202011.pdf

Snow, A. (2019, Jun 9). US-China trade war sparks worries about rare minerals. *Wyoming Tribune-Eagle* https://abcnews.go.com/Technology/wireStory/us-china-trade-war-sparks-worries-rare-earth-63577091

Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., Visser, G., & Kramer, G. J. (2014). Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. *Environmental Science & Technology, 48*(7), 3951-3958. https://doi.org/10.1021/es404596q

Statistica. (2019). *REE share of consumption worldwide by end use 2018.* Statista. Retrieved Jan 6, 2020, from https://www.statista.com/statistics/604190/distribution-of-rare-earth-element-consumption-worldwide-by-end-use/

Suli, L. M., Ibrahim, W. H. W., Aziz, B. A., Deraman, M. R., & Ismail, N. A. (2017). A review of rare earth mineral processing technology. *Chemical Engineering Research Bulletin, 19*, 20-35. https://doi.org/10.3329/cerb.v19i0.33773

Tharumarajah, R., & Koltun, P. (2011). Cradle-to-gate assessment of environmental impact of rare earth metals. Paper presented at the *7th Australian Conference on Life Cycle Assessment,* Melbourne, Vic, Australia, 9-10 March 2011. 5. http://hdl.handle.net/102.100.100/104935?index=1

U.S. Geological Survey. (2020). *Mineral commodity summaries 2020.* Reston, VA: U.S. Geological Survey. https://doi.org/10.3133/mcs2020

United Nations Environment Programme. (2006). *Circular Economy: An alternative model for economic development.* UNEP DTIE: Paris, France. http://www.unep.fr/scp/publications/details.asp?id=DTI/0919/PA

United Nations Environment Programme. (2010). *ABC of SCP clarifying concepts on sustainable consumption and production.* UN Environment Program. https://www.oneplanetnetwork.org/sites/default/files/10yfp-abc_of_scp-en.pdf

United Nations Environment Programme. (2016). *Global material flows and resource productivity: Assessment report for the UNEP international resource panel.* https://wedocs.unep.org/20.500.11822/21557

United Nations Environment Programme. (2017). *SDG 12:Ensure sustainable consumption and production patterns:* UN Environment. http://www.unenvironment.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-12

United Nations Environment Programme. (2019). *Circular economy & the sustainable management of minerals and metal resources.* UN Environment. Retrieved Jan 16, 2020, from http://www.unenvironment.org/events/un-environment-event/circular-economy-sustainable-management-minerals-and-metal-resources

United Nations Environment Programme. (n.da). *Building circularity: Understanding and visualising sectors and circular processes.* UNEP circularity platform. Retrieved Jan 16, 2020, from https://buildingcircularity.org/

United Nations Environment Programme. (n.db). *Sustainable development goals: GOAL 12-Sustainable consumption and production.* UN Environment. Retrieved Aug 16, 2019, from http://www.unenvironment.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-12

United Nations Environmental Programme-Global Environmental Alert Services. (2011). *Resources efficiency and climate change-green economy vulnerable to rare earth minerals shortages.* UN Environment. https://wedocs.unep.org/bitstream/handle/20.500.11822/8824/GreenEconomyVulnerabletoRareEarthMineralsShortages.pdf?sequence=3&isAllowed=y

United State Environmental Protection Agency. (2011a). *Method for estimating greenhouse gas emission reduction from recycling*. EPA's Office of Research and Development. https://ww3.arb.ca.gov/cc/protocols/localgov/pubs/recycling_method.pdf

United State Environmental Protection Agency. (2011b). *A Quantification method for determining emission reduction factors due to recycling in California.* US EPA. Retrieved 2/8/2016 2016, from http://webcache.googleusercontent.com/search?q=cache:67FR-ynyedIJ:www.arb.ca.gov/cc/protocols/localgov/pubs/recycling_method.pdf+&cd=1&hl=en&ct=clnk&gl=kr

United State Environmental Protection Agency. (2012). *Rare earth elements: A review of production, processing, recycling, and associated environmental issues.* National Risk Management Research Laboratory The U.S. Environmental Protection Agency. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EUBC.PDF?Dockey=P100EUBC.PDF

Van Gosen, B. S., Verplanck, P. L., Long, K. R., Gambogi, J., & Seal, R. R. (2014). *The rare earth elements—Vital to modern technologies and lifestyles: U.S. geological survey fact sheet.* (No. 3078). U.S. Geological Survey. http://dx.doi.org/10.3133/fs20143078

