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Material Flow Analysis of The Global Nickel Cycle: Evaluating the Expected Increase in Nickel Demand Toward a Sustainable Future

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Statement of originality

I, Nadhifa Raihanah, hereby declare that the work presented in this dissertation, titled " Material Flow Analysis of The Global Nickel Cycle: Evaluating the Expected Increase in Nickel Demand Toward a Sustainable Future" is entirely my own original work. I affirm that it has not been fully or partially submitted previously in any other Italian or foreign university for assessment purposes.

I further confirm that the content of this dissertation is the result of my own intellectual endeavours, and I have appropriately cited all sources used. This work does not infringe upon the intellectual property rights of any third party, and its contents do not constitute plagiarism.

I understand the consequences of submitting work that is not my own and affirm the honesty and integrity of this academic contribution.

Nadhifa Raihanah

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Special appreciation to my friends, whose companionship and encouragement helped me navigate the challenges of the master’s program. Their support and belief have motivated me to keep moving forward.

Lastly, I hope that this thesis will contribute to the field of nickel material flow analysis. I hope that readers find valuable insights within these pages, enable further studies and research in this area.

Abstract

As the global shift towards sustainable energy rises, the role of nickel is rapidly evolving. Nickel has become essential for enabling a sustainable energy future due to their role in battery systems. Consequently, accurate and updated data on nickel stocks and flows is important to establish a quantitative foundation for understanding the comprehensive nickel cycle and decision making for a sustainable nickel supply. A dynamic nickel flow analysis from 1950 to 2023 was conducted to evaluate the current nickel stocks and flows. The nickel cycle comprises seven stages: mining, smelting, refining, fabrication, manufacturing, use phase, and end-of-life. The fabrication process yields first-use products, classified into stainless steel, nickel alloys, alloy steel, stainless steel foundry, nickel alloy foundry, plating, and batteries. Allocation of first use to end use, which consist of mobility & transport, consumer goods, building & construction, energy, process industries, batteries, other industrial components, and others, has been done. Dynamic nickel flow analysis indicates that the in-use stock of nickel by the end of 2023 was 46,000 kt Ni, with 50% of nickel mined since 1950 remaining still in use. The recycling process was closely examined and quantified with recycling potential of 14,000 kt Ni between 2014 and 2023. Approximately 73% of nickel end-of-life scrap is lost during the collection stages and 520 kt of nickel is recycled per year. Furthermore, the quantity of recycled nickel has decreased recently, with collection and recycling input rates of 22% and 14%, respectively, in 2023.

Keywords: Nickel, Stock and flow modelling, Material flow analysis (MFA), Recycling indicators

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List of abbreviations

B&C	Building and Construction
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BGS	British Geological Survey
CSP	Concentrating Solar Power
Consum	Consumer Goods
EoL	End of life
EoL PR	End of life processing rate
EoL RIR	End of life recycling input rate
EoL RR	End of life recycling rate
EV	Electric Vehicle
kt Ni	Kiloton nickel
LIB	Lithium-ion Batteries
MFA	Material flow analysis
NA	Nickel Alloy
NMC	Nickel Manganese Cobalt
OIC	Other Industrial Components
OPR	Overall processing rate
ORER	Overall recycling efficiency rate
OSR	Old scrap ratio
PI	Process Industry
STS	Stainless steel
Transp	Transportation

1 Introduction

1.1 Nickel

Nickel (Ni), a silvery-white lustrous metal, is an important metal that is widely used in several sectors. Nickel, selected for its anticorrosive characteristics and thermal resistance, is frequently utilized as a component in various alloys, particularly stainless steel (Zeng et al., 2018). Nickel is a favorable material for sustainability due to its extended useful lifespan. The physical and mechanical qualities of nickel have led to its use in various conventional sectors, including building and infrastructure, household appliances and electronics, transportation, metal goods, and industrial machinery (Reck & Rotter, 2012). Beyond their conventional applications, many studies have highlighted the importance of nickel metals in the transition to low-carbon technologies.

Stainless steel (STS) (69%), nickel alloy (NA) (11%), alloy steel (6%), STS foundry (1%), NA foundry (1%), plating (6%), and batteries (5%) are the first-uses of nickel (Reck & Rotter, 2012; SMR, 2023). The term 'first use' of nickel refers to the conversion of nickel products into intermediate products. Based on the first-uses of nickel, super-alloys, which include nickel alloys, are critical in producing turbines for power generation, aerospace, and military sectors. In addition, copper-nickel alloys (75% copper and 25% nickel) are utilized for coinage, while nickel plating is used in computer hard disks, CDs, and DVDs (Dilshara et al., 2024). Additionally, the synthesis of commercial compounds like nickel carbonate ($NiCO_3$), nickel chloride ($NiCl_2$), nickel oxide (NiO), and nickel sulfate ($NiSO_4$) utilizes nickel. In hydrogenation processes, nickel and its alloys frequently serve as catalysts (Dilshara et al., 2024).

Nickel end-use applications are classified into mobility & transport, consumer goods, building & construction, energy, process industries, batteries, other industrial components, and others. However, as the worldwide transition to sustainability rises, nickel's function is swiftly changing. With the rise of low-carbon technologies, such as batteries systems, nickel has become crucial for enabling a sustainable energy future (IEA, 2021).

1.2 Overview of the Importance of Nickel in Energy Transition

As the world commits to responding to global warming, clean energy transition technologies appear to be part of the solution for it. One of the turning points of the energy transition is the Paris agreement to achieve a sustainable low-carbon future by accelerating and increasing the actions needed for the energy transition from fossil fuels into renewable energy. Technologies that allow the transition to clean energy also facilitate the achievement of the United Nations Sustainable Development Goals (UNSDGs), including affordable and clean energy (Goal 7), industry, innovation, and infrastructure (Goal 9), and notably climate action (Goal 13) (United Nations, 2016).

From this point of view, the metal sector has significant responsibility in facilitating a zero carbon emission economy, with nickel playing a crucial part in the transition from fossil fuels to renewable energy (Chordia et al., 2021). Nickel is one of the critical mineral elements used in the energy transition pathway, it is used in the production of several clean energy technologies (Table 1).

Table 1. Importance of nickel for clean energy technologies (IEA, 2021)

Clean Energy Technologies	Importance of Nickel
Solar PV	Low
Wind	Moderate
Hydro	Low
CSP	Moderate
Bioenergy	Low
Geothermal	High
Nuclear	Moderate
Electricity networks	Low
EVs and batteries storage	High
Hydrogen	High

One of the most discussed nickel uses in this context are lithium-ion batteries. Nickel is used in the cathodes of LIB for electric vehicles and energy storage systems. Due to its high energy density, it allows these batteries to combine high storage capacity with a reduced size and lower manufacturing cost (Njema et al., 2024).

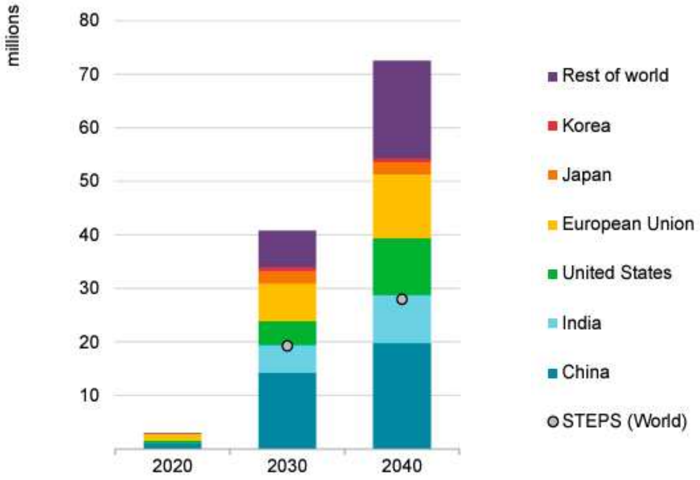

Figure 1. Annual electric vehicles sales (IEA, 2021)

Despite currently representing a minor market share, electric vehicles are projected to experience a significant surge in demand due to the shift to sustainable energy (Figure 1). Similarly, the other listed energy technologies using nickel will most likely rise in importance. Implementing those clean energy transition technologies will increase the mineral demand significantly. For example, the International Energy Agency (IEA) projects a demand increase for metals of four times by 2040 in their sustainable development scenario, with growth of nickel reaching 25 times (IEA, 2021). Understanding nickel's role in the energy transition industry and the implications for the current and future nickel flows is essential to ensuring its availability, a fundamental condition for successful decarbonization.

1.3 Material Flow Analysis (MFA)

Increased consumption has resulted in the accumulation of metal stocks in the environment, making the collection and recycling of metals from secondary resources more important. These activities depend on material cycles knowledge about the amounts, quality, and locations of metal-containing products that have accumulated historically (Müller et al., 2014). Investigation of material cycles can assess historical and future flows and give insights into drivers of resource utilization and early signs of environmental issues, or they can facilitate investment planning in infrastructure for mining, production, and waste management. Numerous studies examining the material cycles of metals within the anthroposphere adopt material flow analysis (MFA) (Brunner & Rechberger, 2016).

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a defined system boundary; it includes the connection between the sources, the production processes, the intermediate and final products, the use phase, and the end of life of a material (Brunner & Rechberger, 2016). MFA is using simple material balance by identifying all inputs and outputs to the different life cycle stages of a material along with the stocks that accumulate over time to generate knowledge regarding the flows of material. By knowing the flow of the material, locations of material losses can be detected, and targeted measures can be proposed. Improvement on the material efficiency in industrial systems can be achieved by using material flow analysis (Cullen & Cooper, 2022).

