Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

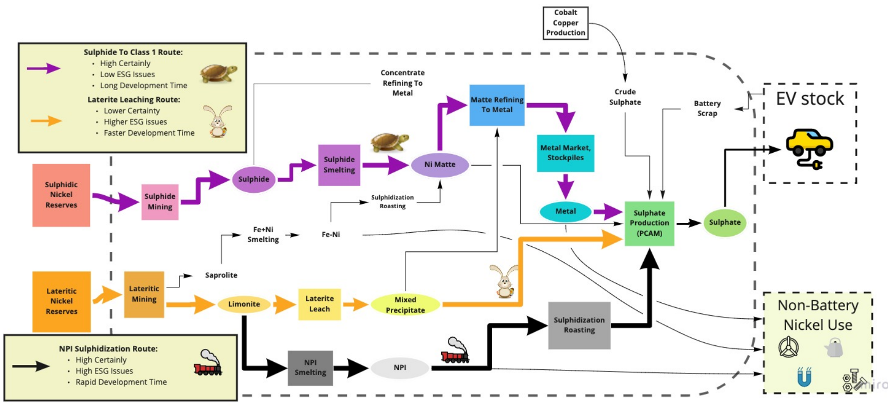
Eric Young

Battery Nickel Bottlenecks

A material flow analysis of the impacts the energy transition will have on the nickel supply system.

Master's thesis in Industrial Ecology
Supervisor: Daniel Beat Müller
Co-supervisor: Fernando Aguilar Lopez, Romain Billy, Evi Petavratzi (BGS), Barbara Reck (Yale)

June 2021



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Abstract

The energy transition is anticipated to create a large increase in the demand for battery grade nickel (Ni) for lithium-ion batteries (LIBs) due to the widespread adoption of electric vehicles (EVs). It is unknown whether Ni manufacturing capacity can meet the demand, and what the unintended consequences of rapid growth might be. This study aims to describe the limitations that the Ni processing infrastructure and technology will have on the timeframe and sustainability of Ni supply. Specifically, identifying potential supply bottlenecks and carbon footprint of the supply system under different development scenarios.

A dynamic material flow analysis model of the Ni system was developed with focus on Ni mining and refining infrastructure, linking the interacting factors of capacity, carbon footprint, environmental governance, and speed of development of different supply pathways of Ni for LIB and non-LIB uses. A range of possible storylines of the future development of Ni supply, battery demand, non-battery demand, and battery recycling were modeled and compared.

The risk of shortfalls was found to be connected to i) sustainability concerns, with likely bottlenecks arising from consumer and regulatory intolerance of the environmental impacts of the fastest developing supply pathways such as nickel pig iron smelting and ii) lack of timely investment in the most well established and green pathways such as sulphide ore refining. The influence of the non-battery supply consumption of Ni was found to have a large effect on both the risk of shortfalls and on the carbon footprint of the battery supply system.

These results suggest that the resilience and sustainability of the Ni industry during the energy transition can be best improved with focus on the Ni supply system as a whole, rather than targeting the battery grade aspects alone to avoid problem shifts. It is found that advanced investment in established and sustainable pathways should be combined with efforts to reduce the environmental impacts of the least sustainable pathways.

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Acknowledgements

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I would also like at thank Romain Billy, Professor Daniel Müller, and Fernando Aguilar Lopez for the generous amount of time, enthusiasm and assistance they each contributed to this project.

1 Introduction

The clean energy transition away from fossil fuels and toward renewable energy sources is being implemented in many countries and in many sectors. Driven not only by the goal of mitigating climate change, but also by promises of cleaner air (Zhang et al., 2020), energy security (Mathews & Tan, 2014), lower costs (Bogdanov et al., 2021), expectations of a shift from internal combustion powered transport to electric vehicles (EVs) has been especially increasing in the last 12 months with EV commitments from major automakers and governments (ACEA, 2020; Preston, 2021) and a 40% increase in EV sales from 2019 to 2020.

Rapid technological change sometimes outpaces the physical infrastructure which it relies on. Rapid adoption of lithium-ion battery (LiB) powered vehicles will drive increased production of the metals which compose the batteries, causing concerns over material sourcing and shortages. A need to have raw materials supplied quickly can influence decisions on how the materials are sourced and can create vulnerabilities to supply shortages. Such vulnerabilities in an unprepared supply system can echo downstream causing shifts in technology adoption. Previous study on critical minerals to LiB have focused on concerns over cobalt and lithium. Already, the LiB industry has been shifting away from technologies using cobalt in response to issues around cobalt supply. Nickel (Ni) is also a very important mineral for LiB manufacture, though having a larger and more established supply chain, it initially generated less concern. However, especially with Ni replacing cobalt in many LiB applications, questions surrounding Ni supply to batteries is becoming of interest to governments and automakers. (Azevedo et al., 2018; Energy Office, 2021; IEA, 2021; Olivetti et al., 2017; Petavratzi & Gunn, 2018; Watari et al., 2018; Yue Li, 2021)

1.1 LiB Demand

LiB components can be made from a variety of materials. Ni is typically used in the cathode of the battery in combination with other valuable metals such as cobalt, manganese, and aluminum. The proportion of Ni in the cathode and the mix of other materials influences the characteristics of the battery such as energy density, thermal stability, charge time, power delivery and more. For existing commercial chemistries, higher Ni content tends to provide a higher energy density and power delivery than alternatives. The Ni is mixed with other elements to increase the stability of the battery as well as simplifying the manufacturing process. The choice of combination of cathode materials, often referred to as the cathode chemistry of the battery, is made by the battery manufacturer on the basis of battery performance, and is influenced by availability and cost of the various materials, geopolitical considerations, as well as the technological complexities of producing the batteries. (Azevedo et al., 2018; Helbig et al., 2018;Graf, 2018; Nitta et al., 2015). In order to maximize the range of electric vehicles, as well as to reduce the use of cobalt, EV battery manufacturers are anticipated to produce many high-Ni chemistry LiBs (Fraser et al. 2021). However, alternate commercial chemistries exist which use no Ni in the cathode, often at a lower cost and lower performance making them less appealing for long range vehicle applications but attractive in economy vehicle or stationary storage applications (Roberts, 2021).

The choice of cathode chemistry and competitiveness of LiB technology in various applications will therefore influence the demand for Ni from the mining and refining industries. At the same time, the ability for the Ni sipply chains to meet the demand, will influence the cathode chemistry choices as well as the development and penetrations of LiBs.

1.2 Ni System

Compared with Li and Co industries, which are each driven approximately 50% by the LiB market (Ding et al., 2019), Ni is a much larger market which mainly serves stainless steel production, though other alloys as well as specialty sectors make up a significant portion of Ni use (see Figure 1). LiB use historically makes up a very small portion of Ni industry but may become significant driver of growth in future years to eventually occupying a large share of the total market. While this makes the scale up of LiB less disruptive on the basis to total system quantity, it also means that the Ni-to battery supply chain has to develop from a minor to a major role in the overall Ni system, and the way that role develops over the coming years may set the standard for what comes after.

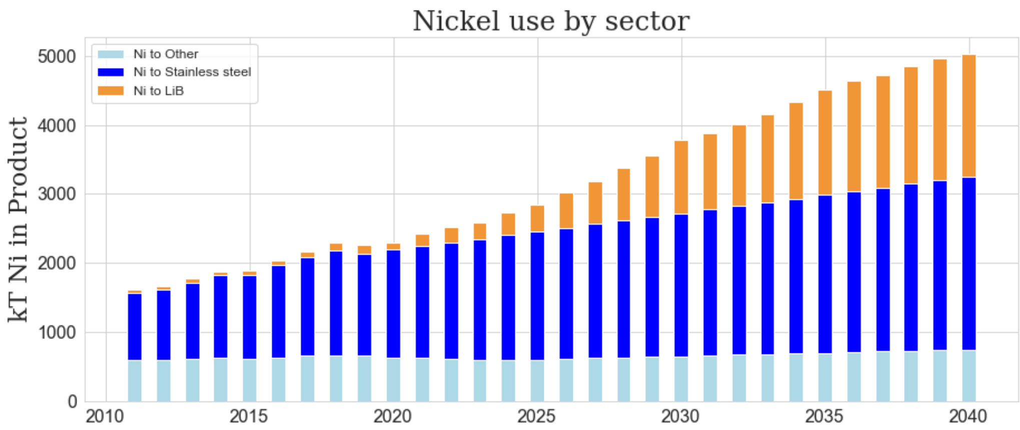


Figure 1 - Historic and projected Ni use by stainless steel, LiB and other sectors. Projections based on Fraser et al., (2021).

The Ni industry not only serves a variety of first use[1] sectors, but produces via a variety of mining and refining pathways. Different pathways to Ni production each have distinct challenges and benefits, and often cluster in different geographic or political areas. In previous work, *Bottlenecks to Global Battery-Grade Ni Supply* (Young, 2020), the various pathways of Ni supply were examined and classified according to the Ni supply system's ability to produce Ni for LiBs. In order to understand how the supply system can accommodate an increase in demand, the operating capacities of the infrastructure in the different Ni production pathways need to be added to the picture, along with the potential for building more capacity, and the time it will take to construct additional infrastructure where needed. Individual technological pathways have unique build-out times, certainty levels of meeting design capacity, and external impacts. By describing the time constraints of

1 1 "The first use of Ni is defined as the conversion of Ni products into intermediate products, which form the basis for Ni-containing end-use products. In nearly all cases, these first use products undergo further processing before they are ready for use." (Nickel Institue, 2016)

infrastructure expansion, bottlenecks in the supply system can be foreseen and strategies can be developed to mitigate shortages.

1.3 Environmental standing

In addition to cost and supply risk, the environmental, social and corporate governance (ESG) standing of the supply system can influence the choice of materials used in battery manufacturing. A main driver of LiB implementation is the goal of reducing emissions from transport, energy production and storage. Local and international regulations, as well as consumer awareness can manifest ethical and environmental sustainability dilemmas as material shortages. This has been prominent with cobalt and lithium where human rights issues surrounding mining have affected reliability of cobalt supply (Gourley et al., 2020), and concerns surrounding water use limit exports (Watari et al., 2018), though many other important minerals for the energy transition must navigate ESG concerns.

Ni production has its own set of concerns ranging from sulphur dioxide emissions (Peek et al., 2011) to tailings disposals (Anderson, 2020) to national economic and sovereignty interests (Jorari, 2020; Terauds, 2017). In order to implement regulations and goals which target the ESG of Ni production and of LiBs, knowledge of system dynamics is important to formulate meaningful and effective targets.

Literature Review

To address the topic of Ni supply to the LiB industry, background research was conducted into the Ni supply system both mining and consumption as well as LiB technology and industry. An attempt was made to understand the different environmental and social factors that affected the supply and the demand of each sector. Additionally, research was done to understand the recent and anticipated technological developments which are likely to cause changes to the sectors.

The topic of mineral resources as relating to anticipated growth of the LiB industry has been receiving an increasing amount of attention. Research findings on related topics are being generated by academic researchers, government institutions, and private consultancies to the minerals industry. The most important sources found relating to each topic are discussed in this section.

1.4 Ni System Dynamics and Technology

A comprehensive overview of the technological processing of Ni throughout the mining and refining value chain is given in reference works specific to the industry (Crundwell et al., 2011; Kerfoot, 2000) including flow transfer rates of Ni and associated elements for representative facilities. More recent developments to Ni processing technologies were investigated in journal articles (Keskinkilic, 2019; Rao et al., 2013), proceedings for industry conferences (Dry et al., 2019; Valle et al., 2016), and company news releases (Blackstone Minerals, 2021; Vale Inco, 2008). These sources explain the technical elements of individual Ni mining and refining processes, but do not draw connections between system elements or quantify the size or proportion of the different technologies.

A thorough overview of the context of Ni mining can be gained in three articles by Gavin Mudd which describe the history , environmental context and resource availability of Ni production (Mudd, 2009, 2010; Mudd & Jowitt, 2014). Mudd quantifies the resource endowments and Ni production at mostly a mining scale, with less attention given to intermediate processing steps, and little attention to differentiating the Ni supply system according to various use sectors.

While these sources are comprehensive in understanding the component parts of the Ni supply system, in order to assess systemic issues such as bottlenecks and burden shifts a methodology is needed which considers the relationships between the components and the system as a whole.

1.5 MFA studies

Studies using Material Flow Analysis (MFA) methodology were found which provide a comprehensive overview of the main production and use processes of Ni generally as well as recycling capabilities and product lifetimes in the system. Reck et al., (2008) quantified the global Ni cycle for the year 2000 at multiple levels, dividing the Ni system into mining, smelting, refining, fabrication, manufacturing, use, and waste management processes. This study differentiated the cycles regionally as well as detailing different goods categories downstream of fabrication, though batteries were not a significant goods category at this time and were categorized together with catalysts, chemicals, dyes and other uses. Elshkaki et al., (2017) extended the same Ni system in time by developing supply and demand projections based on historic flows and lifetimes and also connected the Ni cycle to energy and water use impacts, though again with no attention given to Ni for LiB use. Schmidt et al., (2016) conducted an MFA style analysis of Ni and cobalt use in LiB production with a more targeted focus on Ni to batteries including a system definition specific to batteries, though this study is a static quantification and does not address developments in the system. A noticeable gap in the MFA studies of the Ni cycle was found in the resolution of the mining, smelting, and refining stages of the Ni cycle. While fabrication and use categories were developed, production pathways have been minimally differentiated and not quantified.

1.6 Carbon Footprint of Ni for LiBs

While many of the above noted studies address environmental impacts of Ni production generally, a specific literature review was also conducted targeting carbon impacts stemming from Ni production and especially Ni for batteries. Several studies were found which use LCA methodologies to quantify impacts related to various forms of Ni production generally (Khoo et al., 2017; Ni Institute, 2020; Reuter et al., 2015), with one found to be specific to Ni use in batteries (Majeau-Bettez et al., 2011). While many of these studies provide carbon impacts of Ni products, the differentiation of the impact profiles of the various pathway options to nickel production is not specified. Nor has direct focus been given to the future development of the carbon footprint of the average Ni product.

1.7 Dynamic supply and demand models of Ni for LiBs

This overview of literature on the Ni supply industry indicates a notable gap of studies of Ni industry as it relates to LiBs, particularly quantified studies of the Ni to LiB industry at scale and addressing the potential for change in demand from this sector. This gap is understandable considering that the significant material use of Ni in LiB production is a very recent issue which is only recently being seen in literature focusing on the issue from the battery perspective (Liu et al., 2019; Olivetti et al., 2017), which give only brief and divided attention to Ni as well as other key battery materials such as Cobalt (Co) and Lithium (Li). Publications were also sought describing the most common LiB technologies and the cost benefit analysis of the material components at the battery scale (Kim et al., 2019; Nitta et al., 2015).

Because the topic of LiB technology development and the expected demand for minerals is changing quickly, often beyond the pace of academic scholarship publication, this thesis relies substantially on industry reports from mineral commodity consultancies for recent data and technology developments. While outlooks can be found on the supply and demand for Ni to the LiB sector, produced by consultancies such as Platts S&P Global[2], Roskill[3], Wood Mackenzie[4] and Benchmark Mineral Intelligence[5], the methodology and assumptions used

[2] https://www.spglobal.com/platts/en (accessed June 9, 2021)
[3] https://roskill.com/ (accessed June 9, 2021)
[4] https://www.woodmac.com/ (accessed June 9, 2021)
[5] https://www.benchmarkminerals.com/ (accessed June 9, 2021)

are not made available, making it difficult to assess under which conditions supply shortages might arise.

Two recent reports address directly the anticipated LiB boom and Ni's role in it. *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021), covers many aspects of the energy transition beyond LiBs, though detailed quantitative data is given regarding many material demands and environmental impacts, including Ni. *Study on future demand and supply security of Ni for electric vehicle batteries* (Fraser et al., 2021) provides one consultancy's assessment of the outlook for Ni use and shortages in LiB, based on their own research of ongoing and announced industry developments. Though the study does not describe a system definition, the report provides useful quantification of the global flows of Ni currently and for recent years, though the future development describes only a single base scenario, and does not provide in-depth analysis of the possible alternatives. The historic data from this study has been used significantly in this masters thesis for system quantification of the current year, and the base scenario described in the model has been used as a basis for some of this thesis's storylines.

1.8 Knowledge gap and background report

The literature review of this topic identified a knowledge gap regarding studies which evaluate the ability of Ni supply system to meet potential demand to the LiB industry in a sustainable manner, particularly studies which evaluate this question with a quantified, system wide approach focusing on the infrastructure of production.

This thesis builds on the report *Bottlenecks to Global Battery-Grade Ni Supply* (Young, 2020) which was the first report of this project on the Ni supply to LiBs. In that report a system definition for the global Ni supply system was developed. Process and goods categories were defined into which all existing Ni production facilities and products can be grouped. Additionally, important limitations and impacts of the various process categories were identified. That report quantified the flows of Ni in intermediate products through the supply system for the year 2018, but did not assess the future development of the system.

That report identified avenues of further research, noting especially: 1. The value of improved resolution of the facility-based understanding of the supply system in order to comprehend the dynamics of capacity at a system level; 2. The value of a dynamic material flow model of the Ni supply system to identify and quantify bottlenecks and development pathways in meeting possible battery demand for Ni; 3. A targeted discussion on relationship between design capacity, production, and realistic capacity in conducting supply system studies.

The current work is targeted at addressing the gaps suggested by the review of the existing literature. The goal is to create and quantify a detailed system description of the global Ni supply and demand system as it currently exists, particularly in relation to Ni for the LiB sector; to link the system description to relevant environmental metrics; and to use the system to describe reliable interactive relationships within the system, that can consistently provide insights under various realistic future development scenarios.

Research Questions

The goal of this thesis is to improve understanding of the Ni supply to Lithium-ion battery production in the context of the global Ni supply system. Main research questions to be addressed are :

1. Under what conditions can there be a shortage in Ni supply for the LiB industry? Over the next 30 years, where and when might capacity bottlenecks arise in the Ni supply system?

2. What options are there in the future development of the global Ni supply system to avoid or mitigate shortages?

3. What consequences would different development options have for the carbon footprint of the global Ni supply system?

2 Methodology

To answer these questions, the global Ni system was mapped out using Material Flow Analysis (MFA) principles focusing on separating Ni for batteries from Ni for other uses. Ni demand was quantified for both battery and non-battery uses and the capacities of Ni mining and producing infrastructure was quantified. A dynamic model of the material flows of the Ni supply system was developed based on the principles of mass balance and uses the methodology and terminology of Material Flow Analysis (MFA) in the tradition of Brunner & Rechberger (2016), and Baccini and Brunner (2012). A clear system definition was developed, based on the work presented in the first report of this project. by which the demand processes for Ni in battery and non-battery products were linked to mining and refining processes that supply Ni feedstocks. The demand was projected into future years and the flows of Ni products to meet the demand were constructed based on supply constraints described in the model. Figure 2 describes the basic model overview and model drivers.

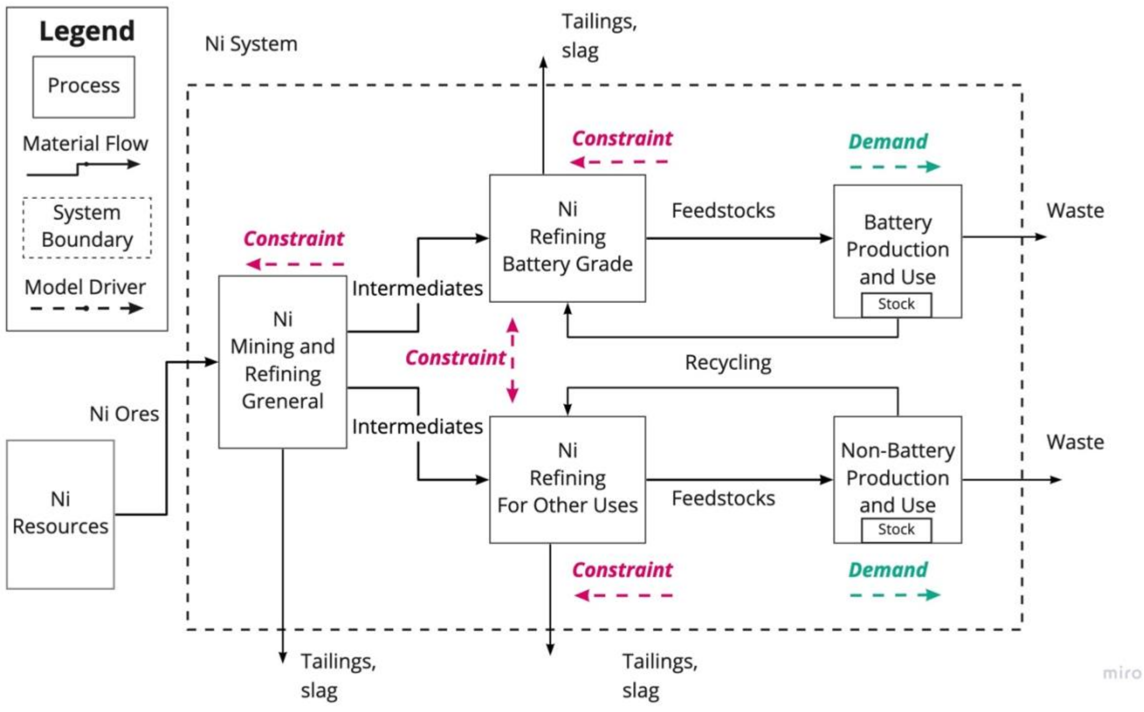


Figure 2 - The Ni system as approached in this study. Production and use of Ni products creates demand for Ni feedstocks which is supplied by Ni mines and refineries which travels up the supply chains. The capacities of the mines and refineries constrain the production of the processes downstream and the amount of total production. Because total upstream production is limited, the flows of Ni going to battery production constrain Ni available for non-battery production, and vice versa.

Different manufacturing routes exist which supply distinct intermediate Ni products, each of which can be used only by certain downstream processes. This variation in quality of feedstocks throughout the supply system provides constraints on how demand can be met, with the feedstock demand of any process in the system only being able to be met by the product of some upstream processes but not all. In order to model the multiple manufacturing routes to a common feedstock, rules were developed to determine the priorities of supply processes used by the model to meet the demand. These priority lists further constrain how the demand is met. Finally, to model the limitations of production of the real-world analogues to the supply processes, capacities were assigned to certain processes to represent the maximum flow value that process could output for a given model year. These capacity limits combine with the other constraints of the model to create a representation of how demand for Ni is supplied in the real world. The system definition, demand profiles, process capacity profiles, and system rules are based as realistically as possible on the author's understanding of the existing Ni supply system and its likely developments. To represent different possible future developments, various profiles of demand and capacity were developed. A demand profile here means a set of flow values for every model year for a certain driver flow, while a capacity profile refers to set of capacity values for a certain system process, again for each model year. A combination of demand and capacity profiles at all relevant system locations (discussed below) will make a scenario, which the model uses to calculate a quantification of flows of Ni throughout the modeled supply system. All demands, capacities and flows are quantified in annual mass of contained Ni. The model calculates a single scenario of historic flows from 1900 to 2019, which is the base year for the model. Future flows are calculated for multiple scenarios over years 2020 to 2050.

2.1 Model and System definition

Figure system definition was developed which was explicit about the geographic and temporal scope of the study. All relevant activities such as production, transformation, storage, distribution and consumption which are modelled in the study are assigned to specific system processes, with the explicit understanding that all activities belong to a single definable system location. As with activities, all quantities of goods represented in the study are described as system variables and are again assigned to a definable system location as either a stock, or a flow. All variables have clearly defined associated processes for all points in time. In the case of a stock the process of residence describes the location of the stock variable in the system, in the case of a flow the system location is defined by a process of origin and a process of destination. Figure 3 diagrams this study's definition of the Ni supply system.

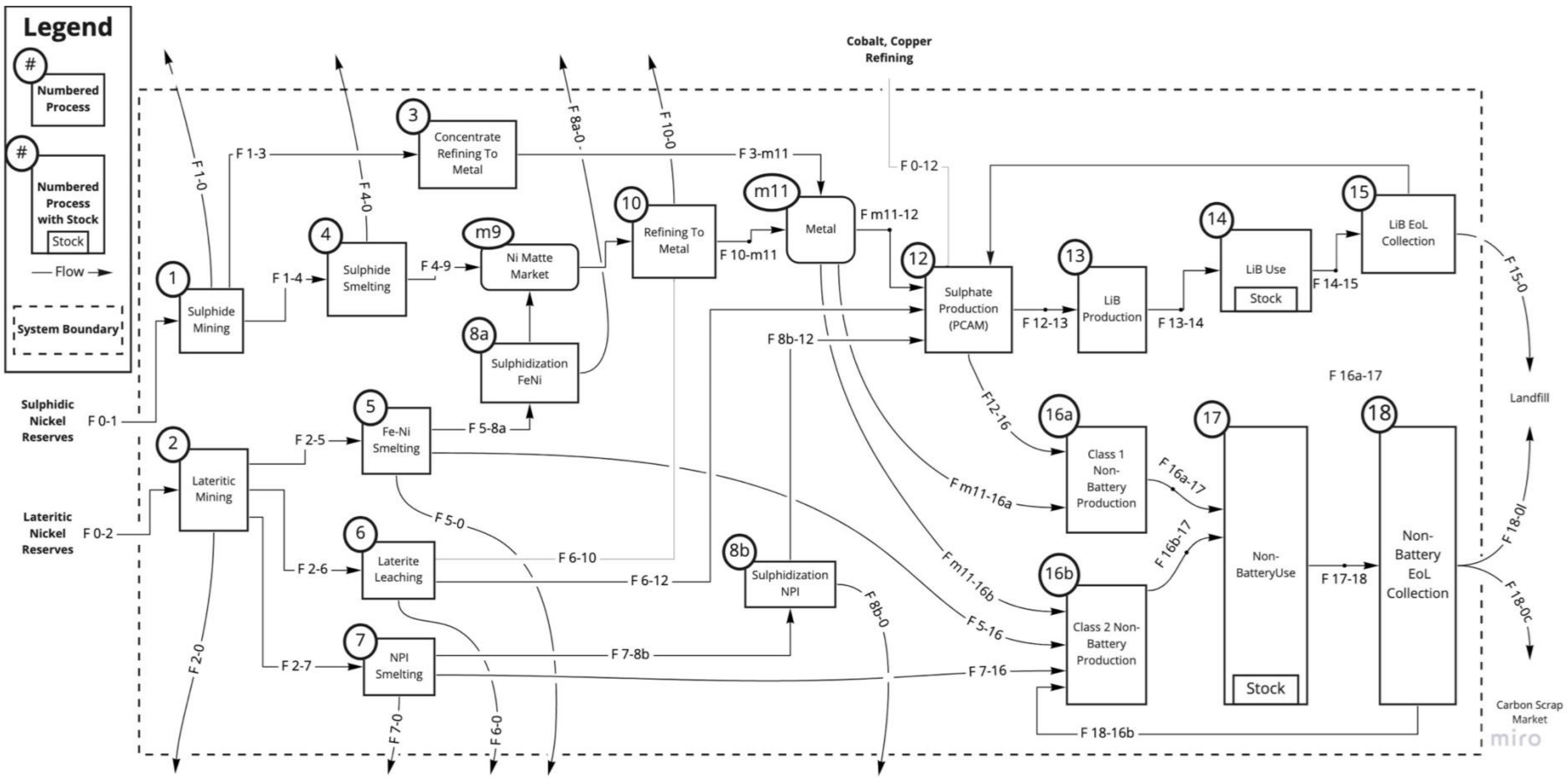


Figure 3 – Global Ni Cycle, 1900-2050. MFA system definition describing the Ni supply system via the interactions of the material Ni itself. System is described as individual processes which are locations of Ni storage or transformation, stocks which represent reservoir amounts of Ni material in residence within a process, and flows which describe the links between processes in amounts of Ni moved from one process to another per year. System boundary conscribes the study area. All stocks and flow values within system boundaries are tracked and mass balance is maintained within the system boundary.

The system boundary contains all Ni which is currently in productive use by the global society. This includes all Ni containing goods such as mined ores, intermediate feedstocks, products and wastes, which are in the course of being made or disposed of.

Most Ni enters the system through mining in processes 1 or 2, with a small amount entering to process 12 as a byproduct from other industries. From mining, Ni ore enters a series of refining processes. Processes 3, 4, 5, 6, 7, 8, 10 represent various hydrometallurgical (refining using aqueous solutions) and pyrometallurgical (refining using temperature) processes which refine and upgrade Ni from raw ore to a feedstock which can be directly used in either Ni sulphate production or in production of non-battery products. Flows moving downstream through these processes are refined step by step to higher purities of Ni. Flows leaving these processes and crossing the system boundary represent Ni material contained in processing wastes such as tailings and slag.

Proceses m9 and m11 are market processes which do not represent transformations to the Ni material but facilitate the combination or separation of Ni flows.

Process 12, Sulphate Production, is a hydrometallurgical process which transforms various feedstocks into Ni sulphate, a necessary feedstock for LiB cathode production but also used in certain non-battery manufacturing processes such as electroplating.

Processes 13-15 represent the manufacture of LiBs, the stock of LiBs in use in society, and the end-of-life collection of used LiBs. From process 15, Ni in used LiBs is either recycled back to process 12 to be remade into Ni Sulphate or is disposed of to landfill.

Processes 16-18 represent the manufacture of all non-battery Ni containing products, the stock of those products throughout their useful lifetime in society, and the end of life collection of those products. From process 18, Ni in end-of-life non-battery products are either recycled as scrap back to production of non-battery products, recycled into carbon steel which causes them to be lost from the nickel system, or sent to landfill.

The main Non-battery first use categories of Ni production are Stainless steel, Cu and Ni based alloys, alloy steels and castings, and electroplating. These different first use categories require different qualities of Ni feedstocks for their production, and the demand for these different quality feedstocks affects the development of the Ni supply system. In the model the feedstocks are divided into Class 1 (high grade) Ni Sulphate (high grade) and Class 2 (low grade). Matching this, the model divides the non-battery demand sectors is into two categories and assigns them to process 16a -demand categories that require high grade Ni feedstocks (all categories other than stainless steel) and 16b - demand categories that can accept both high and low grade feedstocks (stainless steel), and process As some NoB sectors have a strong preference for Ni Sulphate there is a minimum amount of Ni Sulphate that is required to process 16a also.

All processing wastes in processes 12 – 18 are reused in the processes and so no direct losses to tailings occur from the transformation processes.

Outside of the system boundary are Ni goods in states which are not currently being used, such as ore reserves and resources, tailings storage and disposal areas, and landfills. Also outside of the system boundary, and outside of the scope of this study, is Ni in goods which are in use by society though the Ni itself is not serving a purpose and is not likely to be recovered to the Ni system, such as Ni contained in carbon steel products.

The criteria used for determining what is included in the system boundary is significance for the capacity of the supply system infrastructure to meet demand for Ni. The assumption was made that the limiting factors for the supply of LiBs are not geological but technological, this assumption is supported in literature (Elshkaki et al., 2017; Mudd & Jowitt, 2014) and in conversation with industry actors. The scope of this study is limited to bottlenecks caused by the capacities of the infrastructure which produces and processes Ni in the supply system.

2.2 Classification of Processes and Flows

The supply system was built from bottom-up data on existing mining and refining facilities. Each of which was assigned to system processes according to their activity in the system and the products they create (see Figure 3 for processes). For example, in the case of mines, there are many different types and qualities of Ni ore reserves and mined Ni ore products; in the system, however, any mine facility is classified into either the sulphide mining process or the laterite mining process dependent on whether the input to that mine is best classified as sulphide or laterite ore and what next processing step the output is best suited for. For a product manufacturing facility, meanwhile, all facilities will be classified into either LiB production (process 13), class 1 non-battery production (process 16a) or stainless steel production (process 16b). A determination is based on whether the output of the manufacturing process is a LiB cathode and whether the input of the production requires pure class 1 or Ni sulphate feedstock or if it can accept a mixture of class 1 and class 2 Ni feedstocks. Figure 4 gives an overview of the geographical dispersion of Ni processing facilities (mines excluded), and a first-order approximation of the technologies used.

