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Battery as a service: Analysing multiple reuse and recycling loops

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ABSTRACT

This study investigates the effects on new product demand and raw materials from the growth of a company's product-service system (PSS), using dynamic material flow analysis. The PSS involves multiple reuse and recycling of lithium-ion battery subpacks for mining equipment. While effects differ over time, 13% of new subpacks and 13–59% of primary material demand is reduced within the PSS until 2050. Supply of subpacks for reuse surpasses demand, limiting displacement of new subpacks. Reuse increases battery self-sufficiency and has limited effects on primary material demand when recycling is efficient, but more so when recycling is less efficient. Thus, if efficient recycling is unachievable, reuse becomes more important for raw material self-sufficiency in the PSS. Reusing batteries could lead to European recycled content targets not being reached in time. Thus, such targets are challenging to balance with policy goals for reuse and pose risks for companies relying on extensive reuse.

1. Introduction

The circular economy (CE) is increasingly suggested as a solution to current unsustainable production and consumption practices (Ghisellini et al., 2016; Reike et al., 2018) by extending resource life through strategies like reuse, recycling, and improved product durability – underpinned by public policy, product design, and circular business models (CBMs) (Blomsma and Brennan, 2017; Bocken et al., 2016). Incentives for companies to implement CBMs include minimising supply risks, reducing environmental impacts, and decreasing production and material costs (Urbinati et al., 2017). A product-service system (PSS) is a common type of CBM that involves the provision of services, as opposed to traditional sales of goods (Kjaer et al., 2019; Tukker, 2015). This could facilitate circulation of products and materials since product ownership can be maintained throughout the product's lifetime, which in turn could improve the predictability and reliability of the return flows (Linder and Williander, 2017) and is argued to minimise material flows in the economy (Tukker, 2015). However, while a PSS could reduce environmental impacts and material flows, the degree to which this might occur cannot be taken for granted (Blüher et al., 2020; van Loon et al., 2021).

Assessments of CBMs often focus on environmental impacts, which are investigated using life cycle assessment (LCA) (Blüher et al., 2020; Kaddoura et al., 2019; Lindahl et al., 2014; van Loon et al., 2021). For assessments of product and material flows in CE implementation efforts, material flow analysis (MFA) can be applied (Corona et al., 2019) and is already used by companies to evaluate their CBMs (Das et al., 2022; Roos Lindgreen et al., 2022). For instance, Roos Lindgreen et al. (2022) found that one in four frontrunner companies engaged in CE practices use MFA to assess their operations. However, studies evaluating CBMs often assume a static system (Das et al., 2022; van Loon et al., 2021), disregarding that CBMs involve circulating flows of products and materials over time (Bocken et al., 2016). This lack of methods that consider temporal aspects has been suggested to be a barrier for companies to forecast the potential impacts of their business models (Das et al., 2022). Dynamic MFA, in which material stocks and flows are modelled explicitly over time (Baccini and Bader, 1996), has so far mainly been used for assessing the implementation of circular strategies at the macro level (Fu et al., 2021), but could also be used for evaluating and planning CBMs at the company level.

Accordingly, this study analyses the implementation of a CBM for reuse and recycling using dynamic MFA. The object of study is a PSS offered by an underground hard-rock mining-equipment manufacturer in which lithium-ion batteries are provided as a service. Through the PSS, the company enables multiple battery reuse loops across several machine types and closed-loop recycling at end-of-life. Widespread and rapid adoption of batteries to replace internal combustion engines (ICE) is viewed as a central component for decreasing global greenhouse gas emissions. However, it could result in resource challenges and supply risks related to upscaling material extraction and battery production

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capacities (Deetman et al., 2018). Dynamic MFA has been applied to quantify future demand for raw materials for transitioning the vehicle fleet to traction batteries, also examining, the effect of battery development, recycling, or reuse in stationary energy storage applications (Baars et al., 2021; Dunn et al., 2021; Kamran et al., 2021; Xu et al., 2020; Zeng et al., 2022). Here, these studies are complemented by addressing an existing business model for batteries and identifying its specific enablers and barriers. This could provide insights valuable for both companies and policy makers. There is business interest in CBMs for reuse and recycling of lithium-ion batteries, and those organised as a PSS, but research into their effects on environmental sustainability has been pointed out as insufficient (Wrålsen et al., 2021). Policy related to this case is under formulation in the European Union (EU). For instance, the proposal for a new Battery Regulation suggests targets for recycling efficiency for lithium-ion batteries and recycled content[1] for lithium, cobalt, nickel and lead (European Parliament, 2022). The regulation, which is part of the wider EU Circular Economy Action Plan (European Commission, 2020a), also points to circular strategies to facilitate e.g. reuse and remanufacturing.

In sum, the main purpose of this study is to investigate the potential effects on raw material and product flows over time from implementing a PSS based on multiple reuse and recycling. It addresses the lack of studies assessing the dynamics of PSSs and is, to our knowledge, the first study to use dynamic MFA to analyse a company offering. It could thereby highlight potentials and limitations of the PSS over a longer time horizon, and serves as an illustration of how this method can be applied at the level of a company. Further, it addresses the need for studies examining how existing business cases of circular strategies can extend resource life (Blomsma and Brennan, 2017; Geissdoerfer et al., 2017). In addition, the future increasing raw material demand for lithium-ion batteries, and means of mitigation is an urgent issue for business and policy. Since PSSs are regarded as a means for minimisation of material flows as well as a viable business opportunity, an analysis of a specific battery-as-a-service system is of interest.

