Material Requirements in Self-sufficient, Carbon-neutral European Energy Systems Configurations in 2050

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MSc Thesis

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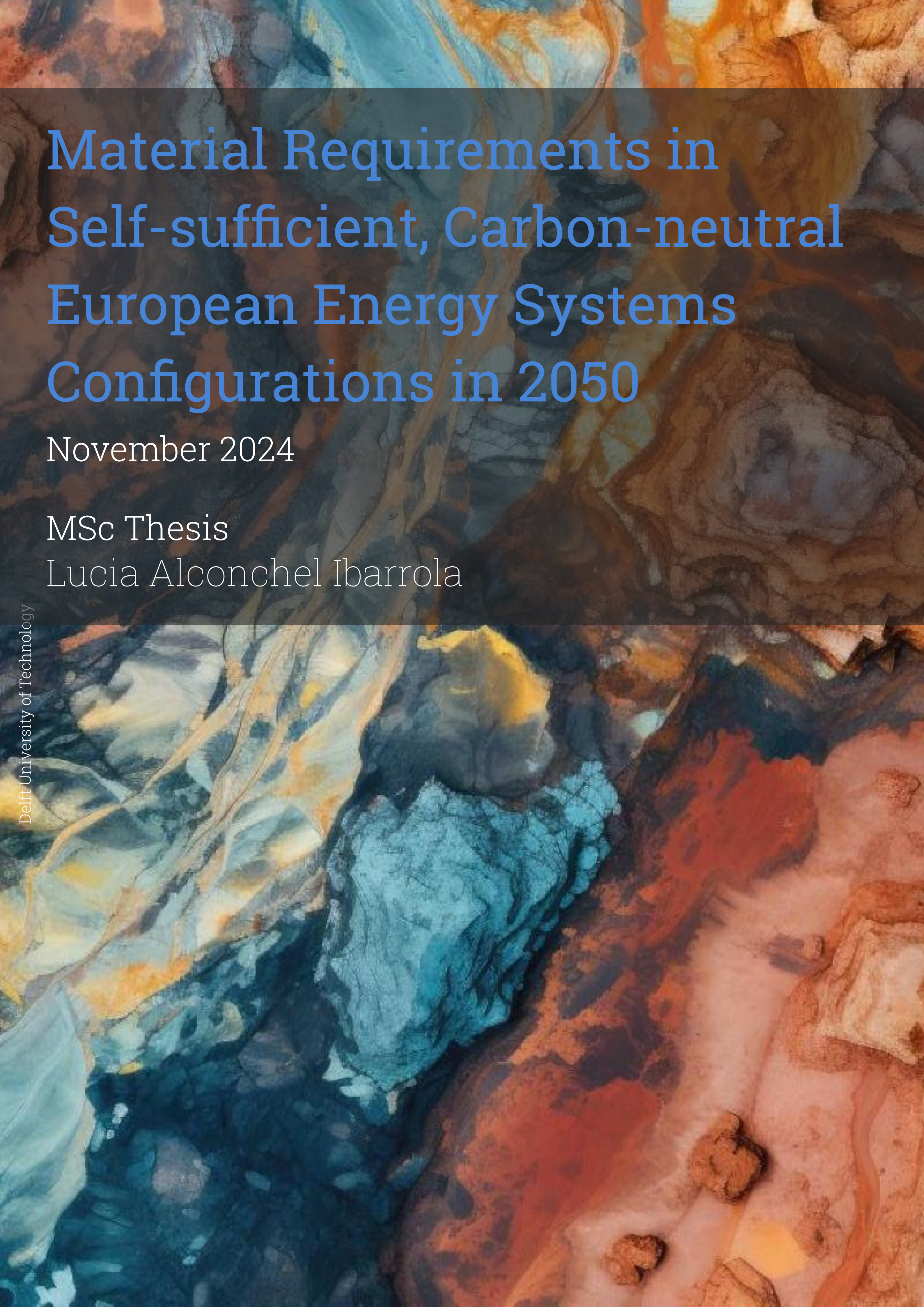

Material Requirements in Self-sufficient, Carbon-neutral European Energy Systems Configurations in 2050

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by

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Preface

This thesis marks the end of my master's degree in Sustainable Energy Technology at the faculty of Electrical Engineering at the Delft University of Technology. I chose the Master's in Sustainable Energy Technology driven by my interest in the energy sector and the energy transition. During the last two years, I have gained valuable insights into the challenges, innovations and research required to address the complexities of the energy transition. Thanks to this journey, I have gained a better understanding of the challenges we face beyond just the technical and economic aspects. I am proud to share the outcomes of this research, as it represents a step toward supporting policymakers and researchers in shaping future developments that contribute to a sustainable future.

I want to express my sincere gratitude to my supervisors, Stefan Pfenninger, Francesco Lombardi and Francesco Sanvito for their guidance and encouragement throughout the thesis. It has been a true honor to work among such inspiring researchers dedicating their time and efforts to finding solutions and helping society envision how Europe can achieve its climate goals. Finally, I would like to thank my family and friends for their continious support.

Lucia Alconchel Ibarrola
Delft, November 2024

Summary

This report focuses on raw material requirements for self-sufficient, carbon-neutral European energy systems. It addresses the need to ensure that the transition to a low-carbon economy in Europe is realistic, feasible, and sustainable. Previous studies have often overlooked the integration of material requirements in optimized designs considering a sector-coupled energy system, or have only considered a single configuration without exploring trade-offs in other equally feasible pathways.

To overcome these limitations, this report evaluates the material requirements of hundreds of radically different energy configurations that would allow Europe to become energy self-sufficient and carbon-neutral by 2050. The solutions were generated with the Euro-Calliope framework using an extension of the modeling-to-generate-alternatives approach, creating spatially explicit practically optimal results (SPORES). This approach broadens the solution space and explores energy configurations that are within 10% of the cost-optimal solution.

The results reveal that future energy configurations will be inherently material-intensive, primarily due to the large-scale deployment of power technologies and electric vehicles. In contrast, technologies such as infrastructure expansion and heating systems pose minimal challenges regarding resource consumption. The findings confirm that equally feasible energy system designs can have significantly different CRM demands, with some configurations more likely to face supply-chain bottlenecks for materials like lithium, cobalt, and nickel. Trade-offs emerge between specific CRMs and energy system options. For example, high electrification of the transport sector requires nearly double the amount of CRMs compared to configurations with greater biofuel utilization. However, reducing the number of EVs significantly limits flexibility in energy configurations, pushing Europe toward an energy system design that maximizes biofuel.

Nevertheless, this research identifies key strategies that may help mitigate CRM demand in electric vehicles. In the next 15 to 20 years, recycling could become a significant alternative to mining for meeting a substantial share of raw material needs. This report estimates that end-of-life battery recycling rates could decrease the need for newly mined materials like lithium, cobalt, and nickel by more than half. However, in the short-term, the availability of these minerals will be insufficient for recycling to become a practical solution. Furthermore, technical and economic barriers currently limit the potential of recycling and the complete shift to battery technologies that do not rely on critical raw materials. This provides actionable guidance for integrating circular economy efforts into energy policy.

Future research would benefit from adopting a more dynamic approach to better capture future material requirements. This can be done by incorporating potential improvements in material intensities, a wider range of sub-technologies, and their evolving market shares. Furthermore, exploring alternative energy configurations and examining how changes in constraints, such as self-sufficiency or moving further away from the cost-optimal solution, affect system design and material demand would be beneficial. Finally, material constraints could be included directly in energy models by limiting CRM demand, which would allow the assessment of feasible energy configurations.

Contents

1 Introduction

Decarbonizing the energy system signifies an important step toward meeting European climate targets by 2050. Future energy systems will need to rely on clean energy technologies, such as wind, solar, storage, and electric vehicles. The anticipated increase in demand for raw materials in clean technologies poses significant challenges related to environmental degradation, supply chain vulnerabilities, and geopolitical tensions [1, 2, 3, 4]. To ensure that the transition to a low-carbon economy in Europe is realistic, feasible, and sustainable, there is growing interest in evaluating possible future energy configurations along with their material demands. This report aims to address these challenges by evaluating the material requirements of hundreds of equally feasible energy configurations that would allow Europe to become self-sufficient and carbon-neutral by 2050.

The central question guiding this study is: *What are the material trade-offs in future energy system designs for a self-sufficient, carbon-neutral Europe by 2050?*

Existing studies on material requirements often focus on isolated parts of the energy sector, considering either the power or transport sector in isolation. By not considering the entire energy system, these studies overlook the interactions between different sectors. Furthermore, many have only considered the material requirements of a single cost-optimal configuration without exploring plausible, equally feasible pathways. Finally, many energy modeling studies have overlooked the integration of material requirements, focusing only on technical and economic factors [5, 6].

To overcome these limitations, this research incorporates material requirements into a sector-coupled energy model that includes technologies for the heating, power, and transport sectors. Furthermore, it evaluates 441 near-optimal configurations, all within 10% of the cost-optimal solution, exploring the many possible ways Europe can achieve carbon neutrality and self-sufficiency while identifying potential trade-offs.

These findings are particularly important as Europe seeks to balance its climate goals with material sustainability and supply chain security, ensuring that the energy transition is not only technically feasible but also sustainable in the long term.

The contents of this thesis are divided into the following chapters: Chapter 2 provides background information regarding the role of energy models in policymaking and critical materials and Europe's dependencies. Chapter 3 offers an overview of existing literature covering material requirements in the context of the energy transition. Chapter 4 outlines the main methods and data inputs used to arrive at the results. Chapter 5 presents the main findings, covering material requirements across different energy configurations and trade-offs between energy configurations. Finally, Chapters 6 and 7 conclude the thesis by summarizing the key findings, discussing their implications, and highlighting areas for future research.

2 Context

2.1. Energy modeling and its role in policy making

Energy system models are the process of building computational tools that simulate the complex dynamics of energy systems. Models are accessible tools in situations where real-world testing or experimentation is impossible or too costly [7]. This allows researchers and policymakers to generate a range of insights, providing the foundation for making informed decisions about future energy strategies and policies [8].

The oil crisis in 1973 was a determining moment in the history of energy modeling, as it highlighted the vulnerability of energy systems to political, economic and physical disruptions [9]. It was the catalyst for exploring scenarios that reduced the dependency on oil. Energy models began to include more detailed representation of alternative energy sources, such as nuclear, coal and renewable, enabling countries to assess their potential in enhancing energy security. Energy models also became more sophisticated by including more dynamic behaviour that could simulate interactions within the energy markets of the broader economy [10]. After the crisis, there was a clear recognition of the need for better policy planning tools to prepare for and mitigate future energy disruptions [8]. Energy models started to be seen as an essential tool in government and industry for strategic planning, policy analysis and decision support, helping to evaluate the long-term impacts of various energy policies and measures.

Energy models are seeing increased relevance in the face of stringent climate policy, energy security and economic development concerns [8]. They have been increasingly used to enable decision making and legitimise policy making. Moreover, energy models are seeing increased relevance for tackling problems related to climate change. Energy models offer valuable insights into how the world's energy system would need to change in order to respond to climate change. For this purpose, various energy modeling tools have been developed. Policy-making has seen a shift in using energy models for establishing the problem of climate change to now using them to answer specific questions about how to achieve important decarbonization targets to avoid dangerous global warming [11]. Various energy modeling tools have been developed to tackle key questions related to climate change, such as minimizing the costs of preventing global warming and assessing the effects on national energy systems and economies in relation to carbon reduction commitments [11].

2.1.1. Integrated assesment models

Integrated assessment models (IAMs) describe a wide range of models used to understand future changes in the interaction between human society and the Earth system [12]. By combining several disciplines, such as climate science, economics, energy systems, land use, and ecology, they provide valuable insights for climate science and policy. These models have been used to advice the Intergovermental Panel on Climate Change (IPCC) in its assesment of climate change [13]. Scientists create baseline scenarios projecting the impacts of global warming if no action is taken, contrasting them with scenarios that show the changes needed to limit warming to 1.5 or 2 degrees [11].

While IAMs are valuable tools, they also have their drawbacks. One drawback of IAMs is that the representation of each discipline tends to be oversimplified compared to dedicated sector-specific energy models. This is due to limited computational power and the need to run the models within a reason-able time frame. As a result of oversimplification, IAMs often sacrifice spatio-temporal detail, leading to an underestimation of the potential for sector coupling to balance renewable variability. Consequently these models typically suggest a significant need for firm capacity, including fossil-fired generation with carbon capture and storage (CCS), contradicting system designs from more detailed models [14].

2.1.2. Energy system modelling

Energy system models (ESM) can be used to develop future scenarios for an energy system or to represent and analyse its current state. The objective is to provide an in-depth analysis of the energy system, including energy carriers, energy technologies, transmission and storage, and the application of various energy-intensive industries, including heavy industry and transportation [15]. In light of climate change mitigation targets for 2050, many energy system models are starting to emerge simulate or optimize an energy system design for that target year, and are starting to emerge as a credible way of planning for the energy transition as the urgency of climate change mitigation has grown in importance [8].

Compared to IAM models, energy optimization models provide a more realistic representation of the energy system configuration, because they have higher spatio-temporal resolutions which allows for highly fluctuating renewable energy technologies to be analyzed. By creating pathways which are economically and technologically viable, they have helped to build political and legislative consensus on how to implement decarbonization measures, vital to get politics to sign on decarbonization policies [16]. Large-scale optimization models have also helped to identify key technologies to mitigate climate change [17]. Other studies have helped put a price on mitigating climate change, showing that it is far cheaper to decarbonize now than investing in greenhouse gas capturing technologies [18]. Furthermore, it has helped in the identification of alternative decarbonization options, which haven't been considered previously [19].

2.2. Critical raw materials

2.2.1. What are critical raw materials?

Critical raw materials are those with significant economic importance and a high risk of supply disruption. They are vital for maintaining the stability and functionality of a diverse range of industrial ecosystems, such as the energy transition. CRMs face high supply risks due to geographic concentration, mining challenges, and increasing demand [4]. In 2011, the European Union published its first list of 14 critical raw materials. This list, revised every three years, reflects changing economic and geopolitical landscapes. As of March 2023, the list has expanded to 34 critical raw materials, highlighting their growing importance. Apart from CRM, the EU has also identified a sub-set of CRM, named Strategic raw materials, which are those that are relevant for Europe's green and digital transition, as well as for space and defense applications [20]. The complete list of critical raw materials is shown in table 2.1.

Table 2.1: 2023 Critical Raw Materials (Strategic Raw Materials in Italics) [20]

Aluminium/Bauxite	**Coking Coal**	***Lithium***	**Phosphorus**
Antimony	**Feldspar**	***LREE***	**Scandium**
Arsenic	**Fluorspar**	**Magnesium**	**Silicon Metal**
Baryte	***Gallium***	**Manganese**	**Strontium**
Beryllium	***Germanium***	**Natural Graphite**	**Tantalum**
Bismuth	**Hafnium**	**Niobium**	**Titanium Metal**
Boron/Borate	**Helium**	***PGM***	**Tungsten**
Cobalt	***HREE***	**Phosphate Rock**	**Vanadium**
		Copper*	***Nickel****

* Copper and Nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

The assessment of critical raw materials uses Economic Importance (EI) and Supply Risk (SR) as the main parameters to determine the criticality of a material. Supply risk is based on a combination of supply risk parameters, taking into account factors like import dependency, concentration of supply, political stability of supplier countries, and the potential for substitution and recycling [21].

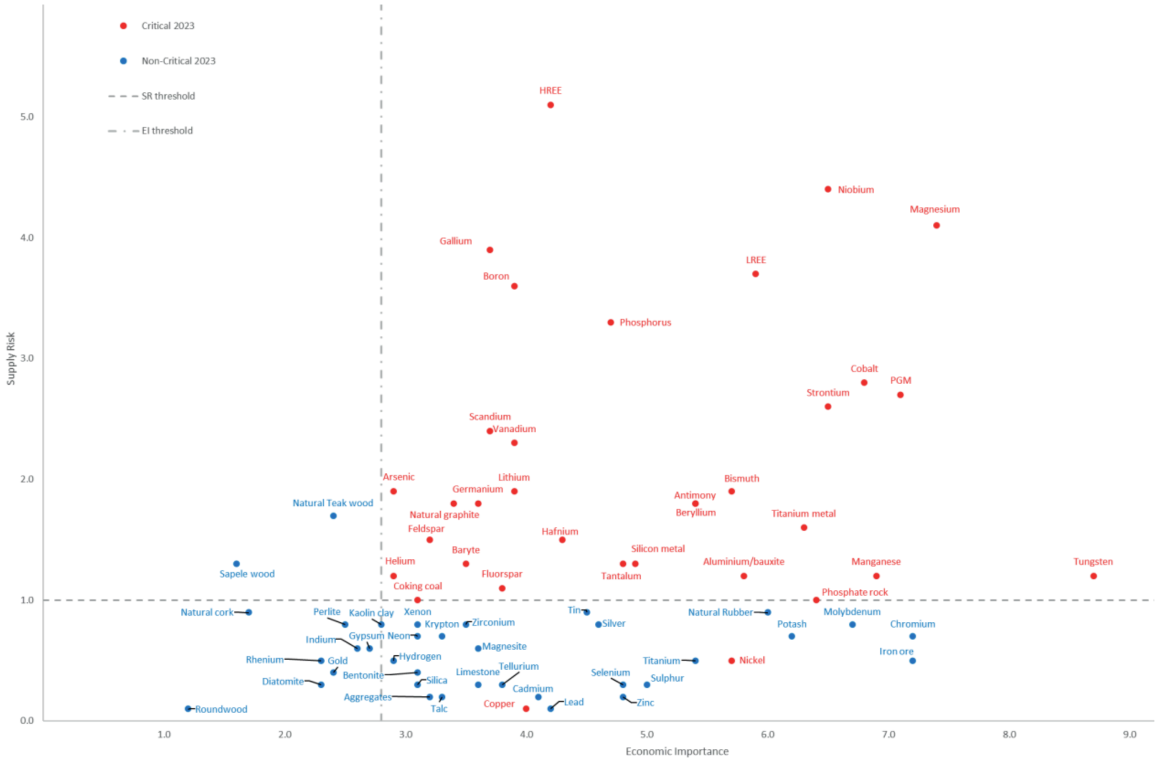


Figure 2.1: Criticality assessment results from the EU report (2023). [3]

2.2.2. Europe's dependency on key critical raw material

Considerable attention is being paid to the EU's and Europe's overall strategic autonomy. This refers to the capacity of the EU to act independently in strategically significant policy without being dependent on other countries. Until a few years ago the topic of critical raw materials received little attention. During the COVID pandemic, global supply chains were disrupted, leading to shortages of critical raw materials in Europe. This served a wake up call to become aware of the importance of critical raw materials and how shortages of critical raw materials could jeopardize the energy transition, but also affect Europe's capacity to innovate and remain competitive [22].

Europe's commitment to becoming carbon-neutral by 2050 is going to drive the demand for base metals, battery materials, rare earths and others critical materials exponentially. Depending on critical raw materials in particular, which have are of high economic and are exposed to high supply risks. Europe is not self-sufficient for many of these materials, nor will they ever be, since it is simply not possible to extract all the materials needed within its borders. Europe heavily relies on international markets for the supply of many raw materials, and nearly all critical raw material are sourced outside of Europe [23].

Depending on a single supplier exposes Europe to significant risks, as any disruption can cause vulnerabilities, delays, and shortages in the supply chain of clean technologies [24]. For example, Europe relies entirely on China for rare earth materials, on Turkey for 99% of its boron, and on South Africa for 71% of its platinum needs, as well as higher shares of iridium, rhodium, and ruthenium [20]. This dependency on raw materials can be exploited as leverage, and political instability or geopolitical rivalries in producer countries can lead to supply disruptions, particularly for CRMs concentrated among a few suppliers. An example of this was back in 2010, when supply of raw materials was used as a geopolitical tool. In order to pressure Japan into releasing a Chinese fishing captain, China completely cut off Japan and slashed rare earth exports globally. Losing strategic autonomy by not securing the supply of CRM undermines Europe's capacity to innovate and remain competitive [3].

As Europe become more aware of its dependence on these materials, they have developed strategies to ensure a stable future supply. The EU recently published its Critical Raw Materials Act. This act aims to increase and diversify the EU's critical raw materials supply, strengthen circularity, including recycling and support research and innovation on resource efficiency and the development of substitutes [25]. By 2030, the EU has set clear targets to diversify its supply and increase domestic capacity along the strategic raw material (SRM) supply chain. These include:

1. At least 10% of SRM production must take place within the EU itself, provided that domestic stocks of these materials exist
2. At least 40% of the processing and refining of strategic materials should take place within the EU
3. At least 15% of Europe's SRM needs to be obtained through recycling and re use
4. Less than 65% of annual consumption for each of these materials should come from a single producer country.

3
Literature review

This literature review exploring the growing literature that examines the relationship between material usage and the energy transition, with a focus on critical raw materials, energy system designs, and how material constrains can influence future decarbonization targets.

3.1. Relationship between material usage and the energy transition

Minerals and metals are fundamental to almost every aspect of modern society [26]. There is a growing body research examining the relationship between material and the energy transition indicating that the transition will go hand in hand with the increase in demand for raw materials. This has now also widely been acknowledged by institutions such as the UN International Resource Panel [27] and the World Bank [28] that point out that the demand for raw materials as the the global economy shifts from fossil fuels to clean energy, the demand for key raw materials will grow exponentially.

As green-technologies, such as solar panels, wind turbines and electric vehicles become central to future energy systems, the supply for lithium,cobalt, nickel and other raw material will inevitably need to increase. The energy system needs to occur in a relatively short time frame, implying that the availability of raw materials will need to be scaled up rapidly, sometimes at volumes ten times or more than the current market size, presenting an incredible challenge for metals and mining companies [29]. Therefore, understanding and avoiding potential bottlenecks is becoming increasingly important for long-term energy planning. Reports examining the general pace and material requirements of the energy transition raise concerns, stating that the transition to clean energy technologies hinges on the availability of critical raw material [30], [31], [32], [33], [34], [35], [36]. The International Energy Agency [2] recently started publishing yearly reports on the outlook for demand and supply for key energy metals, including copper, lithium, nickel, cobalt and rare earth elements. While there are currently no shortages of these critical raw materials, concerns remain about whether growing available supply can keep up with growing demand resource consumption [37]. Although there are no clear signs of any shortages for these materials, the supply of raw material is highly inflexible in the short term, as it takes 10-15 years to develop and operate a mine [23]. This means that in the short-term supply might fall short, and if not properly managed, this could undermine the efforts to meet climate and Sustainable Development goals [28]. Resource competition as well as rise in geopolitical tensions exacerbate supply challenges.

3.1.1. European Material Supply Challenges

Critical raw materials have received significant attention in recent years given their role in strategic sectors and their economic importance. The future supply is said to hinge on geopolitical and geological factors [38].

The European Joint Research center has been investigating various aspects of this issue. The European Joint Research center is the European Commission's science and knowledge service, which supports EU policies. JRC has been actively researching and involved in various areas related to raw materials for years [39], [40], [41], [42]. Much of the work done in relation to critical raw materials has focused on identifying and quantifying the critical raw materials necessary for the EU in strategic sectors, assessing risks related to their supply, and exploring alternatives.

Europe is especially vulnerable for the supply disruptions for many of these materials due to its dependency on other countries for many critical raw materials. Some of these materials are sourced from highly concentrated supply chains, making Europe particularly vulnerable to potential global disruptions. The EU is taking proactive steps to address the security of supply and the anticipated demand for critical raw materials essential for green technologies. The Critical Raw Materials Act aims to enhance material security and build supply chain resilience, both of which are important for sustaining and expanding the capacity to meet the demands of emerging green technologies [43].

3.1.2. Material demand for Power technologies

Wind and solar PV are seen as the most important power generation technologies in the transition to low-carbon future. Demand for raw materials for a given technology is closely linked to the energy density of the source. Given the intermittent nature of renewable sources of solar and wind, they have a lower power density compared to fossil fuel power generation units, translating into substantially higher material demands. Some estimates have said that producing electricity from wind and solar typically requires extraction and processing by a factor of at least 10 compared to fossil fuel based generation [44].

Several studies have shown that the large-scale deployment of PV and wind technologies will significantly increase the demand for materials, in particular rare earths used in wind turbines and germanium in thin-film PV technologies. A recent study by JRC projected material demands in wind turbines and solar PV, driven under different decarbonisation scenarios [40]. The scenarios were based on projections from global commitments to limit greenhouse gas emissions and improve energy efficiency. For the EU, the material demand trends were specifically built on the legally binding climate targets for 2030 and scenarios targeting a climate-neutral economy by 2050. The study's main findings showed that the demand for certain materials, such as rare earth elements for wind turbines and various metals for solar PV technologies, would increase significantly. For wind turbines utilizing permanent magnets, the annual demand for rare earths like neodymium, praseodymium, dysprosium, and terbium could increase up to 15 times by 2050 compared to 2018 levels, especially under high-demand scenarios. For solar PV technologies, the demand for materials like germanium could increase even more dramatically—up to 86 times by 2050 compared to 2018 levels.

Another study that looked at material requirement of low-carbon power generation found that a switch to a non-fossil electricity mix would result in a higher demand primarily driven by PV and wind given their relatively high metal intensity [32]. Another study analyzing how transitioning to a carbon-neutral world in 2100 for electricity generation suggests that a shift would result in a significant increase in the usage of key raw materials emphasizing the need to factor in material availability when designing effective decarbonisation pathways [45].

Many of the studies discussed above highlight considerable increases in the demand for materials that will be needed for low-carbon power generation energy systems. To fulfill the demand for new electricity technologies implies large increases in demand, ranging from a few percent to a factor of thousands [32, 40, 45].
What these studies have in common is that they have examined the material requirements for power technologies by only considering the electricity sector. However, it is likely that the energy transition will also lead to increased demand in other sectors such as the transportation sector. Moreover, the power sector is likely to be influenced by the electrification of end uses, such as transport electrification, increasing the demand for electricity. By looking only at the power sector in isolation,these studies may miss how all the sectors are connected and impact each other.

3.1.3. Material demand for Lithium-ion batteries

The uptake of electric vehicle and their expected demand in material increase has been extensively documented in the literature. Electric vehicles have received a lot of attention, and while they are beneficial for meeting decarbonisation targets in the transport sector, they seem to pose some significant challenges in the context of material demand security and sustainability [46, 47, 48, 49, 50, 51, 52, 53, 54, 55]. Lithium-ion batteries, used in electric vehicles rely on critical raw materials such as Lithium and Cobalt which have an assortment of supply chain issues.

Some studies, highlight the vulnerabilities in Europe's automotive sector, particularly when it comes to securing rare earth elements (REEs) [56]. The paper argues that without a better strategy to secure these materials, the European automotive industry is exposed to serious supply risks as it shifts to electric mobility. Similarly, other studies estimates the metal requirements for lithium-ion batteries used in European EVs and emphasizes that rising demand for lithium, cobalt, and nickel could strain Europe's metal reserves [47]. Both studies call attention to the need for better resource management and recycling initiatives in Europe to reduce its dependency on external suppliers.

Studies with a broader, global scale, look at how vehicle electrification will affect material demand worldwide, particularly in China [57]. While the study suggests that China won't face global shortages in the materials needed for EV development, it does highlight potential domestic supply issues. This contrasts with other studies warning of massive global increases in lithium and cobalt demand up to 37 times current levels by 2030, posing a major challenge for supply chain [49].

A common theme across many of the EV studies is the recognition of the key role recycling and alternative chemistries will play in managing future material demand. For example, a study estimated that without recycling practices, the material requirements for electric vehicles alone could exceed global production capacities [58]. Additionally, increased recycling rates could significantly support the transition to 100% renewable energy scenarios, reducing dependence on primary material extraction [31]. Recycling will also be able to address the new dependencies on raw material, in particular critical raw material [25]. Another study highlights that recycling will play a critical role in reducing dependency on primary raw materials [50]. They estimate future needs for lithium, cobalt, nickel, and manganese, stressing that the recycling potential for these materials must be scaled up to meet demand. Similarly, another study argue that reusing EV batteries and advancing recycling technologies will be key for balancing future material requirements [59].

Overall, it is clear that the transportation sector will impose significant material challenges, particularly battery material metals like Lithium and Cobalt. Recycling and alternative battery technologies are seen as key strategies for managing demand for critical raw material.

3.2. Knowledge gap

Energy system analysis typically focuses on modeling scenarios that optimize costs while limiting greenhouse gas emissions. However, this approach fails to account for other burdens and benefits associated with the deployment of green technologies. Considering only GHG emissions as the unique metric is not suitable for a holistic assessment [5]. There is a general agreement that energy systems should be assessed based on overall cost as well as environmental assessments methodologies, to identify economic and environmental trade-offs [6]. Energy system research should go beyond developing energy scenarios and incorporate resource use and material demand alongside. This gives more meaningful results and allows to answer a wider range of research questions [15] [60]. This provides policymakers with insights beyond those offered by traditional energy models alone [61] and it can enhance awareness of CRM issues and help guide policies that balance resource availability with cleaner energy systems [62].

