Australia's National Science Agency

Known unknowns: the devil in the details of energy metal demand

Using an integrated physical framework to explore opportunities and risks for metals in the energy transition

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Important disclaimer

Foreword

About this paper

1. This paper explores the value of using a Physical Stocks and Flows Framework (PSFF), which is an integrated modelling and accounting method, to track the dynamics of metal supply and demand at a global scale over long timescales.
2. The value of a PSFF is to develop scenarios so users can explore key questions (e.g., technological change, recycling recovery rates) that will impact the demand and supply of metals. The PSFF should also be useful to the long-term strategic planning activities of companies and governments.
3. The model is not a forecasting tool, nor does it incorporate financial factors (like prices, which could further influence metal movements).
4. For demonstration purposes, the paper focuses narrowly on electric vehicles (EVs) and, in particular, three seemingly interlinked metals – nickel (Ni), cobalt (Co) and lithium (Li). However, the method is applicable to other metals, and CSIRO is building models to track metals used in solar photovoltaics (PV) and wind technologies as well.

The energy transition requires a lot of metal

The global transition to low carbon energy systems will be very metals intensive, with some metals facing demand increases of nearly 500% by 2050.[1] This is due to the higher mineral intensity of renewable technologies, like offshore wind turbines, which are 13 times more mineral intensive than an equivalent gas-fired power plant.[2]

The demand for metals is robust because our whole system of electricity generation, transmission, and storage is undergoing rapid transformation (Table 1).

Table 1: Rapid transformation of electricity generation, transmission and storage is increasing demand for metals.

Generation	Renewable technologies will quickly come to dominate the market for electricity generation, replacing fossil fuel infrastructure.
Transmission	Distributed, variable generation of electricity will require radically different requirements for electricity transmission and distribution infrastructure to balance loads.
Storage	All of this will create massive demand for electricity storage capacity, both to make renewables-based electricity systems work (load balancing with short medium and long term storage solutions like battery, hydroelectric, or hydrogen), and for the large-scale electrification of new domains such as vehicles.

1 *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.* World Bank Group. 2020.

2 *The Role of Critical Minerals in Clean Energy Transitions.* IEA. Paris. 2020.

Yet the details remain fuzzy

Reports of future metal demand are often simply compared with current supply levels. This unsophisticated view of supply and demand is leading to many mischaracterisations of the real opportunity for new mining or recycling, and the timing of each.

We need something better. But what?

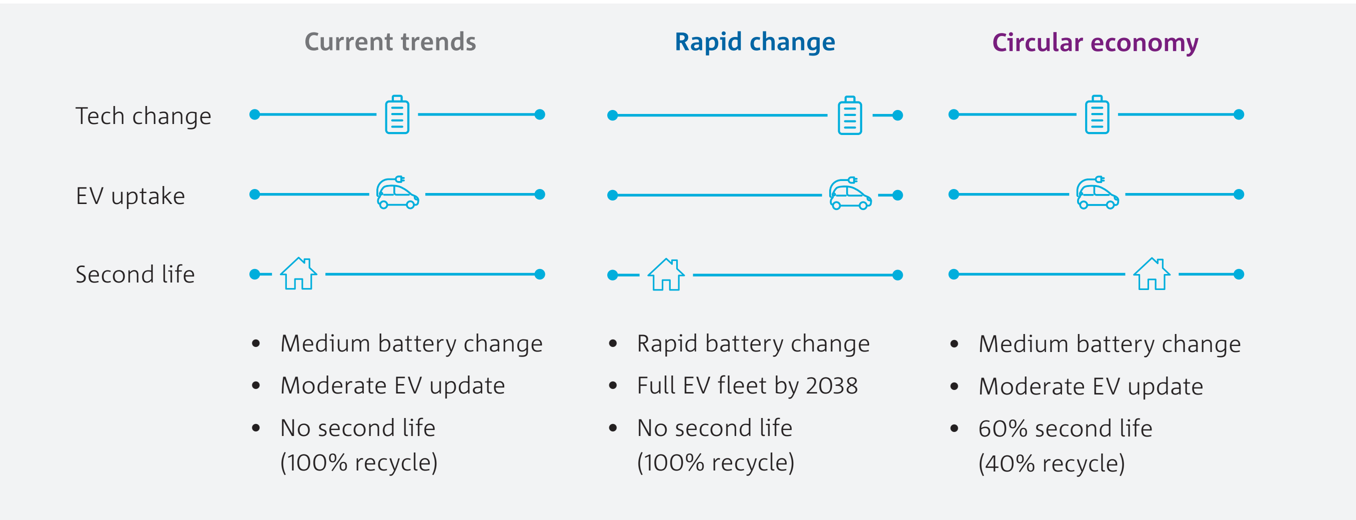
Keeping track of metal flows on a global scale

Metal flows are complicated and dynamic, particularly at a global scale. Metals can be locked-up for decades in durable consumer goods. Product life spans differ. Uptake rates of technologies vary under different policy settings. Technologies such as EV batteries may enter second-life applications like home or grid energy storage. All of these factors interact to create the aggregate demand picture.

Common economic modelling methods do not provide adequate nor coherent accounting of these physical factors. That task requires the special capabilities of a PSFF. PSFFs enable us to keep track of many physical variables and the complex dynamics that emerge when they interact with each other. This capability can yield powerful and often counter-intuitive insights.

In this paper we explore the demand and supply (primary and secondary recycling flows) of three important 'battery metals' (Ni, Co and Li) under three different EV uptake scenarios (Figure 1). Key findings are outlined below.

Figure 1. EV battery metal scenarios



Some metals are more equal than others

A key insight from the EV example is how different the outlook could be for three closely linked metals, even under the same scenario (Figure 2).

Under our Current Trends scenario, for example, the opportunity for growth in Co looks to be quite short term, followed by a long period of decline and, ultimately, a glut. For Ni, there is a longer demand window but it is nevertheless quite constrained, while Li has a long and bright future.

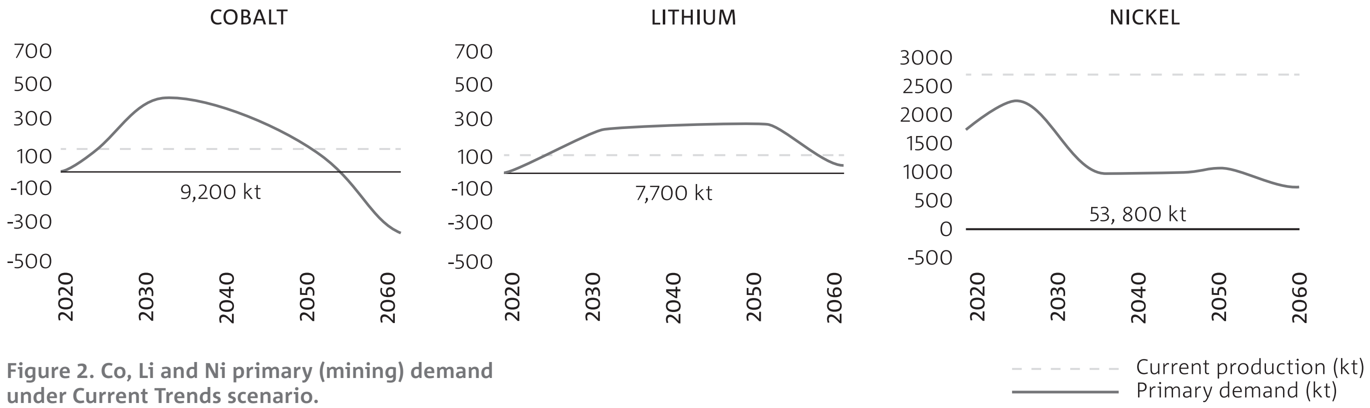


Figure 2. Co, Li and Ni primary (mining) demand under Current Trends scenario.