2. Method

2.1. Case description

The transition to underground hard-rock mining-machines with traction batteries is driven by a requirement to decarbonise operations, cost-savings related to decreased ventilation requirements when using batteries, and improving working conditions for machine operators. The studied case reflects such a transition by a company providing batteries as a service. The description of and data for the investigated business model has been produced in collaboration with the company. It includes three machine types: 1) trucks; 2) loaders, both of which are available in different size classes; and 3) five types of drilling rigs. The market demand for the machines is determined by the run-of-mine[2] extraction in underground hard rock mines.

The batteries[3] consist of standardised 93-kilowatt-hour subpack units, which can be combined into battery packs consisting of up to seven subpacks that are sold as-a-service to the customer. Thus, it is possible to accommodate the machine requirements independent of machine type or size class, using the subpacks as building blocks. Due to differing user needs, intensity of use, and length of operation during one charge, the subpacks are taken out of use at varying levels of degradation depending on the machine they are used in. The batteries in trucks and loaders are used until approximately 80% state of health capacity (SOH) and in rigs until around 60% SOH. As a result, the subpacks in trucks and loaders can be reused in rigs. Furthermore, 20% of truck subpacks are expected to be reusable in loaders. Additionally, truck and loader subpacks could be further reused in battery energy storage systems (BESS), but is not yet part of the PSS (Fig. 1 and supplementary information (SI), S3 and S4). By maintaining ownership of the batteries throughout the lifecycle and monitoring battery health, regarded as vital for validating the technical viability of reused batteries (Martinez-Laserna et al., 2018), the company can manage both reuse and collection for recycling at end-of-life. While the company manufactures the machines, both production and recycling of the batteries is organised through a close partnership with another company.

The study focuses on how the PSS could affect demand for new products and primary materials until 2050 in three scenarios. The presented results are not predictions but rather explorations of possible outcomes, which can highlight opportunities and limitations of the PSS and guide decision-making at company or policy level. For confidentiality, the quantity of batteries and materials in the PSS are scaled up to the total global market. Since the sector is highly concentrated and dominated by a couple of actors operating globally (GlobeNewswire, 2022), the difference is only one of total market size, which does not impact the conclusions regarding how the demand for products and raw materials are influenced by the circular strategies.

2.2. Model framework

A dynamic MFA model based on the modelling framework by Müller (2006) has been developed to account for multiple product reuse loops and closed-loop recycling. The model derives the machine stock (S_M) required on a yearly basis from the mass of run-of-mine ore (*ROM*); mining method used (*MM*); machine requirements per tonne ore extracted (*MpE*), which differs by mining method; and the machine size-class split (*C*). A brief explanation of the model is outlined below, for further details see S6 in SI.

The machine stock at year *t*, by type *j*, and of size class *s*, $S_{M(t,j,s)}$, is determined through:

$$S_{M(t,j,s)} = ROM_{(t)} \cdot MM_{(t)} \cdot MpE_{(j)} \cdot C_{(s)} \quad (1)$$

The subpack stock (S_{SP}) is then calculated using an intensity factor describing the number of subpacks required per battery pack (IF_{SP}), the number of battery packs required per machine (BpM), the extra subpacks required in case of unexpected damage or failure (X_{SP}), and a battery diffusion function (D_{SP}) (Fig. 2).

$$S_{SP(t,j,s)} = S_{M(t,j,s)} \cdot IF_{SP(j,s)} \cdot BpM_{(j)} \cdot (1 + X_{SP}) \cdot D_{SP(t,j,s)} \quad (2)$$

where $D_{SP(t,j,s)}$ is a logistic function describing how the machine stock could transition to traction batteries, which have been found suitable for modelling product diffusions (Lartey, 2020) (see S2.2 in SI).

The inflow ($I_{(t,j,r)}$) and outflow ($O_{(t,j,r)}$) of subpacks are calculated using the stock and a survival function ($sf_{((t-t'),j,r)}$) describing the share of subpacks of a certain type *j* and use phase *r*, operational at time *t* (see SI, S6):

$$I_{(t,j,r)} = S_{SP(t,j,r)} - S_{SP(t-1,j,r)} + O_{(t,j,r)} \quad (3)$$

$$O_{(t,j,r)} = \sum_{t'=t0}^{t'=t-1} I_{(t',j,r)} \cdot \left(1 - sf_{((t-t'),j,r)}\right) \quad (4)$$

Trucks only use new subpacks, so inflows and outflows are calculated using Eqs. (3) and 4. For loaders and rigs, the model prioritises available reuse subpacks as inflows and then adds new subpacks to reach the required stock. Outflows from trucks are first sent to loaders, in which a

[1] A methodology for calculating the recycled content of battery materials is yet to be defined in the proposal for the new EU Battery Regulation (European Commission, 2020b).

[2] Run-of-mine ore is the mass of ore processed and treated including both valuable minerals and worthless rock (Hamrin, 1980).

[3] Batteries and battery packs are used interchangeably throughout this paper and refers to lithium-ion batteries, while subpacks refer to the standardised units that make up the battery packs.