Many of the studies that look at the material demands for the energy sector often only consider isolated sectors, such as the power sector or transport, without considering the how the deployment of these technologies might depend on one another when considering the entire energy system. We address this gap by using a sector-coupled model, which models the energy system for the heating, transport and power sector. This allows to understand the resource implications of future energy configuration from a system-wide perspective. Furthermore, many studies have consider limited number feasible options by considering only cost-optimal solutions.
We propose the following sub-research questions, which address key aspects of material demand and energy system design:

1. SQ1: How do material demands vary across different energy configurations, and what factors

influence these differences?

2. SQ2: What are the trade-offs in energy configurations with reduced vehicle electrification?
3. SQ3: How do projected 2050 material demands compare to current supply and demand dynamics?
4. SQ4: To what extent can alternative battery chemistries and potential recycling practices reduce material demand by 2050?

4 Methodology

This thesis aims to analyze future material requirements of hundreds of equally feasible energy configurations. The first step in doing so is understanding the model that was used to generate these configurations. This is described in section 4.1, where we describe the energy model that has been used and the method behind generating hundreds of near-optimal energy solutions.

The next step is to integrate the material requirements with the solution of the energy model. To do so, we have used life cycle inventories for a range of technologies for power generation, conversion and electric vehicles. These are described in detail in section 4.2. The results are analyzed by considering raw material supply and demand dynamics which is explained in section 4.3.

Finally, we consider the material requirements of different battery technologies and consider recycling input rates of key critical raw materials to explore to what extend the demand for these materials can be mitigated. This takes into account factors like the adoption rate of EVs over time, dynamic scrappage rates and two important recycling metrics, the end of life recycling rate (EOL-RR) and the recycling content (RC).

4.1. Model Inputs

4.1.1. Euro-Calliope Energy Model

This research builds on 441 of techno-economically feasible options that allow Europe to become self-sufficient and carbon-neutral by 2050 generated with the Euro-calliope energy system model in previous work [14].

Euro-Calliope is an energy model that represents all of Europe's energy demands, from industries and corresponding synthetic fuels, transport, heating and electricity demand. It also includes all relevant technologies for energy supply conversion and transport. Typically running this model creates a single - cost optimal European energy system. Carbon-neutrality and self-sufficiency is achieved by constraining the GHG emissions and by not allowing any energy imports into the model region, meaning that all supply in the energy configurations is generated within Europe. The modeled energy demand in Europe is based on today's energy demand assuming no changes in energy demand. This approach ensures that the model reflects a feasible carbon-neutral energy system configuration based on existing demand, avoiding the uncertainties associated with future changes in energy use. The model runs a mathematical linear optimization problem at a 2-hour temporal resolution over 4,380 time steps for a full calendar year. This creates a cost-optimal energy configuration that is capable of supplying the different energy demands ensuring that every hour of the year all energy demand is met at the lowest cost possible. The focus is on understanding the design of the energy system with high spatial and temporal detail, exploring flexibility and sectoral coupling.

4.1.2. Supply, conversion and demand Side Technologies

Supply and conversion technologies

The model includes all relevant technologies for for energy supply, conversion, transport and their possible locations.Power generation technologies include open-field photovoltaic (PV) plants, rooftop PV, onshore and offshore wind turbines, combined cycle gas turbines (CCGT), and hydropower plants. For heat and fuel production, the model includes technologies like heat pumps, biofuel boilers, biodiesel converters, and hydrogen electrolyzer. Storage and transmission technologies include hydro reservoirs, pumped storage hydropower, battery storage systems, and direct current (DC) transmission grids.

Demand-Side Technologies: Battery Demand in the Transport Sector

Transport demand is divided into light and heavy transport, encompassing both battery electric vehicles (BEVs) and internal combustion engine (ICE) vehicles running on renewable-derived hydrocarbons. The model does not include any hydrogen-powered vehicles because including BEVs and ICE vehicles already captures the two extremes in terms of efficiency. Battery electric vehicles (BEVs) are characterized by an overall efficiency rate of 70% - 90%, which includes both well-to-tank and tank-to-wheel losses. Hydrogen vehicles, if included, would have an overall efficiency of only 25% - 35%, due to significant conversion losses in the hydrogen production, storage, and fuel cell process [63]. In contrast, the overall efficiency of a conventional ICE vehicle running on biofuel is expected to be even lower. This is because the tank-to-wheel efficiency of an ICE running on gasoline is typically 14% - 25%, with additional well-to-tank losses from biofuel production further reducing the total efficiency [64].

Light-duty vehicles include passenger cars, commercial vehicles, and motorcycles, while heavy-duty vehicles include freight trucks and buses. The transport sector's energy demand is determined by the total distance traveled and the efficiency of different vehicle types. By knowing the energy required per kilometer, the total number of vehicles and the corresponding battery capacity can be calculated. The assumed battery capacities for different vehicle classes are provided by the European Council for Automotive R&D (EURCAR) and summarized in Table 4.1. The values for battery capacity across SPORES are verified with the number of vehicles and the assumed battery capacities (see Appendix A.0.1).

Vehicle class	**Battery capacity (kWh)**
Heavy duty vehicle	200
Light duty vehicle	100*
Motorcycle	10*
Bus	200*
Passenger car	80

Table 4.1: Battery capacities for different vehicle classes. (*) indicates estimated values.

4.1.3. SPORES: near-optimal energy configurations

Typically, running the Euro-calliope model generates a single cost-optimal energy configuration. SPORES which stands for Spatially Explicit Practically Optimal Results (SPORES) is an algorithm designed by Lombardi which generates near-optimal system designs. Starting from the cost-optimal solution it generates near-optimal energy systems by accepting a range of solutions that are all within 10% of the cost-optimal solution. This approach allows us to explore multiple energy designs that are that are 10% more expensive than the cost-optimal solution [14]. The assumption that these solutions are equally feasible to the cost-optimal solution is acceptable, given the high uncertainty regarding the high uncertainty surrounding the future costs of technologies. The hundreds of near-optimal energy configurations produced by applying this method to the model proves that there are radically different options for designing a self-sufficient, carbon-neutral European energy system. The different energy configurations are created so that they show diverse solutions in terms of use of technologies, where they are built and how they are operated.

The SPORES generation process involves three steps: (1) identifying the cost-optimal solution, (2) assigning weights to decision variables, and (3) generating SPORES [14]. Positive weights are assigned to variables with non-zero values, using methods discussed in detail in Lombardi 2023 [65]. The integer deployment method was used for generated the SPORES used for this thesis, ideal for finding spatially diverse solutions.

4.1.4. Exploring the solution space of the model

In analyzing the results of the energy system model, it can be helpful to interpret the solutions using a set of predefined metrics. These metrics are outputs from the model that summarize the complexity of each configuration and help identify material trade-offs within the solutions. For example, one metric is electricity storage capacity, which the model scores from zero (indicating the least storage required) to one (the most storage required). By assessing all 441 configurations through this and other metrics, we can evaluate how different solutions compare.

Nine predefined metrics in previous work have been defined. These include: vehicle electrification (percentage of vehicles that are electrified), EV as flexibility, , biofuel usage (whether the model opts to utilize Europe's biofuel potential), storage discharge capacity, curtailment (the amount of renewable energy that goes unused), electricity production gini coefficient, national energy imports (how much electricity European countries need to import), Fuel atarky and heat electrification. These inputs provide insight into how configurations balance energy independence, regional production distribution, the role of electric vehicles in storage and provide flexibility to the electricity system, and the extent to which heating and transport are electrified or continue to rely on clean fuels.

By considering these metrics alongside material demand, we can better understand the trade-offs between different configurations and how each solution impacts the demand for raw materials. This ensures that material requirements remain central to the analysis.

4.2. Raw Material Assessment

4.2.1. Soft coupling between Sector-Coupled model output and Life Cycle Inventories (LCI)

The assessment of raw materials is based on data availability and their importance in energy technologies [66]. Selected materials include both critical and non-critical raw materials (see Table 4.2). Technologies from the Euro-Calliope model are matched with those in the ecoinvent database version 3.9.1, and the life cycle inventory of each technology is extracted using Brightway software. This data is then used to compute the raw material demand of each technology across all energy system configurations. Life cycle inventories quantify energy and raw material requirements, emissions, and other releases across the entire life cycle of a product, process, or activity [67]. For technologies not present in the ecoinvent database, data from the literature is used. Hydro power and nuclear technologies are excluded from the analysis, as their capacities are constant across all scenarios, serving as a baseline for raw material demand.

Rather than relying on broader methods used to asses the environmental impact of energy systems, the Euro-Calliope is customized to better match the specific technologies and the European energy system. This is done by using the installed capacity of energy technologies (in GW) as a reference rather than the amount of energy produced. Energy output of renewable technologies such as solar and wind heavily depend on their location, which is calculated in the model with high detail. To avoid double-counting environmental impacts twice, certain processes were removed from the supply chain in the ecoinvent database. An example of this would be to remove any construction phases of power plants such as hydro-power, since these have already been built. For electric vehicles, processes on the assumed electricity inputs from the databases have been removed because the model provides the electricity directly. The complete table with all the material intensities for all technologies can be found in the Appendix (see Figure A.0.2).

Table 4.2: List of Materials (Critical Raw Materials in bold. *listed as strategic materials)

Material	Material	Material
Aluminium	Cadmium	**Chromium**
Cobalt	**Copper***	**Gallium**
Gold	Iron	Lanthanum
Lead	**Lithium**	**Magnesium**
Manganese	Molybdenum	**Neodymium**
Nickel*	**Palladium**	**Platinum**
Rhenium	Rhodium	Silver
Tantalum	Tellurium	Tin
Titanium	Zinc	Zirconium

4.2.2. Solar PV

The ecoinvent dataset distinguishes two set of life cycle inventories for solar PV technology, one for on-land and other for rooftop PV. Since the model also distinguishes these technologies as separate, the material demand for these technologies separately, before adding them together under the larger category of PV. The PV modules are based on multi-silicon crystalline silicon solar cell technology. Both datasets include the materials for all components for the photovoltaic installation, which includes the PV modules, mounting system, electric installation, inverter, assuming a lifetime of 30 years. Crystalline silicon has two types of cells, mono crystalline and multi crystalline. Both use high - purity silicon but involve a different crystallization process. Multi-Si are cheaper and easier to product, however are slightly lower in efficiency.

Type of installation	Location	Unit	Technology used	Components
Open field PV	GLO (global)	kg per 1 unit of 570 kWp	Multi - Si	Modules, mounting system, electric installation, inverter
Solar rooftop PV	RoW (rest of the world)	kg per 1 unit of 3 kWp	Multi - Si	Modules, flat roof mounting structure, rectifier, electric installation

Table 4.3: Installation Types and Details [68], [69]

The units of the materials in the ecoinvent dataset are given in kg per unit of power plant. This needs to be in units of per kg/TW, since that is the unit used for the deployed capacities of technologies in the Euro-calliope model. The conversion factors that are used for this conversion can be seen below.

$$\text{Conversion factor Open Field PV} = \frac{10^9\text{kWp}}{TW} \times \frac{\text{kg}}{570\text{kWp}} = 17.85 \times 10^5\text{kg/TW} \tag{4.1}$$

$$\text{Conversion factor rooftop PV} = \frac{10^9\text{kWp}}{TW} \times \frac{\text{kg}}{3\text{kWp}} = 33.3 \times 10^7\text{kg/TW} \tag{4.2}$$

Figure 4.1 shows the material demand for PV systems using c-Si technology. The open-field PV systems are more material-intensive, requiring more material per TW in absolute terms. A simple reason for the difference in total material intensity between roof-mounted and open-field PV systems, despite using similar c-Si technology, could be related to structural and installation factors. Open-field systems typically require more supportive infrastructure, such as mounting systems, foundations, and possibly additional cabling, leading to a higher material requirement per unit of energy capacity. Roof-mounted systems, on the other hand, benefit from existing structures (the roof itself) to support the panels, thereby reducing the need for extra materials. Figure 4.1 shows the material per unit of installed capacity for PV systems the percentage composition of the materials, highlighting significant similarities in the material profiles of both system types due to their shared c-Si technology. Iron is the predominant material for both, making up a substantial portion of the material demand per TW. Aluminium follows, with copper and zinc also being used in notable quantities.

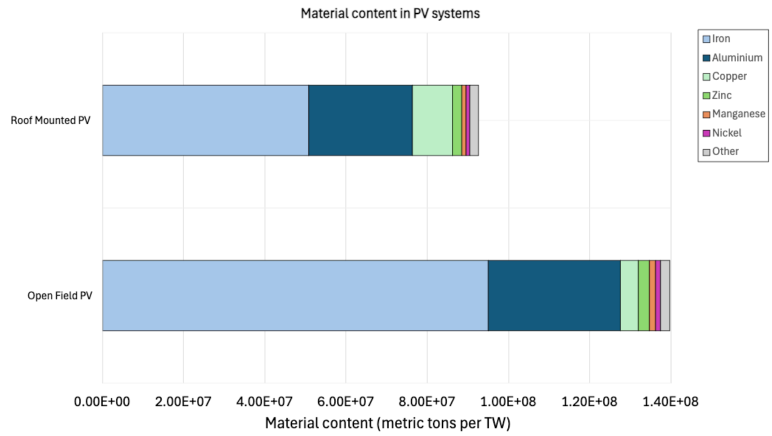


Figure 4.1: Material content in PV systems

4.2.3. Onshore wind and Offshore wind

Wind turbines vary in capacity, drive mechanisms, and generator types. The predominant drive mechanisms include direct drive (DD) and gearbox (GB), with generators typically being permanent magnet synchronous generators (PMSG) or doubly fed induction generators (DFIG) [70]. The wind market is currently dominated by GB-DFIGs accounting for more than 73 % of globally installed wind turbines [71]. The material database for both onshore and offshore wind are based on on wind turbines with a gearbox as drive mechanism with a double fed induction generator (GB-DFIG), with a nominal power capacity of 2 MW. The life cycle inventories for onshore and offshore wind are distinct from one another, and are composed by combining two separate life cycle databases. The database for onshore wind combines a database for the construction of the wind power plant with a database for the connection of the same wind power plant. The former describes the moving and fixed parts of a wind turbine, the latter represents the connection the construction of the network connection for the same onshore wind turbine. This connection connects one turbine to the electricity network. The offshore database combines a database for the moving parts and a database for the fixed parts. For offshore wind the moving and the fixed parts of the wind turbine come from two separate databases. The fixed parts of a wind turbine include the tower and foundation. The moving parts include the rotor, blades, and nacelle housing the gearbox and generator [72]. While both offshore wind turbine datasets do not explicitly mention the materials for the connection to the electricity grid, it is implied to be included, as it states that materials from the foundation and network connection are left in the ocean after decommissioning.

Type of Installation	Location	Unit	Technology Used	Components Included	Source
Wind Onshore	Turbine: GLO Connection: RoW	1 unit of 2 MW	Wind Turbine: (GB - DFIG) Cables and Connection: 10kV cables, 1000m/turbine	Moving Parts, Fixed Parts, Electric Connection	Wind Turbine: [73] Connection: [74]
Wind Offshore	Moving Parts: GLO Fixed Parts: GLO	1 unit of 2 MW	Wind Turbine: GB - DFIG	Moving Parts, Fixed Parts, Electric Connection	Moving Parts: [75] Fixed Parts: [76]

Table 4.4: Overview of Components and Technologies in Wind Installations

The material requirements for both offshore and onshore wind turbines in ecoinvent database are given for a wind turbine with a capacity of 2 MW. This is converted into units of kg/TW using the conversion factor calculated below.

$$\text{Conversion Factor Wind} = \frac{10^6 \text{ MW}}{TW} \times \frac{\text{kg}}{2 \text{ MW}} = 50 \times 10^3 \text{kg/TW} \tag{4.3}$$

Figure 4.2 shows the material share in onshore and offshore wind turbines, showing the share of materials used in these technologies. The material composition for both onshore and offshore wind turbines is dominated by iron, which accounts for nearly 90% of the total material share. Other significant materials include aluminium, copper, and nickel, although their shares are considerably smaller. The high iron content reflects the extensive use of steel in wind turbine structures. Steel accounts for 90 % of the total mass of modern wind turbines. Steel and stainless steel are used to manufacture several components, including the tower, nacelle, rotor and foundation [40]. Besides iron, a vast array of minor and base metals such as nickel, molybdenum, manganese and chromium are used in steel production. Other non-critical materials include key metals that are essential components of high-alloyed steel [70].

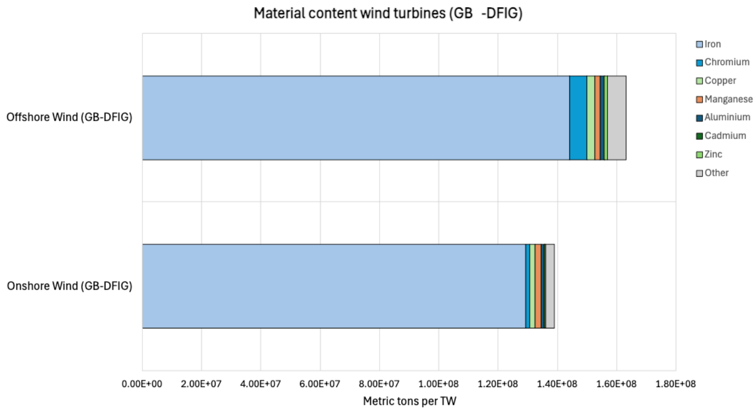


Figure 4.2: Material intensity for wind turbines (metrics tons/ TW)

4.2.4. Electric vehicles and stationary batteries

Lithium-ion batteries encompass a group of batteries that utilize lithium ions to store energy [77]. The choice on the type of battery chemistry can have large implications on the demand for specific battery - material. Currently, the majority of batteries used in Electric vehicles today are Nickel Cobalt Aluminum oxide (NCA) and the Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP). NMC chemistries, in particular, feature a range of compositions that are continuously evolving to enhance performance. The ratio of Nickel, Manganese, and Cobalt (Ni:Mn:Co) is reflected in the naming conventions of NMC variants: NMC111, NMC532, NMC622, and NMC811 [78]. The first round of NMC batteries contains equal concentrations of nickel, cobalt and manganese, which is referred to as NMC111. The price of cathode materials represent 40% of the total battery costs, so there is a huge benefit in reducing the amount of cobalt from a cost and supply chain perspective. The NMC battery manufacturer as a consequence are developing modified versions of the NMC111 material composition that contain less cobalt, coming in ratios of 5:3:2 or 6:2:2 and 8:1:1. By reducing the cobalt content and increasing the nickel content in batteries, the energy density increases, but at the expense of safety and charging issues.

Given the high uncertainty of future battery chemistries, we model the 'average' Li-ion battery to use for the material intensity of Li-ion batteries across the energy configurations. To understand the impact of different battery chemistries we also model the material demand for different by assuming that the battery chemistries NCA, NMC111, NMC532, NMC622, NMC811, LFP, and next-generation All-solid-state batteries (ASSB) make up 100% of the total battery capacity. This results in seven distinct material demand projections, each corresponding to one of these chemistries. While the real-world scenario will likely involve a mix of these chemistries, this approach helps us clearly see how the choice of a specific battery type could influence the overall demand for critical materials within future energy configurations.

The final values used for the calculation of material demand for every battery chemistry are based on the average material intensities stated in the literature (see appendix Table A.3). The material intensity for the different battery chemistries and the 'average' Li-ion battery is shown in Figure 4.3 and the corresponding values in Table 4.5. For battery chemistries not covered in the ecoinvent database, the values were similarly averaged from various literature sources [50, 79, 80].

To understand the impact of different battery chemistries on the material demand, we also material demand

Battery chemistry	Lithium	Cobalt	Nickel	Manganese
NCA	0.113	0.098	0.719	0.000
NCM111	0.113	0.270	0.480	0.442
NMC532	0.137	0.218	0.503	0.276
NMC622	0.120	0.195	0.573	0.182
NMC811	0.095	0.076	0.689	0.132
LFP	0.087	0.000	0.000	0.000
ASSB	0.262	0.000	0.000	0.000
Average Li-ion battery	0.132	0.143	0.494	0.172
Specific material demand of different group of cathodes [kg/kWh]				

Table 4.5: Specific material demand of different groups of cathodes, averages taken across different reported values.

The ecoinvent database provides life cycle inventories for four main battery chemistries: LFP, NMC111, NMC811, and NCA. Each chemistry is modeled according to its specific weight and gross pack energy. The data set is summarized in table 4.6. Using the conversion factors seen below, calculated using the weight of the battery pack and gross pack energy, the data can be converted into units of kg/kWh.

1. LFP: 203 kg, 23.5 kWh
2. NCA: 143 kg, 22.75 kWh
3. NMC111: 164 kg, 23.53 kWh
4. NMC811: 158 kg, 23.53 kWh

$$\text{Conversion factor LFP} = \frac{203}{23.53} = 8.63\text{kg/kWh} \tag{4.4}$$

$$\text{Conversion factor NMC 811} = \frac{158}{23.53} = 6.71\text{kg/kWh} \tag{4.5}$$

$$\text{Conversion factor NMC 111} = \frac{164}{23.53} = 6.99\text{kg/kWh} \tag{4.6}$$

$$\text{Conversion factor NCA} = \frac{143}{22.74} = 6.28\text{kg/kWh} \tag{4.7}$$

Table 4.6: Material usage in different types of batteries

Type of battery	Location	Unit	Components	Source
LFP	China	kg/ 1 kg of Li-ion battery	Battery pack	[81]
NMC 811	China	kg/ 1 kg of Li-ion battery	Battery pack	[82]
NMC 111	China	kg/ 1 kg Li-ion battery	Battery pack	[83]
NCA	China	kg/ 1 kg of Li-ion	Battery pack	[84]

4.2.5. Other technologies

The material intensities for other technologies is shown in figure 4.4.

Power transmission

For power transmission, ecoinvent provides life cycle inventory data on high voltage direct aerial line (HVDC), representing a functional unit of 1 km of transmission line. The service life is assumed to be 40 years. The dataset explicitly mentions that substations are not included, and that maintenance is not included as a service. Euro-calliope provides power transmission output for both alternating current (AC) and direct current (DC). Since ecoinvent only provides data on DC transmission lines, we assume identical material requirements for AC transmission lines. However, since AC systems use three cables instead of two, material requirements might be underestimated [85]. Furthermore, power

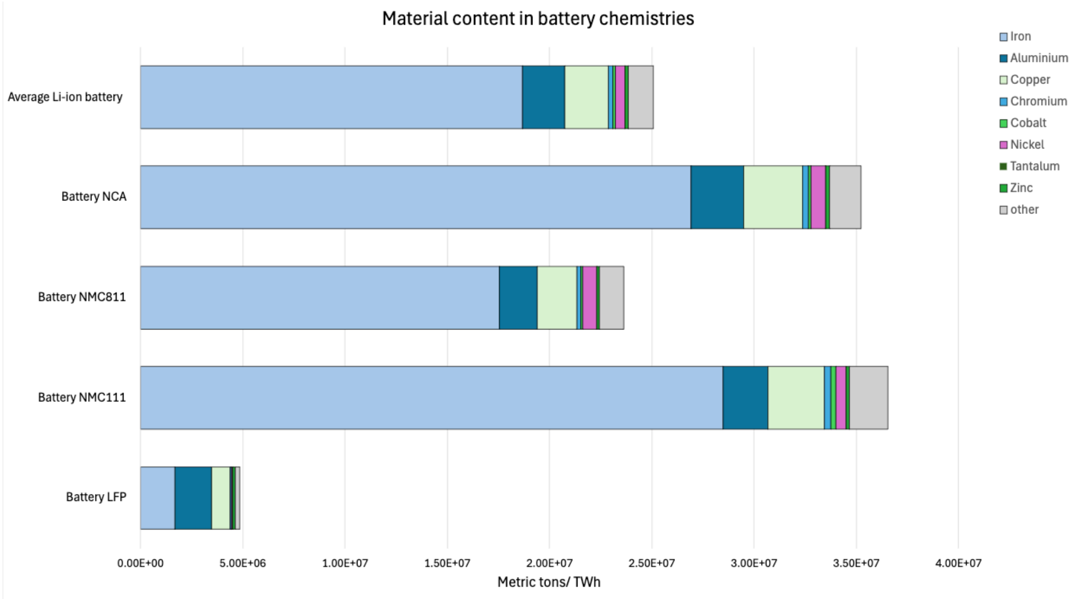


Figure 4.3: Ecoinvent database values for four different battery chemistries

transmission may in the form of both overhead and underground expansion, for which type of material used and intensity are not the same. For example, since weight is not such an issue in underground cables, copper is used instead of aluminum, which has much better conductivity [86].

The units for the materials used in transmission lines in the ecoinvent dataset ([87]) are given in kg/km. These need to be converted into units of kg/TWh. The length-to-capacity ratio is calculated using data from [88] and [89]. Total installed capacity (kW) is divided by the total length of the grid. Grid length (km) in Europe for 2016 is provided by [89], with a total length of 487,450 km. Total capacity (kW) in Europe in 2016 was 1134 TW [88].

$$\text{Length capacity ratio Power Transmission} = \frac{487450\text{km}}{1134\text{TW}} = 429.85\frac{\text{km}}{\text{TW}} \tag{4.8}$$

Heat pump

The ecoinvent database used for heat pumps models a 30 kW brine-water heat pump, extrapolated from a 10 kW unit used in Switzerland for European conditions. This technology uses geothermal energy with a borehole heat exchange, consisting of polyethylene tubes installed vertically in the soil, extracting heat through a closed-loop brine system. The dataset assumes a 20-year lifespan for the heat pump and highlights the high efficiency and performance of brine-water heat pumps compared to air-water heat pumps.

Direct air capture (DAC)

The life cycle inventory for direct air capture (DAC) technology was custom-made, since it does not exist in ecoinvent as its own process. A DAC plant was modelled for a functional unit of 1 t of CO2 captured made up of DAC sorbents and concrete needs [90]. These two components are expected to be the main source of impact in terms of material consumption [91].

Electrolysis

Life cycle inventory for electrolysis technology was custom-made and created using SimaPro processes since it does not exist as its own process in Ecoinvent. Hydrogen production was modelled based on data based on the proton exchange membrane (PEM) technology [92].

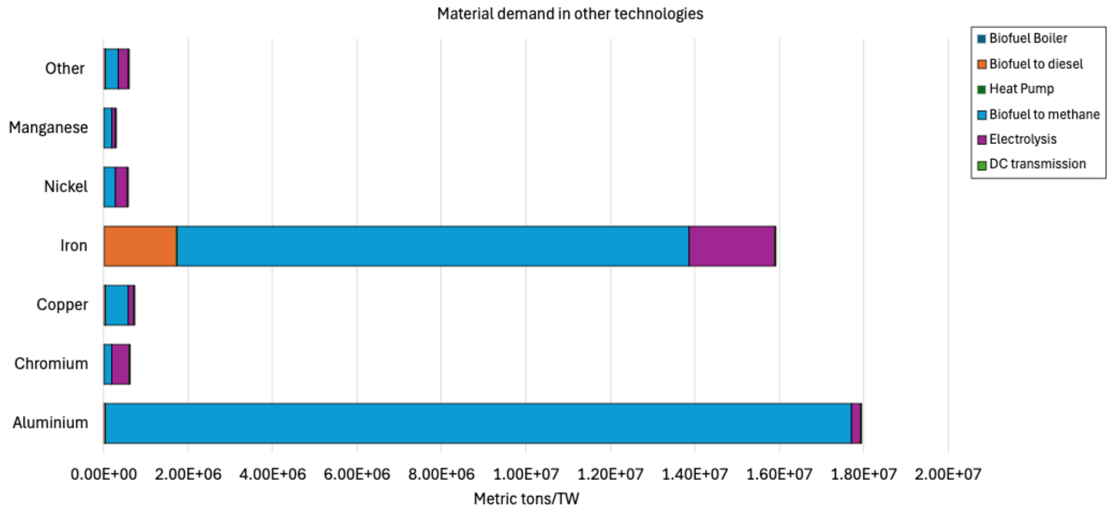


Figure 4.4: Material consumption for heating technologies, grid expansion and electrolysis

4.3. Raw material supply dynamics

To analyze the results we consider current supply and demand dynamics. This will help us understand which materials are more likely to conflict with supply chain issues. For this we consider both the annual global production and current EU consumption as well as current known reserves.

Net cumulative raw material consumption in 2050

The SPORES results provide the near-optimal energy system designs as a snapshot of the end-point year 2050 and assumes that the energy configuration are built from scratch. To assess the total material requirements for future energy system that will be needed from present-day up until 2050, we need to take into account only the capacity of technologies that have yet to be installed. To do this, we subtract current installed capacity from the results given by the model. We do this for technologies such as wind, solar and electric vehicles for which we could find reliable data. Current installed capacities for other technologies, such as electrolysis were negligible or no reliable data could be found for heating technologies such as heat pumps and biofuel heaters. The current installed capacity of technologies is shown in table 4.7.

