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Sustainability of rare earth elements consumption in a circular economy perspective

Mejame Palle Paul Mejame *, David King, Yinghe He

College of Science & Engineering, James Cook University, Douglas Campus, Townsville QLD 4811, Australia

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ABSTRACT

Rare Earth Elements (REEs) play a crucial role in emerging high technologies in the information and telecommunication industries, as well as the renewable and energy efficiency sectors. They are essential for achieving high speed, performance, durability, and low carbon emissions in these industries due to their unique chemical and physical properties. The growing environmental concerns and increasing demand for REEs, combined with limited sourcing locations, pose a significant risk of supply disruption. Despite this threat, there is a lack of comprehensive assessment of the environmental impact and benefits of sustainable consumption of these metals, especially in terms of improving resource efficiency strategies. To address these challenges, a study was conducted to evaluate the sustainability of REEs consumption in Australia using a holistic and systematic approach based on the circular economy (CE) model. This involved developing a sustainability framework and an implementation strategy to close the material loop and minimise the adverse impacts of resource shortages while maximising environmental benefits. The study included (a) analysing the life cycle of REEs material consumption, (b) conducting a material flow analysis to link resource use to environmental impacts, and (c) considering interactions between people and the environment. Key metrics for resource efficiency in a sustainable development framework, including materials use, energy demand, and greenhouse gas emissions, were used to determine the potential environmental impacts. The study's findings are significant as they enable the evaluation of existing resource efficiency strategies for REEs and provide recommendations to enhance sustainability outcomes in Australia for global uptake. The study demonstrates the application of circular economy as a sustainable strategy to mitigate and transform resource use to minimise environmental and socio-economic impacts by improving resource efficiency and promoting sustainable consumption patterns.

1. Introduction

REEs consist of a set of 17 metals that include 15 lanthanides: lanthanum La), cerium(Ce), praseodymium (Pr), neodymium(Nd), promethium(Pm), samarium(Sm), europium(Eu), gadolinium(Gd), terbium (Tb), dysprosium(Dy), holmium(Ho), erbium(Er), hulium(Tm), ytterbium(Yb), and lutetium(Lu) plus scandium(Sc) and yttrium(Y) (Balaram, 2019; Binnemans et al., 2013; Huleatt, 2019). They are major constituents of many advanced materials, particularly in the information and telecommunication industries, as well as renewable and energy efficiency sectors. REEs are used as enablers for speed, performance, durability and low carbon emissions in these industries. They are heavily required in everyday applications because of their unique chemical and physical properties(as seen in Fig. 1, an overview of REEs uses in different sectors) (Balaram, 2019; Huleatt, 2019; 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 projected to increase steadily (Balaram, 2019; Palle Paul Mejame et al., 2023; Silvestri et al., 2021; Yadav et al., 2024). It is expected that the demand for REEs will grow significantly through 2030 and beyond, largely due to their critical role in permanent magnets used in electric vehicle motors, including hybrids, and wind turbines (as seen in Fig. 2) (Andrews-Speed and Hove, 2023).

While the demand for REEs grows, global supply is under threat (Cai, 2019; Yuksekdag et al., 2022). 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 (Chen et al., 2025; Hornby and Sanderson, 2019; Snow, 2019). For example, between 2017

* Corresponding author.
E-mail address: pallepaul.mejamemejame@my.jcu.edu.au (M. Palle Paul Mejame).

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and 2021, U.S. presidents issued three executive orders to address threats from foreign adversaries related to critical minerals, with a specific emphasis on REEs (Chen et al., 2025). 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 global supply when compared to China (as seen in Fig. 3).

Furthermore, recent expert analyses indicate that China strategically employs environmental regulations and export controls to maintain its dominant position in the global REEs market (Chen et al., 2025; Depraiter et al., 2025). These policies profoundly impact international supply chains, hinder technological advancements in other nations, and significantly influence geopolitical relations (Andrews-Speed and Hove, 2023; Chen et al., 2025). This is an urgent crisis that needs to be addressed because shortages in the use of REEs in renewable and energy-efficient technologies such as smart display screens, wind turbines, electric vehicles, solar cells, energy-efficient lighting etc., will adversely affect the development of clean energy technology and the green economic growth (IT and telecommunications 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 and Wang, 2016; Gaustad et al., 2011; Jowitt et al., 2018; McLellan et al., 2014, 2013; Silvestri et al., 2021; Wang et al., 2017; Yadav et al., 2024). 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, 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. Australia, for instance, generates an estimated 6 million tonnes of metal waste annually, 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). Despite this, REEs recycling remains at only 1% (Drost and Wang, 2016; Jowitt et al., 2018). Waste management efforts in Australia mainly target the recovery of scrap magnets (Islam and Huda, 2020). Australia exports the majority of its waste (secondary material sources), specifically e-waste, for downstream recycling (Mahmoudi et al., 2019). This particular waste stream contains a significant amount of EoL REEs (Islam and Huda, 2019, 2020; Xavier et al., 2021). In this view, 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; International Resource Panel, 2017; Mudgal 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 close the material loop to reduce the supply risk impacts of these critical resources and minimise the potential environmental impacts associated with their consumption.

