Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains

Michael L. Machala[a,c,#], Xi Chen[b,#], Samantha P. Bunke[b,#], Gregory Forbes[a], Akarys Yegizbay[d], Jacques de Chalendar[a], Inês L. Azevedo[a,c], Sally Benson[a,c], William A. Tarpeh[b,c,*]

[a]*Department of Energy Resources Engineering, Stanford University, Stanford, California, 94305, United States*

[b]*Department of Chemical Engineering, Stanford University, Stanford, California 94305, United States*

[c]*Precourt Institute for Energy, Stanford University, Stanford, California 94305, United States*

[d]*Department of Physics, Department of Economics, Kenyon College, Gambier, Ohio 43022, United States*

 # denotes equal co-first author contribution

* Corresponding author: email: wtarpeh@stanford.edu

Abstract

Recycling lithium-ion batteries (LIBs) can supplement existing supplies of critical materials and improve the environmental sustainability of LIB supply chains. In this work, environmental impacts (greenhouse gas emissions, water consumption, energy consumption) of industrial-scale production of battery-grade cathode materials from used LIBs are compared to the environmental impacts of conventional mining supply chains. Refining mixed-stream LIBs into battery-grade materials reduces these environmental impacts by at least 59%. Recycling batteries to mixed metal products instead of discrete salts further reduces environmental impacts. Electricity consumption is identified as the principal contributor to all LIB recycling environmental impacts, and different electricity sources can change greenhouse gas emissions up to eight times. Supply chain steps that precede refinement (material extraction and transport) contribute marginally to the environmental impacts of circular LIB supply chains (<5%), but are more significant in conventional supply chains (31%). This analysis disaggregates conventional and circular steps based on material extraction, transport, and industrial refinement operations; provides important insights for advancing sustainable LIB supply chains; and informs optimization of industrial-scale environmental impacts for emerging battery recycling efforts.

Keywords: circular economy, critical materials, hydrometallurgy, life cycle assessment, pyrometallurgy, reductive calcination

The rise of intermittent renewable energy generation and vehicle electrification has created exponential growth in lithium-ion battery (LIB) production beyond consumer electronics. By 2030, the electric vehicle (EV) sector is projected to dominate LIB growth, accounting for 82% of an estimated 2.4 TWh yr^{-1} of total global LIB production (**Fig. S1, Supplementary Information)**. However, the limited supply of critical materials (e.g., Li, Ni, Co, and Cu[1]) needed for prominent LIB chemistries has exacerbated environmental, economic, national security, and human rights concerns[2,3]. Critical LIB materials are projected to reach major global supply-demand balance deficits before 2030 (**Fig. S1**). Further, both mining of LIB materials and improper disposal of end-of-life LIBs can damage natural and human ecosystems, cause occupational hazards during handling, and result in monetary losses[4].

Recycling critical materials in end-of-life LIBs can help alleviate growing environmental concerns and is essential for the long-term sustainability of electrified transportation. While recycled materials may not contribute substantially to global LIB demand for decades, the establishment of domestic circular supply chains is iterative, requiring multiple learning curves as the dominant supply of end-of-life LIB chemistries and form factors evolve and as supply grows. Factors central to the success of recycling include the ease of collecting products, the cost of recycling processes, and the economic value of recovered materials. The average embodied economic values of representative LIBs between 2018–2021 are shown in **Fig. 1a** (complete references are listed in **Supplementary Information**). In LIBs, between 2018–2021, Li, Ni, and Co comprise the highest embodied economic value, and Al and Cu account for a significant weight percentage of EV battery packs (approximately 25%)[5]. Despite an embodied economic value that is 2–10 times higher compared to the lead in lead-acid batteries, LIBs are only recycled 2–47% globally[6], compared to 99% for lead-acid batteries in the U.S. Regardless, the untapped potential of LIB recycling constitutes a significant economic and environmental opportunity that requires evaluation across several application scales, from numerous small-scale consumer electronic LIBs (e.g., 10–100 Wh) to fewer large-scale transportation and stationary storage LIB packs (e.g., 10–100 kWh)[7]. In addition, the preferred chemistries by automakers have evolved to hedge potential critical mineral shortages and react to market shifts, such as the near tripling of lithium carbonate prices in early 2022. Existing LIB variation and supply chain complexity highlight the need for a methodical and comparative life cycle assessment (LCA) between circular (i.e., recycling used batteries) and conventional supply chains, which is also necessary for future recycling of the evolving portfolio of battery chemistries.

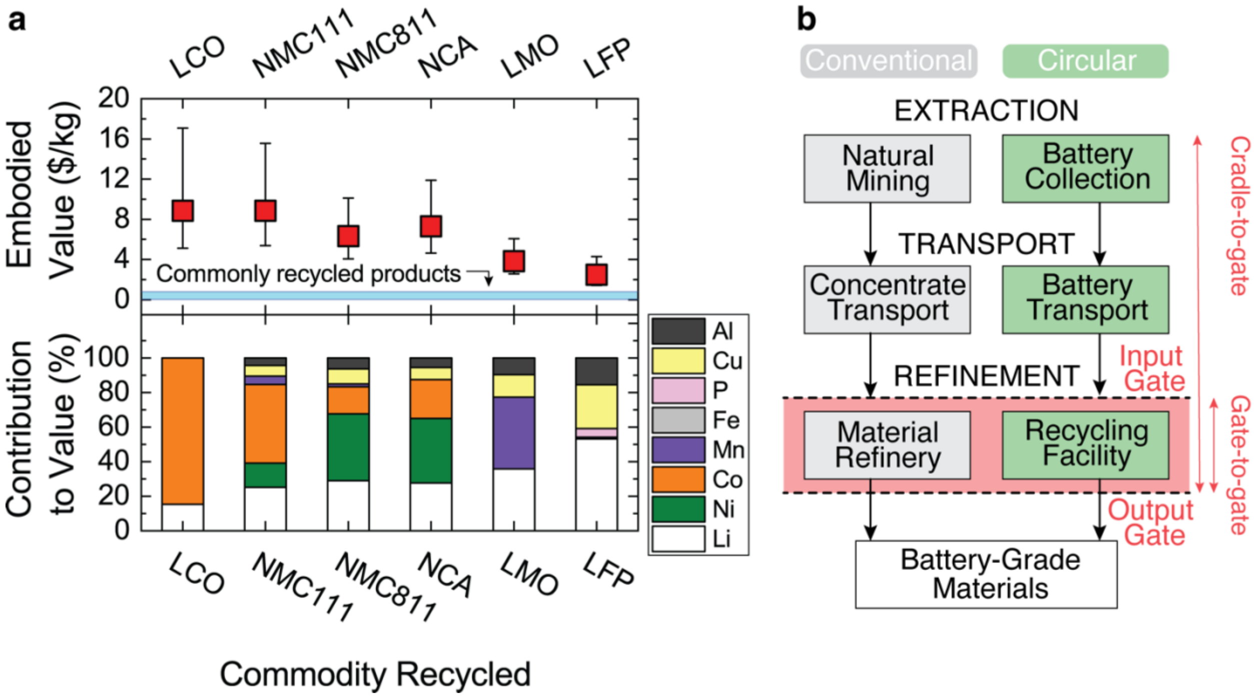

Fig. 1 | Economic drivers of lithium-ion battery (LIB) recycling and supply chain options for producing battery-grade materials. a, Commodity values of representative LIBs (upper panel) and relative contributions of embodied metal elements to the LIB values (lower panel). Representative LIBs are from consumer electronics using lithium cobalt oxide (LCO), and electric vehicle battery packs including lithium nickel manganese cobalt oxide (NMC111 and NMC811), lithium nickel cobalt aluminum oxide (NCA), lithium manganese oxide (LMO), and lithium iron phosphate (LFP). Data are based on market values adjusted for inflation between January 2018 and December 2021 (complete references are listed in **Fig. S1** in **Supplementary Information**), and the uncertainty denotes a 90% confidence interval, which may overlap with the data point in some instances, obscuring their view. The blue shaded area in the upper panel represents the average commodity values of commonly recycled products: glass, paper, plastic, and metal cans (more details are provided in **Fig. S1**). **b**, Cradle-to-gate steps of manufacturing battery-grade LIB materials (i.e., salts) from conventional and circular supply chains, both of which include three steps: extraction, transport, and refinement. Extraction and transport are considered upstream steps relative to gate-to-gate refinement, which is indicated by the red shaded area between “input” and “output” gates. Cradle-to-gate analysis considers the refinement and upstream processes together.