Technology	Installed Capacity	Unit	Source
Solar	268.1	GW	[93]
Wind onshore	200.2	GW	[93]
Wind offshore	18.0225	GW	[93]
Electrolysis	0.0162	GW	[94]
Stationary batteries	0.46	GWh	[41]
Electric vehicles (battery capacity)	552.3	GWh	[95]

Table 4.7: Installed Capacity of Technologies in the EU as of year 2023

Cumulative material demand vs Annual global production

The annual global production values are taken from the USGS USGS (United States Geological Survey) as mentioned in their latest mineral commodity mineral commodity summary [96]. The cumulative material demand is compared to the annual global production to highlight the scale of demand as well as help to understand supply risks.

Cumulative material demand vs Reserves

The data for reserves is taken from the USGS USGS (United States Geological Survey) [96]. Reserves are defined as resources that can be economically extracted at the time of determination. Reserves is a dynamic variable, meaning that it can change over time. Exploration of new deposits, improved technology (making extraction cheaper), or changing market conditions (making the price of a material more expensive) can contribute to changes in an increase of quantity of a material.

Annual material demand vs current annual material consumption in Europe

To put the projected annual demand of European energy systems into perspective we consider current annual European consumption. These values were taken from the SCREEN3 project, which offers updated fact-sheets on critical raw materials (CRMs) for 2023 [97]. The EU consumption is given as the average annual consumption in the time period 2016 - 2020. This consumption is based on apparent consumption which measures the total amount of materials directly used by the economy. It is defined as the annual quantity of raw materials extracted domestically, plus all physical imports, minus all physical exports [98]. This measure does not account for the raw materials embodied in finished goods, potentially underestimating the total raw material footprint required for imports. For example, many European car manufacturers rely on Lithium-ion batteries that are manufactured in China Since these material flows are not embodied in the apparent consumption value, projected increases in material increase might be overestimation's.

4.4. Recycling of Lithium ion batteries

Green energy technologies depend on a limited supply of non-renewable raw material sources. Unlike fossil fuels, these materials are not gone after they have been used, which makes recycling and re-use of materials possible. Recycling will be essential in meeting the material demands of 2050, while also making the supply chains of renewable energy and electric vehicles more sustainable. Technologies reaching their end of life in the coming year will provide stock of secondary material, which can offer significant economic and environmental benefits [99]. If recycling practice are not in place, valuable materials could end up wasted. Recycling methods that are currently available for lithium-ion batteries include pyrometallurgical and hydro metallurgical processes. Both these processes are aimed at recovering critical raw material such as manganese, cobalt and nickel. As well as metals that are used in the exterior of the battery pack, such as steel, aluminum and copper.

This analysis looked at the extend to which recycling can reduce demand of five critical raw materials used in lithium-ion batteries. These included Lithium, Cobalt, Nickel, Copper and Manganese. This analysis is broken down into key steps. Firstly, the growth rate of battery capacity is modeled using an s-curve function assuming a time frame from 2023-2050 (4.4.1). Secondly, using a dynamic scrappage function we estimate the capacity of batteries that reach their end of life (4.4.2). We assume that batteries retire simultaneously with the vehicle. Thirdly, using current and improved recycling metrics we determine the portion of material ends up being recycled 4.4.3. Improved recycling metrics assume gradual linear improvements through the years. Finally, we conduct a sensitivity analysis to evaluate how input parameters like battery lifetime and growth rate would influence material demand and recycled content 4.5. The following sections will cover these steps in more detail.

4.4.1. Modeling expansion capacity

We model the growth rate of EVs by fitting an S-curve growth model to historic data of installed battery capacity in 2016 - 2023. The equation to model the annual growth rate is given in equation 4.9. Of the three main variants of S-curves, we use the Richards curve since this is the S-curve that uses historic data to determine skew [100]. The historic data for the annual battery demand used in electric vehicles is given in table 4.8.

Annual installed battery capacity will be referred to as the expansion capacity, which refers to the capacity needed each year to meet the projected growth rate of EVs needed to electrify the entire road fleet in Europe. The projected battery demand under for SPORE 32 is shown in Figure 4.5.

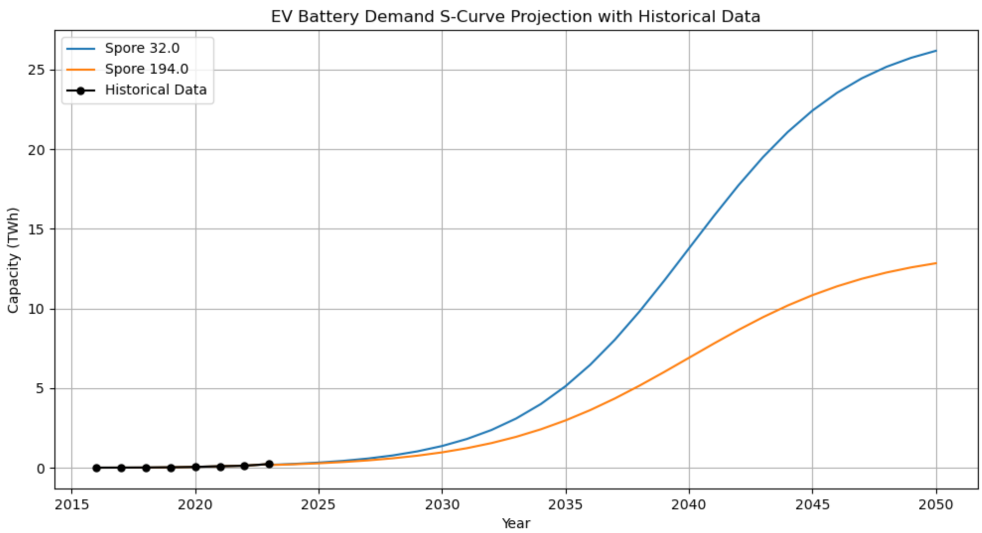


Figure 4.5: Growth rate for EVs

1. **Spore 32: 100% transport electrification:**This configuration assumes that all vehicles in EU are replaced by EVs

$$P(t) = \frac{K}{1 + e^{-r(t-t_0)}} \tag{4.9}$$

In this equation, $P(t)$ represents the projected battery demand in TWh at time t (the year), K is the carrying capacity or the maximum projected demand, r is the growth rate that defines how quickly demand increases, and t_0 is the inflection point or the year in which the growth rate is the highest. These parameters were fitted to the historical data, and their values were adjusted to model two different growth rate scenarios. Both projections follow an S-curve patterns, with growth accelerating after the year 2030. For spore 32, the fitted values are $K = 26.99$, $r = 0.2944$, and $t_0 = 2040$.

Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Battery Demand (GWh/year)	4.8	7.8	12.0	25.3	53.0	91.7	127.7	230.0

Table 4.8: Battery Demand Growth from 2016 to 2023 [95]

4.4.2. Modeling scrappage capacity

Scrappage capacity refers to the capacity of batteries that reach their end of life through, no longer usable, and will have to be replaced by new ones. Scrappage capacity has the potential to become a source of secondary raw material if recycled properly.
We assume that batteries retire simultaneously with the vehicle. We model annual scrap capacity using a survival rate and scrappage function. The survival rate represents the proportion of vehicles surviving to a particular age.The scrappage rate represents the proportion of that are scrapped at a specific age, given that they have survived up to that point. An example of these functions is shown in Figure 4.6.

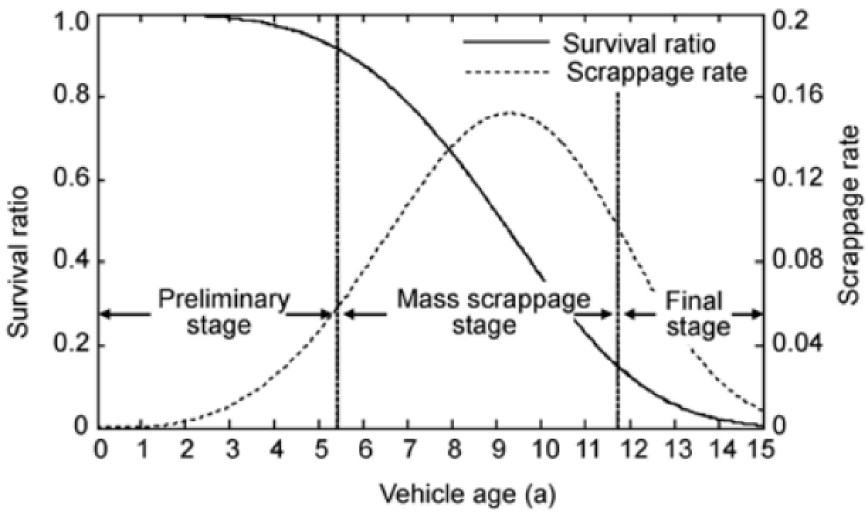


Figure 4.6: Vehicle survival ratio and scrappage rate functions Source: [101]

The vehicle life cycle can be divided into three distinct phases:

1. **Initial Phase:** During this phase, vehicle survival is nearly 100%, with most vehicles being relatively new and very few reach their end of life. As a result, scrappage rates are close to zero.
2. **Mass Scrappage Phase:** During this stage, the rate of vehicle survival declines rapidly, while the scrappage rate reaches its peak as a large number of vehicles are retired.
3. **Final Phase:** In the last phase, both the survival rate and the scrappage rate gradually decline towards zero, as most of the registered vehicles have already been retired.

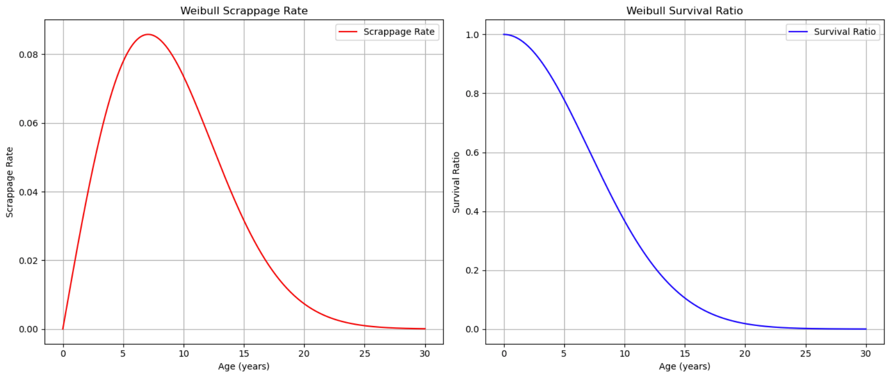


Figure 4.7: Survival and scrappage curves developed for LIBs

Material	EOL RR	RC
Cobalt	68%	32 - 35%
Lithium	<1%	<1%
Nickel	57 - 63%	34%
Manganese	53%	12 - 37%
Copper	40	32

Table 4.9: Current EOL RR and RC rates for battery-critical materials. Source: UNEP, 2011 [105, 106]

The equation for the survival and scrappage functions are modeled using the corresponding equations 4.10, 4.11. The scaling parameters, η and β are used to control the shape of the curves. η is the key parameter used to represent the average lifetime of the vehicle. The scaling parameter β is used to describe how the scrappage rate of vehicles changes over time. A value greater than one implies that scrappage rate increases with time, meaning that vehicles are more likely to be scrapped as they get older. In modeling vehicle lifetimes, studies base these parameters based on empirical data [102]. In the absence of real-life battery degradation data and lifetime distributions for batteries, we set the scale parameter based on literature values.

The scrappage function is modeled by setting η is to 15 years, on the basis of a European study on vehicle lifetime distance traveled and vehicle mass [103]. The shape parameter β is set to 2, reflecting a typical value used in survival analysis. The scrappage and survival function are plotted in Figure 4.7, and the results for the survival and scrappage rates are shown in Table B.2. The interpretation is as follows: the survival ratio after 7 years is 80.4%, indicating the proportion of vehicles that remain operational at this age. In simpler terms, if we started with 1000 vehicles initially, about 804 vehicles would remain in use. The corresponding scrappage rate is 5%. This means that of the remaining 804 vehicles, approximately 40 vehicles will be scrapped during that year.

$$S(t) = \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{4.10}$$

$$u(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \tag{4.11}$$

4.4.3. Recycling metrics

To assess how much demand can be met by secondary sources, we consider two commonly reported recycling metrics: the End of Life Recycling Rate (EOL-RR) and Recycled Content (RC) [104].
The EOL-RR measures the percentage of a material that is collected and recovered when a product reaches the end of its life. It takes into account the efficiency along the entire recycling chain, including the collection rate and the recovery rates of recycling processes. A high value for EOL-RR indicates that material is successfully collected and recycled, while a low EOL-RR would imply inefficiencies in

the collection process, or the recycling process itself. Low EOL-RR rates can occur because of both technical or economical constraints in the material recovery. Lithium for example has a recovery rate of less than one percent. This is because with current recycling methods, it is very difficult to recover Lithium and operational costs are too high.

Recycled content (RC) refers to the proportion of material that comes from recycled sources in the production of new products. In other words, the percentage of secondary material (or recycled material) that is present in new products. The current EOL-RR and RC for the raw materials are given in Table 4.9. The EOL-RR values are always higher in materials than the RC values. This discrepancy exists because the available recycled scrap often cannot meet the growing primary demand. This occurs when demand outpaces the secondary supply [28].

We consider two possible trajectories for the recycling metrics. The first scenario assumes no improvements in current recycling rates, meaning that current EOL-RR and (RC) remain constant. The second scenario assumes improvements in future recycling rates on primary raw material demand. For this, we assume that EOL-RR gradually increases to 100% by 2050. For the RC rates we assume that the ratio between EOL-RR and RC rates remains constant.

Although achieving 100% EOL-RR is likely unrealistic due to inevitable losses in collection and recycling processes, this assumption highlights the potential of ambitious recycling efforts. Studies investigating recycling recovery rates for these materials have shown that it is possible to reach high recovery rates. One study found that recovery rates could reach up to 96.84%, 81.46%, 92.65%, and 91.39% for nickel, cobalt, manganese, and lithium, respectively, throughout the entire recycling process with new innovative recycling methods [79].

Considering the current low recycling rates of lithium in LIBs, different assumptions are used for lithium recovery compared to other materials. We assume an EOL-RR of 60% by 2050, based on a study modeling the potential impact of lithium recycling from electric vehicle (EV) batteries [107].

1. **Base Case Assumption:** Retired LIBs are replaced entirely by new raw materials.
2. **Current Recycling Rates Assumption:** EOL-RR and RC rates remain constant through 2050.
3. **Future Recycling Rates Assumption:** EOL-RR rates increase to 100% by 2050.

4.4.4. Calculating Primary and secondary demand for raw material

Total material demand for a given material m given in year i is calculated as the product between the material intensity of material m (MI_m) and the total battery capacity in that year. Total battery capacity includes expansion and scrappage capacity. The primary material demand is the amount of material that must be extracted from primary sources (mining) each year after accounting for recycled and reused materials.
The secondary supply is calculated by multiplying scrap capacity by the end-of-life recycling rate (EOL RR) and adding the expansion capacity multiplied by the recycled content (RC). Primary raw material is the difference between total demand and secondary supply.

$$\text{Total Demand}_{i,m} = MI_m \times \text{Total Battery Capacity}_i \tag{4.12}$$

$$\text{Secondary Supply}_{i,m} = (\text{Scrap Capacity}_i \times \text{EOL-RR}_m) + (\text{Expansion Capacity}_i \times RC_m) \tag{4.13}$$

$$\text{Primary Demand}_{i,m} = \text{Total Demand}_{i,m} - \text{Secondary Supply}_{i,m} \tag{4.14}$$

4.5. Sensitivity analysis

We performed a sensitivity analysis by adjusting key parameters, specifically the scrappage rate and EV growth, to explore how these factors influence material demand.

4.5.1. Battery lifetime

To analyze the impact on battery lifetime on the recycling results we consider three scenarios which assume different battery lifetimes. The battery lifetimes are set to 8.5, 15 and 30 respectively, while keeping the growth rate constant. The battery lifetime will have an effect on the scrappage function, since this one is directly controlled by the battery lifetime input. Higher battery lifetimes will delay the retirement of batteries, and therefore also replacement capacity. This will cause a decline in the primary demand for materials, but it can also reduce the potential for secondary supply, since it slows down the inflow of retired batteries back into the system.

4.5.2. Uptake of EVs

To analyze the impact of the uptake of EVs we look at how the speed at which EVs growth over the years will have on primary demand as recycling while assuming a fixed battery lifetime fixed at 15 years. Faster EV uptake leads to quicker accumulation of EV stock, which results in batteries reaching their end of life sooner. This could potentially increase the availability of recycled materials, especially in the long term. However, aggressive uptake puts more pressure on annual production material, creating a strain in the short term as the demand for materials ramps up quickly to support that growth.

5
Results

In this chapter we present the main results for the material requirements across 441 energy configurations. These results provide valuable insights into the potential implications and benefits for certain system designs from a material resource point of view. We identify the technologies that under the special constrains of the energy model stand out in terms material demand. We also identify materials whose demand will see exponential increases, posing significant challenges to future supply-chains. Finally, we address the reductions in material demand for critical raw materials used in battery chemistries, by considering alternative battery technologies and recycling.

5.1. Material trade-offs across energy configurations

5.1.1. Material demands variation

The quantities required differ greatly across the various materials needed for future energy configurations. In this section we will look at how demand for materials vary across energy configurations and how the uptake of different technologies across the energy configurations drive demand for specific materials.

Figures 5.1 and 5.2 show the material demands across energy configurations. Left shows the variation in material demand for power and heat technologies, which includes power generation from solar and wind, transmission lines, heat pumps and other conversion technologies. On the right, is the material demand for only EVs. From this we can point out two main things. Firstly, there is greater variation in material demands across power and heating technologies compared to EVs, and secondly, the material demands for EVs stand out considerably. The variation in material demand in the power and heating technologies can be explained by the fact that different the models drives solutions to contain the greatest variety in power technology deployment. Some configurations may rely entirely on wind, while others more on solar PV, and many others somewhere in between. On the other hand, most solutions contain high levels of vehicle electrification.

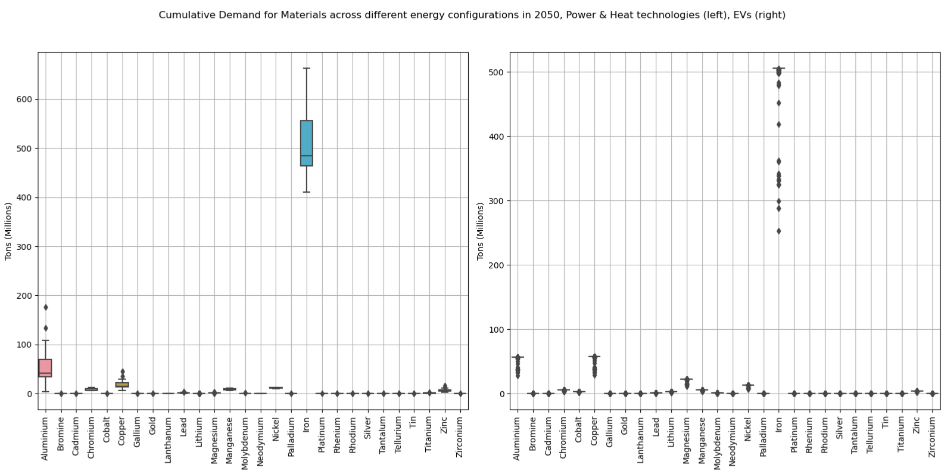


Figure 5.1: Boxplot variation in total material demand for all materials

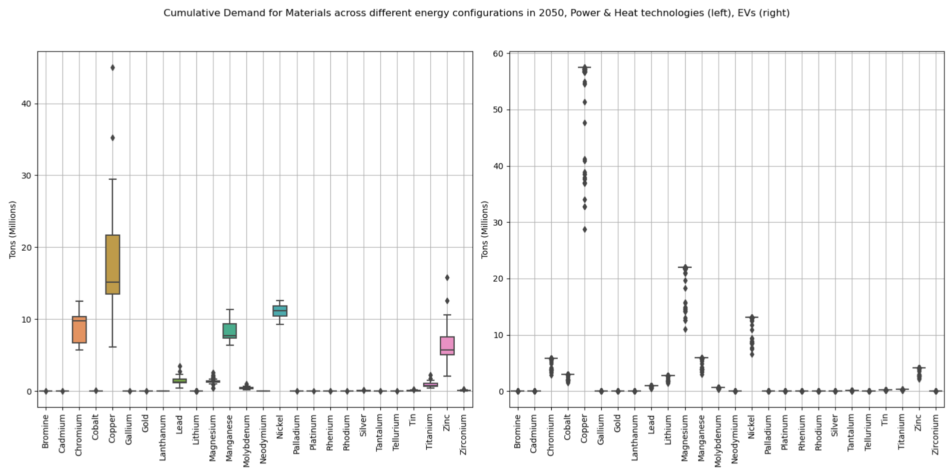


Figure 5.2: Boxplot variation in total material demand for all materials (without iron)

5.1.2. Material share of technologies

Figure 5.3 shows the share of material coming from technologies present in energy configurations. It is clear that Electric vehicles hold the largest share of material demand for a wide range of materials. Critical raw materials, such as Lithium, Tantalum, Nickel and Cobalt show a strong relationship with energy configurations deploying a high number of EVs. We can observe that the share of material demand coming from heating technologies, electrolysis, power grids, and stationary batteries, which are grouped in the 'other' category is negligible compared to the dominant contributions from EVs and renewable energy technologies.

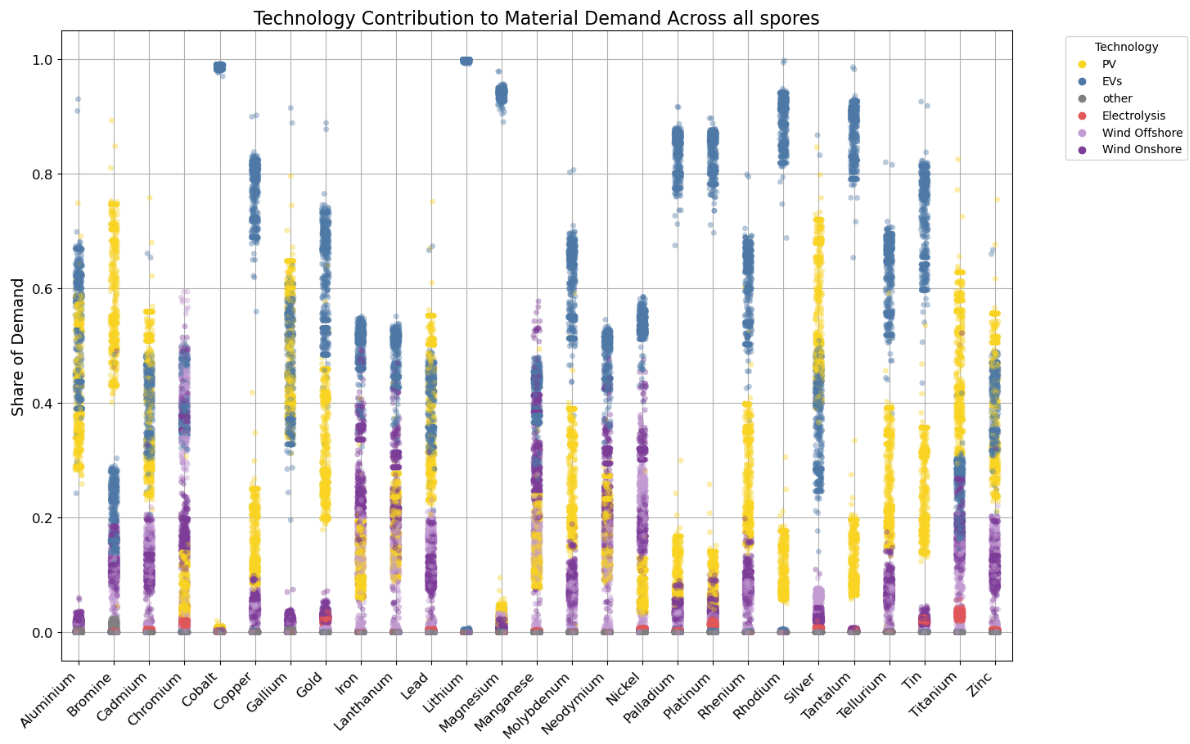
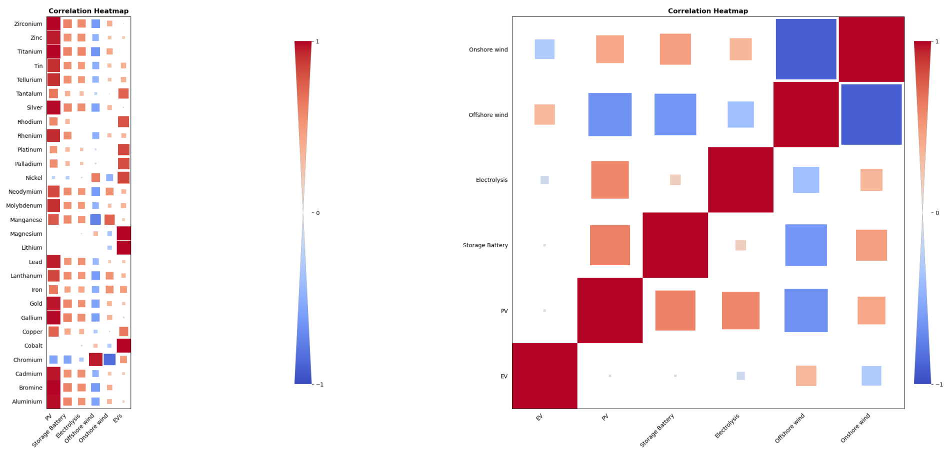


Figure 5.3: Technology contribution to material demand across all SPORES

5.1.3. Pearson correlation: total material demand and deployment of technologies

Pearson correlation is a statistical correlation coefficient that measures the linear correlation between two variables. A value close to 1 signifies a strong positive correlation, meaning material demand increases with the deployment of the technology. Conversely, a value close to -1 indicates a strong negative correlation, where material demand decreases with increased deployment of the technology. In Figure 5.4 we plot the Pearson correlation for the deployment of technologies and the total material demand (5.4a) and pearson correlation between the deployment of different technologies (5.4b). Noticeable correlations are strong correlations with the deployment of PV technologies and demand for Gallium, copper, gold, and molybdenum. Similarly, avoiding EVs in configurations reduces the demand for tantalum, nickel, magnesium, lithium, cobalt and copper. Furthermore, we see that configurations that deploy offshore wind have negative correlations with almost all materials. Offshore wind shows negative correlations with many technologies, meaning it is deployed at the expense of the other technologies. This helps to explain why the presence of offshore wind in energy configurations decreases overall material demand, making it a potentially effective strategy for minimizing material consumption across energy configurations. The model favors deployment of PV, electrolysis and battery storage together, which explains why these technologies share similar material demand correlations as PV.



(a) Total Material demand vs technology deployment

(b) Correlation between deployment of technologies

Figure 5.4: Correlation heatmap diagram

5.2. Trade-offs between energy system preferences and specific CRMs

In the previous section, we identified that problematic materials are driven by the uptake of electric vehicles, followed by PV in energy configurations. Here, we look more closely at the trade-offs of avoiding these materials by assessing the material demand of other materials and the available maneuvering space of remaining technologies in energy configurations with low degree of vehicle electrification.

5.2.1. Impact of Reducing Vehicle Electrification on Material Demand and System Flexibility

Configurations with fewer EVs result in lower demand for a wide range of materials, including Cobalt, Copper, Lithium, Magnesium, Nickel and Tantalum. This can be seen in figure **??**, which compares the material demands of materials in in a configuration with high EV deployment and low EV deployment. However, avoiding using these materials results in a considerably less maneuvering space for remaining technologies. This can be seen in Figure 5.5 which shows the distributions of vehicle electrification across the 441 energy configurations. Energy configurations are categorized a low if they fall within 25% of the lowest value. Medium ranges between 25 - 45% of the lowest value and high is everything above. The model pushes most solutions to contain high number of electric vehicle, because from a system point of view, utilizing electric vehicles means your system is more efficient compared to cars running on synthetic fuels.

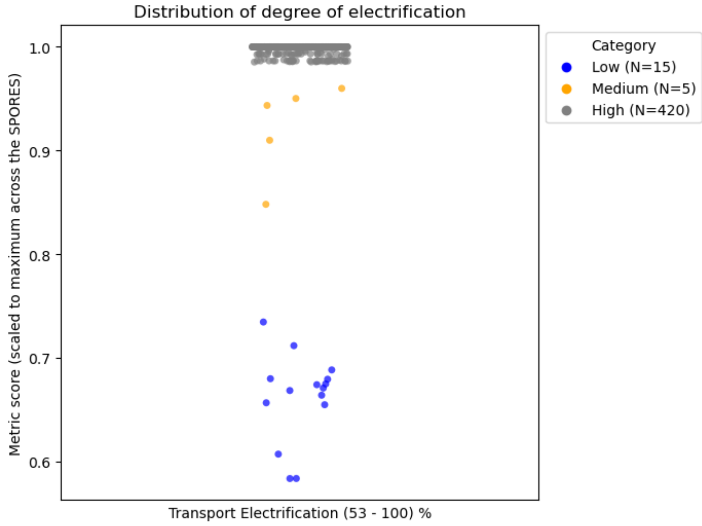


Figure 5.5: Distribution of vehicle electrification in energy configurations

Figure 5.6 compares how low vehicle electrification energy configurations score on other system metrics. Reducing the number of electric vehicles would require using all potential bio-fuel usage in Europe. This requires more renewable electricity generation capacity to make hydrogen and synthetic fuels. With more renewable energy generation and less electric vehicles there is less flexibility in the system, which also tends to have higher curtailment compared to the rest of the energy configurations.