2. Methods

A holistic and systematic approach based on a 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 REEs material use, (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 the goal, the study applied Material Flow Analysis (MFA) and Life Cycle Impact Assessment (LCIA) tools within a sustainable management framework to determine the flows and life cycle environmental 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 implementing

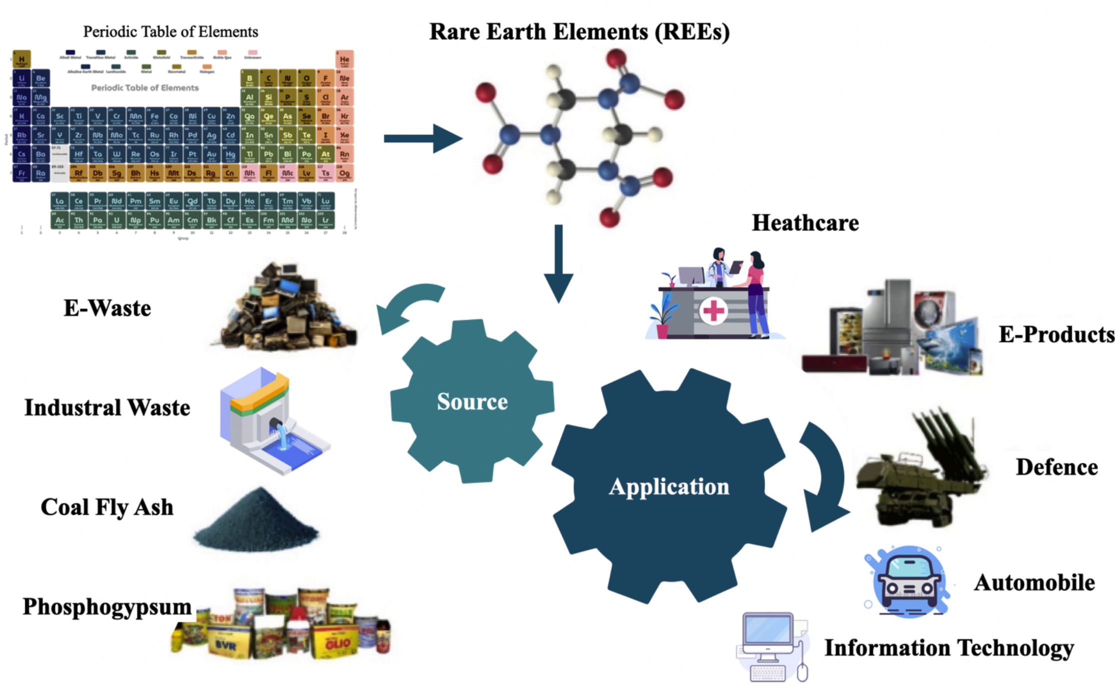

Fig. 1. Different sources of REEs and its application. Source:(Dagwar et al., 2025).

resource efficiency strategies (Palle Paul Mejame et al., 2016, 2020)

To narrow down the focus, five REEs (Neodymium, Dysprosium, Europium, Yttrium, and Terbium) based on their criticality index and importance were selected and analysed using 2019 as the base year for its most updated data at the time of the study. MFA was used to evaluate REEs' material resource usage from extraction through EoL, while LCIA served as the tool to determine the lifecycle-based environmental impact of the material using characterisation factors obtained from Eco-invent. This information is significant as a background for environmental impact assessment, policy and decision-making for socio-economic benefits.

The potential environmental impacts were assessed using three key metrics for resource efficiency in a sustainable development framework: materials use, energy demand, and greenhouse gas emissions indicators. Other resource use indicators include land use and water, which are beyond the scope of this study. Using these three metrics cited above, a material resource (REEs) use assessment and the derived environmental impact and impact reduction was modelled in three steps: 1) To investigate the existing sustainability pattern governing REEs consumption in Australia, we evaluated the primary material inputs of REEs consumption in applications and the derived environmental impacts using IPPC and CED midpoint impact assessment methods in Eco-invent. 2) To demonstrate the significance of sustainability with recycling, we assessed the secondary material inputs of REEs consumption in applications, that is, recycling potential and the derived environmental impacts using the same LCIA methods cited above. 3) Next, we performed an analysis of the benefits associated with sustainable management of natural resources with recycling, with the main goal of determining the advantages of secondary material inputs over primary from a resource management perspective. This approach applied a life cycle recycling impact reduction assessment strategy derived from (United States Environmental Protection Agency, 2011). This approach is based on comparing virgin (primary) material manufacturing with recycled (secondary) material inputs and consideration of recycling efficiency (Grimes et al., 2008; United States Environmental Protection Agency, 2011). This is significant as it promotes CE principles as a sustainable management strategy that can be used to improve REEs resource efficiencies, decouple natural resource use from economic progress, and hence combat supply shortages.

3. Results and discussion

The results and findings are organised into 3 sections. Section 1 discusses material use and impacts for primary and secondary material consumption of REEs in applications, an analysis of the benefits associated with sustainable management of natural resources from a resource management perspective. Section 2 presents a comprehensive CE framework for REEs within the sustainable development paradigm, followed by a practical implementation strategy in Section 3.

