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Circular economy: A sustainable management strategy for rare earth elements consumption in Australia

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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 and consequent 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 risk and its environmental and economic significance, an in-depth examination of the environmental impact and benefits of sustainable consumption of these metals in Australia, as in many other parts of the world, holistically and systematically is lacking, particularly regarding improvement in resource efficiency strategies. Most previous work on REEs has focused either on the politico-economic conflicts over supply and distribution, or the environmental and social impacts of its production and has not holistically examined this problem, as a system.

This paper provides a review of REEs' sustainable consumption in Australia. The study highlights Circular Economy (CE) as a scientifically plausible picture of sustainable management strategy to help address the adverse impacts of resource (REEs) shortages while achieving maximum environmental benefits. It provides answers to how sustainable are the current strategies of REEs consumption and how this can be enhanced from a CE perspective. A comprehensive CE framework was developed, followed by an illustrative example of CE as a tool for sustainability management and a practical implementation strategy to close the material loop and improve resource efficiency.

1. Introduction

REEs consist of a set of 17 metals that include 15 lanthanides 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) plus scandium (Sc) and yttrium (Y) (Balaram, 2019; Huleatt, 2019; Miezitis et al., 2011). REEs are major enablers for technologies aiming to cut down emissions, minimise energy consumption, as well as boost efficiency, speed, performance, longevity and thermal stability (Balaram, 2019; Goonan, 2011; Huleatt, 2019; Long et al., 2017; Reisman et al., 2013; Van Gosen et al., 2014). These metals are also a vital component in technologies seeking to make products lighter and miniaturised (Gibson and Parkinson, 2011; Van Gosen et al., 2014). They are heavily demanded in everyday applications because of their unique chemical and physical properties ranging from catalytic, metallurgical, nuclear, electrical, and magnetic among others (Gibson and Parkinson, 2011; Long et al., 2017; Van Gosen et al., 2014) (as seen in Table 1 showing major uses of REEs in emerging high technologies). 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 (Balaram, 2019; Long et al., 2017; Van Gosen et al., 2014).

While the demand for these metals grows, global supply is under threat (Alonso et al., 2012; Balaram, 2019; Cai, 2019; Jowitt et al., 2018; 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 REEs war or scramble between the USA and China for example (Bradsher, 2010; Cai, 2019; Hornby and Zhang, 2019;

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Table 1
Major uses of the REEs in emerging high technologies. Adapted from Geoscience, Australia reports (Huleatt, 2019; Miezitis et al., 2011).

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)

Hornby and Sanderson, 2019a; Hornby and Sanderson, 2019b; Snow, 2019). The Covid-19 pandemic is a wake-up call, as this has affected many mines, factories and borders exacerbating the supply-demand problems of critical metals (Akcil et al., 2020). Australia is not immune to these conflicts and tensions as a major consumer of REEs, with a relatively small contribution to its global supply (Huleatt, 2019). This is an urgent crisis that needs to be addressed because shortages in the use of REEs in environmental-friendly applications like energy-efficient lighting, wind turbines, solar cells, display screens, electric cars etc., will adversely impact the advancement of clean energy technology and green economic development (IT and telecommunications generally, automotive etc) (United Nations Environmental Programme-Global Environmental Alert Services, 2011).

Most previous work on REEs has focused either on the politico-economic conflicts over supply and distribution, or the social and environmental impacts of its production and did not holistically examine this problem, as a system (Alonso et al., 2012; Drost and 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), an assessment of the environmental burdens and the benefits of sustainable consumption systematically and holistically are lacking, particularly regarding improvements in resource efficiency strategies (Klinger, 2018).

As a response to the gap in knowledge, this study provides an initial review of REEs consumption within a sustainable management framework in Australia, as a strategy for global uptake. The paper highlights CE as a scientifically plausible picture of a sustainable management strategy to help address the adverse impacts of resource shortages while achieving maximum environmental benefits. The paper will provide the basis for the evaluation of existing resource efficiency strategies for REEs and a pathway to improve sustainability outcomes in Australia. In this regard, a comprehensive CE framework for REEs was developed. This will help in the understanding of the benefits of resource efficiency improvements and the contribution of CE to the sustainability of REEs consumption. A material use analysis was conducted to identify the primary material consumption of REEs in applications and to demonstrate the importance of CE tools in sustainability assessment. Based on the CE framework, a conceptual and practical implementation strategy to close the material loop and improve resource efficiency was proposed. Information about the general availability of REEs, and the consumption pattern is essential for the implementation of cost-effective management, sustainable usage, and management of supply capacity. This work aims to further alert both the local and the international community about the global economic and potential political consequences of the eventual fall in the supply of these metals. The mishandling of waste products containing REEs is of paramount importance and common interest.

To achieve the aim of this study, this paper first examines the current research landscape of REEs within a sustainability framework, the application and uses of REEs, availability, locations and reserves, and existing governance policies. To analyse the information, a comprehensive CE scheme for REEs within a sustainable development framework is discussed. 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 paper is organised into 6 sections where Section 2 presents the applied methodology. Section 3 describes the current research on REEs within a sustainability framework, a description of CE as a sustainable development strategy and its significance to REEs' sustainability. Section 4 presents an illustrative example of CE tools for sustainability management through material use analysis. Section 5, a conceptual and practical implementation strategy to close the material loop and improve resource efficiency in REEs. Conclusions and outlooks are drawn in the sixth section.

2. Methods: comprehensive CE framework for criticality mitigation

This section starts by proposing a novel framework for REEs within sustainable development and a holistic view of the contribution of CE to the sustainability of REEs consumption. It went further to provide an illustrative example of CE tools for sustainability management through material use analysis.

2.1. REEs CE framework

REEs' material criticality has attracted global attention mainly due to their economic viability, strategic importance, and availability only in a few nations with high supply risks. Any effort toward combatting material criticality must be directed toward material efficiency (John et al., 2016). The sustainability of REEs' criticality can be well be understood by critically 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 was on the examination of two broad major 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 further classified into various categories such as academic and industrial sources; global and Australia focused. The reason for the global-Australia classification was to find out how much literature covered REEs' sustainability in general but with Australia as a focus.

Overall, this work contributes to advancing the understanding of REEs within the framework of sustainability. It provides the ground for the examination of the consumption pattern 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, a strategy for global uptake. The study aims to demonstrate how the concept of CE in a sustainable development framework can be implemented to tackle the challenge of REEs resource scarcity with reduced environmental burdens.

2.2. CE tools for sustainability management: An illustrative example

The sustainability of REEs consumption can be assessed using a combination of essential CE tools: Material Flow Analysis (MFA) and Life Cycle Impact Analysis (LCIA). These tools combined provide an in-depth structural and systematic evaluation of the material consumption of these metals. MFA provides an analysis of REEs consumption from raw material to End-of-life (EoL) through data compilation, while LCIA provides the analysis of the material life cycle, allowing for environmental impact assessment, policy and sustainability decision making. To link resource use and the associated impacts, the environmental life cycle impact assessment can be carried out using resource efficiency indicators such as Material Use (MU), Global Warming Potential (GWP) and Cumulative Energy Demand (CED). The result of such analysis can help identify which areas in the entire REE life cycle need to be targeted to improve consumption and production, in a way that minimises impacts on the environment and climate change. The goal is to connect economic activities to impacts on the environment with the end goal to promote society's response to target these driving forces to reduce impacts (International Resource Panel, 2017).