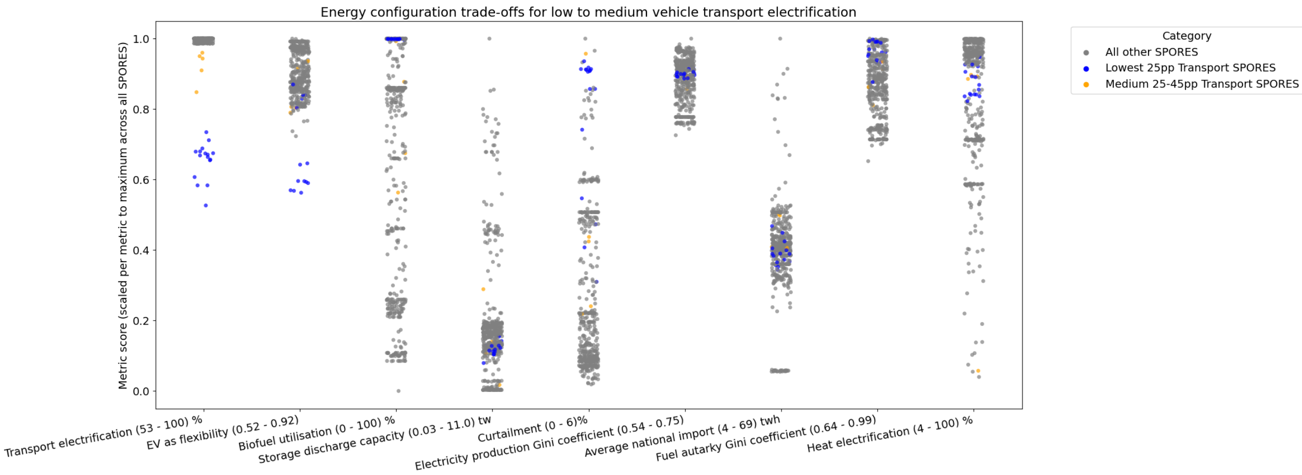


Figure 5.6: EVs vs high level metrics

5.2.2. Trade-offs in Material Demand for Low Vehicle Electrification Configurations

Reducing the number of electric vehicles in the system generally results in a less efficient energy system, leading to an increased need for renewable energy capacity. However, what are the trade-offs in material requirements when focusing on the power and heating sector in configurations with lower vehicle electrification? Figure 5.7 plots the material requirements for the power and heating sector across all energy configurations, with the low vehicle electrification solutions highlighted in blue. The baseline in this comparison represents the average material usage for the power and heating sector combined.We see that for most materials, configurations with lower EV deployment tend to have higher material demand in the power and heating sector compared to the average.

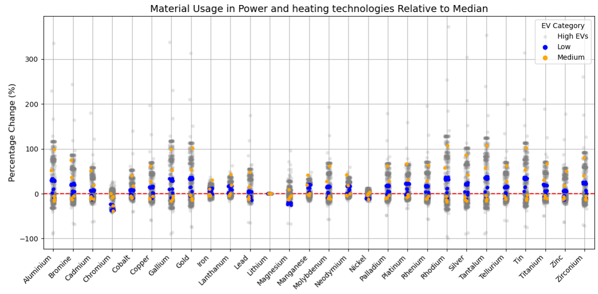


Figure 5.7: Material usage in power and heating technologies relative to baseline (median of power and heating material usage)

However, when we consider the material requirements for the entire energy system, we see that reducing electric vehicle deployment actually lowers total material demand overall. This can be seen in figure 5.8. This is because, although reducing EVs increases material demand in the power and heating sector, the material-intensive nature of electric vehicles means that fewer EVs result in a net reduction in total material requirements across the energy system. As a result, most energy configurations with fewer EVs exhibit lower total material demand compared to the average and to configurations with higher EV deployment. While reducing electric vehicle deployment increases material demand in the power and heating sector due to the need for more renewable energy technologies, the overall material demand for the entire energy system still decreases. Therefore, even though the power and heating sector may demand more materials in low-EV configurations, this increase is offset by the reduction in materials needed for EV production. In other words, the overall system benefits from lower total material requirements, making the increase in power and heating sector materials less significant when looking at the entire energy system.

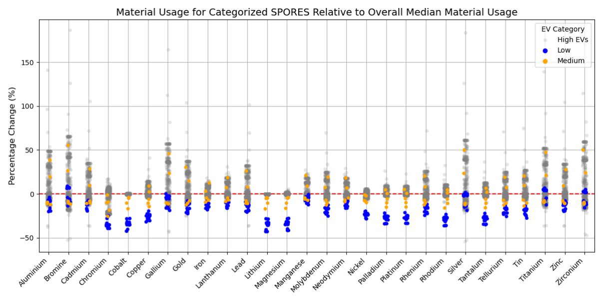


Figure 5.8: Material usage in the entire energy configuration relative to baseline (median of high EV spores)

Noticeably, there are two configurations that have lower material requirements for materials like Aluminum, Cadmium, Gallium, Lead, Silver, Titanium, Zinc and Zirconium. These configurations correspond to spores 213 and 231, which do not deploy any PV. Without the deployment of PV, the configurations these materials are avoided. This scenario assumes PV installation to values below what is already installed. Although this scenario is technically possible, current installed capacities already exceed these installed capacities.

5.3. Material demand across energy configurations

In previous sections we looked at the material demand across energy configurations. In this section we try to understand how bad these material demands are, identifying materials that are likely to conflict with supply-chains and the technologies driving them scaling material demand across energy configurations using current demand and supply dynamics. Projected annual demand refers to the yearly material that would be required for the deployment of technologies in different energy configurations. This is calculated by assuming a linear growth of technologies in the time-frame 2023-2050.

5.3.1. Projected Annual demand perspectives vs Current demand

The difference between the annual demand for common base metals, like iron and copper, and that for critical raw materials (CRMs) like Lithium and Cobalt is substantial. Comparing projected annual demand to current EU consumption shows the extent to which demand must grow, highlighting which materials are expected to see the most rapid increases. Values close to current consumption suggest that green technologies may not drastically alter demand or face significant supply chain issues. In contrast, substantial increases in demand in a short-time are often linked to short-term supply risks and price-peaks given the inflexibility of material supply.

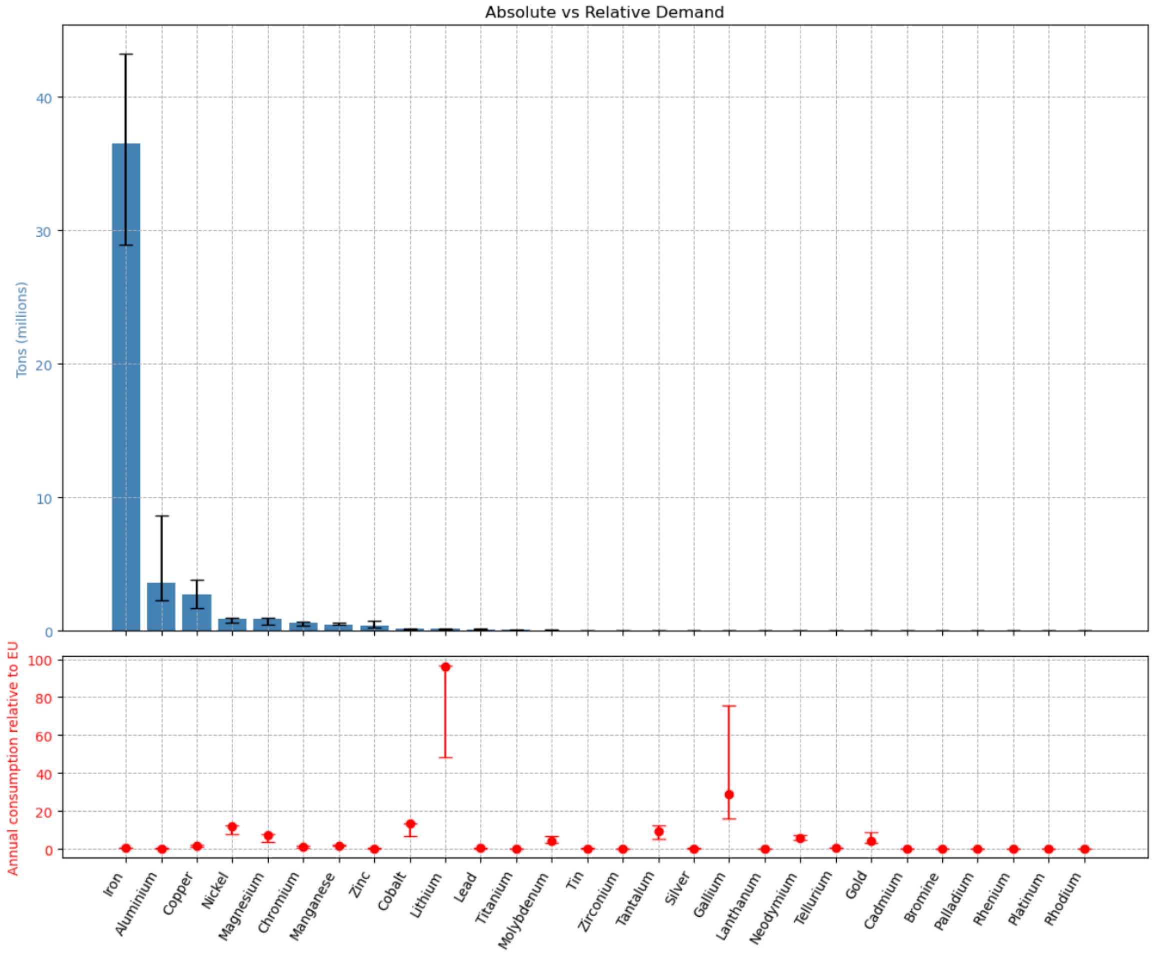


Figure 5.9: Absolute vs relative demand in all materials

Base metals: Large quantities, Moderate relative growth

Common base materials, such as iron, aluminum, copper, chromium, manganese, and zinc, are projected to have some of the highest demands by volume in future energy configurations. However, the growth in demand relative to today's consumption levels varies significantly depending on the energy configuration chosen. Base metals have well-established supply chains and have been have been foundational across a wide range of industries since the Industrial Revolution and therefore more likely to handle projected increases in demand, reducing the risk of supply constraints. The variation in demand increase across energy configurations reveals that different system designs can lead to either a significant increase or a decrease in material demand. These findings show that the choice of energy configuration can significantly influence material demand, especially for materials like chromium and copper, where demand can either surge dramatically or be more moderately contained depending on the system design. In contrast, materials like iron and zinc display more stable demand patterns, with only modest increases across different configurations. This is because the demand for materials that are used more widely across technologies will naturally fluctuate less across energy configurations deploying a combination of all these technologies.

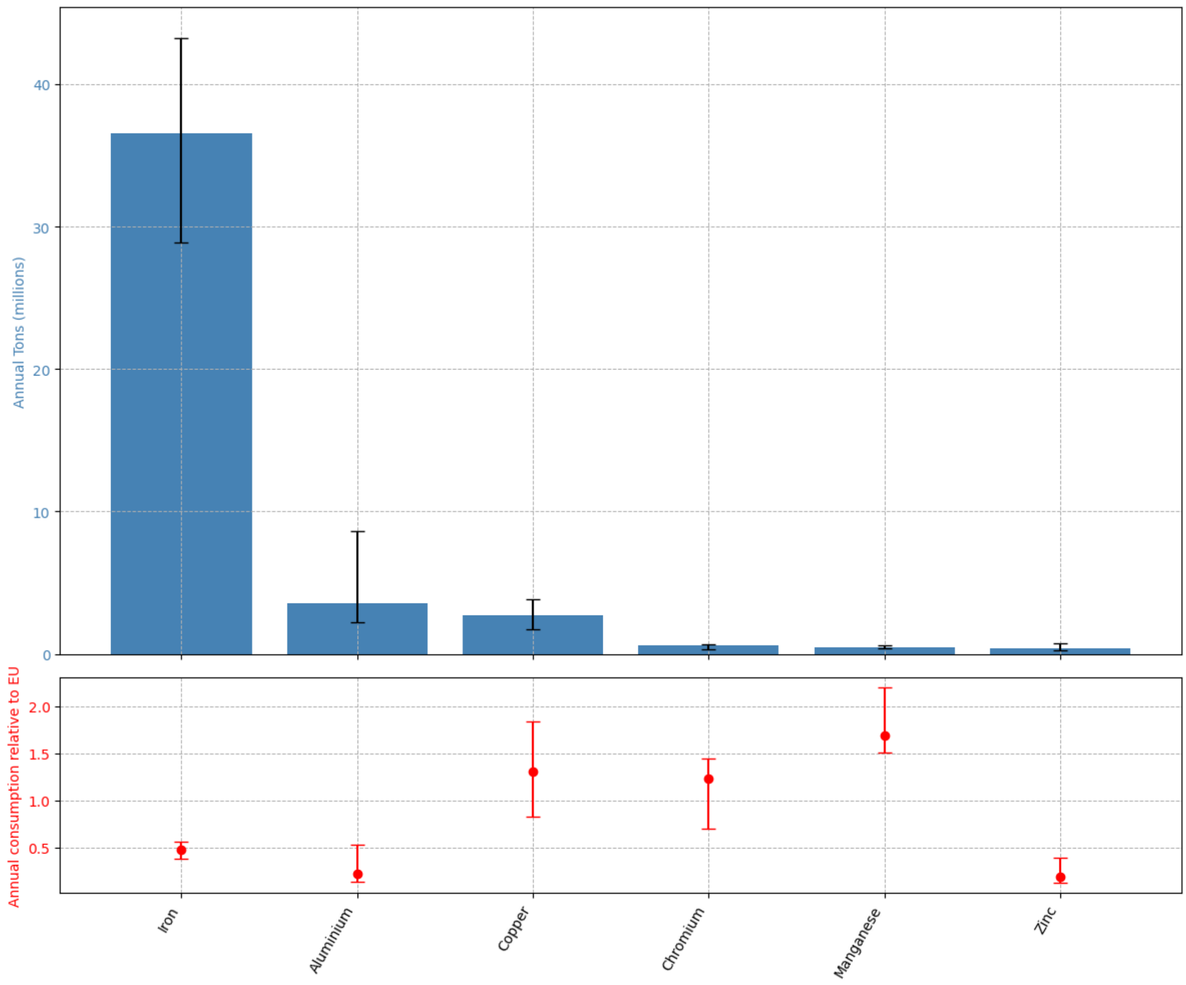


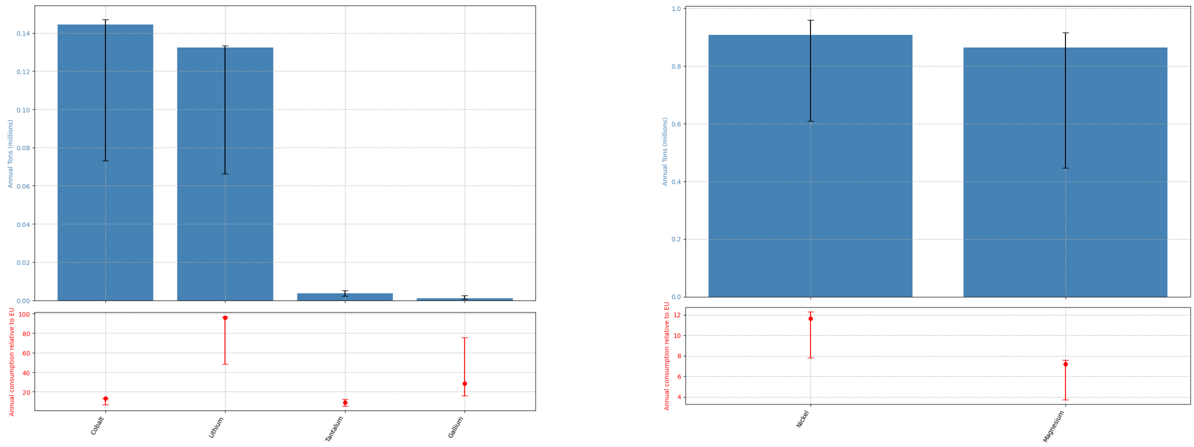
Figure 5.10: Base materials: Range of annual demand across energy configurations, relative to EU

High-Volume materials with High growth

Nickel and magnesium have both high absolute demand and substantial growth relative to current consumption levels. Annual demand for nickel ranges from 0.6 to 1 million tons per year, representing an 8- to 12-fold increase compared to today's consumption. For magnesium, annual demand varies between 0.45 and 0.92 million tons, indicating a 3.7- to 7.6-fold increase. The range of increase reflects the variability across different energy configurations, with nickel showing a more stable increase, while magnesium's demand fluctuates significantly depending on the specific system design.

Critical raw materials, low volume and aggressive growth

Critical raw materials like Cobalt, Lithium, Gallium, and Tantalum are expected to see much smaller absolute demand volumes, but massive growth relative to current EU consumption. The demand for Cobalt, Lithium, Gallium and Tantalum are projected to increase nearly 13 - 6.67, 100- 48, 75 - 16 and 12 - 7 times, respectively. Despite their lower absolute demand compared to other materials, these materials present significant challenges due to required growth relative to today's consumption,and are more likely to conflict with supply chain risks. Reducing and avoiding these materials in energy configurations could be more beneficial for ensuring a stable and sustainable supply for these materials.



(a) Lithium, Cobalt, Gallium, Tantalum

(b) Nickel and Manganese

Figure 5.11: Annual Demand vs Annual Demand / Current EU Consumption

5.3.2. Total material demand vs global production and reserves

In this section we evaluate the material demands in future energy configurations with current supply dynamics, both global production and known reserves.

Cumulative demand/Global production

Figure 5.12 shows two axis providing distinct insights. Cumulative material demand is scaled to global production and annual demand is scaled to EU consumption. Materials whose cumulative demand in 2050 exceeds global production capacity are found above the red horizontal line, indicating the immense scale of future material needs in energy configurations. Satisfying the future energy system needs in Europe will be equivalent to a year's worth of global output. Materials whose demand is expected to increase significantly are those who exceed the vertical red line. The graph emphasizes the significant growth in demand of certain raw materials under a self-sufficient, carbon-neutral energy configuration. The implications of such increases in demand is EU's reliance on these materials will grow significantly, creating greater material dependencies in Europe. Moreover, such increases in demand implies that the supply chain for these materials will need to scale up aggressively and rapidly to keep pace. Without sufficient capacity expansion, this could lead to greater supply risks, especially for materials already constrained by limited sources or geopolitical dependencies.

Materials in the top right corner of the graph, such as copper, molybdenum, nickel, cobalt, gallium, and lithium demonstrate both an aggressive increase in demand relative to today's EU consumption and cumulative demands that exceed current global annual production levels. This suggests that reducing the reliance on or substituting these materials could be a priority to mitigate potential risks and alleviate supply chain constraints, especially given the existing pressures from other sectors and the uncertainty in future global supply dynamics.

Annual demand /Global production vs cumulative demand / reserves

Figure 5.13 plots the annual material demand relative to global production and the cumulative demand relative to reserves. Even though this analysis does not aim to determine whether there will be sufficient material supply (given that other sectors also consume critical raw materials and the geopolitics of supply remain highly uncertain and beyond our scope), it is important to understand whether such demands are even feasible with current reserves. Strictly speaking, quantity does not seem to be the main issue, since reserves are more than sufficient. In some cases, peak annual demand for Gallium and Tantalum could surpass global production by a factor of 1.5, while annual demand for Lithium and Cobalt would need a significant portion of current global production of around 60-30%.

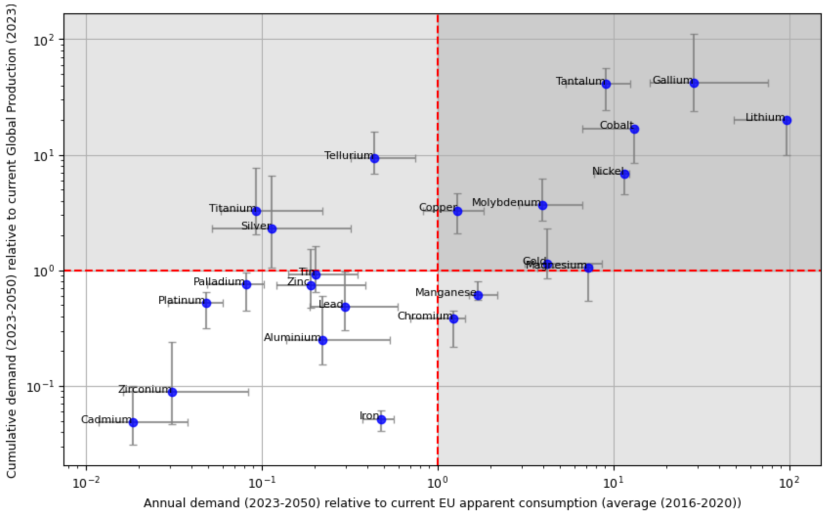


Figure 5.12: Cumulative demand/ global production (2023) vs Annual demand/ EU annual consumption (average 2016-2020)

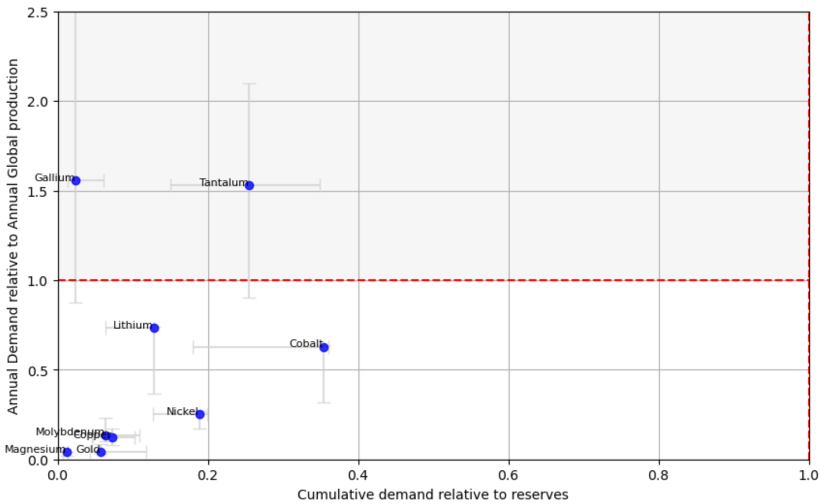


Figure 5.13: Annual demand/ global production (2023) vs cumulative demand/ reserves

5.4. Battery technology trade-offs

Lithium-ion batteries is a broad term applied to a group of batteries containing lithium at the cathode but whose material composition can differ substantially. In previous sections we projected material demand based on the average lithium-ion battery. In this section we consider the uptake of seven different batteries and looking at the differences in four critical raw materials for which these batteries differ. These are Lithium, Cobalt, Nickel and Manganese and Copper. Figure 5.14 compares the material requirements for the different type of batteries. The peak annual demand is assuming an s-curve growth and expansion and replacement capacities (see section 4.4.1, 4.4.2 for methodology explanation). The peak annual demand are plotted scaled to EU consumption and global production respectively in figure 5.14. This graph also shows the difference in material demand relative to the lowest EV SPORE, to compare how effective it is to reduce reduce the number of EVs compared to alternative battery chemistries.

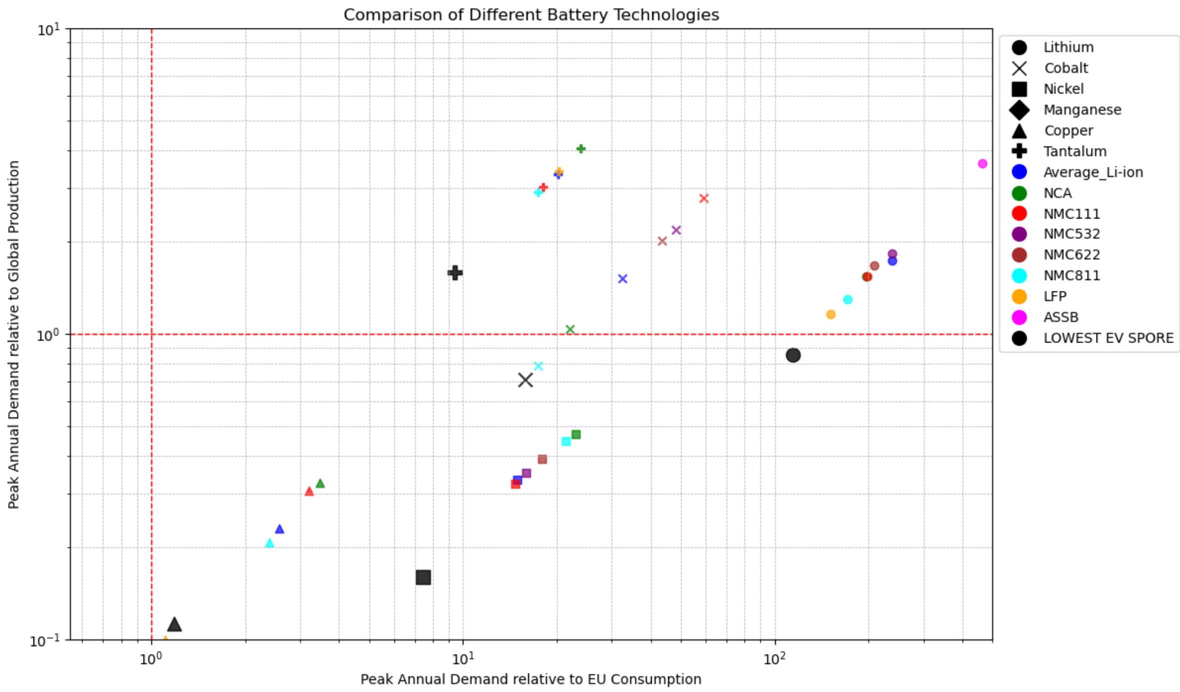


Figure 5.14: Comparison of annual demand/EU consumption and cumulative/global production for different batteries

The results show that the choice of battery chemistry for EV adoption have huge implications for future material demand, with each alternative presenting specific trade-offs. The uptake of battery chemistries, such as LFP and ASSB that are less reliant on critical raw materials offer pathways to reduce dependency on cobalt, nickel and manganese. They reduce overall yearly demand and thereby also reduce the pressure to rapidly accelerate production overall offering great strategies to mitigate supply constrains.

Material	ASSB	LFP	NCA	NMC111	NMC532	NMC622	NMC811
Cobalt	100.0	100.0	63.6	0.0	19.4	27.8	71.9
Lithium	0.0	66.9	56.6	56.8	47.8	53.9	63.8
Nickel	100.0	100.0	0.0	33.2	30.0	20.4	4.2
Manganese	100.0	100.0	100.0	0.0	37.6	58.8	70.0

Table 5.1: Percentage Reduction in Material Demand by Battery Technology

Figure 5.15 plots the annual material demands for different battery chemistries in the time frame 2023-2050 in energy configurations with 100% electrified vehicles. Material demand reaches its peak around in the year 2041.

Cobalt: Among the NMC variants, NMC111 has the highest cobalt demand, with NCA and NMC811 showing signifcant reduction in material demand. LFP and ASSB, offer alternatives to lessen dependency on this critical material. Demand for cobalt in a reduced vehicle configurations using NMC111 would be just as high as in a configuration with full EV adoption scenario with NCA batteries. By the year 2045, a scenario with 100% NMC111 batteries would require over 600 thousand tons of cobalt. Three times the current global production. NCA would reduce this demand by a third, while NMC811 would further reduce it to around 180 thousand tons.

Lithium: ASSB adoption presents a trade-off by increasing lithium demand while reducing reliance on other critical materials. ASSB consumes almost twice the lithium compared to other chemistries, with LFP using the least. ASSB would demand 100 thousand tons more lithium than a full adoption scenario with LFP. This highlights how the choice of battery chemistry directly affects lithium demand.

Nickel: While no scenario surpasses global annual nickel production, current EU consumption levels are projected to be reached shortly after 2025, depending on the battery chemistry. NMC111 has the lowest nickel content among nickel-using chemistries, while NCA has the highest. Using NMC111 could delay reaching EU consumption levels by 2-3 years. The range of nickel demand across chemistries is narrower, with NCA reaching up to 1800 thousand tons and NMC111 around 1400 thousand tons. To significantly reduce nickel demand, lowering the number of EVs or opting for LFP or ASSB (which do not require nickel) would be effective. However, for NMC variants, increasing nickel content typically means reducing cobalt needs.