3.1. Material use and impact analysis

The overall results of REEs material use in Australia from a life cycle material flow approach show the REEs consumption pattern in Australia to be highly dependent on primary material inputs with the main reasons being the low recycling rates of these metals (Drost and Wang, 2016; Jowitt et al., 2018), and export of EoL products abroad for downstream recycling, and a lack of incentives etc. (Corder et al., 2015; Islam and Huda, 2020). It is estimated that over AUD 6 billion worth of metal content is found in Australia's EOL products annually, but only about one-third (AUD 2 Billion of AUD 6 Billion) of the metal value is being recovered through current recovery practices, with approximately half of the nation's scrap metal (2.5 million tonnes) exported abroad for downstream recycling (Corder et al., 2015). Findings indicate a growing trend in the demand for these metals, especially in the clean energy sectors. The life cycle material flow of critical material use analysis suggests that Yttrium (Y) and Neodymium (Nd) make up 50 and 45 % by weight respectively of selected critical metal consumption in the application as opposed to the others (as seen in Fig. 4). The findings also suggested magnets and phosphors to be the applications with the higher demand for these selected critical metals (Fig. 4). It should be noted these are all applications used in the clean energy sectors for low-emissions energy production and low-emissions energy usage. Further, with the dependency of electric vehicles and wind turbines on the rare-earth magnets sector, the demand for Nd, for example, is projected to grow substantially in the years ahead (Andrews-Speed and Hove, 2023). In Australia, there is a growing need for critical metals in the fast-growing clean energy sectors (such as wind turbines and electric vehicles) (Wang and Kara, 2019). It is projected that the fleet proportion of electric vehicles in Australia will grow up to 75 %−100 % by 2050 (Wang and Kara, 2019), which implies a significant increase in the use of critical metals, particularly in the rare-earth magnets sector. With 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 should be a necessity as indicated in this study.

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. The study has also identified that the overall REEs consumption of secondary material inputs in applications will equally result in significantly lower emissions and cumulative energy demand potentials than from corresponding REEs generated for primary material inputs, as seen in Figs. 5 and 6 respectively. One of the

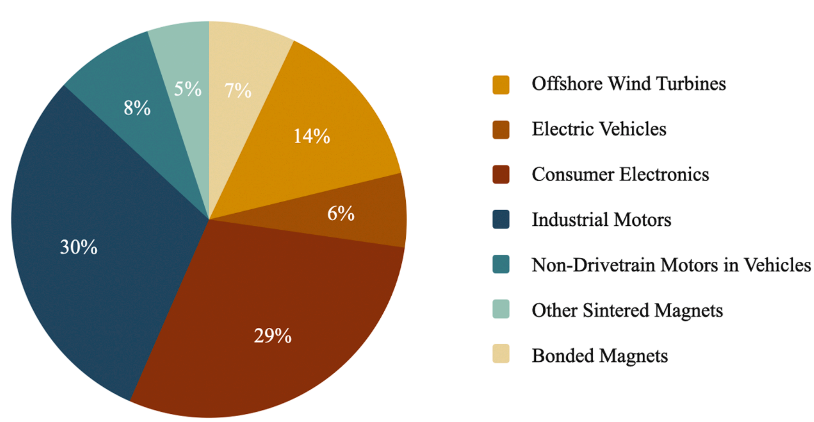

Fig. 2. Demand for NdFeB, US Department of Energy (2022). Source:(Depraiter et al., 2025).

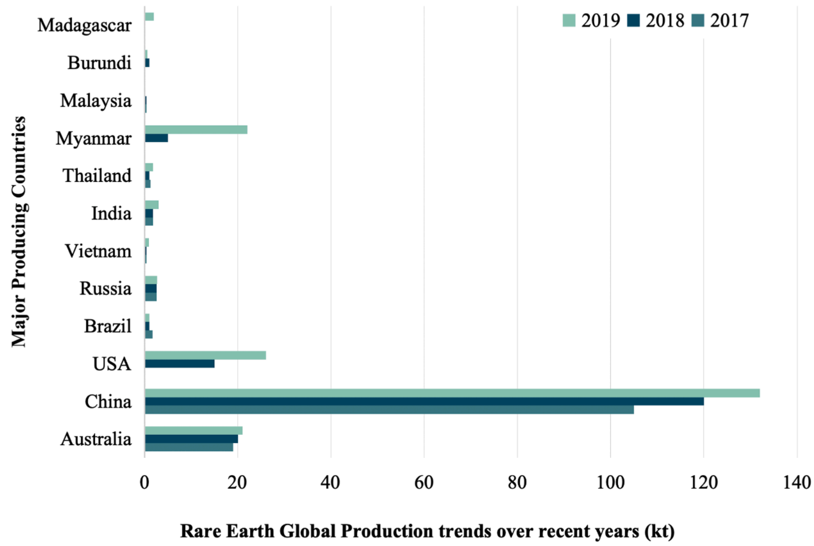

Fig. 3. Trends in Global REEs production: Key contributors(including Australia) and China's predominant role in supply. Data source (U.S. Geological Survey, 2020).

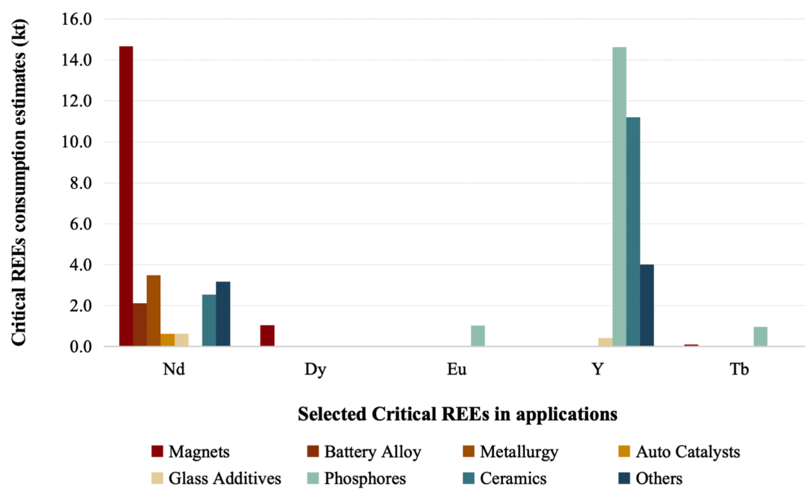

Fig. 4. Selected critical REEs consumption distribution estimates 2019 (kt) by application in Australia.

major objectives of this study was to highlight the importance of secondary material inputs (waste recoveries, recycling) for consumption in applications over a primary (virgin) material generation. From a resource perspective, this study was therefore interested in how much 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 emission for using REE primary material input in applications will fall from 2278.3 to 1253.0 kg CO_2-eq/yr/kt in the case of secondary material inputs. This will lead to an emission reduction of 1589.1 kg CO_2-eq/yr/kt. These findings suggest that a shift from primary material dependency will not only lead to material savings but also to global warming reduction potentials via thousands of CO_2 emissions avoided.