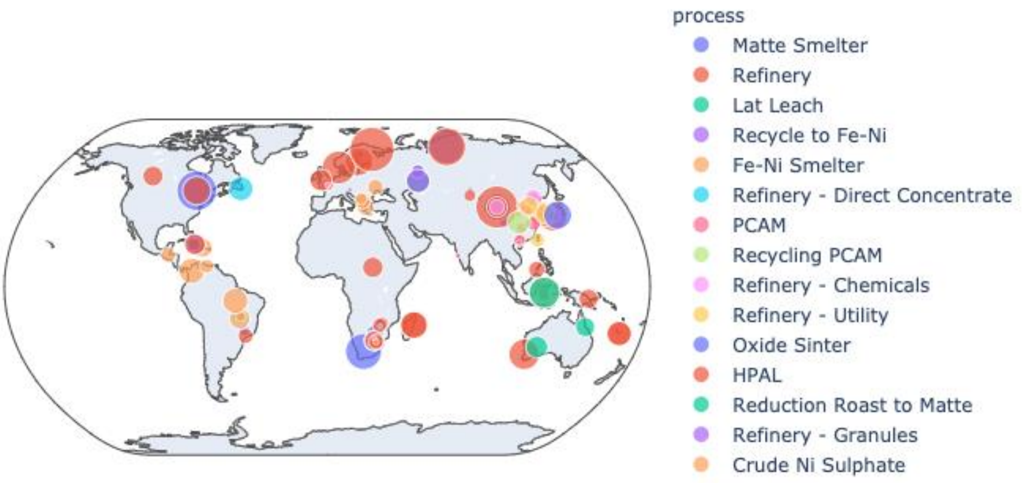


Figure 4 - Geographical location of refining facilities by initial assessment of technology type. Size of icons represents reported capacity of facility.

Throughout this study, flows and stocks of Ni containing goods are referred to according to the common name of the goods, products or intermediate products which they typify, and are classified in the system according to their processes of origin and destination. FerroNi (FeNi) for example is defined in the Ni industry as a nickel product between 25% and 50% Ni with 75% to 50% iron (Crundwell et al., 2011), but for the sake of the model, all Ni in goods which are produced by facilities classified as process 5. Flows F 5-8 or flow F 5-16 are therefore referred to as FeNi regardless of whether the goods represented truly meet the standard definition of FeNi. For example, Ni oxide sinter is also produced in facilities classified into process 5, and is consumed in process 16b. Therefore, Ni oxide sinter are included in flow F 5-16 in this model. An explanation of the different characteristics which were determined to be significant for classification is gone over in detail in this projects earlier report (Young, 2020).

2.3 Model Drivers, Subsystems and Parameter Sets

The driver of the system is assumed to be the consumption of Ni in the battery and non-battery sectors. In the model system, flow F13-14 represents the amount of Ni in LiB manufacture per year while the flow F16-17 represents the amount of Ni in NoB production. The profiles of these flows in combination with the profiles of recycling of these sectors create the demand for new Ni products. Using these flows as drivers, the model system is segmented into four independent sub-systems as visualized in Figure 5. Those subsystems that are downstream of the drivers - the LiB and non-battery subsystems - are modelled using inflow driven time cohort models, while the upstream subsystem – the Ni supply subsystem – is modelled as outflow driven. The LiB recycling subsystem is both upstream and downstream of the drivers, and is modelled with a simple inflow driven transfer coefficient[6]. The details of the subsystem methodologies are described individually below.

The base year of the model is 2019 as this is the most recent year the author was able to find data for the state of the system. The model spans from 1900 to 2050 with all years before 2019 labeled as historic years and a single set of parameter values entered for those years. In the NoB Demand and LiB Demand subsystem these historic years are important for building age cohorts of stock to provide realistic outflow values in future years. No stocks are assigned in the Ni Supply subsystem. In this subsystem the historic years do not affect the future years of the model, though historic capacity values were researched and assigned to try to mimic the historic development of the global Ni supply system as context to the development modeled in future years.

[6] Because the non-battery recycling is outside the scope of this study, non-battery recycling has been incorporated into the non-battery demand system while LiB Recycling has been separated out for explicit study.

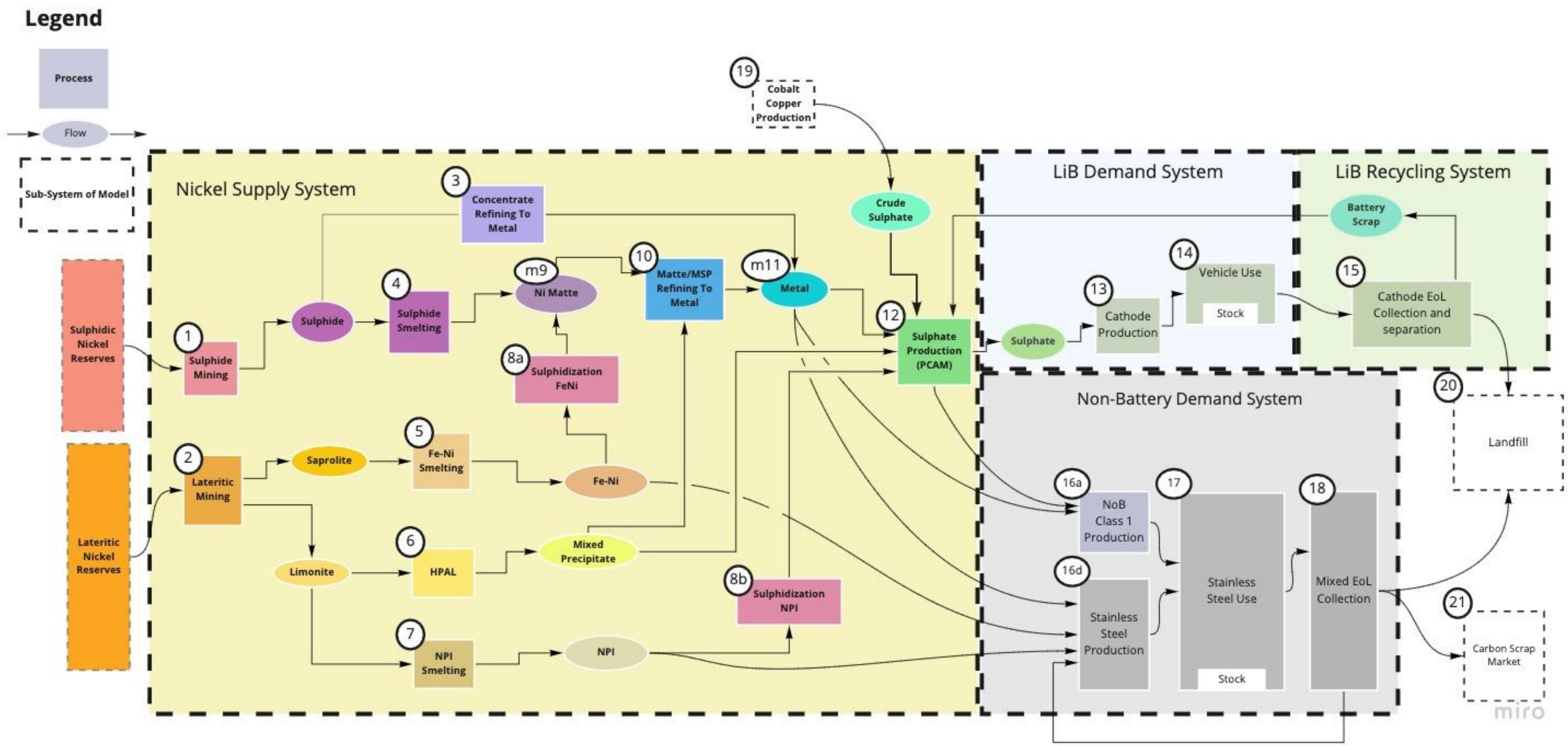


Figure 5 - Subsystems of the model: The yellow system represents the primary production of Ni, while the light blue and grey represent the consumption systems for LIBs and other industries respectively. The green system is the recycling of spent LIBs and recovery of secondary material flowing back into the Ni system.

For future years of the model (2020 – 2050) a variety of parameter profile settings were developed in order to model potential developments in the various subsystems. Each parameter profile is based on research and discussions with experts to try to describe a possible development of the system. Rather than varying the parameters individually to make complete model scenarios, the model parameters have been grouped together into parameter sets which belong to independent subsystems. All capacity values for example are parameters which belong to the supply subsystem set, while profiles for LiB and non-battery demands each belong to their respective subsystem. LiB recycling rate is a parameter set of its own being the only parameter in the LiB recycling subsystem. Parameter set storylines were developed to give insight to relevant issues relating to the research questions of this project. The parameter set storylines of each subsystem are independent of the parameter set storylines of the other subsystems in the model, and combining the parameter set storylines in different permutations creates separate model scenarios. **Error! Reference source not found.** shows an overview of the different parameter set storylines and the data on which they were based.

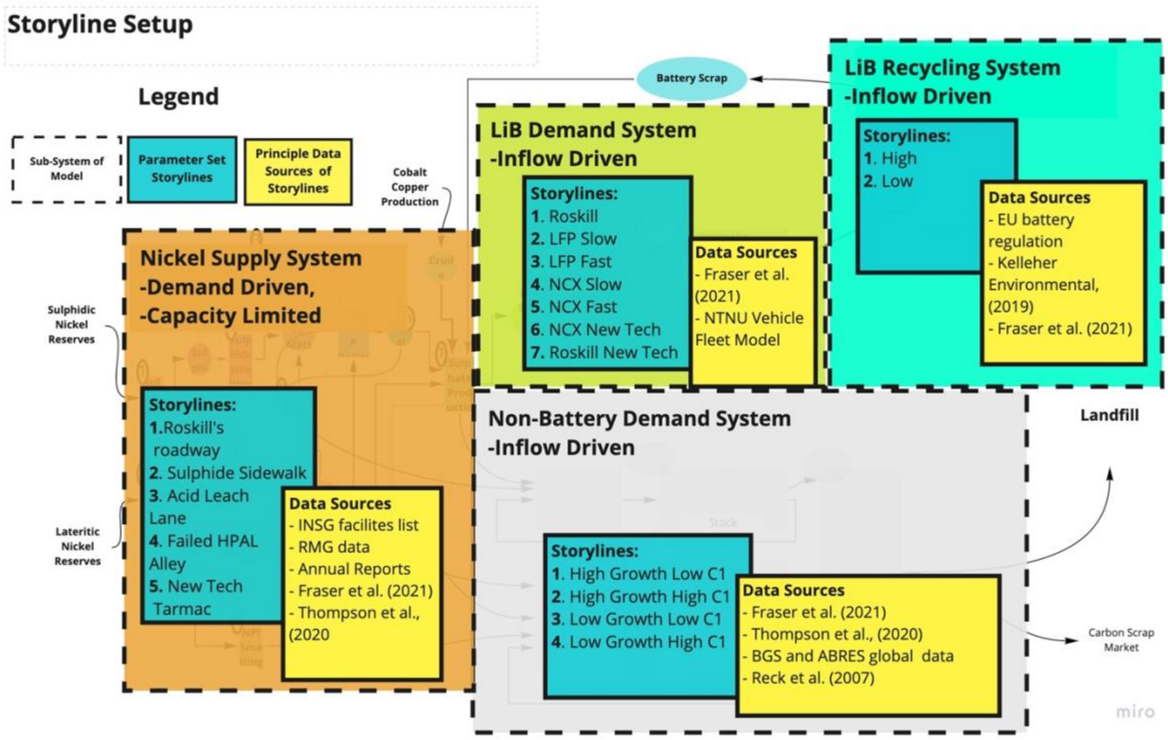


Figure 6 Visualization of model subsystems and their attendant parameter set storylines.

Useful insights are to be derived by comparing model results between scenarios and integrating the model results with knowledge of realities of the Ni supply system. This division is somewhat unrealistic, as the supply and demand from the different systems will influence one another's development. The parameters of the different systems are largely controlled by stakeholders who are mainly associated to a certain subsystem. For example, vehicle manufacturers and users have most control over the battery chemistries and gross EV production/penetration but less control over elements of the Ni Supply system. Mining companies on the other hand may have control over facilities spanning several processes of the Ni Supply subsystem, but have less influence over the LiB Demand subsystem. A similar dynamic exists with policy measures which for the most part target one subsystem. Of course, agreements are made between stakeholders in various subsystems (for example through exclusive offtake agreements), and policy measures in one part of the system may be targeted to another (for example the proposed EU directive limiting embodied carbon in batteries sold in Europe may be targeted to control emissions farther up the supply chain). This is the reason for a systemic analysis. This separation is taken to be useful in understanding the system dynamics and how a desired development in one subsystem can cause a bottleneck in the other.

2.3.1 LiB Demand Subsystem

The inflow-lifetime-driven cohort-based model used in the LiB subsystem uses the inflows of Ni for each year – making a cohort – and applies a lifetime function to them in order to calculate what quantity of the Ni from that cohort leaves the system each year as an outflow. For any model year, the sum of outflows from all previous cohorts makes up the total outflow for that year. The difference between the inflows and the outflows gives the stock change (balance equation). The stock at the end of the year is equal to the sum of the stock at the beginning of the year and the stock change during the year (intrinsic equation) (Lauinger et al., 2021). In this way, the parameters needed for the LiB subsystem are the total inflows of Ni to LiB manufacture and the lifetime profile of Ni in use as LiBs.

The inflow values of Ni to LiB manufacture were modelled based on LiB use in EVs. Though there are anticipated to be large markets for LiBs outside of EVs as well, including personal electronics and stationary energy storage, this study assumes the main driver of Ni to LiBs to be EVs. Higher energy density of Ni bearing cathodes are accompanied with higher costs making stationary storage solutions more likely to use non-nickel cathodes. Personal electronics, meanwhile, are relatively small from a materials perspective and are likely to use high-cobalt chemistries in the interest of thermal stability (Fraser et al., 2021; Holman & Dart, 2020). For this reason, the demand for Ni in the LiB sector is taken to be driven by the EV industry and use by other sectors is takes as negligible.

This study bases its LiB storylines on two sources. Some storylines are based on the demand described in Fraser et al., (2021), a study produced by a knowledgeable industry consultancy based on their assessment of likely developments in the industry. This is taken to be an authoritative description of a likely scenario. Other storylines are based on a stock-lifetime-driven model of the global vehicle fleet developed by Fernando Aguilar Lopez as part of a PhD thesis and remain unpublished as of the writing of this thesis. This stock driven model is based on baseline total stock development of the vehicle sector assumptions about development of cathode chemistry mix first presented by Xu et al., (2020) . Figure 7 shows the market share assumptions used to create the LFP and NCX storylines. The NCX scenario shows an overtaking of the market with increasing shares of chemistries of higher Ni content. Technical challenges currently limit the proportion of Ni in cathodes but advances that allow for economic use of high-Ni chemistries will mean a higher energy density. The LFP scenario in contrast shows the market adapting to make extensive use of zero-nickel LFP cathode chemistries, with high-Ni chemistries being reserved for high-performance applications.

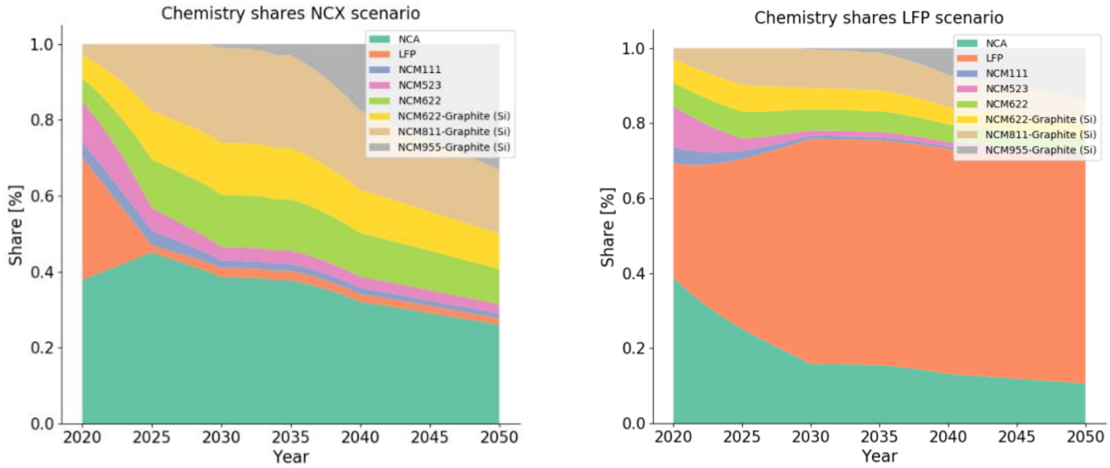


Figure 7 - Cathode chemistry market shares of EV LiBs used to model Ni demand to LiB sector under different technology development scenarios. Figures based on (Xu et al., 2020)

Each chemistry share was also modelled with a slow and a fast storyline of EV penetration, meaning the pace at which EVs come to be the dominant type of vehicle on the roads, shown in Figure 1. The slow storyline, based on the STEP scenario of the IEA *Global EV Outlook* (IEA, 2020), shows EVs growing to be a 20% market share by 2050 with a total vehicle sales increase to 140 million vehicles. The fast storyline meanwhile has a faster market share increase to 50% by 2050, as well as a higher total stock so that the vehicle sales in 2050 reach 160 million vehicles.

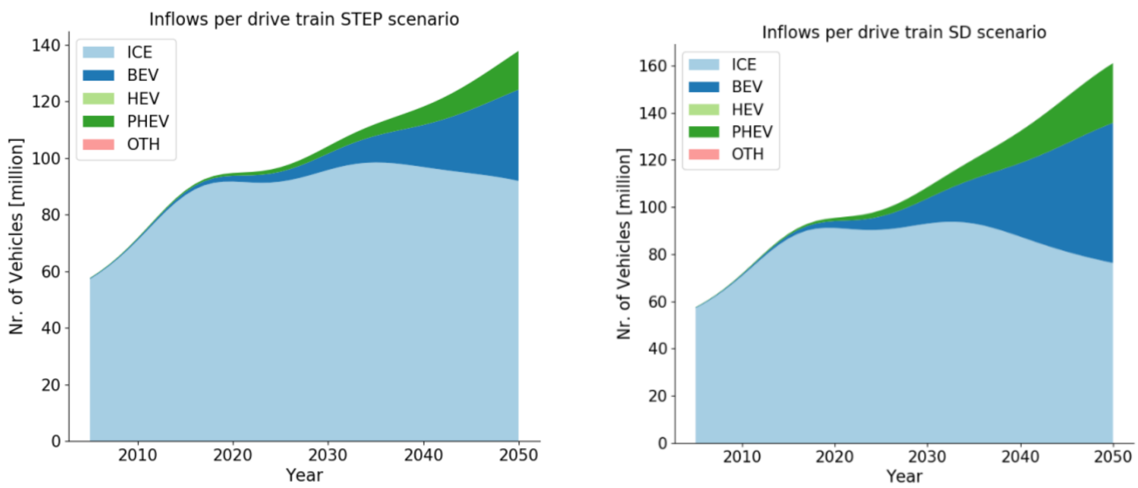


Figure 8 – Inflows by drive train of new vehicles to global supply according to different scenarios used in LiB storylines. Based on (Xu et al., 2020). *ICE: internal combustion engine, BEV: battery electric vehicle, HEV: hybrid electric vehicle, PHEV: plug-in hybrid electric vehicle, OTH: other.*

Additionally, two novel storylines were added to the current study to reflect the rapid pace of change in LiB technology and significant uncertainties of a new and expanding market. These storylines, referred to as 'new tech' storylines follow the steepest growth curves from the other two sources up to year 2030, at which point a precipitous decline in demand for Ni is experienced, representing an implementation of a disruptive new technology that decreases the desirability of nickel-based LiBs.

Normalized lifetime distribution is used with a mean of 10 years and standard deviation of 4 years. This assumption was based on findings in Kempton & Letendre's 1997 study though there are considerable uncertainties surrounding the lifetimes of LiBs in EVs in practice, once again due to the nascence of the industry. **Error! Reference source not found.** gives a visual overview of the differences between the storylines of the LiB subsystems.

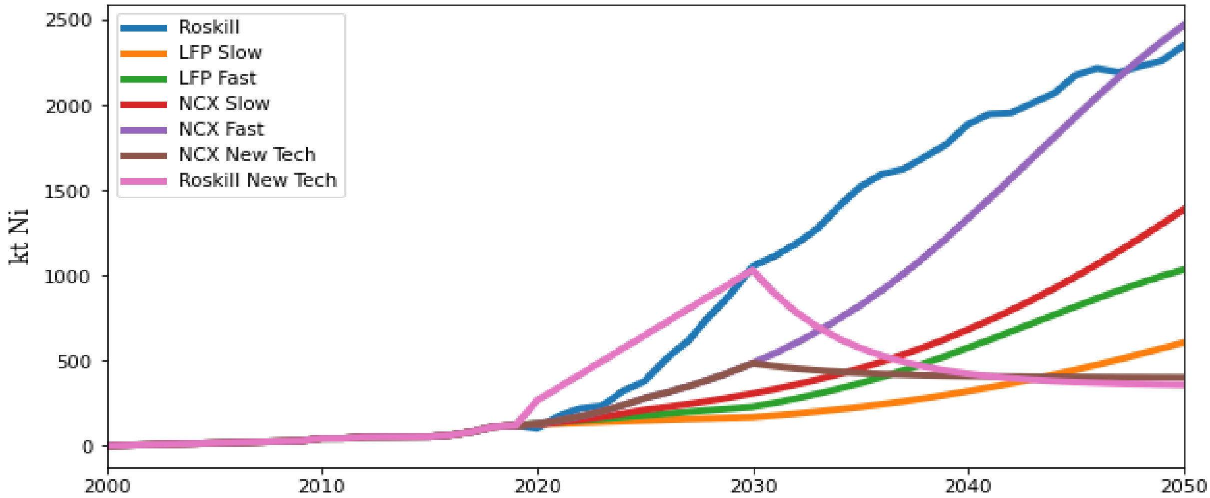


Figure 9 - LiB demand parameter profile for all 7 LiB subsystem storylines

2.3.2 LiB Recycling Subsystem

The end-of-life flows leaving LiB use are then either recycled or landfilled. This is represented in the model by a transfer coefficient from flow 14-15. Two different transfer coefficients are modelled. At the moment the proportion of global battery recycling is difficult to estimate. Eurostat reports that over 50% of batteries are currently recycled [7], hough the recycling behavior of common batteries now may not be a good gauge of LiB recycling trends. The fact that EV LiBs are large, expensive, and contain purified metals which make them likely to be profitable to recycle, causing a high recycling rate (Harper et al., 2019). Additionally, legislation is in place in China mandating high EV collection practices and EU and North-American legislation is likely to mandate LiB recycling in those jurisdictions as well (Kelleher Environmental, 2019). The amount of growth and change anticipated in the industry means there is little existing data to base expectations on. The recycling rates given in the model are not indented to predict global recycling rates but rather illustrate the effect that can be expected from recycling targets. For this purpose, there are two recycling rate storylines, one high and one low. The high recycling storyline tells a story of producers being able to capitalize on the high recyclability of EV batteries and by 2025 90% of the endof-life Ni is recaptured into the LiB system. The low recycling storyline is based on the minimum targets set by the proposed changes to the EU batteries directive for portable batteries, with a proposed target of 45% up to 65% in 2025 and 70% in 2030

[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_recycling_of_batteries_and_accumulators#Recycling_efficiency_for_Ni-Cd_batteries (accessed June 9, 2021)

(European Comission, 2020). Figure 10 gives a visual overview of the differences between the storylines of the LiB recycling subsystems.

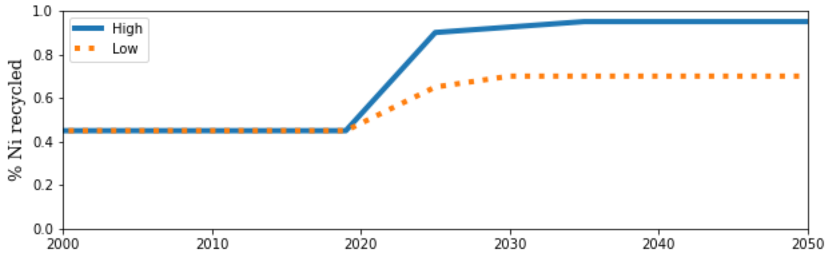


Figure 10 - LiB Recycling parameter profile for two recycling storylines.

2.3.3 Non-Battery Demand Subsystem

The non-battery demand subsystem, like the LiB subsystem, is modelled from the inflow to the system using an inflow-lifetime-driven cohort-based model. This subsystem models all demand for Ni products which are not specifically LiBs. This subsystem plays an important role toward Ni shortfalls and impacts relating to LiB demand for nickel, both in providing market competition to the LiB sector for Ni resources, and in being the historical driver of the Ni supply chain.

Notably, Stainless steel feedstocks can be flexible using either class 1 or class 2, but in order to adjust the purity levels, some amount of class 1 is necessary, this is sometimes called the class 1 loading rate. For historic reasons, the nickel supply system has shifted toward higher production of class 2 feedstocks over time, incentivising the stainless steel industry to lower the amount of class 1 nickel required in their production processes. Because the class 1 Ni can now be used in LiB production, the loading rate of class 1 to stainless steel production is particularly relevant to the issue of availability of Nickel to the LiB sector.

This need for feedstock differentiation is maintained in the model structure by dividing the inflow to process 16 into a total demand parameter, which indicates the total flow value incoming to the combined process 16, and minimum demand parameters of class 1 and of sulphate, which describe the minimum flows to process 16a and 16b from processes m11 and 12. These minimum flows are important in the way that they drive the upstream system, but they do not play a role in the downstream calculation of in-use-stock and end of life flows.

In the model run there are four parameter set storylines for the NoB Demand Subsystem. These are taken from two different publicly available projections for Ni demand into the future produced by minerals consulting firms Roskill and Wood Macenzie (Fraser et al., 2021; Thompson et al., 2020).

The 'High Growth Low C1' set is based on projections of total demand, and minimum class 1 requirements taken from Fraser et al., (2021), which shows a class 1 loading rate to stainless steel decreasing rapidly and holding at 5%.

The 'High Growth High C1" set is based on the same total demand projection from Fraser et al., (2021) with the minimum amount of class 1 to stainless steel held at the 2019 value.

The 'Low Growth Low C1' set is based on projections of total demand, and minimum class 1 requirements taken from Thompson et al., (2020), which shows a class 1 loading rate to stainless steel decreasing rapidly and varying between 3 and 10%.

The 'Low Growth High 1' set is based on the same total demand projection from Thompson et al., (2020), with the minimum amount of class 1 to stainless steel held at the 2019 value.

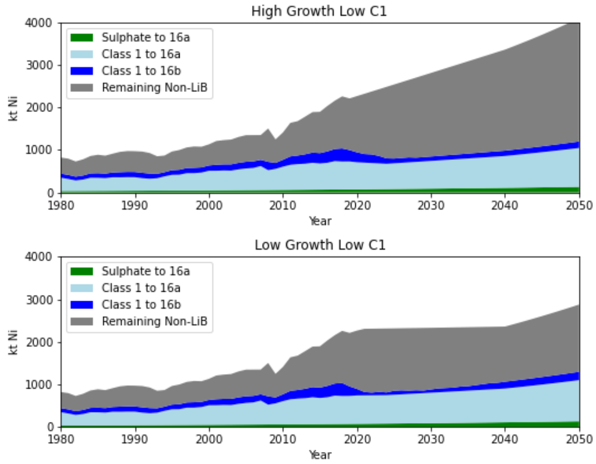


Figure 11 - Parameter settings to non-battery subsystem for four different storylines. Total demand, sulphate and class 1 to process 16a are shared in high growth and low growth storyline pairs. High C1 storyline pairs have minimum class 1 rates to process 16b as 15% while Low C1 storyline pairs reduce those values.

2.3.4 Ni Supply Subsystem

The Ni Supply Subsystem consists of those processes and flows that produce and transform Ni products to supply the LiB and NoB demand. In contrast to the two demand subsystems, the supply subsystem model is demand driven, so that all demand for Ni feedstocks to non-battery and LiB are met in the quantities and types required by those subsystem models. The farthest downstream flows of the Ni supply subsystem are therefore calculated first based on their demands, and the upstream flows are calculated process by process to meet the downstream flow demands. Where a process has multiple inflows, a list of priorities is assigned to instruct which inflow to satisfy the demand from. The model then uses a decision tree to calculate the values of upstream flows based on their downstream demands (See Table 1 in section 2.4, below).

Not all processes have capacity limits in the model setup. Supply processes 1, 2, 4, 7, 8b and 12 are taken as limitless in the current model setup. This does not represent that those processes are capacity unlimited, however. Capacities were not assigned to those processes in an attempt to maintain a comprehensible scope of focus for the model (This is further discussed in section 2.6). Model runs assign production values for all processes; these production value outcomes are interpreted in terms of achievability and the required timeline of measures to be taken to achieve the modeled capacities.

2.4 Feedstock priorities

In many MFA systems, calculating flow values between multiple inflows is achieved using a transfer coefficient (Brunner & Rechberger, 2016). In this system, however, supply processes do not need feedstocks in any combination. In fact, a processing facility or sector prefers to have as uniform feedstocks as possible in order to simplify the processing technology used (Trytten, Lyle, personal communication, 11.11.2020). Moreover, some feedstocks are more preferable than others, for example it is likely that Ni Sulphate producers will prefer recycled LiB feedstocks as they will be of a high purity and often occur with the desired co-elements to LiB manufacture (Harper et al., 2019). In order to replicate this in the model merit order of processes was used where a process demand is met first by the highest priority incoming flow so long as there is capacity in that incoming flow's process of origin. Once the capacity for that flow is exhausted, the remaining demand is met by the next inflow in the priority list for that process. In the case where an incoming flow has a baseline value, the baseline value for that flow is assigned before the priority list. The parameters for the supply system are therefore the priority lists of process feedstocks, the capacities of the processes, and the baseline flow values.

The merit order of feedstock flows to process demands have been set according to a best-understanding of the decisions that drive the supply system in reality. Most production and processing facilities have feedstocks which are more technologically and economically preferred, but could use an alternate, less preferred feedstock if the preferred feedstock is limited. The most important instances of this for the current study are the feedstocks to Ni Sulphate Production, which is visualized in Figure 12. Some feedstocks such as recycled LiBs are preferred because they have a high purity and accompany other desired metals, crude Ni sulphate is a traditional feedstock to battery precursors and is very close in form to pure Ni sulphate (Majeau-Bettez et al., 2011). Leach intermediates are preferred to pure Ni metal on a cost basis and because they are often accompanied with cobalt in solution (Chen, 2020). Class 1 Ni metal will likely be preferred over sulphidized NPI not only on a cost and purity basis but also due to favorable carbon footprint (Trytten, 2021).