Manganese: Demand for manganese varies widely among chemistries. NMC111 has the highest demand, followed by NMC532 and NMC622. NCA, LFP, and ASSB do not use manganese and, therefore, do not appear on the graph. NMC111 is projected to reach current EU consumption levels by 2035, while NMC532 reaches this level around 2038. The battery chemistry chosen thus affects the rate at which supply must scale, with certain chemistries offering more time and flexibility for the mining industry to ramp up production.

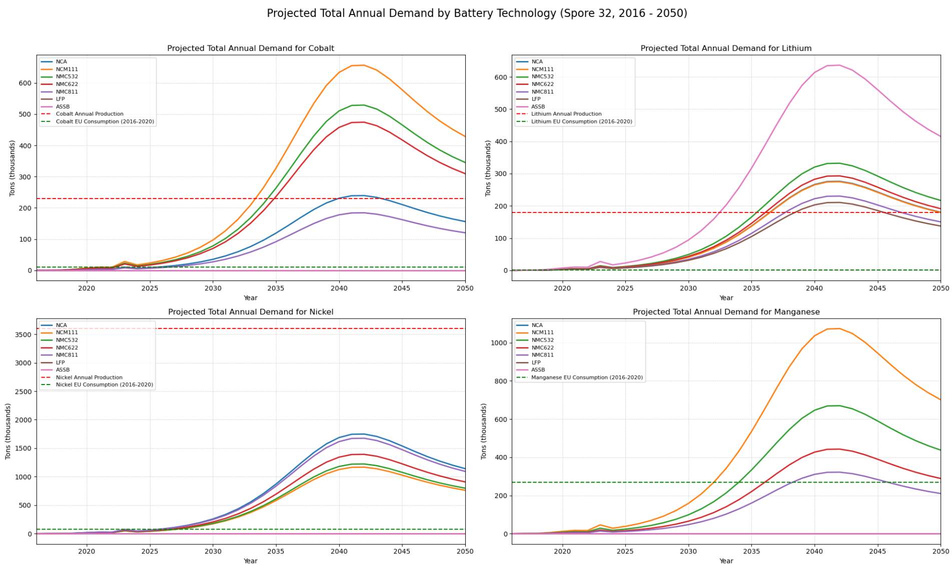


Figure 5.15: Spore 32: 100% Vehicle electrification

5.5. Recycling

In this section we present the results to show to what extend total material demand can be reduced with current recycling and improved recycling practices. Since the recycling rates are assumed to be the same for every material in the different battery chemistries, the percentage decrease in material demand is the same.

Expansion and replacement capacities for EVs

Figure 5.16 shows the annual battery capacity demand (expansion + replacement) assuming an s-curve growth. The orange bars represent the expansion capacity, which is the new demand for EV batteries. The blue portion of each bar indicates the expansion capacity. As the name suggests, this is the capacity of batteries that have reached the end of their life and must be replaced. The replacement capacity has the potential to be collected and recycled flowing back into the production system as secondary supply of material. However, without any recycling, the replacement capacity leads to higher primary demand.

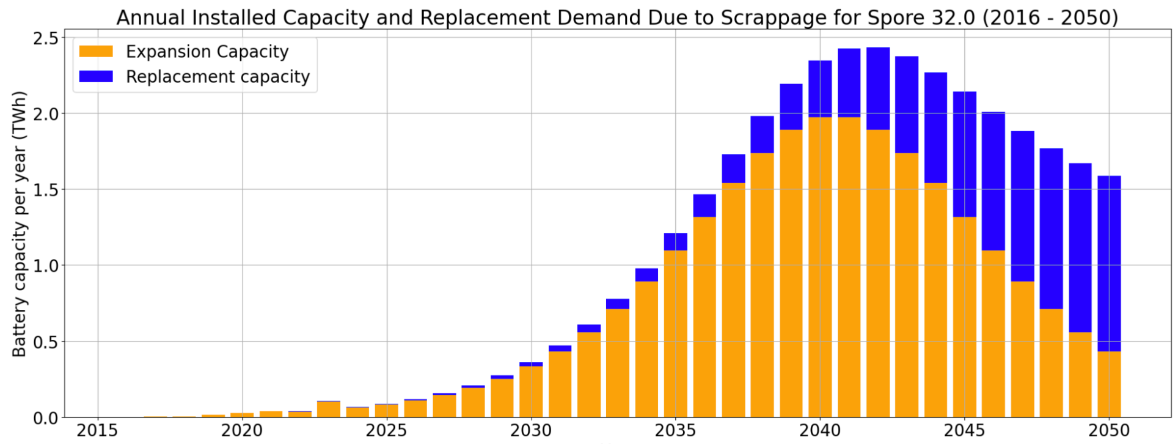


Figure 5.16: Expansion and replacement capacities for EVs

Portion of total demand that met by Secondary supply

The total portion of cumulative demand that can be met with secondary supply for the different materials for current and improved recycling practices is shown in Table 5.2. Figure 5.17 compares the peak annual demand in an energy configuration with 100% vehicle electrification with respect to current EU consumption and global production using the material requirements in the for the average lithium-ion battery. It can be seen with improved recycling practices, the demand for materials used in lithium ion batteries can be reduced more effectively than reducing the number of vehicles without compromising the design of the energy system.

Material	RC A (%)	RC B (%)
Lithium	1	45
Cobalt	42	57
Nickel	41	64
Manganese	24	40
Copper	34	73

Table 5.2: Reduction in Primary Demand by Material under Two Recycling Assumptions (RC A and RC B)

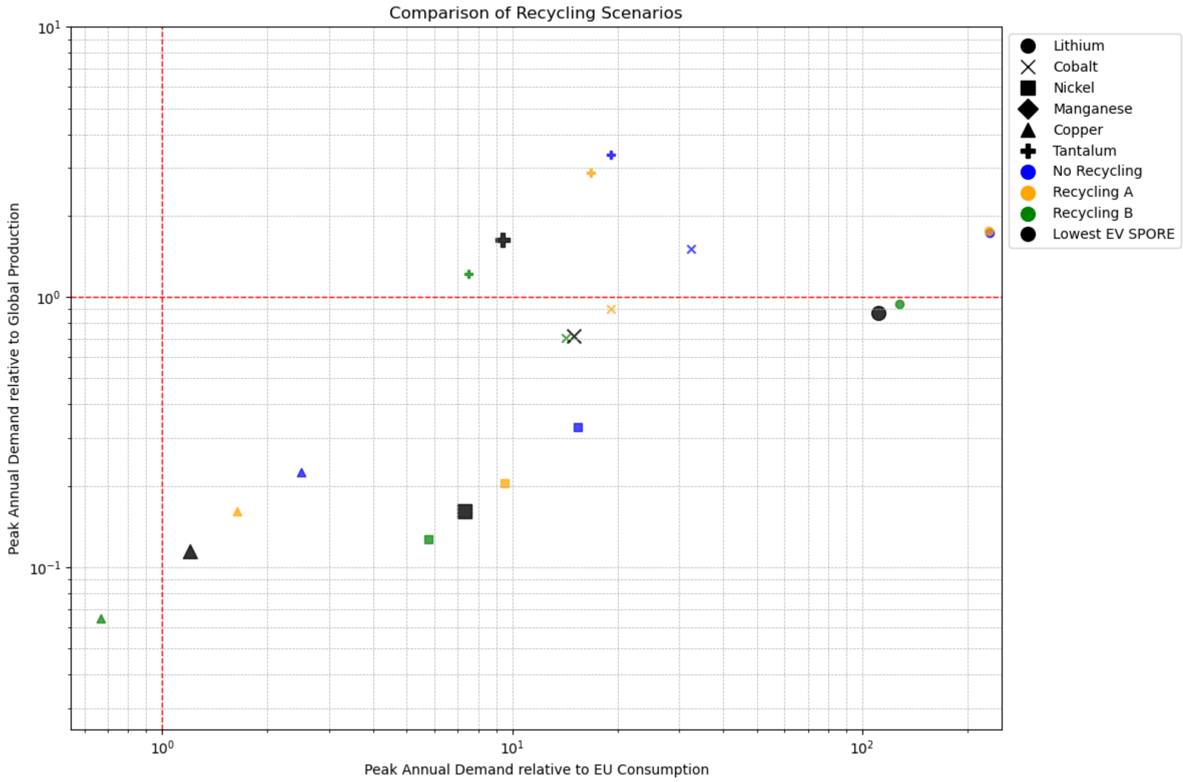


Figure 5.17: Comparison between recycling scenarios, plotting material demand for average Li-ion battery

Cumulative demand

Figure 5.18 shows the maximum and minimum demand for materials across different battery technologies. For Lithium, ASSB and LFP batteries define the extremes, with demand ranging from 9.5 to 3 million tons. With current recycling rates, the demand for primary raw material would remain the same, since Lithium has very low recycling rates of less than <1%. However, with an improvement in recycling practices, we see that the primary raw demand for lithium could be reduced to 45%.

For Cobalt, the maximum and minimum primary demand across battery chemistries is 9.67 - 2.71 million tons for NMC111 and NMC811, respectively. This reflects a potential reduction in demand of 70% by switching to NMC811. LFP and ASSB batteries eliminate Cobalt demand entirely, offering a cobalt-free path to electrification. With current recycling rates the demand for primary raw material could be reduced with a further 42% and with improved rates, up to 57%.

Nickel demand ranges from 25.7 to 17.19 million tons for NCA and NMC111, resulting in a maximum reduction of 33%. Similar to Cobalt, LFP and ASSB batteries eliminate Nickel demand. With current recycling rates, 40% of the total demand can be met with secondary supply, rising to 64% with improved recycling rates.

For Manganese, demand ranges from 15.81 to 4.74 million tons for NMC111 and NMC811, representing a potential 70% reduction. Like Cobalt and Nickel, LFP and ASSB batteries eliminate Manganese demand. Current recycling rates meet 24% of the demand, which could increase to 40% with improved rates.

Annual primary demand

The projected annual primary demand across the seven battery chemistries assuming two different recycling assumptions are shown for Lithium, Cobalt, Nickel and Manganese in Figure 5.19. The demand for these materials shows a continuous growth trend until the year 2041, after which annual demand starts to decrease since the expansion capacity starts declining at a faster rate than the scrap capacity.

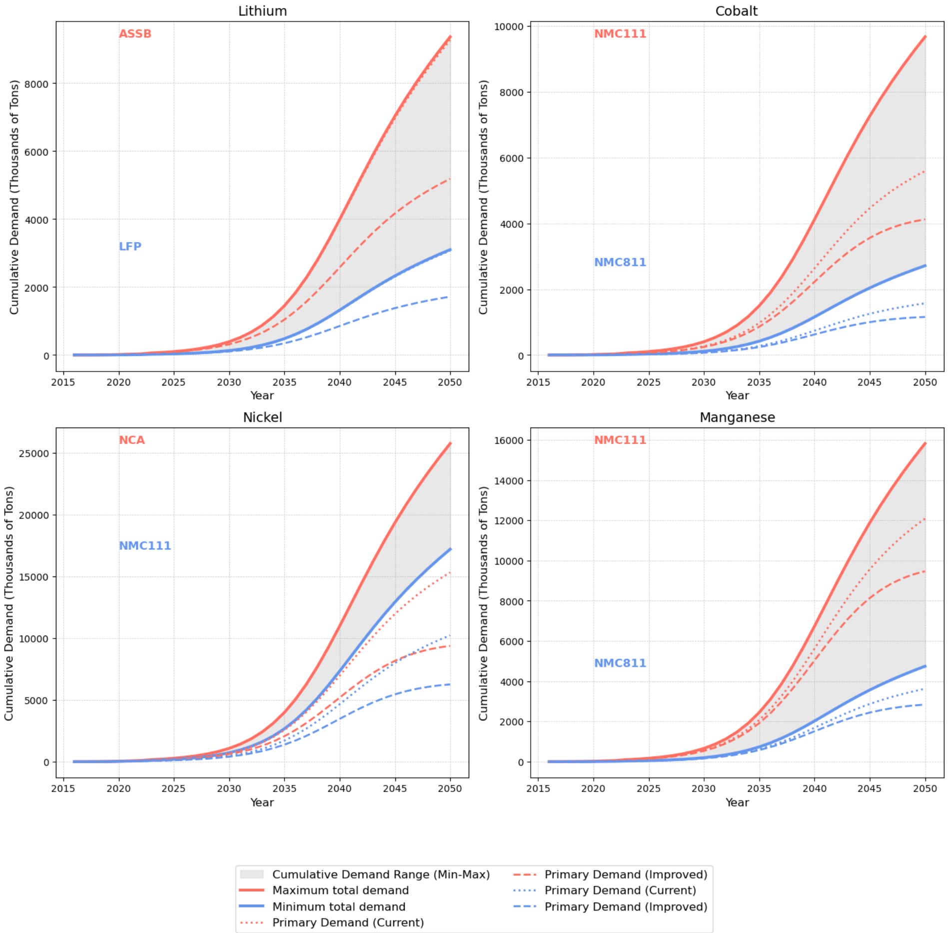


Figure 5.18: Maximum and minimum cumulative demand across battery chemistries

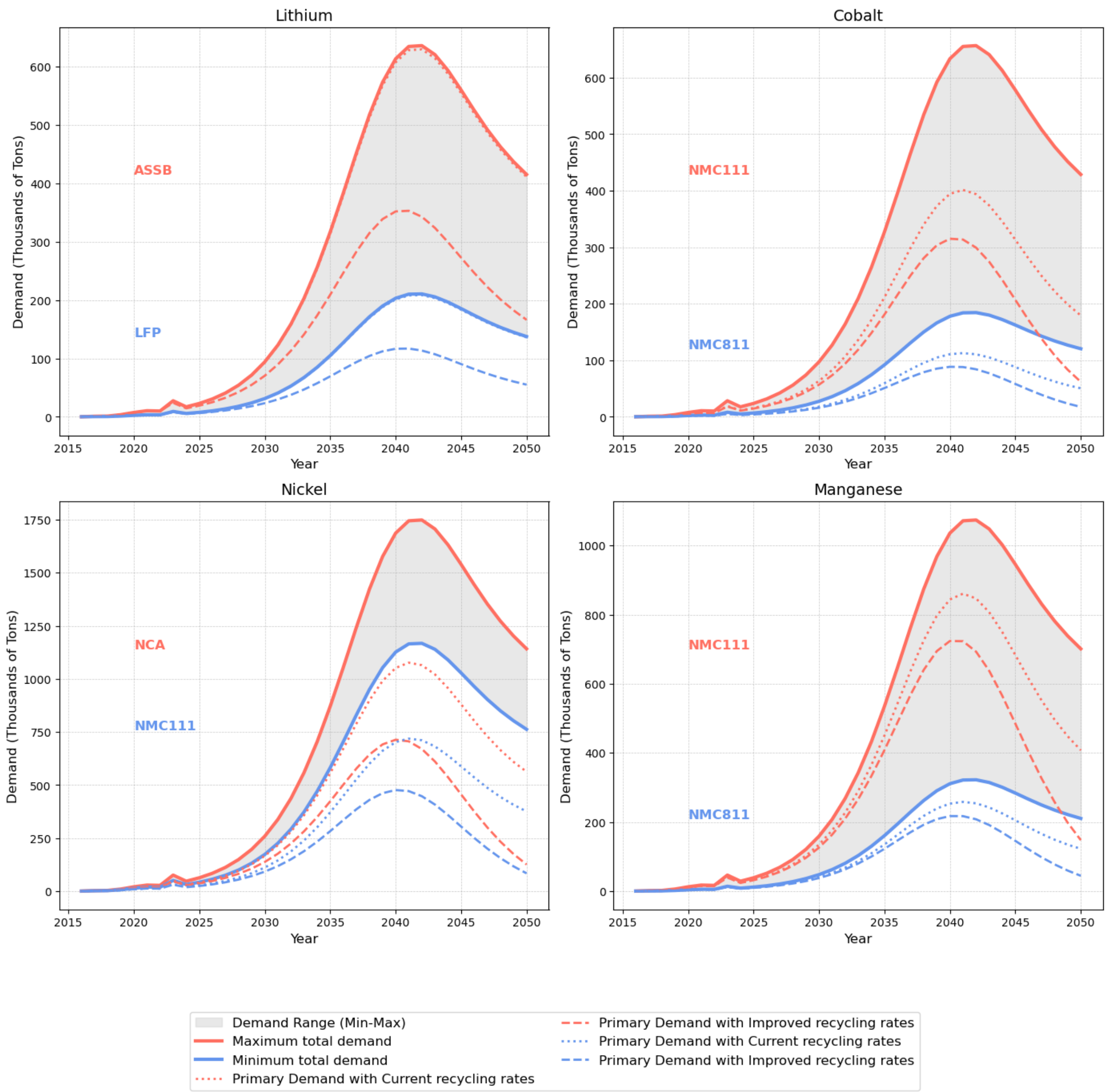


Figure 5.19: Maximum and minimum annual demand across battery chemistries

5.6. Sensitivity analysis results

5.6.1. Battery lifetime

In this section we discuss the outcomes of the sensitivity analysis by looking at three different assumptions for the lifetime of the battery.

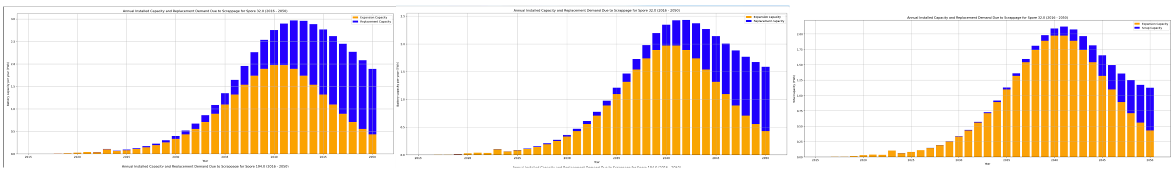
Expansion and Replacement capacity

Extending the lifetime of the battery directly influences the spread and amount of replacement capacity. Table 5.3 shows that decreasing the battery lifetime increases the replacement capacity. As a result, total battery capacity that will be needed in the time-frame 2050 increases accordingly.

Battery lifetime (years)	Total expansion capacity	Total Replacement capacity	Total battery capacity
8.5	25.7	17.4	43.1
15	25.7	10.1	35.8
21.5	25.7	6.1	31.8

Table 5.3: Replacement capacity different battery lifetimes, units given in TWh)

Figures 5.20a , 5.20b , and 5.20c show the replacement capacities over time for battery lifetimes of 8.5, 15, and 21.5 years. Longer battery lifetimes result in replacement capacities that are significantly smaller and more spread out over time, leading to a more gradual buildup. Shorter battery lifetimes, on the other hand, result in larger and faster replacement capacities, as these batteries need to be replaced more frequently. This leads to a faster and higher accumulation of replacement batteries compared to longer battery lifetimes. For the 8.5-year lifetime, the maximum replacement capacity occurs in 2047, with a total replacement capacity of 1.56 TWh and an expansion capacity of 0.89 TWh. For the 15-year lifetime, the peak replacement capacity is in 2050, with a replacement capacity of 1.15 TWh and an expansion capacity of 0.43 TWh. In the case of the 30-year lifetime, the maximum replacement capacity is also reached in 2050, with a replacement capacity of 0.65 and an expansion capacity of 0.03.



(a) Battery lifetime of 8.5 years (b) Battery lifetime of 15 years (c) Battery lifetime of 21.5 years

Figure 5.20: Comparison of scrappage capacity across different battery lifetimes: 8.5, 15, and 21.5 years

Primary demand and portion of recycled content

The general trend between battery lifetime and total demand shows that shows that total demand increases with shorter battery lifetime. The percentage increase and decrease in total demand for the materials due to the changes in battery lifetime are +20% and -8% for 8.5 years and 21.5 years respectively relative to recycling scenarios with 15 years of battery lifetime. Decreasing the battery lifetime increases overall total demand and also primary demand. The portion of recycled material of the total, however is larger for shorter battery lifetimes, since there are so secondary available material is larger.

Increasing lifetime not only reduces overall total and primary material demand, but also delays the accumulation of retired batteries, leading to a slower build up of secondary supply. While shorter battery lifetimes result in a higher portion of recycled material due to faster battery turnover, extending battery lifetime significantly reduces the strain on primary resource extraction, providing a more sustainable long-term solution for meeting future material demand.

Material	Battery Lifetime (years)	RC (Current Recycling Rates)	RC (Improved Recycling Rates)
Lithium	8.5	1	45
	15	1	45
	21.5	1	44
Cobalt	8.5	47	63
	15	42	57
	21.5	39	53
Nickel	8.5	43	68
	15	40	64
	21.5	50	58
Manganese	8.5	29	49
	15	24	40
	21.5	20	33

Table 5.4: Recycling rates for different battery lifetimes

5.6.2. Uptake of EVs

In this section we compare two different growth rates for the uptake of EVs. A faster uptake results in a steeper growth curve, reaching the maximum annual installed capacity earlier than with a more modest growth.

Expansion and Replacement capacity

A faster uptake has a similar effect to shortening battery lifetimes in terms of total replacement capacity. Given the accelerated growth, batteries reach their end of life earlier, providing secondary supply earlier than with a more moderate growth. The total replacement capacities for both growth scenarios are shown in table 5.5.

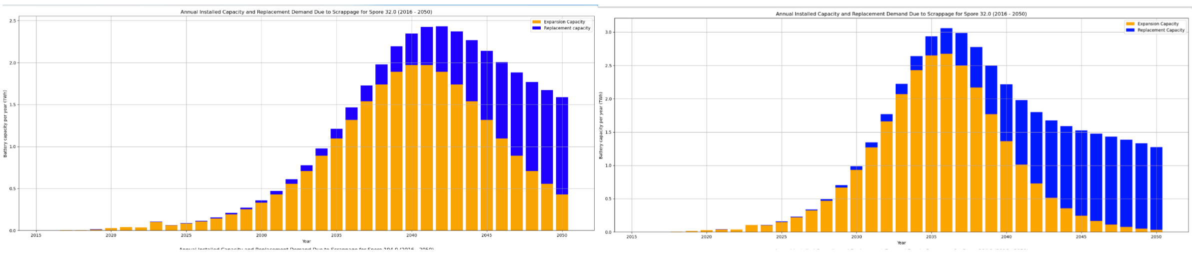
Growth scenario	Total expansion capacity (TWh)	Total Replacement capacity (TWh)	Total battery capacity (TWh)
Moderate	25.7	10.1	35.8
Aggressive	16.2	10.1	43.13

Table 5.5: Replacement capacity different growth rates

The annual replacement capacities for different growth rates are illustrated in Figures 5.21a and 5.21b for modest and aggressive growth scenarios, respectively. For the faster uptake, the annual installment follows a near-perfect Weibull distribution, with similar expansion capacities during the first and last five years, peaking in 2036. In contrast, modest growth reaches a similar peak five years later in 2041. Scrap capacity remains a small portion of total demand in the early years for batteries with a 15 year lifetime, contributing less than one-sixth of the total demand in the year with the highest annual battery demand. However, after the peak, more batteries begin reaching their end of life, and scrap capacity grows almost exponentially. By 2040, scrap capacity accounts for more than half of the total demand, a trend that continues thereafter. By 2050, annual installed capacity becomes negligible compared to the scrap capacity from retired batteries, underscoring the role recycling can play in meeting future material demand.

Primary and portion of recycled content

Relative to the modest growth, an accelerated growth results in a 17% increase in total primary demand, leading to a greater material consumption overall. The portion of secondary supply for the materials



(a) Modest growth, 15 years battery lifetime **(b)** Aggressive growth, 15 years battery lifetime

Figure 5.21: Comparison of Modest and Aggressive growth scenarios with 15 years battery lifetime

are summarized in Table 5.6. Recycled content is higher in scenarios with faster uptake. However, even with the increased recycling, the larger stock of batteries drives up the need for primary materials to meet the initial surge in demand, when available secondary material is still very low.

Material	Growth Scenario	RC (Current Recycling Rates)	RC (Improved Recycling Rates)
Lithium	Moderate	1	45
	Fast	1	59
Cobalt	Moderate	42	57
	Fast	46	61
Nickel	Moderate	40	64
	Fast	43	65
Manganese	Moderate	24	40
	Fast	28	46

Table 5.6: Recycling rates for different growth scenarios

6 Discussion

Moving away from fossil fuels and building an entirely new energy system will require an unprecedented amount of raw materials. Evaluating energy systems from a material perspective adds an additional criterion to decision-making, highlighting trade-offs and complicating the search for feasible solutions. Evaluating possible energy configurations with their material requirements provides a more complete picture of the challenges regarding the energy transition. This thesis attempted to answer the main research question: What are the trade-offs in future energy system designs for a self-sufficient carbon-neutral Europe in 2050 considering their material requirements, and to what extent can recycling and alternative technologies overcome these?

This research provides valuable insights to leave little doubt that future self-sufficient, carbon-neutral energy systems will be inherently material-intensive. While sourcing raw materials is essential for enabling a clean energy future, extracting raw materials poses significant environmental challenges. This highlights the need for policymakers to balance these competing priorities carefully.

Ultimately, this study stresses the importance of incorporating material requirements into energy system models to create realistic and sustainable pathways for Europe's energy transition. Under the special constraints presented in these energy systems, EVs stand out considerably in their material requirements. Therefore, improved recycling practices and switching to alternative battery chemistries that do not rely on critical raw materials will be key to mitigating supply chain risks and ensuring long-term sustainability.

6.1. EVs are a dealbreaker

EVs: good for the energy system, challenging for CRM

Energy configurations with high electrification nearly double the demand for CRMs compared to configurations with greater biofuel utilization. It may therefore be desirable from a material point of view to look at energy configurations that minimize the uptake of EVs. Even though reducing EVs in the energy system requires more power generation, material savings would still outweigh the additional material requirements in the power and heating sector. However, reducing EVs in the system also comes with important drawbacks. These are discussed in the following sections.

Reduced Solution Space

Reducing EVs significantly restricts the solution space for remaining energy configurations. This is because the energy model prioritizes high EV deployment, with only 15 out of 440 configurations having vehicle electrification in the 'lower' range of 52–75%. Under constraints like self-sufficiency and carbon-neutrality, this smaller solution space increases the likelihood of conflicts with other system preferences. As we saw, these solutions would all contain 100% biofuel utilization, which may be undesirable for other reasons.

Higher System Costs

Having fewer EVs would have potential economic downsides. The primary reason why EVs are so often chosen in the model instead of biofuel cars is their associated costs. The overall efficiency of a conventional car is around 14–25%, which is substantially lower than EVs, which have an efficiency of around 70–90% [64]. This difference in efficiency means that regardless of how much cheaper biofuels become, the cost of charging EVs will always remain substantially lower. The exact economic downsides are hard to quantify, but what we can say is that it requires a 10% marginal increase in cost to potentially reduce the vehicle electrification fleet from a cost-optimal solution of 100% to 52%. Previous work has shown that increasing the cost sensitivity up to 15% could further reduce vehicle electrification [14].

High Biofuel Utilization Challenges

As mentioned earlier, having fewer EVs in the energy system would require 100% biofuel utilization. Increasing reliance on biofuel could introduce additional challenges. Producing biofuel requires resources such as land with sufficient water availability, soil quality, nutrients, and proper climatic conditions. As a result, biofuel production will compete with other land uses, potentially impacting food security, rural economic sustainability, and the preservation of natural ecosystems.

6.2. Impact on Raw Material Supply Chains

In Section 5.1, we estimated the quantity of raw materials needed in the EU to achieve carbon-neutrality and self-sufficiency by 2050. We saw that EVs stood out the most compared to other technologies, requiring a significant share of total raw material demand. EVs play a central role in the energy systems of the future. They are efficient, refueling them is cheap, and they would completely phase out the use of fossil fuels in cars. In this section, we discuss the possible implications of such increases in raw material demand.

Supply Security of CRM

Ensuring supply security poses significant challenges due to the vast quantities of critical raw materials needed for the climate transition compared to today's economy. In energy configurations where vehicles are 100% electrified, the total raw material demand for CRMs like copper, cobalt, lithium, and nickel would need 10%, 30%, and 60% of global production respectively, even though Europe accounts for only 12% of global energy consumption [108]. Large increases in demand highlight potential supply bottlenecks. A supply-chain bottleneck is a point, stage, or process in the supply chain that prevents the movement of goods through the supply chain. Many reports indicate that there are no significant signs of shortages for critical raw materials used in EVs. According to the IEA, economically viable reserves have been increasing substantially in recent years [2]. Similarly, the Rocky Mountain Institute concluded that global mineral reserves are sufficient to support the full energy transition, taking into account efforts underway to increase mining capacity.

Therefore, the real bottleneck of raw material extraction is not the quantity of raw materials on Earth but the energy required to extract them and the associated environmental impact [109]. Scaling up demand for raw materials is highly inflexible in the short term since it takes 10–15 years to develop a new mine [23]. The supply for these materials could therefore be constrained in the short term, potentially causing price spikes and shortages when they are most needed.