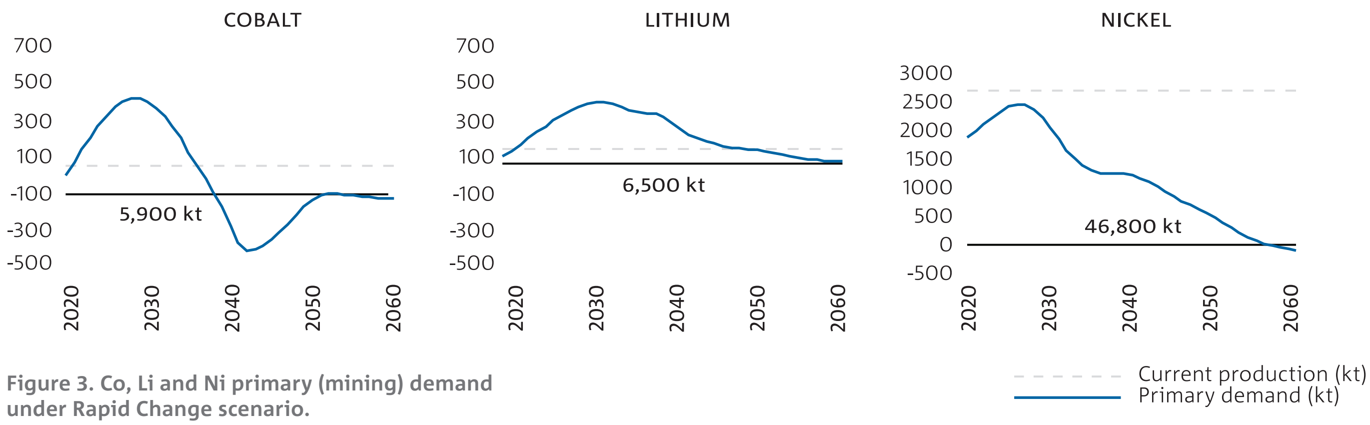


Figure 3. Co, Li and Ni primary (mining) demand under Rapid Change scenario.

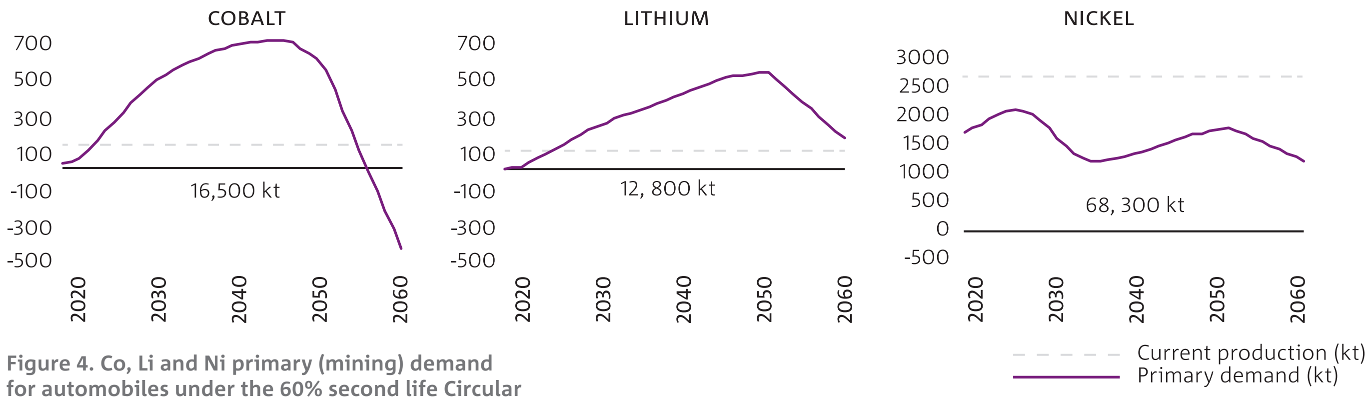


Figure 4. Co, Li and Ni primary (mining) demand for automobiles under the 60% second life Circular Economy scenario.

Under the Rapid Change scenario, which assumes a rapid pace of change in battery chemistry, quick EV uptake, and high levels of recycling, new Co demand has an extremely short window, while both Ni and Li mining have early peaks and trail off in the out years (Figure 3).

A key insight from the Circular Economy scenario is the incentive for **primary Ni and Co producers to encourage, or facilitate, the rehabilitation of ex-EV batteries for second-life applications**. This prolongs the high primary (mining) demand window, and is in direct contrast to the strongly negative effects that the alternative (i.e., more efficient scrappage and recycling) would have on their prospects (Figure 4).

We also demonstrate the unique role that a PSFF can play in linking model outcomes to major challenges and opportunities in the broader national economy.

Using the EV battery example, the PSFF can be easily adapted to keep track of residual storage capacity embodied in retiring EV batteries. Under one relatively conservative EV uptake scenario, we found that **diverting 60% of retiring EV batteries to second life would meet almost 70% of the storage demand required under the Australian Energy Market Operator's (AEMO's) central scenario for (Eastern) Australia's electricity grid by 2040**. Accelerated EV uptake increases this to over 120% of AEMO's requirement.

Significantly, the current AEMO plan relies on being able to complete a massive expansion in Australia's hydroelectric capacity, distributed along much of the Eastern Seaboard, over the same time period. Our results suggest that second life EV batteries may present a serious alternative option.

The findings also flag the potential for a new manufacturing activity (EV battery repurposing) at scale, even if it caters only to a local market, while **simultaneously advancing both the circular economy and extending the demand window for some primary metals**.

More generally, a PSFF is aimed at exploring long-term scenarios and answering questions in strategic areas such as:

1. What is the demand for primary (mined) metals and possible timing of supply pinches?
2. What are the rates of secondary metal flows returning from scrappage and recycling over time, and the interaction with primary demand?
3. How would alternative rates of change in key technologies alter the above (e.g., Co-free batteries, solid-state batteries, etc., taking a larger market share earlier than expected)?

This framework should be of broad interest to:

- **Mining executives** looking to test assumptions about new mining investments
- **Recyclers and remanufacturing entrepreneurs** wanting to anticipate regional differences in the timing and composition of recycling flows
- **Government policy professionals** seeking input for policy considerations
- **Researchers** that want to explore the impact and timing of material supply and demand under different technological change scenarios

Working together to build scenarios and expand the capability.

At this stage, the PSFF only explores EVs in detail although near-term development will expand the PSFF modelling to include wind and solar PV generation technologies.

We are currently in the early stages of engaging with external collaborators, and ready to partner with industry and government to develop bespoke scenarios that reflect partners' key interests. We are interested in sourcing data to improve the model parameters, and in getting industry views on what aspects of the energy transition they see as most important, interesting or concerning for them. Our overarching aim is to better develop and share our capability, to help Australian industry make the smartest investments in the lead-up to a low-carbon future.

Contents

1 Overview

The global transition to net-zero emissions systems will be metals intensive and provide major opportunities for mining and other metal-related industries. Assessing the future demand for these metals, and how they will be sourced, is complex. Crucially, analyses undertaken without explicit modelling of physical stocks and flows can easily yield internally-inconsistent results or recommendations.[3] This is a strong assertion, but the rise of recycling technologies and the circular economy alone justifies it. Other benefits only reinforce the case for adopting this modelling approach.

In this paper, we explore the role of using a PSFF as a risk management/scenario planning support tool for industry. Even a fully comprehensive PSFF cannot provide 'accurate' forecasts because there are so many unknowns, interactions and complexities around the future demand for metals. A PSFF does, however, enable the development of internally-consistent scenarios to explore how 'views' on major components of the energy transition will play out and interact with each other. These interactions can radically affect the demand for metals, and PSFF modelling substantially increases the capacity to identify opportunities and manage risk.

We demonstrate how a PSFF lets us track the complex supply and demand trajectories that result from the interactions of a few simple parameters. Understanding these dynamics is critical to any company wanting to bet its future on particular technological trends and the metals demand they will generate.

To demonstrate the relevance of a PSFF, we concentrate on exploring a small range of scenarios and changing a few key parameters to reflect different assumptions around the uptake, development, and end-of-life (EOL) fate of EVs over time. The EV focus reflects the fact that the electrification of transport must be a major component of decarbonisation, and it is commonly touted as a major driver of future metals demand.

Results from our main examples focus on the flows of three key battery metals, but we also show how PSFFs extend naturally to answering questions where coherent detail on other physical quantities is vital. For the latter, we compare the electrical storage capacity that accumulates in batteries going to second life to current long-term plans for the Australian electricity grid.

Finally, we appeal for industry and policymaker involvement in providing engineering/technical parameters, and in actively providing their views on what scenarios they believe are likely to play out. PSFFs are indispensable in the roles outlined for them here, but they can only be as good as their inputs, and only have practical impact if they are used to explore scenarios of interest to industry and policymakers.

3 An example is using current shares of demand met from primary and secondary metal sources to guide medium-term expectations in an analysis that simultaneously entails a major increase in demand for that metal. As metals typically go into products with long service lives, the lag between a major demand increase, and the return of those metals via recycling, will likely ensure a major shortfall of scrap from which to source secondary materials. This may last years to decades, depending directly on the specific service-life characteristics of products driving the demand.

2 Physical Stocks and Flows Frameworks

2.1 Background and overview of Physical Stocks and Flows Frameworks

PSFF modelling has been used for decades for many different purposes, sometimes with a very broad scope. The usage outlined in this paper, however, has a narrow focus. A common thread is that modelling physical stocks and flows performs a vital function that economic modelling cannot. Tracking the physical requirements of different economic scenarios makes the user fully aware of the timing and size of the physical stocks and flows implied in each scenario. In doing this, it performs a vital 'reality check' function that is not possible using economic models.