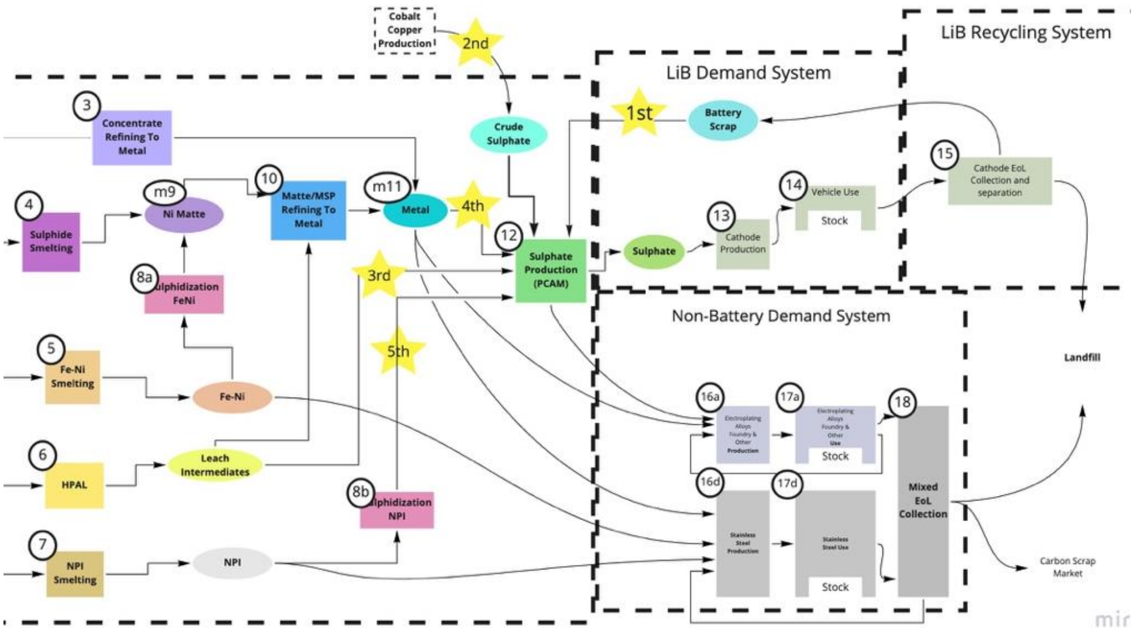


Figure 12 – Order of preference for inflows to sulphate production. Numbered star icons on flows show order of feedstock preference to process 12.

Baseline values are assigned in situations where a certain supply chain is established and will likely persist despite changes in the macro supply environment. For example, certain metal refineries (process 10) are technologically adapted to a particular feedstock from a specific source, and adapting the refinery to accommodate a different feedstock would be technologically difficult and expensive. For this reason, many refineries are vertically integrated with their feedstock facilities and have a supply relationship which is significantly (though not entirely) unresponsive to market forces. In an attempt to include such relationships into the model, vertically integrated facilities have attempted to be identified and the flow between integrated facilities is set at a baseline of the capacities of the facilities. An overview of the order of priorities and the baseline flows used in relevant model processes is shown below in Table 1 - Overview of the merit order of incoming flows to processes in the Ni supply subsystem. Processes which have multiple inflows are shown. Baseline inflows are always satisfied by the model and represent inflexible supply chains. Remaining inflows are calculated according to inflow priority

Table 1 - Overview of the merit order of incoming flows to processes in the Ni supply subsystem. Processes which have multiple inflows are shown. Baseline inflows are always satisfied by the model and represent inflexible supply chains. Remaining inflows are calculated according to inflow priority as shown.

Process	Baseline Inflows	Baseline Flow Description	Priority #	Inflow priority	Inflow Description
16. Non Battery Production	F 12-16	Minimum sulphate to 16a	1	F 12-16	Surplus Ni sulphate
	F m11-16a	Minimum class 1 to 16a	2	F m11-16	Surplus class 1 Ni
	F m11-16b	Minimum class 1 to 16b	3	F 5-16	FeNi
	F 18-16	Recycled scrap	4	F 7-16	NPI
12. Sulphate Production	F 0-12	Baseline crude sulphate by-product	1	F 6-12	Leach intermediates
	F 15-12	LiB recycling	2	F m11-12	Class 1
	F 6-12	Integrated leach intermediates	3		
m11. Metal Market	F 3-m11	Class 1 from concentrate refining	1	F 10-m11	Class 1 from refining to meetal
10. Refining to Metal	F 6-10	Integrated leach intermediates	1	F 6-10	Leach intermediates
			2	F m9-10	Matte
m9. Matte Market			1	F 8a-M9	Matte from FeNi sulphidation
			2	F 4-m9	Matte from sulphide smelting

2.4.1 Capacity Assessment

In order to realistically assess the ability of the Ni system to meet potential demand, a realistic measure was needed to quantify the capacity of the processes. Poor correspondence between modelled capacity figures and real potential to produce Ni could cause mis-estimation of the risk of shortfalls. In this study, the capacity of the facilities was quantified according to the expected throughput of Ni-in-product of the facility in question. Research was conducted to compile a dataset of faciltiesn which mine or refine Ni using mostly International Ni Study Group's World Directory of Ni Production Facilities (INSG, 2020) and other sources. Each facility was assigned a location in the system definition and a capacity figure. Where facilities carried out multiple processing steps they were recorded in each system location and their total capacity was assigned to both locations. For example, Ambatovy in Madagascar is often considered to be a single operation though it conducts laterite mining, laterite leaching, and refining to metal according to this study's system definition. The capacity of Ambatovy was therefore assigned in full to each of these three processes and represented as three facilities on the facilities dataset.

The total process capacity is determined by summing the capacity of all facilities. Defining the expected capacity of any facility is a task which does not have a conventionally agreed-upon method. While most facilities have a publicly available 'design capacity' often referred to as a 'nameplate capacity', the relationship of this stated capacity and the actual throughput of any facility is varied. **Error! Reference source not found.** show a variation in normal production output of facilities. Production varies between facilities and over time within facilities. Facilities differ in their normal output compared with their stated capacity by both overproducing and underproducing. Improvements in system processes can improve a facility's performance over time (Valle et al., 2016), while decreases could be caused by aging equipment and lack of maintenance (Erickson, M., 2021 personal communication) or a declining feedstock quality, especially declining ore grades (Priester et al., 2019).

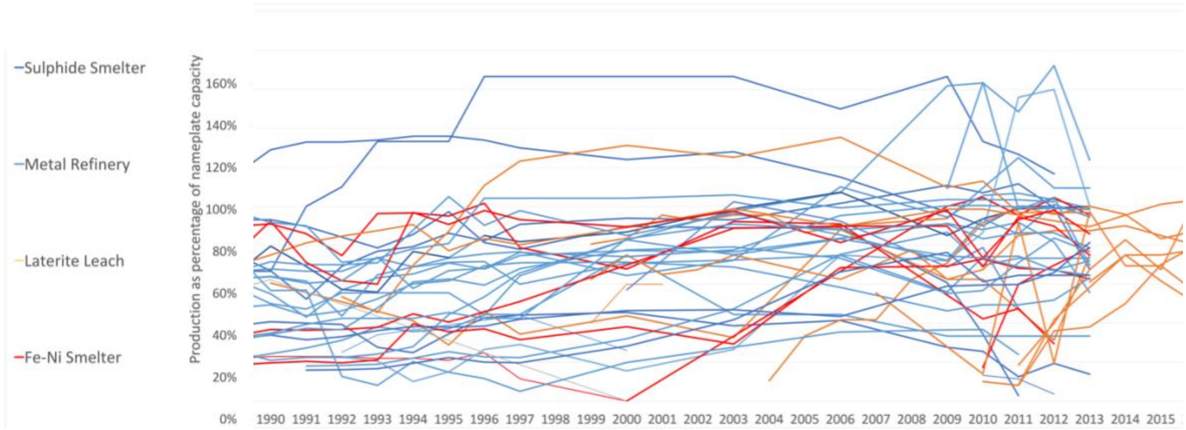


Figure 13 - Facility production as a percentage of reported capacity. Only facilities and years are shown where both production and capacity information was found, (significant data gaps after 2013). Production data from RMG consultants and other sources. Capacity data taken at 2019 values from INSG and other sources. Capacities may not accurately reflect reported capacities at corresponding production years.

As part of determining realistic values for the capacities of various processes, research was done to collect total named capacity of all facilities assigned to each process, and where possible, historic throughput values of various representative facilities was compared to their stated capacity values along with research and expert input on what factors influence a facility's ability to achieve its stated capacity. Figure 13 shows the extent of data which was used. Sulphide refineries and smelters – light and dark blue lines – vary between very high and very low productivity, with low producing facilities tending to be smaller, older facilities which have been poorly maintained. FeNi smelters – red lines tend to operate closer to design capacity though data for these facilities were not large enough to be considered representative. Meanwhile laterite leach facilities – which are shown in orange lines and represent a near complete overview of exising facilities for the time period - tend to operate significantly below design capacity. This appears to be due to technical difficulties in the operations stemming from the complexity of the leaching process. The best performing laterite leach facilities are those which have been established in Cuba in the 1960s, while most of the other facilities were developed in the past twenty years.

This information was combined to make a best estimate of the process capacity to be used in the model. Over future years, where process capacity profiles are provided to the model, the capacities represented are taken to be expected productive capacity, meaning the maximum amount of product which could be produced by the process, assuming that the demand

is present.

2.5 Pathways and Greenhouse Gas Impacts

To simplify the interpretation of the system, the supply system can be visualized as a set of 9 complete pathways from raw ore to first use product. Each pathway is a complete enchained route through mining, plus one or several refining processes which produces a feedstock which can be used either in sulphate production (class 1 metal, crude sulphate, or leach intermediates) or directly in non-battery manufacture (class 1 metal, FeNi, or NPI). These different pathways are a useful representation of the supply system when considering the possibilities for future development of the system. Each pathway has a single representative flow in the model system which indicates the total production of that pathway. From these flows a system quantification can be made showing total amount of Ni production along each pathway per year. Greenhouse gas (GHG) impact factors were researched and assigned to each of the production pathways. The GHG impact factors were quantified as tons CO_2 equivalents per ton of Ni in product produced by the pathway (tCO_2 eq./tNi). Figure 14 shows the nine pathways and their associated GHG impact factors. The GHG impact factors were approximated using a combination of literature sources, LCA database figures and expert interviews. The values are not intended to be authoritative source for assigning values to Ni products, readers should refer to the provided source materials for LCA values of Ni products.

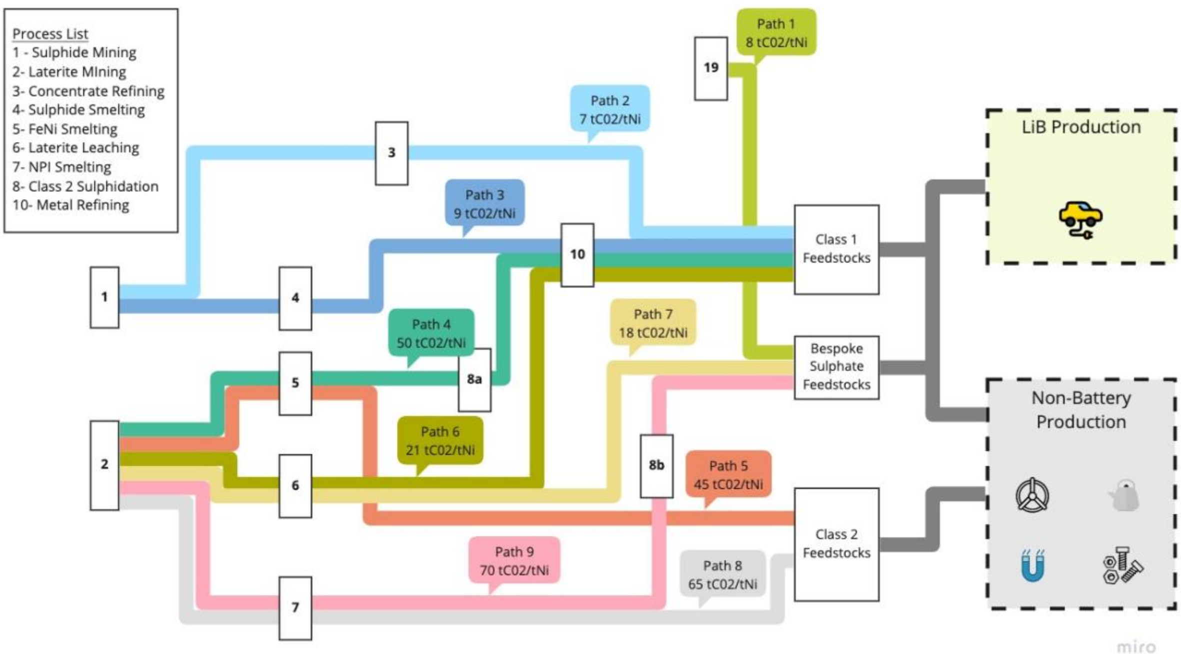


Figure 14 – The nine production pathways through the Ni supply subsystem with their corresponding GHG impact factors .

These pathway impact factors are used here as a method for comparing the various development possibilities of the Ni system. GHG impacts have been chosen because there is a lot of attention and available data relating to this impact category. However, other categories of impact are also very relevant to the environmental and social governance (ESG) considerations of the Ni supply chain and also have different representative impact profiles along the different pathways described here, which can be different from the relative GHG impact factors. For example, according to the Ni Institute LCA, FeNi has 3.5 times the global warming potential of Class 1 Ni, however, Class 1 Ni has 8.2 times the acidification potential of FeNi. For reasons such as this, the ESG application of this study should not be overinterpreted. However, the relative comparisons between pathways serve as a useful benchmark to evaluate outcomes of shifting production between pathways. Summing the CO_2 eq. of all pathways provides the total GHG impact of the entire Ni Supply system for any scenario, which is used as a key indicator in interpretation of supply and demand system choices.

The pathways are explained in detail in the following sections, with references to source information, representative facilities, and greenhouse gas impact factor estimations. Table 2 summarizes the pathways and GHG impact factors.

Table 2 - Pathway overview and GHG impact factors given by source literature and estimation used in this study. GHG impact factors given in tCO_2 eq./tNi.

Path #	Process 1	Process 2	Process 3	Process 4	Impact factor used in this study (tCO2 eq./tNi)	Reference literature	Reference value
1	Co Cu byproduct				8	*Majeau-Bettez et al. 2011*	none given
2	Sulphate Mining	Concentrate Refining			7	*none found*	none
3	Sulphide Mining	Sulphide Smelting	Metal Refining		9	*Simapro Database* *IEA, 2021* *Reuter et al., 2015*	10.8 7 - 10 7.8
4	Laterite Mining	FeNi Smelting	Laterite Sulphidation	Metal Refining	50	*none found*	none
5	Laterite Mining	FeNi Smelting			45	*Reuter et al., 2015* *Nickel Institute, 2020* *Khoo et al., 2016*	43.8 45 42
6	Laterite Mining	Laterite Leaching	Metal Refining		21	*Ni Institute, 2020 (27% share)* *IEA, 2021* *Khoo et al, 2016*	13 18 53
7	Laterite Mining	Laterite Leaching			18	*IEA, 2021*	18 - 32
8	Laterite Mining	NPI Smelting			65	*Reuter et al., 2015* *Dry et al., 2019*	70 - 98 120
9	Laterite Mining	NPI Smelting	Laterite Sulphidation	Sulphate Refining	70	*IEA, 2021*	60

2.5.1 Pathway 1, Cu, Co, and PGM By-products

Pathway 1, Cu and Co, PGM by-products, represents crude Ni sulphate which enters the system from supply chains which are not driven by demand for Ni and so are not very responsive to changes in demand for Ni products. There does appear to be some response in this pathway to increased battery demand - a reference facility for this process is the Western Platinum Base Metal Refinery at Rustenburg, South Aftrica which is increasing its output of crude sulphate by-product from it's PGM operations from 3.3 to 5.7 ktNi/yr, and is building a purification plant to purify to battery-grade Ni sulphate (classified to process 12) (INSG, 2020). Notwithstanding such instances, because the Ni by-products are a very small output of already mature industries, industry experts do not forecast significant growth in this pathway (Fraser et al., 2021).

While no data on GHG impacts of this pathway was found, there are a variety of approaches to allocating impacts of by-products (Weidema, 2000) and the method used can lead to different values given. Following the approach described by Majeau-Bettez et al. (2011) to attribute NiSo4 from this pathway, the impact factor has been crudely approximated based on the LCA data for all Ni production pathways. A value of 8 tCO_2 eq./tNi was attributed to this pathway.

2.5.2 Pathway 2, direct concentrate refining to metal

Pathway 2, direct concentrate refining to metal, represents production of Ni metal through the combination processes 1 and 3, sulphide mining and direct hydrometallurgical refining of concentrated ore. The only commercial operation of this type currently operating is Vale's Long Harbour facility in Canada which developed the process over 15 years as a replacement to existing smelting and refining operations elsewhere in Canada (INSG, 2020; Vale, 2020). While the operation seems to be a success, similar facilities using direct hydrometallurgical refining of sulphide concentrate do not appear to be widely planned. The only currently planned facility to use this pathway that was found is Blackstone Mineral's Ta Khoa project in Vietnam with an advertised production of 12.7 ktNi/yr (Blackstone Minerals, 2021). However, as this pathway appears to have high success and low ESG problems it has been included in this study in order to show the possible effects more investment along this pathway could have on the Ni system.

No direct data on the impacts of this pathway was found and an approximation was made using combined reference figures for sulphide mining and hydrometallurgical refining to metal taken from (Nickel Institute, 2020) and (IEA, 2021). Using these sources, the mining, beneficiation (concentration) and hydrometallurgical refining of sulphide ores was approximated to be 7 tCO_2 eq./tNi, making this the least impactful pathway to Ni production.

2.5.3 Pathway 3, Sulphide Smelting to metal

Pathway 3, sulphide smelting to metal, represents production of Ni metal through the combination of processes 1, 4, and 10, sulphide mining, sulphide smelting, and metal refining. This is traditionally the most common pathway for producing Ni metal. Facilities along this pathway exist in a variety of levels of vertical integration ranging. BHP's Ni West[8] enterprise in Australia is fully integrated in one region with mines, smelters and refinery essentially functioning as a single operation (INSG, 2020). Glencore's operations meanwhile are geographically diverse with mines and smelters in the Sudbury region of Canada shipping matte to be refined to metal in Kristiansand, Norway (INSG, 2020). Alternately, many facilities in this pathway are independent with mines selling to smelters

[8] https://www.bhp.com/our-businesses/minerals-australia/Ni-west/ (last visited 31 May 2021)

and refineries on a tolling basis, Norilsk's refinery in Harjavalta, Finland is an example of an operation that accepts feedstocks from multiple non-integrated sources.

Several sources were found providing carbon footprint data for Ni metal ranging from 7-13 tCO_2 eq./tNi, (IEA, 2021; Nickel Institute, 2020; Reuter et al., 2015). However, as there are several pathways to Ni metal and these values are not necessarily specific to this pathway as opposed to pathways 2, 4 and 6. The IEA report is specific in differentiating between sulphide and HPAL sourced metals however, and the Number 9 tCO_2 eq./tNi is mid-range of their figures. This value has been used in this study as it seems conservatively consistent with all sources.

2.5.4 Pathway 4, Sulphidation of FeNi to Matte to Metal

Pathway 4, sulphidation of FeNi to matte to metal, represents production of Ni metal through the combination of processes 2, 5, 8a, and 10, laterite mining, FeNi smelting, FeNi sulphidation, and metal refining. This process was used historically since 1977 to utilize lower grade feedstocks for first use production that required higher purity feedstocks (Kerfoot, 2000). The industry has moved away from using it as it no longer adds sufficient value to the product (Sharypin et al., 2020). While Eramet's Doniambo smelter in New Caledonia used this technology until 2016, the only commercial operation found to still be using this technology is PT Vale's Sumitomo smelter in Indonesia which does have plans to increase from 80 ktNi/yr to 90 or 120 ktNi/yr in the coming years. It is an important process, however, from the standpoint of possible pathways to avoid battery bottlenecks especially in its potential to be used to upgrade NPI to battery-grade feedstocks (discussed in section 2.5.8 Pathway 8, NPI Smelting to Non-Battery below). It is an important process, however, from the standpoint of possible pathways to avoid battery bottlenecks especially in its potential to be used as a blueprint technology to upgrade NPI to battery-grade feedstocks (discussed in section 2.5.8 below). The reason for including it in this study as a separate pathway is to maintain the distinction between tested and novel pathways to meeting Ni demand, and the distinction between mid-grade FeNi and low grade NPI pathways which tend to have different properties due to the difference in ore grades used.

While no direct data sources for complete carbon footprint analysis were found for this specific pathway, the additional step of sulphidation of FeNi to matte is expected to have minor effect on the GHG impact factor (Trytten, 2021). Therefore the impact factor of this pathway was assigned by taking the FeNi value of 45 tCO_2 eq./tNi, adding 2 tCO_2 eq./tNi for sulphidation to matte, and 3 tCO_2 eq./tNi for refining (Nickel Institute, 2020).

2.5.5 Pathway 5 Laterite to Fe-Ni Smelting

Pathway 5, laterite to FeNi smelting, represents production of Ni metal through the combination of processes 2 and 5, laterite mining and FeNi smelting. This has been the most common pathway for utilizing lateritic Ni ores and has existed for over a century (Crundwell et al., 2011; Kerfoot, 2000). Typically, this process uses the saprolite portion of the ore mined from laterite deposits making growth in this pathway likely to increase along with alternate pathways such as HPAL and NPI which use the remainder of the ore body. In 2019, the INSG reported 35 active smelters along this pathway with a total design capacity of 1042 ktNi/yr. While NPI smelting technology is supplying some of the market for this pathway, additional facilities are planned, and the technology remains important.

Several sources were found providing GHG impact values of FeNi. While Reuter et al. (Reuter et al., 2014)and Khoo et al. (Khoo et al., 2017) published slighly lower values, the value of 45 tCO_2 eq./tNi used in this study was taken from the Ni institutes 2020 LCA.

2.5.6 Pathway 6, Laterite Leaching to Metal

Pathway 6, laterite leaching to metal represents production of Ni metal through a combination of the processes, 2, 6, and 10, laterite mining, laterite leaching and metal refining. The laterite ores are leached in solution either at high pressure or atmospheric conditions in order to make an intermediate product, often mixed sulphide precipitates or mixed hydroxide precipitates which is then sent to a refinery to be purified and reduced to class 1 Ni metal. This is a longstanding technological pathway dating at least from 1961 when Moa Bay in Cuba came online mining and leaching ore locally and shipping the MSP to the soviet union for refining into metal (Kerfoot, 2000). In recent decades more laterite leach facilities have come online with either on-site refining capabilities such as Ambatovy in Madagascar or off-site refining as with Wingstar's Cawse plant which shipped MHP to Finland for refining before it closed in 2008. As most new leach plants set their sights on producing cathode precursors directly rather than metal, this pathway is unlikely to expand beyond the existing integrated facilities of Moa (now shipping to Canada for metal refining) and Ambatovy with a combined capacity of approximately 90 ktNi/yr. Though, if the system does develop a lot of new leaching capacity – as is planned to be used in pathway 5 – that technology could be transferred to this pathway if metal refining capacity and demand are suitable.

The GHG impacts of this pathway are stated in the IEA critical minerals report (2020), and in Khoo et al., (2017) though with a lack of agreement between the values. The value of 21 tCO_2 eq./tNi was settled on for this study after discussions with industry experts.

2.5.7 Pathway 7, Laterite Leaching Direct to Sulphate

Pathway 7, laterite leaching direct to sulphate, represents the production of Ni sulphate through the combination of processes 2, 6, and 12, laterite mining, laterite leaching, and sulphate production. These intermediate products can be used directly by cathode precursor manufacturers to make Ni sulphate without needing to go through the process of being first refined to class 1 metal. A lot of attention is being given to this pathway in recent years with a specific focus on supplying feedstocks to the battery industry. Ramu HPAL (Papua New Guinea) as well as Coral Bay HPAL and Taganito HPAL (both in the Philippines) have been built since the turn of the century to produce intermediate products which are sold internationally to the electroplating and battery supply chains (INSG, 2020). Roskill's Study on future demand and supply security of Ni for electric vehicle batteries (Fraser et al., 2021) lists 7 additional facilities under construction to produce intermediates for this pathway.

The GHG impact factor of this pathway is very similar to pathway 6 though as the step of refining to metal has been avoided the value assigned to the pathway is 18 tCO_2 eq./tNi.

2.5.8 Pathway 8, NPI Smelting to Non-Battery

Pathway 8 represents production of NPI through the combination of processes 2 and 7 laterite mining and NPI smelting. This pathway was developed relatively recently in order to allow the Chinese stainless steel industry to make use of the large availability of low grade laterite ores (Mudd, 2010). While the process is energy intensive per unit of Ni produced (IEA, 2021; Reuter et al., 2015), it is comparatively simple to develop. According to the INSG World Ni directory, more than 30 NPI smelters in China and Indonesia since 2007 and at least 20 more are in some stage of planning or construction.

This pathway is intensive in GHG production due to the low ore grades and typically carbon intensive energy mix that is used to smelt them (Reuter et al., 2015). While very little company data is available from the facilities in operation, a number of impact assessments have been made available finding GWP impacts in the range of 60 to 120 tCO_2 eq./tNi (Dry et al., 2019; IEA, 2021; Reuter et al., 2015). While it is possible that real values do vary considerably, a conservative estimate of 65 tCO_2 eq./tNi is used in this study.

2.5.9 Pathway 9, NPI Sulphidation for Battery Production

Pathway 9 represents production of Ni sulphate feedstock through a combination of processes 2, 7, 8, and 12., laterite mining, NPI smelting, NPI sulphidation, and refining to sulphate. This pathway has not been implemented as of 2020, however the Chinese stainless steel and Ni company Tsingshan Holding Group announced in spring 2021 that it has contracted to employ this pathway to supply Ni sulphate to the LIB supply-chain (Reuters, 2021). This pathway is similar to pathway 5 in which FeNi is upgraded to matte to be refined to metal, though in this pathway it is likely that the stage of producing the Ni metal will be bypassed and the Ni matte will be hydrometallurgically refined directly to sulphate. A step which has been allocated in this study to the Ni sulphate production process (process 12).

GHG emissions along this pathway are the highest of all presented pathways as the high impacts of pathway 8 are incurred as well as marginal increases for sulphidation and refining of the NPI to a more refined state. A value of 70 tCO_2 eq./tNi has been used in this study for consistency with the value of pathway 8.

2.6 Risk of Shortfalls and Capacity Elasticity

In research and discussions with experts no structural limits were discovered to the gross capacity of the Ni supply system. Available Ni resources appear to be sufficient to meet even the highest demand profiles expected over the modeled period (Elshkaki et al., 2017; Mudd & Jowitt, 2014), though that question was not addressed specifically in this study. The risk of supply shortfalls is then modelled based on the demand elasticity of capacity expansion of different processes and pathways. In discussions with experts, a variety of factors were identified as contributing to the speed at which capacity can be increased for various processes. A list of the factors that were identified as relevant to the ease and speed of development is discussed in Table 3.

Table 3 Factors which affect the ease of increasing capacity to meet increasing demands

Factor	Process	Explanation
Ore availability (Hard-rock vs soft-rock)	Sulphide Mining	Typically hard-rock ore types using underground mining, longer construction time.
	Laterite Mining	Typically soft-rock ore types using open pit strip mining
Jurisdictional Factors	Sulphide Mining, Sulphide Smelting, Refining to Metal	Typically developed jurisdictions. Longer permitting and approval processes but high certainty and stability
	Laterite Mining, Laterite Leaching	Typically less developed jurisdictions. Little permitting hurdles but prone to regulatory changes or social push-back
	Laterite Leaching	As of writing, several leach facilities struggle with receiving approval for tailings plans.
Technological Factors	Sulphide Mining, Laterite Smelting, FeNi Smelting, NPI smelting	Established, relatively simple processes which have high assurance of meeting technical design specifications.
	Laterite Leaching Refining to Metal New Technologies	Technically complex and often require bespoke adjustment to particular feedstock and environment. Can take time to 'tune' facilities.

Quantifications were made of the timelines of adding new capacity to the different supply processes. This was conducted through researching exemplar facilities of the different processes which have been constructed in recent years, and analysing the timeframes of their construction. Figure 15 shows a best estimate of differences in expected construction time between facilities assuming suitable economic conditions. While some processes such as laterite leaching have numerous recent facilities constructed, other processes, such as metal refining, have not had new facilities built in recent decades. This lack of realistic exemplar facilities in combination with variation found between construction times of similar facilities results in the expansion times being presented as an expected range.

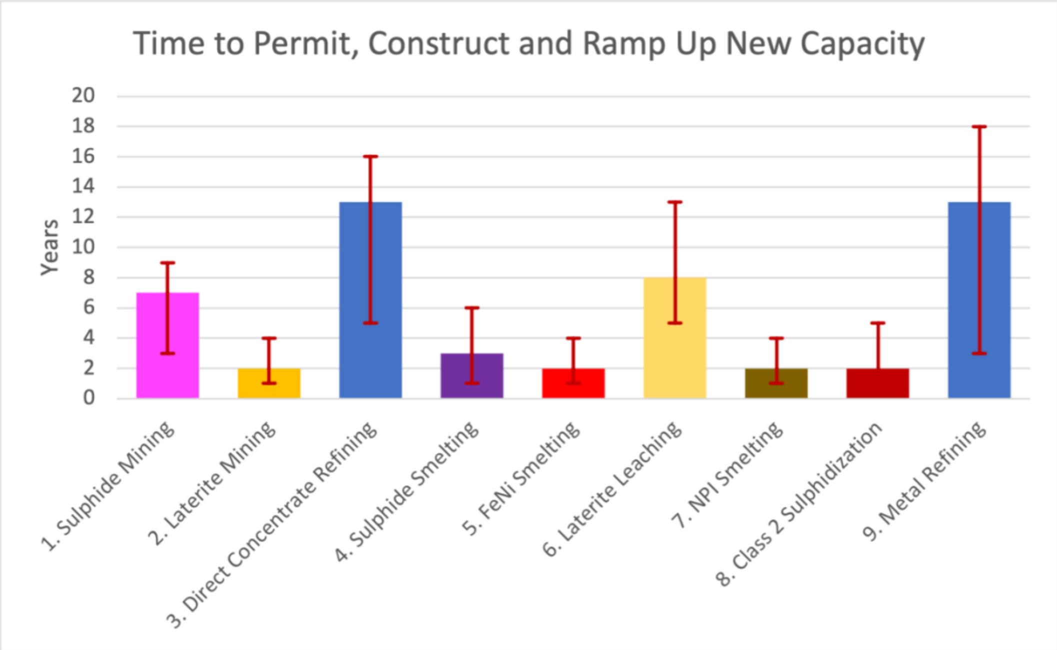


Figure 15 - Bar height represents expected time required to develop a greenfield facility from initial exploration to full operation. Range represent uncertainties and variation in expectations.

The timeframes to capacity expansion in combination with the best understanding of the state of the industry guided the development of the model rules as well as the parameter set storylines.

When determining how to model a potential shortfall, the model structure reflects that Pathway 9 has very high demand elasticity and that all processes along this pathway can likely increase capacity rapidly enough to meet all demand. However, as the pathway is the least desirable pathway from an ESG perspective and may encounter roadblocks to widespread adoption from both consumers and regulators, the flow quantity along pathway 8 serves as a proxy indicator for shortfall risks.

The model was programmed using a combination of Microsoft Excel tables and Python scripts, and used the ODYM Python module (Pauliuk & Heeren, 2020) as a framework for the data management of the model. An annotated notebook of the Python code which was used to run the model can be found at https://github.com/Young-Eric/Ni_Bottlenecks.

3 Results

The model runs produces a system quantification of the modeled Ni system for all model years and for all parameter-set combinations. For brevity, some exemplar system quantification Sankey diagrams are shown at representative time and scenario combinations, as well as summary statistics describing the effects of the different subsystem storylines. Total first use Ni demand, total amount of Ni consumed, total amount of Ni lost from system, total amount of greenhouse gas impacts created in the system and total amounts amount of Ni sulphate produced by NPI sulphidation are key indicator flows (or flow combinations) that have been presented.