Dependency on Countries for CRM Supply

Europe's growing demand for CRMs makes it relatively vulnerable since very few of these materials are extracted and processed within its borders. Considering that the whole world is currently undertaking a similar energy transition, global competition to secure supplies is likely to intensify, potentially worsening geopolitical tensions. Lithium-ion batteries, therefore, present challenges for Europe's strategic autonomy. China controls the majority of the global lithium-ion battery supply chain, producing almost 80% of lithium-ion batteries and controlling 60% of global cobalt and lithium refinery capacity, despite only holding 7% of the Worlds Lithium reserves [110].Europe's EV supply chain still requires time to develop, and many EVs sold under European brands are manufactured in China.

Europe accounted for just 3% of the world's battery cell production in 2020 but aims to capture 25% of the market by the end of the decade. However, achieving this goal is proving extremely difficult. For instance, Northvolt, a Swedish company that was expected to have the fifth-highest battery production capacity in Europe by 2030, recently filed for bankruptcy. It struggled to reach an annual production capacity of 1 GWh despite plans for 16 GWh. This setback highlights the challenges Europe faces in scaling up battery production to compete with major Asian producers [111].

Impact on the Environment

Extracting raw materials comes with significant environmental downsides, particularly due to mining activities. For example, lithium and cobalt mining have widespread and severe environmental impacts. Extracting one tonne of lithium consumes approximately 2 million liters of water, often in regions already experiencing water scarcity. Additionally, the chemicals used in lithium extraction can contaminate ecosystems, threatening wildlife and biodiversity [112]. A recent example is the Rhyolite Ridge Lithium mine in Nevada, which was approved by the U.S. Interior Department despite environmental protests. While the project could significantly increase U.S. lithium output, it risks driving a wildflower species to extinction [110]. This demonstrates the difficult trade-offs involved in expanding raw material extraction. As demand for these materials rises, it will be essential to adopt responsible mining practices that minimize environmental risks.

6.3. Mitigating Trade-Offs

Alternative Battery Chemistries

The fast-evolving battery landscape has the potential to reduce dependence on CRMs significantly. Depending on the battery chemistry, reductions in lithium, cobalt, nickel, and manganese usage can range from 30–70%. While LFP and ASSB batteries still rely on lithium, they eliminate the need for cobalt, nickel, and manganese. Reducing dependence on these materials could ease supply chain pressures and reduce societal and environmental impacts. However, it is unlikely that LFP batteries will completely replace NMC and NCA batteries due to their lower performance. Nevertheless, increased adoption of LFP batteries could reduce the demand for new mines to extract materials like cobalt and nickel.

Currently, NMC and NCA batteries dominate EVs in Europe, favored for their superior energy and power density. LFP batteries, known since the 1990s for being more sustainable, robust, and cheaper, have only recently gained attention from European automakers, with their market share gradually growing [113]. Barriers to their adoption include their 25–30% lower energy density compared to NMC variants, which is a concern for consumers prioritizing driving range.

Companies like Volkswagen plan to use LFP batteries in entry-level models to attract price-sensitive customers who are less concerned with range [114]. Similarly, Tesla has expressed interest in incorporating LFP batteries into its standard-range models. Lower costs could make EVs more affordable, accelerating the shift toward electric mobility while alleviating supply constraints for cobalt and nickel. However, higher-density batteries like NMC and NCA will likely still be needed for certain applications.

Next-generation all-solid-state batteries (ASSBs) offer a promising alternative, potentially replacing high-power-density batteries that rely on cobalt and nickel. ASSBs are expected to provide better thermal and performance stability, lower costs, and greater energy density than current lithium-ion batteries [115]. However, commercial production is not expected before 2025 and is more likely to scale after 2030.

Recycling

Although raw materials are finite, recycling offers a pathway to reduce reliance on resource extraction. Table 5.2 shows how secondary supply could meet portions of total material demand under two recycling scenarios in 2050, assuming a battery lifetime of 15 years. Under current recycling rates, recycled content could reduce primary raw material demand for lithium, cobalt, nickel, and manganese by 1%, 42%, 41%, and 24%, respectively. Increased recycling rates could raise these reductions to 45%, 57%, 64%, and 40%. However, even with higher recycling rates, primary raw materials will still be required to meet growing demand.

Recycling enhances supply security, reduces environmental impacts, and lowers battery production costs by over 20% [115]. Secondary material inflows become significant after 2030, primarily reducing CRM strain in the long term. In the short term, however, rapid battery expansion and limited availability of recyclable batteries make recycling less effective.

Achieving higher recycling rates will require overcoming significant technical and commercial challenges. For example, lithium recycling is not economically viable using current practices, as a significant portion of lithium is lost during the process. Additionally, the lack of standardization in lithium-ion battery designs makes sorting and disassembly costly, further reducing profitability. Recycling is currently driven by cobalt's high value, but as battery chemistries shift to those with lower cobalt content, economic incentives for recycling may diminish. To address these challenges, the EU could enforce stricter recycling regulations, such as extended producer responsibility programs, to ensure sustainable material recovery.

6.4. Limitations and Possible Future Research

This section has identified several limitations and areas for future research that would help address uncertainties.

Static Material Intensities

In this research, we relied on static life cycle inventory datasets for the material requirements of different technologies. Life cycle inventory provides a comprehensive assessment of material requirements based on current technologies. By assuming a static life cycle inventory, we do not consider possible improvements in future material demands, which may reduce the amount of materials needed. Technological innovation can also result in higher material usage. For example, wind technology development has seen an increase in turbine size and capacity, potentially leading to an increase in mass per unit of installed capacity [70]. Likewise, current market trends suggest an increase in the battery capacity of EVs, which would potentially lead to a higher material burden [48].

Without considering potential material efficiency improvements, the estimates of material demand in this study may be overly pessimistic or optimistic depending on the type of development of certain technologies. Having used the most up-to-date data on material requirements, this research effectively calculates the demand for materials in a worst-case scenario. However, future research could benefit from considering a more dynamic approach for material intensity, as it would provide a better and more accurate prediction of future material demand. Nonetheless, the findings of the study still offer a useful starting point for understanding the short-term difficulties that will be presented by green technologies.

Excluding Sub-Technologies

Material demand projections for future energy technologies in this study are based on the material requirements of technologies that currently dominate the market. However, the market share of sub-technologies is likely to evolve, including niche emerging technologies and those with high technological readiness but limited current adoption. Future research could benefit from exploring a wider set of sub-technologies to account for potential trajectories in their adoption and development.

For solar and wind technologies in particular, the ecoinvent database relies on a single sub-technology, despite the existence of multiple sub-technologies with varying material requirements. Solar PV is represented by crystalline silicon (c-Si), while wind energy is modeled using gearbox-based (GB) DFIG wind turbines. This approach provides an accurate snapshot of current market shares but does not account for projected changes in sub-technology adoption and their differing material demands. As a result, material demand for certain raw materials may be underestimated or overestimated. For instance, offshore wind is likely to increasingly adopt direct-drive generators that use permanent magnets, which require rare earth elements, such as neodymium, which could lead to significant trade-offs, especially in scenarios with reduced EV deployment. Given that lower EV configurations were associated with greater wind deployment in the model, the demand for rare earth materials could become a notable trade-off and challenge in such situations. The uptake of thin-film PV technologies could drive demand for critical raw materials such as cadmium, indium, and gallium.

Alternative Technologies for Heavy-Duty Vehicles

There are large uncertainties surrounding the adoption of EVs for heavy-duty vehicles, including trucks and long-haul transportation. In the transport sector, we only account for battery EVs or conventional cars that run on biodiesel. In reality, however, it is possible that hydrogen fuel cells will gain some market share in the future. Whereas the electrification of passenger vehicles is well underway, there is still a lot of uncertainty surrounding the electrification of heavy-duty vehicles, especially long-distance haul trucks. Experts are still divided over which technology is likely to replace conventional fossil fuel heavy-duty vehicles, given that current battery technology and charging infrastructure, in their current form, are not suitable for these vehicles. Material demand for fuel cells is similar to EVs, but would require less since the batteries used are much smaller in size. However, fuel cells would increase the demand for materials like palladium, platinum, strontium, and titanium, creating additional material trade-offs between these technologies.

Alternative System Designs Under New Constraints

Future research could expand on this work by exploring energy configurations under different constraints and comparing the resulting material requirements. For example, the model used in this study was constrained to exclude energy imports outside of Europe and relied primarily on renewable energy sources. Tweaking these hard constraints, such as allowing energy imports from outside Europe, could result in significantly different energy configurations and provide insights into trade-offs related to material dependency and energy supply diversification. Similarly, enabling the expanded use of alternative technologies, such as nuclear power, might influence the demand for critical raw materials and shift the balance between different energy system designs. Another way would be to include CRM constraints in the model, such as capping material demand at levels aligned with projected supply or the EU's strategic material goals. This could also shed light on how such limitations impact energy configurations and the potential role of recycling.

Finally, future research could explore moving further away from the cost-optimal solution to assess how an increased willingness to pay could reduce CRM demand. For instance, we saw that allowing greater biofuel use in the transport sector reduces the demand for CRM. As already seen in previous sensitivity analyses of prior work, a 15% increase in allowable costs expanded the range of vehicle electrification options [14]. Exploring these adjustments could offer a deeper understanding of the trade-offs involved in material demand across various energy configurations.

7 Conclusion

The energy transition represents one of the most significant challenges of our time. There are many possible ways to design future energy systems that are self-sufficient, carbon-neutral, and sustainable. However, the energy transition will be inherently more material-intensive, heavily relying on critical raw materials (CRMs).

This study highlights that while different energy configurations may appear equally feasible from a techno-economic perspective, their material requirements can vary significantly. This is a strong reminder to policymakers that our choices can have far-reaching implications for resource use, supply chains, and the environment. Configurations with high electrification demonstrate superior energy efficiency but require nearly double the CRM supply compared to configurations that prioritize biofuels. On the other hand, alternative technologies and improved recycling practices offer ways to reduce material demand, enhance the sustainability of electric vehicles, strengthen supply security, and boost domestic production in the EU.

In conclusion, transitioning to an energy system that relies on green technologies promises a sustainable future. While we should applaud strides toward a greener future, it is important that we acknowledge the challenges involved. We need to ensure that the energy transition occurs in a way that does not create additional burdens on the environment while trying to solve the issue of climate change. We need to address how to responsibly scale up mining and processing operations in a way that minimizes environmental and social risks. To this end, focusing on technological innovation to reduce CRM dependency and implementing systems for material collection and recovery should be central to mitigate challenges related to raw materials. Furthermore, much greener solutions might require changing the mindset of society as a whole. For example, using cars only when strictly necessary and shifting from private cars to shared solutions, such as heavily investing in public transport.

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List of Figures

List of Tables

A
Material data collection

A.0.1. Battery capacity in the transport sector

Type of Vehicle	Category	Number of Vehicles (millions)	Battery Size (kWh)	Total Battery Cap (million kWh)	Battery Cap (TWh)
Passenger Car	Light	294	80	23520	23.52
Commercial Light	Light	35	100	3500	3.50
Heavy Duty	Heavy	7.3	200	1460	1.46
Buses	Heavy	0.8	200	160	0.16
Motor	Light	338	10	3380	3.38
Total				**32020**	**32.02**

Table A.1: Battery Capacity Breakdown by Vehicle Type [116]

A.0.2. LCI Final dataset for all technologies (metric tons/TW)

Table A.2: Material Intensity by Technology (ton/TWh or ton/TWh)

Technology	Al	Br	Cd	Cr	Co	Cu	Ga	Au	Fe	La	Pb	Li	Mg	Mn	Mo	Nd	Ni	Pd	Pt	Re	Rh	Ag	Ta	Te	Sn	Ti	Zn	Zr
Battery LFP	1773104	4	17	44306	1368	925334	547	83	1704094	579	31276	86563	33384	20332	22675	460	56267	2	2	2	0	873	3326	143	7363	10882	142861	1457
Battery NMC111	2183234	4	17	313835	270000	2746235	431	77	28506474	369	34965	112920	1271396	441522	21074	279	480000	4	2	2	0	817	2959	133	6844	9770	154731	1519
Battery NMC811	1834301	3	15	201072	75762	1951485	421	74	17551536	363	29908	94649	768198	246670	19956	281	688583	6	3	2	0	777	2896	126	6627	9021	133684	1417
Battery NCA	2557670	5	21	304537	98396	2876911	564	103	26935347	438	41639	113485	1185522	163671	27371	336	718971	8	5	3	1	1074	3964	173	9294	12380	185618	1945
Average Li-ion battery	2087077	4	17.5	215937	111381	2124991	490	85	18674362	437	34447	132000	814625	218048	22769	339	485955	5	3	2	0.25	885	3286	143	7532	10513	154223	1584
Biofuel Boiler	70	0	0	73	0	114	0	0	20207	0	4	0	8	370	3	0	314	0	0	0	0	0	0	0	1	20	18	1
Biofuel to diesel	35030	9	1	9266	112	31028	11	1	1707740	130	2682	0	3040	22675	793	74	19165	0	0	0	0	20	4	4	62	7441	12215	920
CCGT	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat Pump	75	0	0	57	2	1830	0	0	10759	0	31	0	45	144	41	0	137	0	0	0	0	0	0	0	0	13	140	1
Nuclear	9	0	0	14	0	7	0	0	166	0	1	0	1	2	0	0	9	0	0	0	0	0	0	0	0	1	4	0
Open field PV	32491681	198	322	713530	6791	4436383	10064	589	95019171	3152	603693	2	375760	1559740	99017	2442	1146129	6	3	10	0	22803	139	616	10108	376795	2772372	48179
Roof Mounted PV	25533877	199	258	482432	13768	9868011	7886	890	50886673	2097	490260	2	409157	1073037	221663	1593	959304	14	7	23	1	25063	14995	1393	73309	326781	2234894	46110
DC transmission	2930	0	0	5	0	32	1	0	13372	0	39	0	19	104	1	0	29	0	0	0	0	0	0	0	0	10	181	1
Wind onshore	967284	29	62	1549773	4403	1587948	287	49	129229232	2791	115149	1	109937	2163347	38132	2227	2517402	3	2	4	0	801	167	220	2673	94197	531084	5885
Wind offshore	1175032	44	144	5721322	7899	2696088	339	19	144152184	3010	300209	0	574413	1971716	60947	2411	5066702	4	2	6	0	3012	7	368	927	121371	1274157	8631
DAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electrolysis	214332	2	12	419144	418	134924	32	187	2041386	29	21936	0	15687	91576	2437	22	293222	1	3	0	0	1090	792	15	11231	77920	100936	622
Biofuel to methane	17682594	213	20	182964	1848	543460	5482	18	12127580	869	38962	0	47124	159567	14122	484	248034	3	2	1	0	320	62	75	1289	31878	177237	3373

A.0.3. Battery material intensities in the literature

Table A.3: Material Intensity of Different Battery Chemistries (kg/kWh)

Chemistry	Material Intensity (kg/kWh)					Sources
	Lithium	Cobalt	Nickel	Manganese	Iron	
NCA	0.063	0.060	0.770	0.118	-	
	0.095	0.065	0.725	-	-	
	0.100	0.125	0.661	0.000	-	
	0.198	0.140	0.720	-	-	
Average NCA	0.11	0.10	0.72	0.04	-	[50, 79, 80]
NMC111	0.067	0.080	0.750	0.643	-	
	0.120	0.330	0.320	0.312	-	
	0.150	0.394	0.370	0.370	-	
Average NMC111	0.11	0.27	0.48	0.44	-	[50, 79, 80]
NMC532	-	-	-	-	-	
	0.121	0.205	0.512	0.191	-	
Average NMC532	0.137	0.218	0.503	0.276	-	[50, 79, 80]
NMC622	0.104	0.176	0.525	0.164	-	
	0.140	0.214	0.620	0.200	-	
Average NMC622	0.120	0.195	0.573	0.182	-	[50, 79, 80]
NMC811	0.060	0.050	0.660	0.230	-	
	0.096	0.082	0.655	0.076	-	
Average NMC811	0.090	0.080	0.690	0.130	-	[50, 79, 80]
LFP	0.060	-	-	0.040	0.691	
	0.086	-	-	-	0.000	
Average LFP	0.09	-	-	0.01	0.00	[50, 79, 80]
ASSB	0.111	-	-	-	-	
Overall Average	0.26	0.00	0.00	0.00	-	[50, 79, 80]

A.0.4. Global production and European consumption

Table A.4: Annual and Global Production of Various Materials (2016-2023) in Metric Tons/Year. Sources: [96], [97]

Material	Global Production (2023)	Global Production (2016-2020)	EU Consumption (2016-2020)
Aluminum/bauxite (Al ore)	390,000,000	336,000,000	16,146,077
Bromine	400,000	-	-
Cadmium	23,000	26,100	2,236
Chromium	41,000,000	13,000,000	471,288
Cobalt	230,000	136,000	10,946
Copper	22,000,000	20,500,000	2,065,554
REE (Dy, Pr, La)	350,000	-	-
Gallium	610	301	33
Gold	3,000	3,300	76,644,797
Iron and steel	1,515,358,230	1,900,000,000	76,644,797
Iridium	990	845	76
Lanthanum	-	-	-
Lead	4,500,000	4,640,000	270,998
Lithium	180,000	76,200	1,377
Magnesium	22,000,000	983,000	120,520
Manganese	20,000,000	18,900,000	270,393
Molybdenum	260,000	276,000	9,018
Neodymium	-	26,845	119
Nickel	3,600,000	2,330,000	78,084
Palladium (PGMs)	210	213	72
Platinum (PGMs)	180	185	72
Rhenium	560	N/A	N/A
Rhodium	-	23	N/A
Silver	26,000	27,500	19,514
Tantalum	2,400	1,533	404
Tellurium	640	540	507
Tin	290,000	300,400	49,000
Titanium	330,000	449,700	425,694
Zinc	13,000,000	12,140,000	1,900,000
Zirconium	1,400	928,830	147,666

A.0.5. Cumulative and annual demand across the solution space

*Annual demand is calculated assuming a linear growth for technologies in the time frame (2023-2050). Peak annual demand using this assumption is the same for all years.

Table A.5: Cumulative and Annual Demand Range Across Energy Configurations in Million Tons

Material	Cumulative Demand		Annual Demand	
	Maximum	Minimum	Maximum	Minimum
Aluminium	232.69	60.35	8.62	2.24
Bromine	0.00134	0.00022	0.00005	0.00001
Cadmium	0.00230	0.00071	0.00009	0.00003
Chromium	18.30	8.97	0.68	0.33
Cobalt	3.97	1.97	0.15	0.07
Copper	102.71	46.19	3.80	1.71
Gallium	0.06771	0.01443	0.00251	0.00053
Gold	0.00695	0.00255	0.00026	0.00009
Iron	1167.68	780.36	43.24	28.90
Lanthanum	0.03044	0.01914	0.00113	0.00071
Lead	4.37	1.38	0.16	0.05
Lithium	3.60	1.79	0.13	0.07
Magnesium	24.74	12.08	0.92	0.45
Manganese	16.02	11.04	0.59	0.41
Molybdenum	1.63	0.71	0.06	0.03
Neodymium	0.0236	0.0150	0.00087	0.00056
Nickel	25.92	16.46	0.96	0.61
Palladium	0.000200	0.000095	0.000007	0.000004
Platinum	0.000116	0.000057	0.000004	0.000002
Rhenium	0.000165	0.000071	0.000006	0.000003
Rhodium	0.000010	0.000004	0.0000004	0.0000001
Silver	0.1699	0.0275	0.00629	0.00102
Tantalum	0.1360	0.0586	0.00504	0.00217
Tellurium	0.01020	0.00438	0.00038	0.00016
Tin	0.4682	0.1883	0.01734	0.00697
Titanium	2.5612	0.6780	0.09486	0.02511
Zinc	19.92	6.22	0.74	0.23
Zirconium	0.3331	0.0653	0.01234	0.00242

Table A.6: Demand Relative to EU Consumption, Global Production, and Reserves (Max - Min)

Material	Annual Demand		Cumulative Demand	
	/ EU Consumption	/ Global Production	/ Global Production	/ Reserves
Aluminum	0.53 - 0.14	0.02 - 0.01	0.60 - 0.15	N/A
Bromine	0.00 - 0.00	N/A	N/A	N/A
Cadmium	0.04 - 0.01	0.00 - 0.00	0.10 - 0.03	N/A
Chromium	1.44 - 0.70	0.02 - 0.01	0.45 - 0.22	N/A
Cobalt	13.43 - 6.67	0.64 - 0.32	17.25 - 8.57	0.36 - 0.18
Copper	1.84 - 0.83	0.17 - 0.08	4.67 - 2.10	0.10 - 0.05
Gallium	75.54 - 16.10	4.11 - 0.88	111.01 - 23.65	0.06 - 0.01
Gold	8.58 - 3.15	0.09 - 0.03	2.32 - 0.85	0.12 - 0.04
Iron	0.56 - 0.38	0.002 - 0.001	0.06 - 0.04	N/A
Lanthanum	0.00 - 0.00	N/A	N/A	N/A
Lead	0.60 - 0.19	0.04 - 0.01	0.97 - 0.31	N/A
Lithium	96.86 - 48.16	0.74 - 0.37	20.01 - 9.95	0.13 - 0.06
Magnesium	7.60 - 3.71	0.04 - 0.02	1.12 - 0.55	0.01 - 0.01
Manganese	2.20 - 1.51	0.03 - 0.02	0.80 - 0.55	N/A
Molybdenum	6.68 - 2.90	0.23 - 0.10	6.25 - 2.71	0.11 - 0.05
Neodymium	7.33 - 4.67	N/A	N/A	N/A
Nickel	12.30 - 7.81	0.27 - 0.17	7.20 - 4.57	0.20 - 0.13
Palladium	0.10 - 0.05	0.04 - 0.02	0.95 - 0.45	N/A
Platinum	0.06 - 0.03	0.02 - 0.01	0.65 - 0.32	N/A
Rhenium	0.00 - 0.00	N/A	N/A	N/A
Rhodium	0.00 - 0.00	N/A	N/A	N/A
Silver	0.32 - 0.05	0.24 - 0.04	6.53 - 1.06	N/A
Tantalum	12.48 - 5.38	2.10 - 0.90	56.65 - 24.41	0.35 - 0.15
Tellurium	0.74 - 0.32	0.59 - 0.25	15.93 - 6.84	N/A
Tin	0.35 - 0.14	0.06 - 0.02	1.61 - 0.65	N/A
Titanium	0.22 - 0.06	0.29 - 0.08	7.76 - 2.05	N/A
Zinc	0.39 - 0.12	0.06 - 0.02	1.53 - 0.48	N/A
Zirconium	0.08 - 0.02	0.01 - 0.002	0.24 - 0.05	N/A

B
Recycling extra's

B.1. S-growth projections for 100% vehicle electrification

B.1.1. Expansion and replacement capacities for EVs: S-growth and linear growth

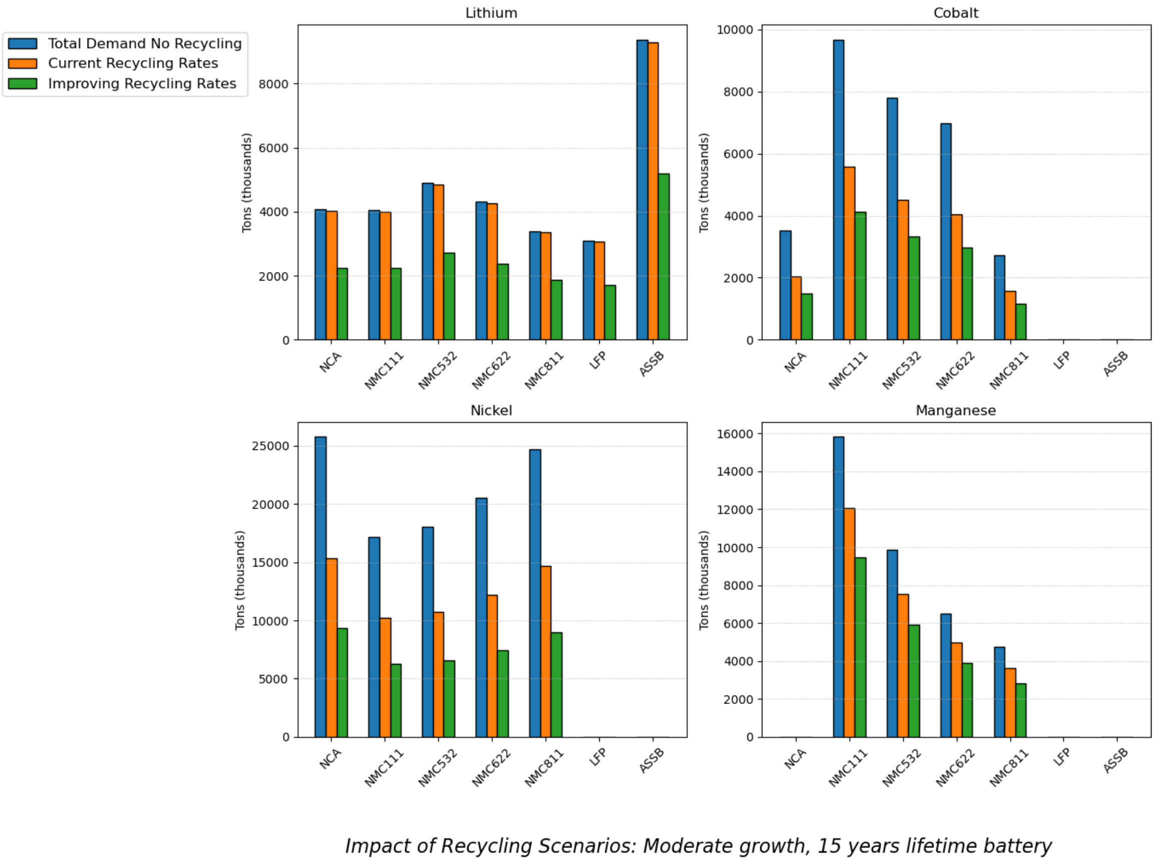


Figure B.1: Primary raw demand comparison across different recycling rates

Table B.1: Annual Installed Capacity, EV Scrap per Year, and Total Battery Demand Comparison (S-Growth vs. Linear)

Year	S-Growth			Linear		
	Inst. Cap. (TWh)	EV Scrap (TWh)	Total Demand (TWh)	Inst. Cap. (TWh)	EV Scrap (TWh)	Total Demand (TWh)
2016	0.00	0.00	0.00	0.00	0.00	0.00
2017	0.00	0.00	0.00	0.00	0.00	0.00
2018	0.00	0.00	0.00	0.00	0.00	0.00
2019	0.01	0.00	0.01	0.01	0.00	0.01
2020	0.03	0.00	0.03	0.03	0.00	0.03
2021	0.04	0.00	0.04	0.04	0.00	0.04
2022	0.04	0.00	0.04	0.04	0.00	0.04
2023	0.10	0.00	0.10	0.10	0.00	0.10
2024	0.06	0.00	0.06	0.99	0.00	0.99
2025	0.08	0.01	0.09	0.99	0.01	1.00
2026	0.11	0.01	0.12	0.99	0.03	1.02
2027	0.14	0.01	0.16	0.99	0.06	1.05
2028	0.19	0.02	0.21	0.99	0.09	1.09
2029	0.25	0.02	0.27	0.99	0.13	1.13
2030	0.33	0.03	0.36	0.99	0.18	1.17
2031	0.43	0.04	0.47	0.99	0.23	1.22
2032	0.56	0.05	0.61	0.99	0.28	1.28
2033	0.71	0.07	0.78	0.99	0.34	1.33
2034	0.89	0.09	0.98	0.99	0.40	1.39
2035	1.10	0.11	1.21	0.99	0.45	1.44
2036	1.32	0.15	1.47	0.99	0.51	1.50
2037	1.54	0.19	1.73	0.99	0.56	1.55
2038	1.74	0.24	1.98	0.99	0.61	1.60
2039	1.89	0.30	2.19	0.99	0.66	1.65
2040	1.97	0.37	2.35	0.99	0.70	1.69
2041	1.97	0.45	2.43	0.99	0.74	1.74
2042	1.89	0.54	2.43	0.99	0.78	1.77
2043	1.74	0.64	2.37	0.99	0.81	1.80
2044	1.54	0.73	2.27	0.99	0.84	1.83
2045	1.32	0.82	2.14	0.99	0.87	1.86
2046	1.10	0.91	2.01	0.99	0.89	1.88
2047	0.89	0.99	1.88	0.99	0.91	1.90
2048	0.71	1.06	1.77	0.99	0.92	1.92
2049	0.56	1.12	1.67	0.99	0.94	1.93
2050	0.43	1.16	1.59	0.99	0.95	1.94

B.1.2. Survival ratio and scrappage rates

B.2. Improved Recycling rates

Table B.2: Age-dependent survival ratio and scrappage rates for electric vehicles