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 25,674.9 to 14,482.7 (MJ-Eq/yr/kt) for a given year (2019). This means an estimate of 17,709.4 (MJ-Eq/yr/kt) energy savings over this period. In a nutshell, improvement 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 need for the development of recycling technologies and infrastructure. According to Golroudbary's research, the global use of permanent magnets alone between 2010 and 2020 led to a cumulative total of 32 billion tonnes of CO_2-equivalent greenhouse gas emissions (Golroudbary et al., 2022).

In terms of individual applications, recovery interest for EoL products should focus on phosphors and magnets as findings show that these products contain potential sources for secondary material inputs of these metals. It was identified that these products consume 26 and 27 % respectively of selected critical REEs in applications with the highest demand from Nd and Y. Regaining REEs from EoL products in the waste stream can significantly contribute to combating some of the critical issues these metals face today such as supply disruption, and radioactive elements like uranium, thorium associated with their primary production etc. (Jowitt et al., 2018). Besides, according to Arshi et al. (2018), recycling of magnets even produces a significantly lower impact compared to the primary material inputs (Arshi et al., 2018). Though slow and labour-intensive, 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).

3.2. A comprehensive CE framework: REEs within the framework of sustainability

REEs' material criticality has attracted global attention mainly due

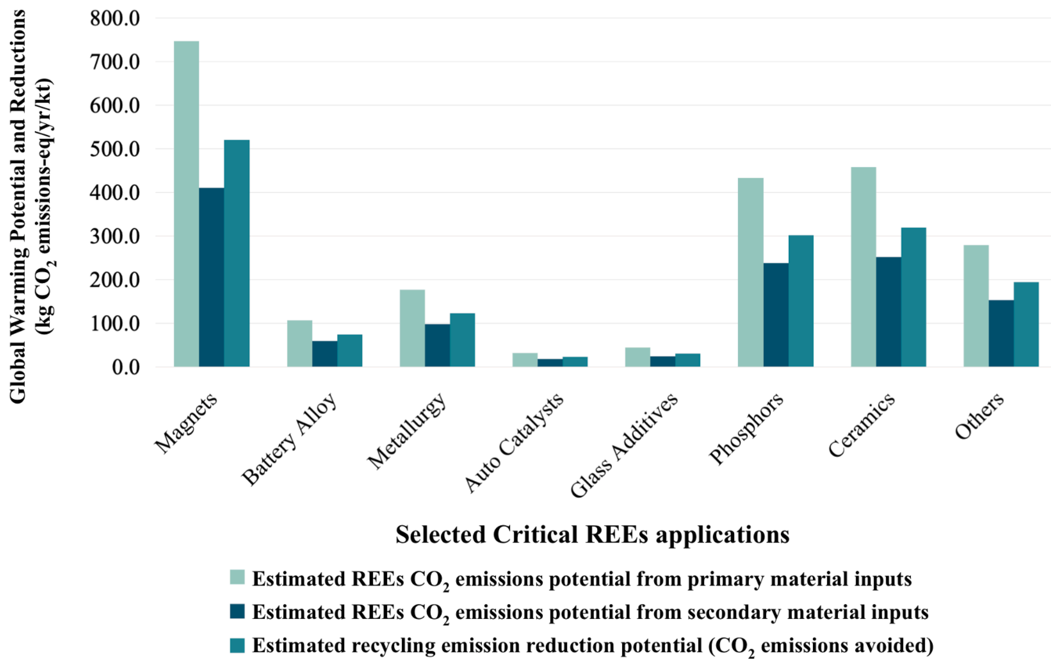

Fig. 5. Global Warming Potential and Reductions by REEs applications in a given year (2019 kg CO_2-eq/yr/kt).