3.1 Sankey Diagram of Base Year.

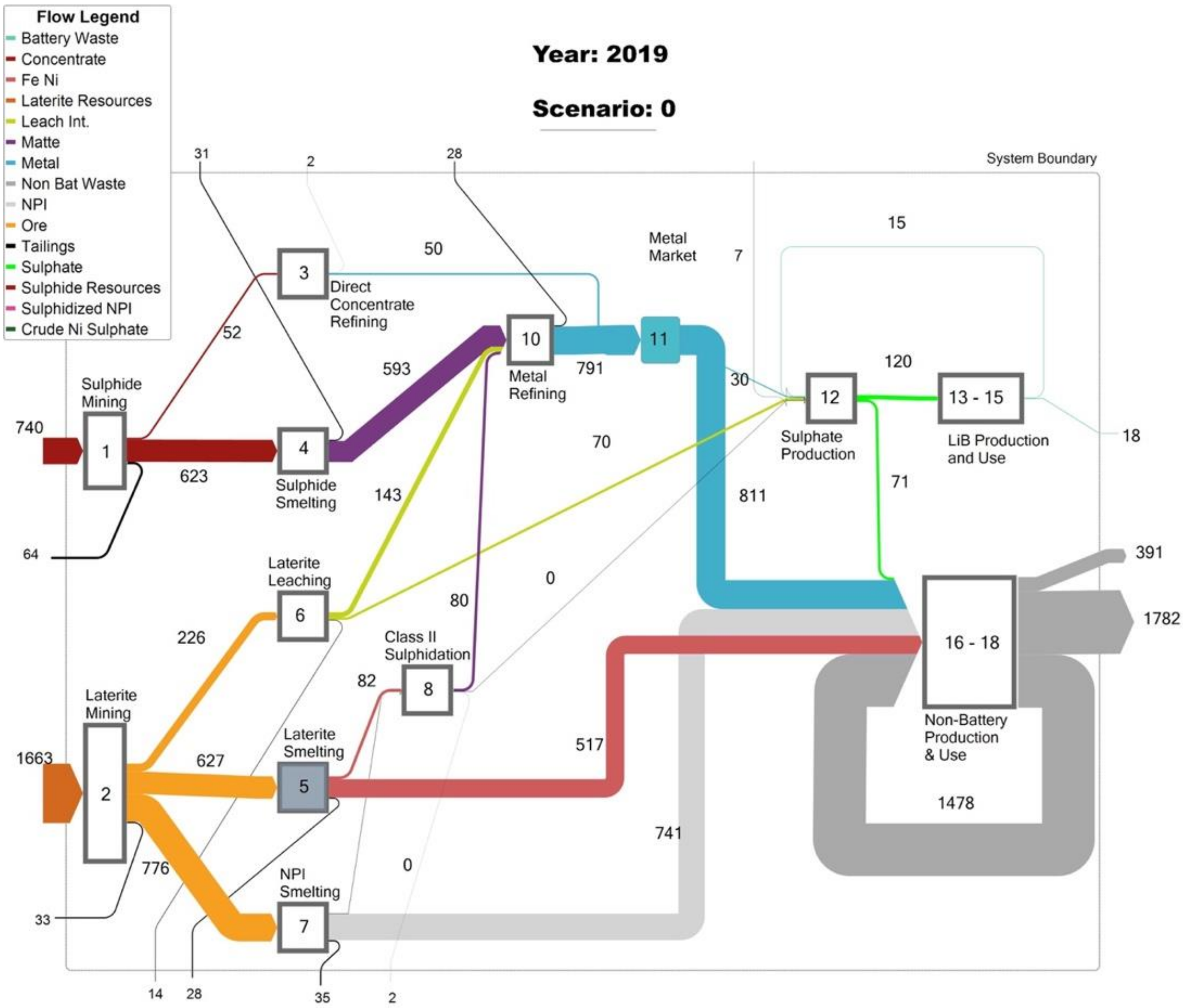


Figure 16 - Sankey diagram showing significant flow quantities of model system for year 2018. For ease of visualization, the stocks and LiB and non-battery subsystems have been collapsed into a single process. Stocks and stock changes are not shown. Flows shown in kt-yr.

Figure 16 visualizes the flow quantities for the year 2019 which is the last year where flows values were sourced from external data rather than generated by the model. The flow quantities under the different scenarios for different years represent the amount of activity of different components of the Ni supply system. At the current year, the quantity of Nickel flowing into and out of the LiB subsystem (processes 13-15) is very small in proportion to the overall context of the Ni system. Flows into the LiB system are also larger than flows out of the subsystem indicating that the system is in a state of growth, while for Non-battery system inflows and outflows are much more equalized. The largest pathways are the sulphide smelting pathway producing metal for non-battery use, and the two laterite smelting pathways making FeNi and NPI for non-battery use. More Sankey diagrams of various time frames and storyline combinations have been included in Appendix 2.

3.2 Summary Statistics and Sensitivity to Storylines

The model runs produce a large amount of data. Because the model output is contingent upon the parameter inputs, which were designed to represent possible development outcomes, the model does not output predictions but rather produces ranges of values which are considered to be reasonable estimates. These estimates generate relevant insights into the different strategies that can produce a desired outcome under specific conditions. System quantification is presented under the complete range of parameter set storyline combinations showing the variation and effects of different model settings.

3.2.1 First-Use of New Ni Feedstocks

Figure 17 compares the recent production of first-use Ni feedstocks by type to the projected demand ranges for first-use Ni which are anticipated to the LiB sector (flow 12-13 minus flow 15-12) and to the combined system (flows 12-13, 12-16, 11-16, 5-16, 7-16 combined, minus flow 15-12).

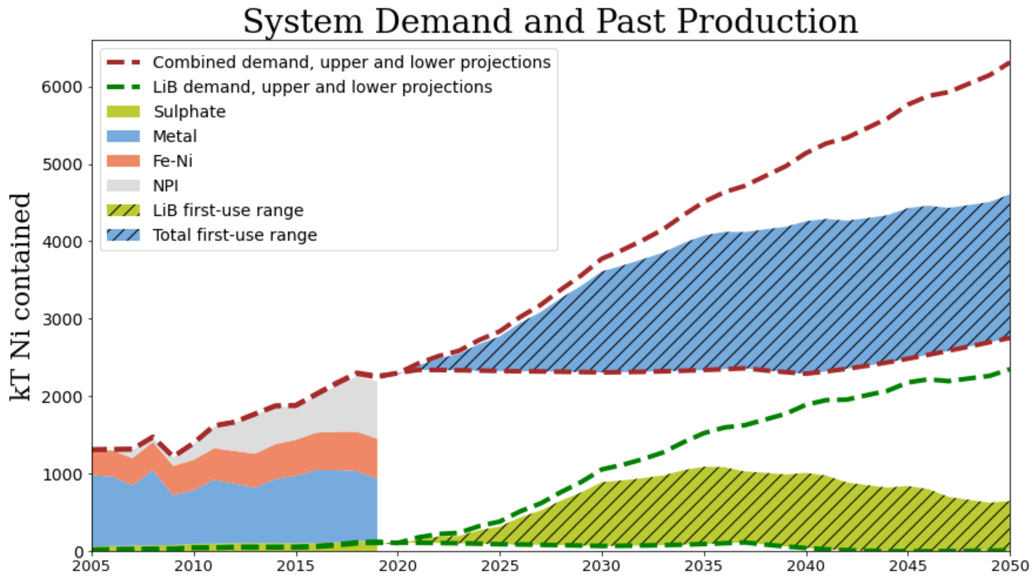


Figure 17 - Past consumption of first-use Ni is shown by the different feedstocks. Future range of demand for new Ni to LiB sector (green infill) and for new Ni to combined LiB and non-LiB sector (blue infill).

The demand ranges show the anticipated demand for new Ni products over all scenarios included in the model, including under both recycling storylines. The upper range of new Ni demand to LiB is shown to grow to 2035, where it caps at 1092 kt/yr in year 2036, while the lowest range shows no growth over the 2019 value of 120 kt/yr, declining to no new demand in 2042. For the combined LiB and non-LiB nickel system, the upper range climbs steeply to a value of 3803 kt/yr first-use Ni in 2030 whereafter it continues increasing more gradually through the model run to 4720 kt/yr by 2050, 2.17 times the 2019 value. The lower range of modeled combined first-use Ni demand remains essentially flat at existing levels until 2040 when it gradually increases to 2815 kt/yr by the end of the model run. Past production is seen to be largely composed of metal historically (flow 11-16) with production holding relatively steady around 800-1100 kt/yr in the past 20 years. FeNi production (flow 5-16) has grown moderately over the same time period while NPI first-use (flow 7-16) has drastically increased since its inception in 2006 to comprise 33% of first-use in 2019. Ni sulphate first use is seen to be growing over the past 20 years to a 8.5% share of the 2019 first-use production.

3.2.2 Primary Ni Consumed

Primary Ni consumed per year is represented as the sum of the three inflows to the system, sulphidic ores (flow 0-1), lateritic ores (flow 0-2) and Ni from by-product mining (flow 0-12). Figure 18 - Total Ni mined over model run, all scenarios. (a) Box and whisker plot of total Ni consumed over model run, given by each ore type and by combined total. Whiskers show the total range of values over all scenarios. Boxes show the median 50% of values over all scenarios with median value shown by horizontal line. (b) Ni inflows to system from byproducts, sulphide and laterite shown additively over all scenarios. (c-e) Total Ni consumed coloured by various subsystem storylines, recycling subsystem variation represented via line styles with solid lines showing high recycling and dotted lines showing low recycling storylines.

provides an overview of Ni consumption over the model run.

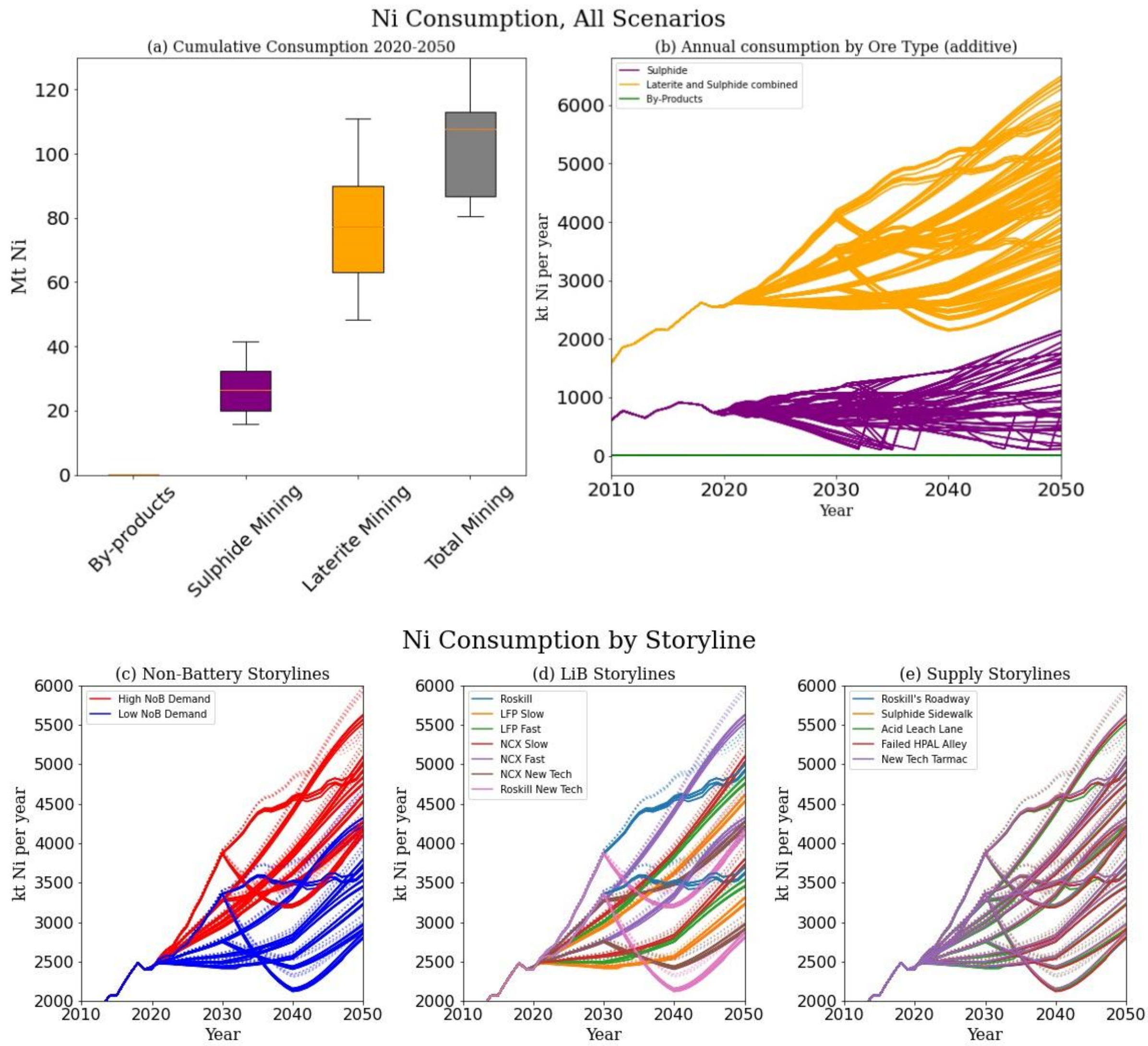


Figure 18 - Total Ni mined over model run, all scenarios. (a) Box and whisker plot of total Ni consumed over model run, given by each ore type and by combined total. Whiskers show the total range of values over all scenarios. Boxes show the median 50% of values over all scenarios with median value shown by horizontal line. (b) Ni inflows to system from byproducts, sulphide and laterite shown additively over all scenarios. (c-e) Total Ni consumed coloured by various subsystem storylines, recycling subsystem variation represented via line styles with solid lines showing high recycling and dotted lines showing low recycling storylines.

The range of Ni consumed over the model generally increases in future years with a total range of Ni in cumulative ore consumed over the model run between 80 Mt Ni and 136 Mt Ni. Of this, 0.3 Mt is consumed from the supply of crude sulphate byproducts (flow 0-12) and this number does not vary over model scenarios. While cumulative sulphate ore consumption ranges between 17 and 41 Mt Ni, the bulk of the Ni production in all scenarios comes from laterite ores (flow 0-2) ranging between 45 and 104 Mt Ni.

The consumption of Ni is most heavily influenced by the non-LiB subsystem, With figure Figure 18 (c) showing a significant divergence between high and low non-LiB demand storylines. The LiB demand also shows very strong and consistent effect Figure 18 (d) on the consumption of Ni within the visible split caused by the non-LiB storylines.

The supply subsystem storylines Figure 18 (e) meanwhile show a consistent but minor influence on consumption.

Recycling storylines (dashed vs dotted lines in Figure 18 (c-e) can be seen to have a consistent effect over all scenarios. Recycling storyline influence is larger in magnitude than the supply subsystem storylines but smaller than LiB and non-LiB demand storylines. With the effect increasing gradually over time.

3.2.3 Total Ni Losses

Total Ni lost from the system is represented as the sum of all outflows from the system. Losses from LiB subsystem are lost from end-of-life to landfill (flow 15-0) while from the non-LiB subsystem losses flow to landfill and also to carbon scrap subsystem (flows 18-0l and 18-0c). Losses from the supply subsystem are lost from mining and refining processes to tailings (flows 1-0, 2-0, 3-0, 4-0, 5-0, 6-0, 7-0, 8a-0, 8b-0, 10-0).

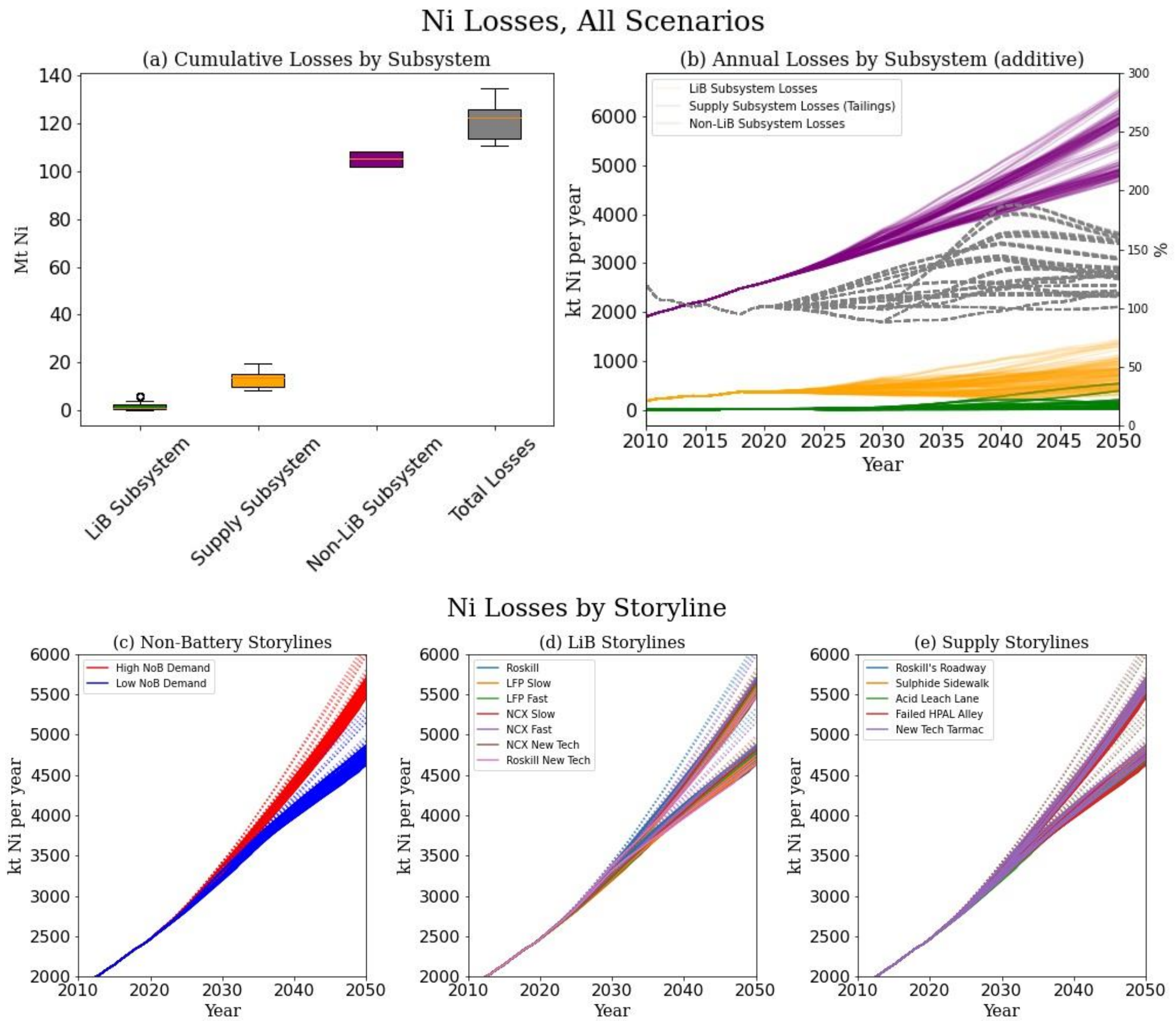


Figure 19 - Total Ni losses from system over model run, all scenarios. (a) Box and whisker plot shows total Ni lost from each subsystem over model run, given for each subsystem individually and by combined total. Whiskers show the total range of values over all scenarios. Boxes show the median 50% of values over all scenarios with median value shown by horizontal line. Outliers are marked with "o"symbol[9] (b) Ni outflows from LiB system (landfilling), supply system (tailings), and non-battery system (landfilling and carbon steel) shown additively over all scenarios. Right axis shows total losses as a percentage of total consumption annually. (c-d) Shows total losses coloured according to various storylines belonging to individual subsystems, recycling subsystem variation represented via line styles with solid lines showing high recycling and dotted lines showing low recycling storylines.

[9] Boxplot details can be found here: https://matplotlib.org/stable/api/_as_gen/matplotlib.pyplot.boxplot.html (accessed June 16, 2021)

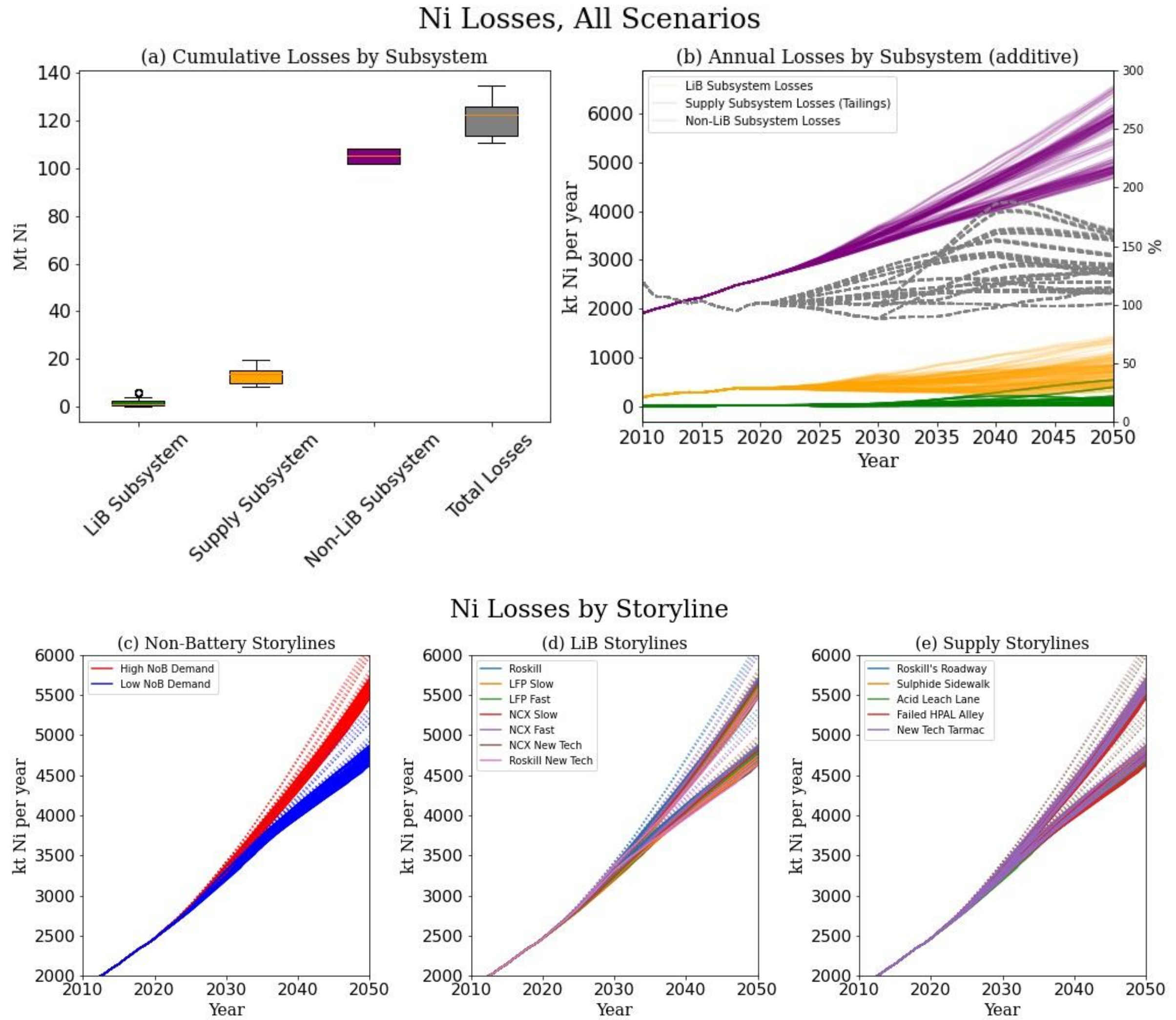


Figure 19 (a) shows that the majority of losses from the Ni system, cumulative over the model period, are lost from the non-LiB subsystem with a total of 105-109 Mt Ni. this range is relatively small and while it cannot be seen in the figure, the distribution is split between a low value of 101.7 Mt Ni and a high value of 108.3. This clean bifurcating of values from the non-LiB subsystem reflects the low resolution applied to this subsystem in this model. With the only variation within the subsystem coming from the high and low demand profiles.

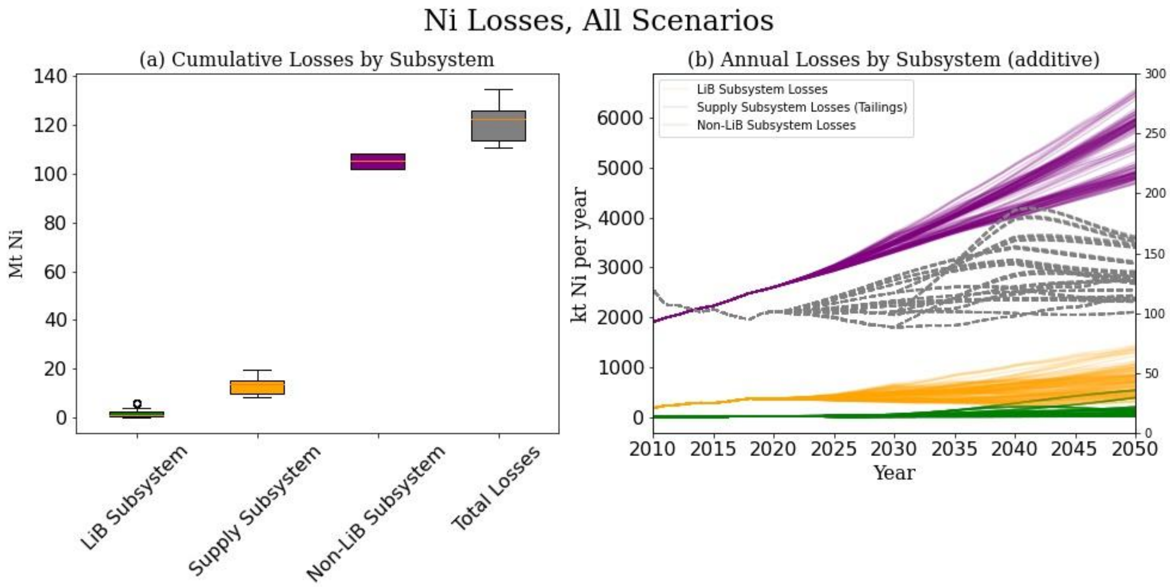
Losses from the supply subsystem represent the next most significant loss of nickel. Here, losses to tailings stem from inefficiencies in the processing technologies. Table 4 shows the different recovery rates used in model processes. Some pathways are more efficient than others, because some refining processes have a higher yield than others. For the same Ni demand, the total amount of losses depends on the ore and refining processes used.

Table 4 – Process recovery rates for all transformation processes of Ni supply subsystem. Percent value Ni in process input which is recovered in process output, remainder is lost to tailings. Average values calculated from example facilities found in literature. Sources and reference facilities shown.

Process	Facility	Value	Average	Source
1. Sulphide Mining	Kambalda Australia	90%	91.3%	Crundwell et al., 2011
	Ragland, Canada	87%		Crundwell et al., 2011
	Thompson, Canada	90%		Crundwell et al., 2011
	Clarbelle Mill, Inco	94%		Kerfoot, 2000
	Copper Cliff Mill, Inco	95%		Kerfoot, 2000
	Thompson, Inco	92%		Kerfoot, 2000
2. Laterite Mining	Estimate	95%	95.0%	Expert Interview
3. DC Refining	Vale Long Harbour, Canada	98%	97.8%	Vale Inco, 2008
4. Sulphide Smelting	Kalgoorlie, Australia	95%	95.1%	Crundwell et al., 2011
	Faconbridge, Canada	98%		Crundwell et al., 2011
	Outokumpu, Japan	95%		Kerfoot, 2000
	BCL, Botswana	92%		Kerfoot, 2000
	WMC, Australia	96%		Kerfoot, 2000
5. FeNi Smelter	Falcando, Dominican Republic	91%	94.8%	Crundwell et al., 2011
	Hyuga, Japan	98%		Crundwell et al., 2011
	Hachinohe, Japan	98%		Crundwell et al., 2011
	Oheyama, Japan	95%		Kerfoot, 2000
	LCA study	92%		Khoo et al., 2016
6. Laterite Leach	Ravensthorpe, Australia	96%	93.7%	Crundwell et al., 2011
	Moa Bay, Cuba	96%		Crundwell et al., 2011
	Ambatovy, Madagascar	97%		Crundwell et al., 2011
	Coral Bay, Philippines	95%		Crundwell et al., 2011
	Typical Atmospheric Leach'	90%		Kerfoot, 2000
	Moa Bay, Cuba	90%		Kerfoot, 2000
	LCA study	92%		Khoo et al., 2016
7. NPI Smelting	Experimental with Sorowako ore	82%	81.0%	Andika et al., 2019
	BF/SAF process	80%		Rao et al., 2013
8. Sulphidation Roasting	PT Inco, Sorowako, Indonesia	97%	97.0%	Crundwell et al., 2011
10. Metal Refining	Nikkelverk, Norway	99%	99.0%	Crundwell et al., 2011
	Sumitomo, Japan	99%		Crundwell et al., 2011

The LiB subsystem has very small losses over the model run period, representing waste LiBs to landfilling. The variation of LiB to landfill losses under different scenarios are densely clustered around the mean value of 1.9 Mt over the model run with high values of 6.2 Mt Ni in scenarios with high and sustained LiB demand for Ni and low LiB recycling.

The system loses are shows to increase gradually and steadily over the model run, and have a total range of 111 MtNi to 134 MtNi. The magnitude of losses over the model run is on a similar scale to system consumption over the model period, though with a smaller range and less volatile variations over time.



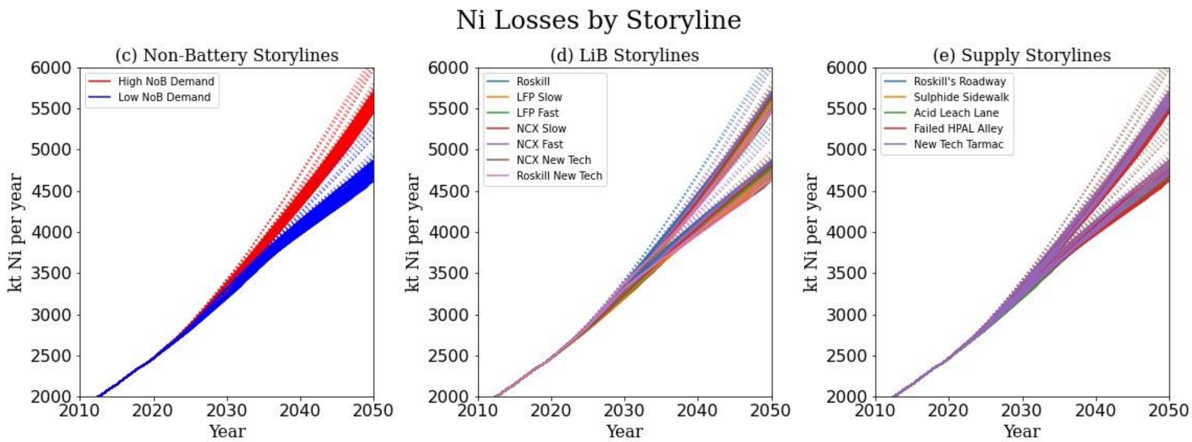
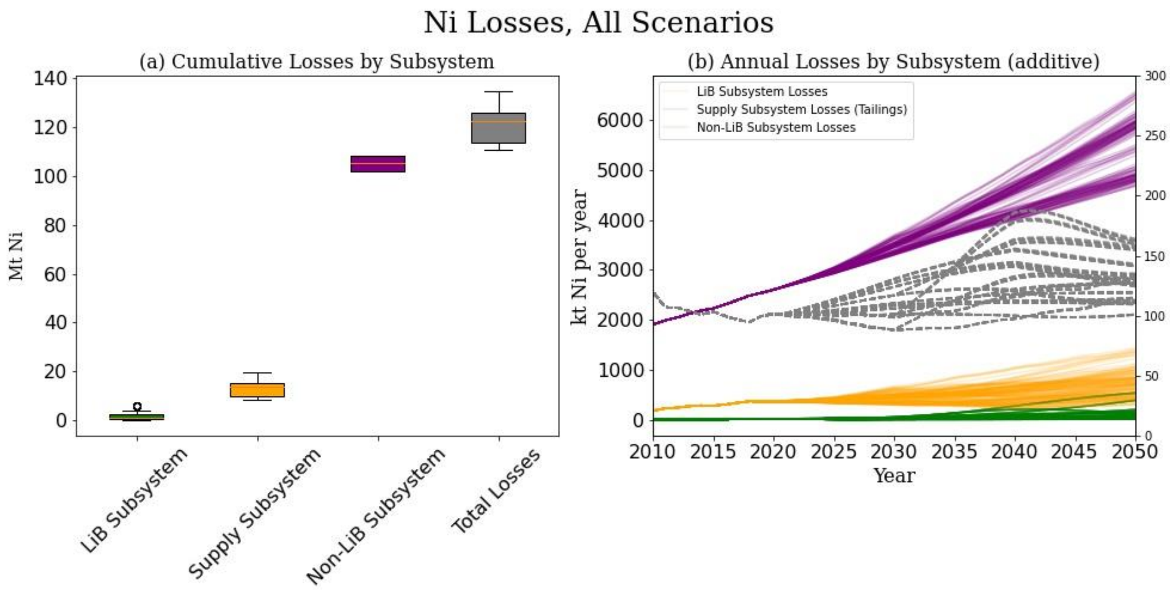


Figure 19 (b) shows the relationship between Ni consumption as a percentage of Ni losses, with consumption ranging between 100% and 200% of losses for various scenarios and time periods.