Despite significant progress, current understanding of the relative environmental impacts of recycling LIBs is still incomplete. The most significant environmental differences between LIB production from circular and conventionally mined cathode material lie early in supply chains, comprised of extraction, transport, and refinement steps (together "cradle-to-gate," **Fig. 1b**). While several previous studies have investigated cradle-to-gate environmental impacts, gate-to-gate analyses of circular refinement processes are inconsistent, reporting environmental impacts that differ by >30%[8-10], and are not completely based on industrial-scale LIB recycling operations. The gate-to-gate refinement processes utilized at established and emerging circular refinement facilities may include mechanical separation (Me), pyrometallurgy (Py), and hydrometallurgy (Hy)[8,9]. Specifically, Me physically dismantles LIBs into constituent components, Py leverages elevated temperature to facilitate thermally-driven material transformations, and Hy separates materials in the aqueous phase via leaching, precipitation, and solvent extraction processes. Variations in environmental impacts arise from the specific operational choices at refinement facilities that utilize different processing pathways and from the methods to evaluate them. There is a critical need for transparency and detailed insights into the environmental impacts (e.g., energy consumption, greenhouse gas emission, and water consumption) of LIB refinement pathways and all cradle-to-gate supply chain steps. Previous efforts have worked towards addressing this need[8,11], and this study builds on the comparative methodology of a recent step-by-step study to provide higher resolution and more actionable primary data, insights, and recommendations. Advancing decision-making capabilities to scale sustainable LIB supply chains requires life cycle assessment with more granular data at each step, inclusion of industrial-scale refinement operations with practical mixed-stream battery feedstocks, documentation of operational parameters, and qualification of results in terms of limitations and applicability to real-world scenarios.

In this study we quantify the cradle-to-gate environmental impacts of battery-grade cathode material salts manufactured in conventional and circular supply chains across three major steps: material extraction, transport, and refinement (**Fig. 1b**). First, we quantify and compare the refinement of mined concentrate from natural deposits into battery-grade materials in conventional supply chains with production of these materials by Redwood Materials (a recycling company in Nevada, U.S.). Two LIB feedstocks are explored: non-energized LIB production scrap from manufacturing facilities and energized end-of-life LIBs collected from consumers. Industrial-scale operational data provided by Redwood Materials are analyzed and compared to conventional LIB supply chain values based on Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET 2021) model[12]. Second, influences of the product formats in the refinement pathways on environmental impacts are examined. For both conventional and circular refinement, impacts of producing mixed Ni-Co compounds and discrete salts are analyzed. Third, we assess the environmental impacts of upstream processes before gate-to-gate refinement based on modeling. The upstream assessment includes the extraction of LIB material from conventional (i.e., mined ore) or circular (i.e., collected batteries) sources and the transport of extracted material to relevant refinement facilities for production of battery-grade cathode materials as Li, Co and Ni sulfate or carbonate salts. To the best of our knowledge, this study is the first life cycle assessment with primary industrial-scale circular refinement data that includes stepwise, cradle-to-gate comparison of conventional and circular LIB supply chains. With the methodologies and results reported herein, researchers can prioritize major opportunities to improve process efficiencies, practitioners can benchmark their environmental impacts, and policymakers can incentivize best environmental practices in LIB supply chain management. Insights provided by this study can also help recyclers optimize the environmental impacts of their refinement processes.

Results

In LIB supply chains, the refinement step converts the collected feedstocks into battery-grade salts for further manufacturing (**Fig. 2a**). In both conventional and circular supply chains, the refinement pathways vary significantly depending on multiple factors. Five refinement pathways are compared in this study (**Fig. 2b**). While conventional refinement starts with mined ores/brines (1 and 2), circular refinement starts with either end-of-life batteries (1 and 2) or battery scrap (5). Ni and Co in refinement products for subsequent manufacturing can be discrete salts (1 and 3) or mixed compounds (2, 4, and 5).

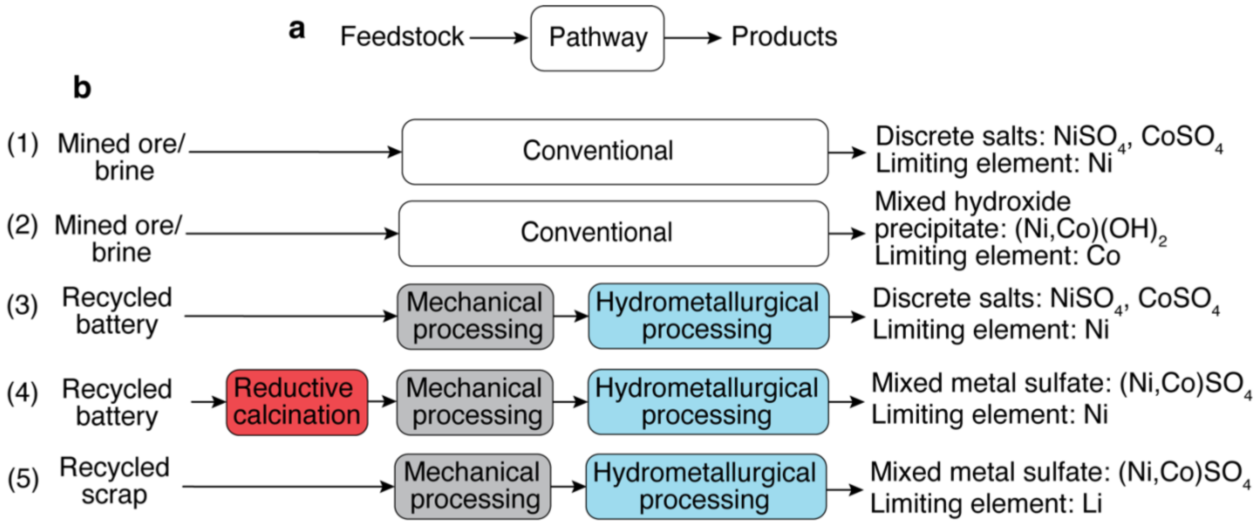

Fig. 2 | Schematic summarizing feedstocks, pathways, and products in refinement analyses. a, General schematic showing the feedstock, pathway, and products as a legend for the refinement methods shown below. **b,** Five specific refinement analyses in this study: conventional refining (1 and 2) receives mined ore and brines, and circular refining methods (3−5) recycle from end-of-life batteries or scraps. While all methods produce identical Li_2SO_4 and Al_2O_3, Ni and Co products exist in the form of discrete salts, $NiSO_4$ and $CoSO_4$ (1 and 3), mixed hydroxide $(Ni,Co)(OH)_2$ (2), or mixed metal sulfate $(Ni,Co)SO_4$ (4–5).

Refining lithium-ion batteries into battery-grade materials exhibits lower environmental impacts than production from mined natural materials. The upstream steps of material extraction and transport are considered in later sections. Environmental impacts including energy consumption, greenhouse gas emissions (CO_2-equivalents, CO_2-eq; additional criteria air pollutants are detailed in **Table S1**) and water consumption of refinement pathways in conventional and circular LIB supply chains are compared in **Fig. 3** for the gate-to-gate production of battery-grade cathode materials. State-of-the-art conventional pathways generating discrete salts (Method (1) in **Fig. 2**) are analyzed here. One kg of lithium-nickel-cobalt-aluminum-oxide cathode-equivalent material (NCA-eq) is employed as a functional unit throughout this study for supply chain comparison, accounting for the elemental requirements to produce stoichiometric $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$. NCA chemistry is selected for the functional unit because it comprises the second-largest category of EV battery chemistries following NMC batteries[7,13], and is projected to utilize less Co compared to NMC[6]. Excluding the environmental impacts of material extraction and transport steps, the gate-to-gate production of one kg NCA-eq battery-grade material from conventional mined natural materials consumes 193.9 MJ and 77.3 L H_2O while emitting 14.5 kg CO_2-eq (**Fig. 3**). The values of energy consumption and greenhouse gas emissions are comparable with previous studies based on GREET datasets[11,12] (**Fig. S3**). Refinement of mined material concentrate into battery-grade Ni material dominates NCA environmental impacts, representing >57% of total values.