For this study, sustainability assessment of REEs consumption would be limited to material use analysis (MUA) only, primarily as the goal is to provide an example to demonstrate the importance of an application of a CE tool for resource efficiency improvement. Furthermore, the work described herein is a part of an ongoing project. At the time of drafting this paper, the work was 14 months old. Hence, the findings presented here afterwards (Section 4) should be considered preliminary. Future work will continue the assessment of environmental impact (GWP and CED) derived from material use and the impact reductions as described above.

For the material use study, the year 2019 was chosen as the base year for the 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 objective is to develop a sustainable framework that can be used to assess material use and impact over a given period). For this study, five REEs were selected: Nd, Dy, Eu, Y, and Tb based on their economic viability, criticality index, and supply risk because in the medium term they are more critical in terms of economic importance in green economic growth (higher demand in applications), supply risks and availability in other parts of the globe (Bauer et al., 2010; Bauer et al., 2011; European Commission, 2017).

2.2.1. Material use (MU)

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 the primary material consumption of REEs in applications across Australia (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). The pattern in which materials are utilised for production and consumption in systems reflects the waste streams and emissions that are an inevitable outcome of the material cycle (International Resource Panel, 2017). Material use assessment is an essential aspect of sustainable resource management as it provides information on environmental impacts across the entire material cycle of a resource (covering aspects such as energy use, air pollution, resource depletion and human health, etc.) It is a good tool for evidence-based policy-making (International Resource Panel, 2017).

The consumption of selected REEs in the application was estimated based on the individual estimates of the proportions of these elements found in applications derived from Binnemans et al. (Binnemans et al., 2013) and Australian REEs annual mine production from USGS and Geoscience Australia (Huleatt, 2019; U.S. Geological Survey, 2020), export and import statistics from WITS (World Integrated Trade Solution) database (WITS, 2019) as illustrated in Section 4 of this work.

3. REEs within the framework of sustainability

3.1. Sustainability and REEs criticality

When looking at the sustainability of REEs, it is important to consider the full life cycle of the material; that is, from material extraction, through manufacturing, EoL 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 (flow) in the system. The material criticality of REEs has attracted worldwide attention due to the growing demand and supply risk issues. Improving the circularity of this material use by transforming products at their EoL services into new sources for others is an important component (McLellan et al., 2014). CE is considered by many industrial economies as essential in addressing material criticality (McLellan et al., 2014; Wang and Kara, 2019). It is a solution to resource scarcity and waste reduction, especially if a full life cycle of the material is being examined (John et al., 2016; McLellan et al., 2014).

To be able to examine the sustainability of REEs and their criticality, consideration of a full life cycle of the material (from extraction to recycling) focal point must be on the three main pillars of the sustainable development framework: economy, environment, and society (as illustrated in Fig. 4, a comprehensive CE framework for REEs), and in addition consideration of the geological and technical aspects of REEs.

3.1.1. Economy

The economic sustainability of REEs metal criticality can be examined in terms of the high continuous demand of REEs vs low supply, its importance to clean energy and inequality in global distribution (Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; Gordon et al., 2002; King, 2013; McLellan et al., 2014). 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). To make it worse, these materials generally have limited effective substitutes and very poor recycling rates (Balaram, 2019) mainly because of the absence of strong regulating policies in the waste management system such as the absence of incentives to recycle etc. *E*-waste for instance constitutes a very high percentage of REEs (Islam and Huda, 2019). However, Australia is the highest producer of these wastes in the Oceania region and exports more than half of its wastes abroad for downstream recycling while landfill is a common practice (Islam and Huda, 2019; Islam and Huda, 2020). In terms of material circularity, this is a loss, and unsustainable practice, as interest is being placed more on the use of virgin material than the recovery of secondary materials from waste.

Furthermore, a major problem with these materials is not so much their rarity, but it is about their unequal global distribution. REEs are currently available in just a few countries of the world (Akcil et al., 2020; Balaram, 2019; McLellan et al., 2014) with a supply dominated by a single country (China). Mines in Australia are only currently becoming active again due to China's limited exports and supply restrictions, high prices and taxes coupled with the increasing demand for these metals (Klinger, 2018). As of 2019, China alone holds more than 38% of the world's reserves and controls more than 62% of the global supply (as seen in Figs. 1 and 2 respectively). Other major REEs production countries include the United States, Brazil, Russia, Myanmar, Burundi, India, Malaysia, Madagascar, Thailand, and Vietnam (Huleatt, 2019). According to Australian resource reviews of REEs 2019 and US Geological Survey (USGS) mineral reports 2020, Australia has the world's sixth-largest reserves of REEs and is currently the second-largest producer of REEs (Huleatt, 2019; U.S. Geological Survey, 2020). These reports show that in 2019, Australia produced 10% of these metals which is an increase compared to the previous years. These supplies came predominantly from Lynas Corporation's (now Lynas Rare Earths) Mount Weld mine 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. Current REE reserves in Australia as of 2019 are 3300 kt which is 3% of global reserves. However, the position as the second-largest producer might sound big but 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. Fig. 1 below shows the global reserve of REEs, Australia's position and China's dominance. While Fig. 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 so much location of these minerals just in one country as it is now, and with the current situation of China placing supply restrictions on other countries, this means a big threat to all the major consumer countries (King, 2013; Klinger, 2018). This specific situation, therefore, calls for an urgent need for the implementation of sustainable environmental management techniques for the consumption of these critical resources to minimise not only the current but also the future socio-economic and environmental impacts associated with its use. The 2019 covid impact on the mining industry such as border closures reducing imports and exports among countries is a good example of an awakening call for the implementation of sustainability strategies in the consumption of these metals to reduce dependency and supply failures (Akcil et al., 2020). Even though Australia currently seems to hold good potential for these metals as compared to other countries, this is however accompanied by low government investment in these sectors particularly the weak collection, reuse and recycling of the EoL products containing these metals (Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; Huleatt, 2019; Miezitis et al., 2011). Recycling currently is being focused on a small scale and is mostly on magnet scrap (Department of Industry Innovation and Science, and 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. They are of significant economic and strategic benefits for Australia if they can secure this market permanently (Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019).