As with system consumption, losses are most sensitive to non-LiB subsystem storylines.



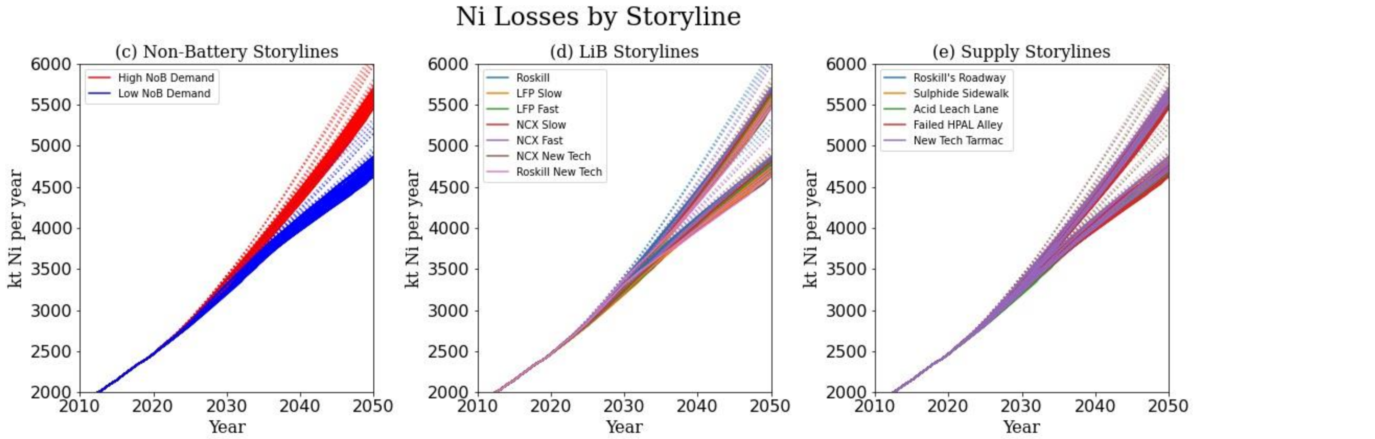


Figure 19 (b) shows a clear divergence between storylines, with low demand to non-LiB sectors resulting in lower system losses.

Again, as with system consumption, LiB subsystem storylines show consistent effects on system losses. Losses correlate positively with the demand profiles of the LiB storylines though the amount of variation in losses between these storylines is smaller than was seen for consumption. This is explained by the dampening effects of the lifetime of Ni in the LiB subsystem and the high rate of recycling once LiBs reach their end of life.

LiB recycling storylines show a consistent and marked effect of significantly higher losses for storylines with lower total recycling. While this effect is slightly smaller than the variation caused by high and low non-LiB demand storylines, the LiB recycling storylines have a more pronounced effect on losses than do the LiB demand storylines or the supply subsystem storylines, though the effects of LiB recycling storylines are modulated with the LiB demand storylines.

The effect of the supply subsystem storylines is nearly negligible, despite that this subsystem contributes larger losses than the LiB subsystem. This appears to be due to fairly balanced losses between the different pathways. However, by zooming in on a single storyline some differentiation becomes visible. Figure 20 shows that at the period between 2040 and 2045, holding all other subsystems at a single storyline, a variation of 80 kt Ni or approximately 1.5 % of total losses is caused by supply storyline variation.

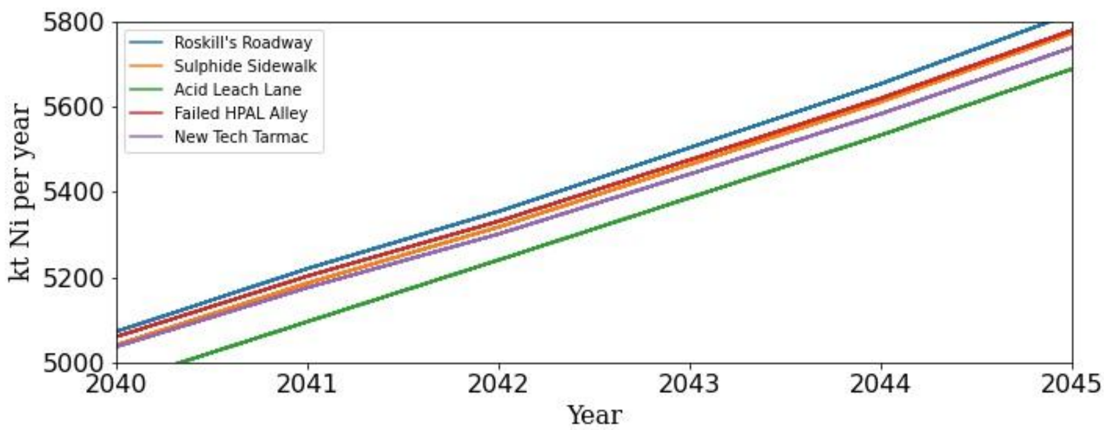


Figure 20 - Ni losses by supply subsystem scenario. Highest demand storylines in both LiB demand and non-LiB demand and low LiB recycling storyline.

3.2.4 GHG Emissions

Total GHG emissions are a direct function of the production of the different supply pathways and the GHG impact factor of the individual pathways. Figure 21 shows the modelled production of the pathways in Ni as well as in CO2 equivalents.

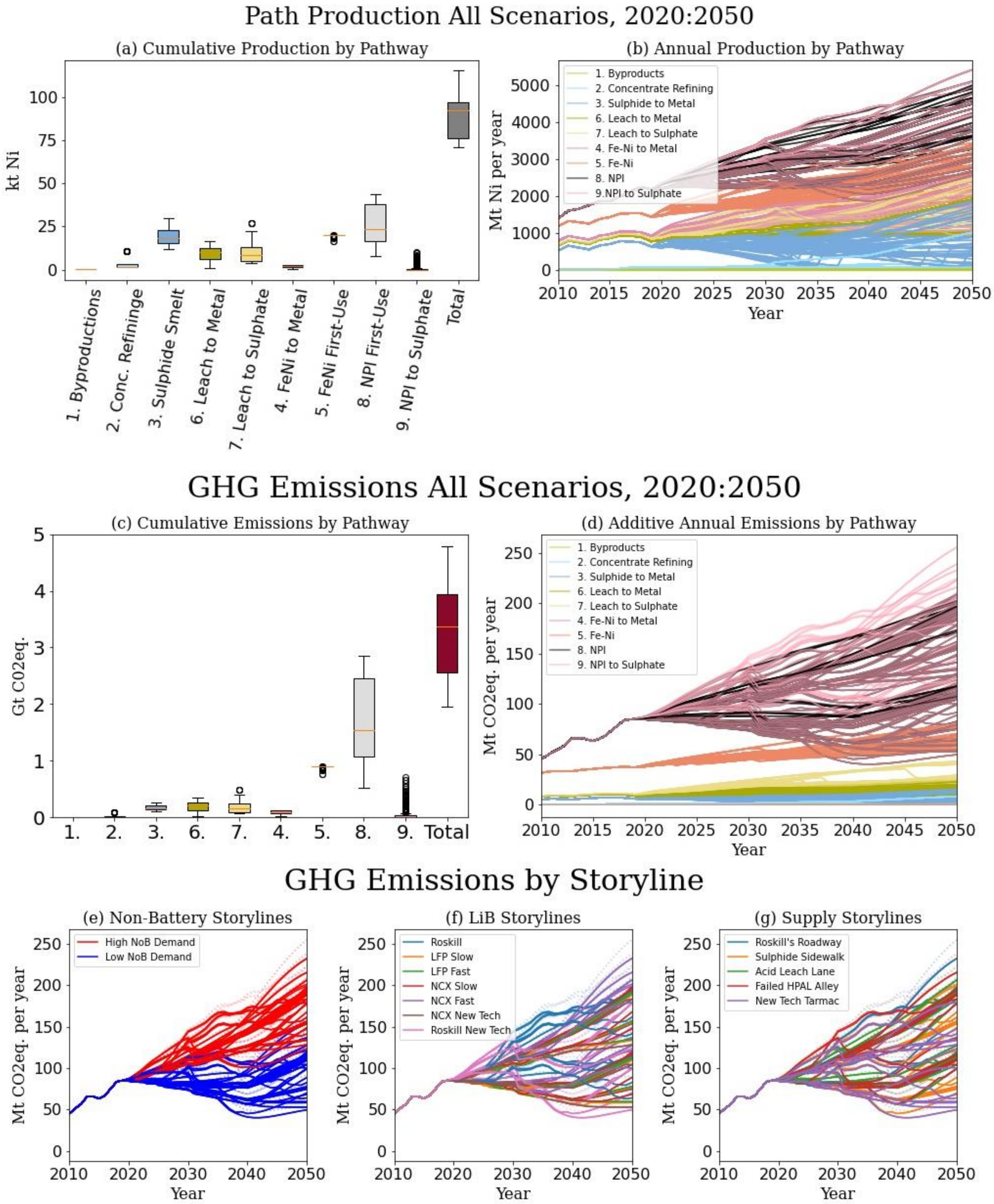


Figure 21 - Total GHG emissions from system over model run, all scenarios. (a) Box and whisker plot shows cumulative production from each pathway over model run variation between scenarios. Whiskers show the total range of values over all scenarios. Boxes show the median 50% of values over all scenarios with median value shown by horizontal line. (b) Annual Ni production shown by pathway additively. All scenarios plotted separately for all pathways (c) Box and whisker plot shows total emissions from each pathway over model run. (d) Annual Ni production shown by pathway additively. All scenarios plotted separately for all pathways. (e-g) Total system emissions coloured according to storylines. Recycling subsystem variation represented via solid lines showing high recycling and dotted lines showing low recycling storylines.

While the Ni production is somewhat evenly split between pathways, the greenhouse gas emissions of the nickel system come largely from the NPI and FeNi pathways 5, and 8, with pathway 9 making a significant contribution under certain outlier scenarios (see section 0 below for discussion of scenarios which cause pathway 9). Most of the variation in the emissions of the system is caused by variation in the two NPI pathways, 8 and 9.

A comparison between plots (a) and (c) in Figure 21 show the strong effect that differences in the GHG impact factors of the different pathways have on the emission profile of the system. The most notable effect is seen in the two pathways with high production and extreme impact factors, pathways 3 and 8. Pathway 3 sulphide smelting to metal, is the second largest producer of Ni, yet has amongst the lowest contribution to system emissions. Meanwhile, NPI production in pathway 8 plays the largest production role in the system under most scenarios, and is extremely dominant in the GHG profile of the entire system under. The ability of pathway 3 to produce significant Ni with a small carbon footprint, and the variation of pathway 8 make these the two pathways with the strongest influence of the GHG emissions of the system.

As with the indicator flows of the previous sections, the non-LiB demand storyline has a large and binary effect on the greenhouse gas profiles of the system. Emphasizing again the sensitivity of the system to this storyline. Likewise with the LiB recycling storyline, which shows a consistent effect on the system GHG emissions which grows larger in later model years.

The LiB demand storyline has a strong, positively correlated, effect on the GHG emissions of the system, with higher LiB demand storylines generally leading to higher GHG emissions. However, unlike the consumption and loss profiles, the LiB and non-LiB storylines do not clearly combine to explain the majority of the variation in the emissions profiles. GHG emissions of the Ni system are also significantly sensitive to the supply subsystem storyline, with variations in this storyline having a noticeable effect on the total system emissions under all other storyline combinations.

The supply subsystem storylines that consistently produce the lowest GHG emissions under all other storyline combinations are the New Tech Tarmac and the Sulphide Sidewalk storylines. These storylines make the most use of pathways 2 and 3, the pathways with the lowest GHG factors. The Failed HPAL Alley storyline, meanwhile, produces the highest GHG emissions in the short term, as it describes a scenario in which little new investment is made in pathways 2 and 3 and pathways 6 and 7 struggle to reach anticipated capacity, with the remainder of demand met by NPI until the leach facilities reach higher production capacities in later decades. The Roskills Roadway storyline produces the highest GHG emissions in the later half of the model run, as it describes significant development along pathways 6 and 7 until 2030 after which little new capacity is developed, again relying on NPI to make up the difference.

3.3 Shortfall Risk Dynamics

The key indicator of shortfall risk in the model is pathway 9, where NPI is upgraded into Ni sulphate to be usable in battery production. Flow 8b-12 directly quantifies this pathway. Figure 22 shows the variation in use of this pathway over all model scenarios.

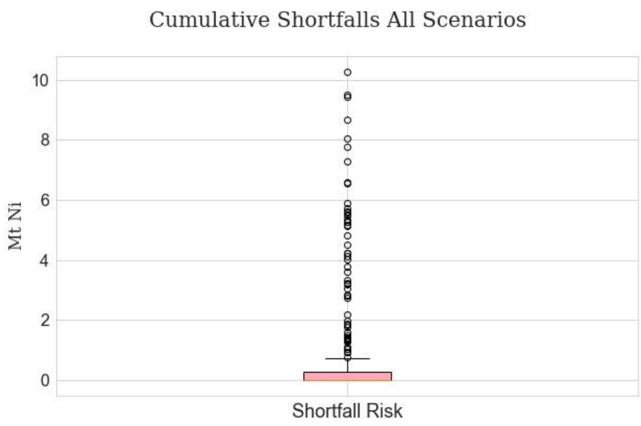


Figure 22 – Cumulative production of novel NPI to sulphate pathway. Box and whisker plot shows cumulative Ni produced by this pathway. Whiskers show the total range of values over all scenarios. Boxes show the median 50% of values over all scenarios with median value shown by horizontal line. Outliers are marked with "o"symbol[10]

Most scenarios of the model show no amount or low amounts of Ni produced by the NPI sulphidation pathway, while under certain scenarios significantly larger amounts of NPI sulphidation is required to fill the gap in demand for Ni sulphate for both LiB and non-LiB uses. Below the storylines which lead to use of this pathway are examined.

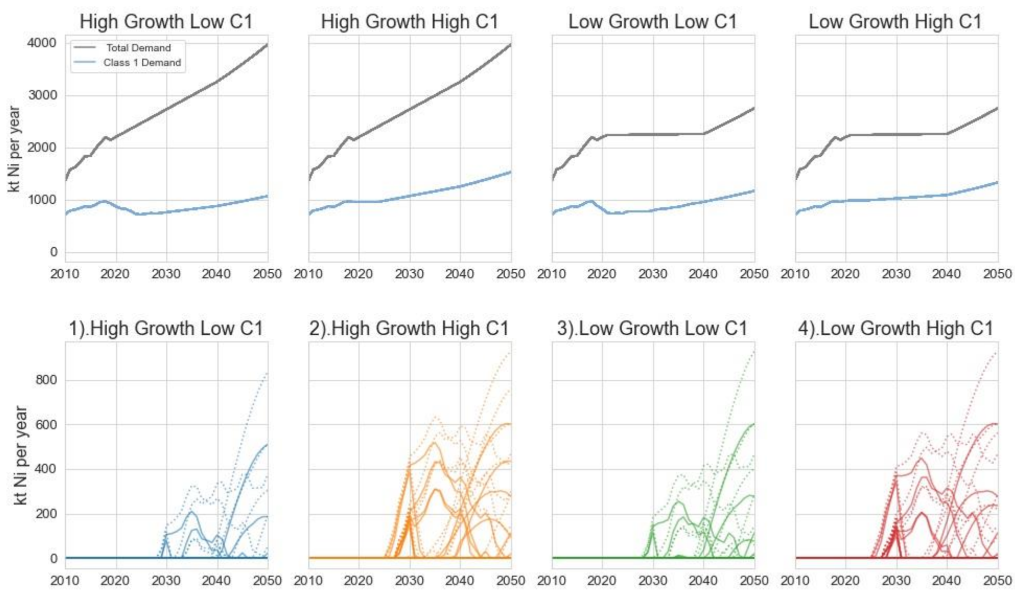


Figure 23 - NPI sulphidation requirement shown by non-battery demand storylines. Top row shows key details of storylines, which are the total amounts of demand to the non-battery subsystem and the amount of that demand which must be supplied by class 1 sources (non-battery demand for sulphate included in class 1 demand). Bottom row shows annual flows of NPI sulphidation for all scenarios using each storyline. Recycling subsystem variation represented via solid lines showing high recycling and dotted lines showing low recycling storylines.

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[10] Boxplot details: https://matplotlib.org/stable/api/_as_gen/matplotlib.pyplot.boxplot.html (accessed June 16, 2021)

Risk of shortfalls to battery grade Ni supply are not significantly affected by the total demand of Ni to the non-battery system as the difference in use NPI sulphidation is only slightly larger in the high growth storylines over their low growth counterparts (plots 1. and 3. in Figure 23, above). However, the difference between the non-battery demand for class 1 feedstocks shows a significant influence on the risk of shortfalls. This is a strong indication that the LiB sector is not significantly different than other sectors which demand class 1 Ni feedstocks, and is directly affected by the same markets as other class 1 uses.

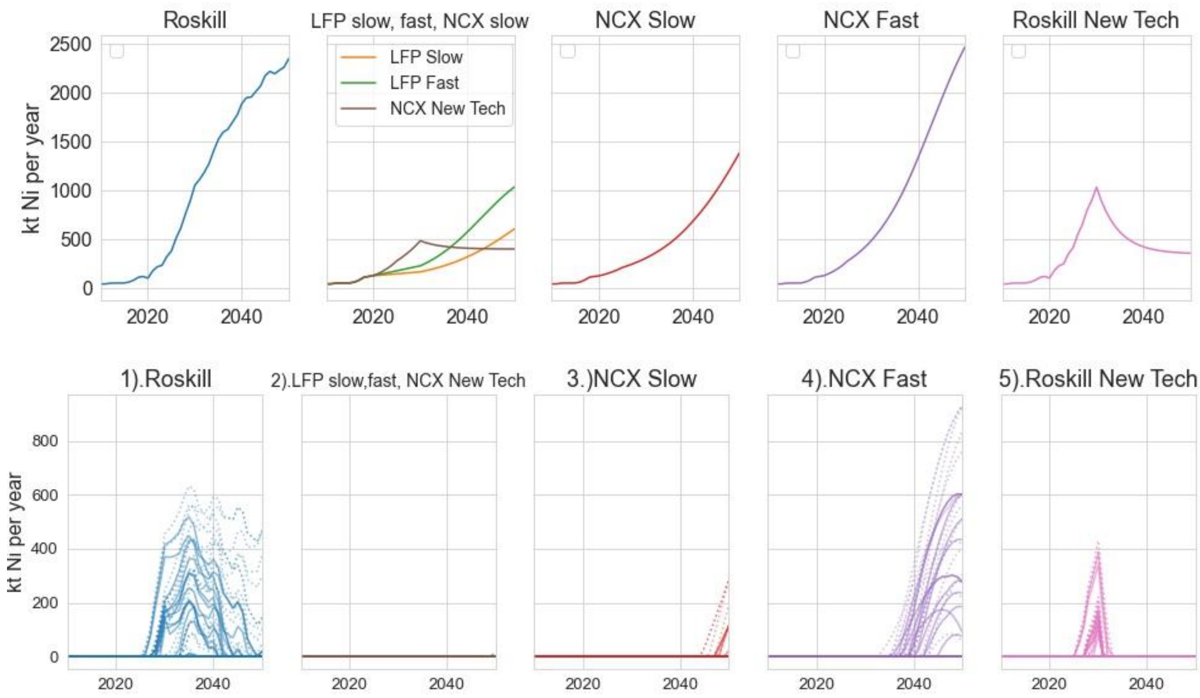

Figure 24 - NPI sulphidation requirement shown by LiB demand storylines. Top row shows key details of storylines, which are the total amounts of demand to LiB manufacture. Bottom row shows annual flows of NPI sulphidation for all scenarios using each storyline. Recycling subsystem variation represented via solid lines showing high recycling and dotted lines showing low recycling storylines.

The LiB demand storylines have a strong and consistent effect on the risk of shortfall, and can be understood to be the main driver of shortfall risk to the system. The speed of increase of demand has a stronger influence than the absolute quantity of demand. The earliest shortfalls are shown to arise in 2027 under the two Roskill storylines, while the next fastest storyline shows no shortfall risk before 2034. The recycling storylines have a large impact on the risk of shortfalls especially in later years. It is notable that the Roskill storyline shows the shortfalls diminishing through the later years of the model period, while the stock-driven storylines show much more risk later in the model run.

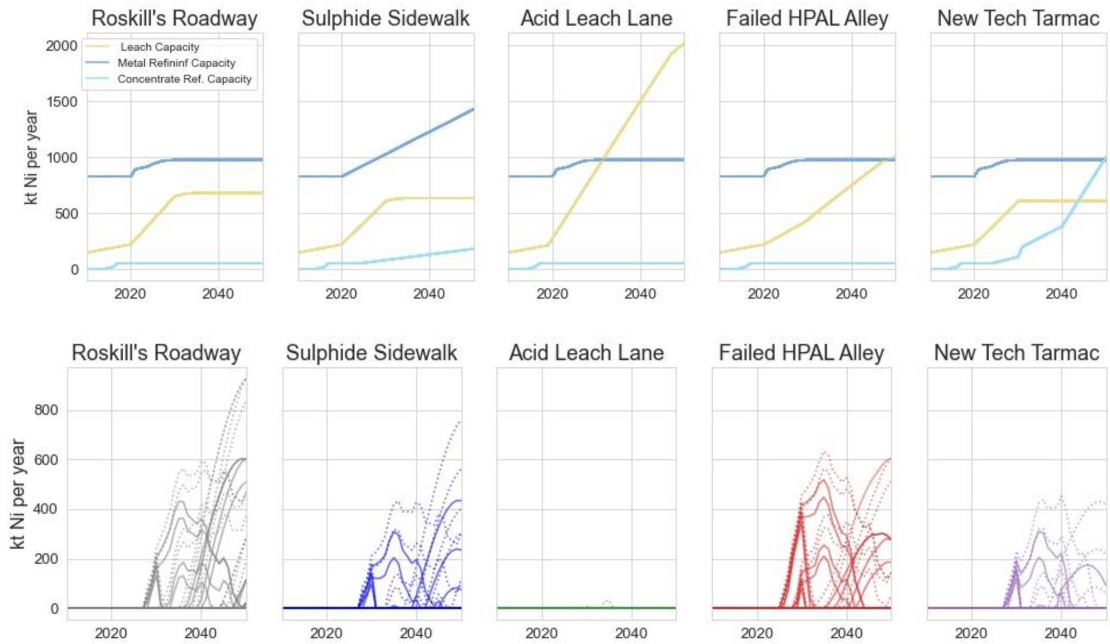

Figure 25 - NPI sulphidation requirement shown by supply system storylines. Top row shows key details of storylines, which are the capacity limitations on the three main battergy grade processes: laterite leaching, metal refining, and direct concentrate refining. Bottom row shows annual flows of NPI sulphidation for all scenarios using each storyline. Recycling subsystem variation represented via solid lines showing high recycling and dotted lines showing low recycling storylines.

The supply subsystem storylines also have a strong and consistent effect on the risk of shortfall, and indicate a strong degree of mitigation is possible by supply system development. The storylines are described by varying levels of production capacity in the three main battery grade processes. Figure 25 shows the effect the supply storylines have on the need for NPI sulphidation. The Acid Leach Lane storyline shows the highest total growth in capacity, relying almost entirely on HPAL development to increase the system capacity and manages to avoid any use of NPI sulphidation. Meanwhile Roskill's Roadway and Failed HPAL alleys show insuffiecient development of capacity for shortfall risks to be avoided. The New Tech Tarmac and Sulphide Sidewalk storylines however show gradual development of the two sulphide pathways, and manage to avoid significant shortfall risks.

See Appendix 1 for a higher resolution break-down of the storyline effects on NPI sulphidation.

3.4 Greenhouse Gas System Dynamics

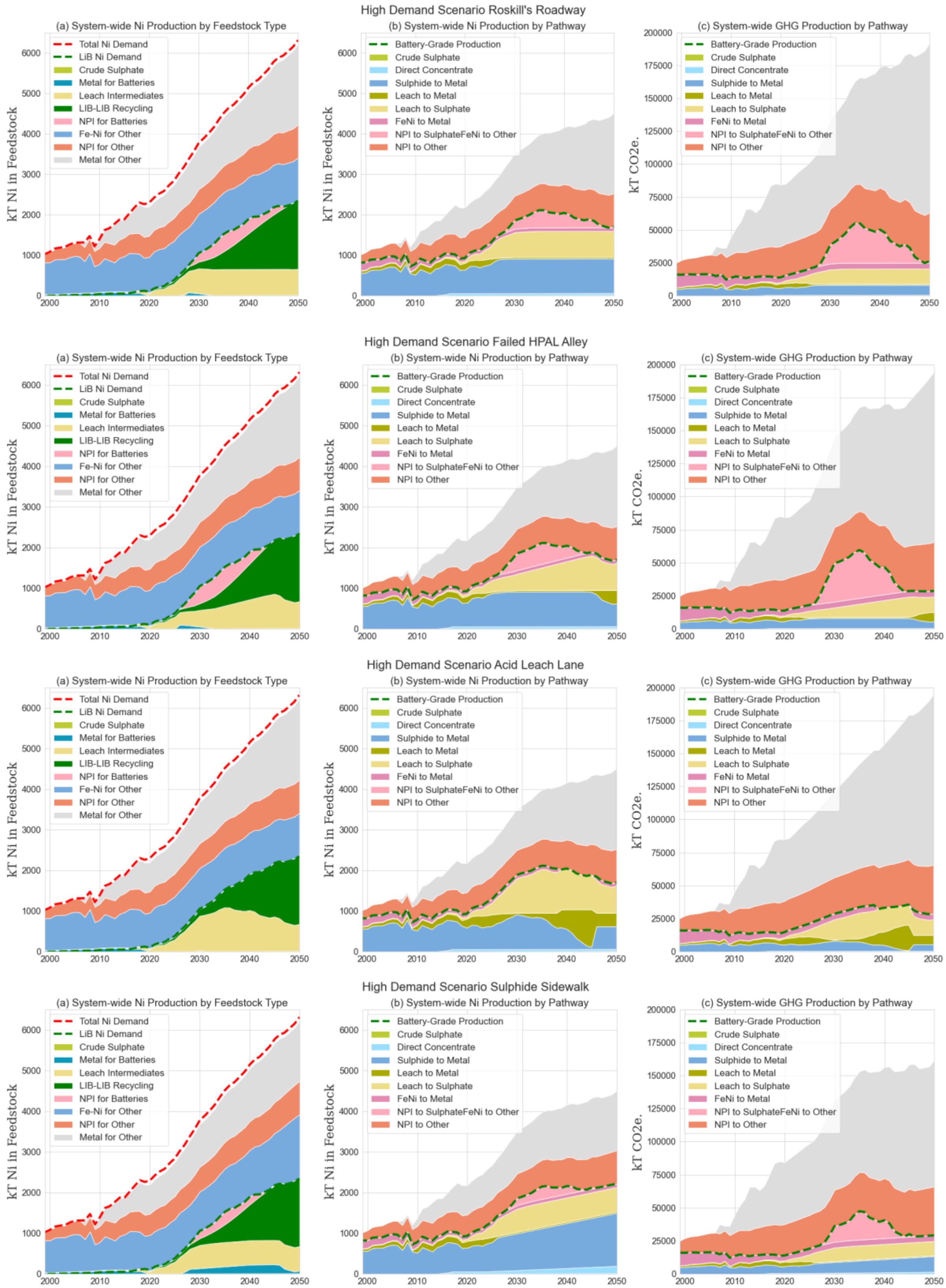

Figure 26 - System producion of Ni by feedstock (column a), and by production pathway (column (b). Compared with GHG production by pathway (c). Shown for highest demand scenarios of LiB and non-Battery subsystems in order to show largest effects. Feedstocks separated below and above dotted green line by battery vs non battery use in column a, and by battery grade (including class 1) vs non battery grade production in columns b and c.

The main pathways which supply Ni to class 1 and Ni sulphate feedstocks have significantly lower GHG emission factors than the pathways which traditionally supply class 2 feedstocks. Figure 26 shows how demand for feedstocks translates Ni and GHG production by pathways under the highest demand storylines of the model runs.[11] The comparison between columns a and b in the figure visulaise how the same demand profiles can be supplied by a variety of supply system configurations. The recycling of LiB reduces the demand on the supply system from the LiB subsystem especially in later years. Pathway uses shift over time in supplying demand for feedstocks according to what pathway capacities are available and most preferable for meeting the demand. Pathway 9, NPI sulphidation, arises in the model when demand for battery-grade feedstocks cannot be met by other pathway.

A comparison between columns b and c in the figure visualizes the differences between Ni production and GHG production of the system as a whole. While battery grade pathways occupy a large portion of total Ni production in column b figures, they occupy a much smaller portion of the total GHG production in column c, with the exception of NPI sulphidation which creates a visible bulge in GHG production when it is used. However, NPI sulphidation is not the only variable of importance when considering the GHG profile of the battery-grade Ni production options. The Sulphide Sidewalk storyline which make strong use of pathways 3 shows a significantly lower total GHG emission for the later years of the study than any of the other supply storylines.

[11] The highest demand storylines have been used in this section for clear visualization of system dynamics, but the trends described hold consistently for other demand storylines.

Greenhouse Gas emissions per Unit Nickel

The varying supply system storylines in combination with the demand for Ni has a large influence on the average carbon footprint of any Ni unit produced by the system. Figures Figure 27 (loest carbon footprint) and Figure 28 (highest carbon footprint) show that the carbon footprint of the average unit of Ni has been increasing in recent decades, and that this trend could either continue upwards or revert downwards depending on future system developments. Two most extreme scenarios of all model runs are shown here in order to provide range of values to the reader.