A brief cross-section of work relevant to broader PSFF usage is provided in the following two paragraphs for more general reference.

Early foundational work involving PSFFs is detailed in Gault et al. (1987), who proposed the method to allow national statistical offices to identify and resolve inconsistencies ('tensions' in their terminology) between the different but related series of statistics they compile. The framework could be used as a tool to bring together planners and policymakers who have similar tensions in the physical supply/demands of different proposed national development scenarios. This vein of national level, broad sectoral scope PSFF work was influential in later work such as Foran and Poldy (2002) and Lennox et al. (2004). In West et al. (2007) and Turner and West (2012), a PSFF is used to simulate alternative scenarios for the evolution of a state-level electricity system, exploring the cross-sectoral physical impacts on greenhouse gas (GHG) emissions, land and water resources over time. The latter work also illustrates the long-term, lock-in effects of current decisions on generator technologies. The development of a more narrowly-focused PSFF as a tool for state-level water accounting is documented in Baynes et al. (2011).

In a separate but highly relevant research stream, dating back to at least Hu et al. (2010), 'dynamic material flow analysis' was used to analyse, in detail, the stock and flow dynamics of steel, initially for an individual nation, and by Pauliuk et al. (2013) at a global scale. More recently, researchers have established an open source dynamic stocks modelling capacity in studies of greatly expanded scope (Pauliuk & Heeren, 2020), while Deetman et al. (2018) analysed how global material stocks and flows related to the electricity sector may develop towards 2050. Fishman et al. (2021) extended the scope even further to include global housing requirements.

2.2 The approach taken in this study

The approach used in our PSFF modelling has been to narrow the focus compared with many of the studies outlined above. This allows us to concentrate more effort on increasing the technical detail of the core systems being modelled, and facilitates more agile integration of end-user views of how specific aspects of the system may change over time.

In the main examples outlined in this paper, the PSFF is demonstrated using the case of EV batteries to keep track of where specific products are in their life cycle, and the stocks and flows of the specific materials embodied in them. In the Discussion (section 5), we extend this by using the example of charge storage capacity to demonstrate the value of the PSFF for keeping track of physical quantities more generally.

In the case of EVs, when a certain number enter service in a given year, they will require, and lock-in, a quantity of processed metals and other materials. That quantity will be determined by the material composition of the EVs being produced. The metals required for the new EVs can come from either primary sources (i.e., newly mined and refined) or from secondary sources (recycling).

After those EVs enter service they will begin to wear out, ultimately being retired at their EOL. These EOL vehicles then become available for scrappage, and the materials they contain available for recycling. The timing of when the EVs reach EOL will directly impact the rate at which new EVs need to be built, the availability of recycled metals and, subsequently, the demand for newly-mined metals in future years.

The preceding two paragraphs sum up the main dynamic of the PSFF. Unfortunately, this conceptual simplicity can become quite complex in implementation if we wish to adequately reflect the real-world systems being modelled.

Different models of EVs have different material compositions, and dominant EV battery chemistries will change over time. Similarly, the average service lives of EVs vary between different models over time, and even for the same EV model and time when used in different environments.

Furthermore, EVs might be seen as containing at least two distinct systems – the vehicle and the battery pack. It is possible that the vehicle reaches EOL and becomes available for recycling, while the battery goes on to serve in a second life, e.g., as stationary storage in the electricity grid. This can greatly delay the return of battery metals for recycling.

Finally, the percentage of EOL products that are actually collected for recycling, and the efficiency with which materials can be recovered can vary greatly between products and materials over time, and between different regions. In the body of this paper, we focus on describing the results and implications for industry of a small selection of scenarios built to reflect some important alternative views on how EV deployment may play out. Further detail on key assumptions and decisions made in constructing scenarios are provided in the Appendices.

3 Scenarios and rationales

In this section we provide an overview of the key settings for each scenario and the rationale behind those settings. Before that, we provide a brief description of the Base Scenario and how it frames the results for other scenarios. To simplify comparisons, for this paper, we have used the same underlying gross demand for total passenger cars to drive all scenarios. The PSFF can, however, easily incorporate whatever alternative demand scenarios a user specifies.

The scenario results shown are aggregated up to the global level, because Australian metal mining is overwhelmingly driven by the international export market rather than domestic demand. The PSFF itself, however, calculates results for 28 individual countries and global regions. Detail on important modelling parameters such as regions used, products included, assumed product recovery and recycling efficiency over time, product service lives, product compositions, etc., are provided in Appendix B.10.

3.1 Base Scenario

The Base Scenario assumes that internal combustion engine vehicles (ICEVs) continue to comprise 98% of the global fleet, with 2% EVs. It serves as a baseline against which to compare the main EV-dominated scenarios. The Base Scenario assumes the same rates of increased light-weighting for all vehicles, and changes in battery chemistries for the small number of EVs it does include.

3.2 Standard Scenario

The Standard Scenario is the first 'real' scenario, in that it is meant to represent a prospective future trend in the makeup of passenger car fleets. It can be characterised as a scenario that assumes moderate[4] rates of change over the period modelled, for the following:

1. Substitution of EVs for ICEVs in new car sales.
2. Change in dominant EV battery chemistries away from Co-intensive lithium-nickel-manganese-cobalt-oxide (NMC) variants.
3. Increases in recovery efficiency from recycled EOL products.
4. Light-weighting of both ICEV and EV (excluding the battery) components.

It also assumes that no batteries from EOL EVs go on to serve in any second-life capacity, e.g., as stationary storage for electricity grid stabilisation, home electricity storage, etc. They instead go directly to disposal/scrap/recycling.

The Standard Scenario should not be thought of as a forecast, but rather a relatively moderate and uncontroversial starting point. As outlined above, this is because the uncertainties in the technologies involved over the time period modelled are too great to responsibly make such claims.

3.3 Rapid EV Uptake, Battery Evolution, and Light-weighting Scenario

This scenario has identical settings to the Standard Scenario except:

1. Substitution of EVs for ICEVs happens more rapidly (ICEV sales end globally by 2038 rather than 2050).
2. Accelerated change in dominant EV battery chemistries towards lower-Co NMC and lithium-iron-phosphate (LFP) is assumed.
3. Light-weighting of vehicles is pursued more aggressively.

The aim of this scenario is to explore the effects of a more rapid introduction schedule for EVs and changes in battery technologies, combined with simultaneous efforts to improve vehicle performance/efficiency by reducing overall vehicle weight.

3.4 Standard Scenario with Battery Second Life

This scenario has identical settings to the Standard Scenario, except that 60% of EOL batteries go on to serve in a second life prior to disposal/scrappage/recycling.

This scenario is important in the context of EV batteries typically being deemed as EOL for EV use while still retaining 70–80% of their charging capacity.

Many of the battery performance considerations that apply for mobile use do not apply for stationary use, so it is quite conceivable that EOL EV batteries will go on to serve extended second lives until they have lost much more of their charging capacity. This would likely take many years.

The aim of this scenario is to explore the effects that widespread diversion of EOL EV batteries for use as relatively cheap stationary storage would have on the disposition of key metals over time.

4 For detail on the rates of change for key parameters such as EV uptake, changes in battery chemistries, light-weighting of vehicle structures, etc., used in the different scenarios, please refer to Appendix B.

4 Selected metal flow results

In this section we briefly describe the results for three different metals of critical importance for current EV battery technologies – Ni, Co, and Li.

The 'total car demand growth' that underlies all scenarios outlined below is identical. It is based on the personal transport requirements under one of the 'Shared Socio-economic Pathways' (SSPs)[5], combined with new car sales forecasts (see Appendix B for detail). While total car demand is identical, the EV share and types of both ICEVs and EVs produced to meet that total demand varies.

The flows of the metals Ni, Co and Li are shown in Figures 5, 6 and 7, respectively, under four scenarios as follows:

- **Base Case** (assumes current 98% ICEV mix)
- **Current Trends** (assumes current EV growth trends continue, and a moderate pace of change in battery chemistries toward lower-Co versions)
- **Circular Economy** (same as Current Trends, but with 60% of used EV batteries entering a second-life application like energy storage).
- **Rapid Change** (completely EV fleet by 2039, a faster progression toward lower-Co batteries including LFP, and no second life for used EV batteries).