The critical nature of these materials, their strategic importance, and their uses should not only be a driving force in the rush to explore other reserves in different parts of the earth and increase mining, but a call for an expansion in recycling and development of environmentally friendly technologies for the recovery of these metals at the end of their use to reduce waste and associated environmental burdens, designs for the environment to increase product longevity and easy repairs, research into alternatives, and more changes in international policy (King, 2013;

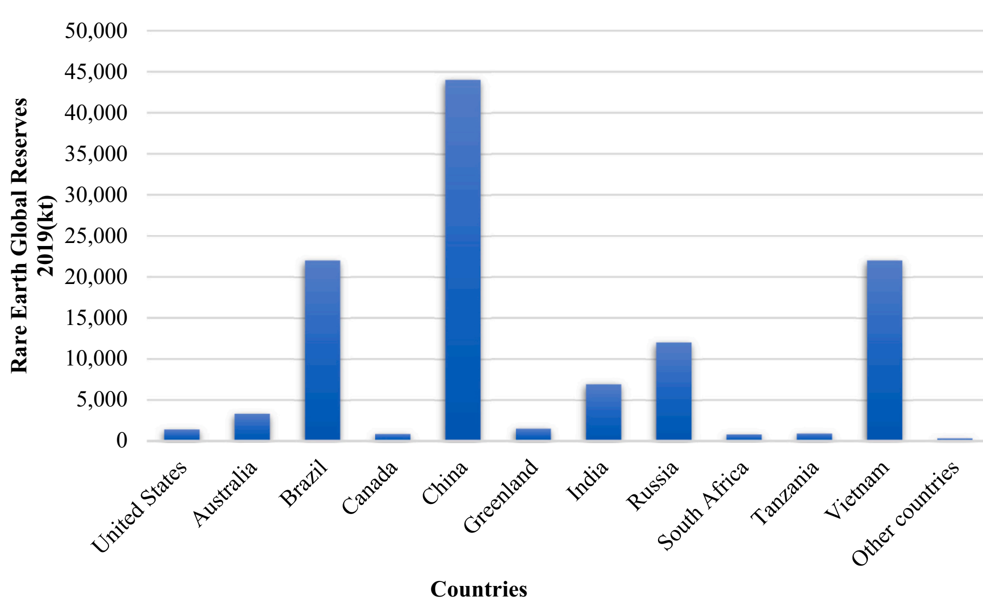


Fig. 1. Global reserves of REEs 2019: Australia's position. Source: (U.S. Geological Survey, 2020).

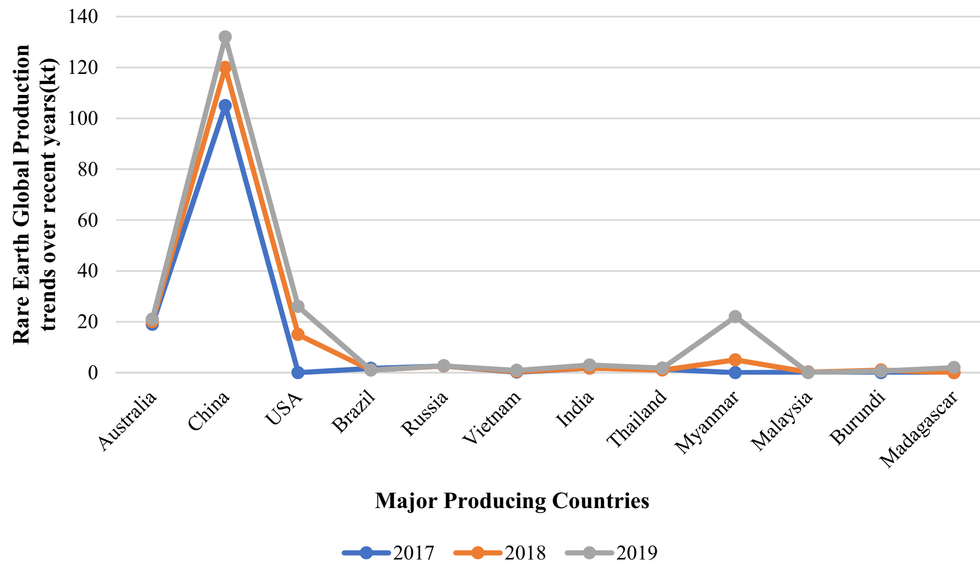


Fig. 2. Global REEs production trends (2017, 2018, 2019), Australia's position, and China's dominance over supply. Data source: (U.S. Geological Survey, 2020).

United Nations Environmental Programme-Global Environmental Alert Services, 2011). (As seen in Fig. 3).

3.1.2. *Socio-environmental aspects*

The sustainability of REEs criticality can also be examined socially regarding those aspects relating to the health of people within society (McLellan et al., 2013). This is because a bigger problem with REEs is not just about their low concentration characteristic but the fact that they are highly linked with radioactive elements (especially uranium and thorium) (Rim, 2016; Zaimes et al., 2015). This requires that

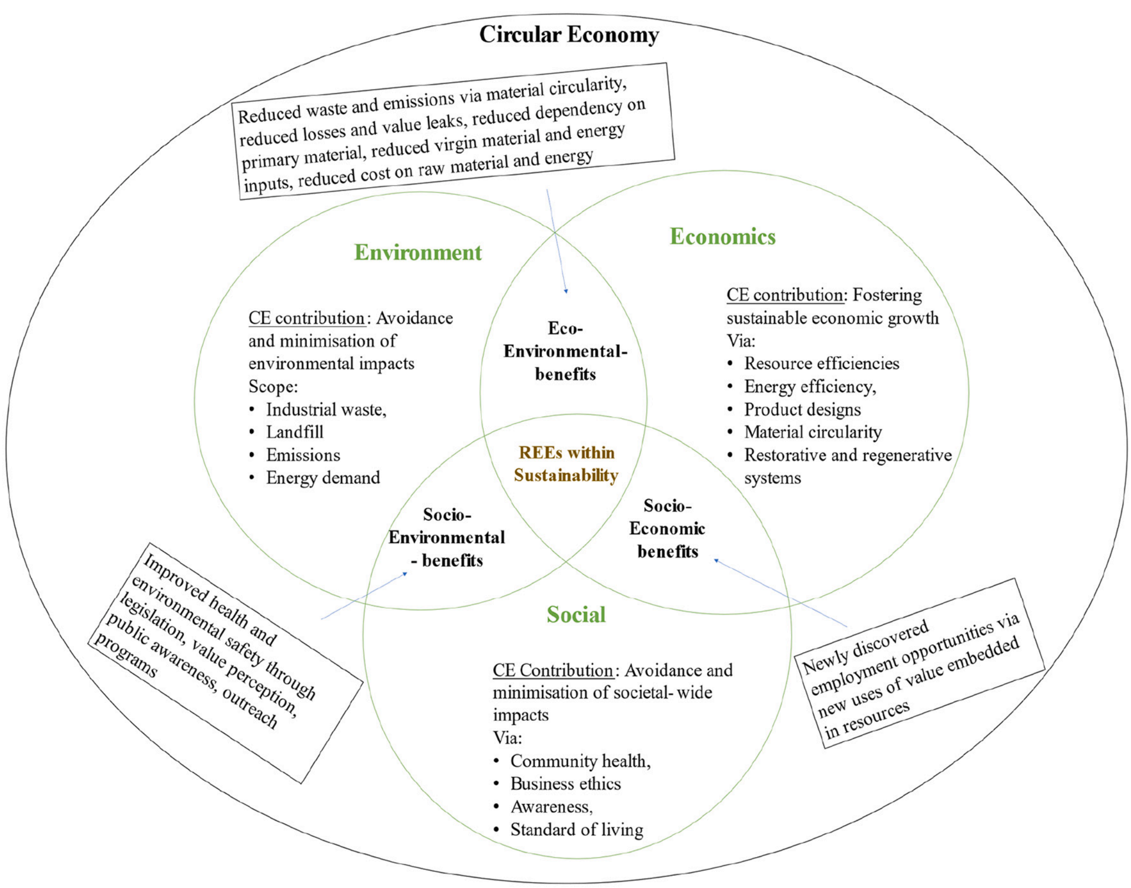


Fig. 3. A comprehensive CE Scheme. Moving toward circularity.
REEs within the framework of sustainable development. The work suggests that sustainability in REEs consumption from a CE perspective contributes to all the three pillars of sustainable development (Economics, Environmental and social). We 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.