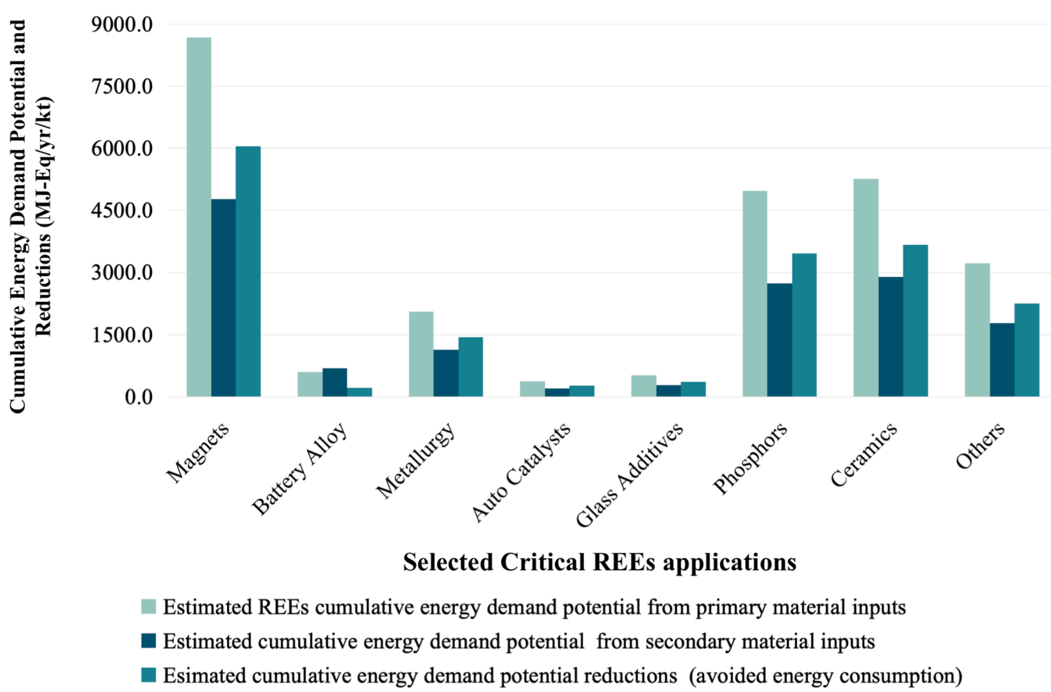

Fig. 6. Cumulative Energy Demand Potential and Reductions by REEs applications in a given year (2019 MJ-Eq/yr/kt).

to their economic viability and availability only in a few nations with high supply risks. As of 2019, China alone holds >38 % of the world's reserves and controls >62 % of global supply (Palle Paul Mejame et al., 2022). Australia's REEs reserves as of 2019 were 3300 kt, which is 3 % of global reserves, and the total global supply was 21 kt(10 %) (Palle Paul Mejame et al., 2022) (other major REEs production countries include the United States, Brazil, Russia, Myanmar, Burundi, India, Malaysia, Madagascar, Thailand, and Vietnam as seen in Fig. 3). Transforming materials during and at the end of their life cycles into resources for other applications can address the material criticality in CE (MacArthur, 2017; McLellan et al., 2014; Zeng et al., 2022). The sustainability and criticality of REEs can well be understood by considering the consumption of these metals from the perspective of sustainable development and its three pillars (environmental, social, and economic). An understanding of REEs consumption within the framework of sustainability provides a background for the implementation of CE strategies to achieve material resource efficiencies and minimise environmental and social impact. Fig. 7 below presents a comprehensive

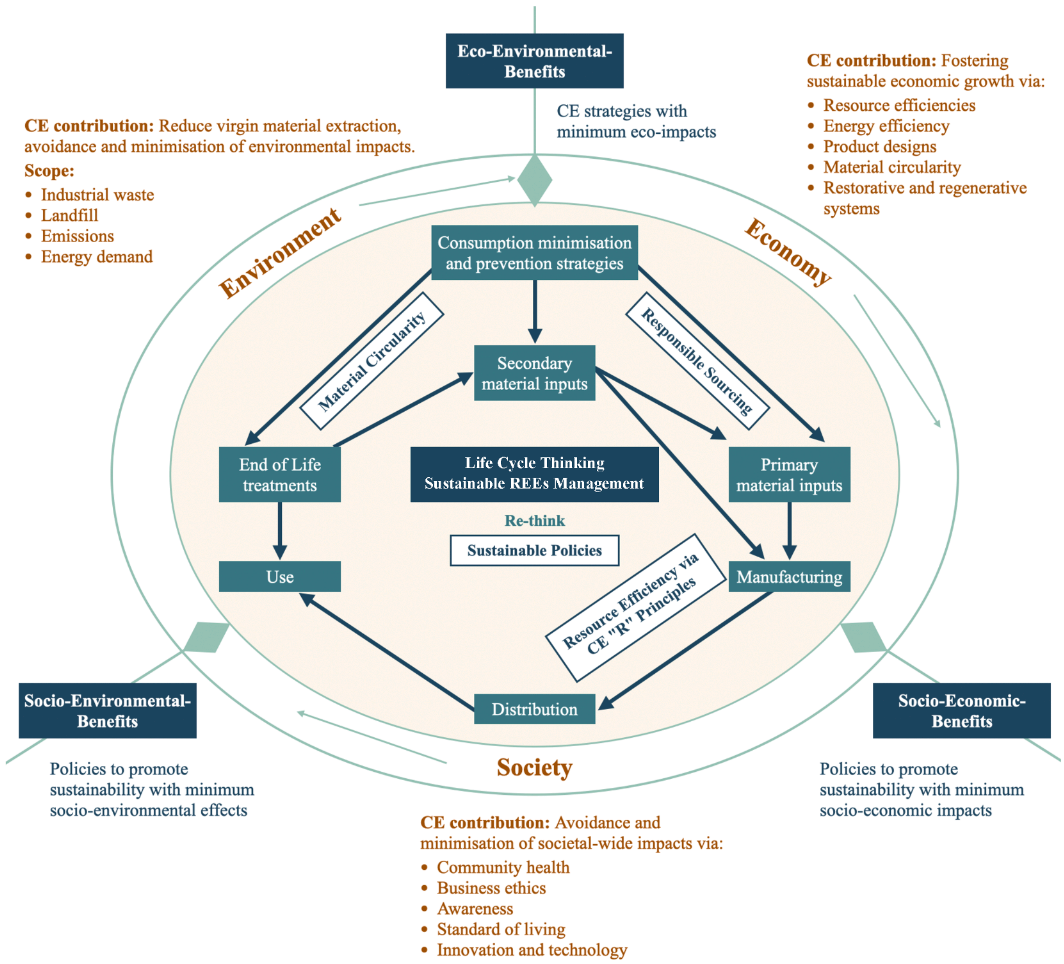

Fig. 7. A comprehensive CE framework: REEs within a sustainability framework. Developed from (Palle Paul Mejame et al., 2022).