The set of metal flows displayed are:

- New Products – the metal required to build new stock entering service each year
- Primary Demand – new metal input required from mining
- End-of-first-life (EOFL) Flow Total – all metal contained in products is reaching the end of their (first) service life
- EOFL Recovered – metal recovered via recycling from the EOFL Flow Total stream
- EOFL Lost – metal dissipated from the EOFL Flow Total stream to landfill, by not being collected or via sub-100% yields in the recycling process, etc
- End-of-second-life (EOSL) Recovered – metal recovered via recycling from products that were diverted to a second service life, and then reach the EOSL.

Note that these flows assume no inputs of metal from outside the PSFF system under consideration. All metals are thus primary in year one, with zero recycled material available. This point is important for understanding the early trajectories in these figures and is expanded upon in Appendix A.1.

5 Background on the origin and rationale for the full range of SSP growth scenarios is available at *Explainer: How 'Shared Socioeconomic Pathways' explore future climate change* | Carbon Brief. Source: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

4.1 Nickel

For Ni, under the Base Case (where ICEVs continue to totally dominate personal car fleets) (Figure 5, top left), in little more than a decade the return flows of secondary Ni begin to supply most of the Ni required for new production. Primary Ni settles into a near steady state at the relatively low (~500,000 tonnes) level, which is sufficient to fill the secondary Ni deficit driven by the growing total demand for vehicles.

Under the standard Current Trends scenario (Figure 5, top right) there is a broadly similar pattern for primary Ni demand, but with the steady state establishing itself at a much higher level for several decades. This is driven by the higher Ni intensity of EVs, as they replace an increasing proportion of ICEVs. Once the substitution of EVs for ICEV is complete, by 2050 we see a second decrease in primary demand as return flows from scrapped EOFL vehicles close the gap with Ni required for new products.

The scenario for accelerated technological change, Rapid Change (Figure 5, bottom left), provides an example of the potential value of a PSFF for timing risk management. The earlier years appear more bullish for Ni demand, but soon evolve into one that is worse for primary Ni producers over the longer term. The trajectory could reflect a real-world scenario where high early demand for Ni drives prices higher, incentivising moves to less Ni-intensive battery technologies such as LFP, and leading ultimately to low-to-negative primary Ni demand in later years.

The Circular Economy scenario (Figure 5, bottom right) illustrates the large and long-lasting effect that diverting 60% of EOFL EV batteries to a second life could have on primary Ni demand. This one change in scenario assumptions compared to Current Trends leads to primary Ni demand settling at levels of a factor of two to four times higher for several decades, until the batteries diverted to a second life become available for scrappage in significant numbers several decades later. This is a stark illustration of the importance of the second life issue to primary producers, and the potential stake they could have in encouraging and facilitating it.

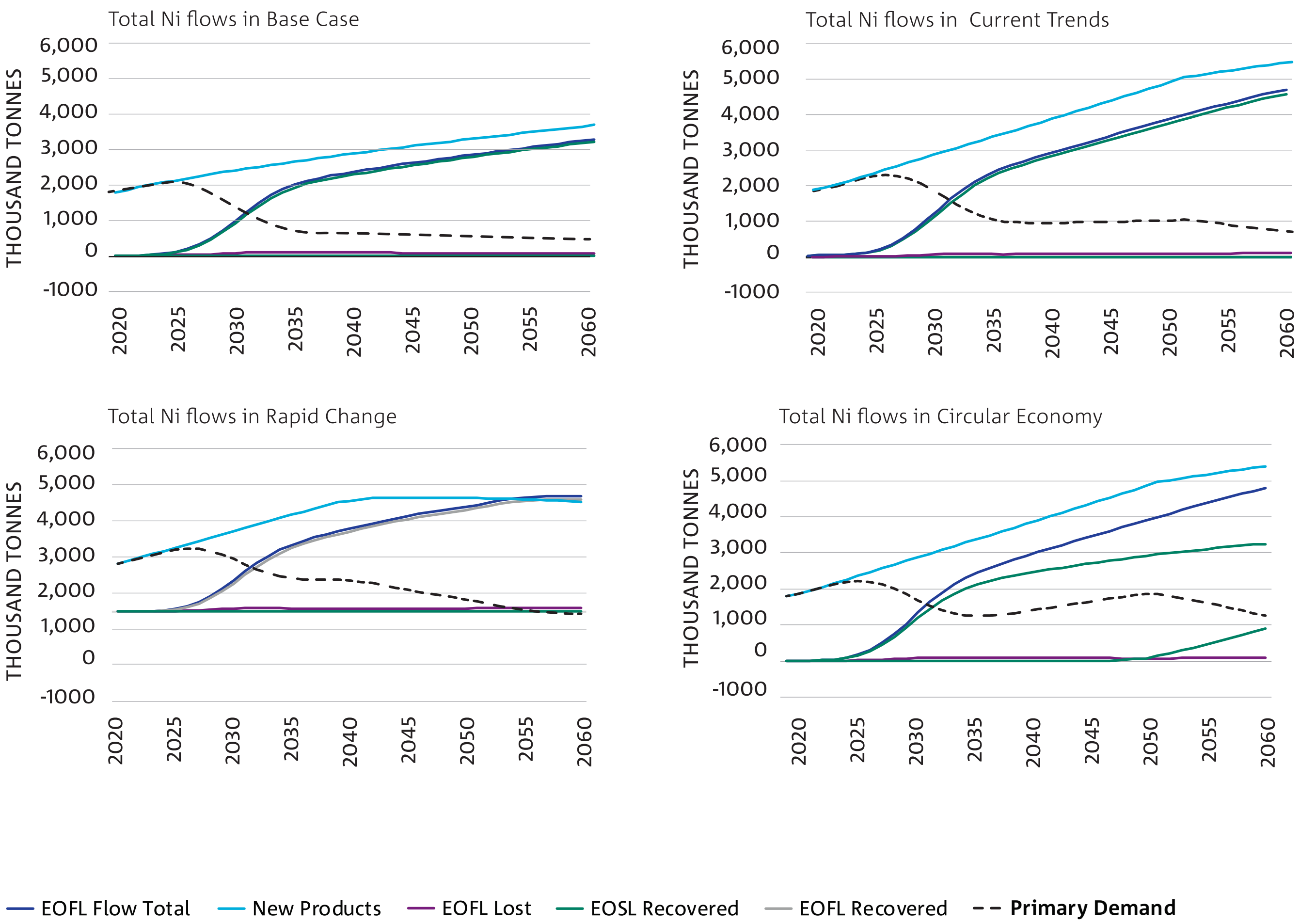


Figure 5. Selected stocks and flows for Ni associated with car production and subsequent scrappage, from 2020, under four different scenarios.

4.2 Cobalt

While there were major differences in the outlook for Ni under these four scenarios, Figure 6 shows that they pale in comparison to those for Co under the same set of scenarios.

The main reason for this is clear from the Base Case scenario (Figure 6, top left), with ICEVs using considerable amounts of Ni but very little Co in comparison to current EV technologies. It is only in the scenarios where EVs begin to displace ICEVs, that Co usage, demand and recycling become significant.

Under Current Trends (Figure 6, top right), ongoing substitution of EVs for ICEVs produces rapid growth in Co demand by the mid-2020s, to levels several times higher than current total global production.[6] A move towards lower-Co formulations for NMC batteries slows this demand growth appreciably from around 2040, augmented by some shift towards non-NMC chemistries, but demand for new products continues to increase through to 2050. Effective recycling, however, ends any boom in primary Co demand by the early 2030s. When the additional demand driven by substitution for ICEVs ends in 2050, the return flows from retiring older, high-Co batteries quickly drives primary demand negative.

The Rapid Change scenario (Figure 6, bottom left) shows how Co miners could be misled by the high Co demand trend early in an accelerated technology shift scenario. Primary demand peaks in under a decade, turning strongly negative in less than two decades. This scenario is not particularly radical, it simply reflects earlier substitution of EVs (completed by 2038) combined with a more rapid shift to low-Co battery chemistries.

Comparing Circular Economy to Current Trends (Figure 6, right) shows how central the single variable of second-life usage ratios could be to the prospects of primary Co producers. Rather than Current Trend's brief boom followed by decades of decline, under Circular Economy the outlook for primary Co demand spans several decades, at three to five times current global demand.