Wagner, L. A. (2002). *Materials in the economy; material flows, scarcity, and the environment.* (No. 1221). Reston, VA: U.S. Geological Survey. https://doi.org/10.3133/cir1221

Wang, P., & Kara, S. (2019). Material criticality and circular economy: Necessity of manufacturing oriented strategies. *Procedia CIRP, 8*, 667-672. https://doi.org/10.1016/j.procir.2019.01.056

Wang, X., Yao, M., Li, J., Zhang, K., Zhu, H., & Zheng, M. (2017). China's rare earths production forecasting and sustainable development policy implications. *Sustainability, 9*(6), 1003. https://doi.org/10.3390/su9061003

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1109-6

WITS. (2019). *World integrated trade solution(import-export database).* https://wits.worldbank.org/about_wits.html. Retrieved 15,10, 2020, from

Xavier, L. H., Giese, E. C., Ribeiro-Duthie, A. C., & Lins, F. A. F. (2021). Sustainability and the circular economy: A theoretical approach focused on e-waste urban mining. *Resources Policy, 74*, 101467. 10.1016/j.resourpol.2019.101467

Xu, G., Yano, J., & Sakai, S. (2019). Recycling potentials of precious metals from end-of-life vehicle parts by selective dismantling. *Environmental Science & Technology, 53*(2), 733-742. 10.1021/acs.est.8b04273

Yang, S., Ma, K., Liu, Z., Ren, J., & Man, Y. (2020). Chapter 5 - Development and applicability of life cycle impact assessment methodologies. In J. Ren, & S. Toniolo (Eds.), *Life Cycle Sustainability Assessment for Decision-Making* (pp. 95-124). Elsevier. 10.1016/B978-0-12-818355-7.00005-1

Yuksekdag, A., Kose-Mutlu, B., Siddiqui, A. F., Wiesner, M. R., & Koyuncu, I. (2022). A holistic approach for the recovery of rare earth elements and scandium from secondary sources under a circular economy framework – A review. *Chemosphere, 293*, 133620. 10.1016/j.chemosphere.2022.133620

Zaghdaoui, H., Jaegler, A., Gondran, N., & Montoya-Torres, J. R. (2017). Material flow analysis to evaluate sustainability in supply chains. Paper presented at the *20th World Congress the International Federation of Automatic Control, Jul 2017,* Toulouse, France. https://hal-emse.ccsd.cnrs.fr/emse-01633801