adequate environmental and health safety mitigation methods must be ensured, thus increasing operational costs. These radioactive elements associated with REEs production are a major key environmental component of concern to the community and constitute a crucial problem in mined waste processing and disposal (Balaram, 2019; Binnemans et al., 2013; Reisman et al., 2013). The extraction of primary REEs materials equally includes toxic elements dangerous to human health including chemical liquids destructive to the surrounding environment (water, soil, groundwater, etc) (Balaram, 2019; Binnemans et al., 2013; Eckelman and Chertow, 2009). Secondary materials on the other hand are radioactive free (Binnemans et al., 2013). Radioactive tailing stockpiles and mining health problems can therefore be partially avoided with recycling (Balaram, 2019; Eckelman and Chertow, 2009). The advancement in environmentally friendly recycling technologies, community awareness etc… can therefore be regarded as significant CE pathways toward material efficiency and REEs sustainability (as seen in Fig. 3).

The environmental aspect of REEs sustainability can equally be assessed in terms of REE technologies and processes (Drost and Wang, 2016; McLellan et al., 2013). Generally, this aspect has been much examined in terms of association with the clean energy of REEs' technologies. Emerging high technologies from REEs use are environmentally friendly and low in carbon production. This includes electric vehicles, energy-efficient lighting, wind turbines etc. as seen in Table 1 (Miezitis et al., 2011). Fig. 3 below suggests a comprehensive CE scheme, positioning REEs within a sustainable development framework developed from (Korhonen et al., 2018).

3.1.3. Technological and geological aspects

In addition to the sustainability pillars (Economic, Social and Environmental), the sustainability of REEs criticality can also be well understood when considering the crustal concentration and difficulties in the exploitation of these metals. The similarity in properties and, the geological deposits of these metals are major constraints affecting their supply (Gordon et al., 2002; Van Gosen et al., 2014). These 17 REEs are found in all REE deposits, but with varying distribution and concentrations (Gordon et al., 2002). It is partly because of these reasons that they are described as rare, as commercially viable concentrations are not commonly located (King, 2013). The reserves of these metals might either be rich in one type of REE or another but will rarely be in significant commercial quantities (Gordon et al., 2002; GEAS, 2011). These similarities in geochemical properties have therefore made mining a costly and complex process (King, 2013). Furthermore, the difficulty in separating concentrated REE rich minerals to actual elements usually in the form of oxide compounds is another problem. Therefore, because of these problems, it is not common to locate economically viable deposits and straightforward techniques of extraction and separation (Van Gosen et al., 2014). Additionally, the lead times for fresh mining projects to be operational are long - from 2 to 10 years (Zaimes et al., 2015).

As of now, two main projects are producing REEs in Australia, with several other projects in the development pipeline (DIIS & Austrade, 2019; Huleatt, 2019). This includes Lynas Rare Earths' Mount Weld mine and Northern Minerals' Brown Range project. Lynas Rare Earths' 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 2 show major Australia's REEs mine 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, and 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, and 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).

Table 2
Major Australia's REEs mine projects. Adapted from Austrade (Austrade, 2019).

Mines and projects name	Location/state	Companies
Mount Weld	Western Australia	Lynas Rare Earths
Nolans	Northern Territory	Arafura Resources Limited
Browns Range	Northern western	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

3.2. REEs and sustainable management policies in Australia

As a result of the global challenge concerning the supply risks of these metals, Australia as with many industrial economies has been proposing different strategies to address the supply problem.

3.2.1. Efforts toward combatting supply risks

As one way to address this global challenge, REEs have been listed as "critical and strategic metals" in Australia as in other industrial economies around the world (Bauer et al., 2011; Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; European Comission, 2017; Gordon et al., 2002; United Nations Environmental Programme-Global Environmental Alert Services, 2011). In the last decades, specific REEs (Neodymium, Dysprosium, Europium, Terbium and Yttrium) have been identified by expert panels composed of research institutes and representatives from other countries around the World to be raw materials critical to growing technologies, such as electronic, clean energy and sophisticated military applications (Bauer et al., 2010; Bauer et al., 2011; Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; European Comission, 2017; Gordon et al., 2002; Long et al., 2017; United Nations Environmental Programme-Global Environmental Alert Services, 2011). These reports indicate the existence of a potentially high risk to supply disruption of these metals. In this regard, REEs were ranked high on the criticality factor of raw materials. This placed them to be metals of high supply risk with strong economic and technological importance (Bauer et al., 2010; Bauer et al., 2011; Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019 Van Gosen et al., 2014). In Australia, this has already been affirmed by major institutions such as the Australian Trade and Investment Commission, the

Department of Industry, Innovation and Science in their collaborative reports with Geoscience Australia (Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; Dulfer et al., 2013; Huleatt, 2019). The main goal of these conventions is to promote movement toward the adoption of sustainable management patterns for the consumption of these resources.

Furthermore, many governments have been implementing strategies to address the potential supply risks of these metals (Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019; United Nations Environmental Programme-Global Environmental Alert Services, 2011). For instance, multiple bills have been launched in the House of Representatives in the United States to tackle this problem (United Nations Environmental Programme-Global Environmental Alert Services, 2011). Several strategies have been introduced to promote the awareness of critical metals and tactics to combat supply risks. These include the search for substitutes, diversification of REEs supply chain, development of efficient recycling technologies, improvement in the efficiency in use and reuse of REEs (Bauer et al., 2010; United Nations Environmental Programme-Global Environmental Alert Services, 2011). In Japan, many companies have taken swift action to sign deals with India for the supply of REEs. In Australia, the government is alerting other bodies about the need to explore more sources for REEs and improve their production (Australia Trade and Investment Commission, 2019; Department of Industry Innovation and Science, and Australia Trade and Investment Commission, 2019). Recently, the US government has joined forces with Australia and other major consumer countries. The US warned the Australian government about the need to boost its production sector of REEs to supplement the cuts from China (Crooks, 2019).