CE framework that situates REEs consumption within the sustainable development framework. The framework is developed from previous research (Palle Paul Mejame et al., 2022), part I of this study.

The suggested Framework highlights that the economic, environmental, and social challenges of REEs, both present and future, are interconnected and require a comprehensive, integrated approach to be effectively addressed. Effective implementation of CE strategies yields multifaceted benefits encompassing environmental, social, and economic dimensions (Tsironis et al., 2024). *CE "R" principles: *Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover and Rethink.*

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. 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 (Goonan, 2011; Yadav et al., 2024), and worse, their unequal global distribution, whereby China controls most of the world's supply and demand (Balaram, 2019; Goonan, 2011; McLellan et al., 2014; Yadav et al., 2024). Mines in Australia and other parts of the world are only currently becoming active again due to China's limited exports and supply restrictions, high prices and taxes over these years (King, 2021). The strategic and economic importance of these metals and their critical nature should not only be a driving force in the rush to explore other reserves in different parts of the earth and increase mining, but also a reason for the expansion of sustainability strategies for the consumption and production of these metals such as 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 aspect: When looking at the social aspect of REEs within a sustainability framework, it is paramount to take into account those components relating to the physical and psychological well-being 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 ensuring adequate environmental and health safety mitigation methods to be operational (United States Environmental Protection Agency, 2012). This aspect of REEs sustainability is a major 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 with recycling (Balaram, 2019; Eckelman and 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 Fig. 7 above.

Furthermore, Current industrial production of REEs relies heavily on solvent extraction(using various chemicals/acids), a process that is expensive, energy-intensive, environmentally harmful, and inefficient, especially for heavy REE separation (Schroeder et al., 2024). This method uses toxic and flammable organic solvents such as di (2-ethylhexyl) phosphoric acid), generating hazardous waste and contributing significantly to greenhouse gas emissions (Arshi et al., 2018; Schroeder et al., 2024). Schroeder et al. (2024), investigated a new technique, field-effect separation (FES), which uses electric and magnetic fields to separate Rare Earth Elements more efficiently and sustainably than current methods. Early results show it can effectively separate REEs based on their charge and magnetic properties, offering a more effective and scalable solution to meet rising global demand (Schroeder et al., 2024).

3.3. *Sustainable management framework and mitigation strategies for REEs (SMF-MSR) from a circular economy perspective (A material consumption minimisation and waste prevention approach)*

Though EoL products containing REEs are potential sources to supplement shortages in REEs and reduce the high supply risk problem as demonstrated in this study, from a holistic perspective, recycling alone cannot be regarded as a panacea to the whole REEs problem (Zaimes et al., 2015). Improvement in recycling efficiency cannot be achieved without a broad consideration of the implied economic and socio-environmental effects of the consumption of these metals. 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 to capture all the areas where strategies can be implemented to achieve sustainable consumption of these critical metals. Fig. 8 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.

The framework considers that apart from the focus on improving Eol strategies (collection, recycling) for the consumption of these critical