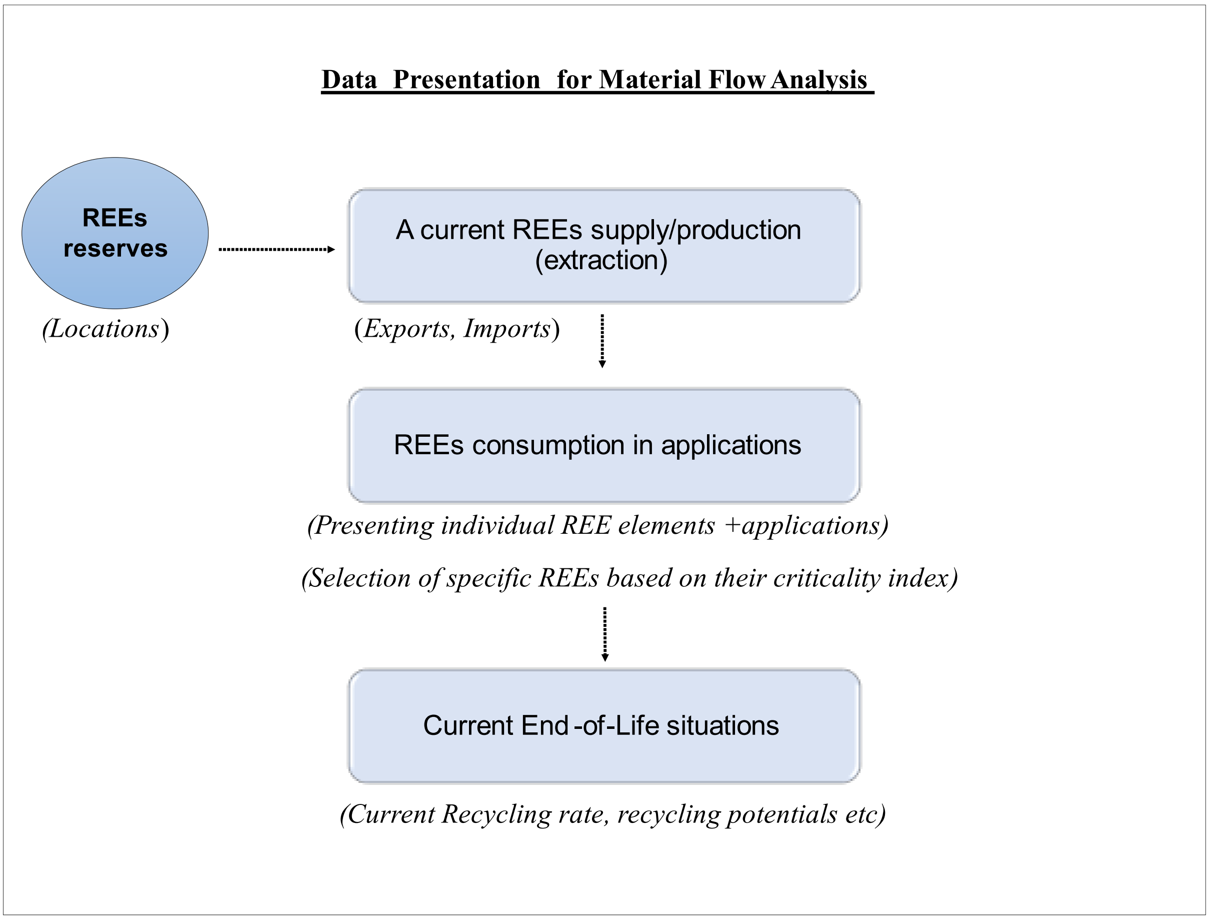
Zaimes, G. G., Hubler, B. J., Wang, S., & Khanna, V. (2015). Environmental life cycle perspective on rare earth oxide production. *ACS Sustainable Chemistry & Engineering, 3*(2), 237-244. https://doi.org/10.1021/sc500573b

Appendices

Appendices 1: Data Presentation Plan for Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA)

Appendix 1.1 Data Presentation Plan for Material Flow Analysis (MFA)

MFA: a tool to compile REEs data from extraction through to end-of-life (EoL)



MFA serves as the tool recording materials and energy flow entering and leaving the system thus representing Life cycle inventory (LCI) which is later used to calculate life cycle impact assessment.

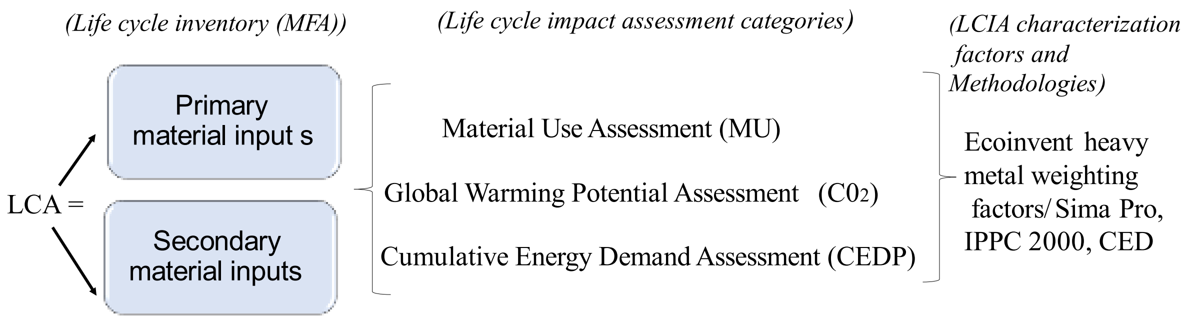
Appendix 1.2 Data Presentation Plan for Life Cycle Impact Assessment (LCIA)

LCIA: a tool to analyse the whole life cycle of data compilation for environmental impact assessment, policy and decision-making for societal benefit.