3.2.2. Waste management

In terms of waste management, the recycling rate of REEs is still around 1% (Drost and Wang, 2016; Haque et al., 2014; Jowitt et al., 2018). Focus is being placed more on scrap magnet recoveries and regulating policies that do not indicate how the whole waste management system can be improved (Islam and Huda, 2020). Most of Australia's secondary sources of these metals are found overseas, and landfill is still being practised (Islam and Huda, 2019; Islam and Huda, 2020). For instance, although Waste Electrical and Electronic Equipment (WEEE referred to as e-waste) are said to contain a very high portion of REEs in its waste stream, there is no proper regulation in Australia to fully manage this waste stream (Islam and Huda, 2019; Islam and Huda, 2020). *E*-waste in Australia arising from IT parts, computers, waste televisions, and printers is being managed by the National Television and Computer Recycling Scheme (NTCRS) (Dias et al., 2018). As its name suggests, this current Australian scheme only considers as e-waste: old televisions, computer parts, printers etc. (Dias et al., 2018; Islam and Huda, 2019; Islam and Huda, 2020).

Under the European Union WEEE (EU WEEE) Directive 12 (European Union, 2012), there are six classified categories of e-waste with distinct goals for collection and recycling rates. This NTCRS scheme falls under categories 2 (small household appliances) and 6 (electrical and electronic tools) only of this directive (Dias et al., 2018; Islam and Huda, 2019; Islam and Huda, 2020). There is no regulation indicating how to manage the other e-waste products found in the EU WEEE Directive (Dias et al., 2018; Islam and Huda, 2019; Islam and Huda, 2020). Most of these products end up in landfills and the rest is collected as scrap (Dias et al., 2018; Islam and Huda, 2019). Category 1, 3 and 4 products under the WEEE Directive for example made up a large portion of renewable and green energy products such as photovoltaic panels, and energy-efficient fluorescent lamps which contain a high usage of REEs. Other products in this category include headphones, refrigerators, CD players, cameras, washing machines, air, conditioners etc. that currently are not regulated in Australia under the NTCRS e-waste management scheme (Dias et al., 2018; Islam and Huda, 2019). Recent studies show that Eol solar PV panels are major e-waste streams in Australia (Mahmoudi et al., 2019; Salim et al., 2019). These are all products that contain a very high percentage of magnets (Islam and 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).

In summary, the NTCRS-oriented e-waste scheme conducts phase one recycling operations in Australia and subsequently transports the waste abroad for downstream recycling to developing nations such as Indonesia, Vietnam, China, and India (Islam and Huda, 2019; Statistica., 2019). E-waste recovery from the other electronic products (category 1, 3 and 4) which are considered as garbage sees the majority ending up in landfills (Dias et al., 2018; Islam and Huda, 2019; Islam and Huda, 2020). In terms of material circularity, this is a permanent loss and thus an unsustainable practice. More emphasis should be placed on recuperating secondary materials from waste and optimization 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).

3.3. CE as a sustainable development strategy and strategy for REEs sustainability

The following section describes CE as a sustainable development concept and 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.

3.3.1. CE as a sustainable development strategy

Sustainable development is the fundamental framework behind the pursuit of resource efficiency of REEs (as demonstrated in Fig. 3). As defined by the Brundtland Commission, "Sustainable Development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). The whole concept emphasised how to build intragenerational prosperity while concurrently sustaining the living systems necessary to meet intergenerational demands. The idea of limited natural resources and the goal to manage those sustainably to meet present and future needs are stipulated in this definition. This also introduces the concept of weak and strong sustainability which is very important as both concepts have implications for the level of conservation, control, and adjustments in the consumption of resources for the well-being of the current generation without jeopardising the needs of generations to come. The planetary boundaries specifically serve as a guide for the current generation to adjust their consumption patterns of natural resources sustainably (Balanay and 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 already (John et al., 2016). In this regard, a strategy and a paradigm for these goals need to be established (Balanay and Halog, 2019; John et al., 2016). In relation to this, CE has been promoted as a strategy that brings promising systemic solutions to the global economy and environmental issues such as waste reduction, resource scarcity, etc. (Balanay and Halog, 2019; Wang and Kara, 2019). The reasoning of Sustainable Development Goals (SDG) is well echoed within the definition of what is the CE and its foundation (Camilleri, 2018).

To achieve resource (REE) efficiency, a systematic perspective must be adopted and implemented (John et al., 2016). This includes assessing the full life cycle of the dynamics of flows and stocks of these resources in the whole system (John et al., 2016; McLellan et al., 2014; Wang and Kara, 2019). This will enable us to know these materials and to make decisions on the various parts of the system to tackle reduction not only for resource consumption but also to improve the sustainable and efficient use of these metals, minimise CO_2 emissions and to a broad extent regulate human-environmental activities. This pattern of looking at REE life cycle material flow in the context of a system can be visualised under the concept of the CE system.

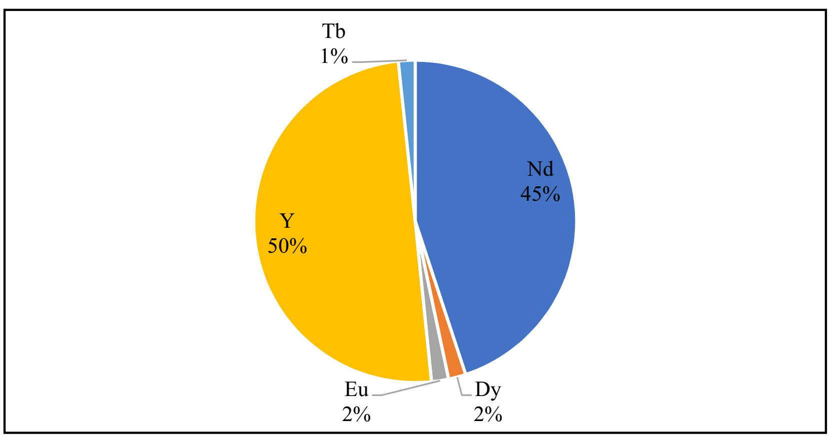
3.3.2. CE as a sustainable strategy for REEs sustainability

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). A vital strategy necessary for the sustainable management of REEs consumption to combat supply risk and reduce impact. 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 the production of waste and pollution (European Commission, 2018). CE redefines growth, focusing on positive society-wide benefits (MacArthur, 2017). Its main principles (as illustrated in Fig. 3) include designing out waste and pollution, maintaining products and resources in use, and restoring natural systems (MacArthur, 2017).