The material inventory of a process can be quantified using two distinct methodologies (Brunner & Rechberger, 2016). The first method, commonly known as the top-down approach, calculates the stock based on the net flow: the difference between inflows and outflows. The second method, known as the bottom-up approach, directly calculates the stock by estimating the material present within the system boundary at a specific time. Additionally, an MFA can be either retrospective, examining historical stocks and flows, or prospective, forecasting future trends through data extrapolation, or a synthesis of both methodologies (Müller et al., 2014).

The material flow analysis method has been used on several metals, which in terms of nickel are summarized in Table 2. The table also outlines the use of past MFAs across the various stages of nickel utilization. Reck et al. (2008) conducted an analysis for the anthropogenic nickel cycle for the year 2000, followed by (Reck & Rotter, 2012) who compared growth rates of nickel and stainless steel consumption between 2000 and 2005. (Elshkaki et al., 2017) investigated the future supply and demand for all primary uses of nickel from the period 1988 and projected it to 2050. (Wang et al., 2022) examined the anthropogenic nickel cycle based on the industrial chain using trade data for nickel content. (Su et al., 2023) provided the most comprehensive nickel cycle for China from 2000 to 2019, defining the types of nickel in each process.

Table 2. Comparison of nickel flow studies

	Region	Reference	Period	Details provided in each MFA			
				Refining	Fabrication	End use	Recycling
1	52 countries	Reck et al., 2008	2000			✓	✓
2	52 countries	Reck & Rotter, 2012	2000 & 2005		✓	✓	
3	Global	Elshkaki et al., 2017	1988-2050			✓	✓
4	Global	Wang et al., 2022	2019	✓	✓	✓	
5	EU	Ciacci et al., 2022	2012-2016			✓	✓
6	China	Su et al., 2023	2000-2009	✓	✓	✓	✓

These previous studies do not represent the current situation, as they were conducted several years ago. To provide a more accurate result, MFA studies need to be updated regularly, as the rapid growth of technologies can quickly change the demand patterns for nickel. One example is the global energy transition plan, which intensifies the need for nickel in the renewable energy sector. Moreover, the specific type of nickel produce in each process is not thoroughly classified, only studies by Su et al. (2023) covered all the details, but the scope is limited to China. An up-to-date dynamic analysis of the global nickel cycle with a good understanding of the details of each life cycle stage is not available in literature.

1.4 Motivation

As stated above, nickel plays a crucial role in the transition to renewable energy sources. The rising importance of nickel is due to the development of lithium-ion-batteries and their applications, which has generated a new market for this metal. Nickel reserves are mainly concentrated in Indonesia (22.4%), Australia (21.3%), Brazil (17%), Russia (7.3%), Cuba (5.9%), and the Philippines (5.1%) (Nickel Institute, 2022). The primary producers of nickel minerals, Indonesia and the Philippines, have declared their intention not to continue exporting nickel ores, potentially disrupting the existing nickel supply chain (Su et al., 2023). The vulnerabilities associated with the supply constraint are significant, thus, understanding its flow is essential.

The growing demand for nickel must be carefully managed to minimize environmental impact and avoid excessive nickel mining. The implementation of a circular economy is an option to avoid excessive mining by using a closed-loop approach to reduce the need for virgin nickel. A thorough material flow analysis of nickel serves as an instrument to understand the global nickel supply chain for the purpose of optimizing nickel utilization. By understanding the flow of nickel, the establishment of a robust and resilient system can be achieved to satisfy future demand while maintaining the environment.

1.5 Research Objective

Numerous studies (Table 2) have recently been conducted to analyse nickel flows and stocks at both global and regional levels (Elshkaki et al., 2017; Reck et al., 2008; Reck & Rotter, 2012; Su et al., 2023; Wang et al., 2022). No research has examined the historic nickel flows over a broad span of years and over the entire life cycle and the details of nickel involved in each life cycle stages. This study aims to analyze and quantify the global flows of nickel, providing a comprehensive insight from mining production to end-of-life and recycling, including end-use applications, scrap creation, and supply from primary and secondary sources. The thesis will examine the historical and current data about nickel flow from 1950 to 2023. Nickel cycle stages is classified into mining production, smelting, refining, fabrication, manufacturing, end use, and recycling. Each stage involves a thorough analysis of the specific nickel type and its demand according to the application sector. The analysis uses a dynamic material flow-stock model that integrates data on the supply of nickel from both primary (mining) and secondary (recycled) sources, enabling a comprehensive understanding of its production, use, and recycling patterns.

The potential effects of shifts in nickel supply on recycling, driven by the demand of the energy transition, will be examined. This work aims to close the knowledge gap through an updated dynamic analysis of the global nickel cycle with a good understanding of the details in each life cycle stage. The results of the research include assessments of production and recycling flows, the structure of the stock of finished goods, and recycling indicators. This provides a quantitative foundation for identifying material losses in the nickel cycle and could serve as a basis for proposing necessary measures.

2 Methods

A top-down material flow study was performed on the global nickel cycle to quantify nickel flows and stockpiles. The system boundary covers a global scale. The nickel flow model was created using the System Dynamics software Vensim. The covered period starts in 1950 to build up the finished goods stocks naturally and concludes in 2023. The top-down modeling approach is used to model global nickel stocks and flows, providing a comprehensive understanding of the size of the nickel cycle, its recycling flows and current recycling efficiency.

The global nickel flow model includes multiple stages: mining, smelting, refining, fabrication, manufacturing, use phase, and end-of-life (EoL). The model analyzes the pathway of each tonne of nickel from extraction to EoL. Following multiple production steps, the nickel contained in various end-use products enters the use phase, the duration of which varies according to the product's lifespan. After the conclusion of the use phase, the nickel contained in these items is referred to as scrap and can be gathered and recycled, thus returning into the cycle as secondary nickel to be manufactured into new products together with primary nickel.

2.1 Data input

The data for this study is obtained and collected from several sources shown in Table 3. The Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) data is used for global mining and refining since 1960 (BGR 2024). The mining data from 1950 to 1959 is sourced from the British Geological Survey (BGS) database. During the same timeframe, the primary refining nickel data is obtained by multiplying the mined nickel amount with a smelting efficiency of 94% and a refining efficiency of 97%, as reported by Reck & Rotter (2012).

Table 3. List of data input with their respective source

Term	Source
Nickel mining	BGR, BGS
Nickel refining	BGR
First-use consumption	SMR
Process efficiencies	Ciacci et al., 2022; Reck et al., 2008
Product lifetime distributions	Daigo et al., 2010; Elshkaki et al., 2017
First-use to end-use distribution	SMR

After the refining stage, nickel advances to the fabrication stage, which involves production processes that create nickel-based products. These products are categorized into stainless steel, nickel alloys, alloy steel, STS foundry, NA foundry, plating, and batteries. The SMR, 2023 data gives the consumption of first use goods per end use sector for the years 2012 to 2023.

The end use sectors are mobility & transport, consumer goods, building & construction, energy, process industries, batteries, other industrial components, and others. For the years before the SMR data, interpolation for the consumption of nickel first uses for each category was conducted between the available data points, as data availability is restricted to the years 2000, 2005, and 2012-2022. In the years before 2000, a 30% growth in refining was implemented. This growth rate was derived from the growth observed between refining and fabrication in 2000, as this is the last data point that contains the complete information on refining and fabrication. The growth rate was assumed to be the same for each of the years between 1950 until 1999. Both production processes, first use fabrication and end use goods manufacturing have attached production efficiencies in terms of percent generated scrap (Table 4).

Table 4. Fabrication scrap percentage (Reck et al., 2008)

Nickel fabrication	Scrap
Stainless steel	0.5%
Ni Alloy	0.5%
Alloy steel	0.5%
STS Foundry	0.5%
NA Foundry	0.5%
Plating	3%
Batteries	0.5%

The first-uses are distributed to the end-uses category using an accounting matrix (Appendix 5.1). The accounting matrix is available only from 2013 to 2022. The allocation of first-uses to end-uses for the years before 2013 was assumed to be equal to that of 2013, while for 2023, it was considered to resemble that of 2022. There is an exception for the batteries category, as the available data is limited to the years 2000, 2005, and 2022, requiring interpolation using these three data points. For the years before 2000, the shares of batteries were assumed to be the same as 2000. Nickel end-use products will reach the end of their lifetime in a specific number of years. The lifetime distributions included in the modeling of the end use are shown in Table 5.

Table 5. Normal distribution parameters (Daigo et al., 2010; Elshkaki et al., 2017)

Use	Average Life time (years)	Standard deviation
Building & construction	50	7
Consumer goods	15	4
Mobility & transport	19	4
Energy	30	4
Process industries	25	4
Batteries	10	5
Other industrial components	25	4
Other	15	4

In the end-of-life stage, scrap generated from the nickel cycle is divided into two categories: new scrap and old scrap, which are separated for recycling. New scrap is produced during the manufacturing stages. However, as the separation process is not entirely efficient, some nickel is lost. The efficiency loss in new scrap processing is estimated to be around 5%, which is relatively low since manufacturers typically know the composition of the scrap, making the recycling process technically easier and minimizing losses. In contrast, old scrap, generated at the end of a product's life, has processing efficiencies that vary based on its end-use (as detailed in Table 6).