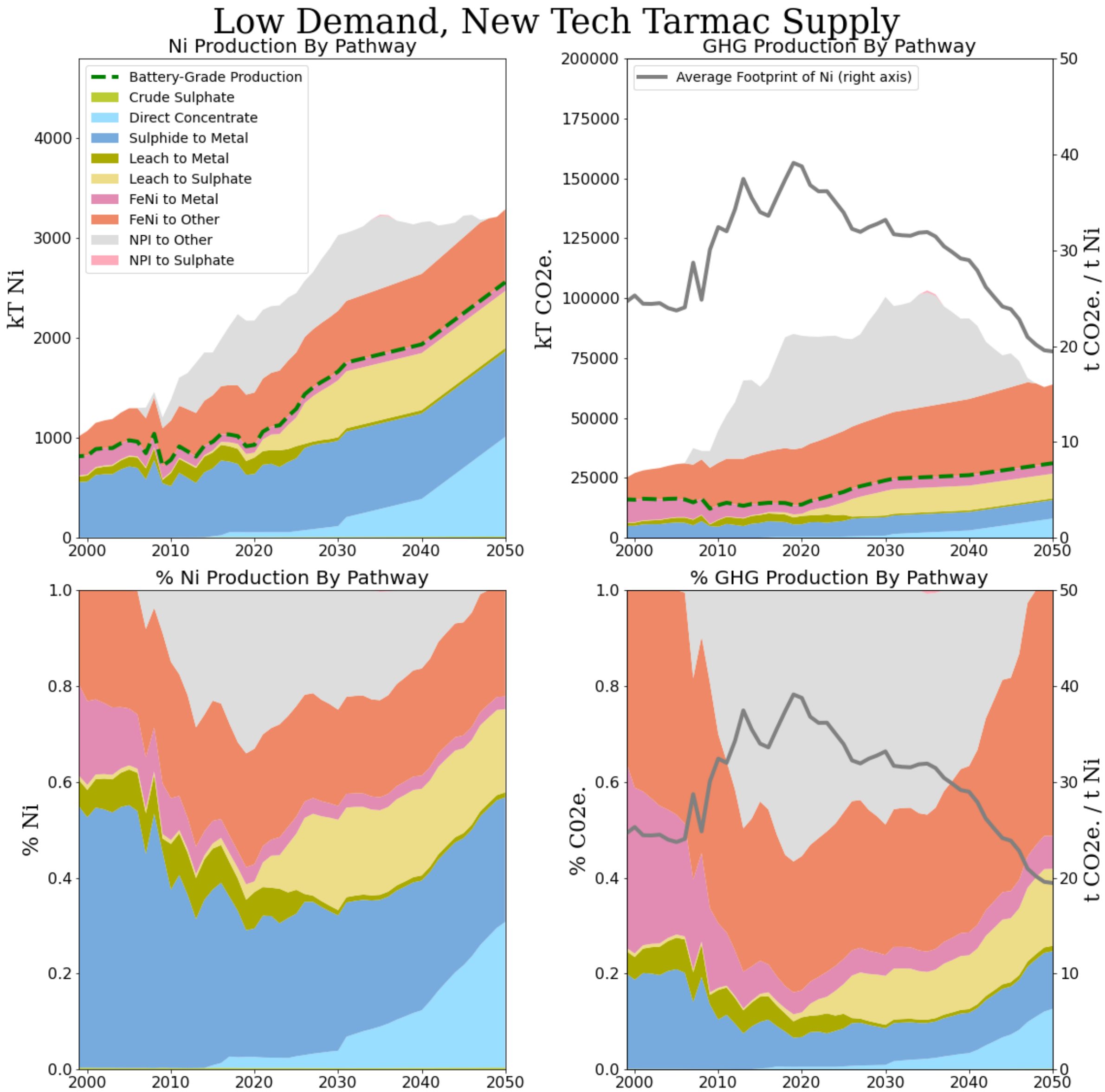

Figure 27 – Comparison of system production and normalized production by pathway for scenario with low total demand and high capacity of low carbon pathways. Top row shows total production and GHG production of Ni system is shown by different pathways. Bottom row shows normalized composition of average unit of nickel by pathway. Average carbon footprint of one ton Ni shown on right axis of right column plots.

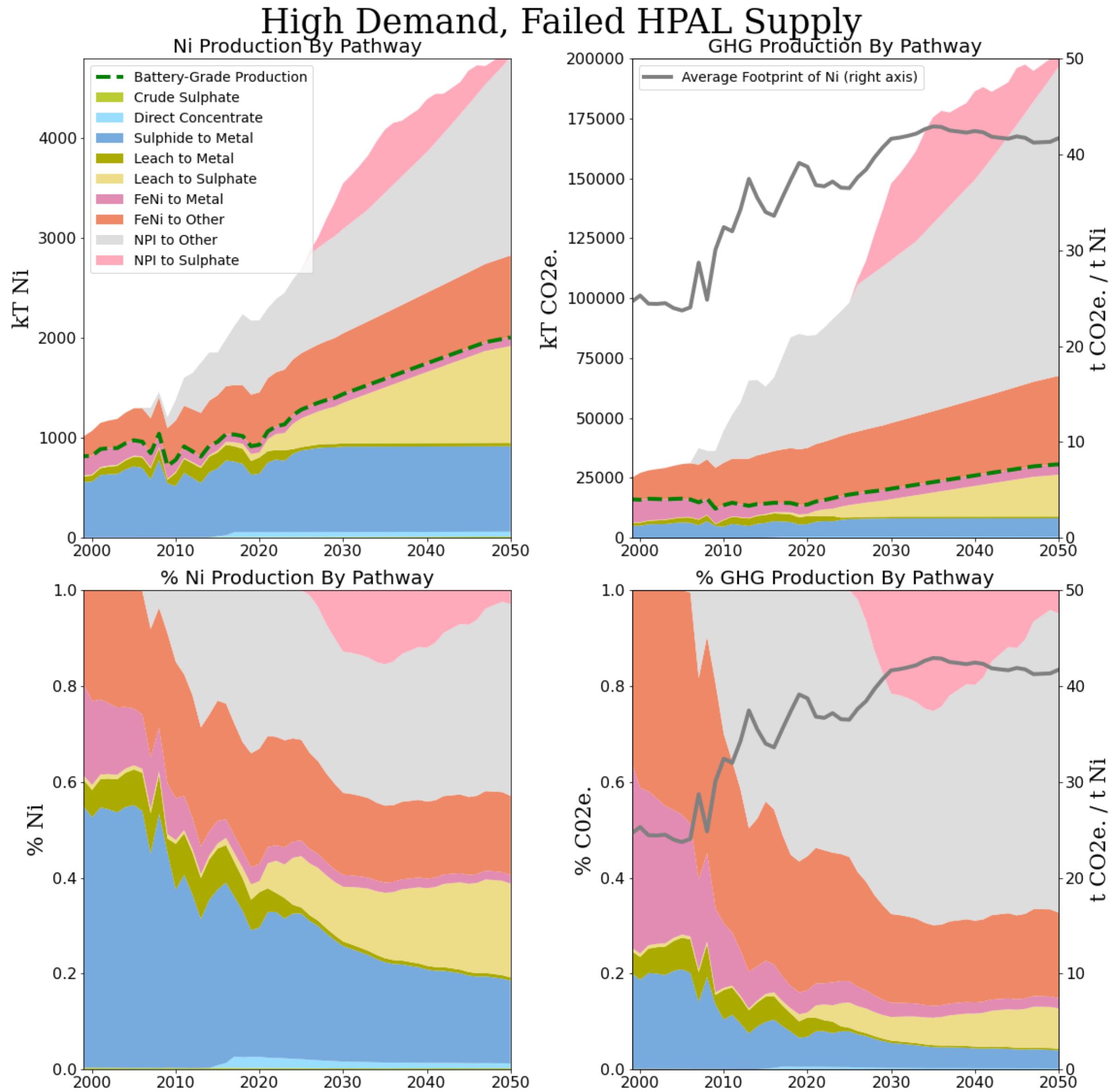

Figure 28 - Comparison of system production and normalized production by pathway for scenario with high total demand and struggling supply. Top row shows total production and GHG production of Ni system is shown by different pathways. Bottom row shows normalized composition of average unit of nickel by pathway. Average carbon footprint of one ton Ni shown on right axis of right column plots.

4 Discussion

4.1 Options for avoiding shortfalls

Effective mechanisms for reducing the likelihood and magnitude of shortfalls in the Ni supply system were found in all subsystems of the Ni system, though the ease of influencing the changes that are modeled varies and is in all cases diffuse amongst stakeholders throughout the system. The mechanisms will be discussed subsystem by subsystem below.

4.1.1 Demand

The most consistent mechanism for reducing both the risk of shortfalls and the system GHG emissions is reducing demand. The demand to LiB manufacture was the strongest predictor of shortfalls, but class 1 demand to non-battery manufacture also has a strong influence. This means that products in the non-battery sector which use exclusively class 1 feedstock, compete directly with LiB batteries for battery-grade Ni. Decrease in reliance on class 1 feedstock or substitution with other materials will alleviate strains on the battery-grade Ni system.

While a reduction in demand either of the LiB system or the total demand is unlikely (see Figure 17), the rate of increase in demand is important. A more gradual increase in demand is significantly less disruptive. The LiB demand profiles taken from Fraser et al. (2021) on which the Roskill storylines were based, were found to show highest demand and were the more problematic for the Ni system. More significant use of LFP or other low/no-Ni cathode technologies in EVs can ease the demand for Ni to LiB manufacture and mitigate some of the disruptions.

Non-battery demand for battery grade Ni is a much larger slice of the total Ni market, at least for the coming decade. This means that these sectors are still the main driver of shortfalls for the time being, it also means that reductions in these sectors have a lot of potential to mitigate shortfalls.

4.1.2 Recycling

One of the largest possibilities for reducing demand appears to be the capture and recycling of non-battery Ni products. As of 2010 the global recycling rate of all Ni products was 68%[12]. At this rate the amount of Ni expected to be lost to landfill or carbon steel between 2020 and 2030 is significantly more than the total amount of battery grade Ni needed for the system that decade. It should be emphasized that the non-battery subsystem has been modelled in this study only to a very approximate level, since the focus of this study has been targeted to the supply system and the LiB subsystem. Reck et al. indicates that all first use sectors save electroplating are able to use recycled scrap materials. The present study uses that finding to support the insight that recycling in non-battery sectors can alleviate the need for new Ni feedstocks, even battery grade. The magnitude of the recycling flows can be seen under both high and low non-battery demand in Appendix 2.

[12] Reck et al. as cited in https://Niinstitute.org/media/2273/Ni_recycling_2709_final_nobleed.pdf accessed 03/05/2021.

4.1.3 Supply

Increased capacity along all pathways that produce battery-grade or class 1 feedstocks will reduce the risk of shortfalls. Constructing new capacity along pathways 1,2,3,4,6 and 7 have equal effect on alleviating shortfall situations. Meanwhile, pathways 1 and 4 (sourcing battery grade Ni from by-products or FeNi) are unlikely to play a significant role.

However, as pathways 2, 4 and 6 all route through process 10, metal refining, lack of capacity at this process is a significant potential bottleneck to supply. In situations of low demand for sulphate to the LiB chain, unused laterite leach intermediates will need to be refined in this process to be used in used as Class 1 in other applications, which would occupy capacity and limiting the use of sulphide mining and smelting. Therefore, it is advisable to develop capacity along either of the sulphide pathways (2 and 3) rather than investing entirely in laterite leaching. Compare figures 37 and 38 in appendix 2 to see how lack of refining capacity can lead to higher use of NPI under low demand conditions. Compare figures 43 and 44 in appendix 2 to see how same bottleneck can result in significant use of NPI sulphidation route under high demand conditions.

4.1.4 The Metal Refining Bottleneck.

A central concept in the dynamics of the Ni system is the integration of a facility with facilities in preceding and following processes. The different supply pathways developed in this study share processes with one another, and there is no set of processes that can consistently sum to be the total capacity of the Ni system. A notable instance of this effect is the various pathways that converge at process 10, refining to metal. Matte products from process 4, sulphide smelting, and process 8a, FeNi sulphidation, require this process before they can be first-use products in either battery or non-battery production, whereas leach intermediates from process 6 require process 10 only to be used in certain non-battery first uses. This creates a potential bottleneck in process 10, which arises in situations where large capacity of matte and laterite leach production coincide with low demand for sulphate feedstocks. In such a case, the model indicates that there is a demand for Ni metal product from the refineries, and a large supply of feedstocks to the refineries, but that the refining capacity is the limiting factor, meaning that some matte or leach intermediate capacity will be unused while FeNi or NPI smelting will supply the non-battery sector. This will create competition between the matte producers and the leach intermediate producers for available refining capacity.

Vertical integration of facilities along the supply chain from mining to production is an important element of the supply system that has been observed increasingly in the automotive sector, which aims at securing their supply of batteries and associated materials alike.

4.2 Options for minimizing GHG impacts

The GHG emissions of the Ni supply system vary greatly between model runs showing a factor five different between the highest impact scenario and the lowest for model year 50 (see Figure 21). While the total demand for Ni production has the greatest influence on the carbon footprint of the system, the supply pathways used have a large impact on the carbon footprint of the nickel they produce. The GHG impacts of the supply system depend to a great extent on the future development pathways taken.

4.2.1 Supply Pathway Preferences

This study has found a general correspondence between the purity of the feedstock, the carbon footprint of the feedstock pathway, and the time required to develop new capacity along the pathway. As a loose rule it can be said that the faster the pathway is to develop, the higher the carbon emissions of the development are likely to be. The sulphide pathways, both traditional and direct refining technologies are the most preferable pathway to use, but they require many years of planning and investment before they can be put into use. Once they are in use, however, they tend to operate smoothly, at or near capacity, and have low opeating costs. This is the pathway that should be invested in to see the largest mitigation in GHG emissions from battery-grade Ni. The laterite leaching pathway to making Ni sulphate is significantly faster than the sulphide pathways especially with high laterite ore availability, however it has significantly higher impacts, and historically has not operated consistently at the design capacity. In order to meet higher demand projections, a significant amount of use of this pathway will be employed. The final main pathway to making Ni for the battery system is the sulphidation of NPI. These pathway is extremely flexible and rapid to implement, however it has significant environmental concerns. In order to minimise the carbon impacts of new Ni developments to meet the demand from the energy transition, investment will have to be made well in advance of the demand materializing, so that the preferable pathways can be used as much as possible.

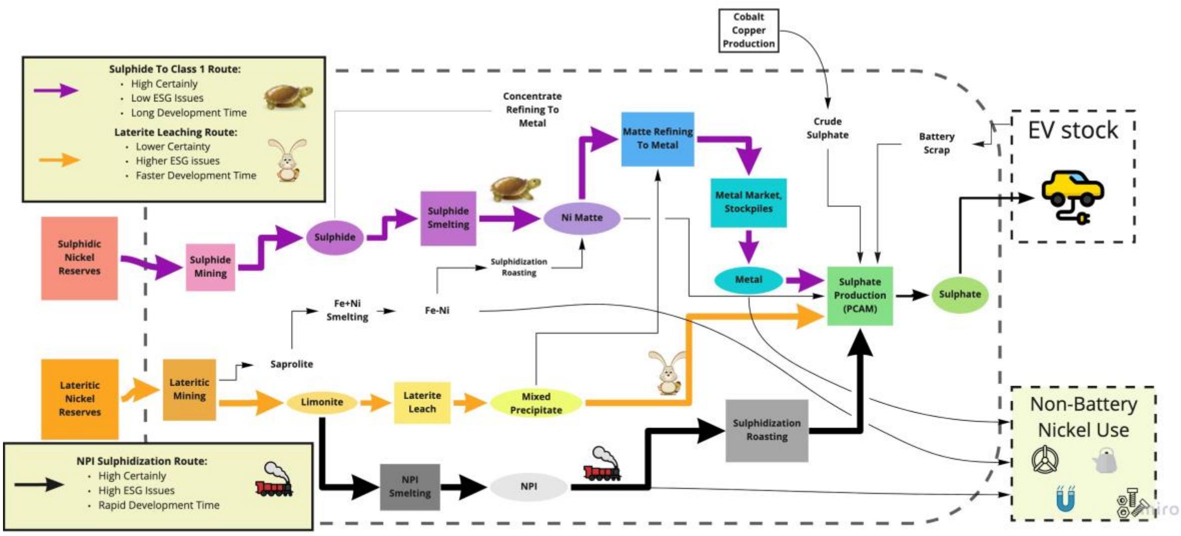

Figure 29 - Artist's representation of the Ni supply conundrum, using the system definition determined in this study

4.2.2 Burden shifts around emissions targets.

A number of measures have been proposed by various stakeholders to motivate a greening of the minerals supply chains which supply battery metals. Most notable is the European Comissions proposal for a sustainable battery regulation that would include provisions for electronic 'passports' recording the carbon footprint of materials which go into batteries and limiting the sale of batteries with carbon footprints above set thresholds (European Comission, 2020). Such targets on the battery supply chain may make pathway nine, NPI sulphidation, an unworkable feedstock supply pathway for many battery manufacturers, due to that pathway high carbon emissions.

However, due to the large quantities of Ni, including class 1 and sulphate, used in other applications, such regulations may have little or no effect on reducing the GHG emissions. While such targets could cause a price premium for feedstocks produced by lower-carbon pathways, incentivizing capacity buildout along low carbon pathways or improvements in carbon emissions of high carbon pathways, this study suggests that the same price premiums could incentivize rearranging Ni feedstocks where low-carbon feedstocks in non-battery products are exchanged with higher-carbon feedstocks freeing them up for the battery sector without affecting the overall system.

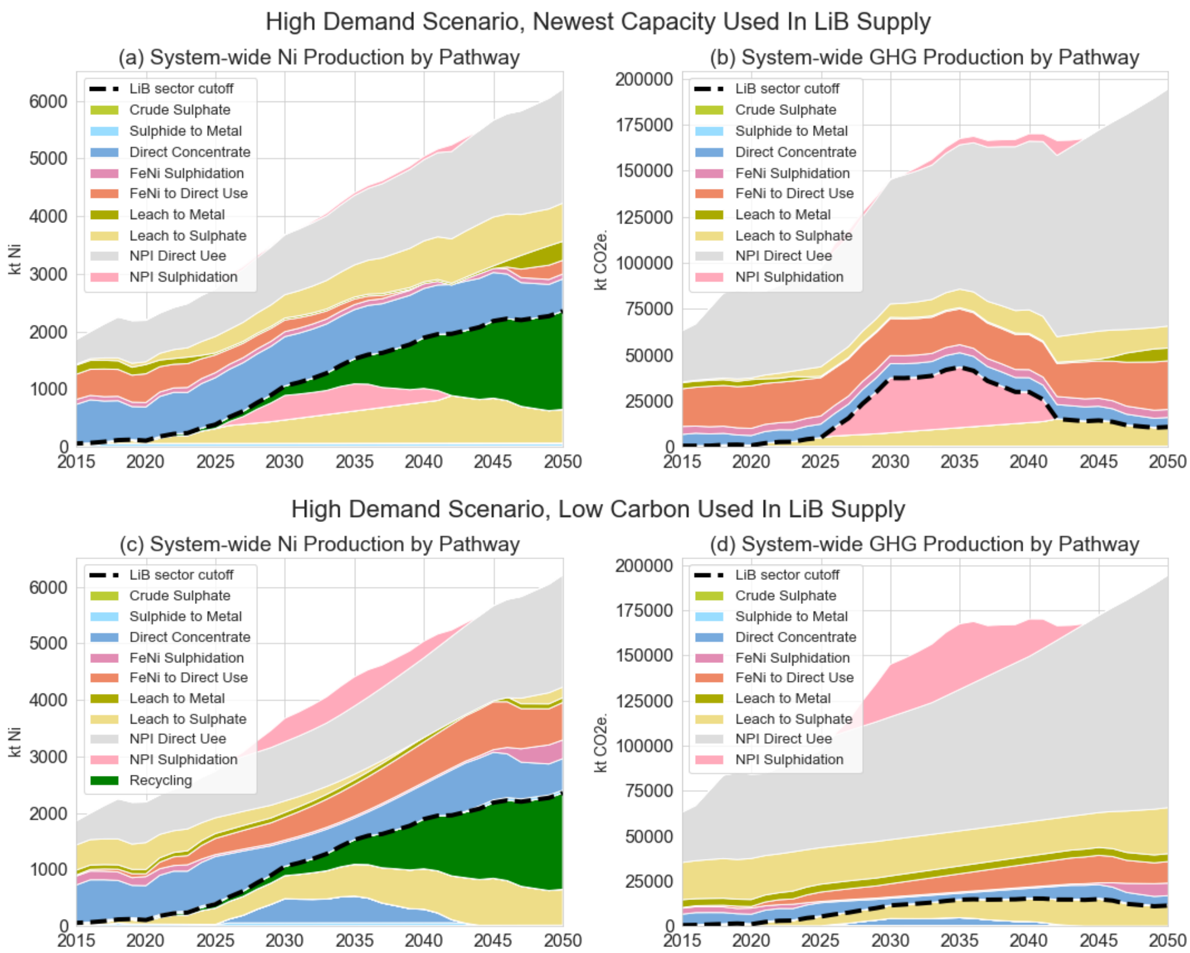

Figure 30 – Burden shifts of high carbon nickel. Left plots show nickel system by supply pathway with LiB manufacturing separated from non battery manufacturing by black dashed line. Right plots show GHG impacts of the same pathways and same division. Top plots show attribution of feedstocks between LiB and non-battery manufacture according to which

capacities were developed most recently to model year. Bottom plots show same scenario with attribution of feedstocks with lowest carbon footrprint to LiB manufacture.

Figure 30 shows visually the effect which such price premiums might have. Under the natural case, shown on the top row, high carbon nickel is produced in this scenario by NPI sulphidation in order to satisfy rapid growth in LiB sector. The pink bulge can be seen in the leftmost figure quantified by Ni production, however in the rightmost figure the same NPI sulphidation has caused a massive increase in the carbon emissions of the Ni system. Notice too that some additional NPI sulphidation is used in the non-battery sector as well meeting class 1 demand to non-battery applications, as can be seen by the sliver of pink along the top of the grey NPI wedge on both plots. The bottom row of the figure shows the burden shift that may occur by incentivizing the lowest carbon Ni to be used in the LiB system. The NPI sulpidation in the battery system is replaced not with new sulphide to metal production, but with sulphide to metal production that would otherwise have gone to non-battery manufacturing. And the NPI sulphidation is shifted into the non-battery manufacturing in place of the sulphide-based metal.

Another system shift that could free up lower-carbon feedstocks is by lowering the class 1 loading rate for stainless steel. This refers to the amount of class 1 metal used in stainless steel production. Industry reports indicate that current standard is approximately 15% but that the industry could reduce this down to 5% or lower (Fraser et al., 2021; Thompson et al., 2020).

This study modelled the difference between the shift class one holding all other variables constant. Figure 31 shows that a shifting class 1 feedstock away from stainless steel use, makes more class 1 Ni available, decreasing the need for sulphidation of NPI. However, the missing Ni in the stainless-steel production is then replaced with the same NPI smelting that has been avoided. Making very little real change in the system.

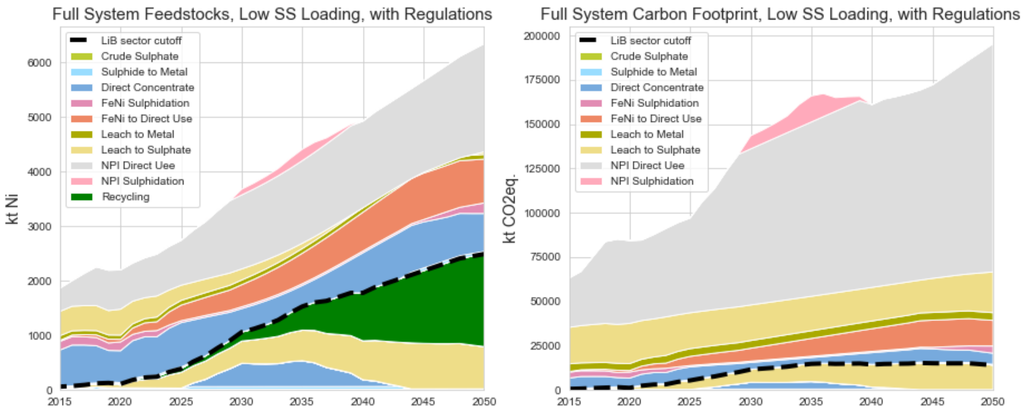

Figure 31 - Attribution of Ni feedstocks to LiB system modelled with low carbon battery grade feedstock capacity sering battery production where possible, and class 1 loading to stainless steel reduced to 5%, representing a system-wide shift toward using making higher valued class 1 and battery grade feedstocks available. Left figure shows composition of Ni supply over time according to pathway of production, right figure shows GHG emissions of same. Reducion of NPI Sulphidation as compared to ***Error! Reference source not found.*** *does not result in a significant lowering of system emissions as direct use of NPI is increased to make up the gap.*

Because the non-battery system is large enough to execute this shift for even the largest demands for Ni to the LiB system, there is little incentive to invest in the slower, less impactful route. In order to incentivize the long term investment in lower carbon technologies the pressure to reduce impacts will need to be applied more evenly along the whole system

4.3 Sulphide Supply Investment Despite Demand Uncertainty.

The lowest demand projections show the total Ni demand for all future years exceeding the current production levels, meaning that under any scenario, more capacity will be needed. However, given the long timeframes required in adding capacity, especially in the battery-grade pathways, investment carries risk that the demand will drop off in the future or that too much capacity will be added leading to a Ni glut. Variations in the demand projections for Ni use in all industries leads to considerable uncertainty. In conversations with experts in the Ni industry, this uncertainty leads to reluctance to invest in the long-term projects. This study suggests that capacity built in the sulphide or laterite leaching pathways may be relatively resilient to oversupply, as it is buffered by capacity in laterite smelting pathways 4,5,8 & 9.

The total capacity of the battery grade supply pathways is well below the total demand even under the lowest demand projections, (see Figure 18 above) meaning that under all scenarios and over all model years the system can use more sulphide supply capacity. Class 1 metal is the most flexible feedstock being able to be used in any first-use manufacturing. In situations where demand decreases below supply, the capacity that would be taken offline would be the the low-commitment laterite smelting pathways.

The assumption that new battery grade production will be more resilient to system oversupply than will non-battery grade production, is a simplification of the system dynamics. It appears at this study's level of analysis, though the question of what causes some facilities to shut down and others to continue operation despite market dips involves complexity beyond the scope of this study. Our research suggests that the two main drivers of Ni supply preference going forward are going to be cost of production and carbon footprint due to more stringent environmental requirements particularly related to battery manufacturing, and the battery-grade supply pathways tend to outperform the non-battery grade supply chains along both aspects. The carbon footprint has been discussed above, but cost of production has been largely set outside the scope of this study.

These pathways appear also to be the most cost-effective per unit of Ni produced. Figure 32 shows the cost of production of existing Ni operations according to the technologies used. The laterite smelting technologies, both NPI and FeNi are seen to be the highest cost technologies used (Nickel Mines Limited., 2020). While sulphide and laterite leaching pathways are not distinguished in the figure, discussions with experts in the field indicate that sulphide pathways tend to outperform existing leach pathways due to consistency of operation, higher ore grades, and more consistent operation.

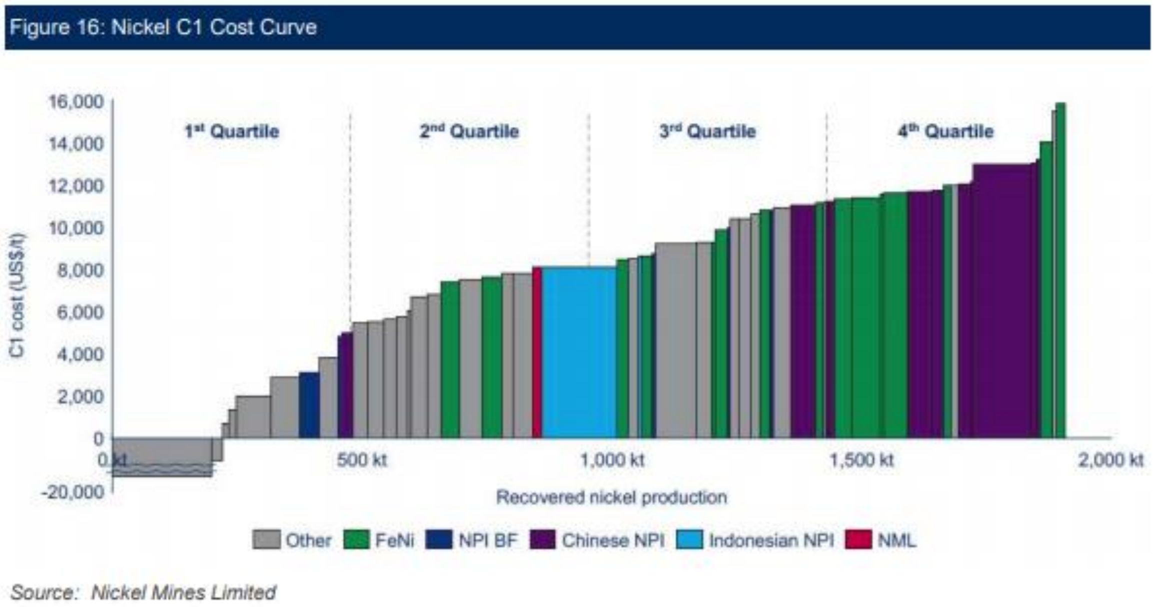

Figure 32 - Cost cuve of global ni production by first-use feedstock produced.

4.4 Limitations of the Current Study and Suggestions for Future Work

4.4.1 Low Non-battery System Resolution

This study found the non-battery Ni system to play a very strong role both on questions of shortcomings and GHG impacts of battery grade Ni. Yet the study uses a quite rudimentary model structure for this aspect of the system. Improving the resolution of this subsystem, especially with regards to lifetimes and recycling potentials of different use categories, would improve the validity of this study's findings. A particular weakness is this model's use of a single lifetime parameter to model a variety of products. In *The Anthropogenic Ni Cycle: Insights into Use, Trade, and Recycling*, Reck et al. (2008) give an in-depth account of the greater Ni system including differentiating landfilling rates and lifetimes of different end-use sectors as well as different scrap utilization rates of different first-use sectors. Such details have not been included in the present study.

4.4.2 Inconsistency in treatment of matte in model.

Matte produced by sulphide and by FeNi sulphidation is modelled as needing the metal refining process step before it can be used in Ni sulphate production. Meanwhile, process 8b, NPI sulphidation, output is modelled as being directly used in sulphate production, despite that this process is akin to process 8a and also produces a matte product. This was a modelling decision that was made in order to convey the realities of the system limitations as they were found in research. The refining of matte to metal is an important stage in the nickel processing chain and under normal processing pathways it is a necessary step between matte and sulphide production. However, the basic processes of refining to metal and sulphide production can in principle be combined in a single facility. This is perhaps going to be the case in future sulphate production facilities if NPI sulphidation becomes implemented into the battery supply chain. The decision was therefore made to model matte from the new NPI pathway as being directly used in Sulphate production, though it is not an internally consistent treatment of matte.

4.4.3 Feedbacks Between Subsystems

Perhaps the biggest limitation of this system is the lack of realistic feedback from the Ni supply subsystem into the two Ni demand subsystems. The use of Ni in both LiB and non-battery products will be influenced by the price and availability of Ni feedstocks. Yet in this model setup the no mechanism was found to allow shortfalls of the supply system to affect the manufacture of products.

4.4.4 GHG impacts of Recycling not Quantified.

LiB to sulphate recycling is shown to have a large impact in reducing the need for new Ni feedstocks and for reducing the carbon footprint of the Ni supply system. In this model, the GHG impact of all recycling activity was assumed to be zero. This assumption may serve to create an overly optimistic picture of the circularity of LiB recycling in the system.

4.4.5 Impacts beyond GHG

While carbon footprint of Ni is particularly relevant regarding the goal of the energy transition and the switch to EVs, the GHG impacts are far from the only environmental impact of Ni production. Deforestation, land-use change. and biodiversity impacts are a major issue for Ni production, especially in tropical areas, as are tailings disposal and water acidification. While awareness of these factors was incorporated into the flow priorities of the model structure, quantification and inclusion of such aspects in future studies would meaningfully contribute to understanding the total impacts of the Ni supply system.

5 Conclusion

Individual stakeholders at various locations in the Ni system have diverse interests specific to their situation. General, system-wide interests however fall broadly into two categories: the ability of the Ni supply system to meet the increasing demand for Ni, especially battery grade Ni, and the impacts generated by the Ni supply system. When approaching the topic of minerals supply to the lithium-ion battery supply chain, it is often these two issues that are brought up, whether the concerns are primarily for supply, or impacts, or often both. This study has found that when the questions are investigated from a system-wide approach, the distinction between a supply issue and an impact issue blurs to the point that they are best addressed together. If there are supply shortages in the Ni system, it is unlikely that they will be caused by physical or logistical limits, but rather by an intolerance for the impacts associated with rapid development.