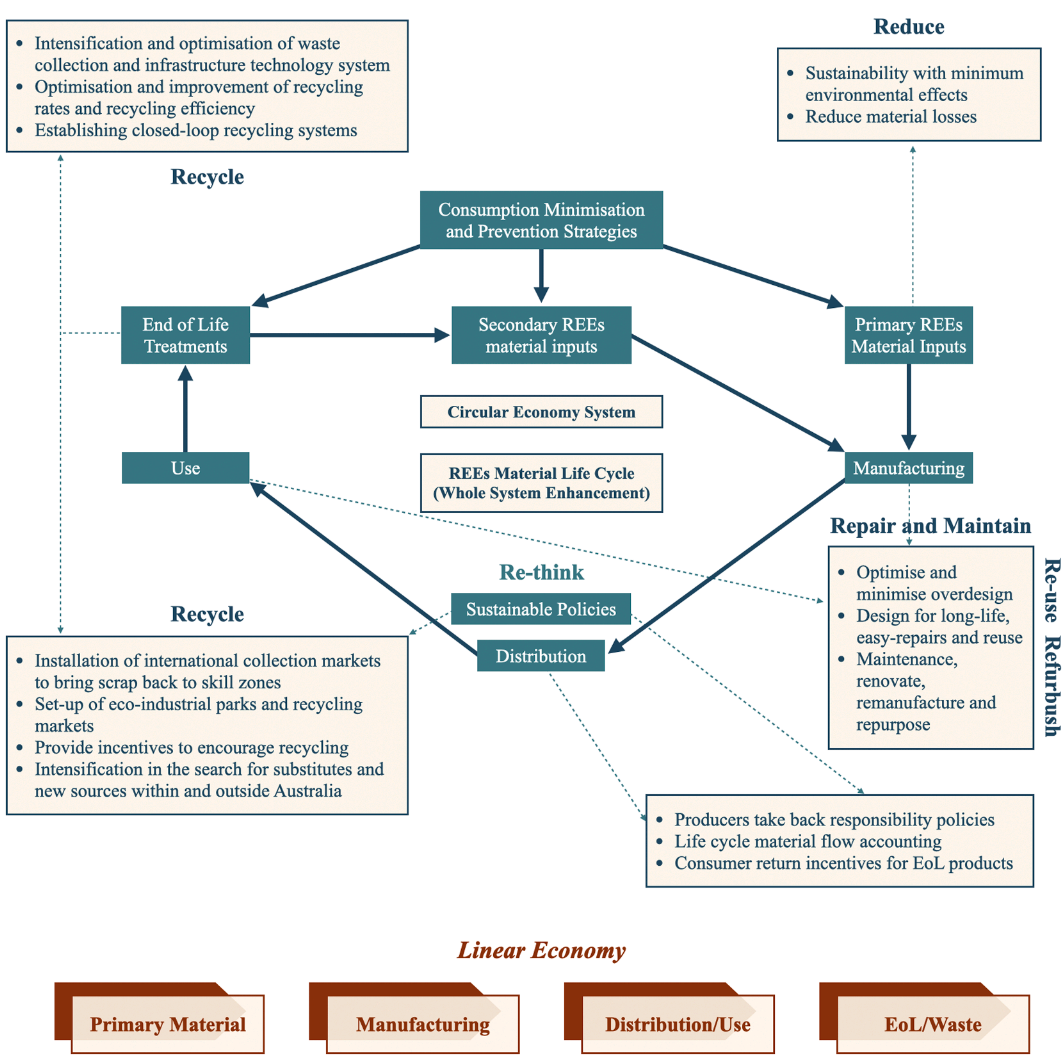

Fig. 8. Sustainable Management Framework and Mitigation Strategies for REEs (SMF-MSR) in Australia from a CE perspective. A material consumption minimisation and waste prevention approach. Developed from (Palle Paul Mejame et al., 2022).

metals, the different components within the CE model such as the manufacturing-orientated strategies offer alternative potential to improve the sustainability of REEs consumption. In this regard, emphasis is not only laid on recycling but also on the need to tackle the consumption aspect of these metals. Below are some mitigation strategies based on a combination of CE principles and resource management practices that can be implemented to help close the material loop and enhance sustainable consumption of REEs in Australia, to minimise consumption to combat supply risks, waste prevention and environmental impacts (Fig. 8).

3.3.1. REEs sustainable consumption mitigation strategies based on circularity

3.3.1.1. Collection, recycling (EoL CE oriented approaches). The EoL recycling rate of REEs is generally low (<1 %) (Balaram, 2019; Binnemans et al., 2013; Guyonnet et al., 2015; Sprecher et al., 2014; Yadav et al., 2024; Zaimes et al., 2015). The main reasons are due to the inefficient collection, technological problems, low yields plus the cost and, especially, a lack of incentives (Balaram, 2019; Binnemans et al., 2013; Du and Graedel, 2011a, 2011b; Yuksekdag et al., 2022). As observed in Fig. 8 'a sustainable management framework for REEs', an increase in EoL recycling rates can only be achieved through a drastic improvement of the aforementioned factors affecting recycling efficiencies (Balaram, 2019; Binnemans et al., 2013; Goonan, 2011). To do so, improving the whole system (Rethinking) is necessary to target the weakest links in the chain as outlined in the following paragraphs.

To start, the perception of EoL products as waste needs to change to resources to promote the effective collection and proper treatment of these materials and enforce legislation. For instance, the efficiency of the initial phase of waste recycling (collection) can be drastically improved by the installation of international and local collection points and markets to bring scrap back to skill zones alongside a setup of economic designs and recycling markets for easy collection and recovery of EoL products containing these metals (especially applications like phosphors and magnets with the highest concentration of these metals as seen in this study), implementation of compulsory producer take-back policies and, consumer and recycler incentives etc. The extended producer responsibility, for example, is a type of stewardship that places primary responsibility on the manufacturer, importer, or seller for the management of EoL products. The approach involves a take-back system, where these stakeholders are responsible for collecting EoL products from consumers. With the majority of EoL REEs containing applications ending up in less developed countries for downstream recycling (Islam and Huda, 2019, 2020), an implementation of the above-mentioned CE EoL strategies can help to close the material loop by bringing back materials in circulation, reducing losses and eliminating the import of scrap to unskilled zones. Compulsory producer take-back strategies, for instance, would put the burden for the collection of EoL REEs products in the hands of the producers while incentives to consumers could facilitate the return of EoL products to service points or recycling markets. Implementing sustainable management practices for waste products containing these metals can have a dual impact. It can contribute to the preservation of critical REEs resources by reducing the demand for virgin sources and mitigating the associated environmental impacts discussed in this study, in addition to minimising waste generation.

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 of the life of products (Binnemans et al., 2013; Du and Graedel, 2011c; International Resource Panel, 2011). This rate depends on the efficiency of the metal collection (collection system) and of the recycling process efficiency and technology (extraction of metals from EoL products) (Binnemans et al., 2013; International Resource Panel, 2011). An improvement in the waste collection system, the legal enforcement governing the recycling section, incentives to recyclers) and environmentally friendly technology (recycling process efficiency) can have a drastic impact on EoL recycling rates (Binnemans et al., 2013; Goonan, 2011; Yuksekdag et al., 2022). The findings from this study (as seen in Section 3.1) show that improvement in sustainable resource consumption practices like recycling efficiency can improve recycling rates and add significantly to the overall supply of REEs, minimising overall primary material consumption inputs. Previous studies suggested that REEs can be recycled efficiently through the development of environmental-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; Goonan, 2011). 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 and others (Binnemans et al., 2013; Goonan, 2011). Efficient recycling of REEs can add a significant amount to the global market (Binnemans et al., 2013; Du and Graedel, 2011c; Goonan, 2011; Silvestri et al., 2021; Zaimes et al., 2015) and reduce dependency on primary material use, providing both economic and environmental benefits in terms of contributing to addressing resource scarcity, in addition to resource conservation and environmental impact reductions from avoided mining.