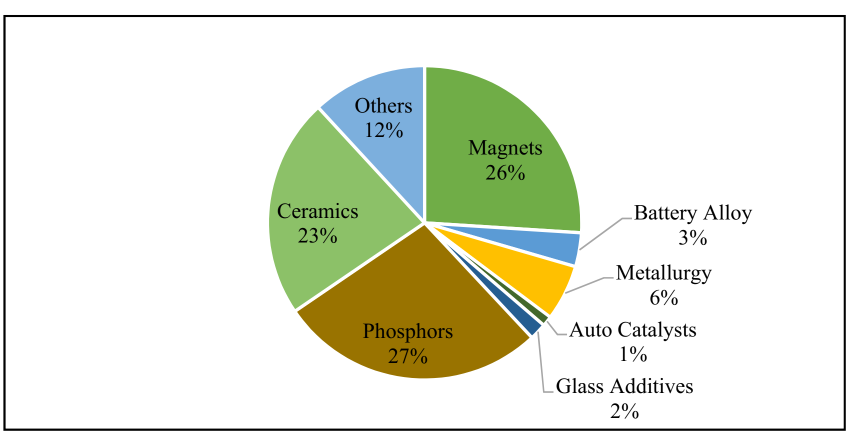
4. REEs material use analysis (MUA)

This section presents findings from material use analysis of REEs consumption in applications, as an illustrative example of CE tools for sustainability assessment. An analysis of individual critical REEs' average consumption disruption by application suggested Y and Nd to be metals of higher concern. These critical metals both made up 50 and 45% respectively of selected critical metal consumption in the application as opposed to the others as seen in Fig. 4a. A possible reason for this result could be due to their higher demand for applications. This accords with previous studies, which suggested that these metals, especially Nd, constitute one of the REEs with the highest demand in applications (Binnemans et al., 2013; Guyonnet et al., 2015; Jowitt et al., 2018). Alonso et al.(Alonso et al., 2012) went further to suggest that the demand for Dy and Nd for example may grow above 700% and 2600% respectively in the next 25 years due to the high dependency on electric cars and wind turbines on the REEs magnets sectors. These findings, while preliminary, suggest metals which top the list for criticality and where more sustainable actions can be directed to combat supply risk.

In terms of the individual applications compared, the results show that phosphors and magnets have a higher consumption of the selected REEs as opposed to the other applications found in the analysis as seen in Fig. 4b. Both make up 27 and 26% respectively of the estimated



a) Average consumption distribution by individual REEs. Note: Neodymium (Nd), Dysprosium (Dy), Europium (Eu), Yttrium(Y), and Terbium (Tb)



b) Average consumption distribution by application

Fig. 4. Selected critical REEs' average consumption distribution percentage estimates in Australia 2019 (a, b).
a) Average consumption distribution by individual REEs. Note: Neodymium (Nd), Dysprosium (Dy), Europium (Eu), Yttrium(Y), and Terbium (Tb).
b) Average consumption distribution by application.

consumption of critical REEs as compared to 2 or 1% from glass additives and auto-catalyst respectively. These results further support the idea of magnets and phosphors being applications with the highest demand for REEs and the reasons for the current emphasis on recycling from these sectors (Australia Trade and Investment Commission, 2019; Binnemans et al., 2013; Haque et al., 2014; Jowitt et al., 2018). These findings may help us to understand which REEs products policymakers and stakeholders from the recycling industry can direct recycling decisions for sustainable management of EoL products containing these metals.

The overall results from this investigation 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 policy for resource efficiency improvement. A sustainable framework approach using CE tools can be adopted to estimate resource use and the associated environmental impact and societal-wide effects over any period and place to measure the environmental sustainability of resource consumption. A material flow study combined with life cycle analysis would provide in-depth structural and systematic information on the whole life cycle of REEs consumption. This can connect resource use to environmental impacts. Such a framework can capture the main phases where CE strategies can be implemented to achieve sustainable end goals.

5. A practical implementation strategy

One of the major goals of this study was to introduce a novel framework for sustainable consumption of REEs in Australia from a CE perspective. To demonstrate the importance of implementing CE to improve recycling rates and resource efficiency. This section, therefore, provides an answer to the question of how the sustainability of REEs consumption in Australia can be enhanced based on circularity strategies. Based on resource efficiency road map strategies, if waste is to be managed valuably as a resource, in a CE waste generation must be minimised while recovery must be optimised such that landfill is only available for 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. By resource efficiency, we mean, consuming the Earth's limited resources sustainably while minimising impacts on the environment (Mudgal et al., 2012; United Nations Environment Programme, 2010). 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 Fig. 5 below, a sustainable management CE model.

However, enhancing recycling efficiency alone is not sufficient to achieve sustainability in the REEs industry without considering the implied socio-economic and environmental effects (as suggested in Fig. 3). **A whole system refinement** is necessary from material extraction through manufacturing and EoL treatments without omitting any stage (see Fig. 6). 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 burden 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 and Huda, 2020). As a sustainable CE strategy, more emphasis needs to be directed to the recovery of secondary REEs materials from waste and optimization of the whole system to close the loop and reduce dependency on virgin material sourcing.

The crucial goal of the CE approach is to develop sustainable mitigation strategies and policies that will 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 socio-economic development. CE as a regenerative system with its 6R's principles **Reduce; Reuse; Repair Refurbish and Recycle** (Geissdoerfer et al., 2017; MacArthur, 2017; Organisation for Economic Co-operation and Development, 2015) all embodied under the umbrella term **Re-thinking**, is proposed to help close material loops and keep resources in circulation. Re-thinking involves a whole process of reflecting on every action of material consumption to reduce waste and increase material use efficiency. Fig. 6 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.

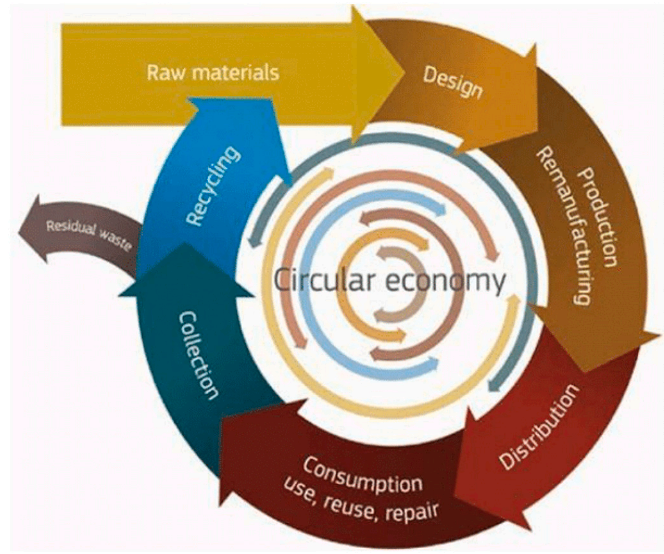


Fig. 5. CE, a sustainable management model for resource production and consumption. Source: (European Comission, 2014).

Fig. 6 shows a holistic and systematic CE framework necessary to support REEs material efficiency from raw material through use and EoL. This framework captures each phase where strategies can be implemented to achieve sustainable consumption of these critical metals. The focus will not only be to improve the EoL strategies for the consumption of these metals but also on the manufacturing-oriented strategies. The EoL strategies are usually implemented with the main goal of transforming wastes into resources for new products (recycling) while the manufacturing-oriented strategies are usually implemented to improve sustainable use of materials via life cycles engineering approaches such as design for durability, intense use, remanufacture, design for easy reuse and recyclability (Wang and Kara, 2019). In this way, the usual emphasis on waste and recycling does not distract from the need to address the consumption aspect. In this regard, resource efficiency, a CE strategy can be viewed not only as a one-way strategy that depends on recycling efficiency but rather as a holistic system that requires efficiency.