Table 6. Separation efficiency of each end use applications (Ciacci et al., 2022)

End use applications	Separation efficiency
Mobility & transport	74%
Consumer goods	48%
Building & construction	87%
Energy	87%
Process industries	87%
Batteries	68%
Other industrial components	70%
Others	29%

2.2 Model structure

The following section gives an overview of the model structure used in Vensim. Figure 2 shows a simplified framework of the model.

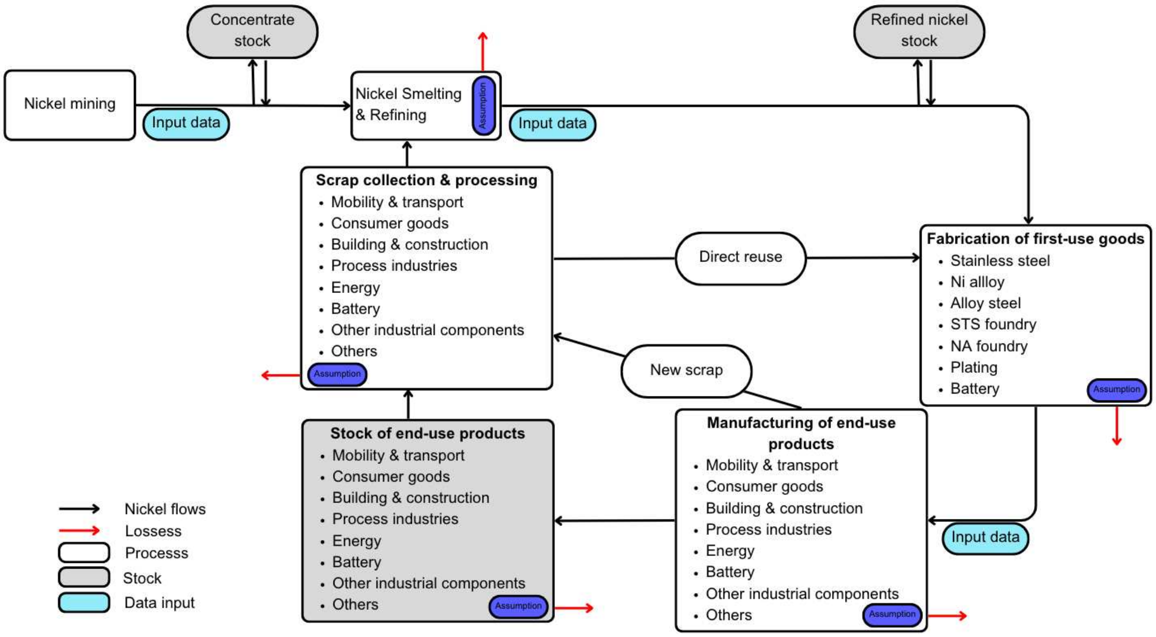

Figure 2. Simplified structure of the MFA model for the global nickel cycle

The refining production data from BGR includes the total of primary and secondary refined nickel production, with the secondary contributing a minor fraction of the total. The specific proportion of primary and secondary data is unavailable; therefore, it is obtained from the difference between primary refining data and total refining data to obtain the secondary amount. The primary refined data is calculated using the mining data multiplied by the smelting and refining process efficiency. The percentage of secondary refining data is derived by comparing it to the total refined nickel. The resulting percentage indicates an imbalance caused by higher primary refining data compared to overall refining data; thus, a nickel concentrate stock is utilised to balance the nickel quantity between the mining and smelting phases.

The nickel concentrate stock is determined by subtracting mined nickel from smelted nickel. The losses in smelting and refining resulted from the efficiency of each operation. The efficiency is presumed to be consistent over all years. The refined nickel stock is also calculated by subtracting the total amount of refined nickel production with the refined nickel usage in fabrication stages.

The fabrication stage produces first-use goods; the fabrication efficiency of each first-use generates how much first-use nickel product remains in the product and the permanent losses of the fabrication process. The quantity of nickel used in the fabrication stage is determined by calculating backward the first-use consumption multiplied by the fabrication efficiency.

Losses occurred during the fabrication and manufacturing stages due to process inefficiency. Fabrication losses are permanent losses. Manufacturing scrap could happen because of rejects, offcuts, or other forms of damage during production. The scrap produced during the manufacturing process is classified as new scrap, functioning as an input in the recycling process. Referring to Section 2.1, only a small percentage of new scrap is lost in the collection process and is assumed to be permanently lost.

The first-uses are distributed to end-uses using an accounting matrix as stated in Section 2.1. The end-use production data was derived by multiplying the first use consumption by the manufacture process efficiency of 90% for all of the end-uses category (Reck et al., 2008). Nickel end-use products which are currently being used will reach the end of their lifespan in a specific number of years. The lifetime distributions included in the modeling of the end use are shown in Table 5. The lifespan of the product's age is determined using a Gaussian distribution. The distribution is characterized by its mean lifetime and standard deviation, as presented in Table 5. The use of lifetime distributions has the effect of reducing year-to-year variability in the waste flows by distributing the variability in nickel use to several years (Glöser et al., 2013). Due to a lack of data, the standard deviation is estimated according to the assumptions on length of their lifespan, due to the limited availability of data on this matter. An aging chain is employed to represent the stock and flow structure of the system in these models. Aging chains advance the products by one year at each time step to monitor the ageing process till the EoL for each product in the use phase (Sterman, op. 2000).

At the EoL stage, waste is classified according to its end-use application. At this step, the EoL scrap is subjected to collection and separation processes. To close the model loop and ensure the mass balance of the cycle annually, the calculation of the EoL collection rate is carried out. The EoL collection rate is determined by dividing the amount of used scrap by the total quantity of available EoL scrap, taking into account the losses related to inefficiencies in scrap separation. The amount of used scrap equals to the sum of the secondary input to refining and the scrap input to fabrication. The losses at this step are related to inefficiencies in the collection and separating processes.

After the collection stages, the waste is separated for recycling processes. The separation efficiency for each category throughout all analyzed years is assumed to be the same, as defined in Table 6. To analyze the current trend of global nickel recycling, recycling indicators are calculated based on the flows of the model. The indicators calculated are Recycling Input Rate (RIR), End of Life Recycling Rate (EoL RR), End of Life Recycling Input Rate (EoL RIR), Overall Recycling Efficiency Rate (ORER), Overall Processing Rate (OPR), End of Life Processing Rate (EoL PR) and Old Scrap Ratio (OSR). Formula in Table 7 refers to Rostek et al. (2022) with an adjustment to fit the nickel model and in regards to Figure 3.

Table 7. Recycling indicator calculations

Recycling Indicator	Formula
EoL RR	$\frac{\mathrm{M}}{\mathrm{J}}$
EoL RIR	$\frac{\mathrm{M}}{\mathrm{A}+\mathrm{O}+\mathrm{N}}$
RIR	$\frac{\mathrm{M}+\mathrm{I}}{\mathrm{A}+\mathrm{O}+\mathrm{N}}$
EoL PR	$\frac{\mathrm{M}}{\mathrm{M}+\mathrm{L}}$
OPR	$\frac{\mathrm{M}+\mathrm{I}}{\mathrm{M}+\mathrm{L}+\mathrm{I}+\mathrm{H}}$
ORER	$\frac{\mathrm{M}+\mathrm{I}}{\mathrm{M}+\mathrm{L}+\mathrm{K}+\mathrm{I}+\mathrm{H}}$
OSR	$\frac{\mathrm{M}}{\mathrm{M}+\mathrm{I}}$

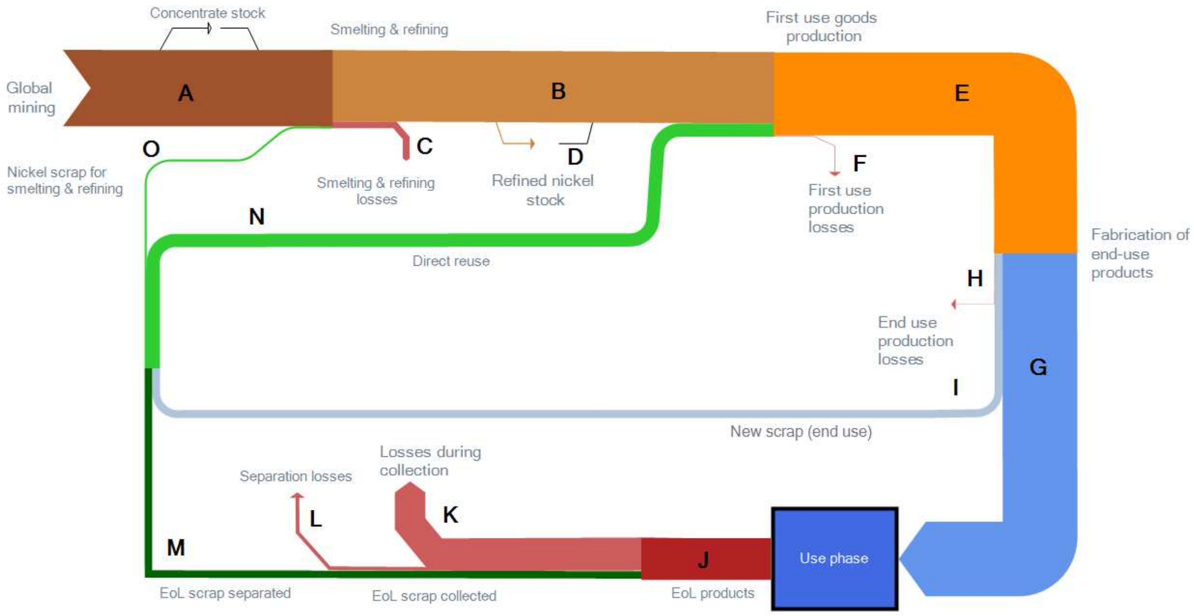

Figure 3. Sankey diagram of the material flows of nickel indicating the labels for each flow

3 Results and Discussion

3.1 The availability of data as the basis of material flow analysis

To produce a material flow analysis of the global nickel cycle with the best accuracy, accurate input data is necessary in addition to a well-structured model framework fitted to the research question. Data availability in mining and refining is sourced from the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and British Geological Survey (BGS) databases. Assumptions were necessary in several years with no available data by calculating using the process efficiencies (Reck et al., 2008) as explained in section 2. The available refining data consists of the total of primary and secondary nickel, using process efficiencies and reverse-calculating, smelting, primary, and secondary refined nickel can be obtained.