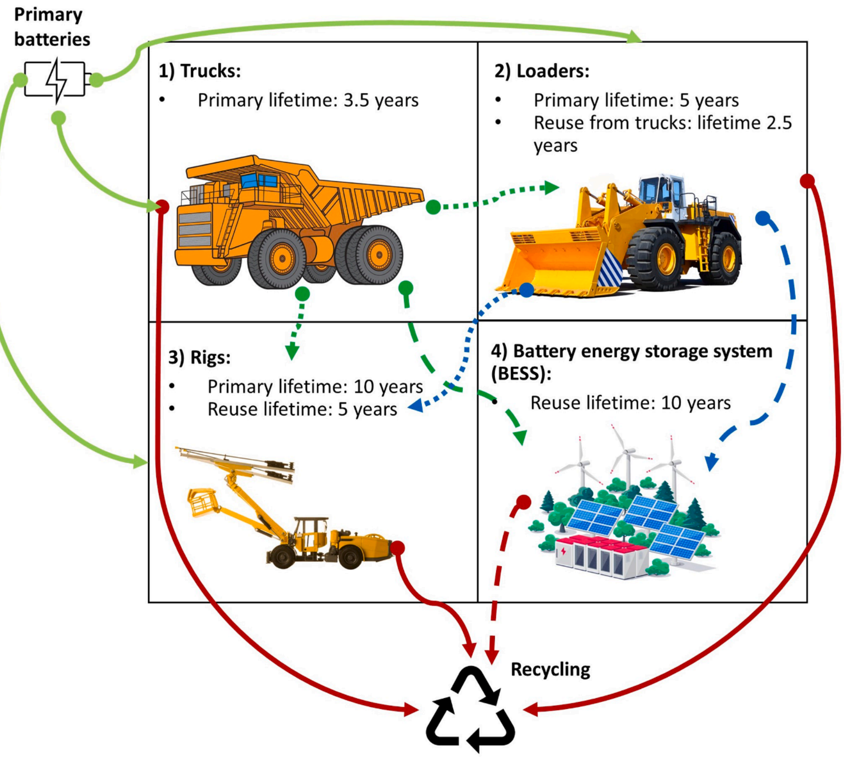

Fig. 1. Schematic of the possible battery subpack flows in the business-as-usual (BAU), reuse (Reuse), and reuse including battery energy storage systems (Reuse-BESS) scenarios. Solid lines are flows in BAU, dotted lines are the additional possible flows in reuse, and dashed lines are the additional possible flows in Reuse-BESS. See 2.3 and S3 and S4 in SI.

maximum of 20% can be entered as reused inflows. Any remaining outflows from trucks are sent to rigs. If the available outflows from trucks and loaders are larger than the required inflows to rigs, the reuse inflows will be split evenly from the two sources and the remainder either sent to BESS or recycling, depending on the scenario. The BESS inflows, outflows, and stocks are derived in a similar manner, but only if there are no possible reuse inflows to the machines.

Finally, the recycled content of a raw material used in production ($RC_{(t,m)}$) is calculated from the non-reused outflows ($O_{EOL(t,j,r)}$), the new inflows ($I_{new(t,j)}$), and a recycling efficiency specific to a certain material ($RE_{(m)}$), which includes both collection and recycling process losses:

$$RC_{(t,m)} = \frac{\sum_j \sum_r O_{EOL(t,j,r)} \cdot RE_{(m)}}{\sum_j I_{new(t,j)}} \tag{5}$$

The recycled content indicates the extent to which the business model is self-sufficient on raw materials and is an important target in the proposal for the EU Battery Regulation.

Note that the battery stock is derived from the machine stock, but only the battery inflows and outflows are calculated—and not the inflows and outflows of machines. Through the PSS, both new and reused batteries can be used independently of the age of the machine. The batteries are thus modelled as separate products from the machines they are contained in.

2.3. Data, assumptions, and scenarios

To retrieve a time series of *ROM* in underground hard-rock mines, a dataset covering approximately 80% of global mines in 2014 was used, differentiated by mining method (see S1.1 in SI) (Mining Intelligence Systems, 2015). A linear extrapolation increase of 150% by 2050, relative to 2014, was assumed, based on literature on future demand projections (Figs. 3a, and S1.2 in SI). Data for *MpE* was taken from a survey carried out by the company (S2.1 in SI), and IF_{SP}, *BpM*, *C*, and X_{SP}, are based on company estimates (Table 1). Trucks and loaders require nearly two battery packs per machine to enable fast swapping when the batteries are discharged, but since five machines can share four extra battery packs, an average of 1.8 packs per machine is assumed.

Three battery-flow scenarios are studied:

1) Business as usual (BAU) where no subpacks are reused but instead directly sent to recycling at end-of-life.
2) Battery reuse (Reuse) where the subpacks are reused between the machines as explained in Section 2.2.
3) Battery reuse with additional stationary storage (Reuse-BESS) where excess truck and loader subpacks can be used additionally as BESS.

The effects on the primary raw material demand for three active cathode materials: lithium, cobalt, and nickel, are explored assuming three levels of overall recycling-chain efficiencies: High, Mid, and No recycling (Tables 2 and S5 in SI). High recycling represents high collection rates combined with high recycling process efficiencies from hydrometallurgical recycling (Costa et al., 2021). Mid recycling assumes an overall halving of that efficiency and No recycling illustrates a situation without recycling within the PSS, e.g. to reflect how the system would be affected by traditional sales in which a share of, or all, the batteries can be assumed to not reach recycling. The build-up of large-scale battery recycling infrastructure is ongoing and could enable high recycling process efficiencies in the future, but since recycling is currently low or non-existent for some cathode materials it is unclear whether, and to what extent, these efficiencies will materialise in the medium-term future (Neumann et al., 2022). As such, the three efficiency levels can also represent recycling of other battery pack materials besides the active cathode materials.