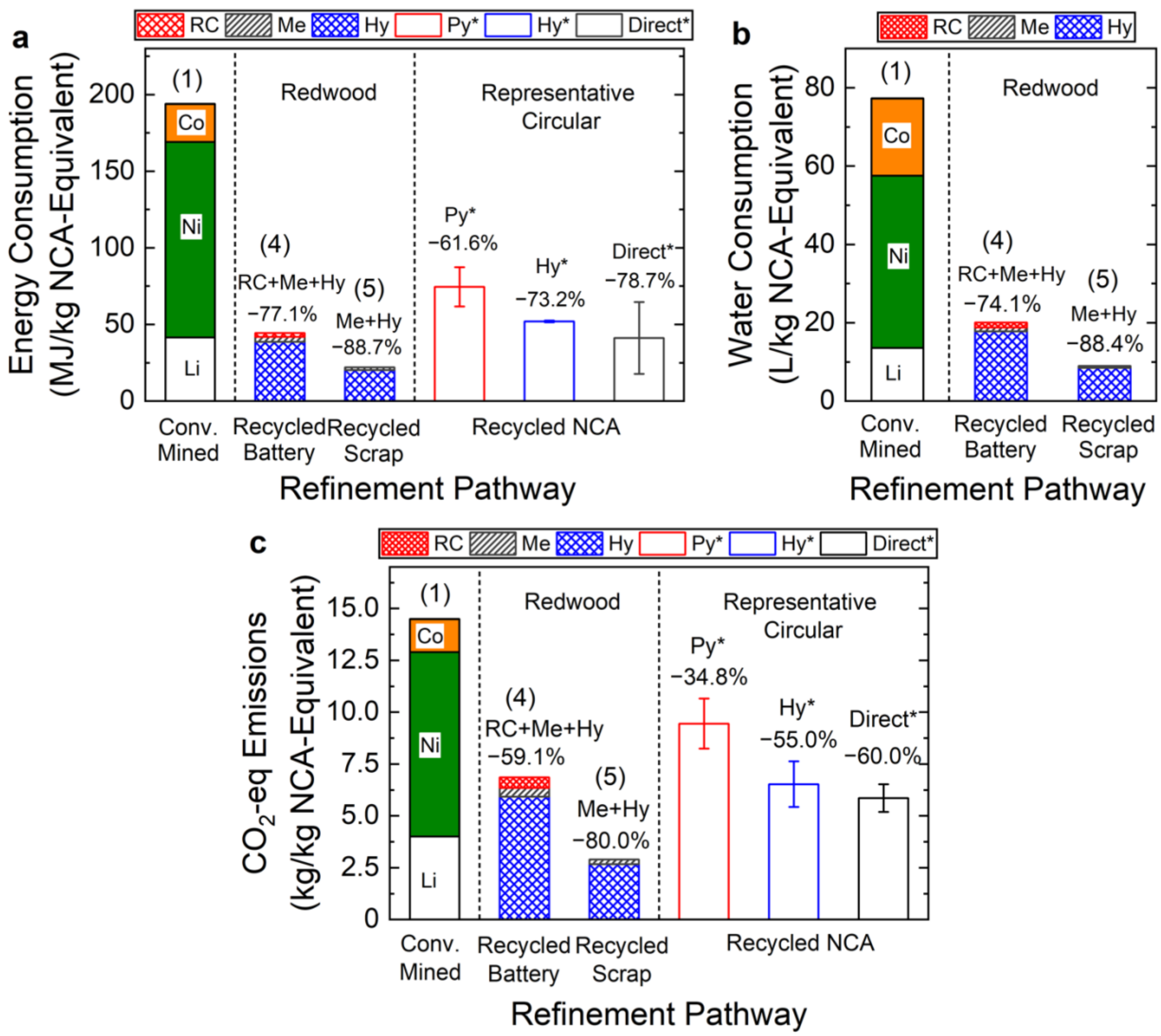

Fig. 3 | Environmental impacts of conventional and circular refining technologies. a, Energy consumption, **b**, CO_2-eq emissions, and **c**, water consumption of gate-to-gate refinement by different pathways for NCA battery-grade salts. Numbers in parentheses labelled on the top of stacked bars denote the refinement methods summarized in **Fig. 2**. The conventional mined pathway (Conv. Mined) refines natural deposits and produce discrete salts (Method (1) in **Fig. 2**); note that Al is presented on the top of the stacked bars but its contributions are too small to be seen; however specific environmental impacts of each element contributor are detailed in Table S1. Circular supply chains refine from either mixed energized end-of-life lithium-ion batteries collected from consumers (Recycled Battery, Method (4) in **Fig. 2**) or non-energized battery scrap from a production facility (Recycled Scrap, Method (5) in **Fig. 2**), producing mixed metal sulfates. Multi-step circular refinement pathways include mechanical processing (Me, grey), reductive calcination (RC, red), and hydrometallurgy (Hy, blue). RC is an additional processing step for energized batteries and is not used for non-energized recycled scrap. Open bars in the right panels denote environmental impacts of recycling NCA batteries with representative existing pyrometallurgical (Py*), hydrometallurgical (Hy*), and direct recycling (Direct*) methods as comparison, and data are obtained from the literature[8]. Literature data is normalized by the same functional unit in this study, and uncertainties are determined by combining two different battery form factors: pouch and cylindrical (detailed in **Table S14–S15**). The vertical dashed line in each graph demarcates different data types, where the model-based conventional and representative existing pathways are summarized in the left panel, operational data from Redwood Materials are presented in the middle panel, and literature data in the right panel. Note that water consumption has generally not been quantified in previous studies, leading to no literature data panel for **Fig. 3b**. Environmental impacts of material extraction and transport in the supply chains are not included.

The environmental impacts of two circular refinement pathways are presented in each graph in **Fig. 3** for mixed-stream LIB feedstocks processed at Redwood Materials: non-energized production scrap from LIB production facilities (recycled scrap) and energized, end-of-life LIBs collected from consumers (recycled battery). Using a limiting-reagent approach of output products to produce one kg NCA-eq material, energy requirements for processing recycled scrap and recycled battery streams are 22.0 MJ/kg and 44.4 MJ/kg NCA-eq materials, significantly lower than conventional refinement by 88.7% and 77.1%, respectively (**Fig. 3a**). Relatedly, 2.9 and 6.9 kg CO_2-eq/kg NCA-eq materials are generated from scrap and battery streams, respectively, a substantial reduction in CO_2-eq emissions by 80.0% and 59.1% (**Fig. 3b**). Water consumption is also lower by 88.4% for scrap and 74.1% for battery streams relative to the conventional scenario, resulting from the consumption of 9.0 and 20.0 L H_2O/kg NCA-eq materials, respectively (**Fig. 3c**). Note that while the elemental stoichiometry is identical, the output battery-grade materials vary slightly between conventional (Li_2CO_3, $NiSO_4$, $CoSO_4$) and circular (Li_2SO_4, (Ni, Co)SO_4) supply chains (detailed in **Methods**). Converting the final lithium product to Li_2CO_3 does not substantially change the environmental impacts of the circular supply chains (Supplementary Note 3, **Fig. S3**), and impacts of producing discrete or mixed products are examined in the following section.

To produce battery-grade cathode materials, Redwood Materials uses a combination of reductive calcination (RC), mechanical (Me), and hydrometallurgical (Hy) LIB refinement processes (pathways detailed in **Fig. S2**). The RC process converts energized battery feedstock under certain conditions that leverage heat from exothermic processes and inhibit graphite combustion. This process does not use direct fossil fuel inputs onsite and facilitates subsequent hydrometallurgical refinement into battery-grade materials. Because RC is not required for non-energized LIB production scrap materials, the two feedstock streams (recycled scrap and recycled batteries) are analyzed separately. Energy consumption and CO_2-eq emissions of representative existing recycling pathways from the literature, including pyrometallurgy (Py*), hydrometallurgy (Hy*), and direct recycling (Direct*), are also presented in **Fig. 3** for comparison. In general, the RC+Me+Hy pathway at Redwood exhibits comparable energy consumption and CO_2-eq emissions with Hy and Direct literature values[8], and substantially lower environmental impacts than Py*. Note that traditional pyrometallurgy and Redwood Material's reductive calcination can process energized batteries of varying states of charge, health, and formats with minimal modification, whereas traditional hydrometallurgy may need to discharge energized batteries in salt bath or cryogenically remove electrolyte for safe mechanical processing. While this analysis is focused on Redwood Materials refinement pathways, the methodology can be used to evaluate additional refinement pathways (e.g., hydrometallurgy in **Fig. S3c**), or others that use different material feedstocks, refinement processes, and energy supplies.