Age	Survival Ratio (-)	Scrappage u(t) (%)
0	1.000	0.00
1	0.996	0.88
2	0.982	1.75
3	0.961	2.56
4	0.931	3.31
5	0.895	3.98
6	0.852	4.54
7	0.804	5.00
8	0.752	5.35
9	0.698	5.58
10	0.641	5.70
11	0.584	5.71
12	0.527	5.62
13	0.472	5.45
14	0.418	5.21
15	0.368	4.91
16	0.321	4.56
17	0.277	4.18
18	0.237	3.79
19	0.201	3.39
20	0.169	3.00
21	0.141	2.63
22	0.116	2.28
23	0.095	1.95
24	0.077	1.65
25	0.062	1.38
26	0.050	1.15
27	0.039	0.94
28	0.031	0.76
29	0.024	0.61
30	0.018	0.49

Year	Cobalt_RR	Cobalt_RC	Lithium_RR	Lithium_RC	Nickel_RR	Nickel_RC	Manganese_RR	Manganese_RC
2016	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2017	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2018	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2019	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2020	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2021	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2022	0.68	0.32	0.01	0.01	0.57	0.34	0.53	0.12
2023	0.75	0.35	0.01	0.01	0.66	0.39	0.63	0.14
2024	0.76	0.36	0.03	0.03	0.67	0.40	0.64	0.15
2025	0.76	0.36	0.05	0.05	0.68	0.41	0.65	0.15
2026	0.77	0.36	0.07	0.07	0.70	0.42	0.66	0.15
2027	0.78	0.37	0.09	0.09	0.71	0.43	0.68	0.15
2028	0.79	0.37	0.11	0.11	0.72	0.44	0.70	0.16
2029	0.80	0.38	0.13	0.13	0.73	0.44	0.71	0.16
2030	0.81	0.38	0.15	0.15	0.74	0.45	0.72	0.16
2031	0.82	0.39	0.17	0.17	0.76	0.45	0.74	0.17
2032	0.83	0.39	0.19	0.19	0.77	0.45	0.75	0.17
2033	0.84	0.40	0.21	0.21	0.78	0.48	0.77	0.17
2034	0.85	0.40	0.23	0.23	0.80	0.48	0.78	0.18
2035	0.87	0.40	0.25	0.25	0.81	0.48	0.79	0.18
2036	0.87	0.41	0.27	0.27	0.82	0.49	0.81	0.18
2037	0.88	0.41	0.29	0.29	0.84	0.50	0.82	0.19
2038	0.89	0.41	0.31	0.31	0.84	0.51	0.83	0.19
2039	0.90	0.42	0.33	0.33	0.87	0.51	0.86	0.19
2040	0.91	0.43	0.35	0.35	0.88	0.52	0.88	0.20
2041	0.92	0.43	0.37	0.37	0.89	0.53	0.88	0.20
2042	0.92	0.43	0.39	0.39	0.89	0.53	0.90	0.20
2043	0.93	0.44	0.41	0.41	0.91	0.54	0.90	0.20
2044	0.94	0.44	0.43	0.43	0.92	0.55	0.91	0.21
2045	0.95	0.45	0.45	0.45	0.92	0.56	0.94	0.21
2046	0.96	0.45	0.47	0.47	0.94	0.57	0.94	0.21
2047	0.97	0.46	0.49	0.49	0.96	0.57	0.96	0.22
2048	0.98	0.46	0.51	0.51	0.97	0.58	0.97	0.22
2049	0.99	0.47	0.53	0.53	0.99	0.59	0.99	0.22
2050	1.00	0.47	0.60	0.60	1.00	0.60	1.00	0.23

Table B.3: Improved recycling rates over Time

B.3. Material demand with and without recycling

B.3.1. Lithium

Table B.4: Demand Comparison for Lithium, units given in kt

year	Lithium total Demand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	0.40	0.39	0.39
2018	0.56	0.55	0.55
2019	1.77	1.75	1.75
2020	3.69	3.65	3.65
2021	5.20	5.15	5.15
2022	4.94	4.89	4.89
2023	13.83	13.69	12.01
2024	8.56	8.48	7.29
2025	11.51	11.39	9.60
2026	15.41	15.25	12.58
2027	20.55	20.35	16.42
2028	27.30	27.03	21.35
2029	36.11	35.74	27.60
2030	47.47	47.00	35.47
2031	61.97	61.35	45.22
2032	80.17	79.37	57.11
2033	102.52	101.49	71.25
2034	129.20	127.91	87.55
2035	159.90	158.30	105.58
2036	193.57	191.64	124.46
2037	228.30	226.02	142.82
2038	261.33	258.72	158.95
2039	289.46	286.56	171.04
2040	309.76	306.66	177.66
2041	320.38	317.17	178.19
2042	321.09	317.88	173.01
2043	313.32	310.18	163.39
2044	299.58	296.59	151.03
2045	282.71	279.88	137.61
2046	265.12	262.47	124.45
2047	248.49	246.00	112.33
2048	233.64	231.30	101.56
2049	220.76	218.55	92.13
2050	209.61	207.52	83.85

B.3.2. Cobalt

Table B.5: Demand Comparison for Cobalt, units given in kt

year	Cobalt total Demand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	0.43	0.29	0.29
2018	0.60	0.41	0.41
2019	1.91	1.30	1.30
2020	4.00	2.71	2.71
2021	5.63	3.79	3.79
2022	5.35	3.57	3.57
2023	14.98	10.06	9.58
2024	9.28	6.11	5.76
2025	12.47	8.18	7.65
2026	16.69	10.93	10.13
2027	22.26	14.55	13.38
2028	29.58	19.31	17.61
2029	39.11	25.51	23.07
2030	51.43	33.51	30.04
2031	67.14	43.71	38.84
2032	86.85	56.47	49.75
2033	111.06	72.10	62.94
2034	139.96	90.68	78.40
2035	173.22	111.91	95.79
2036	209.70	134.98	114.29
2037	247.33	158.39	132.54
2038	283.11	180.07	148.70
2039	313.58	197.64	160.73
2040	335.57	208.92	166.85
2041	347.07	212.60	166.07
2042	347.85	208.60	158.49
2043	339.43	198.10	145.28
2044	324.55	183.10	128.28
2045	306.27	165.88	109.53
2046	287.22	148.39	90.75
2047	269.19	132.03	73.18
2048	253.11	117.56	57.52
2049	239.16	105.21	44.03
2050	227.08	94.89	32.68

B.3.3. Nickel

Table B.6: Demand Comparison for Nickel, units given in kt

year	Nickel total Demand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	1.48	0.98	0.98
2018	2.09	1.38	1.38
2019	6.61	4.36	4.36
2020	13.82	9.09	9.09
2021	19.46	12.76	12.76
2022	18.49	12.04	12.04
2023	51.75	33.87	31.10
2024	32.05	20.71	18.70
2025	43.07	27.77	24.72
2026	57.66	37.13	32.57
2027	76.91	49.47	42.77
2028	102.18	65.67	55.95
2029	135.12	86.79	72.84
2030	177.66	114.04	94.28
2031	231.93	148.78	121.10
2032	300.03	192.31	154.07
2033	383.67	245.67	193.62
2034	483.51	309.19	239.57
2035	598.40	381.97	290.73
2036	724.43	461.30	344.54
2037	854.40	542.29	396.87
2038	978.01	618.03	442.31
2039	1083.28	680.53	475.01
2040	1159.25	722.57	490.04
2041	1198.98	739.66	484.87
2042	1201.65	731.43	460.17
2043	1172.57	701.69	419.60
2044	1121.17	657.00	368.64
2045	1058.01	604.74	313.09
2046	992.20	551.31	257.83
2047	929.94	501.16	206.23
2048	874.37	456.68	160.11
2049	826.18	418.56	120.10
2050	784.46	386.37	86.05

B.3.4. Manganese

Table B.7: Demand Comparison for Manganese, units given in kt

year	Manganese total Demand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	0.52	0.45	0.45
2018	0.73	0.64	0.64
2019	2.30	2.02	2.02
2020	4.81	4.21	4.21
2021	6.77	5.91	5.91
2022	6.44	5.56	5.56
2023	18.02	15.68	15.26
2024	11.16	9.55	9.21
2025	14.99	12.79	12.27
2026	20.08	17.09	16.31
2027	26.78	22.76	21.61
2028	35.58	30.21	28.53
2029	47.05	39.92	37.50
2030	61.86	52.44	49.00
2031	80.75	68.40	63.56
2032	104.47	88.39	81.68
2033	133.58	112.87	103.69
2034	168.35	141.99	129.61
2035	208.35	175.30	158.92
2036	252.23	211.52	190.29
2037	297.48	248.37	221.47
2038	340.52	282.62	249.39
2039	377.17	310.54	270.57
2040	403.63	328.79	281.95
2041	417.46	335.29	281.72
2042	418.39	329.91	269.92
2043	408.26	314.46	248.39
2044	390.37	292.03	220.21
2045	368.38	266.11	188.76
2046	345.46	239.74	157.02
2047	323.78	215.04	127.12
2048	304.44	193.17	100.30
2049	287.66	174.49	77.08
2050	273.13	158.81	57.44

B.3.5. Copper

Table B.8: Demand Comparison for Copper, units given in kt

year	Copper total Demand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	6.37	4.33	4.33
2018	8.98	6.10	6.10
2019	28.45	19.33	19.33
2020	59.43	40.37	40.37
2021	83.69	56.79	56.79
2022	79.53	53.84	53.84
2023	222.59	150.94	128.82
2024	137.85	93.08	77.28
2025	185.26	125.00	101.07
2026	248.03	167.27	131.65
2027	330.85	223.05	170.73
2028	439.55	296.25	220.39
2029	581.25	391.66	282.93
2030	764.24	514.87	360.85
2031	997.68	671.99	456.47
2032	1290.63	869.08	571.53
2033	1650.39	1110.97	706.41
2034	2079.87	1399.46	859.14
2035	2574.06	1730.95	1024.23
2036	3116.20	2093.85	1191.77
2037	3675.30	2466.87	1347.29
2038	4207.00	2819.68	1473.16
2039	4659.84	3117.18	1551.83
2040	4986.63	3327.28	1570.31
2041	5157.55	3429.82	1524.25
2042	5169.02	3422.69	1419.54
2043	5043.92	3321.83	1270.52
2044	4822.81	3155.38	1095.60
2045	4551.15	2954.82	912.45
2046	4268.05	2747.35	734.65
2047	4000.22	2551.67	570.57
2048	3761.19	2377.45	423.94
2049	3553.89	2227.04	295.31
2050	3374.43	2098.05	183.47

B.3.6. Tantalum

Table B.9: Demand Comparison for Tantalum, units given in kt

year	Tantalum totalDemand	Primary Demand (Recycled A)	Primary Demand (Recycled B)
2016	0.00	0.00	0.00
2017	0.01	0.01	0.01
2018	0.01	0.01	0.01
2019	0.04	0.04	0.04
2020	0.09	0.08	0.08
2021	0.13	0.11	0.11
2022	0.12	0.11	0.11
2023	0.34	0.30	0.26
2024	0.21	0.18	0.15
2025	0.29	0.25	0.20
2026	0.38	0.33	0.26
2027	0.51	0.44	0.34
2028	0.68	0.59	0.44
2029	0.90	0.78	0.57
2030	1.18	1.02	0.73
2031	1.54	1.34	0.92
2032	2.00	1.73	1.15
2033	2.55	2.21	1.43
2034	3.22	2.78	1.74
2035	3.98	3.44	2.08
2036	4.82	4.17	2.42
2037	5.68	4.91	2.75
2038	6.51	5.62	3.01
2039	7.21	6.22	3.18
2040	7.71	6.65	3.23
2041	7.98	6.86	3.14
2042	7.99	6.86	2.93
2043	7.80	6.68	2.64
2044	7.46	6.37	2.28
2045	7.04	5.99	1.91
2046	6.60	5.59	1.54
2047	6.19	5.22	1.20
2048	5.82	4.89	0.90
2049	5.50	4.60	0.63
2050	5.22	4.35	0.39

C Sensitivity analysis

C.1. Scenario 1: Modest growth, optimistic battery lifetime

C.2. Base case | battery lifetime 15 year

C.2.1. Cumulative demand

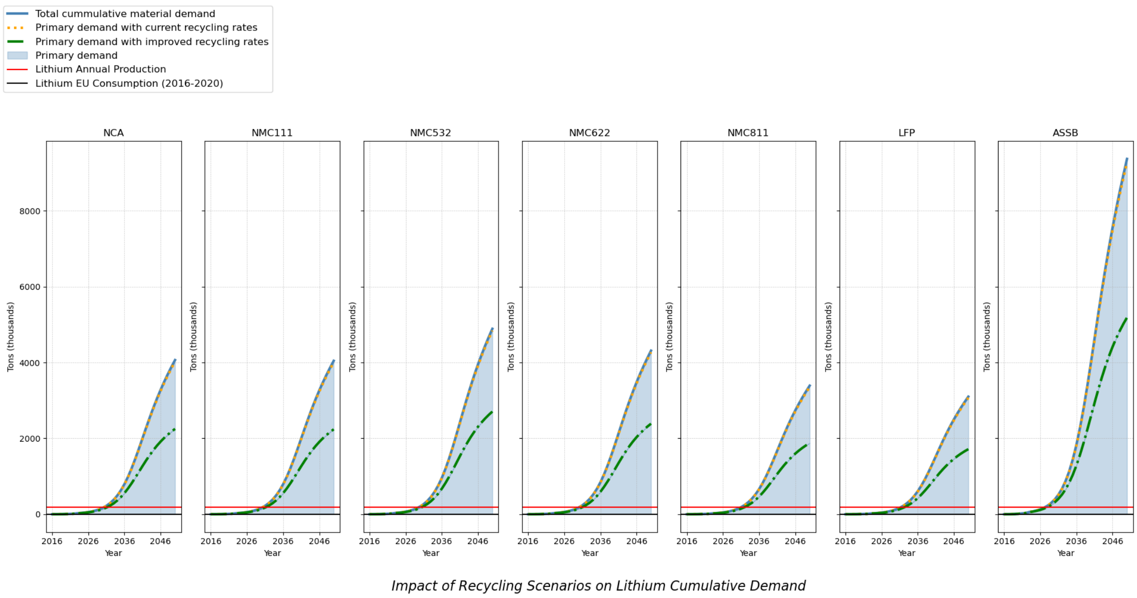


Figure C.1: Cumulative demand Lithium

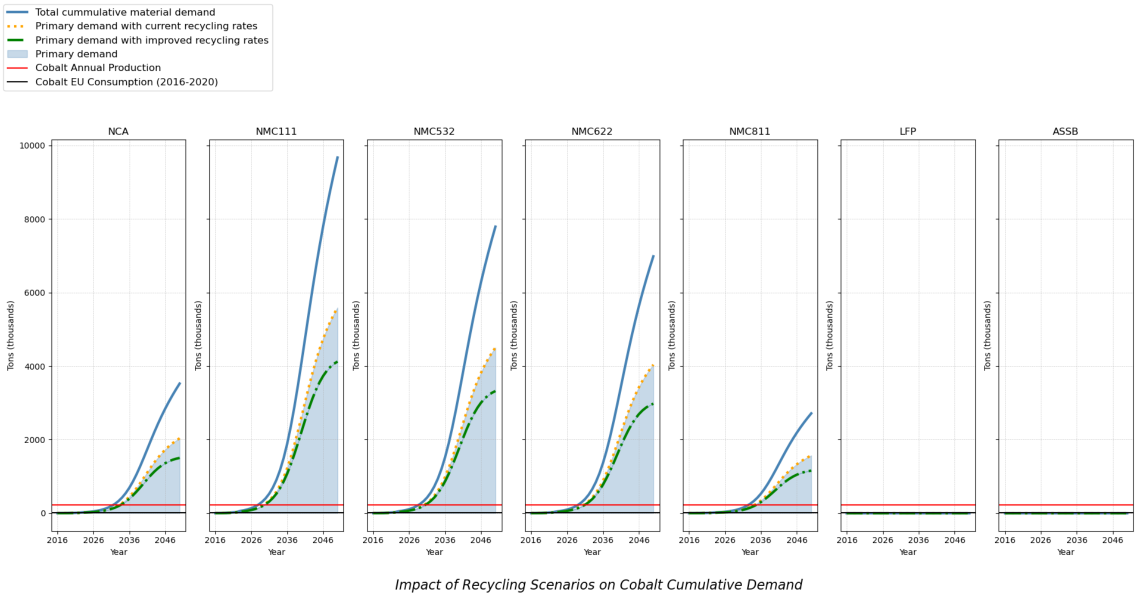


Figure C.2: Cumulative demand Cobalt

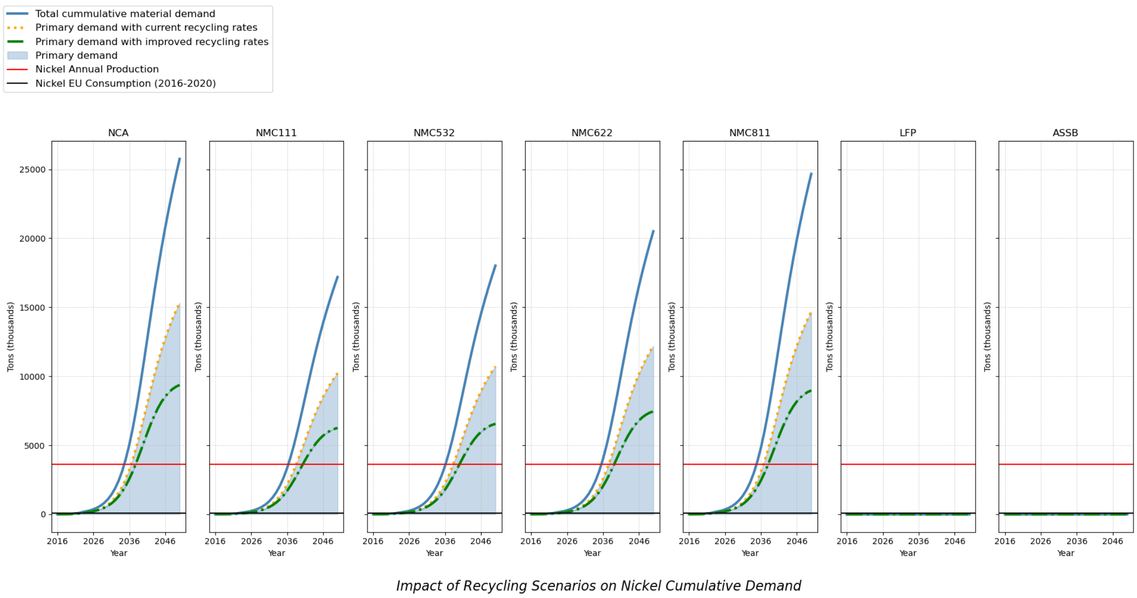


Figure C.3: Cumulative demand Nickel

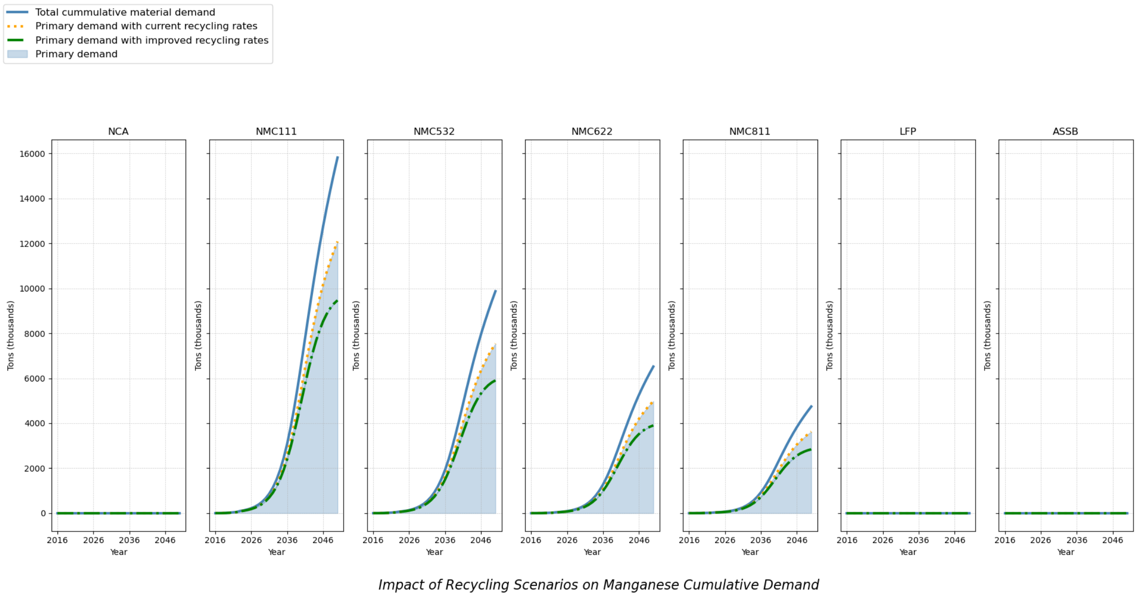


Figure C.4: Cumulative demand Manganese

C.2.2. Annual demand

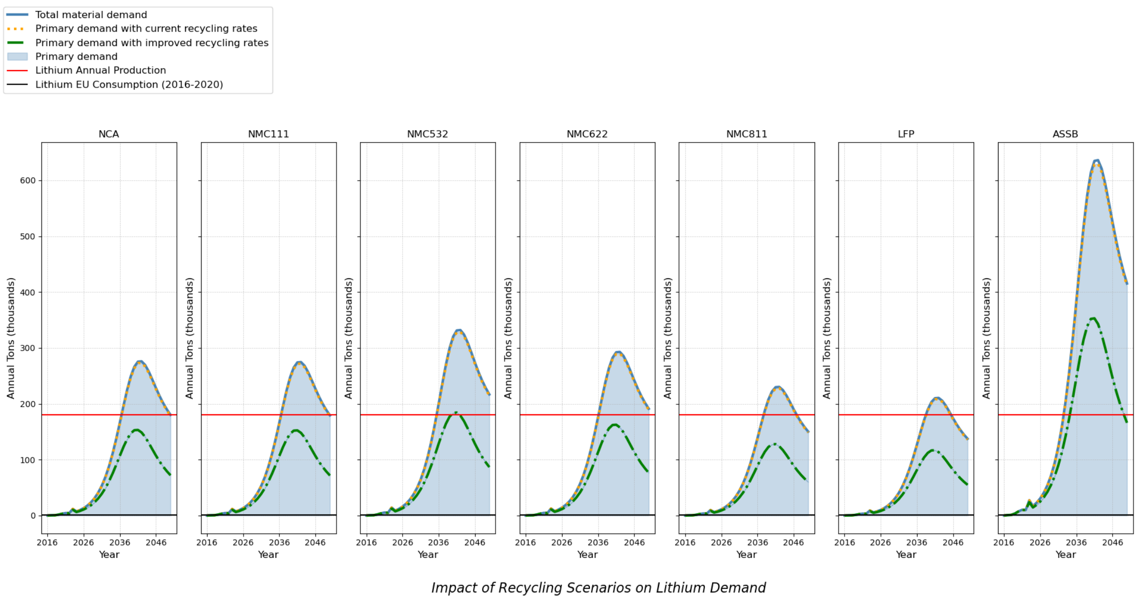
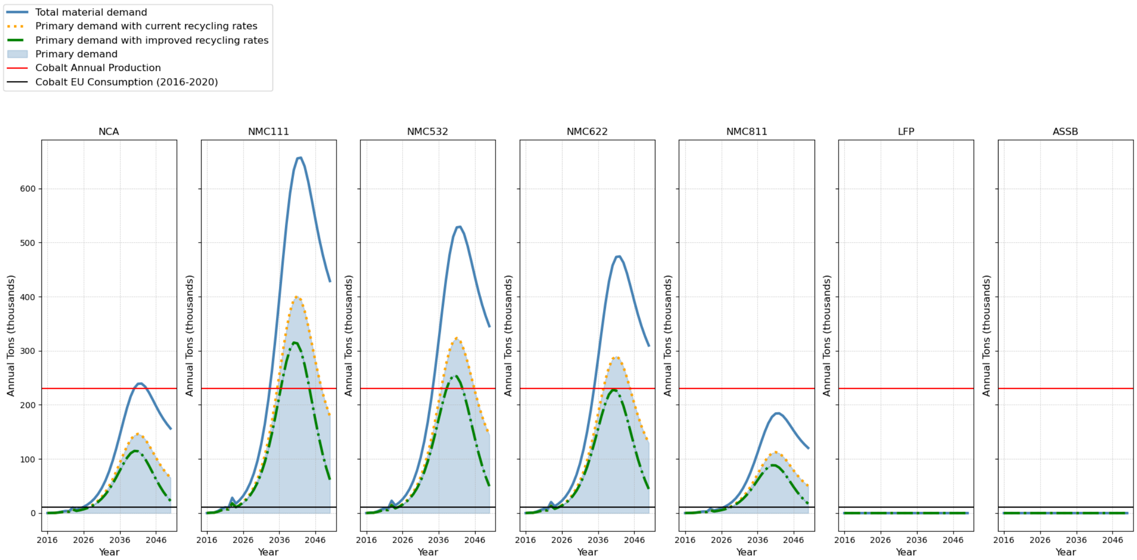
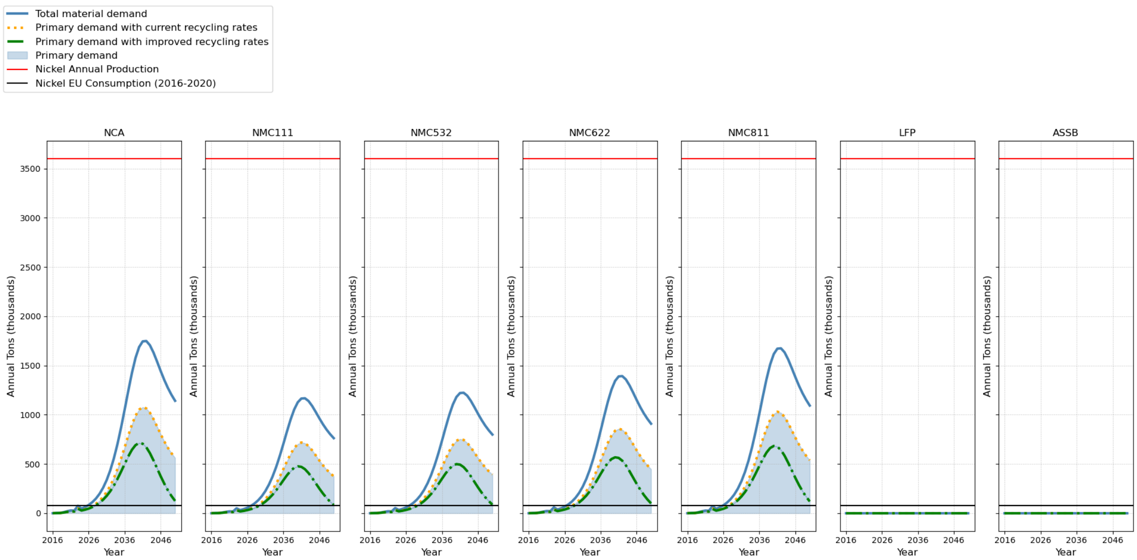