Data Presentation Plan for LCIA

Environmental Impact Assessment (LCIA)

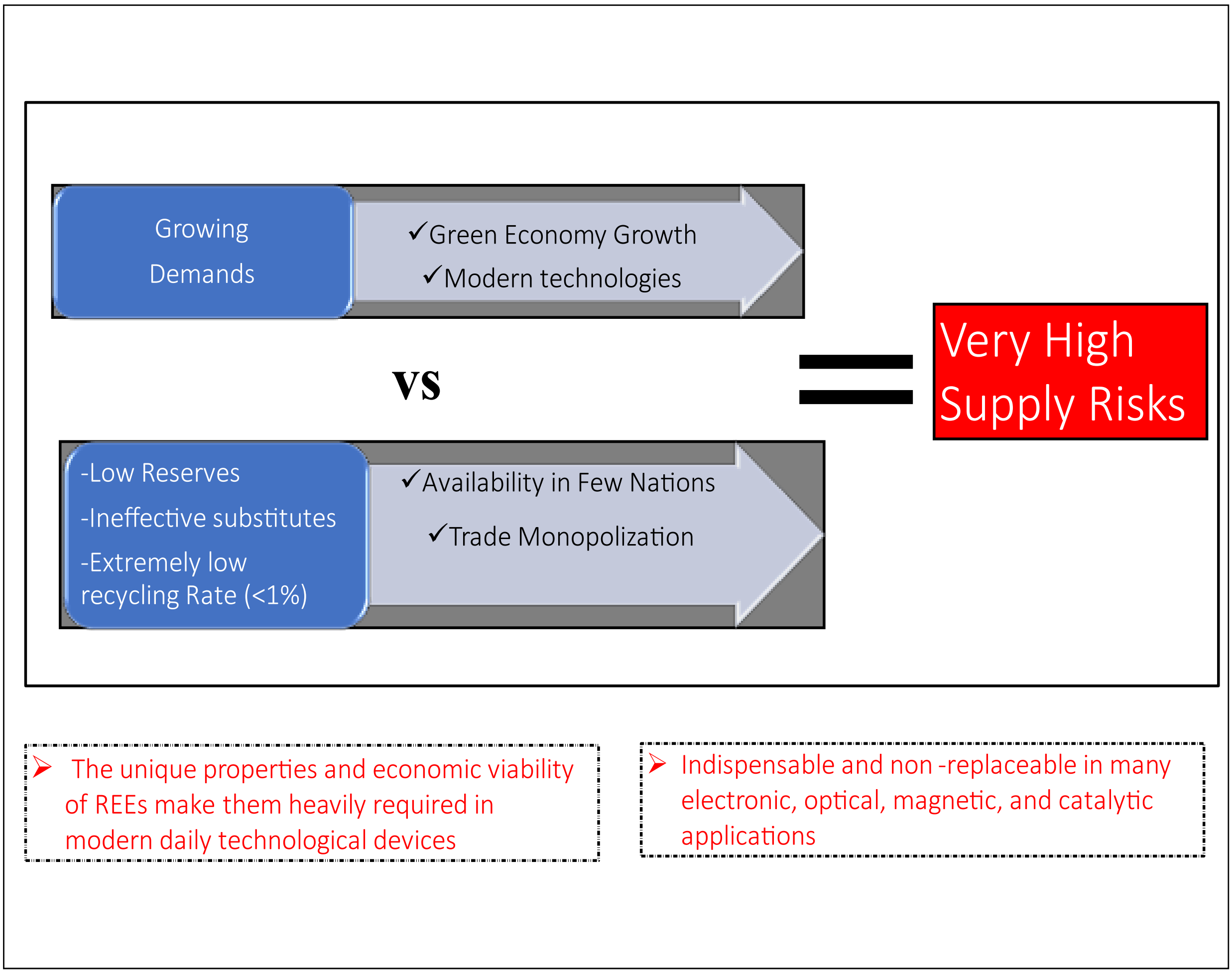
(Using Resource Efficiency Indicators (Material use, GWP, Energy Demand)



Appendix 2: REEs significance to clean technology and growth of a Green Economy

(Cai, 2019; Goonan, 2011; Huleatt, 2019; Lynas Rare Earths, n.d; Van Gosen et al., 2014)

Appendix 3: REEs Problems



Appendices 4: REEs Consumption and Distribution

Appendix 4.1: REEs consumption Distribution. The estimated average consumption distribution by applications