Among the few studies that directly compare environmental impacts of circular and conventional NCA refinement using industrial-scale operational data, 35% lower greenhouse gas emissions (**Fig. S3**) are reported for Me+Hy circular refinement compared with the current study[8,11]. However, direct comparison can be inexact due to varying underlying assumptions and data sources. For example, Argonne National Laboratory's GREET and EverBatt models leverage a combination of technology descriptions from patent applications (the most recent from 2007), literature data on process flow consumptions, industry site visits and surveys, expert advice solicitation, and stated assumptions to form complete pathways. Further, Ciez and Whitacre quantified environmental impacts using output products represented as "metal offsets" for pyrometallurgy or with metals in solution for hydrometallurgy[8] (**Note 3** in **Supplementary Information**), rather than cathode salts in this study. In addition, the previous studies included a portion of recycled metal materials in its conventional supply chain analysis, whereas this work references only mined natural deposits in conventional supply chains to fully deconvolute the environmental impacts[11]. The different conclusions highlight divergent life cycle assessment approaches, processing conditions, and the utility of primary industrial data access over modeling processes from literature sources.

Formats of refinement products influence environmental impacts

Ni and Co are key elements for battery manufacturing, and can be traded in the format of mixed metal salts or discrete salt products between battery refiners and battery manufacturers[14,15]. To examine the influences of the refinement product formats, the environmental impacts of refinement to mixed salt are compared to the refinement to discrete sulfate salts, $NiSO_4$ and $CoSO_4$ (**Fig. 4**). Both conventional and circular refinement pathways are analyzed.

The GREET model is employed to analyze different conventional mining pathways generating different product formats (detailed in **Methods**). In conventional mining, refining Ni-Co ores to mixed hydroxide precipitate, $(Ni,Co)(OH)_2$ (Method (2) in **Fig. 2**), elevates energy consumption and CO_2-eq emissions by 77.% and 89.4%, respectively, over the discrete salts-based pathway (**Fig. 4A** and **4B**, left panels). While the discrete products $NiSO_4$ and $CoSO_4$ are produced from the mixed hydroxide precipitates through additional post-treatment, the very low composition of Co (3.6%) in the latter limits the NCA stoichiometry, thus increasing the total energy cost to generate 1 kg NCA-equivalent materials. On the other hand, water consumption of refining mixed hydroxides is slightly lower (−6.6%) than that in producing discrete salts.

Circular pathways refining batteries to different products are analyzed using the Redwood data by the RC+Me+Hy process and the modeling of a representative battery recycling method combining mechanical and hydrometallurgy (Me+Hy) refinement (Method (3) in **Fig. 2)**. The Redwood process refines recycled batteries to mixed metal sulfate, $(Ni,Co)SO_4$, whereas the representative Me+Hy produces discrete $NiSO_4$ and $CoSO_4$ as the products. The RC pathway (RC+Me+Hy) exhibits lower energy consumption (−72.3%), CO_2-eq emissions (−39.5%), and water consumption (−12%) relative to the Me+Hy pathway (**Fig. 4**), because it avoids additional treatment separating $(Ni,Co)SO_4$ to discrete salts. Overall, our results indicate that refining batteries to mixed metal salts instead of discrete salts can substantially save environmental impacts while still satisfying the needs of circular LIB supply chains. Our findings also provide important insights to optimizing plant-scale battery refining operations. In the following sections, mixed salt-based pathways are analyzed for refinement.

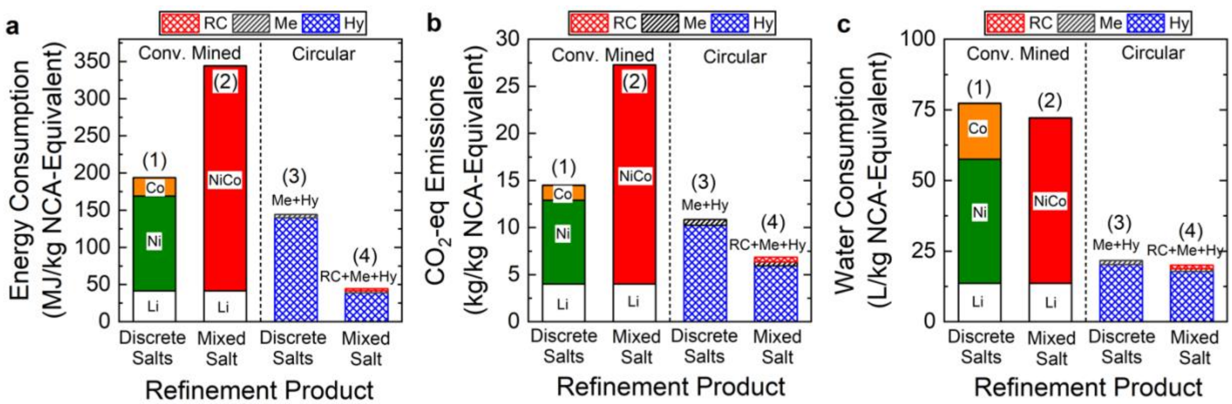

Fig. 4 | Influences of refining products on environmental impacts in circular refining. a, energy consumption, **b,** CO_2-eq emissions, and **c,** water consumption. Left and right panels denote conventional (Conv. Mined) and circular pathways refining end-of-life batteries to discrete Ni and Co salts, or mixed Ni-Co salts. Note that Al is presented on the top of the stack bars of conventional supply chains but its contributions are too small to be seen (detailed values in **Table S1**). Numbers in parentheses labelled on the top of stacked bars denote the refinement methods summarized in **Fig. 2**.

Electricity consumption dominates the environmental impacts of lithium-ion battery circular refinement. The relative environmental impacts of input consumables (e.g., energy, water, commodity chemicals) in the gate-to-gate refinement processes are disaggregated in **Fig. 5** (additional criteria air pollutants in **Tables S2–S3, Figs. S4–S5**). Note that the embodied environmental impacts of electricity consumption in **Fig. 3** are based on the Nevada Power Company (NEVP) at the Redwood Materials location. Electricity consumption is a principal factor dominating the environmental impacts. For both LIB feedstock pathways (Methods (4) and (5) in **Fig. 2**), electricity accounts for 70.3–91.0% of the total energy consumption, 71.8–79.1% of the total CO_2-eq emissions, and 54.3–63.6% of water consumption (**Fig. 5a**). For both feedstocks, Hy processes comprise the majority of environmental impacts, contributing more than 87.3% to energy consumption, 86.3% to CO_2-eq emission, and 88.8% to water consumption. Notably, the additional RC step required for processing energized batteries only marginally contributes to CO_2-eq emissions (7.4% of total). Unlike conventional pyrometallurgical processes that require external energy sources[8,16], the RC process is primarily autothermic because it leverages process heat released from exothermic reactions of the LIB materials[17,18]. In addition to electricity consumption, chemical reagents used in circular refinement processes also contribute to embodied environmental impacts. Alkali reagents used to precipitate metals contribute between 19.0–21.3% of environmental impacts (largest relative contribution to water consumption). H_2O_2 is used to reduce high-oxidation state metal compounds for hydrometallurgical leaching of scrap material, and accounts for 11.3–20.1% of environmental impacts (largest relative contribution to energy consumption).