Looking at material consumption 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 negative impacts (as seen in Fig. 6) (Wagner, 2002). It provides an important tool, which helps to rethink any consumption habit employed. As presented in Fig. 6, 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, minimise consumption to combat supply risks, waste prevention and environmental burdens:

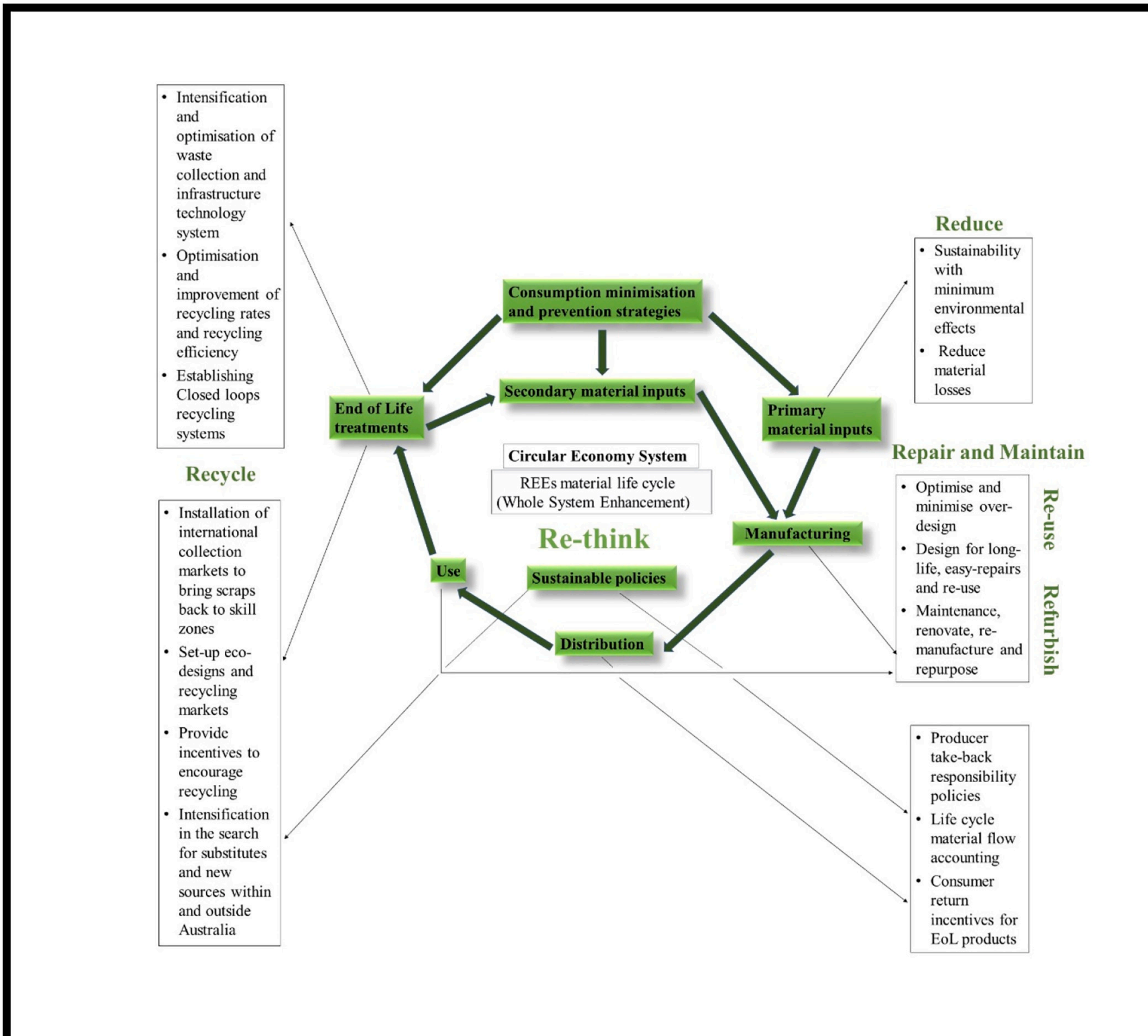


Fig. 6. Sustainable Management Framework and Mitigation Strategies for REEs (SMF-MSR) in Australia in a CE perspective. A material consumption minimisation and waste prevention approach. Adapted from EC, 2014.

5.1. REEs sustainable consumption mitigation strategies based on circularity

5.1.1. Collection, recycling (CE EoL oriented approach)

As reported in the literature, although REEs from pre-consumer scrap, industrial wastes and EoL applications containing REEs are potential sources to supplement shortages in REEs supply and mitigate supply risks, the EoL recycling rate of REEs is very low (below 1%) (Balaram, 2019; Binnemans et al., 2013; Guyonnet et al., 2015; Sprecher et al., 2014; Zaimes et al., 2015). The main reasons are due to poor collection and technological problems including the absence of incentives (Binnemans et al., 2013; Du and Graedel, 2011a; Du and Graedel, 2011b). As observed in Fig. 6: a sustainable management framework for REEs, an increase in EoL recycling rates can only be attained by a drastic improvement of the aforementioned factors affecting recycling efficiencies. To do so, whole system optimisation (Rethinking) is a necessity targeting the weakest link in the entire material cycle (International Resource Panel, 2011).

For instance, the initial phase of waste recycling which is the collection phase can be drastically improved by the installation of international/local collection points and markets to bring scrap back to skill zones and a setup of economic designs and recycling markets, implementation of compulsory producer take-back policies, and consumer incentives etc. (see Fig. 6). The 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. The EPR approach involves a take-back system, where these stakeholders are responsible to collect EoL products from consumers (International Resource Panel, 2017). With the majority of Eol REEs containing applications ending up in less developed countries for downstream recycling (Islam and Huda, 2019; Islam and Huda, 2020), an implementation of these CE strategies can help to close the material loop by bringing material back in circulation, reducing losses and eliminating the import of scrap to unskilled zones.

Another instance can be the optimisation of the recycling phase to improve the EoL recycling rate and recycling efficiencies (Binnemans et al., 2013). EoL recycling rates compare the quantity of metal acquired from recycling with the amount theoretically available at the end-use of the products (Binnemans et al., 2013; Du and Graedel, 2011a; International Resource Panel, 2011). This rate is influenced by the efficiency of the metal collection (collection system), and the efficiency of the recycling process efficiency and technology (International Resource Panel, 2011). An improvement in the waste collection system, legal enforcements 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). Previous studies suggested that REEs can be recycled efficiently by putting in place environmentally- friendly and holistically established recycling flow sheets, together with dismantling, sorting, pre-processing, and hydro-, pyro-, and/or electrometallurgical approaches to regaining these metals in the waste stream (Binnemans et al., 2013; Guyonnet et al., 2015). Efficient recycling of REEs can add a significant amount to the global market (Balaram, 2019; Du and Graedel, 2011b; Zaimes et al., 2015) and reduce dependency on primary material use. 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" consisted of the value lost with landfills and export of wastes abroad for downstream recycling (Corder et al., 2015).