The consumption of first use goods per end use sector for the years 2012 to 2023 is sourced from the SMR. For the years before the SMR data, interpolation for the consumption of nickel first uses for each category was done. The first-uses are distributed to end-uses category using an accounting matrix. The lifetime distributions (Daigo et al., 2010; Elshkaki et al., 2017) were also implemented to be observed when nickel usage reaches the end of their lifetime.

In the end-of-life stage, the EoL collection rate is calculated in order to close the model loop. While Recycling Input Rate (RIR), End of Life Recycling Rate (EoL RR), End of Life Recycling Input Rate (EoL RIR), Overall Recycling Efficiency Rate (ORER), Overall Processing Rate (OPR), End of Life Processing Rate (EoL PR) and Old Scrap Ratio (OSR) are calculated using the formulas in Table 7.

3.2 Nickel stocks and flows

Figure 4. Sankey diagram of the cumulative nickel flow between 2014 and 2023

A dynamic stock and flow model for the anthropogenic cycle of nickel was constructed using the method described in Section 2. A dynamic stock and flow model approach is used to internally build up the nickel usephase stock, which is why the model begins in 1950 to accumulate the stock. Given the model excludes nickel production before 1950, the stocks of finished goods is applicable only after all nickel items manufactured from 1950 have been used up from the stock in use. The maximum lifespan of nickel applications in the building and construction sectors is 50 years, hence reporting of the stock and connected variables such as waste streams could begin from the year 2000. Production data is independent from the stock dynamic and can therefore be interpreted over the entire timeframe.

The overview of the nickel cycle for the accumulated years between 2014 and 2023 is shown in Figure 4 in the form of a Sankey diagram. A ten-year period is shown to simplify the visualization and override short term fluctuations. The thickness of the arrow corresponds to the size of the nickel flow and the difference of color corresponding to different stages. All stocks and flow are expressed in kilo tons of nickel equivalent (kt Ni). Value may not match due to rounding.

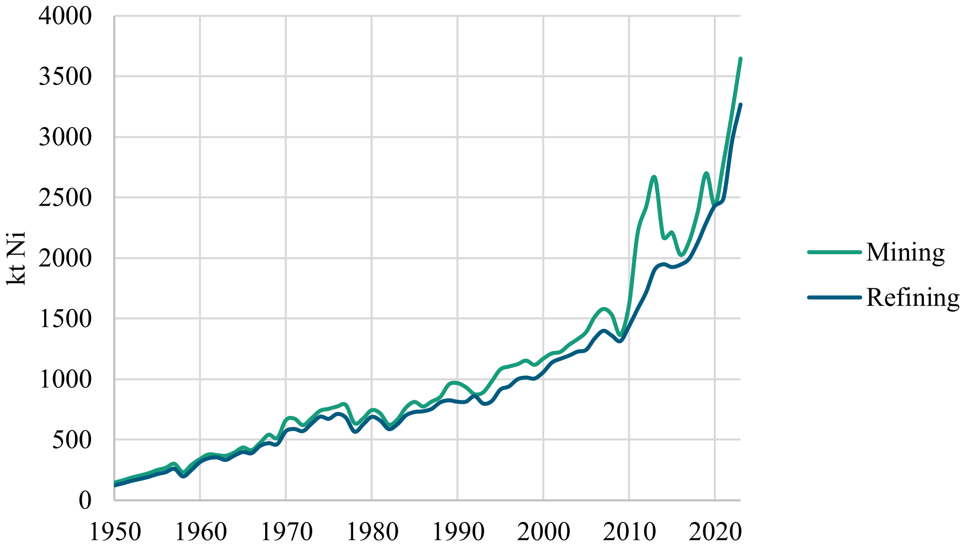

Figure 5. Mining and Refining trend from 1950 to 2023

The global nickel production between 2014 and 2023 accounted for 26,000 kt of nickel mined (BGR, 2024). The nickel concentrate stock happened between mining and smelting stages due to an unbalanced amount between the stages. The phenomenon occurred due to a sudden jump in mining production in the years 2011-2013 but the total refining amount stays in the same trend as shown in Figure 5. The rapid increase in nickel production is particularly from Indonesia, however the production capacity increase is not accompanied by increase in refining capacity (SFA Oxford, 2024), this information was also confirmed by BGR. The imbalance has led to an oversupply of nickel concentrate, which is certainly one reason for decreases in recycling but is also being stocked rather than processed. Therefore, concentrate nickel stocking is implemented to balance the nickel amount between mining and the smelting process.

According to Figure 5, the explosion of nickel mining occurred in 2010. The emergence of electric vehicles and lithium-ion batteries in 2010 contributed to the reason (Fraser et al., 2021). Global attention to electric vehicles is influencing the growing number of nickel mining operations, resulting in increased demand for nickel. Indonesia, possessing the biggest nickel ore reserves, became a major contributor to world nickel production. Nevertheless, Indonesia's refining infrastructure is inadequate to accommodate this, further worsened by the country's ban on nickel ore exports, which regulate domestic processing of nickel for export (Minister of Energy and Mineral Resources Regulation No. 17 of 2020, 2020). This policy caused a surge in mining operations before the implementation of the ban, although the domestic refining infrastructure was not prepared to handle the increased nickel ore supply.

Additionally, China's investment in Southeast Asia, particularly in nickel mining and processing in Indonesia and the Philippines, increased significantly during the early 2010s (Sangadji et al., 2023). Yet the construction of refining facilities required more time, resulting in a delay between the escalation of mining and refining activities. For instance, industrial zones such as the Indonesia Morowali Industrial Park (IMIP) started smelting activities in 2015, some years later.

Throughout the refining process, refined nickel stock is adjusted over the given period. The refined nickel stock is typically those held by exchanges like the London Metal Exchange (LME) and the Shanghai Futures Exchanges (SHFE). On the other hand, there are also unreported stocks held by manufacturers or other private entities. The interpretation of refined nickel stocks indicates that unreported inventories held by traders or manufacturers are more accessible and economical to use in times of nickel supply imbalance; consequently, stocking or destocking occurs to balance the nickel supply (Rostek et al., 2022).

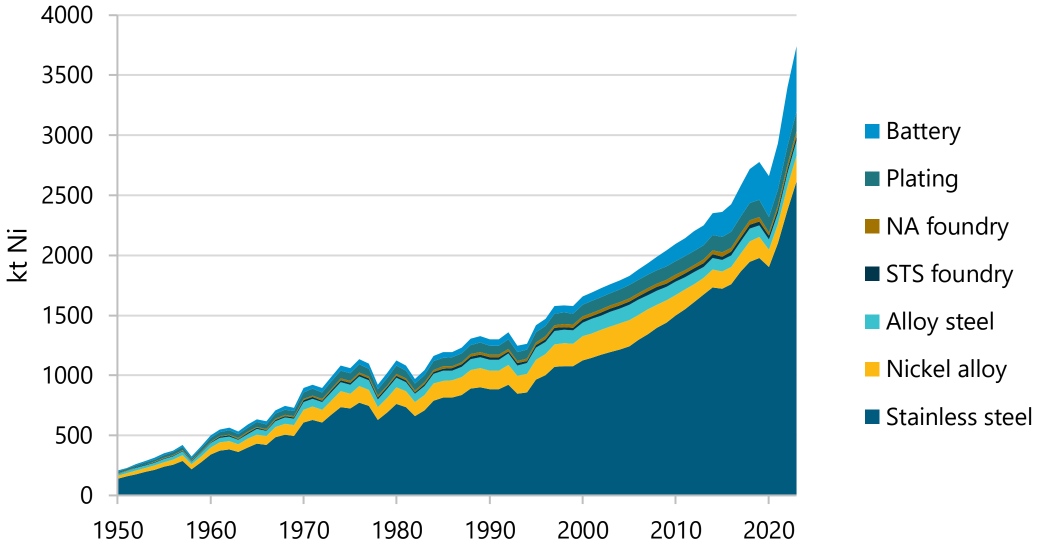

Figure 6. Production of first-use goods

Figure 6 shows the first-use goods production in the fabrication stages. The production trend shows a decrease in some years; however, it remains overall continually growing upward, totaling approximately 3700 kt Ni in 2023. Stainless steel makes up the biggest category, representing about 70% of nickel first-use production, followed by 12% for nickel alloy, 7% for alloy steel, 6% for plating, 4% for batteries, and 2% each for NA and STS foundries. All categories are growing in production numbers but have a decreasing share in overall production caused by the development of the electric vehicle industry and the connected massive increase in batteries production starting around 2010. The share of batteries production rose from 4% in

2000 to 6% in 2010, with continued increase reaching around 14% by 2023. The increase in nickel use in batteries production can be explained by the increasing demand for electric vehicle production, as nickel is a vital component in Nickel Manganese Cobalt (NMC) batteries which are widely used in EVs. This is because nickel has advantages as an electrode component with its greater stability, higher capacity, and lower cost compared to other metals (Li et al., 2024).