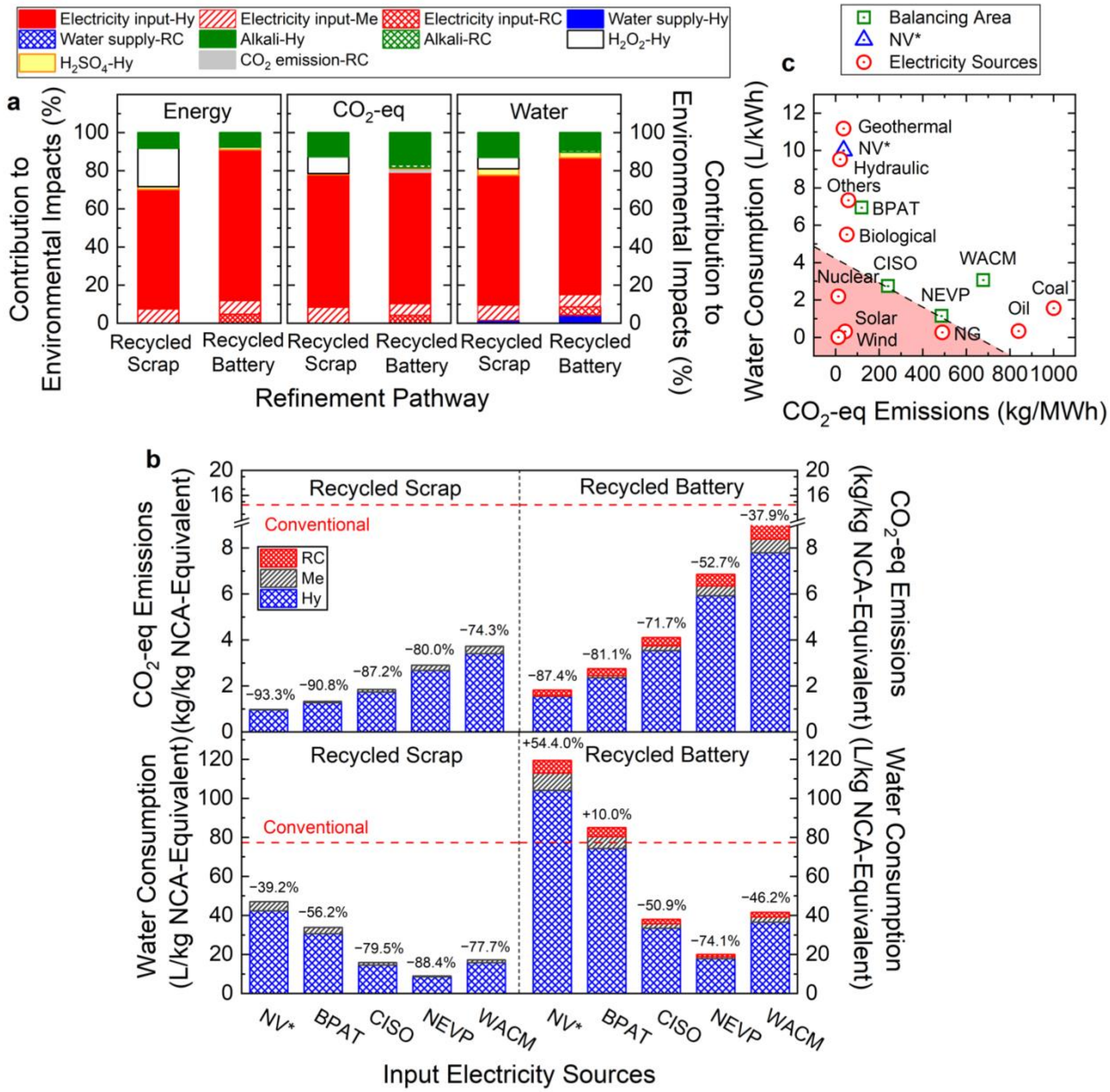

Fig. 5 | Breakdown of environmental impacts of lithium-ion battery (LIB) recycling using different input electricity sources. **a**, Contributions to the environmental impacts of recycling processes using electricity from the Nevada Power Company, including energy consumption, CO_2-eq emission, and water consumption by different input consumables used in circular processes for LIB feedstocks from production scrap (recycled scrap) and used energized batteries (recycled battery) used by Redwood Materials. **b**, Environmental impacts of input electricity sources on CO_2-eq emissions and water consumption in the LIB recycling operations employed by Redwood Materials methods for production scrap and energized batteries. CO_2-eq emissions and water consumption are based on the resources consumed by unit electricity generated from a Nevada renewable energy tariff (NV*), Bonneville Power Administration (BPAT), California Independent System Operator (CISO), Nevada Power Company (NEVP), and Western Area Power Administration: Colorado-Missouri (WACM). The red dashed lines denote the environmental impacts of the analogous conventional refining process. Note that influences of energy sources on environmental impacts are only presented for the circular supply chains, but not for conventional supply chains. Specific environmental impacts presented in the figures are detailed in **Table S5**. **c,** Tradeoff relationship between embodied water consumption and CO_2-eq emission by different power sources, including electricity grids in different locations (⊙), purely power sources (⊡), and Nevada renewable energy tariff (NV*, △). The red dashed line denotes the lower bound of the water-CO_2 performance, i.e., the existing electricity grids that have the lowest water consumption and CO_2-eq emission simultaneously, and the green shaded area covers the power sources that can transcend the current limit of water-CO_2 performance.

Because electricity dominates the environmental impacts of LIB recycling processes, a comparison of electricity grid balancing areas that emit a range of CO_2-eq emissions per MWh (averaged for 2019)[19-21] are examined in **Fig. 5b** (additional criteria air pollutants detailed in **Table S5**). Substituting NEVP electricity with other balancing areas including Bonneville Power Administration Transmission (BPAT), California Independent System Operator (CISO), Western Area Power Administration of Colorado-Missouri (WACM), and a 100% renewable energy tariff in Nevada (NV*), yields a significant reduction in CO_2-eq emissions of up to 93.3% (recycled scrap) and 87.4% (recycled battery) relative to conventional refinement (**Fig. 5b**). Conversely, employing low-carbon electricity grids can increase water consumption compared with NEVP-based operation, following the order of NV* > BPAT > WACM > CISO > NEVP (**Fig. 5b**). Note that NV*- and BPAT-based circular refinement processes exceed the water consumption level of conventional refinement due to significant contributions from hydro- and geothermal power. Further investigation into the grid electricity sources of balancing areas reveals a tradeoff between CO_2-eq emissions and water consumption based on electricity generation type (**Fig. 5c)**; most electricity sources with relatively low CO_2-eq emissions (e.g., those based on bio-, hydro-, or geothermal energy) exhibit high water consumption, and vice versa. This tradeoff also explains the different influences of electricity source on environmental impacts of the Redwood Materials refinement step and other pathways (**Fig. S3d**). However, the electricity sources for each balancing area will affect both CO_2-eq emissions and water consumption. For example, because NEVP-based electricity includes a relatively large proportion (70%) from CO_2-eq emissions-intensive natural gas with low water consumption, a switch to hydro-intensive (73%) BPAT electricity decreases CO_2-eq emissions while increasing water consumption.

Environmental impacts of material extraction and transport are significantly lower in circular lithium-ion battery supply chains than in conventional supply chains. Upstream of gate-to-gate refinement are material extraction and transport to refinement facilities (**Fig. 1b**). Environmental impacts of these upstream steps are analyzed for two representative LIB chemistries and battery use cases: NCA in EV battery packs, and lithium cobalt oxide ($LiCoO_2$ or LCO) in smartphones. California is chosen to assess circular extraction because it has the largest population and EV market share of any state in the U.S.[22,23]. Smartphones are considered extracted when collected, aggregated, and transported from all California residents (analyzed per census block) to the nearest existing collection facility (CF)[24]. The analytical model for this circular extraction is depicted in **Fig. 6a**, where a shortest-path route for collection from block group to CF is modeled[22]. To quantify conventional material extraction environmental impacts from mining, global supply chain data are adapted from GREET (**Table S6–S7**)[12]. Smartphone extraction in the circular supply chain emits only 0.0189 kg CO_2-eq/kg LCO-eq, significantly lower than conventional mining (1.96 kg CO_2-eq/kg LCO-eq) by 99.0%. Energy and water consumption are similarly lower in the circular supply chain (**Table S9**).