100% of the machines in use are assumed to have traction batteries by 2050. Only a share of the machines are currently available with batteries, while the rest is assumed to be so by 2025 (Table 1). As a

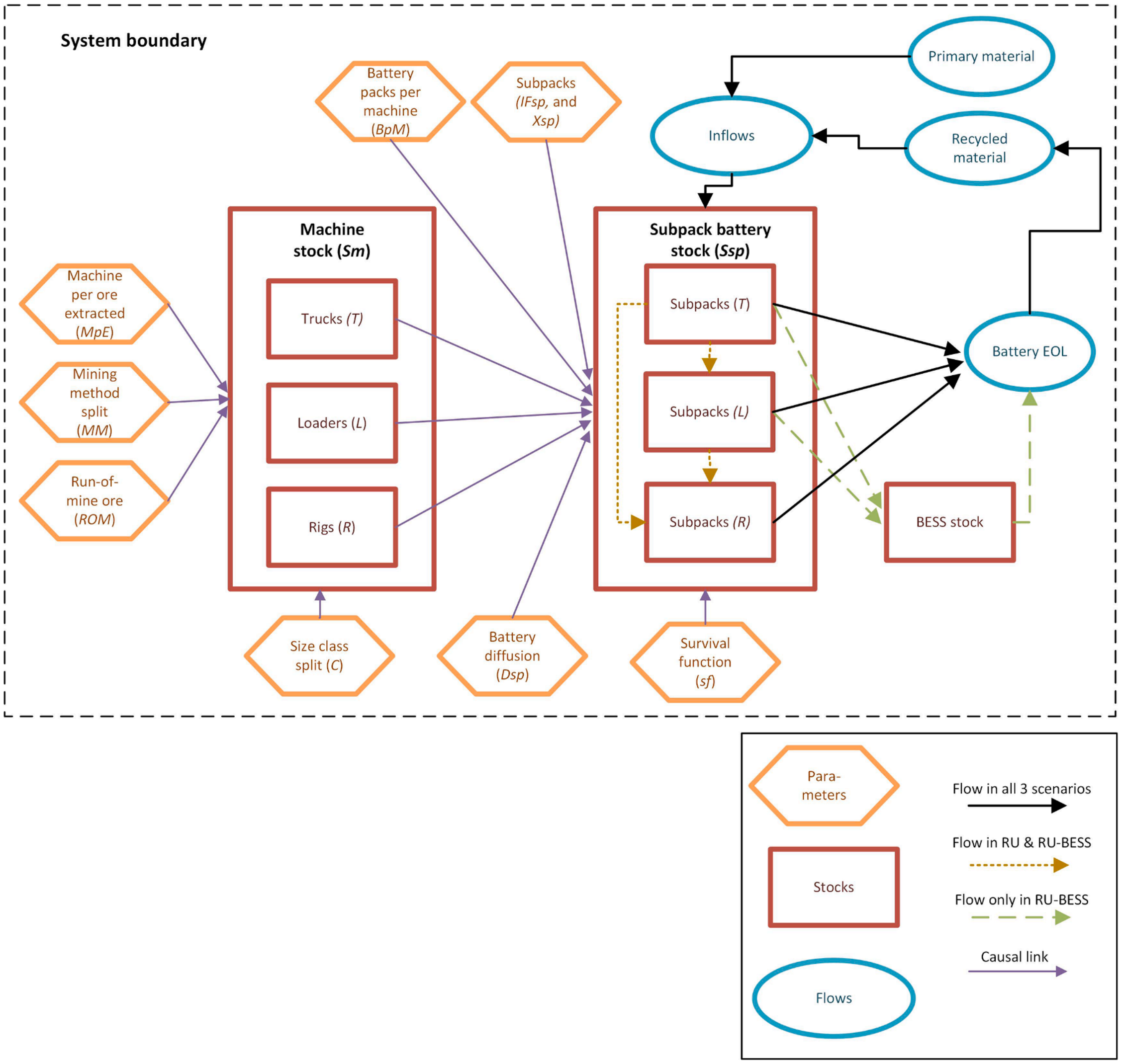

Fig. 2. Conceptual representation of the model showing the parameters, causal links, stocks, and flows.

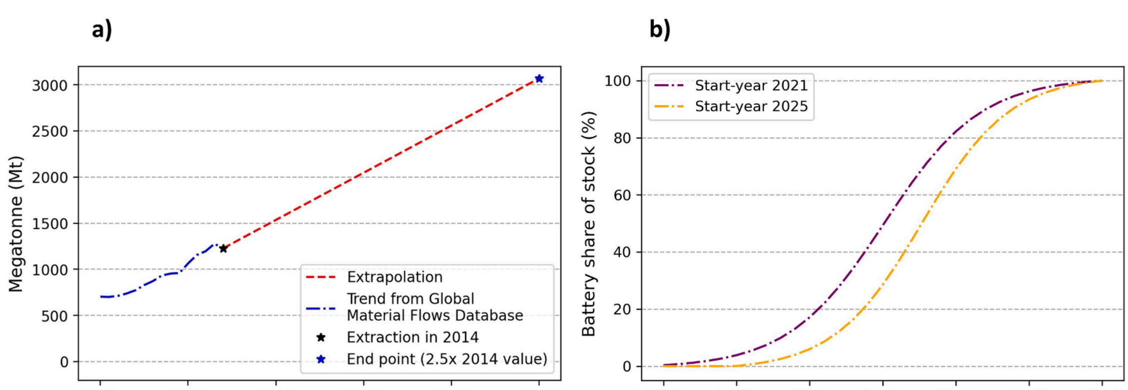

Fig. 3. a) The assumed global run-of-mine ore from 2020 to 2050 (derived from a 2014 underground hard rock mining dataset (Mining Intelligence Systems, 2015) and linear extrapolation until 2050). To contextualise the assumed growth, also shown is the global metal extraction trend for 2000–2014 (taken from the Global Material Flows Database of the United Nations Environment Programme normalised to the 2014 underground hard rock mining data). Only the years to the right of the vertical dotted line are part of the analysis. See S1.2 in SI for details; 3b) the share of the stock with start-year 2021 and 2025 consisting of battery driven machinery over time.

Table 1
Data used in the model covering the machine types, size classes, size class splits, subpacks per battery packs, battery packs per machine, extra backup subpacks, and year of introduction.