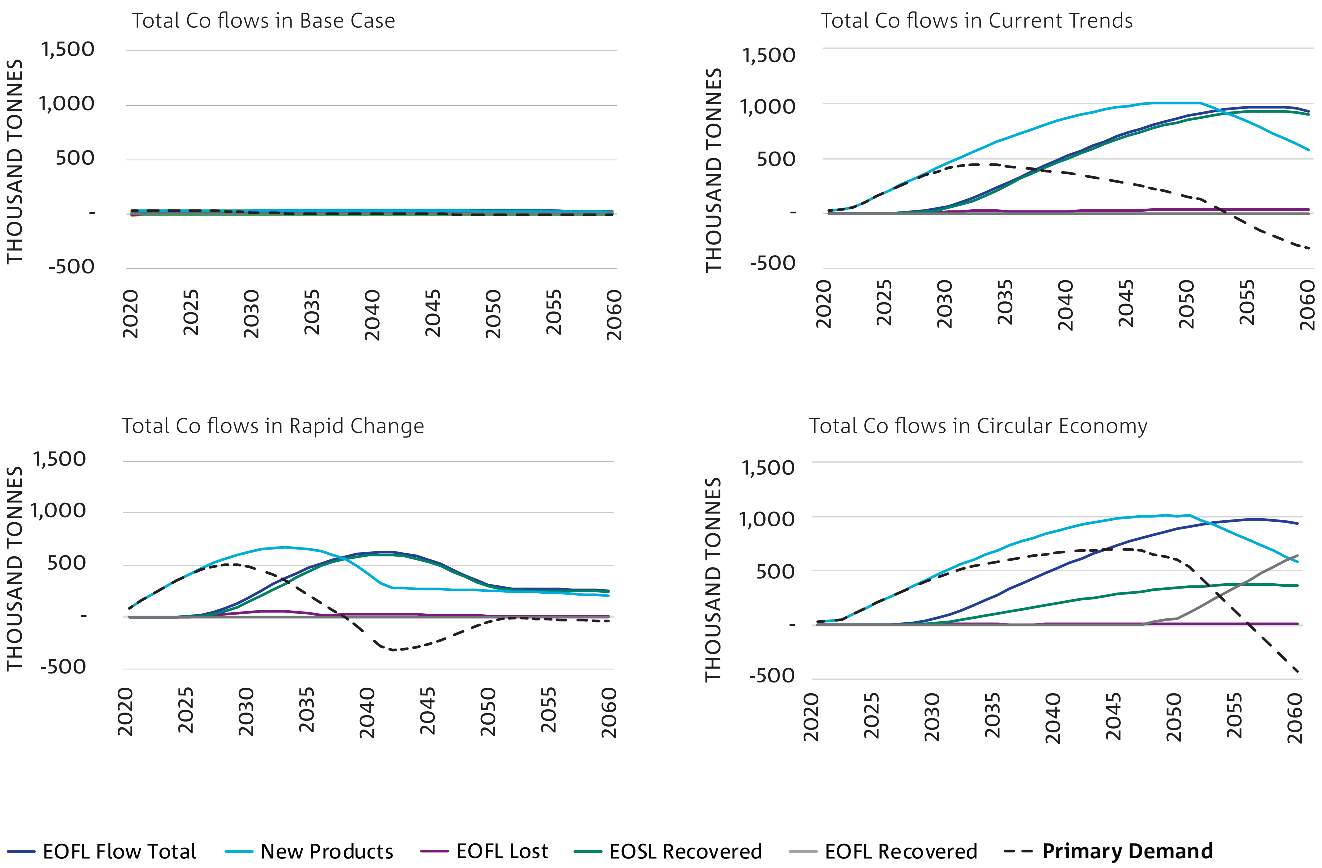


Figure 6. Selected stocks and flows for Co associated with car production and subsequent scrappage, from 2020, under four different scenarios.

6 144 kilotons (kt) in 2019 according to Cobalt (usgs.gov). Source: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cobalt.pdf.

4.3 Lithium

Like Co, Li is of little importance in ICEV technology but extremely important in current EV technology. Unlike Co, it remains central to most of the main battery chemistries being considered over the long term for use in EVs.

This is reflected in the Current Trends scenario (Figure 7, top right), which shows ongoing stable primary demand for Li over the full period when EVs are substituting for ICEVs. Primary demand only goes into serious decline when demand for use in new product peaks, and lagging return flows from EOFL vehicles can subsequently begin to catch up.

In the Rapid Change scenario (Figure 7, bottom left) the accelerated uptake of EVs brings demand for Li forward, until the substitution is complete by 2038, at which point, secondary Li supply begins to rapidly catch up with plateauing demand from new products, driving primary Li demand into a second, prolonged phase of decline. The modest declines in primary demand prior to that point are driven by changing battery chemistry shares. While Li is used in all batteries, the different chemistries have differing Li intensities per kilowatt hours (kWh) stored.

As with both Ni and Co, Circular Economy (Figure 7, bottom right) shows how important the viability of a second life for EV batteries will be for understanding the trajectories of both primary demand and for the expansion of recycling capacity required to deal with EOL batteries.

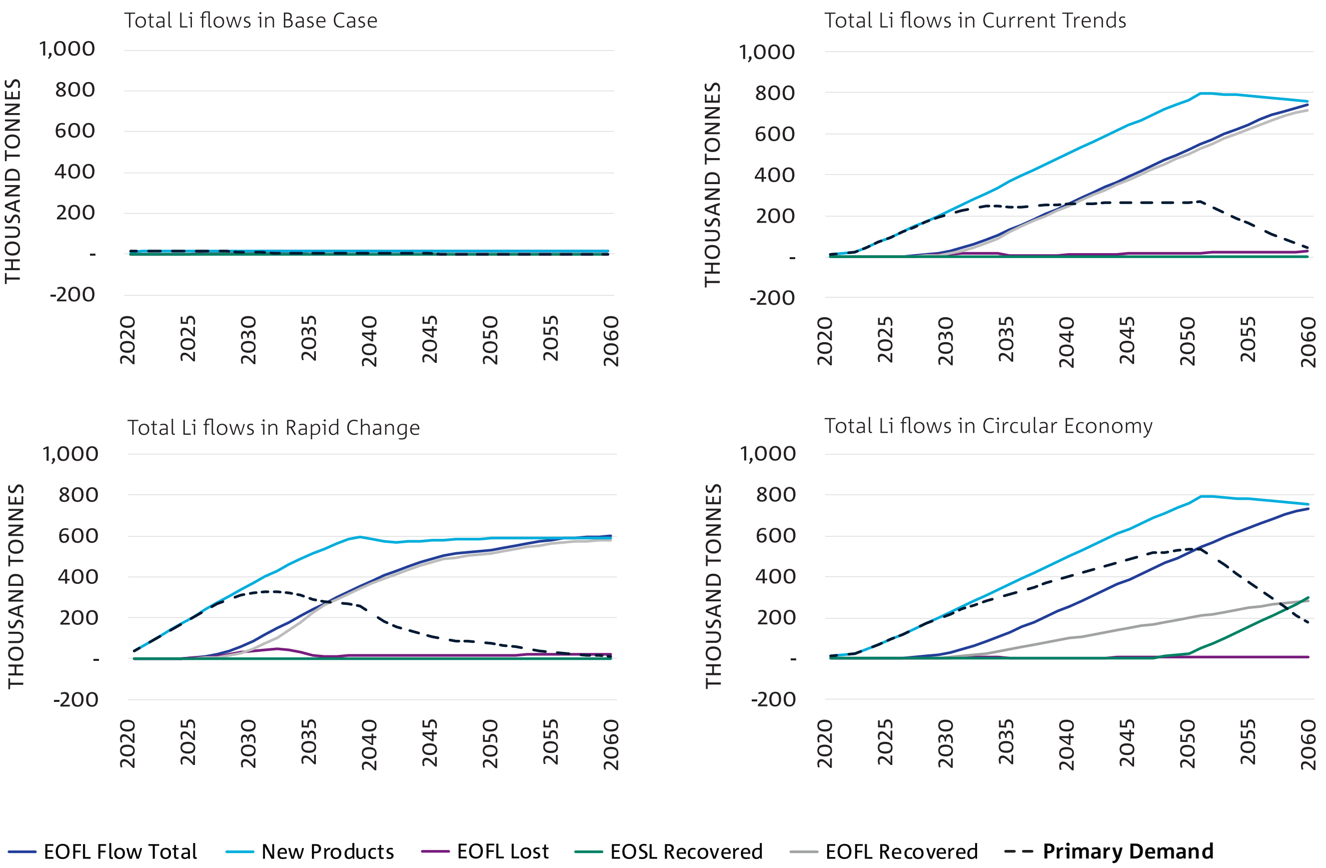


Figure 7. Selected stocks and flows for Li associated with car production and subsequent scrappage, from 2020, under four different scenarios.

5 Discussion

The nuances of metal supply and demand

The previous section demonstrates how varying a few basic assumptions can radically alter metals demand, and the balance between primary and secondary supply of those metals over time. Furthermore, the outlook for individual metals can diverge quite rapidly, even for metals as tightly linked as Ni, Co, and Li in EV usage.

Other informative scenarios can be created in the PSFF to investigate the impact of differing EOFL collection and recycling efficiency rates, product service lives, step changes in dominant product technologies, etc. Examples of where this is both simple and critical to understanding future metal flows are easy to identify.