In the manufacturing stages, nickel demand is categorized based on the end-uses using the allocation matrix from first uses (Appendix 5.1). Figure 7 shows the stocks of finished goods in use, while Figure 8 shows end-uses production as yearly stock inflow and the waste generation as outflow (EoL) from the in-use stock. The primary application of nickel is in the consumer goods sector, with the proportion of nickel utilized around 29%. Nickel use in process industry is the second highest with 14% proportion of the total use, followed by the transportation sector, construction, and energy by 15%, 14%, 13% respectively. The other sector percentage falls below 10%. Between 2014 and 2023, there has been a growing trend in production, totaling 25,000 kt Ni cumulatively. In 2023, the current stock totaled 46,000 kt Ni, while the cumulative waste disposal was 14,000 kt Ni.

According to Figure 5, nickel mining production increased from 1,200 kt in 2000 to 3,600 kt in 2023, representing a threefold growth over 23 years. Regarding the use phase, approximately 50% of the nickel in end-use goods produced since 1950 remains in use. This is attributed to rising demand and the predominant application of nickel in stainless steel, which has a longer lifespan due to its widespread use in construction and building projects.

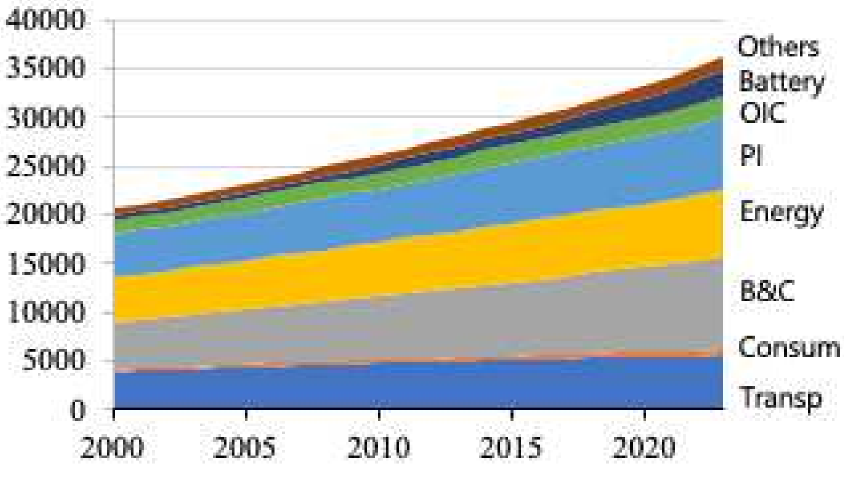

Figure 7. Nickel in use stocks

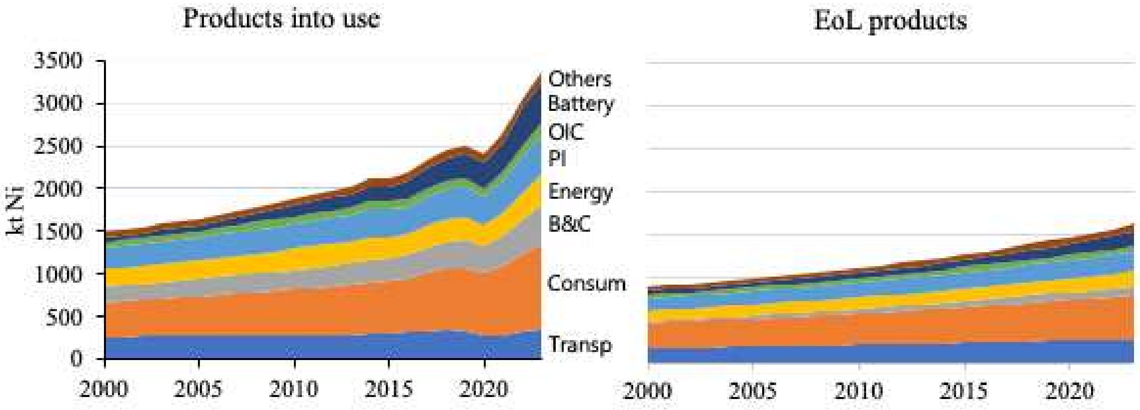

Figure 8. End-uses production and EoL products. OIC = Other Industrial Components; PI = Process Industry; B&C = Building and Construction; Consum = Consumer Goods; Transp = Transport

A previous study (Reck et al., 2008) estimated that less than 40% of the nickel entering use eventually exited use. However, our model output indicates that about 56% of the nickel exiting use originated from the total nickel inflow between 2014 and 2023. In the earlier study, the outflow was calculated based on the inflow into use with specific percentage assumptions. In contrast, using a dynamic model allows for a natural buildup of stock derived from production data, making it more reliable. This suggests that the nickel outflow from in-use stock was previously underestimated.

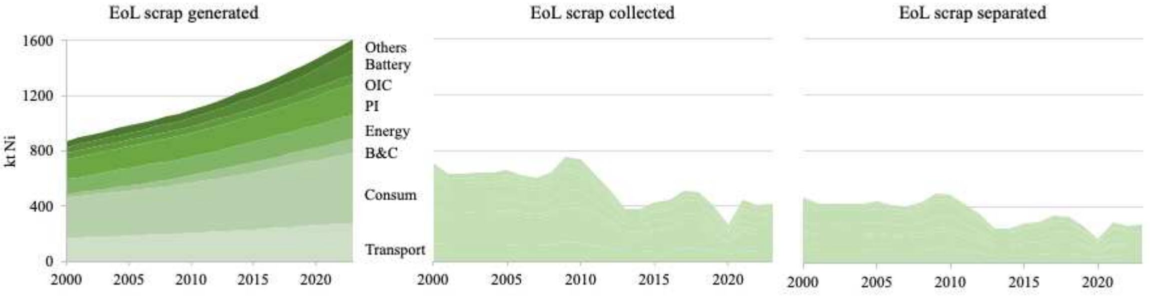

Figure 9. The EoL products stages

During the EoL stages, scrap is classified according to its end-uses. From 2014 to 2023, 14,000 kt Ni accumulated in the waste outflow. Figure 9 shows the flows of EoL, the highest losses in the entire cycle result from the EoL collection stage. The amount of nickel in scrap not collected for recycling accounts for 10,000 kt Ni, or 73% of the generated EoL scrap from 2014 to 2023, a figure derived from the mass balance closure of the cycle. The collected waste then continues to the separation phase. The EoL separation losses during this period amounted to 1,200 kt Ni, representing 33% of the total collected scrap.

The 73% losses can be explained by several reasons. First, the preference to process nickel scrap is decreasing due to abundant nickel concentrate stock which consequently results in lower nickel price; therefore manufacturer choose to use nickel from primary sources. Then, the increasing batteries production is not yet accompanied by increase in batteries recycling, this is because batteries recycling is harder compared to recycling other product containing nickel (Sun et al., 2024).

Another reason for the losses is low separation efficiency. Nakamura et al. (2017) identified collection losses from end-of-life goods as constituting the largest share of nickel losses in steel, followed by losses from scrap, with manufacturing losses being the least significant. This model confirms their assessment.

3.3 Nickel recycling practice

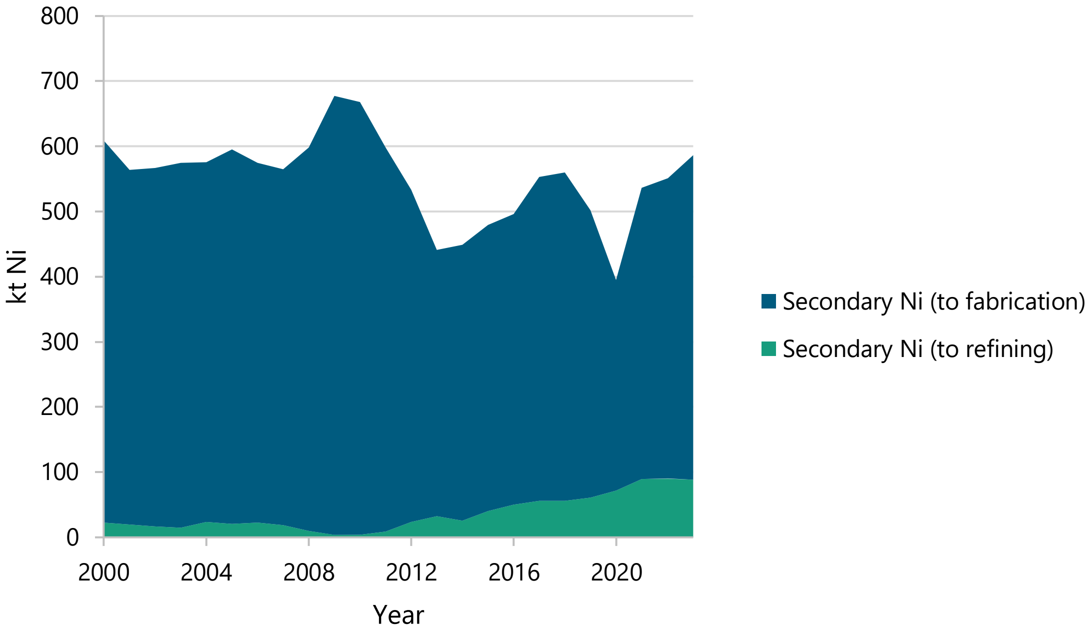

Figure 10. Nickel recycling by recycling pathway

Figure 10 shows the development of recycling flows since 2000. Around 7% of the total recycled nickel entered the refinery stage, while almost 93% of the total recycled nickel entered the fabrication step without refining. In the secondary nickel going to refining, there is a growth trend starting from around 2010.