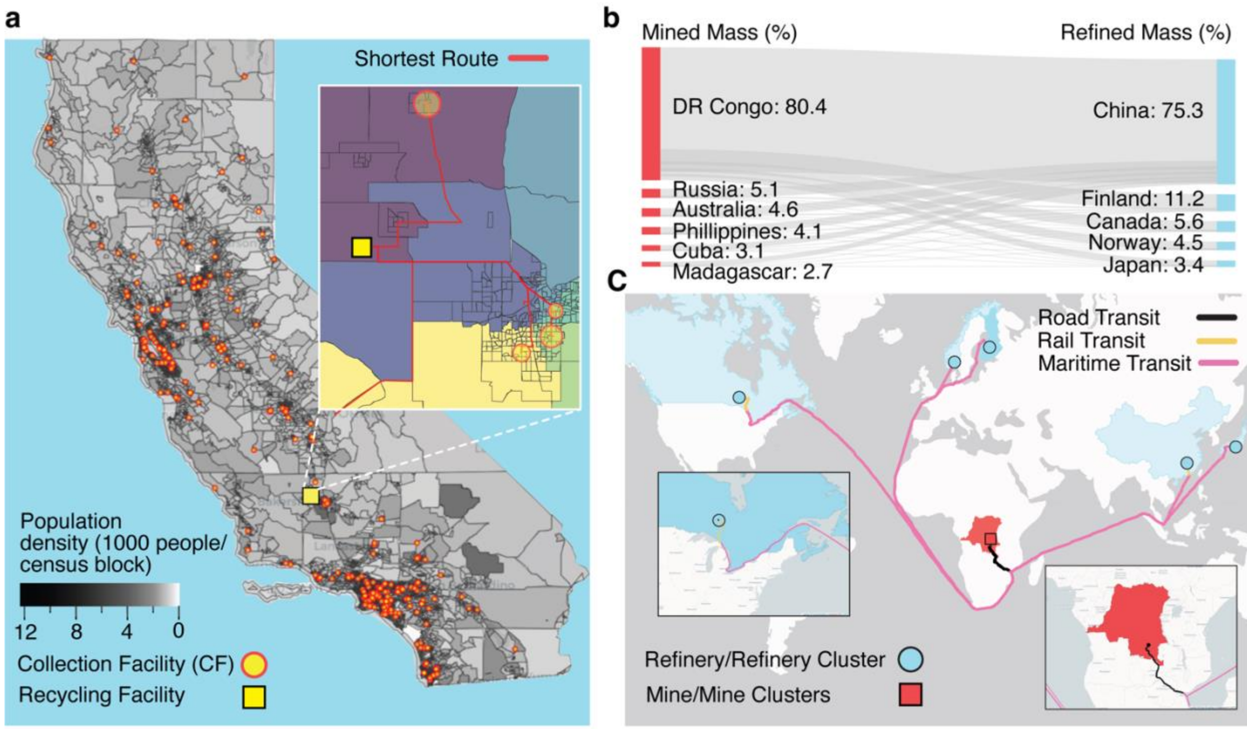

Fig. 6 | A logistics model for assessing upstream environmental impacts of extraction and transport in circular and conventional lithium-ion battery supply chains. a, Modeled circular extraction of LCO-based smartphones from every census-block group based on population to the closest, existing private or municipal collection facility (CF) using a shortest-route algorithm. Inset details modeled circular transport of smartphones aggregated at CFs and then transported to a central recycling facility at the center (gravity point) of the California population by the shortest route (red lines). Colors of block groups indicate the catchment area of a specific CF, where CF size shows the relative number of smartphones collected in 2019. **b**, A weighted distribution estimate of international transport logistics for conventional supply chains between mining and refining countries based on cobalt productivity in the top Sankey diagram. **c**, An example of transport logistics for cobalt mined and aggregated in the Democratic Republic of the Congo (DRC) and then shipped via primary road, train rail, and maritime routes using a shortest-distance path to major refinery locations, with insets showing the degree of detail considered. Similar analyses were performed for Li, Ni, Co, and Al. Inserts present more detailed transit routes in DRC and Canada.

After extraction, LIB material concentrates are transported along domestic and international routes by truck, train rail, and maritime cargo ship to refinery locations (**Fig. S7** and **Table S8–S15**; complete references in **Supplementary Information)**. An algorithm is developed to quantify environmental impacts based on a weighted distribution of participating countries and the shortest distance along major transport routes (the case of cobalt is presented as an example in **Fig. 6b.**) Conventional mine-to-refinery environmental impacts are calculated for one kg of embodied Li, Ni, Co, and Al metal (**Table S7**). While transport emissions for Li, Ni, and Co range from 5.4–6.4 kg CO_2-eq/kg embodied metal, Al is three times lower. For the circular case applied to California, smartphones and EV battery packs collected at CFs are transported to a hypothetical central LIB circular refinement facility at the population-weighted center (i.e., gravity point) of California (near Bakersfield)[22]. In conventional supply chains, transporting mined material concentrates accounts for 3.68 kg CO_2-eq/kg NCA-eq and 4.32 kg CO_2-eq/kg LCO-eq. By comparison, emissions for the transport of aggregated end-of-life NCA EV battery packs (i.e., not disassembled) and LCO smartphone batteries (not separated from phones) to a circular refinement facility are 0.073 kg CO_2-eq/kg NCA-eq and 0.47 kg CO_2-eq/kg LCO-eq, 98.2% and 89.1% lower than transport of mined concentrate, respectively. The reduction in CO_2-eq emissions is attributed to differences in elemental concentrations of transported materials and aggregate transport distance (e.g., a weighted average of 224 km for circular NCA-eq materials, and 57,600 km for conventional NCA-eq materials).

The refinement step dominates environmental impacts of circular and conventional supply chains. Combining material extraction, transport, and refinement steps yields a cradle-to-gate comparison of the most differentiated steps of conventional and circular LIB supply chains for producing battery-grade cathode materials (**Fig. 7**). Here the environmental impacts of the LIB refinement step in California are analyzed for a hypothetical scenario employing the same circular multi-step refinement technologies as Redwood Materials (i.e., RC+Me+Hy) in Nevada, but using California (CISO) electricity to produce battery-grade cathode materials. A circular supply chain in California for NCA EV and LCO smartphone batteries lowers energy and greenhouse gas emissions by at least 47.3% and water consumption by over 37.6%. In the case of recycling NCA EV batteries in California, the entire cradle-to-gate greenhouse gas emissions of the circular supply chain are lower than the transport emissions of mined concentrate in conventional supply chains

(**Fig. 7**, **Table S8)**. Circular production of LCO-grade materials leads to higher environmental impacts than that of NCA-grade materials based on the mixed-stream feedstock composition processed by Redwood Materials. Overall, upstream steps (extraction and transport) contribute marginally to the total environmental impacts of both circular supply chains, accounting for ≤4.9% CO_2-eq emission, ≤8.2% energy consumption, and ≤0.24% water consumption. Accordingly, the refinement process dominates the environmental impacts of the circular supply chain. In contrast, upstream steps in the conventional supply chain play a larger role (still smaller than refinement) in cradle-to-gate environmental impacts, contributing between 7.8–31.0% to the environmental metrics considered (**Table S8**).

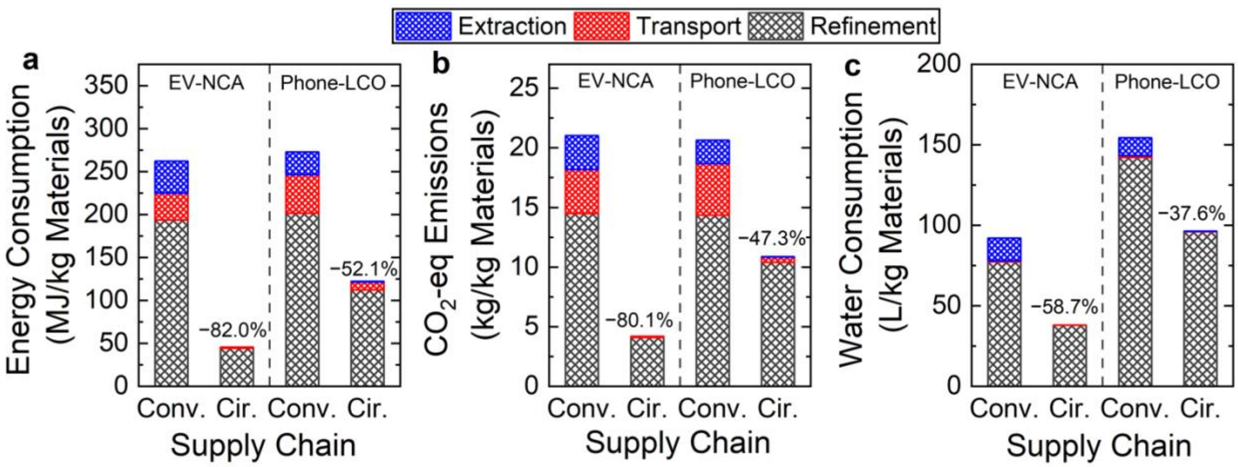

Fig. 7 | Cradle-to-gate environmental impacts of different supply chains. a, Energy consumption (left), **b,** CO_2-eq emissions (middle), and **c,** water consumption (right) of conventional (conv.) and circular (cir.) supply chains by step including material extraction, transport, and refinement. NCA-eq cathode used in electric vehicles (EV-NCA, left panels) and LCO-eq cathode material used in smartphones (Phone-LCO, right panels) are provided. Environmental impacts of refinement are analyzed based on electricity generated from balancing grid authority CISO and upstream supply chain steps (extraction and transport) are based on data from GREET and transport models developed in the preceding section and depicted in **Fig. 6**. Specific environmental impacts of each step are detailed in **Tables S5–S7**.