For example, in the case of Li, an important additional matter is the effect of lower 'functional recycling' rates, as defined in Graedel et al. (2011). The scenarios above assume that both EOL product collection and recycling efficiencies (element recovery) for all metals reaches 98% by 2035. These rates may not be controversial for metals like Ni but are very optimistic for Li. Currently, little Li is recovered from EOL batteries in any usable form and even less (effectively none) is functionally recycled, i.e., recovered in a form that can be economically re-used in new batteries (Miatto et al. 2020). While not modelled for this paper, it could be expected that dropping maximum recycling rates, to say 40% for Li, will have a similarly large effect on primary demand as the 60% second-life assumption.

The above example demonstrates the huge influence that second life could have on metals demand. We now revisit that question, to show how other information organised by the PSFF is also very useful for forming our view of how likely significant second-life usage will be.

Keeping track of embodied energy storage too

The PSFF keeps track of the size of each cohort of batteries surviving, and the rate at which their charging capacity degrades. From this, we can directly calculate the storage capacity reaching EOFL each year, total storage capacity of all batteries serving in a second life, and the total residual storage capacity being scrapped at both EOFL and EOSL. This lets us compare the value of the materials embodied in EOFL to their potential value as stationary storage. Having the PSFF disaggregated at regional/national level also lets us link these flows to specific regional issues and plans, and allows us to gauge the potential significance of battery second life.

To demonstrate this we first extract the energy storage embodied in key stocks and flows for Australia under two different EV scenarios:

1. Current Trends + 60% second life.
2. Rapid Change + 60% second life (the accelerated EV technology shift scenario) (Table 1).

Storage capacity is in gigawatt hours (GWh), embodied in total annual EOL EV battery (EOFL) flow, the share going to second life (SL Inflow), and the total accumulated storage in second-life batteries (SL in service). Both scenarios assume 60% go to second life.

We then compare those results to the storage requirements for Australia's future electricity system under two different scenarios given in the AEMO's Integrated System Plan (ISP) (AEMO, 2020) (Table 2).

Table 1. Storage capacity in GWh embodied in total annual EOL EV battery (EOFL) flow, the share going to second life (SL Inflow), and the total accumulated storage in second-life batteries (SL in service). Both scenarios assume 60% go to second life.

A) CURRENT TRENDS + 60% SECOND LIFE (GWH)									
	2021	2025	2030	2035	2040	2045	2050	2055	2060
EOFL	0.0	0.1	1.9	8.0	15.6	24.0	32.8	41.9	49.6
SL Inflow	0.0	0.0	1.2	4.8	9.4	14.4	19.7	25.1	29.7
SL in service	0.0	0.1	2.7	17.4	50.2	100.2	164.7	237.2	312.2

B) RAPID CHANGE + 60% SECOND LIFE (GWH)									
	2021	2025	2030	2035	2040	2045	2050	2055	2060
EOFL	0.0	0.3	5.6	14.7	23.3	30.5	34.5	44.3	50.7
SL Inflow	0.0	0.2	3.3	8.8	14.0	18.3	20.7	26.6	30.4
SL in service	0.0	0.2	8.3	38.6	89.0	153.2	217.0	279.2	345.3

Table 2. Storage capacity in GWh indicated under AEMO (2020) ISP, under a) the Central scenario and b) High Distributed Energy scenario.

A) ISP CENTRAL SCENARIO (GWH)					
	2021–22	2025–26	2030–31	2035–36	2040–41
Total Battery	0.2	1.5	3.4	5.6	8.5
Total PHES Excluding Snowy 2.0	0.0	0.0	0.0	34.3	64.7
Total Battery and PHES excluding Snowy 2.0	0.2	1.5	3.4	40.0	73.2

B) ISP HIGH DISTRIBUTED ENERGY CASE (GWH)					
	2021–22	2025–26	2030–31	2035–36	2040-41
Total Battery	3.6	17.5	44.2	70.8	94.7
Total PHES Excluding Snowy 2.0	0.0	0.0	0.0	11.5	32.0
Total Battery and PHES excluding Snowy 2.0	3.6	17.5	44.2	82.2	126.7

The feature of interest in this comparison is that a very significant share of the AEMO ISP's total required storage, including its very large assumed pumped hydroelectric storage (PHES), could be met from second-life EV batteries within two decades (AEMO, 2020).

Second-life EV batteries accumulated in service by 2040 under the Current Trends + 60% second-life scenario would meet almost 70% of the AEMO ISP Central scenario total storage demand, and exceed battery demand by almost 500%. The corresponding figures for the High Distributed Energy Resources (DER) scenario, which assumes widespread distributed storage at the household level, are 40% and 53%, respectively.

Under the Rapid Change + 60% second-life scenario, second-life batteries in service actually exceed the AEMO ISP Central scenario total demand by 2040 (120%) and meet 70% of total storage demand under the High DER scenario. Furthermore, the rate at which available storage is accumulating in second-life batteries is just entering its most rapid growth phase from around 2040 under both EV scenarios. Note that these storage values fully account for the ongoing decrease in capacity of each individual cohort of batteries as they age, an example of an important capacity which comes with using a PSFF.

This example illustrates the versatility of PSFFs and the internally-consistent information they produce. The information and structures initially assembled to analyse metal requirements for EVs were readily adapted to explore the potential for an alternative to pumped hydro energy storage (PHES) for grid firming. Given that potential looks significant, and the historical political sensitivity to large-scale hydro development in Australia, results suggest the analysis should be taken further.

Again, information already organised within the PSFF would be vital input to an initial comparison of the value of second-life batteries as storage versus their value as scrap. This point is expanded upon in Appendix A.2. The results of this comparison should, in turn, feed back into our view of how significant the share of batteries going to second life from EVs might be. Performing such an analysis was outside the scope of this article.

6 Conclusion

An important point about what PSFFs do not do needs to be clarified. A PSFF or closely analogous tool for modelling physical stocks and flows is irreplaceable for ensuring that scenarios are internally consistent and physically credible. It remains, however, basically a tool limited to coherent physical accounting. As such, it cannot replace economic modelling for estimating the ultimate supply/demand/prices that will develop under any particular scenario as market forces come into play. For example, a PSFF will not tell us how the evolution of different supply and demand flows of Co shown in Figure 6 would affect the price of Co under any of those scenarios. This is a critical point, because that pricing will presumably alter the propensity of EV manufacturers to change battery chemistries. That, in turn, could affect a user's assessment of the initial assumptions underlying the scenario.

The direct role of a PSFF, as used here, is simply to make clear the physical implications of exogenously-specified scenarios and, in doing that, provide both insights and a vital reality check/audit function of those scenarios. This relies on expert input to the systems being modelled. In this case, it included economic modelling of vehicle demand and EV uptake, engineering data on current technologies, and informed opinion on the future development of those technologies.

A PSFF can only be as good as the expert inputs it translates into physical stocks and flows. Given that, ongoing involvement of experts and stakeholders, who have both strong technical knowledge and strong views on how the systems being modelled will develop, will largely determine the practical value of a PSFF. This goes for the existing EV scenarios and for the new modules under construction for other aspects of the energy transition, notably variable renewable energy. We end this paper with an invitation for relevant industry and policymaking stakeholders to become involved in the active formation and parameterisation of scenarios for analysis.

7 Ideally, economic modelling could then be used to refine the initial starting inputs to the PSFF. There is no theoretical reason why subsequent economic modelling, which takes into account the physical demand output from the PSFF, could not then be performed with the resulting revised economic outlook forming the basis for new and refined scenarios in the PSFF.

While this is a potentially attractive longer-term expansion/option, there are major practical questions over the computational costs and timescales involved in running such a system, especially given the intended role of this PSFF as a platform to permit relatively rapid integration and exploration of end-user views. If we begin feeding updated economic scenarios into the PSFF, doing it in a rigorous and repeatable manner probably requires an iterative system with hard linkages between the PSFF and economic model, which iterates all the way to an acceptable level of convergence/stability. Iterative systems can require many rounds of iteration to achieve this state, while detailed integrated economic models can require hours to days for individual runs.

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Appendices

A. Expanded explanations of selected points

A.1 Effects of model boundaries on apparent demand for primary materials

The scenarios modelled in a PSFF are restricted to those stocks and flows directly driven by products explicitly included in the model. In this case, the only stocks modelled are different mixes of new automobile systems starting from 2020 onwards. All metal required to make those automobiles in the first year must necessarily be assumed to come from primary production. This is because recycled material does not become available in the model until these systems begin to be scrapped.

This is important in interpreting the earlier years of scenarios, in particular the early peak in primary demand evident in most cases.