Machine	Size class/rig type	Split (C)	Subpacks per battery pack (IF_{SP})	Battery packs per machine (BpM)	Backup subpacks (X_{SP})	Year of introduction
Trucks	Large	40%	7	1.8	0.2	2025
	Mid-large	30%	5	1.8	0.2	2021
	Medium	20%	4	1.8	0.2	2025
	Small	10%	3	1.8	0.2	2025
Loaders	Large	35%	7	1.8	0.2	2025
	Mid-large	35%	4	1.8	0.2	2021
	Medium	20%	3	1.8	0.2	2025
	Small	10%	2	1.8	0.2	2025
Rigs	Face drill		2	1	0.2	2021
	Rock bolt		2	1	0.2	2021
	Production drill		2	1	0.2	2021
	Cable bolt		2	1	0.2	2021
	Raisebore		2	1	0.2	2021

Table 2
Material intensity data per kilowatt-hour (kWh) and recycling efficiencies for the active cathode materials in the batteries which are of the type: lithium-nickel-manganese-cobalt-oxide 622 (NMC-622). Material intensities are averages from Azevedo et al. (2018); Baars et al. (2021); Hoarau & Lorang (2022); Olivetti et al. (2017); Xu et al. (2020); Zeng et al. (2022), and recycling process efficiencies based on Costa et al. (2021); Melin (2019); Mossali et al. (2020), where the overall Mid-efficiency is 50% of high-recycling.

Model input	Lithium	Cobalt	Nickel
Material intensity, kg/kWh (NMC-622)	0.122	0.197	0.559
Recycling-chain efficiency, incl. collection (High)	0.90	0.95	0.95
Recycling-chain efficiency, incl. collection (Mid)	0.45	0.475	0.475
Recycling-chain efficiency, incl. collection (No recycling)	0	0	0

result, two diffusion curves with start-years 2021 and 2025 have been defined, both of which are assumed to reach 100% by 2050 (Figs. 3b and S2.2). This battery diffusion is assumed to correspond to a battery growth where no machines with ICE are decommissioned early to allow for inflows of machines with traction batteries. Consequently, the growth of traction battery machines is primarily due to the shift to batteries, and not due to the growth of the underground mining market itself.

Battery ageing is uncertain and degradation patterns difficult to predict (Braco et al., 2020). As a result, the actual lifetimes and SOH at end-of-use will likely depend on local conditions and future capabilities of battery remanufacturing to restore capacity. It is assumed that 20% of truck subpacks are taken out of use before reaching 80% SOH and can be reused in loaders. A sensitivity analysis is also carried out to investigate the effects of changing the share of truck-to-loader reuse (0% and 100%), and thereby changing the possible reuse potential.

3. Results

All scenarios rely on the same growth of battery machines in use and subpacks contained within them, but the market grows further in Reuse-BESS compared to BAU and Reuse, due to the additional BESS use phase (Fig. 4a-b). Initially, growth is slow with no availability of reuse batteries, and there is a time delay until reuse subpacks become increasingly available to displace new batteries (Fig. 4c-d). The PSS does not initially affect primary material demand since the availability of secondary materials remains low until halfway through the period, decreasing with increasing levels of reuse (Fig. 4e-f).

3.1. New battery demand

The reuse scenarios (Reuse and Reuse-BESS) lead to a gradually increasing annual displacement of new subpacks, relative to BAU, which saturates in 2036 when the supply of subpacks for reuse exceeds demand. Over the period, 13% of new subpacks are displaced in the reuse scenarios. The share of subpacks that can be displaced is limited by the possible reuse loops and relative battery demand for the different machine types. The subpack demand depends on machine demand and number of subpacks required per machine in the various size classes and machine types. Rigs are the most numerous segments but require fewer subpacks than trucks and loaders since rigs both need fewer subpacks per battery pack and fewer battery packs per machine (Table 1). Approximately 70% of the market for loaders and trucks, including the largest size classes that require the highest number of subpacks, are not introduced until 2025 (see Section 2.3). As a result, the supply of reuse subpacks does not become significant until around 2035. At this point, opportunities to expand the PSS could become significant, as illustrated in Reuse-BESS (Fig. 4b). This potential for expansion occurs when large numbers of subpacks become available from trucks and loaders and once the annual supply of reuse subpacks to rigs have surpassed demand.

Although the *relative* displacement of new subpacks saturates, the *absolute* number displaced through reuse keeps increasing, since the market continues to grow. By 2050, the annual demand for new subpacks is around 8000 units lower in Reuse and Reuse-BESS, compared to BAU (Fig. 4d). With increased truck-to-loader reuse, the displacement of new subpacks saturates later and at a lower level since the demand for reuse subpacks increases, and vice versa. If all truck subpacks can be reused in loaders, the annual displaced new subpack demand is 31% by 2050 (Fig. 4c), corresponding to 20,000 fewer than in BAU (Fig. 4d). With no truck-to-loader reuse this number is 8% by 2050.

Higher annual subpack inflows (new and reused) are needed to meet demand in the two reuse scenarios since reuse subpacks have shorter lifetimes. Consequently, the annual replacements are 10% higher with reuse than in BAU by 2050 (Fig. 4c). With a higher share of truck-to-loader reuse the annual replacements increase further since a larger share of the machines then uses subpacks with shorter lifetimes. This increase in replacements is mainly due to the rigs, in which reuse subpacks eventually completely displace primary subpacks in Reuse and Reuse-BESS (Fig. 4a), decreasing their average lifetime from 10 to 5 years.