However, many of these applications (like mobile phones for example) only contain small amounts of REEs (Balaram, 2019; Du and Graedel, 2011b; Navarro and 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. Therefore, from the recycler's point of view it is not economically feasible (Du and Graedel, 2011a; Jowitt et al., 2018; Navarro and Zhao, 2014; Zaimes et al., 2015). For recycling to be feasible on a commercial scale, a solution must be provided to many of the identified constraints (Jowitt et al., 2018; Zaimes et al., 2015). Previous studies have mentioned that recycling REEs is possible if recycling can be mandated or elevated REE prices make REE recycling economically feasible (Goonan, 2011). Hence, although recycling has a promising future to offset the demand for primary material, this alone cannot be the solution to REEs' supply risk (Zaimes et al., 2015). Whole system optimisation is necessary from material extraction through manufacturing and EoL treatments without omitting any stage (as demonstrated in Fig. 6). CE as a holistic and systematic management tool can provide this necessary framework for system optimisation.

5.1.2. *Reduced, long-lasting design, maintenance, and repair, renovate, remanufacturing and refurbish (CE manufacturing-oriented approach)*

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 seen in Fig. 6 above, design for long-life, maintenance, and easy repairs, reuse, remanufacturing, and refurbishing of REEs resources become more important for efficient material use and waste prevention in a closed-loop system (Geissdoerfer et al., 2017). An REE element in an object that lasts a year is much less sustainable than in something that keeps functioning for 10 years through long-lasting designs for easy repairs, re-use and recovery of materials. The continuous increase of REEs demands in applications and their importance in the growth of the green economy, military and health technologies, and availability in a few nations is the principal cause of its criticality. Any measure aiming to minimise the material demand for REEs is essential for material criticality mitigation. Although recycling is promoted as a resource efficiency strategy with the potential to contribute significantly to primary material input, 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 (like wind turbines, electric vehicles) and usually with a small proportion of REEs concentration (like mobile phones, computer disc drives). Thus, recycling is a less efficient option at this time due to the limited amount of Eol products available to be recovered to substitute primary material inputs (Jowitt et al., 2018; Rademaker et al., 2013; Zaimes et al., 2015). In this regard, implementation of CE manufacturing-oriented strategies as a waste prevention option offers other environmental and economic benefits in terms of material efficiencies, waste prevention and supply risks mitigations.

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 designs of applications by extending product lifetime, through manufacturing for easy-repairs, reuse, remanufacturing and refurbish, renovate, and repurpose. This would not only help to increase material efficiency but can equally help minimise waste generation through less material consumption and longer use as well as diminishing overall associated environmental burdens.

5.1.3. *Life cycle material flow accounting*

A sustainable CE however cannot be achieved without an accounting system as this is pivotal for a sustainable economy. A life cycle material flow accounting is essential to provide in-depth structural and systematic information on the whole life cycle of REEs consumption. An establishment of 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 on REEs material availability across the nation, the production, consumption and circulation, export and imports of these materials, recycling information etc. Material flow accounting for critical material can help to reduce impacts by providing information necessary to develop strategies for sustainable use of these resources across the entire economy. Therefore, as an implication, this study serves to demonstrate the significance and need of material flow accounting as a pivotal policy and decision-making tool to improve resource management to achieve sustainable end goals.

To achieve resource efficiency, a holistic perspective must be implemented. The findings discovered in this study underline the implication of evaluating REEs consumption using a holistic and systematic approach. This incorporates evaluating the full lifecycle of these materials' circularity and the changes in their flows. Such in-depth and structural knowledge of these material consumption patterns provides a better understanding of the product life cycle to facilitate decision making to tackle those sectors in the system that needs immediate attention. In this study, we have mentioned how CE tools such as MFA and LCIA combined, can be instrumented in sustainability assessment. This includes providing grounds for the modelling of a sustainable management framework and mitigation strategies for the consumption of material resources. Thus, an account of the interactions between human and their surroundings such as production and consumption processes are paramount to implementing strategies to improve sustainability in resource use (Organisation for Economic Co-operation and Development, 2008).

In sum, the concept of CE within a sustainability framework is proposed as a panacea to help address the challenge of REEs resource scarcity, material use and associated impacts. CE is an approach that better highlights the concept of resource efficiency and the closed-loop system of the entire material life cycle of a product.

6. Conclusion and outlook

REEs are found in just a few countries of the world and global supply is dominated by one nation, China. Despite the major concerns about the high supply risk, the recycling rate of REEs is said to be just 1% (Drost and Wang, 2016; Haque et al., 2014; Jowitt et al., 2018). Even though Australia currently seems to hold good potential for these metals as compared to other countries except China, this is accompanied by low government investment in these sectors specifically the weak collection, reuse and recycling of the EoL products containing these metals.

A life cycle material flow of critical material use analysis suggested magnets and phosphors to be the applications with the higher demand for these critical metals. It should be noted that these are all applications used in the clean energy sectors for low-emissions energy production and low-emissions energy usage. It is suggested that with the dependency of clean energy applications like electric cars and wind turbines, on the REEs magnets sector, Nd demand for example may increase more than 2600% in the next 25 years (Alonso et al., 2012). Looking at the rise in environmental concerns and the consequent demand for REEs with limited locations where they can be sourced, a sustainable management strategy to help address the adverse impacts of resource (REEs) shortages while achieving maximum environmental benefits is a necessity.

In this study, we illustrated how the concept of CE in a sustainable development framework can be implemented to tackle the challenge of REEs resource scarcity to reduce environmental burdens. 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. Though recycling is a promising option in 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, electric vehicles have a long-life span and not yet ready to be recycled. In addition to the large timeframe required to establish recycling infrastructures. The sustainability of REEs must 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, the prolonged lifespan of applications using REEs can be some of the efficient approaches to boost the environmental performance of products and services that rely on REEs (Zaimes et al., 2015).

Despite the above-mentioned thread of REEs supply-risk, while the sustainability of REEs has been examined in several papers, including in Australia, the evaluation of the environmental impacts and the benefits of sustainable consumption systematically and holistically are lacking, particularly regarding improvements in resource efficiency strategies thus leaving a notable gap in knowledge for future works in the area. The literature also reveals a lack of academic research covering the REEs industry in Australia and thus calls for a joint effort between academia and industry to understand the sustainability of these metals, the global economy, and potential political consequences of the eventual fall in its supply. The mishandling of waste products containing REEs is of paramount importance and common interest.

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Glossary of principal abbreviations

CE	Circular Economy
CED	Cumulative Energy Demand
DfE	Design for the Environment
EPR	Extended Producer Responsibility
EoL	End of Life
GWP	Global Warming Potential
LCIA	Life cycle Impact Analysis
MU	Material Use
MFA	Material Flow Analysis
REEs	Rare Earth Elements
USGS	US Geological Survey
WEEE	Waste Electrical and Electronic Equipment

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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