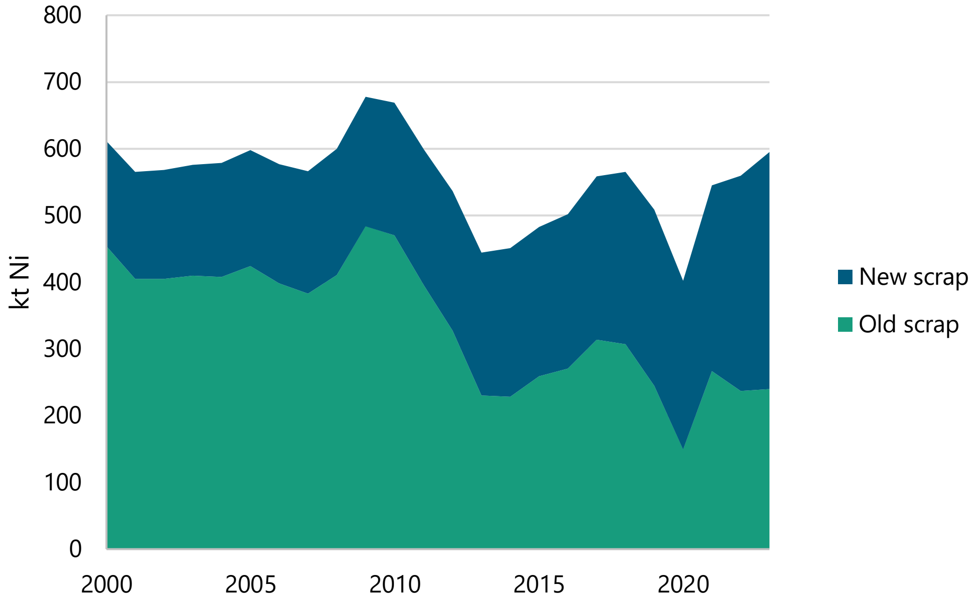

Figure 11. Nickel recycling by material source: Old and new scrap ratio

There are two sources of recycling materials, which is old scrap from EoL products and new scrap from finished goods manufacture (figure 11). Between 2014 and 2023, materials from recycling accounted for 2,500 kt Ni from old scrap and 2,700 kt Ni from new scrap. This means around 10% share for each scrap category from the primary nickel production. Before 2010, the yearly amount of scrap slightly fluctuated and increased in 2010. Starting in 2010 when the production of batteries technology starts to accelerate, a significant decrease in both of the scrap categories used for recycling is happening. The reason for this phenomenon can also be seen in Figure 4, which shows there is a significant increase in nickel mining production, which can also lead to lower nickel prices. Nickel prices have been declining since 2010 (Trading Economics, 2024). The decrease in price made primary nickel more economical for manufacturers in comparison to recycled nickel. The lower expense encouraged industry to depend more heavily on primary nickel supplies instead of recycled resources.

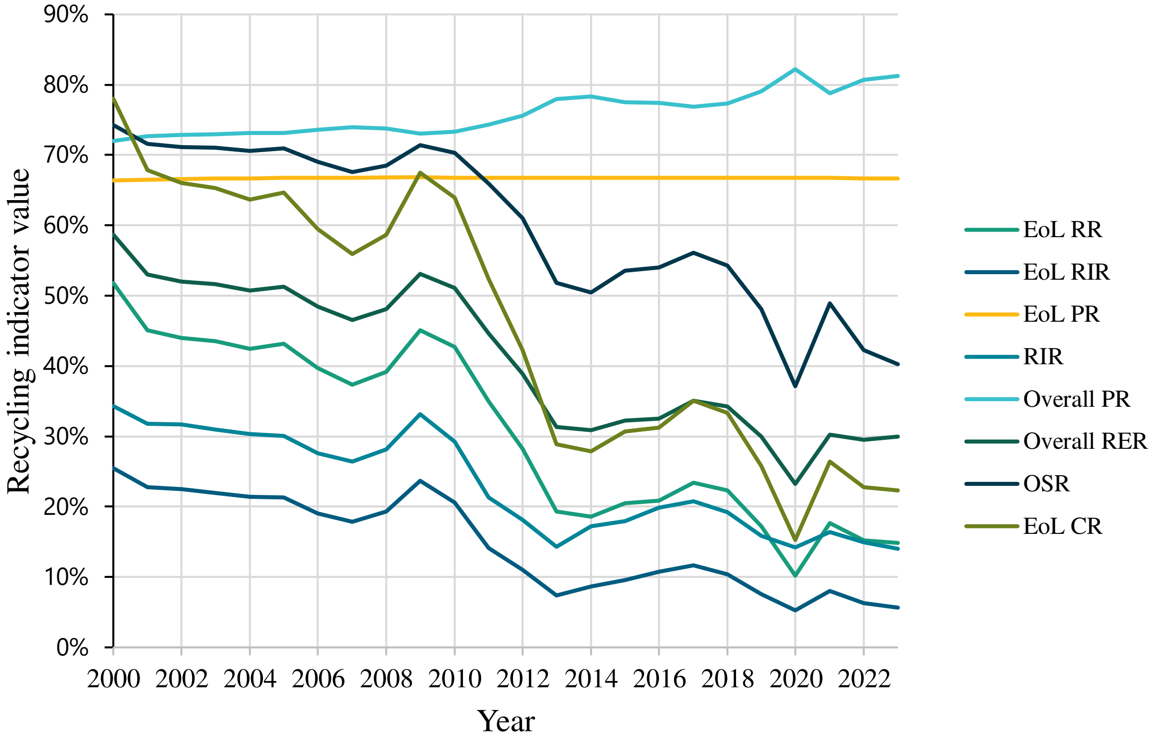

Figure 12. Nickel recycling indicators over time

The recycling indicators are calculated based on the formula in Section 2 for the years 2000 until 2023. The amount of recycled nickel has been decreasing in recent years, which is reflected in the RIR value. Before 2010, the RIR trend underwent a little fluctuation around 30%. Starting in 2010, the RIR dropped below 20% until 2016, when it began to rise above 20%. However, a downward trend continued in 2019, resulting in a decrease to 14% by 2023.

Reck et al. (2008) modeled the anthropogenic nickel cycle for 2000 and calculated an EoL RR of 57%. From the result of the model, the global nickel EoL RR fluctuated around 50% with RR of 52% in 2000, which is similar to the developed model. The declining trend in recycling indicator also happens in EoL CR from around 60% before 2010 to around 30% after. In recent years, there has been no prior study modeling the nickel flow analysis for EoL RR, however, the output model indicates a consistent decline in EoL RR, which is expected to result from a strong increase in mining led to lower prices and preferences to use primary nickel sources, as explained in the previous paragraph.

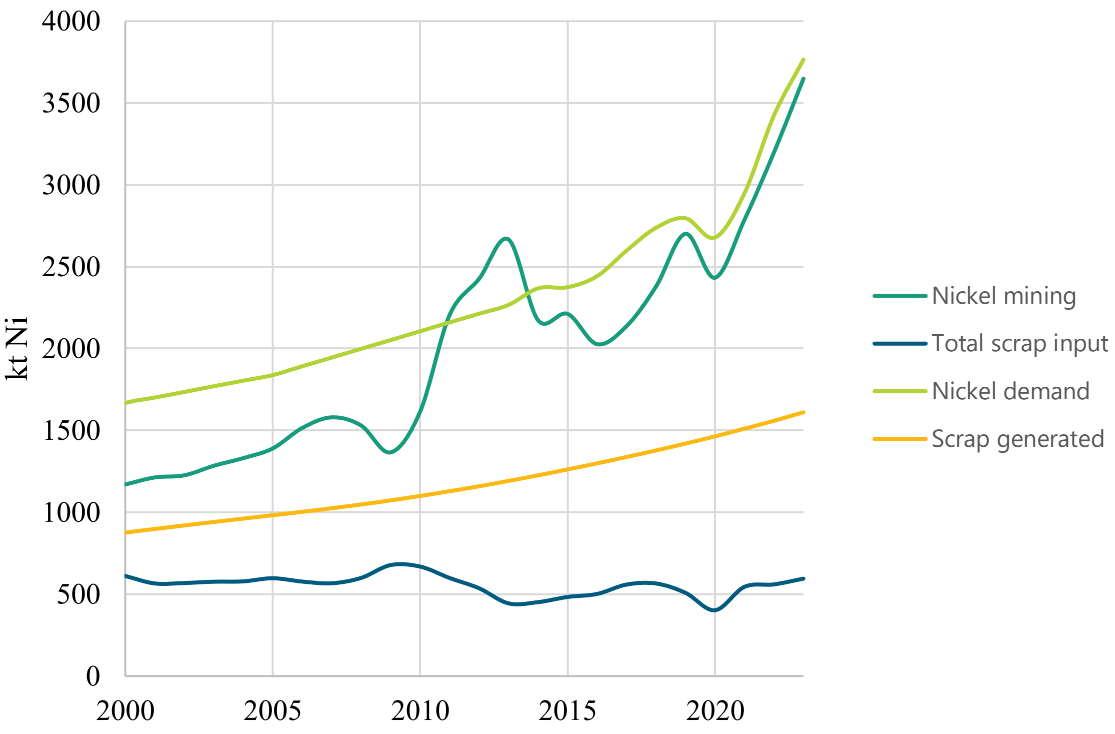

Figure 13. Comparison of nickel mining, demand, and scrap

Mathematically, the RIR equals the total input from old and new scrap divided by the sum of primary nickel production and the total of nickel input for recycling, therefore the decline in nickel recycling results from an increasing mine production but the recycling scrap input is stagnant as shown in Figure 13. In addition, referring to Figure 4, the sudden increase in mining without an increase in refining amount processed showed that there is a nickel concentrate stocked which is also affecting the RIR value. The condition occurred due to higher demand for nickel batteries, resulting in increased nickel mining activities. However, this was not accompanied by adequate refining facilities in Indonesia, the largest nickel producer. Additionally, China's investments in Southeast Asia, particularly in Indonesia and the Philippines, have been delayed by the prolonged construction time of refining facilities, thereby delaying refining operations.