3.2. Raw material demand

In Reuse, the availability of secondary raw materials and, thus, the recycled content starts to increase halfway through the period when the annual supply of reuse subpacks exceeds demand and the surplus is recycled (Fig. 4e). In Reuse and BAU, the primary material demand peaks in the late 2030s when subpack inflows start to slow down and significant amounts of secondary material becomes available. In Reuse-BESS, the market expands and materials are kept longer in use, leading to a larger primary demand peaking at a later point since the availability of secondary materials is delayed further (Fig. 4f). For cobalt, the

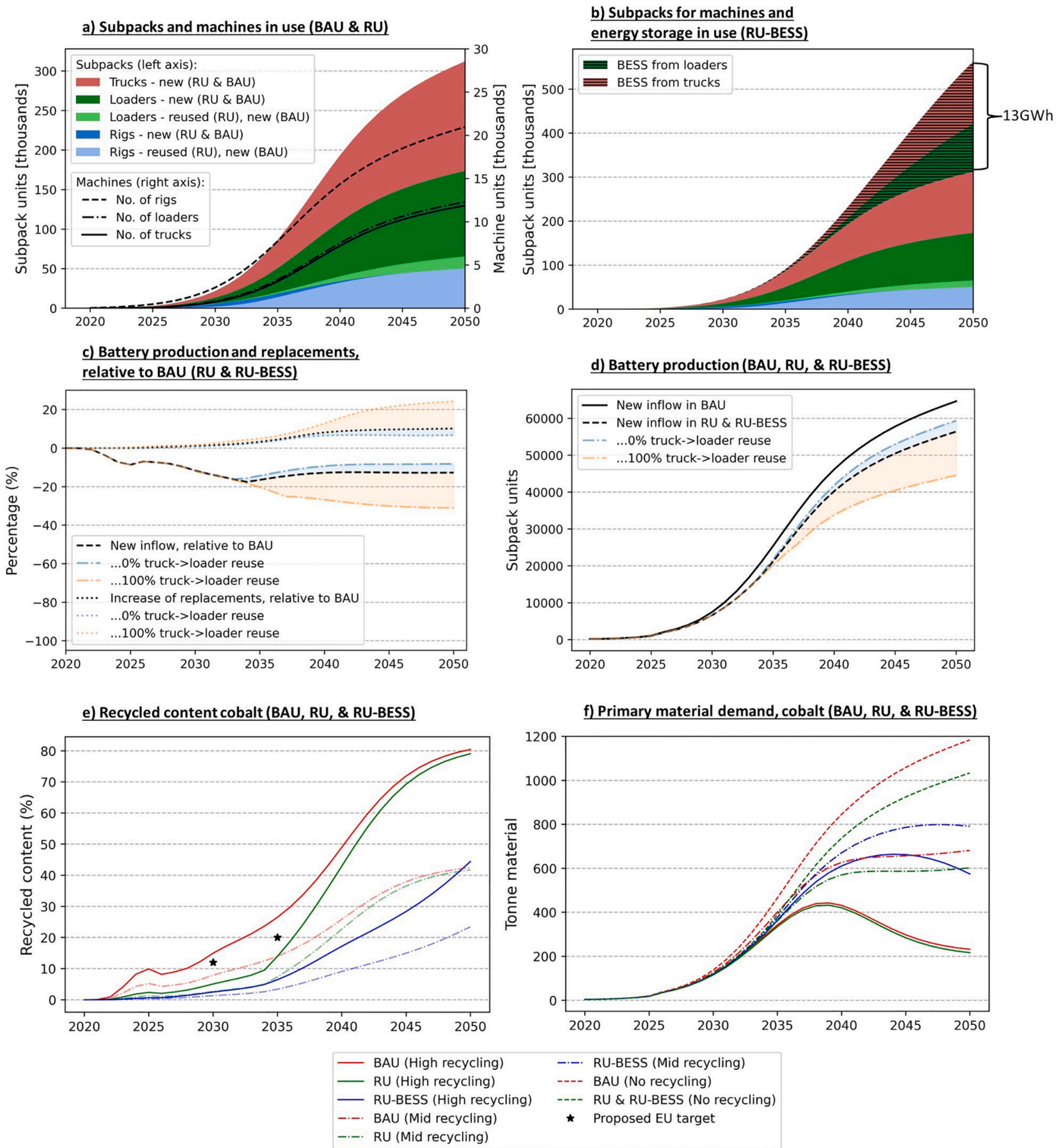

Fig. 4. a) Subpacks in use in machines in BAU and Reuse (RU) scenarios (left axis) and battery machines in use, same in all scenarios (right axis), 4b) Subpacks in use in the Reuse-BESS (RU-BESS) scenario with stationary energy storage capacity in 2050 indicated (NB differences in scale), 4c) Annual subpack production and replacements in RU and RU-BESS, relative to BAU, including sensitivity analyses of share of truck-to-loader reuse. Orange area represents increasing share of truck subpacks available for reuse in loaders and blue area a decreasing share, compared to base assumption of 20% (see Section 2.3), 4d) Subpack production in absolute terms in scenarios, including sensitivity analyses of share of truck-to-loader reuse, 4e) Recycled content of cobalt in scenarios, including assuming high and mid recycling in the three scenarios (see SI for additional materials), and 4f) primary material demand of cobalt with no, mid, and high recycling in the three scenarios (see SI for additional materials).

proposed recycled content targets for 2030 and 2035 in the EU Battery Regulation are missed by 5 and 2 years in Reuse, and 8 and 7 years in Reuse-BESS, respectively. The targets are also missed for lithium and nickel in Reuse-BESS (SI, S7.5). This illustrates the conflict between maximising availability of secondary materials and extending product lifetimes.