	REEs Usage in % by application										
Applications	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Others
Magnets	-	-	23.4	69.4	-	-	2	0.2	5	-	-
Battery Alloy	50	33.4	3.3	10	3.3	-	-	-	-	-	-
Metallurgy	26	52	5.5	16.5	-	-	-	-	-	-	-
Auto Catalysts	5	90	2	3	-	-	-	-	-	-	-
Fluide catalyst cracking (FCC)	90	10	-	-	-	-	-	-	-	-	-
Polishing Powder	31.5	65	3.5	-	-	-	-	-	-	-	-
Glass Additives	24	66	1	3	-	-	-	-	-	2	4
Phosphores	8.5	11	-	-	-	4.9	1.8	4.6	-	69.2	-
Ceramics	17	12	6	12	-	-	-	-	-	53	-
Others	19	39	4	15	2	-	1	-	-	19	-

Note: The dash (-) represents no metal consumption in that end-use sector/application.

Source: (Binnemans et al., 2013)

Appendix 4.2: The percentage of individual REEs consumption distribution by applications

	REEs Usage by application tons, volume										
Applications	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Others
Magnets	-	-	4.9	14.7	-	-	0.4	0.04	1.1	-	-
Battery Alloy	10.6	7.1	0.7	2.1	0.7	-	-	-	-	-	-
Metallurgy	5.5	11.0	1.2	3.5	-	-	-	-	-	-	-
Auto Catalysts	1.1	19.0	0.4	0.6	-	-	-	-	-	-	-
Fluide catalyst cracking (FCC)	19.0	2.1	-	-	-	-	-	-	-	-	-
Polishing Powder	6.7	13.7	0.7	-	-	-	-	-	-	-	-
Glass Additives	5.1	13.9	0.2	0.6	-	-	-	-	-	0.4	0.8
Phosphores	1.8	2.3	-	-	-	1.0	0.4	1.0	-	14.6	-
Ceramics	3.6	2.5	1.3	2.5	-	-	-	-	-	11.2	-
Others	4.0	8.2	0.8	3.2	0.4	-	0.2	-	-	4.0	-
Sum	57.3	80.0	10.3	27.2	1.1	1.0	1.0	1.0	1.1	30.3	0.8

Note: The dash (-) represents no metal consumption in that end-use sector/application.

Appendix 4.3 Australia REEs export 2019 in metric tons, Sum in kilotons (kt). Source: (WITS, 2019)

Countries	quantity
New Zealand	3.88298
United States	0.4
United Kingdom	10
China	0.0062
France	0.05
Philippines	0.0024
New Caledonia	0.005
Total	14.34658
Sum in kt	0.01

Source: (WITS, 2019)

Appendix 4.4: Australia REEs Import 2019 in metric tons, Sum in kilotons (kt)

Countries	Quantity
China	139.3777
Germany	0.30728
Canada	0.00135
United States	0.15944
Russian Federation	0.00045
South Africa	1.066
Singapore	0.016
Japan	0.0195
Korea, Rep.	0.005
France	0.00001
United Kingdom	2.002
Total	142.95473
Sum in kt	0.14

Source: (WITS, 2019)

Appendix 4.5: Global mine Production of REEs in percentages (%)

Countries	**Mine Production 2019**	**%**
United States	26	**12%**
Australia	**21**	**10%**
Brazil	1	**0.5%**
Myanmar	22	**10%**
Burundi	0.6	**0.3%**
China	132	**62%**
India	3	**1%**
Madagascar	2	**1%**
Russia	2.7	**1%**
Thailand	1.8	**1%**
Vietnam	0.9	**0.4%**
World total (rounded)	210	100%

Source: (Huleatt, 2019; U.S. Geological Survey, 2020)

Appendices 5. Life cycle methodologies characterisation factors from ecoinvent

Appendix 5.1 CO_2 emission weighting/characterisation factors/IPCC GWP 100a 2013/ecoinvent database/Simapro

Weighting Factors IPCC GWP 100a 2013	
Metals	(kg CO_2-eq)
Nd	50.82
Dy	1.2079
Eu	0.97337
y	29.371
Tb	3.0677

Appendix 5.2: CEDP weighting/characterisation factors ecoinvent database/Simapro non-renewable energy resources, fossil

Weighting Factors CEDP	
Metals	MJ-Eq
Nd	590.51
Dy	13.995
Eu	12.15
Y	336.62
Tb	35.3