A notable difference in Figure 13 exists between the amount of scrap generated and the total scrap input for recycling, it shows there is a loss of scrap not being recycled, which indicates inefficiencies in the collection and processing of nickel scrap. This difference reflects a loss of material that could have been a source in nickel production. Additionally, the difference between nickel demand and total scrap input shows that nickel mining still continues to serve as the primary source of nickel as a result of a lack of recycling. The correlation between nickel demand and total scrap input shows the missing opportunities to take advantage of the increasing volume of scrap produced, which, if efficiently recycled, could reduce dependence on resource-intensive nickel mining activities.

Another explanation of the decline in recycling phenomenon: Due to increasing demand in nickel for batteries which caused a rapid increase in production but since the batteries production has just recently trended, they are still in their use stage and no backflow is available for secondary sourcing to fill the increased demand. Another explanation is that there is difficulty in recycling batteries and therefore this problem needs to be solved in order to increase the circularity of nickel. Furthermore, the market demand for waste batteries is not yet enough to generate significant economic advantages such as recycling site establishment, and the composition of waste batteries is inherently complex, containing numerous hazardous substances and valuable materials (Kang et al., 2023).

Challenges regarding the use of recycled for batteries also occurred due to their purity requirement (Neidhardt et al., 2022). Secondary or recycled nickel often does not meet the high purity requirements necessary for lithium-ion batteries. This is particularly critical for EV batteries, where impurities can severely impact performance and safety. Consequently, the use of primary nickel is preferred.

3.4 Improving the circularity of nickel

Trends in nickel recycling practices can be observed through the results of the nickel model. Recycling indicator values, presented in Figure 12, show a decreasing trend starting from 2010. The nickel model's MFA enables essential quantification of these findings, providing evidence-based insights to close the material loop. By identifying opportunities for improvement, the model supports efforts to enhance circular economy practices.

According to the model results during collection phases, 73% of the overall nickel losses in the cycle occur between 2014 to 2023. The rationale for this is because the recycling of metals from various end-of-life materials is complicated due to the existence of numerous different and interconnected layers of materials. Therefore, improving the collection stages can significantly contribute to more circularity.

Based on their end use application, waste from construction, transportation, and industry is-relatively easy to collect and separate by mechanical sorting and pyrometallurgical methods. On the other hand, Waste Electronic and Electrical Equipment (WEEE) has poor levels of recyclability due to high statistical entropy and low metal content, resulting in unfavorable economic conditions (Zante et al., 2024). The largest share of WEEE is linked to end-use applications in the consumer goods and batteries category. This includes items such as computers, mobile phones, televisions, appliances, and batteries, which are notoriously hard to collect.

Studies indicate that WEEE, particularly tiny electronic devices, are frequently kept by customers rather than being put towards proper recycling (Shevchenko et al., 2019). This behavior may arise from convenience or a lack of awareness regarding recycling alternatives. Furthermore, numerous consumers dispose of WEEE in general garbage bins instead of transporting it to designated recycling facilities due to the compact size and convenience of discarding many of these gadgets. Recycling these products is crucial, involving a stronger regulatory framework and advanced technologies that can optimize collection, sorting, and recycling rates. For example, implemented digital product passports (Jensen et al., 2023) and automatic sorting using artificial intelligence (Charpentier et al., 2023).

3.5 Examining the expected increase in nickel demand

Nickel is used in several renewable energy technologies, with a significant portion allocated to the production of electric vehicle batteries. In the increasing concern regarding global warming, the consumption of fossil fuels must be reduced. As a result, sustainability strategies have come out as a strategic focus for the automotive sector. The industry has adopted vehicle electrification as its strategy.

The model results indicate a declining trend in the recycling indicator since the start of increased demand for nickel batteries. According to the IEA prediction, the primary driver for the growth in nickel demand remains EV batteries across all scenarios. Nickel for batteries demand is projected to rise in all scenarios, reaching 4.5 Mt by 2030 in the STEPS. In the APS, demand growth is slightly raised, increasing to 4.8 Mt by 2030. In the NZE scenario, demand escalates rapidly to 5.6 Mt by 2030 (IEA, 2024). This situation is concerning, especially if not complemented by an increase in nickel recycling. Because it will result in increased nickel extraction from primary sources, which will therefore harm the sustainability of the environment.

This MFA study pointed out a declining trend in nickel recycling caused by the rising demand for nickel in batteries. To reduce the decreasing trend of nickel recycling, reasons need to be investigated and political or technical instruments need to be discussed. To boost batteries recycling, it is important to assess the economic costs and associated policies of batteries recovery. On one side, the disposal of EV batteries also needs to be focused on since it required complicated discharge and disassembly processes, hence the reason for the high cost (Zanoletti et al., 2024). It is necessary to have a well thought-out collection and processing system in place when relevant amounts of EoL batteries start to become available.

4 Conclusions

This thesis presented a current dynamic model of the anthropogenic nickel cycle. The model enables a systematic analysis of the nickel cycle and an established assessment of nickel stocks and flows. Adequate data availability and increased efforts in collecting data are important to develop a model with reduced uncertainties and to achieve higher quality and more detailed information regarding the nickel cycle. Stakeholders are urged to collect better data in the future to enhance the model's quality. Nonetheless, this model offers a quantitative basis for assessing the material efficiency and circularity of nickel.

Additional research is necessary to obtain more precise evidence-based data by applying detailed information on each category of EoL scrap collection. This might be helpful in identifying which categories of scrap and recycling experience greater losses, thereby facilitating the implementation of targeted improvement strategies.

The key finding of the model indicates that there is a strong increase in nickel demand to reach 3,600 kt today. An accumulation from 1950 of 46,000 kt of nickel is currently in the use phase. Between 10 years analyzed, there is a 14,000 kt recycling potential of generated nickel waste, in which 73% of end-of-life scrap remains uncollected, representing the most significant losses in the nickel cycle. On average, recycling of 520 kt of nickel per year is happening. Greater efforts must be made to improve resource efficiency at this stage. Furthermore, the rising need for energy transition, particularly for nickel in batteries, is impacting nickel recycling indicators, all of which are experiencing a downward trend.