Discussion

This study is the first quantitative cradle-to-gate life cycle assessment of disaggregated conventional and circular LIB supply chains that include primary data from an industrial-scale recycling facility. Practical LIB feedstock and refinement pathways are analyzed from recycling company (Redwood Materials) and modeling is employed to examine the environmental impacts of upstream material extraction and transport steps. The analysis reveals that refining end-of-life LIBs into battery-grade cathode materials exhibits lower environmental impacts than conventional refinement of mined materials, mixed salts products are more beneficial for circular refinement, and the source of input electricity is the principal factor governing circular refinement environmental impacts. Upstream circular supply chain steps contribute marginally to overall environmental impacts, and the refinement step comprises the largest source of cradle-to-gate environmental impacts.

Disaggregated analysis of LIB refinement pathways at Redwood Materials provides important insights into the performance and potential of different refinement processes. While pyrometallurgical processing is widely considered as more environmentally intensive than hydrometallurgy, Redwood Materials' RC pathway exhibits much lower environmental impacts than current Hy-containing pathways reported in practice and in literature (**Fig. S3**). The optimized conditions of RC processing minimizes the combustion of carbon-containing LIB materials, significantly reducing CO_2-eq emissions while simultaneously generating products that are amenable for hydrometallurgical separation. Because chemical consumables such as H_2O_2 are important contributors to hydrometallurgy, environmental impacts of Hy processes could be reduced through more sustainable (e.g., electrochemical) production methods[25]. Our findings also advocate the refinement products of mixed metal sulfates over the single salts, indicating that the further separations among Ni and Co salts can be avoided. An emerging alternative LIB recycling technology, "direct recycling", recovers functional battery materials without decomposition into substituent elements, and is reported to exhibit comparable environmental impacts to Redwood Materials methods[9]. However, direct recycling is still under development and warrants further assessment after process optimization and industrial-scale implementation.

Electricity greatly influences environmental impacts in LIB circular refinement, and the variability among grid electricity sources elucidates a tradeoff between CO_2-eq emissions and water consumption (**Fig. 5**). Therefore, considering water consumption and CO_2-eq emissions is necessary for selecting recycling facility locations, particularly in water-sensitive or emissions-sensitive scenarios. Further examination suggests that the tradeoff is primarily driven by water-intensive hydroelectric and geothermal electricity in certain locations versus CO_2-intensive coal and natural gas in others, implying that increasing the proportion of electricity from nuclear, wind, and solar energy sources simultaneously reduces CO_2-eq emissions and water consumption relative to existing balancing areas (**Fig. 5**).

Analyses of upstream environmental impacts inform better operations for future resource-saving extraction and transport. Conventional mining and concentrating of ore or brine is resource-intensive due to the low natural concentrations of critical materials (0.01–1%), while critical material concentrations for transport rise to 3–15% after beneficiation. Further concentrating materials near mine sites or building reinterests closer to sources can efficiently reduce environmental impacts of the conventional mined materials. In contrast, smartphones contain 5% LCO material by mass, with the batteries themselves at 24% LCO[25]. Circular material extraction via LIB collection decreases environmental impacts by 99% versus conventional. A "shortest-route" approach is used in this study to quantify the environmental impacts of battery extraction and transport supply chain steps. Practical battery collection operations will likely vary based on route selection and preprocessing strategy further influencing environmental impacts[26]. For example, the disassembly of collected EV battery packs or removal of smartphone batteries from devices prior to transport to a recycling facility can increase energy usage through extraction but reduce environmental impacts by lowering transportation weight (**Table S10**). Trucks are used as the primary vehicle for transport analysis given regulatory concerns that consider LIBs hazardous material in many transportation scenarios[27]. However, alternative transport like railway can further lower environmental impacts by approximately four times versus trucking (**Tables S12**). Upstream process optimization of environmental impacts warrants further investigation, such as the active area of high-throughput automation of LIB extraction from non-standardized devices and EV battery packs or rapid assessment of LIBS for second life uses.

While the current cradle-to-gate study is focused on Li, Ni, and Co as the major output materials, the potential benefits of extracting additional LIB constitutive elements from ore (e.g., Cu and Co in Cu-Co sulfides) or from LIBs (e.g., Cu or Mn) warrants further investigation. Additionally, the same mixed-stream LIB feedstocks consumed at Redwood Materials are used to quantify NCA- and LCO-equivalent values, and results would vary for single-stream LIB feedstocks. Generally, the incremental benefits of extracting additional critical materials from concentrated sources like LIBs can offset the environmental impacts of both supply chains.

As the prevalence of LIBs grows in the mobility sector and beyond, strategic placement of domestic LIB collection, refinement and manufacturing facilities can further minimize future environmental impacts by considering heterogenous LIB growth by location, collection approach, transportation distance, and electricity source for refinement processes. As LIB production scales, policies informed by consumer surveys, focus groups, pilot testing, and diverse stakeholder engagement will be needed to research and scale battery collection[28]. Business models for collection of all LIB types and sizes will likely vary from manufacturer-led to municipal or private collection programs. In addition to collection costs, the varied scale of collection requires further investigation, particularly for localized environmental impacts. Notably, analogous economic and environmental impacts to local ecosystems of conventional mining are not considered in this analysis, and warrant future studies[29]. Additionally, designing and manufacturing LIBs for recycling in a circular economy can reduce resource usage identified in this study[30]. Future efforts should also focus on optimizing refinement processes for subsequent steps of the circular supply chain in LIB manufacturing, product performance, and economic cost.

Methods

Goal and scope. The goal of this study is to compare stepwise cradle-to-gate environmental impacts (energy consumption, CO_2-eq emission, and water consumption) for two supply chains: a conventional, linear supply chain fed by natural mined material for refinement into battery materials, and a circular supply chain fed by LIBs. Both supply chains produce battery-grade cathode materials. A cradle-to-gate analysis of the whole supply chain considers steps of material extraction, transport, and refinement, and gate-to-gate analysis investigates the refinement step, which is focused on in this study. A gate-to-gate scope is broadly defined as the boundary surrounding processing facility operations. In this analysis, gate-to-gate refinement only considers direct processing (e.g., alteration, concentration, precipitation) of the feedstock material once it is extracted from its original state and transported to the refinement location (shown in **Fig. 1b**). For Redwood Materials, this scope includes mechanical processing, reductive calcination, and hydrometallurgy (**Fig. S2**). The system boundary does not include other operations outside of the direct refinement processes as discussed in study limitations below.

Two LIB feedstock streams are evaluated: (1) battery production scrap and (2) mixed, spent LIBs from consumers (**Fig. S2)**. The study scope upstream of the gate-to-gate supply chain step completes cradle-to-gate analysis, and includes both material extraction and transport steps. For conventional extraction, GREET is used for quantifying the environmental impacts of mining. Transport between supply chain steps and for the circular extraction step are quantified using a logistics transportation model developed in this study, where limitations are summarized below.

Methodology. An attributional life cycle assessment is conducted to quantify and compare conventional and circular LIB supply chains for the production of battery cathode materials. This analysis complies with the International Organization for Standardization (ISO) 14040 standards but omits conversion to environmental impact indicators and external review[31]. Data for conventional material extraction (e.g., mining) and refining are adapted from the Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) 2021 model. GREET and the ecoinvent 3.3 database[32] are employed for life cycle inventory data of chemical consumables for the conventional and circular supply chains.