The aspect of time constraints cannot be understated. While a rapid transition away from carbon-intensive technologies such as the internal combustion engine is important, a steady transition toward LiB technologies will more sustainable than a rapid shift to a Ni intensive technology, especially if it is followed by a drop-off in demand, at least from a Ni-focused perspective. This might mean that a gradual uptake of high Ni cathode chemistries would lead to a healthier environment for Ni producers than a sharp spike in Ni demand.The impacts generated by supplying Ni vary considerably, but a general rule is that the developments that can be taken fastest, have the most negative impacts. Long-term thinking and planning are critical for a smooth and sustainable transition.

The best recommendation for minimizing shortfall risks is investing in the traditional pathway of sulphide ore mining to metal refining, either via the established technology of matte smelting or the recent technology of direct concentrate refining. While this pathway requires the most commitment in time and investment, the demand for Ni produced by this pathway is large enough to accommodate large increases in production above what exists and what is currently planned.

Moreover, bottlenecks and impacts are a result of system-wide activity, mitigation activities should include preparations for large demands across all system pathways. The potential for shifting of burdens between system elements is significant. While the least-preferable pathways, such as NPI smelting, can be minimized they are unlikely to be avoided. Focus should be set on improving as much as possible the impacts of the laterite supply chain, as this is where the bulk of the GHG impacts will come from.

To that end this study commends attempts to curtail the carbon footprint of Ni used in the battery supply chain, but suggests that such a focus be extended as quickly as possible to include other products of the Ni system, as the potential for high carbon Ni production to leak out of the LiB supply chain is visible. Basing policies or marketing on attributional approaches so that only the carbon footprint of the best pathways is used for EVs would be beneficial for the environmental image of car manufacturers but not for the system as a whole. As Ni production is a large existing industry, in which LiB production will be a minority player for many years, attempts to address the battery subsystem should always be made while keeping the larger system context in view.

Bibliography

ACEA. (2020). *Interactive map - Electric vehicle purchase incentives per country in Europe (2020 update)*. The European Automobile Manufacturers' Association. https://www.acea.auto/figure/interactive-map-electric-vehicle-purchase-incentives-per-country-in-europe-2020-update/

Anderson, J. (2020). *Nickel: Morowali projects opt against deep-sea tailings placement — Roskill*. https://roskill.com/news/nickel-morowali-projects-opt-against-deep-sea-tailings-placement/

Andika, R., Astuti, W., Syafriadi, & Nurjaman, F. (2019). Effect of flux addition and reductant type in smelting process of Indonesian limonite ore in electric arc furnace. *IOP Conference Series: Materials Science and Engineering*, *478*(1), 012007. https://doi.org/10.1088/1757-899X/478/1/012007

Azevedo, M., Campagnol, N., Hagenbruch, T., Hoffman, K., Lala, A., & Ramsbottom, O. (2018). *Lithium and Cobalt - a tale of two commodities*. https://www.mckinsey.com/~/media/mckinsey/industries/metals and mining/our insights/lithium and cobalt a tale of two commodities/lithium-and-cobalt-a-tale-of-two-commodities.ashx

Baccini, P., & Brunner, P. (2012). *Metabolism of the anthroposphere: analysis, evaluation, design*. https://books.google.com/books?hl=no&lr=&id=Rsea8m-kTpAC&oi=fnd&pg=PR5&ots=Y3erBRIVKz&sig=eRCE1oN9ls-xo5_Hcp5r3p15USs

Blackstone Minerals. (2021). *Ta Khoa Project*. https://www.blackstoneminerals.com.au/ta-khoa-project

Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A. S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., De Souza Noel Simas Barbosa, L., Fasihi, M., Khalili, S., Traber, T., & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, *227*, 120467. https://doi.org/10.1016/j.energy.2021.120467

Brunner, P. H., & Rechberger, H. (2016). Practical handbook of material flow analysis. In *Practical Handbook of Material Flow Analysis*. https://doi.org/10.1007/bf02979426

Chen, D. (2020). *Understanding nickel usage in lithium batteries | CRU*. https://www.crugroup.com/knowledge-and-insights/insights/2020/understanding-nickel-usage-in-lithium-batteries/?utm_medium=Press_release

Crundwell, F., Moats, M., Ramachandran, V., Robinson, T., & Davenport, W. G. (2011). Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals. In *Elsevier*. Elsevier Ltd. https://doi.org/10.1016/C2009-0-63541-8

Ding, Y., Cano, Z. P., Yu, A., Lu, J., & Chen, Z. (2019). Automotive Li-Ion Batteries: Current Status and Future Perspectives. *Electrochemical Energy Reviews*, *2*(1), 1–28. https://doi.org/10.1007/s41918-018-0022-z

Dry, M., Vaughan, J., & Wiliam, H. (2019). Environmental evaluation of making nickel sulphate. *Proceedings of ALTA 2019 Nickel-Cobalt-Copper Conference*, *May*, 136–151. https://www.altamet.com.au/product/arithmetek-uq-pbt-environmental-evaluation-of-making-nickel-sulphate/

Eckelman, M. J., Reck, B. K., & Graedel, T. E. (2012). Exploring the Global Journey of Nickel with Markov Chain Models. *Journal of Industrial Ecology*, *16*(3), 334–342. https://doi.org/10.1111/j.1530-9290.2011.00425.x

Elshkaki, A., Reck, B. K., & Graedel, T. E. (2017). Anthropogenic nickel supply, demand, and associated energy and water use. *Resources, Conservation and Recycling*, *125*(March), 300–307. https://doi.org/10.1016/j.resconrec.2017.07.002

Energy Office. (2021, April 6). *Reducing Reliance on Cobalt for Lithium-ion Batteries | Department of Energy*. Office of Energy Efficiency & Renewable Energy, United States Government. https://www.energy.gov/eere/vehicles/articles/reducing-reliance-cobalt-lithium-ion-batteries

European Comission. (2020). *Questions and Answers on Sustainable Batteries Regulation*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2311

Fraser, J., Anderson, J., Lazuen, J., Lu, Y., Heathman, O., Brewster, N., Bedder, J., & Masson, O. (2021). Study on future demand and supply security of nickel for electric vehicle batteries. In *Publications Office of the European Union, Luxembourg*. https://doi.org/10.2760/212807 (online)

Gourley, S. W. D., Or, T., & Chen, Z. (2020). Breaking Free from Cobalt Reliance in Lithium-Ion Batteries. In *iScience* (Vol. 23, Issue 9, p. 101505). Elsevier Inc. https://doi.org/10.1016/j.isci.2020.101505

Graf, C. (2018). Cathode materials for lithium-ion batteries. In *Lithium-Ion Batteries: Basics and Applications* (pp. 29–41). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-53071-9_4

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., & Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. In *Nature* (Vol. 575, Issue 7781, pp. 75–86). Nature Publishing Group. https://doi.org/10.1038/s41586-019-1682-5

Helbig, C., Bradshaw, A. M., Wietschel, L., Thorenz, A., & Tuma, A. (2018). Supply risks associated with lithium-ion battery materials. *Journal of Cleaner Production*, *172*, 274–286.

https://doi.org/10.1016/j.jclepro.2017.10.122

Holman, J., & Dart, J. (2020, August 17). LFP batteries to dominate stationary storage chemistry by 2030: WoodMac | S&P Global Platts. *S&P Global*. https://www.spglobal.com/platts/en/market-insights/latest-news/metals/081720-lfp-batteries-to-dominate-stationary-storage-chemistry-by-2030-woodmac

IEA. (2020). *Global EV Outlook 2020*.

IEA. (2021). *IEA (2021), The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

INSG. (2020). *INSG World Directory of Nickel Production Facilities 2019*.

Jorari, L. (2020, December 10). Protests erupt in New Caledonia over proposed sale of major nickel plant | World news | The Guardian. *The Guardian*. https://www.theguardian.com/world/2020/dec/11/protests-erupt-in-new-caledonia-over-proposed-sale-of-major-nickel-mine

Kelleher Environmental. (2019). *Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles: The Technical, Environmental, Economic, Energy and Cost Implications of Reusing and Recycling EV Batteries*.

Kempton, W., & Letendre, S. E. (1997). Electric vehicles as a new power source for electric utilities. *Transportation Research Part D: Transport and Environment*, *2*(3), 157–175. https://doi.org/10.1016/S1361-9209(97)00001-1

Kerfoot, D. G. E. (2000). Nickel. In *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/14356007.a17_157

Keskinkilic, E. (2019). Nickel laterite smelting processes and some examples of recent possible modifications to the conventional route. In *Metals* (Vol. 9, Issue 9). MDPI AG. https://doi.org/10.3390/met9090974

Khoo, J. Z., Haque, N., Woodbridge, G., McDonald, R., & Bhattacharya, S. (2017). A life cycle assessment of a new laterite processing technology. *Journal of Cleaner Production*, *142*, 1765–1777. https://doi.org/10.1016/j.jclepro.2016.11.111

Kim, T., Song, W., Son, D. Y., Ono, L. K., & Qi, Y. (2019). Lithium-ion batteries: outlook on present, future, and hybridized technologies. In *Journal of Materials Chemistry A* (Vol. 7, Issue 7, pp. 2942–2964). Royal Society of Chemistry. https://doi.org/10.1039/C8TA10513H

Lauinger, D., Billy, R. G., Vásquez, F., & Müller, D. B. (2021). A general framework for stock dynamics of populations and built and natural environments. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13117

Liu, C., Lin, J., Cao, H., Zhang, Y., & Sun, Z. (2019). Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review. In *Journal of Cleaner Production* (Vol. 228, pp. 801–813). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2019.04.304

Majeau-Bettez, G., Hawkins, T. R., & StrØmman, A. H. (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology*, *45*(10), 4548–4554. https://doi.org/10.1021/es103607c

Mathews, J. A., & Tan, H. (2014). Economics: Manufacture renewables to build energy security. In *Nature* (Vol. 513, Issue 7517, pp. 166–168). Nature Publishing Group. https://doi.org/10.1038/513166a

Mudd, G. M. (2009). Nickel Sulfide Versus Laterite: The Hard Sustainability Challenge Remains. *48th Conference of Metallurgists*, *August 2009*, 1–10. https://www.researchgate.net/publication/228470255_Nickel_Sulfide_Versus_Laterite_The_Hard_Sustainability_Challenge_Remains

Mudd, G. M. (2010). Global trends and environmental issues in nickel mining: Sulfides versus laterites. *Ore Geology Reviews*, *38*(1–2), 9–26. https://doi.org/10.1016/j.oregeorev.2010.05.003

Mudd, G. M., & Jowitt, S. M. (2014). A detailed assessment of global nickel resource trends and endowments. In *Economic Geology* (Vol. 109, Issue 7, pp. 1813–1841). Society of Economic Geologists, Inc. https://doi.org/10.2113/econgeo.109.7.1813

Nickel Institue. (2016). *The life of Ni*.

Nickel Institute. (2020). *Life Cycle Assessment of Nickel Products: Reference year 2017. Final Report.*

Nitta, N., Wu, F., Lee, J. T., & Yushin, G. (2015). Li-ion battery materials: Present and future. In *Materials Today* (Vol. 18, Issue 5, pp. 252–264). Elsevier B.V. https://doi.org/10.1016/j.mattod.2014.10.040

Olivetti, E. A., Ceder, G., Gaustad, G. G., & Fu, X. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. In *Joule* (Vol. 1, Issue 2, pp. 229–243). Cell Press. https://doi.org/10.1016/j.joule.2017.08.019

Pauliuk, S., & Heeren, N. (2020). ODYM—An open software framework for studying dynamic material systems: Principles, implementation, and data structures. *Journal of Industrial Ecology*, *24*(3), 446–458. https://doi.org/10.1111/jiec.12952

Peek, E., Barnes, A., & Tuzun, A. (2011). Nickeliferous pyrrhotite - "waste or resource?" *Minerals Engineering*, *24*(7), 625–637. https://doi.org/10.1016/j.mineng.2010.10.004

Petavratzi, E., & Gunn, G. (2018). *Briefing note on raw materials for batteries in electric vehicles*.

Preston, B. (2021, April 26). Here Are Automakers' Plans for Adding More Electric Vehicles to Their Lineups - Consumer Reports. *Consumer Reports*. https://www.consumerreports.org/hybrids-evs/why-electric-cars-may-soon-flood-the-us-market/

Priester, M., Ericsson, M., Dolega, P., & Löf, O. (2019). Mineral grades: an important indicator for environmental impact of mineral exploitation. *Mineral Economics*, *32*(1), 49–73. https://doi.org/10.1007/s13563-018-00168-x

Rao, M., Li, G., Jiang, T., Luo, J., Zhang, Y., & Fan, X. (2013). Carbothermic reduction of nickeliferous laterite ores for nickel pig iron production in China: A review. *JOM*, *65*(11), 1573–1583. https://doi.org/10.1007/s11837-013-0760-7

Reck, B. K., Müller, D. B., Rostkowski, K., & Graedel, T. E. (2008). Anthropogenic nickel cycle: Insights into use, trade, and recycling. *Environmental Science and Technology*, *42*(9), 3394–3400. https://doi.org/10.1021/es072108l

Reuter, M. A., Schaik, A. van, Gediga, J., Kojo, I., & Horn, S. (2014). SIMULATION-BASED DESIGN FOR RESOURCE EFFICIENCY OF METAL PRODUCTION AND RECYCLING SYSTEMS. *International Journal of Life Cycle Assessment*, 1–26.

Reuter, M. A., van Schaik, A., & Gediga, J. (2015). Simulation-based design for resource efficiency of metal production and recycling systems: Cases - copper production and recycling, e-waste (LED lamps) and nickel pig iron. *International Journal of Life Cycle Assessment*, *20*(5), 671–693. https://doi.org/10.1007/s11367-015-0860-4

Reuters. (2021, March 3). CORRECTED-China's Tsingshan signs pacts for 100,000 T nickel matte in EV push | Reuters. *Reuters*. https://www.reuters.com/article/china-nickel-idINL3N2L10VC

Roberts, D. (2021). *Competitors to lithium-ion batteries in the grid storage market - Volts*. https://www.volts.wtf/p/battery-week-competitors-to-lithium

Schmidt, T., Buchert, M., & Schebek, L. (2016). Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. *Resources, Conservation and Recycling*, *112*, 107–122. https://doi.org/10.1016/j.resconrec.2016.04.017

Sharypin, D., Lipovskiy, A., & Racu, A. (2020). *Quintessentially Nickel* (Issue December).

Terauds, K. (2017). *Using trade policy to drive value addition: Lessons from Indonesia's ban on nickel exports*. 33.

Thompson, I., Rosario, P., Jones, E., Schwab, G., Hlouschko, S., Kirkham, G., Friedman, D., Knight, P., Monk, R., & Martin, C. (2020). *TECHNICAL REPORT & PRELIMINARY ECONOMIC ASSESSMENT FOR THE TURNAGAIN PROJECT*. www.gigametals.com

Trytten, L. (2020). *(5) (PDF) Will Cheap Asian HPAL Save the EV Industry from its Looming*

Success? https://www.researchgate.net/publication/344713446_Will_Cheap_Asian_HPAL_Save_the_EV_Industry_from_its_Looming_Success

Trytten, L. (2021). *Matte from NPI – A Good Idea ?* (Issue April 2006).

Vale. (2020). *Long Harbour*. http://www.vale.com/canada/en/aboutvale/communities/long-harbour/pages/default.aspx

Vale Inco. (2008). *Environmental Impact Statement - Long Harbour Commercial Nickel Processing Plant*. http://www.env.gov.nl.ca/env/env_assessment/projects/Y2008/1243/05_eis_amend_volume_1.pdf

Valle, L., Benz, M., Chalkley, M., Collins, M., Dobson, T., Holmwood, R., Malevich, A., Tuffrey, N., & Vrolson, R. (2016). Completing the Ambatovy Ramp-up: The Road to successful financial completion. *ALTA 2016 Nickel-Cobalt-Copper Proceedings*, 62–80.

Watari, T., McLellan, B. C., Ogata, S., & Tezuka, T. (2018). Analysis of potential for critical metal resource constraints in the international energy agency's long-term low-carbon energy scenarios. *Minerals*, *8*(4). https://doi.org/10.3390/min8040156

Weidema, B. (2000). Avoiding co-product allocation in life-cycle assessment. In *Journal of Industrial Ecology* (Vol. 4, Issue 3, pp. 11–33). MIT Press Journals. https://doi.org/10.1162/108819800300106366

Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., & Steubing, B. (2020). Future material demand for automotive lithium-based batteries. *Communications Materials*, *1*(1), 1–10. https://doi.org/10.1038/s43246-020-00095-x

Young, E. (2020). *Bottlenecks to Global Battery-Grade Nickel Supply*.

Yue Li, Y. (2021, February 25). Musk says nickel is "biggest concern" for EV batteries - BNN Bloomberg. *Bloomberg News*. https://www.bnnbloomberg.ca/musk-says-nickel-is-biggest-concern-for-ev-batteries-1.1568998

Zhang, Y., Li, W., & Wu, F. (2020). Does energy transition improve air quality? Evidence derived from China's Winter Clean Heating Pilot (WCHP) project. *Energy*, *206*, 118130. https://doi.org/10.1016/j.energy.2020.118130

Appendix 1 – Shortfall Risk Matrix Plots

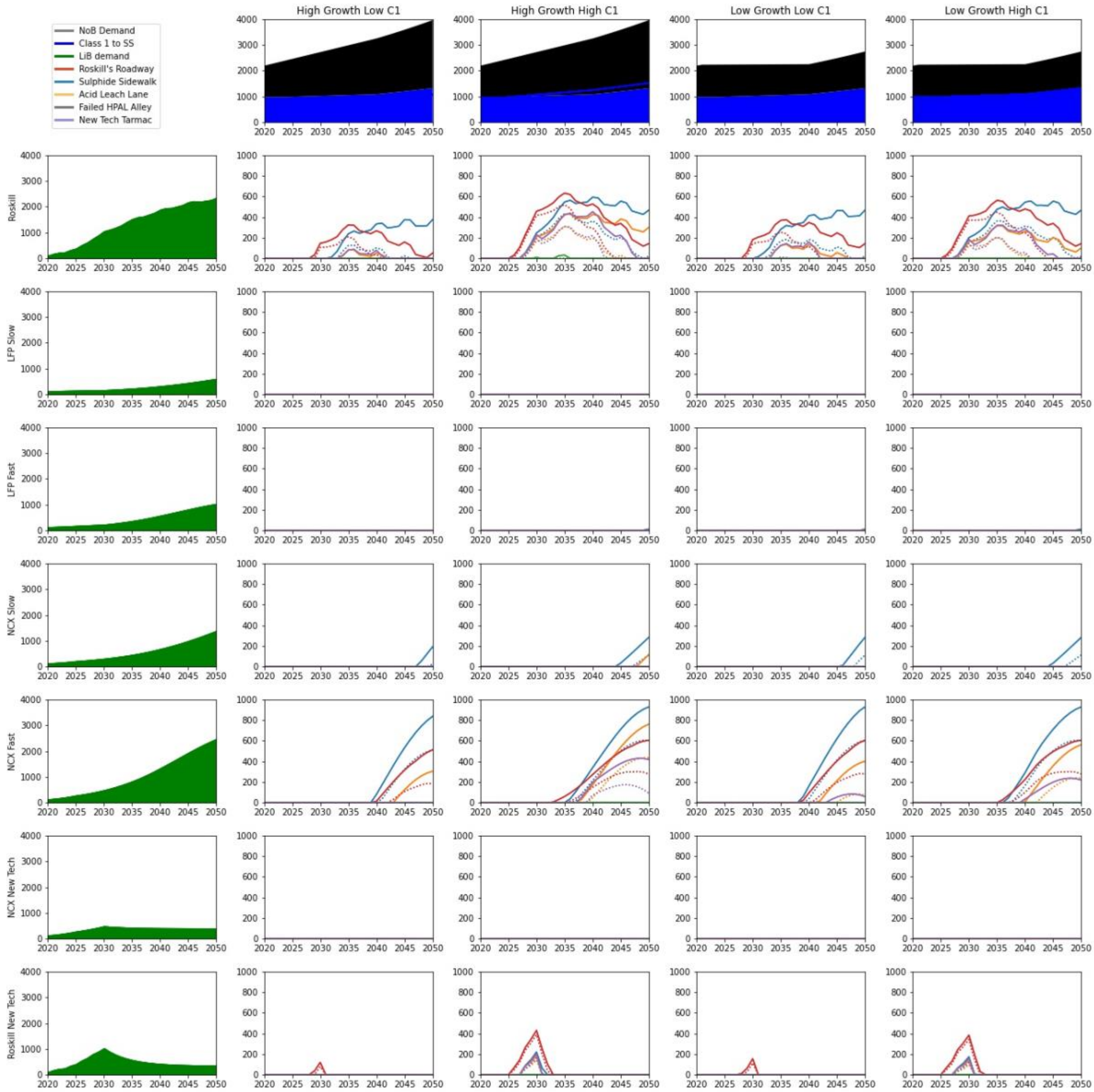

Figure 33 – NPI shortfalls are shown with all storyline variations. Rows show different LiB demand storylines while columns show non-battery demand storylines. Supply storylines shown using line colouring and LiB recycling storylines shown using linestyles with solid lines being high recycling storyline and dotted lines being low recycling storyline.

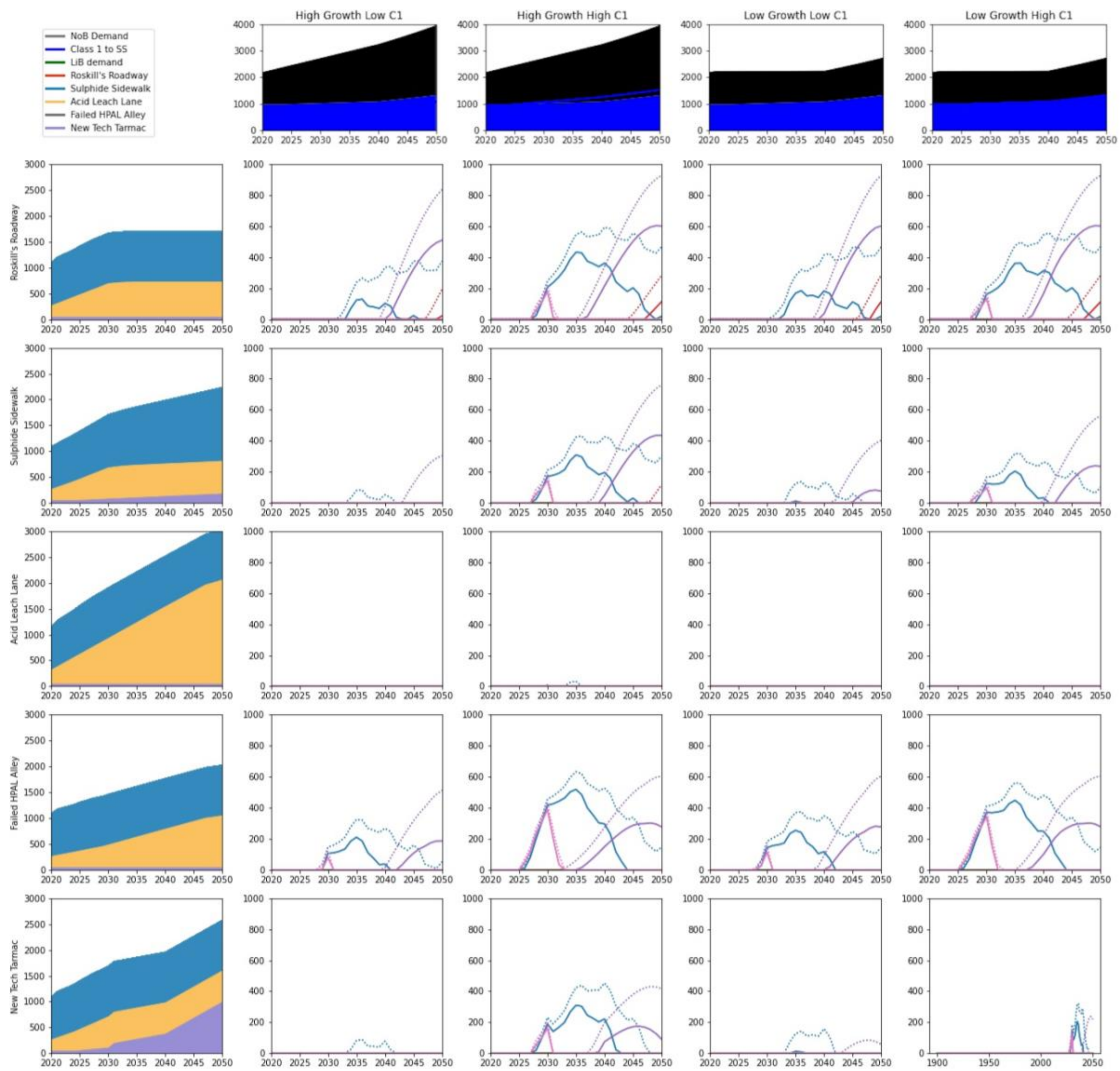

Figure 34 -– NPI shortfalls are shown with all storyline variations. Rows show different supply system storylines while columns show non-battery demand storylines. LiB demand storylines shown using line colouring and LiB recycling storylines shown using linestyles with solid lines being high recycling storyline and dotted lines being low recycling storyline.

Appendix 2 – Sankey Diagrams of Select Model Years and Scenarios

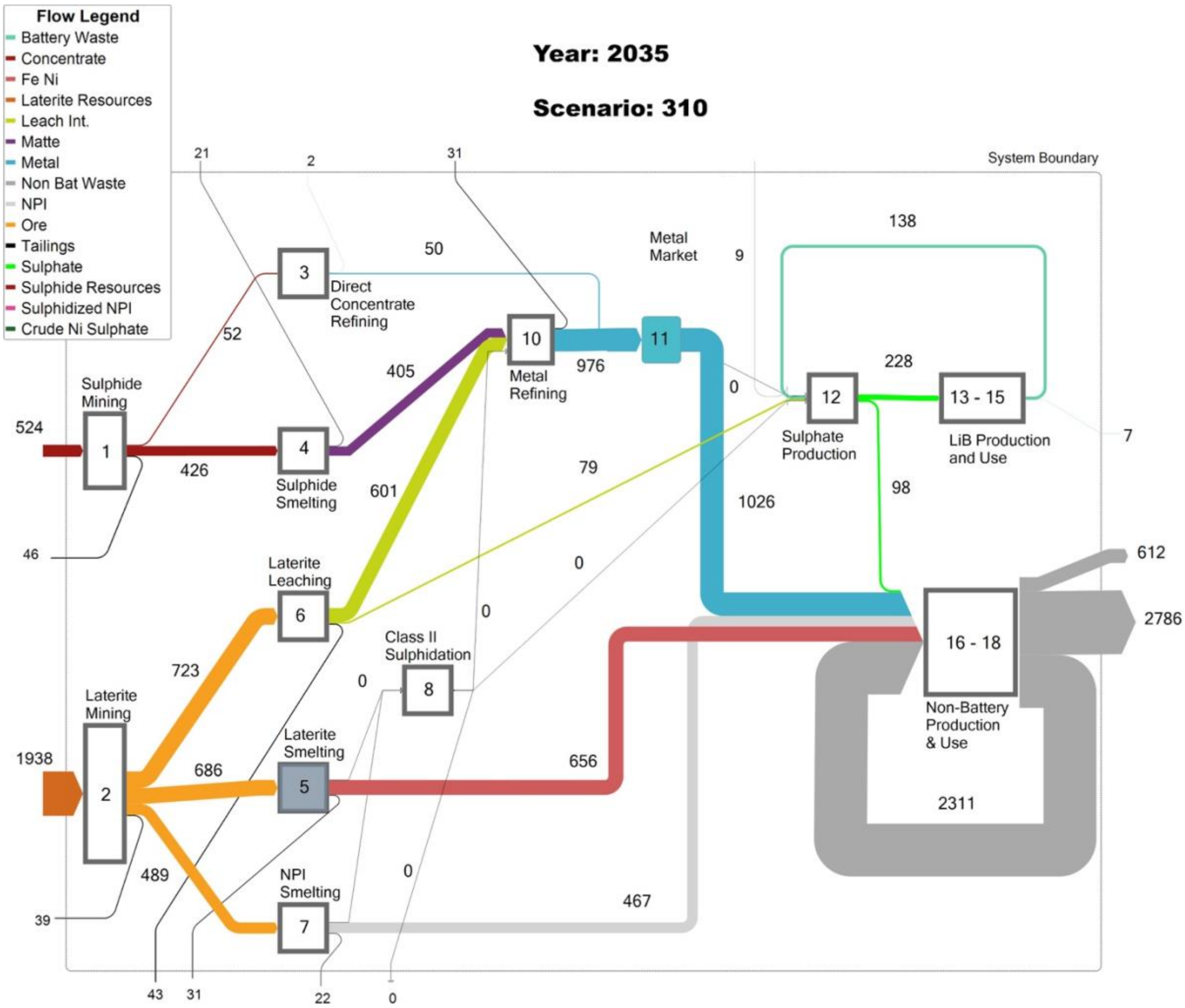

Figure 35 - Quantified Flows at year 2035 under the following storylines:
Supply System = Roskill's Roadway,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = LFP slow,
LiB Recycling = High

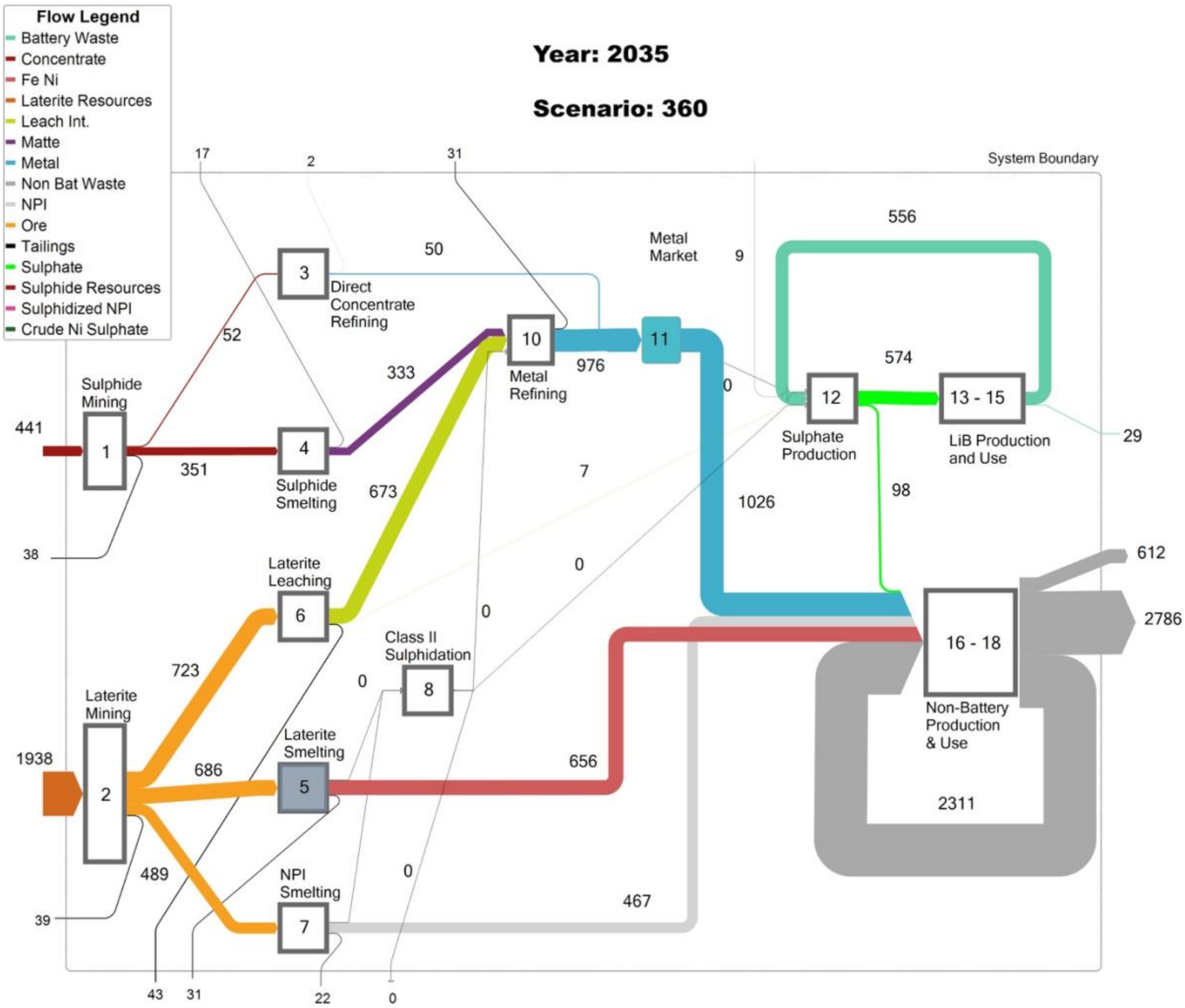

Figure 36 - Quantified Flows at year 2035 under the following storylines:
Supply System = Roskil1s Roadwayl,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = NCX New Technology,
LiB Recycling = High