If, for example, we knew that 30% of current demand for any of these metals is met from recycled material, and that modelled demand for the PSFF system is not large compared to existing current demand, then it would be reasonable to assume that primary demand for the earliest years should be (externally and informally) discounted by 30% or so. The discount should be decreased as we approach EOL for the earlier cohorts of products modelled and internal recycling flows take over.

The larger demand in the modelled system is in comparison to current demand; and the lower current recycling rates, the less the need to take this effect into account. This will be the case for Li and Co.

The only way we could formally adjust for this effect, while retaining full internal consistency in a PSFF (one of their main analytical strengths), would be to construct a ‘history’ of all those products that contribute significantly to current recycling flows, complete with robust data on the material compositions and service lives of those products. This would be an extremely large task, assuming such data are even available (unlikely), and so it is not attempted for this work, nor a prospect at this point in time.

This means that practical implementation of a PSFF will generally best serve as a tool for analysing comparative differences between alternative future scenarios for specific systems. It just happens that, in some cases, like that of EVs and battery metals, the scale of difference between different specific systems is large enough to have whole-of-economy-scale importance.

A.2 Effects of changing battery chemistry and service lives on second life assumptions

In these scenarios, some important assumed trends in EV batteries over time include that:

- They will evolve to use lower value materials over time, e.g., towards less Co-intensive NMC chemistries, and also away from NMC to LFP chemistries
- The service lives of the dominant EV batteries will increase, which means that their storage capacity will deteriorate more slowly.

Taken together, these two trends should lead to the scrap value per kWh capacity of EOL batteries declining strongly over time, while their retained storage capacity over time in a second life will increase.

All else being equal, over time this this will increase the relative value of batteries going to second life compared to the scrappage alternative.

The PSFF keeps track of both the materials and the remnant charge capacity of each individual cohort of batteries. Having the capacity to retain and access this level of detail is central to being able to perform a meaningful analysis of how the relative values would develop under different scenarios.

As stated in the conclusion, however, it is important that the PSFF be seen as an important adjunct/complement to economic modelling, not as some sort of alternative. The PSFF will simply account for the physical stocks and flows required under exogenously-specified scenarios. There is nothing in the PSFF that will subsequently ‘adjust’ to reflect how markets will react to the indicated supply and demand levels. That remains the domain of economic models. The most practical relationship between PSFFs and economic models is probably one of iterative interaction and feedback.

B. Detail on main scenario inputs

B.1 Derivation of total automobile demand

All of the scenarios described in this paper use the same projection for total demand for autos from 2020 to 2060 to allow for direct comparison between scenarios.

This common demand projection was established by combining the annual growth rates in 'household demand for land transport', modelled in a computable general equilibrium economic model (CGE) with data on global auto sales/registrations. The former was used to scale and project the latter.

The CGE model output used was from GTEM-C (Cai, Newth, Finnigan and Gunasekera, 2015), configured to model the SSP scenarios as described in Schandl et al. (2020). SSP2 was used as the basis for all scenarios, because this represents a 'Middle of the Road' scenario (medium challenges to mitigation and adaptation) (Hausfather, 2018).

Automobile sales figures were sourced from the International Organization of Motor Vehicle Manufacturers (OICA) (2020). The base figures used for the projections were only for passenger cars in 2019. As the regional resolution of the OICA data is higher than the GTEM-C demand growth data, the former were aggregated to match the latter before being projected over the period 2020–2060.

GTEM-C is disaggregated into 28 different countries/regions, which cover the world, so the PSFF modelling can accommodate parameter settings differentiated at this level. Individual trends for each region have been used for total automobile demand, using data available from the SSP scenarios. Most of the other parameters discussed below, however, used one common global trend, applied across all countries and regions.

Note that results for other auto demand scenarios are available, for SSP 1 and 5, as well as for demand scenarios with a totally different modelling origin (using output from the GALLM-T model described in Hayward, Foster, Graham and Reedman, 2017).

B.2 Derivation of EV / ICEV shares

All 28 regions in the scenarios discussed use one global setting for this variable, common within each scenario, but differing between scenarios.

Base Case

The 2% EV share of new auto sales assumed to persist for the entire modelled period under this scenario was selected as approximately equal to that for 2019. In retrospect, the real figure for 2019 appears to have been closer to 3%, but this does not materially affect SSP2_ICEV98 in its role as a baseline against which to compare the other scenarios.

Current Trends and Circular Economy

The phase-in of EVs in these scenarios uses a line of best fit through the global market share projections available from BNEF (2020) for 2020, 2025, 2030 and 2040 (of 2.7%, 10%, 28% and 58%, respectively), with an additional assumption that 100% of new cars are EVs by 2050. As for all scenarios here, the rate of uptake is not differentiated by region.

Rapid Change

The phase-in of EVs in this scenario assumes linear substitution of EVs for ICEVs by 2039, starting from 2% EVs in 2019. The basis for this was simply to bring complete substitution under the Standard Scenario forward by a decade as an accelerated EV uptake scenario.

B.3 Shares of discrete technologies within EV and ICEV categories

All 28 regions in the scenarios discussed use one global setting for this variable.

Little was found in the way of authoritative forecasts to inform the shift in technologies over time within the EV and ICEV categories. As a result, our scenarios were constructed to simply assume dominance in the early years of existing technologies, for which there were some material breakdowns available, then shifting towards one or more technologies that seem likely to become more important over the longer term.

For example, consulting the literature and CSIRO battery experts indicated that the NMC battery technology used in many EVs was already changing rapidly from the high-Co formulations, such as the NMC111 formulation used in the Chevy Bolt 2016 model (an important baseline for this study) to lower-Co formulations, e.g., NMC622 and NMC811. Similarly, migration away from NMC entirely, to low/zero-Co and -Ni chemistries (notably LFP), was included as a trend.

It was also anticipated that the composition of ICEVs, as well as the non-battery pack component of EVs, would continue to evolve, with ongoing light-weighting to achieve higher energy efficiencies an important part of this. This is reflected in these scenarios by having the mix of individual 'products' (a product is an individual type of ICEV, EV battery pack or EV ex-battery) shift towards products that have an increasing percentage of steel replaced by aluminium (Al).

All battery pack element compositions for capacities and chemistries, other than the 60 kWh NMC111, were derived by:

1. Scaling overall 60 kWh NMC111 battery pack breakdown given in UBS (2017) according to capacity (e.g., halving for 30 kWh).
2. Adjusting for average specific energy capacities of the different chemistries derived from Buchmann (2020), by assuming that the rest of the battery pack scales proportionally to the active components. Exchanging the cell component active elements – Ni, manganese (Mn), Co, iron (Fe) and phosphate (P) – largely by stoichiometric calculations.

Base Case

The same shift in EV technologies described for Current Trends (described below) were applied here but, with the total share of EVs only 2%, this has little effect on overall material stocks and flows.

Significant metal stocks and flows impacts do result from the dominant types of ICEVs shifting composition over time as ongoing 'light-weighting' occurs. However, the main impact of this is in Al and Fe, not in battery metals.

ICEV shares in 2020 were set as:

- 50% 'ICEV_Golf_UBS_2016' based on the composition of a 2016 VW Golf as reported in UBS (2017)
- 50% 'ICEV_US_LtDuty_2014' with composition largely based on Dai, Kelly, and Elgowainy (2017), with additional input from Pauliuk (2019b).

These shares decrease linearly over time to only 10% each by 2060, with the remaining 80% of ICEV production accounted for by a hypothetical 'ICEV_Equal_AlFe'. This takes the mean light ICEV composition from Pauliuk (2019b), and replaces half of the Fe with Al at a rate of 1 kg Al for each 1.667 kg Fe.

Current Trends and Circular Economy

In these scenarios, the battery pack technology/ composition shares of EV begin in 2020 at:

- 88% 60 kWh NMC111 ('LionNiCoMn_60kwh_BoltType_2016')
- 11% 30 kWh LFP ('LFP_30Kwh')
- 1% 60 kWh NMC811 ('NMC811_60Kwh').

These shares then change linearly over time to 8%, 51% and 41%, respectively, by 2060.

These battery shares carry over to the EV-excluding-battery (EV_ExBat) products, with each battery matched to one specific EV_ExBat (Table 3). The three EV ex-battery products used were:

- 'EV_ExBat_BoltType_2016' – a vehicle based on the breakdown for a 2016 model Chevy Bolt in UBS (2017)
- 'EV_ExBat_BoltType_EqualAlFe' – a hypothetical vehicle based on the EV_ExBat_BoltType_2016 with half of its Fe replaced by Al
- 'EV_ExBat_BoltType_AlReplacesFe' – an EV_ExBat_BoltType_2016 with all Fe replaced by Al for maximum light-weighting.