Figure C.5: Annual demand Lithium



Impact of Recycling Scenarios on Cobalt Demand

Figure C.6: Annual demand Cobalt



Impact of Recycling Scenarios on Nickel Demand

Figure C.7: Anunal demand Nickel

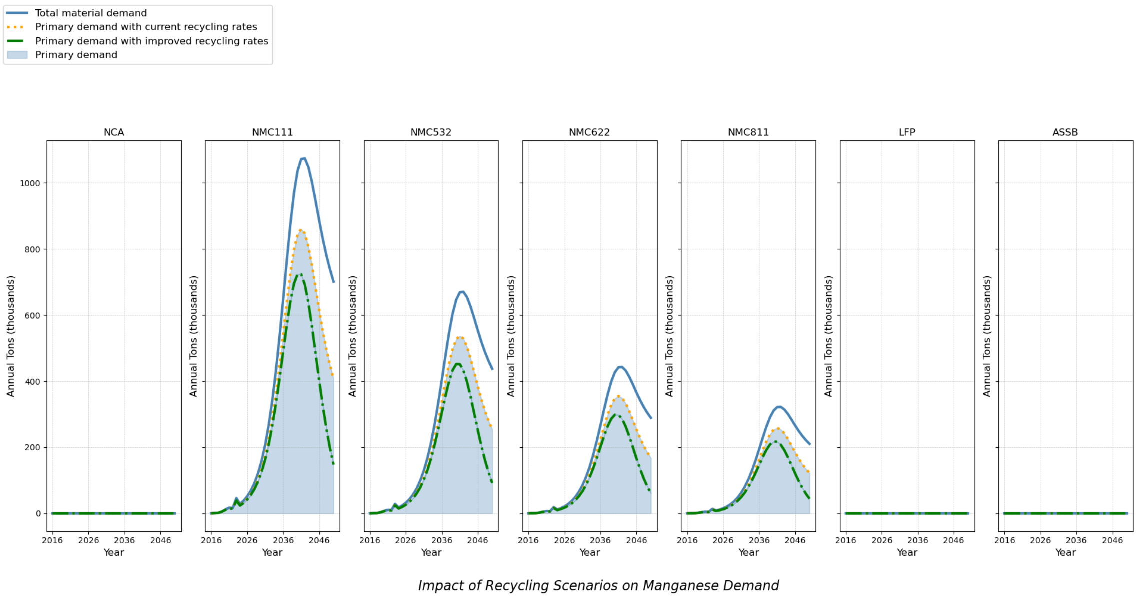


Figure C.8: Annual demand Manganese

C.2.3. Portion of recycled material

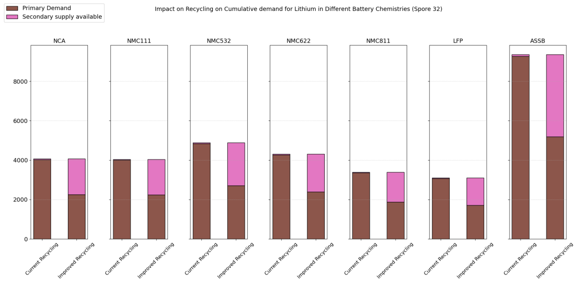


Figure C.9: Portion of recycled material Lithium

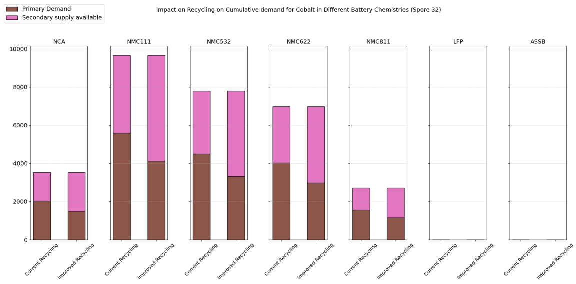


Figure C.10: Portion of recycled material Cobalt

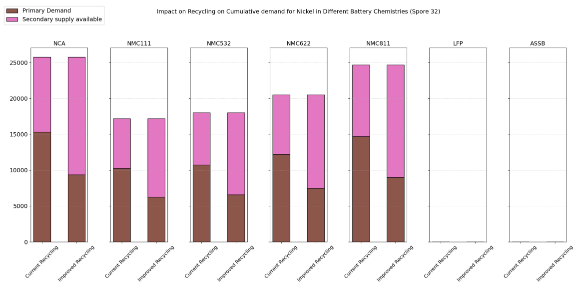


Figure C.11: Portion of recycled material Nickel

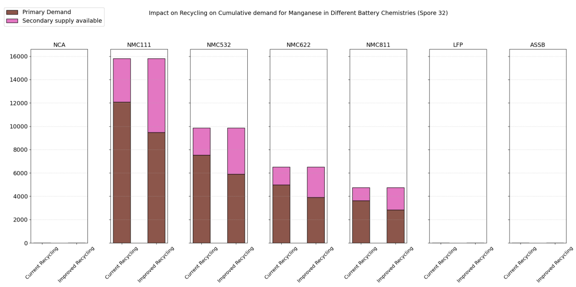


Figure C.12: Portion of recycled material Manganese

C.3. Battery lifetime: 8.5 years

C.3.1. Cumulative demand

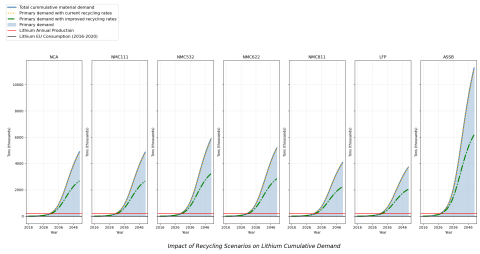


Figure C.13: Lithium

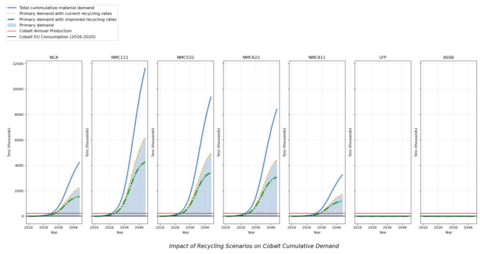


Figure C.14: Cobalt

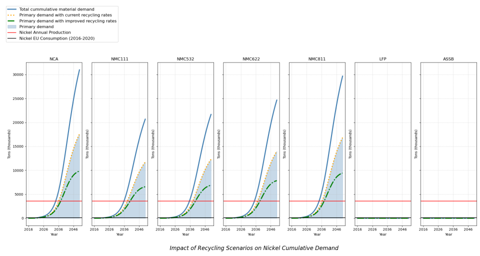


Figure C.15: Nickel

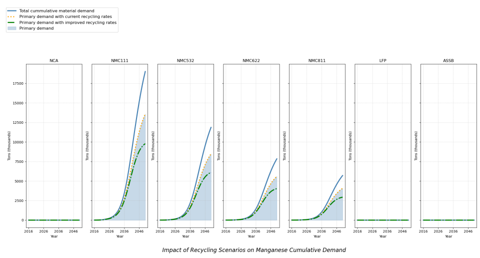


Figure C.16: Manganese

C.3.2. Annual demand

C.3.3. Portion of recycled material

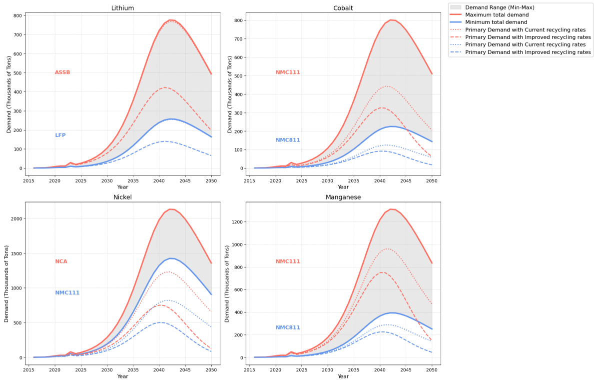


Figure C.17: Maximum and minimum

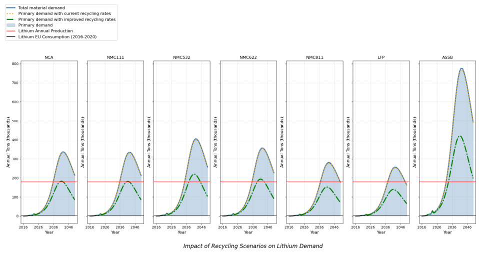


Figure C.18: Lithium

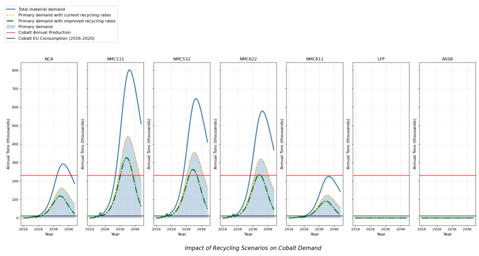


Figure C.19: Cobalt

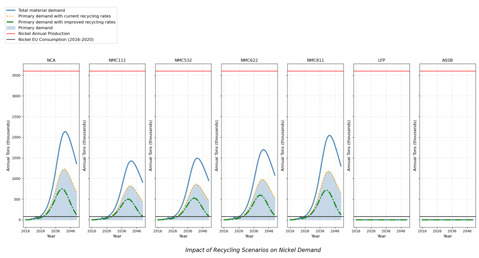


Figure C.20: Nickel

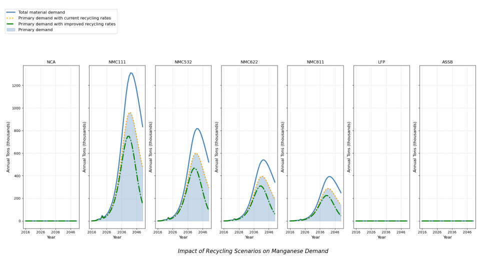


Figure C.21: Manganese

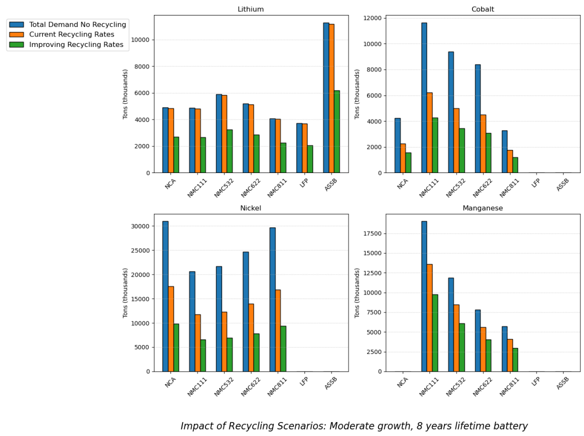


Figure C.22: Caption

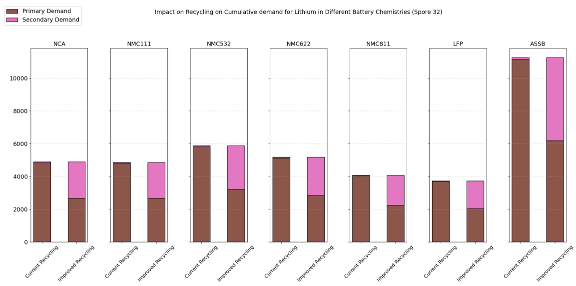


Figure C.23: Lithium

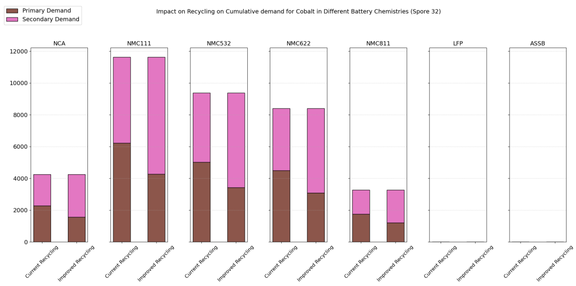


Figure C.24: Cobalt

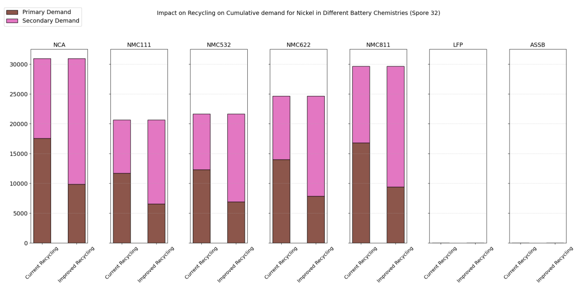


Figure C.25: Nickel

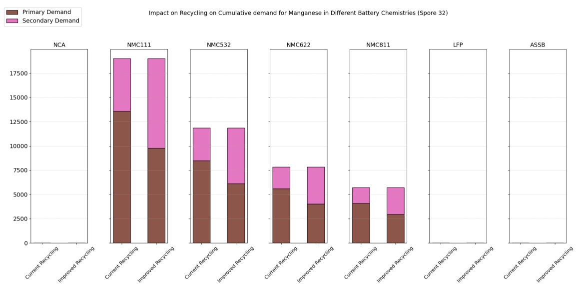


Figure C.26: Manganese

C.4. Battery lifetime: 21.5 year

C.4.1. Cumulative demand

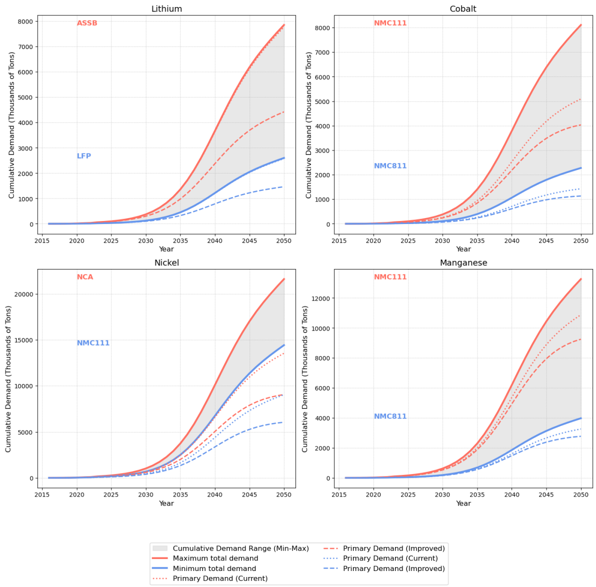


Figure C.27: Maximum and minimum cumulative demand

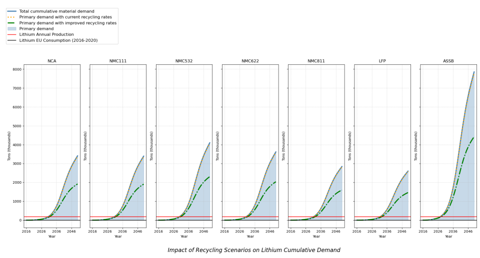


Figure C.28: Lithium

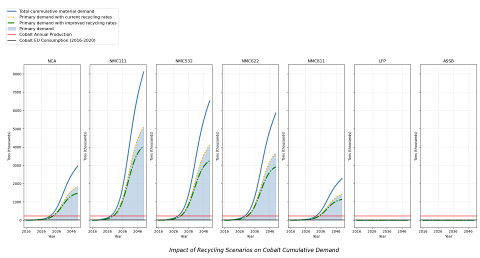


Figure C.29: Cobalt

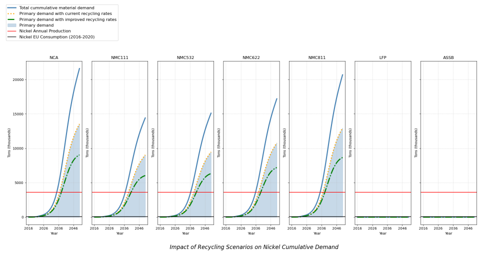


Figure C.30: Nickel

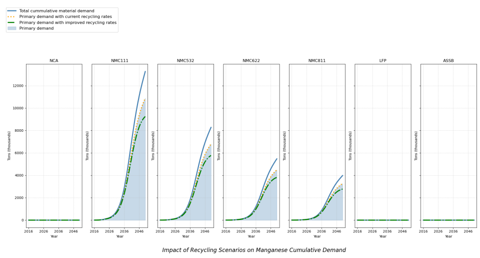


Figure C.31: Manganese

C.4.2. Annual demand

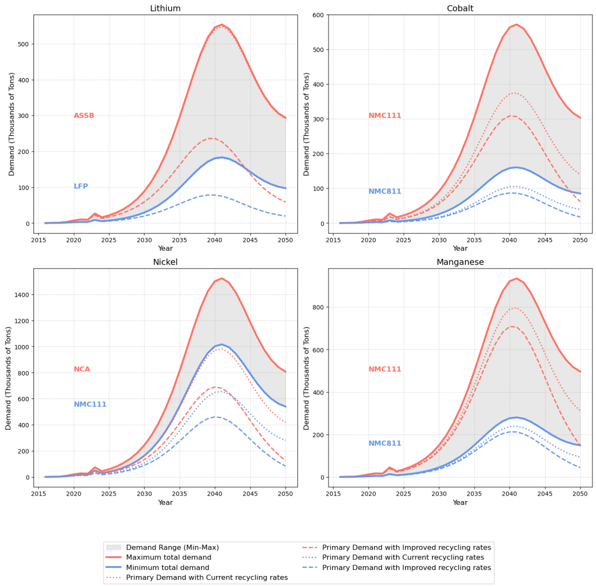


Figure C.32: Max and min annual demand

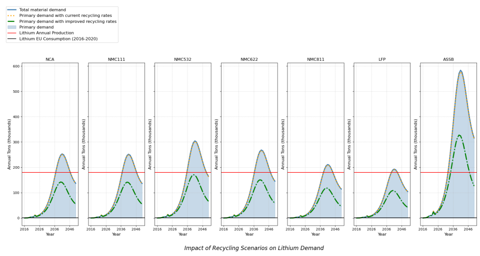


Figure C.33: Lithium

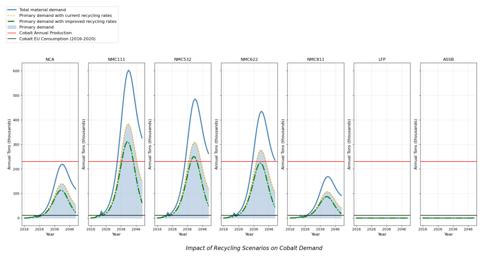


Figure C.34: Cobalt

C.4.3. Portion of recycled material

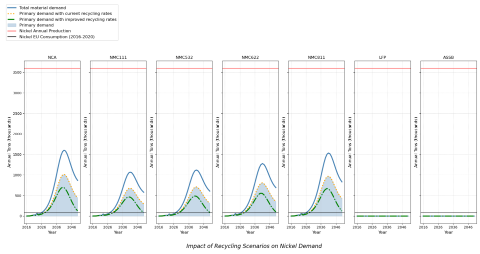


Figure C.35: Nickel

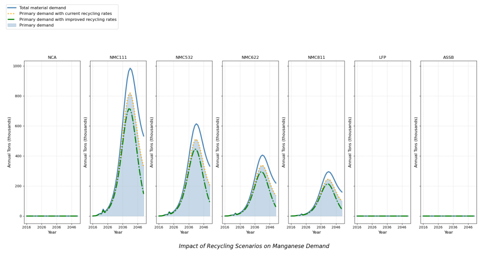


Figure C.36: Manganese

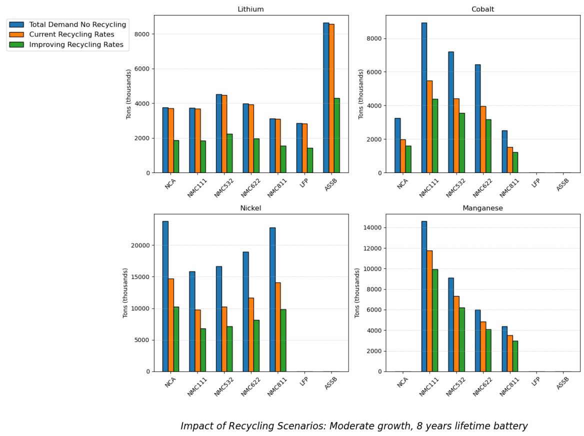


Figure C.37: Portion of all recycled materials

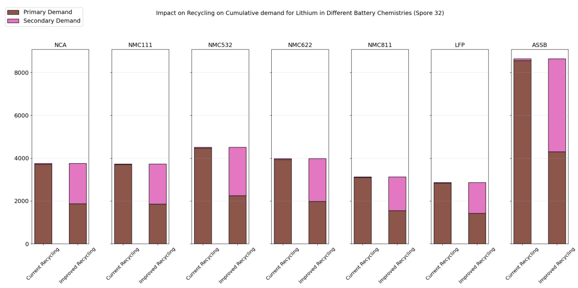


Figure C.38: Lithium

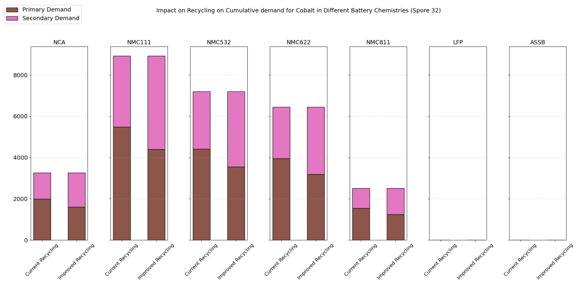


Figure C.39: Cobalt

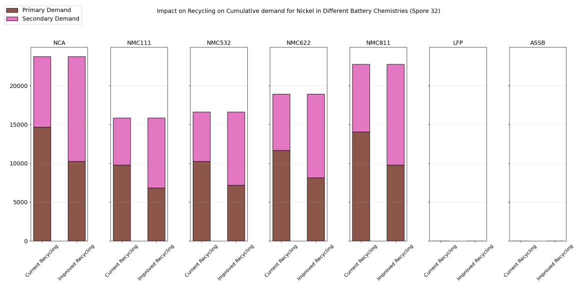


Figure C.40: Nickel

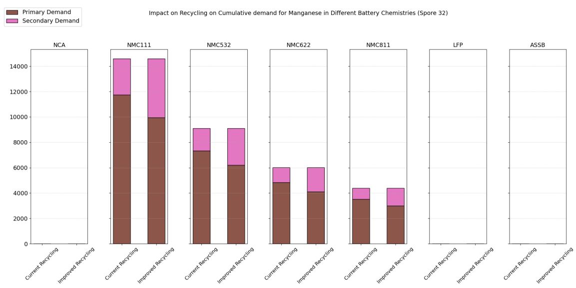


Figure C.41: Manganese

C.5. Accelerated uptake growth

C.5.1. Cumulative demand

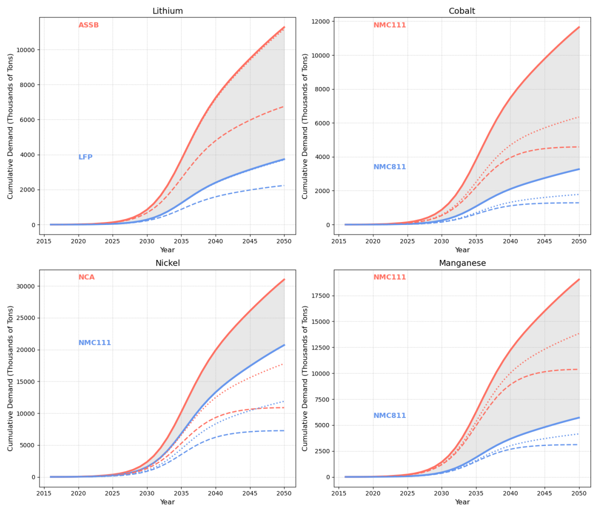


Figure C.42: Cumulative demand

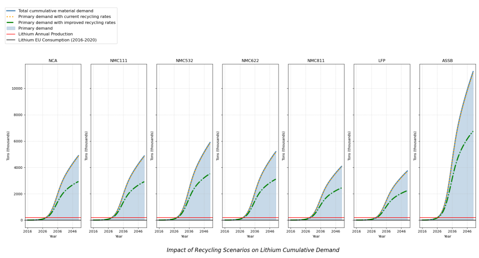


Figure C.43: Cumulative demand Lithium

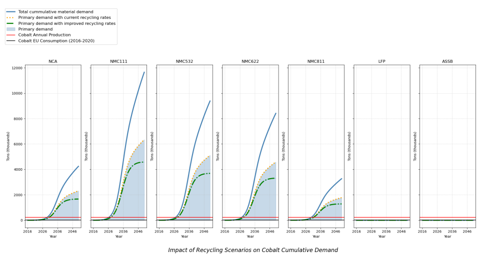


Figure C.44: Cumulative demand Cobalt

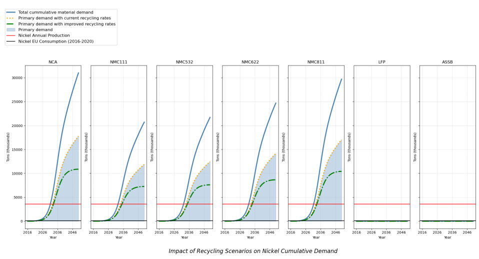


Figure C.45: Cumulative demand Nickel

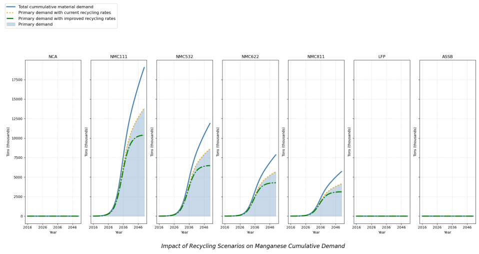


Figure C.46: Cumulative demand Manganese

C.5.2. Annual demand

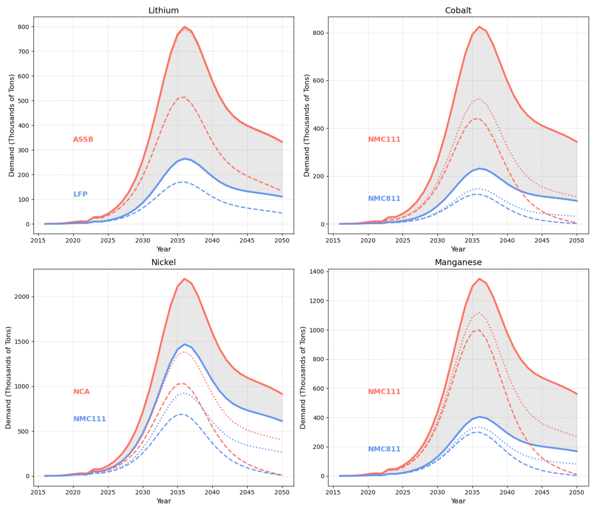


Figure C.47: Annual demand

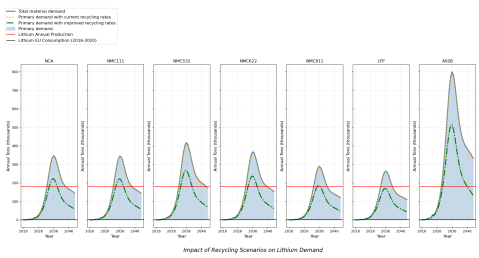


Figure C.48: Annual demand Lithium

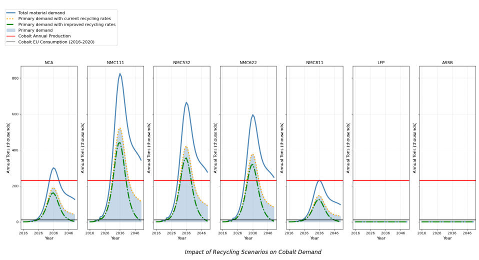


Figure C.49: Annual demand Cobalt

C.5.3. Portion of recycled material

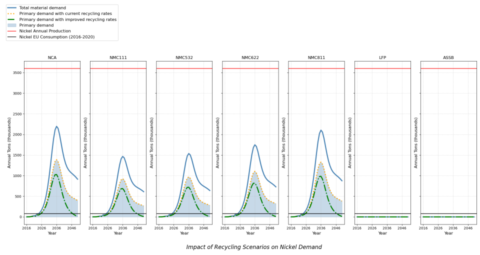


Figure C.50: Annual demand Nickel

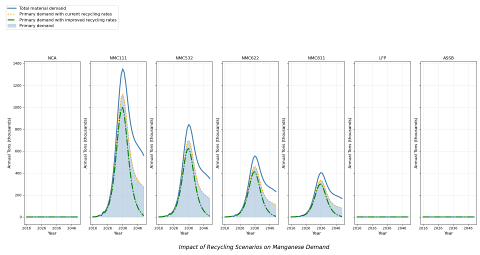


Figure C.51: Annual demand Manganese

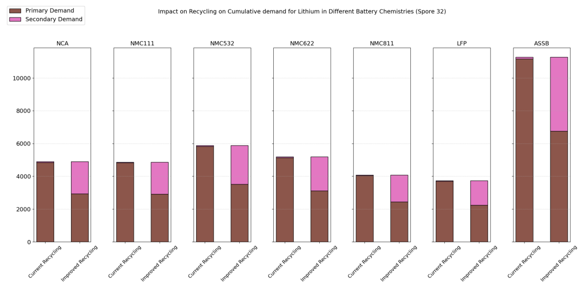


Figure C.52: Lithium

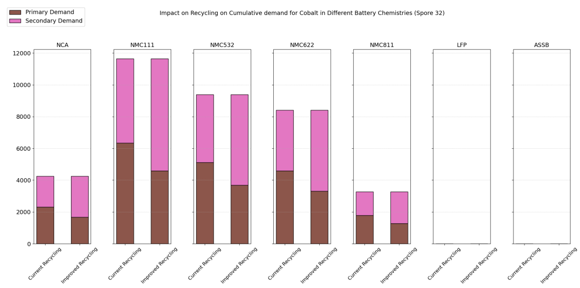


Figure C.53: Cobalt

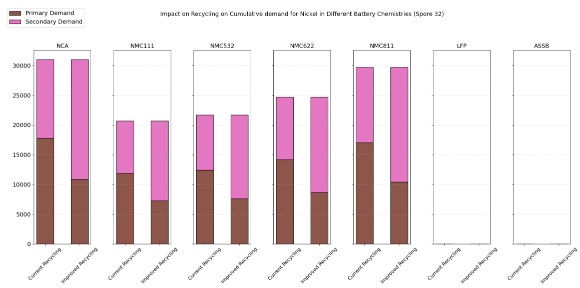


Figure C.54: Nickel

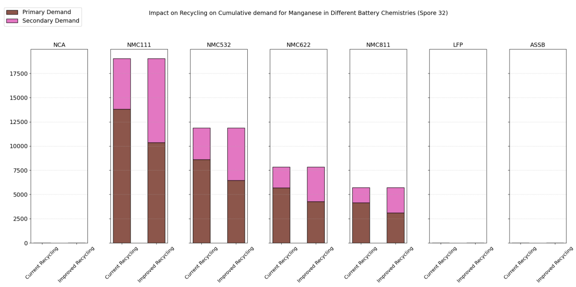


Figure C.55: Manganese