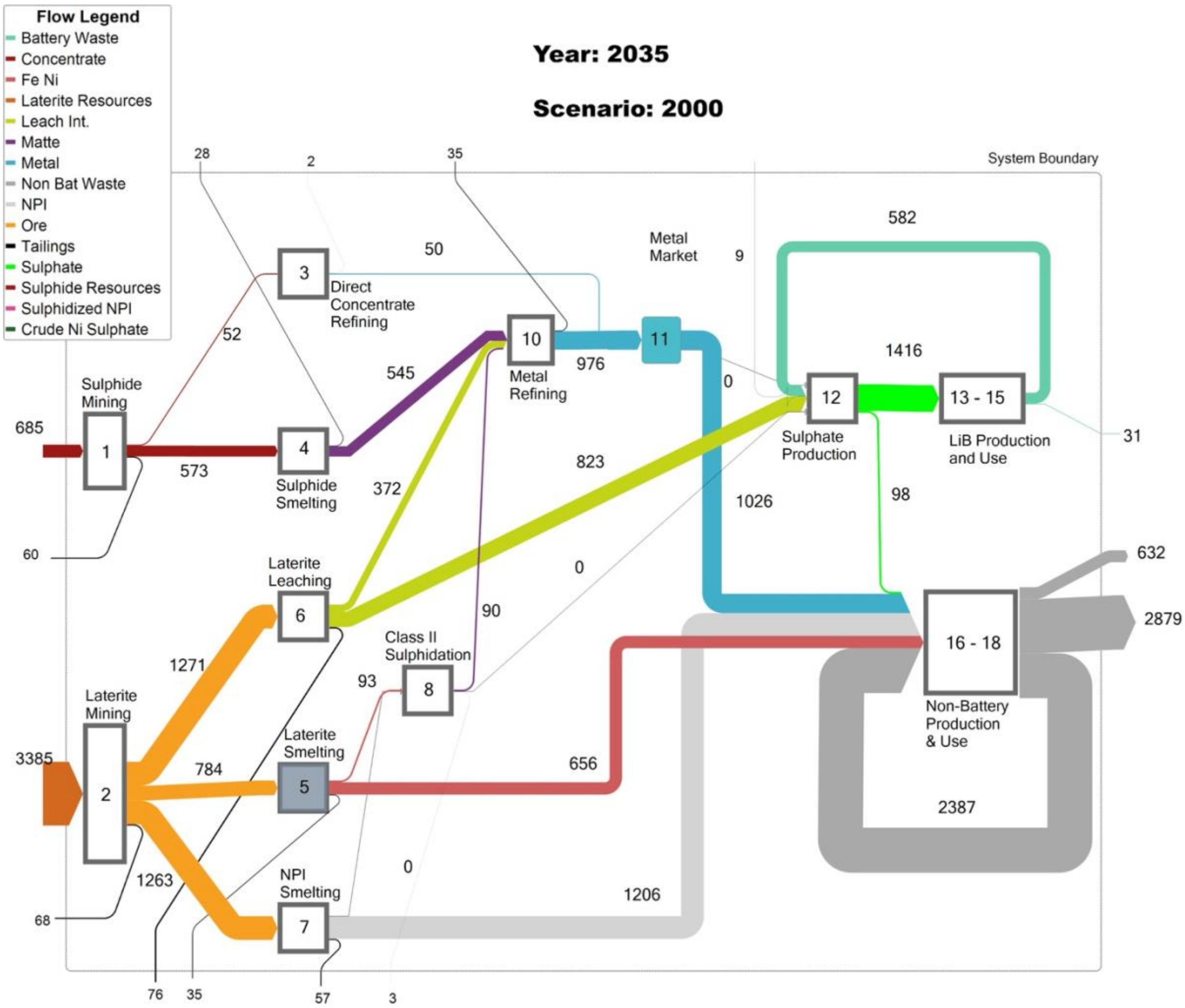

Figure 37 - Quantified Flows at year 2035 under the following storylines:
Supply System = Acid Leach Lane,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = LFP slow,
LiB Recycling = High

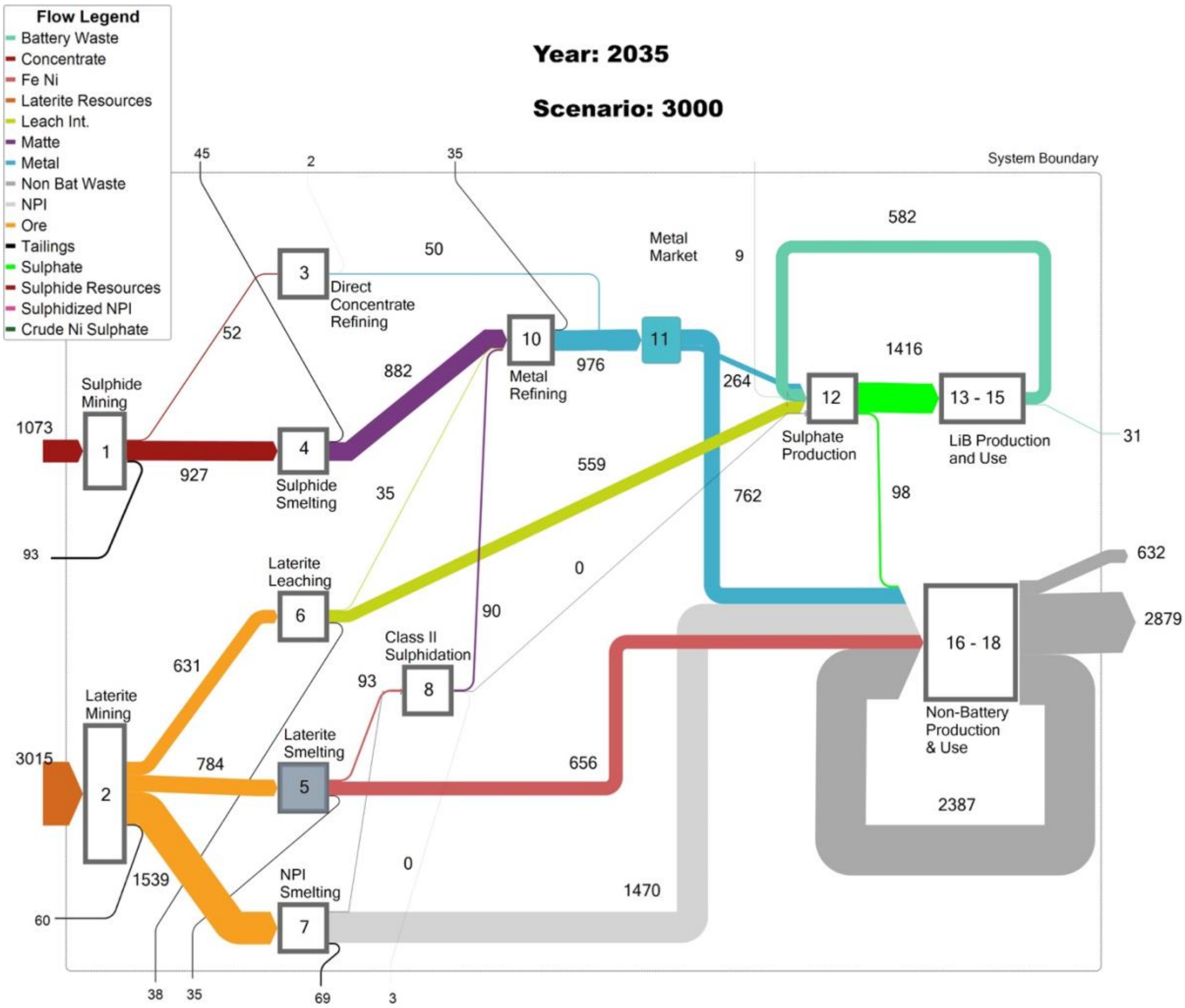

Figure 38 - Quantified Flows at year 2035 under the following storylines:
Supply System = Failed HPAL Alley,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = Roskill,
LiB Recycling = High

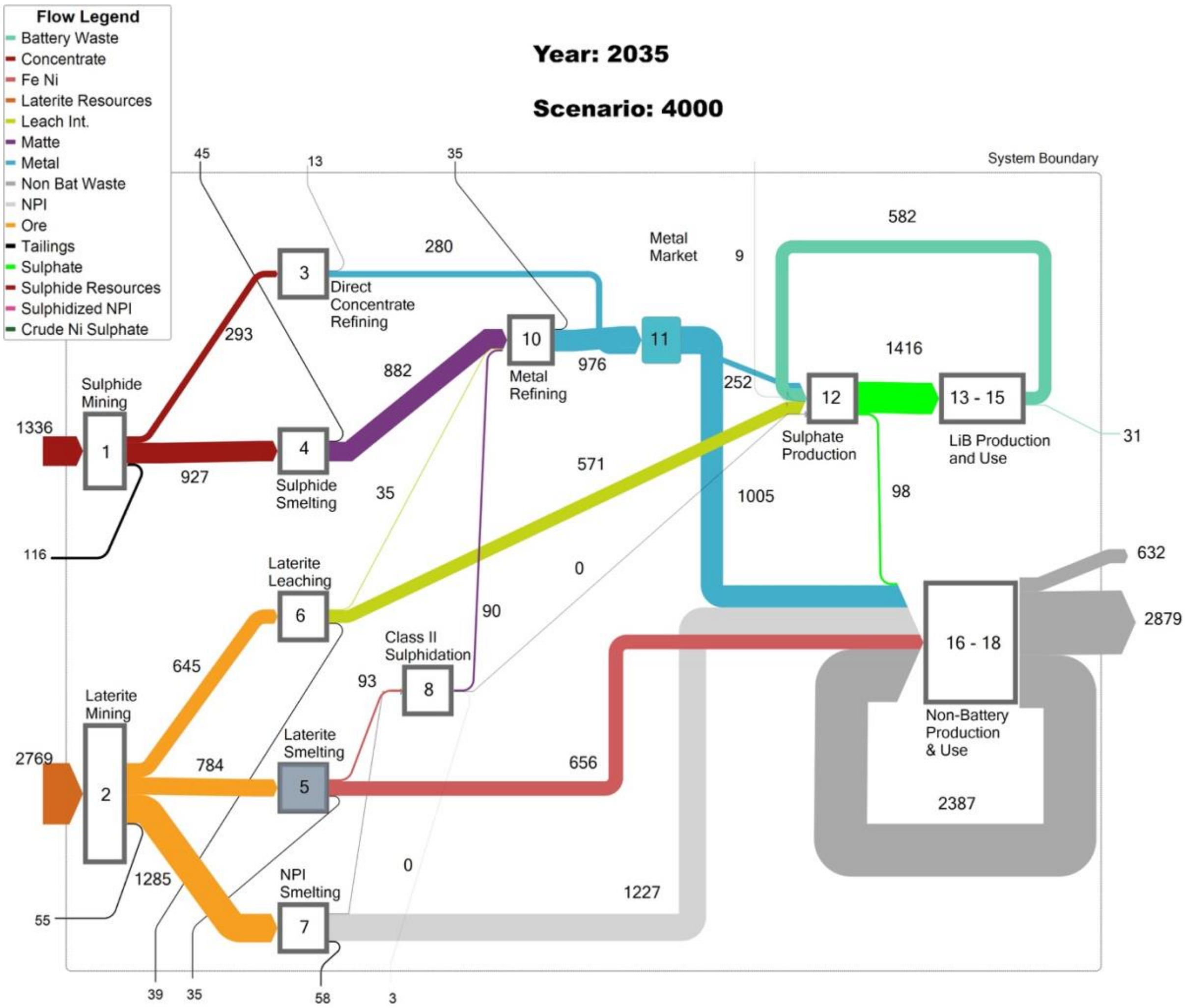

Figure 39 35- Quantified flows at year 2035 under the following storylines:
Supply System = New Tech Tarmac,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = LFP slow,
LiB Recycling = High

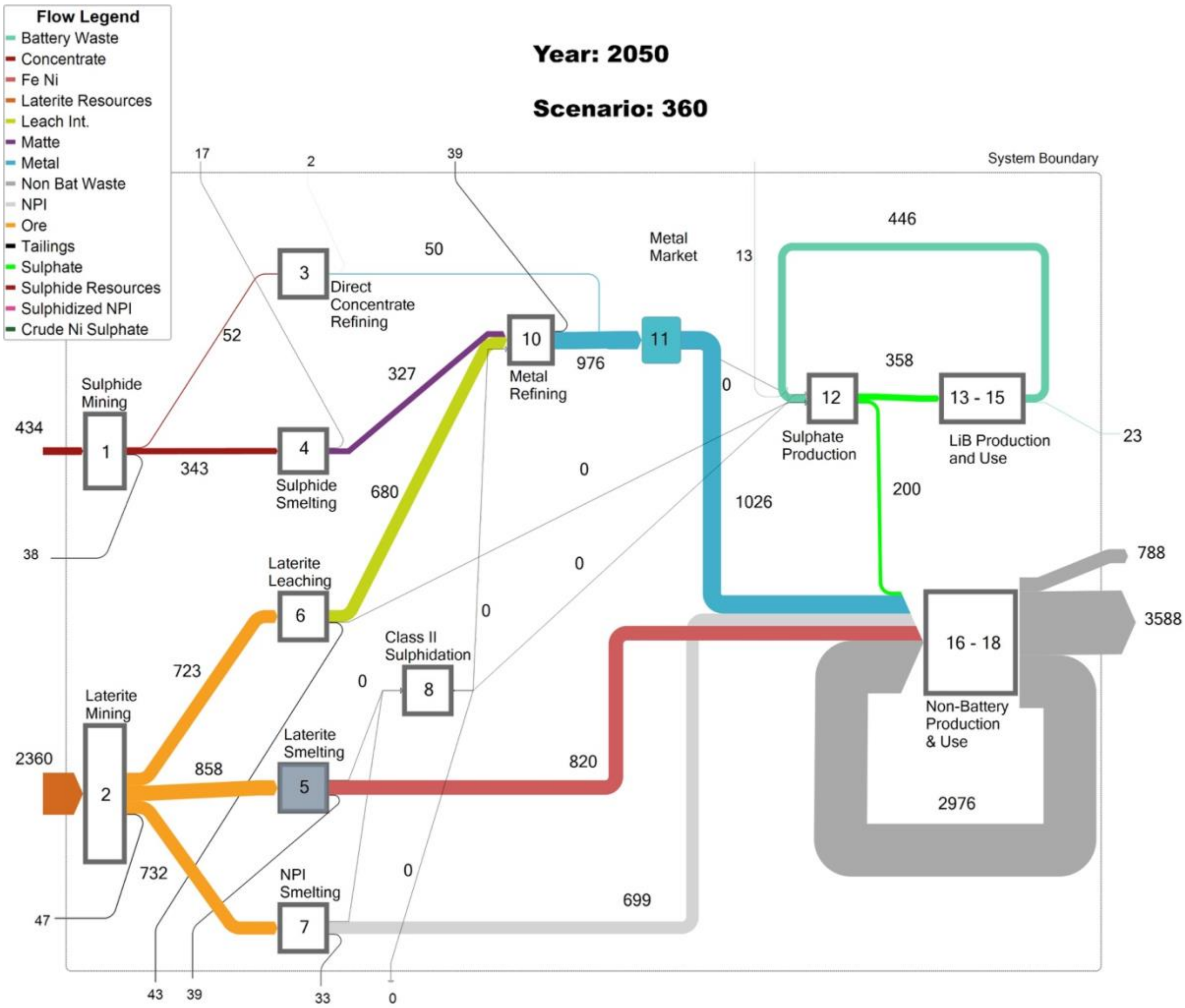

Figure 40 - Quantified flows at year 2050 under the following storylines:
Supply System = Roskill's Roadwayl,
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = LFP slow,
LiB Recycling = High

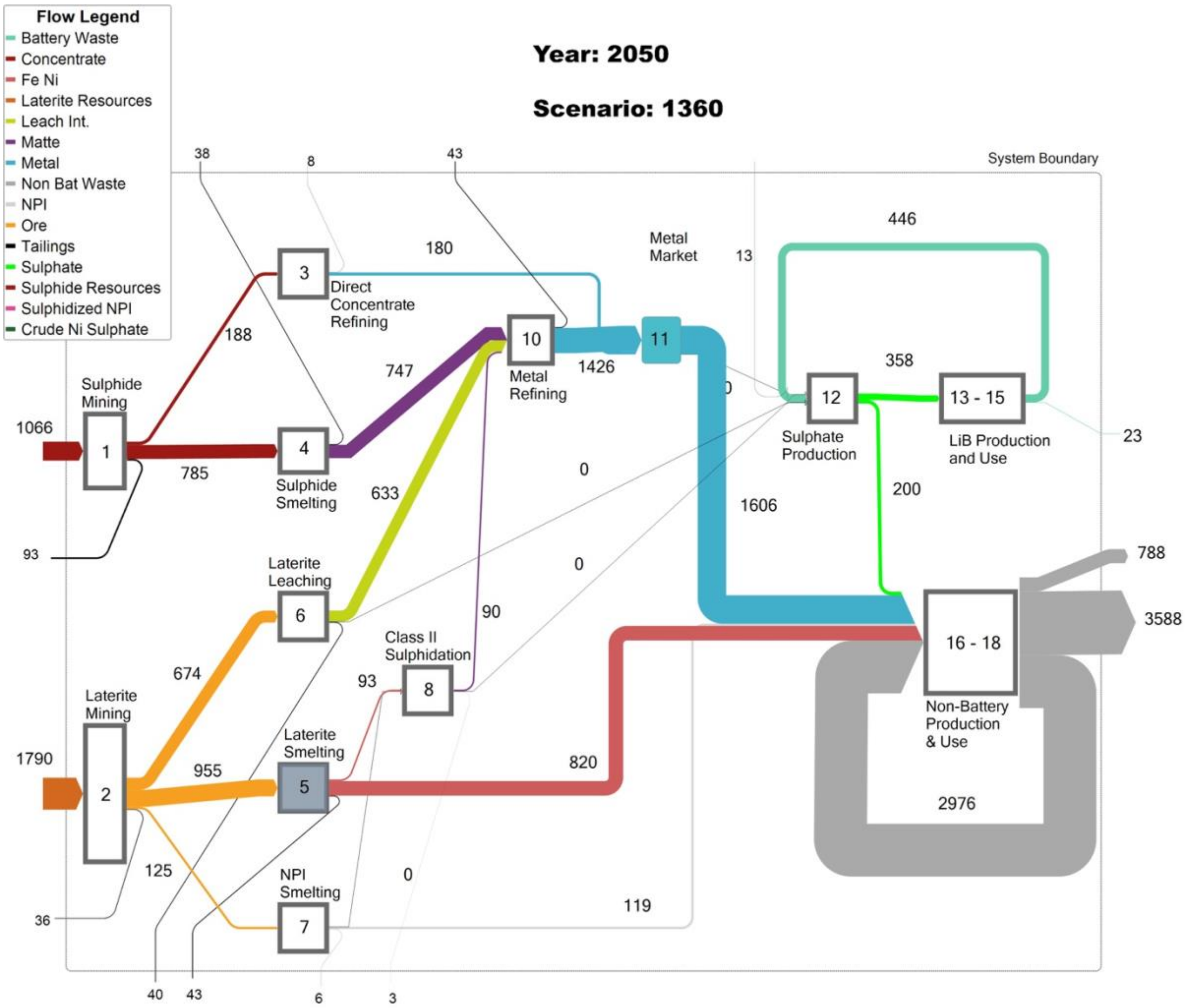

Figure 41 - Quantified Flows at year 2035 under the following storylines:
Supply System = Sulphide Sidewalk
Non-Battery Demand = Low Demand Low Class 1,
LiB demand = NCX New Tech,
LiB Recycling = High

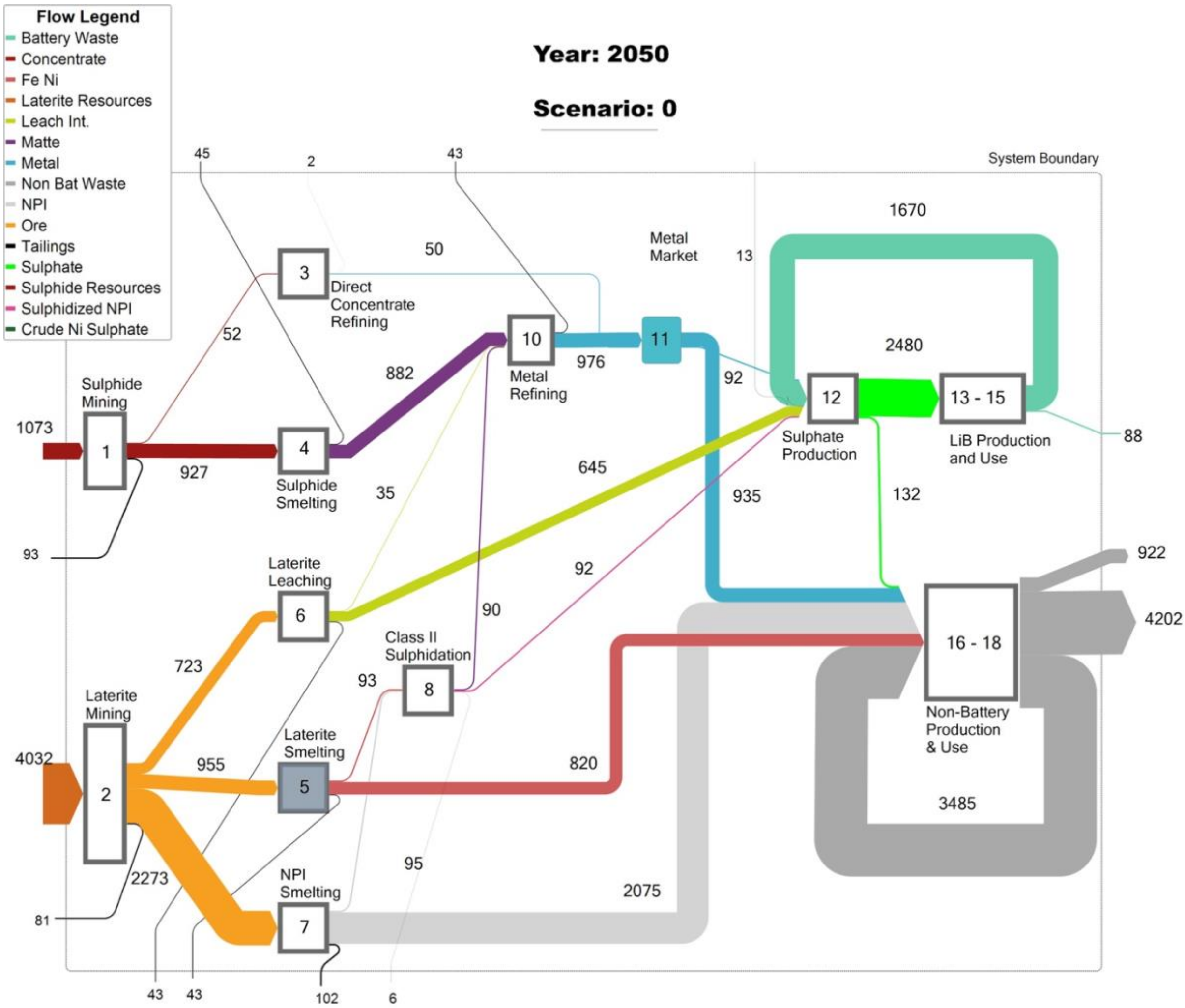

Figure 42- Quantified Flows at year 2035 under the following storylines:
Supply System Roskill's Roadway
Non-Battery Demand = High Demand Low Class 1,
LiB demand = Roskill,
LiB Recycling = High

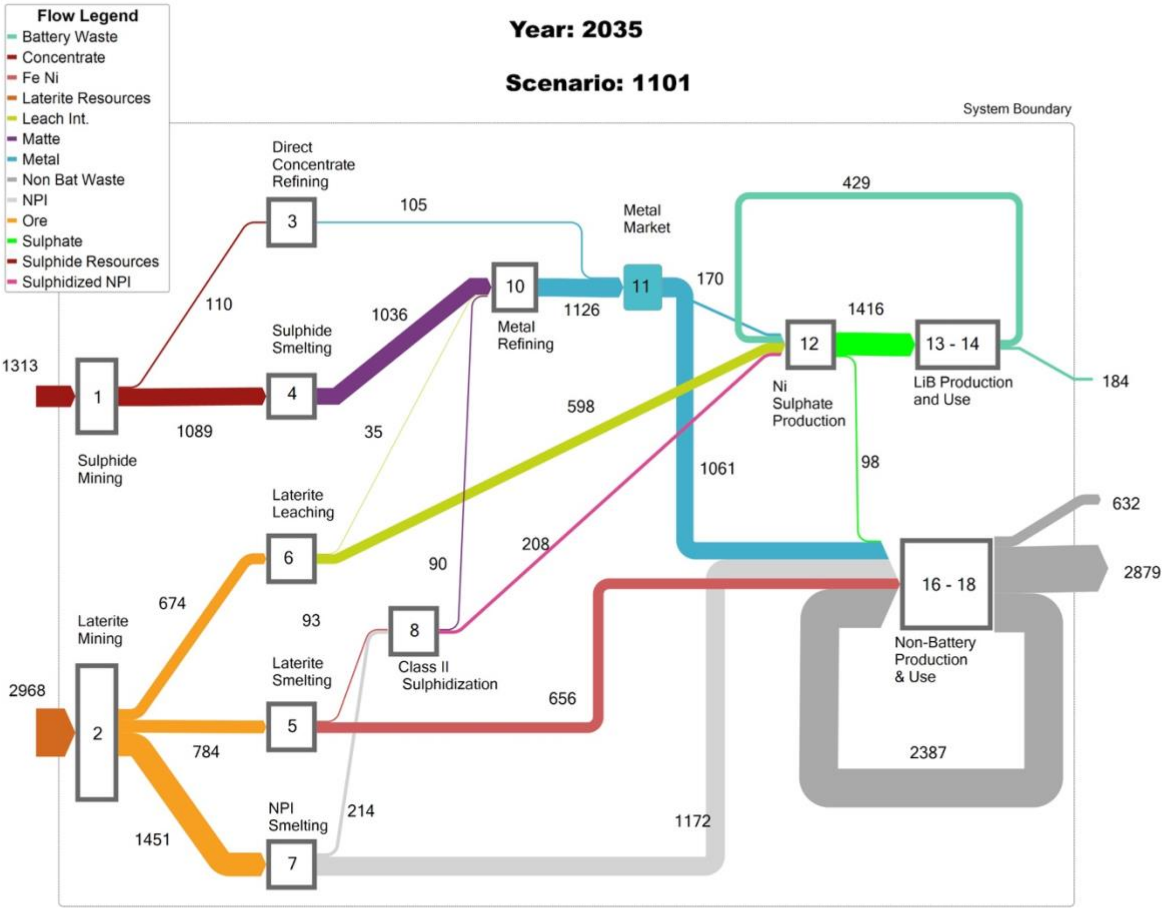

Figure 43- Quantified Flows at year 2035 under the following storylines:
Supply System = Sulphide Sidewalk
Non-Battery Demand = High Demand High Class 1,
LiB demand = Roskill,
LiB Recycling = Low

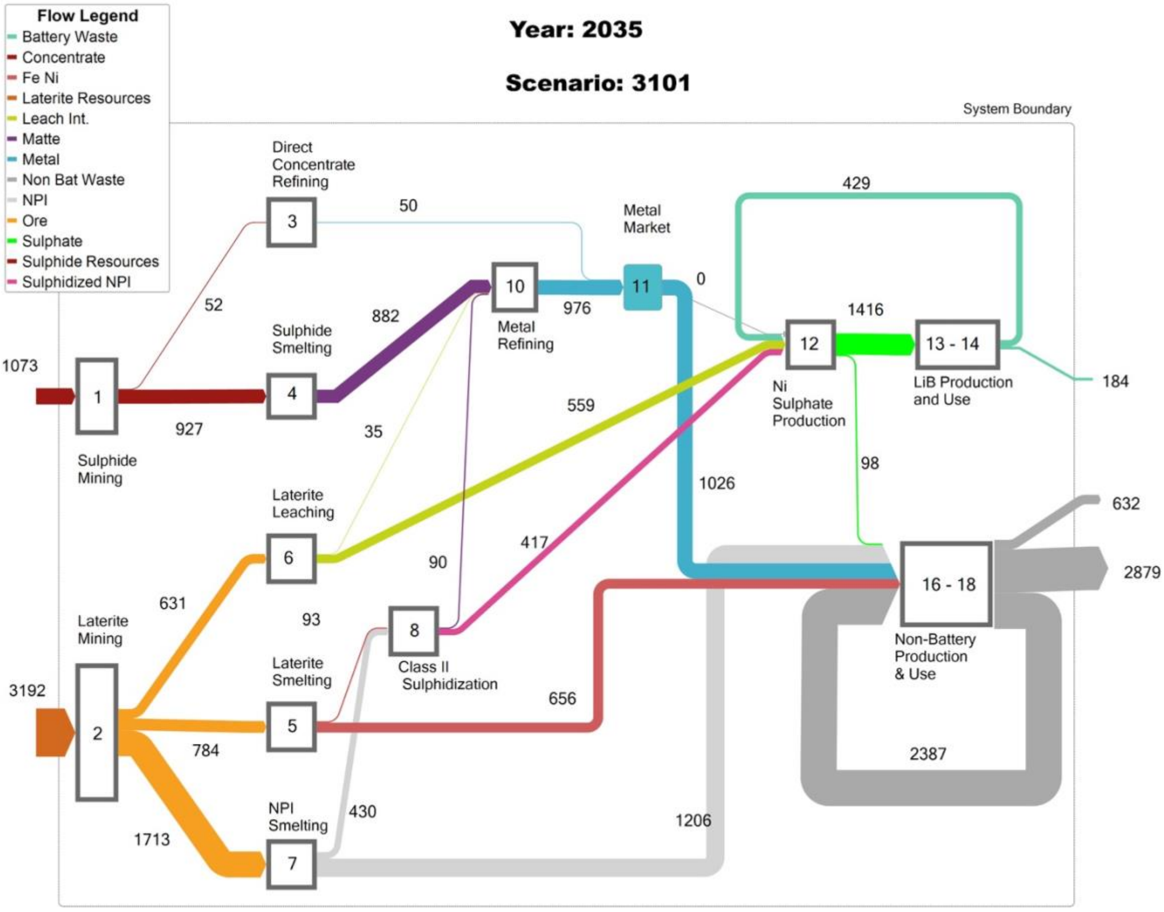

Figure 44 - Quantified Flows at year 2035 under the following storylines:
Supply System = Acid Leach Lane
Non-Battery Demand = High Demand High Class 1,
LiB demand = Roskill,
LiB Recycling = Low

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