5 Appendix

5.1 Allocation of first-use to end-uses

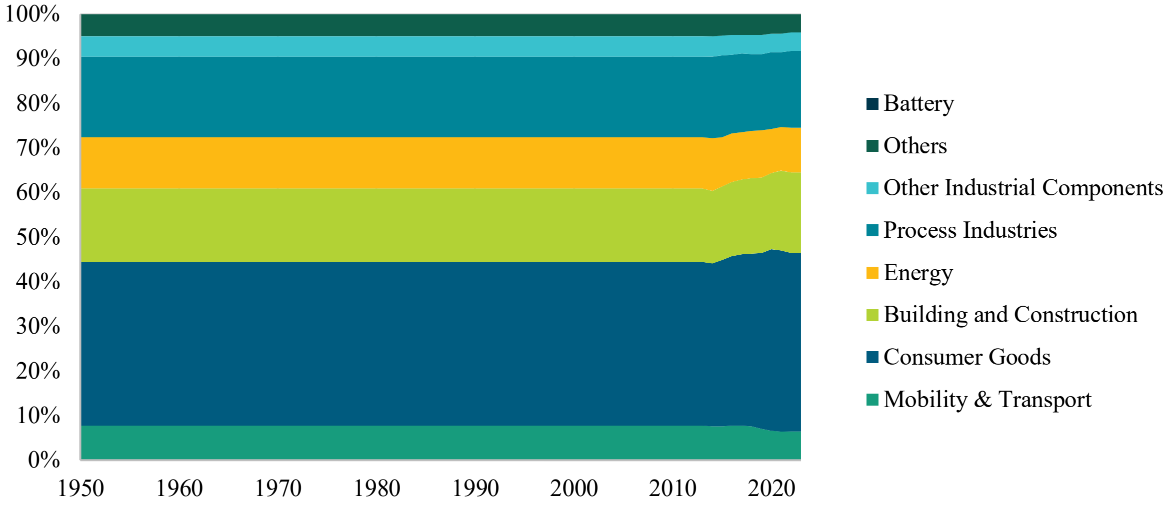

Figure 14. Allocation of stainless steel first-use to end-uses

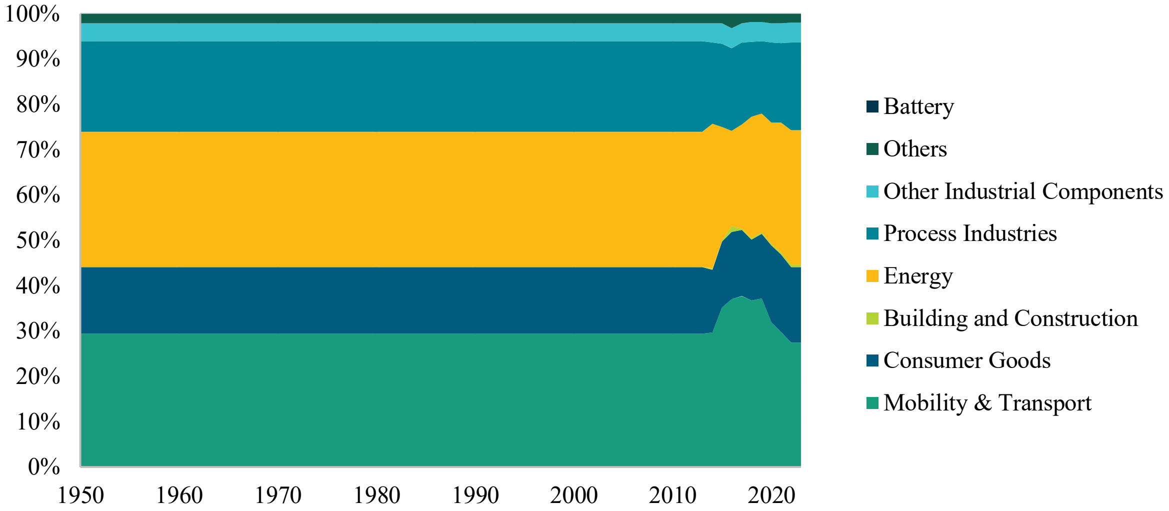

Figure 15. Allocation of Ni alloy first-use to end-uses

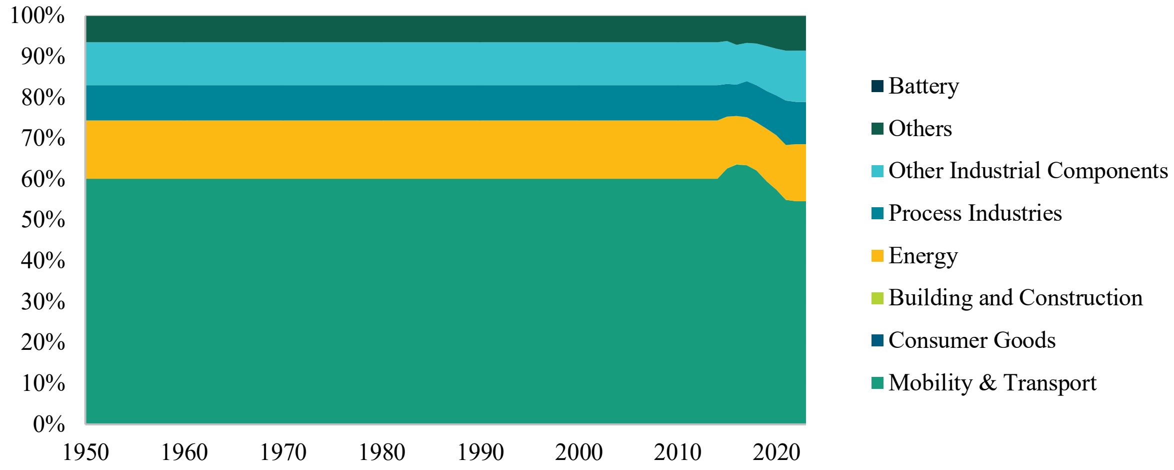

Figure 16. Allocation of alloy steel first-use to end-uses

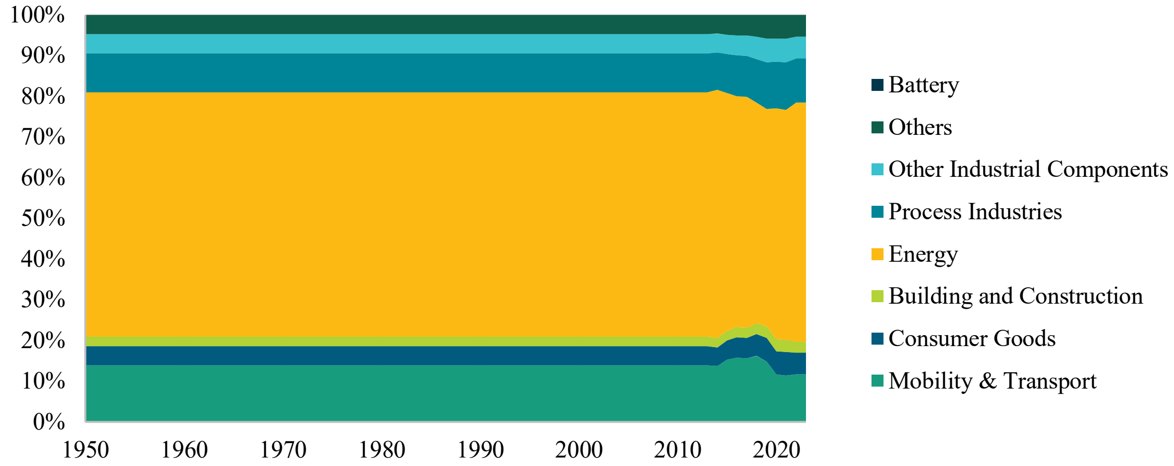

Figure 17. Allocation of STS foundry first-use to end-uses

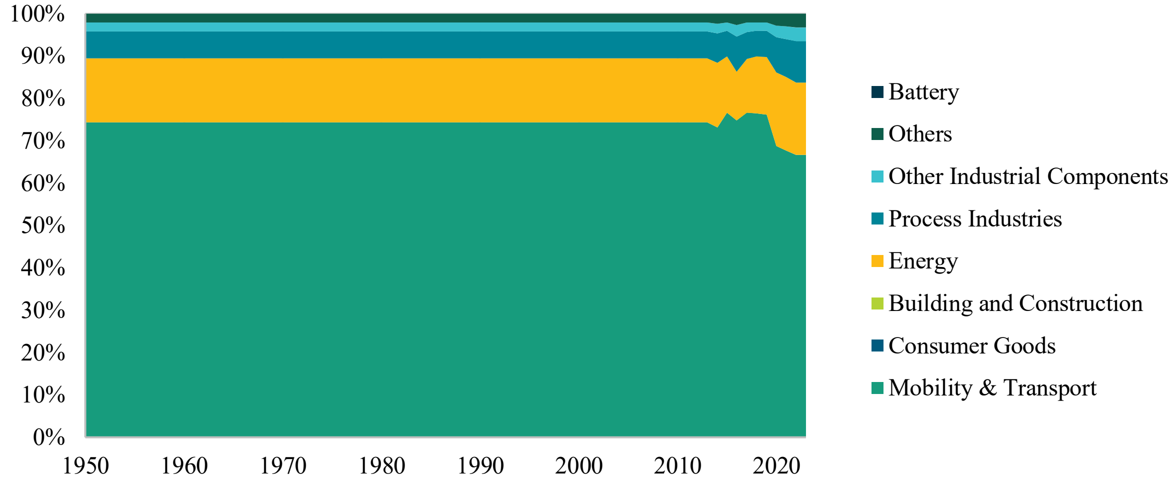

Figure 18. Allocation of NA foundry first-use to end-uses

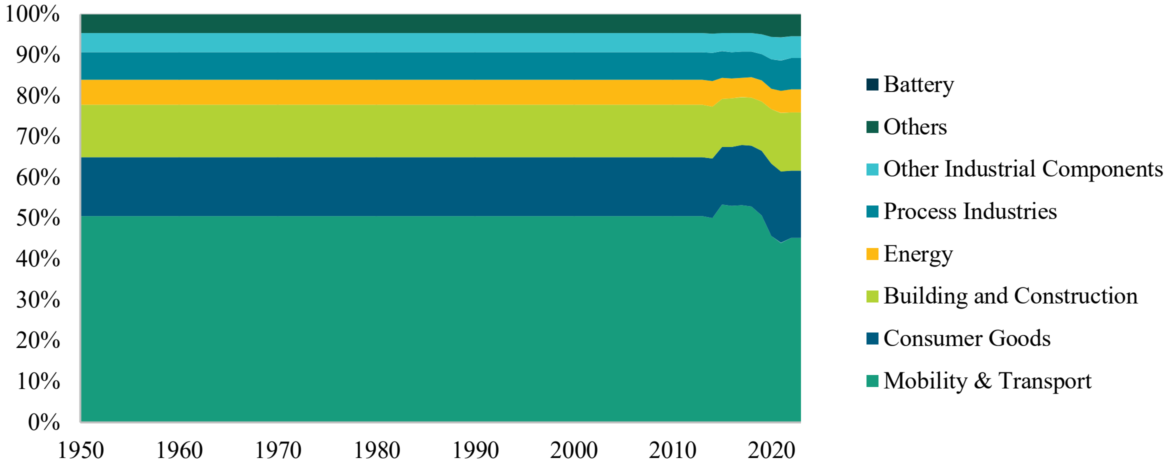

Figure 19. Allocation of plating first-use to end-uses

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