Compared to BAU without recycling, the cumulative primary raw material reduction from reuse and recycling over the period is 13–59%, using cobalt as an example (see SI, S7.4 for lithium and nickel). Ensuring high recycling-chain efficiencies has a significantly larger potential to reduce primary material demand than what is achieved from reusing subpacks. For instance, Reuse without recycling leads to a 13% cumulative reduction, while BAU with High recycling leads to a 58% reduction, both compared to BAU with No recycling (green dashed line and red solid line, compared to red dashed line, Fig. 4f).

Furthermore, the effect from reuse on primary material demand depends on the recycling efficiency. Reuse has a smaller impact on primary material demand with a high recycling-chain efficiency than when recycling is lower or non-existent. This is because reusing subpacks leads to a decrease in new subpack demand, but also to a lower number of subpacks reaching end-of-life, compared to BAU. When recycling is efficient, this decrease in end-of-life subpacks causes a large reduction of available secondary materials. With lower recycling-chain efficiencies, the end-of-life subpack reduction results in a lower reduction of available secondary materials. Again, using cobalt as an example, with High recycling, the cumulative primary material savings in Reuse is 210 tonnes, corresponding to 3% of the cumulative primary demand in BAU (difference between solid red and green lines, Fig. 4f). With Mid recycling, the cumulative primary reduction in Reuse is instead 1116 tonnes, corresponding to around 10% of the cumulative primary demand in BAU (difference between dash-dotted red and green lines, Fig. 4f).

These results build on a closed loop in a growing market with no additional inputs of secondary materials external to the PSS. Such closed loops may become increasingly important for companies to enable self-sufficiency of raw materials due to the expected increased competition over battery metals in coming decades (Deetman et al., 2018).

4. Discussion

4.1. Effects of reuse and recycling on demand for new products and raw materials

Some of the observations regarding the specific PSS are similar to those reported in previous battery studies using dynamic MFA. For instance, recycling can in the near future only lead to small primary material reductions since end-of-life flows are limited in the early phase of the transition (Zeng et al., 2022). Availability of secondary material is delayed by additional battery reuse in stationary applications (Baars et al., 2021; Dunn et al., 2021; Xu et al., 2020). The potential for battery reuse in BESS applications could eventually become significant relative to the batteries used in the vehicle fleet (Baars et al., 2021; Xu et al., 2023), similar to the PSS despite including multiple reuse loops.

The multiple reuse loops in the PSS are facilitated by the product design: the standardised subpacks fit all machine types and can be combined to meet the machines' different battery performance requirements. Despite the facilitating design, the cumulative demand reduction for new subpacks is moderate (around 13% lower over the whole period in the reuse scenarios, compared to BAU), since fewer subpacks are required in reusing machines. Analysing both supply and demand for reuse batteries is thus important to estimate the reuse potential, see also e.g. Xu et al. (2023) and Kamran et al. (2021). Multiple reuse is recognised as an important strategy for extending resource use in a circular economy (Campbell-Johnston et al., 2020) and modular designs, standardisation across product types, and quality monitoring are regarded as essential for the outcome of reuse (Bocken et al., 2016; Cooper and Gutowski, 2015). Such requirements are consciously managed by the case company, but large reuse potentials are nevertheless challenging to accomplish.

Demand for reuse outside the current PSS is more difficult to control for the company. The PSS could be extended through BESS-services to be used on mining sites or by selling batteries through a traditional sales model. If the batteries are sold, the take-back and recovery of secondary materials for battery production would be affected. By 2050, the installed storage capacity in Reuse-BESS is 13 GWh, corresponding to approximately 75% of the subpacks in use in the machines at that time. This storage capacity is small compared to the estimated 3.4–19.2 TWh of short-term grid storage demand globally by 2050, which could be supplied from retired EV-batteries with a potential capacity of 14.8–31.5 TWh (Xu et al., 2023). Due to the potential risk of oversupply of retired EV batteries, it might be more fruitful for the company to expand the offering by providing energy storage to existing customers or reusing them in short-range applications like utility vehicles or forklifts on mining sites.

Maintaining a high degree of self-sufficiency of raw materials in the PSS will depend significantly on achieving high recycling-chain efficiencies. Cathode materials like lithium and manganese are not yet functionally recycled and recycling of anode and electrolyte materials like graphite and lithium salt are at lab scale (Mossali et al., 2020). The high efficiencies in the analysis represents those achievable in new battery recycling processes currently being built up (Neumann et al., 2022) and the company's battery recycling partner may shortly reach such efficiencies. However, even at these high efficiencies, the proposed recycled content targets in the EU Battery Regulation are not reached in time when reusing batteries. This conflict between additional use and increased durability on the one hand and targets for availability of secondary battery materials on the other has been pointed out (Albertsen et al., 2021) but to our knowledge not quantified. The implications of non-compliance have not yet been determined, nor has the methodology for calculating the recycled content, and the targets will be revised by the end of 2027 in view of the availability of secondary materials at that time (European Parliament, 2021). While the company itself would not be liable for non-compliance, it is still relevant to consider since the business model is made possible through the close partnership with the battery producer, for whom the targets apply. The incentives of the battery producer might then be at odds with the lifetime extensions of the reuse business model since the producer might prioritise getting access to sufficient amounts of secondary material, which could be a risk for the company. Regardless of the exact levels of such recycled content targets, they present risks for business models relying on extensive reuse or extended product lifetimes, either by undermining the potential for reuse and extended lifetime or by creating competition for secondary materials between actors.

One could expect a decline period to eventually occur due to lower market demand, which could lead to an even more pronounced oversupply of reused products (Östlin et al., 2009). Battery technology is rapidly developing (Armand et al., 2020) and the company might want to shift to better performing new battery chemistries which could make older reuse batteries obsolete. New technologies like solid state batteries or fuel cells may appear (IEA, 2020). This could undermine the reuse potential over time, but also the recycling potential if the recycling infrastructure is not sufficiently flexible to accommodate resulting changes to the material composition (Harper et al., 2019).