However, many of these applications only contain small proportions of REEs (like mobile phones for example) (Du and Graedel, 2011a; Navarro and Zhao, 2014; Zaimes et al., 2015). This combined with the complexity of their use, and difficulties in extracting and recovering the constituent within the EoL products makes recycling considered costly and energy-intensive and therefore, from the recycler's point of view, not economically feasible (Du and Graedel, 2011c; Jowitt et al., 2018; Navarro and 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 elevate REEs prices to make REE recycling economically feasible (Balaram, 2019; Goonan, 2011; Jowitt et al., 2018; Zaimes et al., 2015). Hence, although recycling has a promising future to offset the demand for primary materials, this alone cannot be the sole solution to REEs supply risk (Zaimes et al., 2015). An improvement of the whole system is necessary from raw material extraction through manufacturing and End-of-Life treatments without omitting any stage. CE, as demonstrated in this study, serves as a holistic and systematic management tool that provides the necessary framework for optimising systems. In addition to End-of-Life (EoL) oriented CE strategies for promoting sustainability in REE consumption, the manufacturing-oriented approach offers a complementary perspective as described below

3.3.1.2. Reduced, long-lasting design, maintenance, and repair, renovate, remanufacturing and refurbish (Manufacturing oriented CE approaches). As framed in Fig. 8, in a closed-loop system, long-lasting design, maintenance, repair, reuse, remanufacturing, and refurbishing of REEs resources become more important for efficient material use and waste prevention (Geissdoerfer et al., 2017). An RE 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. As demonstrated in this study, the continuous increase of REEs demand in applications and their importance in the growth of the green economy, military and health technologies, and their availability in just a few nations is the principal cause of their criticality. Any measure aimed at minimising the material demand for REEs is beneficial for material criticality mitigation. Although recycling is promoted as a resource efficiency strategy with the potential to contribute significantly to primary material input (as cited in the results), 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 and usually a small proportion of REEs. This renders recycling a less efficient option at this time due to the limited amount of EoL products available to be recovered to substitute primary material inputs. In this regard, the implementation of manufacturing-oriented CE strategies as a waste prevention option offers alternative environmental and economic benefits (options) in terms of material efficiencies, waste prevention and supply risk mitigation to complement the EoL-oriented CE strategies, closing the loop.

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 refurbishing, renovating, and repurposing. 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.

3.3.1.3. 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 system is essential to provide in-depth structural and systematic information on the whole life cycle of REEs consumption. 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 waste 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 emphasise 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 as demonstrated in this study.

The findings identified in this study underline the significance of evaluating REEs consumption using a holistic and systematic approach. The implementation of an MFA combined with an 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 manufacturing, waste disposal and recycling, and environmental impacts. Thus, the CE model as adopted in this study with its restorative and regenerative system through its manufacturing oriented-strategies (long-lasting designs of applications by extending product life, through manufacturing for easy-repairs, maintenance, re-use, repurpose, remanufacturing, refurbishing), and EoL oriented strategies (recovery and recycling principles) combined, can be implemented to close material and energy loops and keep resources in circulation.

4. Conclusion and recommendations

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 the sustainability outcomes of these metals in Australia and contributes to a strategy for global uptake.

Overall, the study shows that improvements in sustainable resource consumption practices like recycling efficiency are promising strategies to improve REEs resource use efficiency. However, this must be achieved with a broader consideration of environmental, socio-economic, and technological aspects of the consumption of these metals. This study demonstrates sustainability approaches to identifying policy priorities for material consumption and impact reductions. 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 long-lasting magnets and phosphors; the repair or refurbishment of EoL products, and improvement in their collection rate. 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 the Design for the Environment (DfE) and waste management policy for EoL products containing these metals.

A major limitation of this study is 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 the 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 reduction.

Finally, the overall literature reports a lack of academic research addressing the REEs industry in Australia (Palle Paul Mejame et al., 2022) hence, a call for more collaboration between industry and academia is needed to understand the global importance of these metals and the need for sustainable and resource efficiency strategies to combat supply risks while minimising socio-environmental and economic burdens. The literature also 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 and Graedel, 2011b, 2011c). 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.

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 (Palle Paul Mejame, 2022).

Ethics approval and consent to participate

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CRediT authorship contribution statement

Mejame Palle Paul Mejame: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **David King:** Visualization, Resources, Investigation, Conceptualization, Writing – review & editing, Supervision, Methodology, Data curation, Validation, Project administration, Formal analysis. **Yinghe He:** Validation, Methodology, Data curation, Visualization, Project administration, Formal analysis, Writing – review & editing, Supervision, Investigation, Conceptualization.

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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Mejame Palle Paul Mejame received his doctoral degree in 2023 from the College of Science and Engineering, James Cook University, Townsville, Australia. His research focuses on sustainability and the circular economy.

David King is an Associate Professor of Geography in the College of Science and Engineering at James Cook University, and is director of the Centre for Disaster Studies, and the Centre for Tropical Urban and Regional Planning. His research focuses on sustainable development, climate change adaptation and resilience, disaster mitigation and recovery, as well as the social impact of mining projects, development projects, and census analysis.

Yinghe He is a Professor of Engineering at Brunel University of London with a keen interest in sustainable developments. His current research emphasis is on the development and design of innovative engineering processes for a cleaner environment and more sustainable future.