Table 3. Battery/EV_ExBat pairings

BATTERY	EV_EXBAT
LionNiCoMn_60kwh_BoltType_2016	EV_ExBat_BoltType_2016
LFP_30Kwh	EV_ExBat_BoltType_EqualAlFe
NMC811_60Kwh	EV_ExBat_BoltType_AlReplacesFe

Note that these EV_ExBat details are significant for Fe and Al but have little effect on main battery metals discussed in this paper.

Light-weighting of ICEVs follows the same pattern described for the Base Case, however, it has much less impact on metal flows due to simultaneous substitution of EVs for ICEVs in this scenario.

Rapid Change and Rapid Change + 60% second life

These scenarios model a much faster rate of change towards both more advanced battery technologies and light-weighting than the other scenarios explored. Battery pack technology/composition shares of EV begin in 2020 at:

- 86% 60 kWh NMC111 ('LionNiCoMn_60kwh_BoltType_2016')
- 12% 30 kWh LFP ('LFP_30Kwh')
- 2% 60 kWh NMC811 ('NMC811_60Kwh')
- Shares change to 0%, 55% and 45%, respectively, by 2042, and 0%, 73% and 27%, respectively, by 2060.

The same battery packs are again matched to the same specific EV_ExBat given in Table 4. The rapid share changes yield accelerated light-weighting of the EV_ExBat components compared to the Standard Scenario.

B.4 Product service lives (first life)

All 28 regions for the scenarios discussed used one global vector of settings for this variable, differentiated only between products.

For simplicity:

- All service lives were assumed to follow a normal distribution
- Battery/EV_ExBat pairs were assumed to have the same (first) service life, reflecting an assumption that both components of an EV system will reach EOL together.

More advanced EV/NMC811 battery systems, which become prominent in later years, were assumed to have somewhat extended lives (equal to that assumed for ICEVs).

Table 4. Service life distributions assumed for products. Service Life (norm,8,2) translates to normal distribution, 8-year mean, 2-year standard deviation.

CATEGORY	SUB-CATEGORY	SERVICE LIFE
Battery	LionNiCoMn_60kwh_BoltType_2016	norm,8,2
Battery	NMC811_60Kwh	norm,10,3
Battery	LFP_30Kwh	norm,8,2
EV_ExBat	EV_ExBat_BoltType_2016	norm,8,2
EV_ExBat	EV_ExBat_BoltType_EqualAlFe	norm,8,2
EV_ExBat	EV_ExBat_BoltType_AlReplacesFe	norm,10,3
ICEV	ICEV_Golf_UBS_2016	norm,10,3
ICEV	ICEV_US_LtDuty_2014	norm,10,3
ICEV	ICEV_Equal_AlFe	norm,10,3

The basis for the 8-year service life for EVs was from internal CSIRO consultation on trends in Original Equipment Manufacturer (OEM) warrantees for EV batteries.
The 10-year, ICEV-assumed service life serves as a simple and transparent basis for demonstration purposes.
It is, however, considerably less than recent studies suggest, e.g., Pauliuk (2019a), which defaults to 16 years, but contains national level variation from 12–23 years and US-specific data at US BTS (2015) of 11.4 years in 2014).

B.5 Product second life retirement criteria

Only batteries have second-life retirement criteria that actually come into play for the scenarios discussed.

The second-life retirement criteria for all three of the battery types used were set in terms of their original charging capacity. All batteries that entered second life were subsequently scrapped when they had degraded to 30% of their original charging capacity. This criterion was applied for all scenarios. Changing this retirement criterion can have a strong effect on metal flow dynamics. For example, increasing the remnant capacity requirement for EOSL to 60%, under an otherwise identical Circular Economy scenario, would see primary demand for both Co and Li peak earlier (by the mid-to-late 2030s), and at significantly lower levels.

This uniform capacity criterion interacts with battery type-specific rates of capacity decay to give different effective service lives for those batteries that go on to serve in a second life (see next section).

B.6 Battery capacity decay rates

All NMC chemistry batteries were assumed to lose capacity at a rate of 2.5% of their original capacity per year, while the corresponding rate for LFP batteries was 1.9%. Note that these rates of decline are relatively rapid compared to the much-extended EV battery service lives mooted over the medium term in some sources, e.g., Nathan Niese, Cornelius Pieper, Aakash Arora and Xie (2020), which postulate 20-year service lives with 80% retained capacity at the end of that service life.

For batteries that go to second life, battery decay rates combine with the second-life retirement criterion to yield an EOSL age of 28 years for NMC batteries and 38 years for LFP batteries.

Under these assumptions, second-life batteries would be locked into second-life usage for two to three decades after initial EOL before they become available for recycling.

B.6 Product shares to second life

Base Case, Current Trends, and Rapid Change

These three scenarios assume that no products of any type go on to serve in a second life, and so become available for scrappage at EOL.

Circular Economy and Rapid Change + 60% second life

Both of these scenarios assume that 60% of EOL batteries go on to serve in a second life until their EOSL retirement criteria is exceeded. The 60% level was chosen arbitrarily, for demonstration purposes.

B.7 Product recycling rates

The term ‘product recycling rate’ is used here to denote the share of EOL products that are collected and make it to a recycling facility. It is differentiated only according to product, and over time, to simulate rates increasing as more circular economy-related initiatives are implemented. The same rates are applied to all countries/regions for these scenarios.

Recycling rates for ICEVs are already generally high, and a similar rate was assumed for EV_ExtBat. Both begin in 2020 at a rate of 90%, rising by 1% p.a. to plateau at 98% from 2028 on. The initial recycling rates for all EV batteries were assumed to be much lower initially, due to their relative newness and the lack of existing recycling infrastructure geared to them. From 50% in 2020, this rate then climbs rapidly at 3% p.a. to plateau at 98% by 2036.

B.8 Recycling element recovery factor

This factor parameter sets the efficiency with which individual elements are recovered in re-usable form from the EOL products that enter recycling. It is specified as a percentage, with 100% representing the element contained in the original product.

It is differentiated by product, element, and over time. The elements that can be included are numerous, however, we only conducted research into reasonable current rates for the battery metals Ni, Co and Li, plus Al and Fe.

For the subset of elements reported on in this paper, Ni and Co begin in 2020 with recovery rates set to 90%, while Li is set at 10%. All rates improve linearly to plateau at 98% by 2035 for all three elements.

The same rates are applied across all countries/regions for these scenarios.

This factor, combined with the product recycling rate, determine how much of each element in EOL flows is recovered from EOL product flows in a form that can functionally substitute for new, primary production. This factor is important in explaining why the rate for Li is set so low.

An (2019) contains studies of processes where recovery of all battery metals, including Li, is 90% or higher. Given we know that in 2020 recycling of Li is low (Miatto et al. 2020), and the end products are rarely if ever functionally recycled (ending up in pavement/cement type products), these high rates are not relevant.

B.9 Product element compositions

The individual product element compositions used for all scenarios was the same across all countries and time periods. The compositions for the subset of products and elements discussed in this paper are given in Table 5.

Table 5. Product element compositions for Ni, Co, and Li per individual product unit.

CATEGORY	SUB-CATEGORY	CO (KG)	LI (KG)	NI (KG)
Battery	LionNiCoMn_60kwh_BoltType_2016	24.00	10.00	25.71
Battery	NMC811_60Kwh	5.43	7.55	46.56
Battery	LFP_30Kwh	0.00	3.06	0.00
EV_ExBat	EV_ExBat_BoltType_2016	0.03	0.00	17.85
EV_ExBat	EV_ExBat_BoltType_EqualAlFe	0.03	0.00	17.85
EV_ExBat	EV_ExBat_BoltType_AlReplacesFe	0.03	0.00	17.85
ICEV	ICEV_Golf_UBS_2016	0.03	0.00	21.21
ICEV	ICEV_US_LtDuty_2014	0.00	0.00	30.68
ICEV	ICEV_Equal_AlFe	0.03	0.00	26.46

B.10. Regional resolution

Regional resolution used as input to the PSFF was driven by the regions used in the GTEM-C SSP scenario work (Cai et al. 2015) to drive one overarching total automobile demand scenario (under SSP2).

Table 6. The 28 countries/regions used for all PSFF scenarios, derived from GTEM-C SSP scenarios used in creating overall automobile demand.

Australia	New Zealand	Northern South America	Western Europe (ex-G7)
China	South Asia	Southern South America	East Europe and West Asia
East Asia and Oceania	Canada	Central Europe	Russia
India	Mexico	France	Central Africa
Indonesia	United States	Germany	North and West Africa
Japan	Brazil	Italy	Other Africa
Korea	Central America	United Kingdom	South Africa

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