The study does not investigate the company's drivers for introducing a PSS, but generally PSSs are viewed as means for minimising material flows (Blüher et al., 2020; Tukker, 2015). In the specific case, this could involve minimising flows of new products or primary raw materials. If the company prioritises increased self-sufficiency of batteries, reuse is beneficial since it unsurprisingly reduces new battery demand. If the company wants to increase self-sufficiency of raw materials, achieving efficient recycling increases in significance since this reduces primary material demand more than reuse. However, if recycling-chain efficiencies are low or if functional recycling of important raw materials is missing completely (Ljunggren Söderman and André, 2019), reuse becomes more important for reducing primary raw material demand. The preferred set-up of a PSS should thus be balanced on the flows that the company gains most from minimising.

4.2. Using dynamic MFA for analysing a PSS

Predicting return flows of products for reuse, materials for recycling and new use are important aspects for the success of implementing a PSS (Pagoropoulos et al., 2017). This study illustrates that such aspects can be captured with a dynamic MFA. Thus, it goes beyond a more limiting static assessment (Das et al., 2022; van Loon et al., 2021) and instead provides the means for exploring impacts and uncertainties that are challenging for the strategic planning of many CBMs (Linder and Williander, 2017).

This specific study involves the introduction and growth of a PSS. It explores, in scenarios that reflect various reusability and recycling-chain efficiencies, the quantities and timings of products becoming available for additional uses, and how demand for new products and raw materials is impacted. The ability to model the reuse flows across the specific machines over time, how this affects battery lifetimes and the rate of replacements under a growing market is central for understanding the potential of the PSS. In addition, the model forecasts the size and timing of available additional applications like BESS. Expanding the PSS can be an important business consideration for the company, but the results show that an expansion would increase raw material demand which could only be supplied within the PSS to a limited extent, even in a high-recycling context. The alternative of traditional sales, where the company loses control of the materials, would require even more raw materials supplied to the PSS (as represented by the 0% recycling-chain efficiency calculations). In particular as regards battery materials, the future value and competition can become significant due to bottlenecks in the primary material supply chain (Valero et al., 2018; Xu et al., 2020), why the company might prioritise access to secondary materials over expansion. Although currently limited on a large-scale (Hua et al., 2020), battery remanufacturing is another opportunity for the company which could lead to a higher share of truck-to-loader reuse (as in the sensitivity analysis). This study shows the differences in available secondary materials over time between these alternatives.

Digital technologies and big data have also been suggested to be critical enablers of CBMs, e.g. by tracking product and material flows and monitoring the balance between supply and demand over time (Kristoffersen et al., 2020). For instance, battery passports are proposed in the EU Battery Regulation. But as illustrated here, dynamic MFA could be used for exploring future strategic opportunities and rather as a complement to digital passports for batteries in use, which are more suited for monitoring and short-term planning.

A limiting factor of a dynamic MFA study is that it does not provide information on environmental impacts. The specific case shows that reuse has limited effects on reducing primary material demand in a high-recycling context. But at the same time reuse leads to reduced battery manufacturing, which is likely to decrease environmental impacts (Chordia et al., 2021). Additionally, through the shift from ICE to traction batteries in underground mining machines, diesel fuels can be avoided and underground ventilation reduced. If reuse requires additional transports, these may also be important to consider since reuse transports have been shown to outweigh the benefits of displacing new production, for other products (Böckin et al., 2020). The environmental consequences of such changes could be clarified in a complementary study using LCA.

5. Conclusions

This study investigates the effects on new product demand and raw materials from the introduction and growth of a company's PSS based on multiple reuse and recycling of battery subpacks, and is compared to business as usual with traditional sales and recycling at end-of-life outside the company's control. The effect on new subpack demand is initially low since there is a time delay until reuse subpacks become increasingly available to displace new ones. Until 2050, in total 13% of new subpacks are displaced. The annual displacement of new subpacks saturates when reuse supply exceeds demand. At this point subpacks can be recycled or reused outside the current PSS, e.g. through BESS-services to be used on mining sites or by selling batteries through traditional sales. Expanding the PSS can be an important business consideration but would increase raw material demand, which can only be supplied within the PSS to a limited extent.

Until 2050, the total primary material reduction is 13–59% from the PSS. While reuse increases self-sufficiency of batteries, ensuring high recycling-chain efficiencies has a larger potential to reduce primary material demand than what is achieved from reusing subpacks. The effect from reuse on primary material demand is lower in a high-recycling context, but reuse becomes more important if functional recycling is low or non-existent. Despite potentially high recycling-chain efficiencies, the proposed recycled content targets in the EU Battery Regulation are not reached in time for cobalt with reuse, and not for lithium and nickel if reuse is expanded outside the current PSS. This illustrates the conflict between maximising availability of secondary materials and extending product lifetimes, and challenges policymakers to balance targets for use of recycled materials and reuse. Targets on recycled materials use could present risks for companies relying on extensive reuse, either by undermining the potential for reuse or by creating competition for secondary materials between actors.

Analysing a PSS over time goes beyond a more limiting static assessment and shows that dynamic MFA could be used for exploring the size and timings of product return flows, the availability of secondary materials, and changes in primary material demand. The specific case shows that despite multiple reuse loops being facilitated by a standardised battery design and the PSS business model, the effect on new subpack demand is moderate. This points to the value of examining existing circular business cases to better understand the potentials and limitations of such solutions.

CRediT authorship contribution statement

Harald Helander: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Maria Ljunggren:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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