To assess circular LIB refinement, primary operational data detailing energy, water, on-site emissions, and consumables usage are provided by Redwood Materials and normalized to mass flows of the different elements of interest in input feedstocks and output products. A representative prevailing circular refinement, Method (2) in **Fig. 2**, is modeled with the software HSC Sim[33], based on the technical procedures available in the literature[34-37] and the practical feedstock amount received by Redwood.

Conventional refinement was modeled by aggregating the environmental impacts of the individual refining pathways for each LIB cathode element (**Table S1**), normalizing by the mass of the individual element of interest within the output product (e.g., Li in Li_2CO_3) and then normalizing again by the mass of that element in the functional unit for this life cycle assessment (defined in the next section). For elements where more than one pathway of production exists in the GREET model (i.e., Ni and Li), the overall environmental impacts are calculated by averaging pathways weighted by their respective share of global production (45% Li production from brine and 55% from ore, and 60% Ni production from mixed hydroxide precipitate and 40% from Class 1 Ni). Both discrete and mixed output products are considered. Discrete salts from conventional refinement are Li_2CO_3, $NiSO_4$, $CoSO_4$, and Al_2O_3; alternatively, $(Ni,Co)(OH)_2$ is considered as the mixed product. Lithium outputs produced by Redwood Materials are Li_2SO_4 (environmental impacts for converting to Li_2CO_3 are detailed in Supplemental Information **Note 3**), and other outputs exist as mixed metal sulfates of (Ni, Co)SO_4 or as Al_2O_3 and $Al(OH)_3$. With additional treatment further transform the mixed metal sulfate into separate Ni and Co compounds, discrete salts as $NiSO_4$ and $CoSO_4$ are analyzed based on modeling of a prevailing Hy+Me refinement pathway. In the cradle-to-gate analysis, material transportation between stages was not included because it was not consistently available in the GREET model. Mixes vary between elements, as well as between pathway stages. For example, crude production of $Co(OH)_2$ uses a distributed electricity source in the Democratic Republic of the Congo, and the refinement of these materials into $CoSO_4$ and $CoCl_2$ uses a distributed electricity source in China. While exploring the sensitivity of environmental impacts for conventional battery material production is important, it is beyond the scope of this paper, and instead, this work focuses on the sensitivity of electricity sources in U.S.-based LIB recycling. See **Supplementary Data File A** for the breakdown of the conventional refining data workflow.

Defining functional units. Functional units standardize comparisons of the resource consumption and emissions in life cycle assessments. In this study, two functional units are considered in this assessment to normalize environmental impacts between conventional and circular supply chains: the battery-grade material required to make one kg of stoichiometric lithium nickel cobalt aluminum oxide ($LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$, NCA-eq) and lithium cobalt oxide ($LiCoO_2$, LCO-eq) cathode material. Mass was selected as the primary normalizing factor because any energy-based functional unit (e.g., per kWh) could vary based on battery manufacturing and cycling characteristics. The NCA chemistry was selected because reports suggest future cathodes may utilize less Co compared to NMC batteries in EVs, and NCA comprised the second-largest category of EV battery chemistries in 2016, following NMC batteries[7]. LCO is a representative chemistry used in handheld rechargeable devices (e.g., cellphones and laptops) which are currently available to recycle in larger quantities than EV LIBs. The environmental impacts of other LIB-relevant materials (Cu and Mn) in conventional supply chains can be found in **Table S7**.

In both conventional and circular supply chains, the extraction, transport, and refinement steps are converted into environmental impacts metrics for the production of battery-grade materials and normalized by NCA and LCO functional units. A limiting reagent approach is used to quantify the environmental impacts of a functional unit in circular refinement pathways. According to current multi-step pathways using mixed-stream LIB feedstocks (either recycled scrap or recycled battery), the Li output is the limiting element for creating one kg of NCA-eq materials from recycled scrap, where other refined elemental products are produced in excess. Relatedly, Ni is the limiting output element from recycled batteries. For multi-step refinement processes, the recovery rate of Ni and Co is 95% and for Li is 92%. Additionally, a sensitivity analysis of environmental impacts from circular refinement is conducted based on facility location in different grid balancing areas and their associated electricity sources.

Life cycle inventory and assessment. The life cycle inventory (LCI) data for conventional mining pathways are normalized by each critical metal element: Li, Ni, Co, Al, Cu, and Mn (**Table S7**). The LCI for consumables in the Redwood process are adapted from the GREET 2021 model and ecoinvent 3.3 (**Table S2**).[12,32] The LCI for the Redwood processes also lists water consumption and criteria emissions for different electricity sources by grid balancing areas in the Western U.S. (**Table S6**). Three categories of environmental impacts are detailed in this study: energy consumption, air pollutant emissions, and water consumption. Energy consumption includes the input electricity for different applications and the energy required to produce required consumables. Criteria air pollutant emissions include the embodied emissions generated by the production of input electricity and the consumed reagents. CO_2, CH_4, CO, NO_x, N_2O, SO_x, PM_{10}, and $PM_{2.5}$ are the air pollutants provided in the GREET model and considered here. The greenhouse gas emissions are reported as CO_2 equivalents (CO_2-eq) summing CO_2, CH_4, and N_2O weighed by the corresponding 100-year global warming potential (GWP). Water consumption considers the withdrawn water that is not returned to the original source, and both the input city water usage and the embodied water consumption in electricity generation and the manufacturing of consumable materials are included.

Estimating environmental impacts of material extraction. For conventionally mined ore and brine, energy consumption, CO_2-eq emission, and water consumption values are separated for the material extraction processes found in the GREET model. For the circular extraction case, LCO-based smartphones are assumed to be collected and transported to existing private and municipal collection facilities (CFs) from each census block group in CA, assuming every person owned a cell phone and purchased a new phone every three years. A shortest-route algorithm was used for collection at the closest municipal collection facility determined by *k*-means clustering (**Note 4** in **Supplementary Information**).

Estimating environmental impacts of material transport. In the conventional supply chain, a network model of primary transport routes is established that connects mines to refinery locations for Li, Co, Ni, and Al on a country-level basis (**Tables S8–S15**) because the amount of mined material transported from each mine to each refinery was not known. The distances of the shortest-path routes are calculated between mines and refineries by country, predicated on the closest available modes of transport (including road, rail, and maritime). A major mine cluster or refinery location was selected to represent country-level transport values (**Tables S14–S15**) based on production volumes, and distances are quantified between international destinations. These distances are used to calculate the energy consumption, CO_2-eq emission, and water consumption associated with transportation of critical materials as mined concentrate. Mined concentrate is ore or brine that is concentrated locally beyond natural concentration values to reduce weight for transport to a refinery. By considering the total elemental mass and elemental weight percentage of the mined concentrate transported along a route (**Tables S14–15**), the environmental impacts on a per-element basis are calculated as a global weighted average (**Table S11**) with additional process details in **Supplementary Information**.

For the circular case applied to California, end-of-life EV NCA LIBs are aggregated at one CF per county closest to its centroid, where county-level data was the most granular data available. All smartphones are aggregated at their nearest CFs. Aggregated smartphone and EV batteries are assumed transported via truck to a single recycling facility located at the gravity point of California's population based on census block-level data (detailed in **Note 4** in **Supplementary Information**). The mass-distances traveled are converted to energy consumption, CO_2-eq emission, and water consumption (**Table S8–S9**).

Summary of study limitations. Limitations based on key assumptions of supply chain steps (extraction, transport, refinement) in each supply chain (conventional and circular) are briefly discussed in this section.

Extraction. Mining data in conventional supply chains in GREET often only refer to one mining country per material, meaning the global supply chain is not well captured. Transport required between mining unit processes (e.g., crushing, flotation, and concentration) prior to refinement is excluded from the analysis due to the lack of information in GREET. In collection of end-of-life batteries in smartphones, inefficient transport to a CF (e.g., driving each smartphone individually or taking longer transport routes to a CF) is not considered. In addition, all end-of-life EV battery packs are assumed to be driven to each CF in their original vehicles, which is attributed to the "product use" stage instead of extraction in life cycle assessment; therefore, zero CO_2-eq emissions are assumed for the extraction step of EV batteries.

Transport. An inter-country LIB material transportation assessment is performed as a weighted distribution between all major mining and refining countries. Results are sensitive to the weight percentage of critical material in transported concentrate found in **Tables S14-S15**. Transport between a domestic mine and refinery is not considered, resulting in net zero use of resources in such cases. The resources required to separate an embedded battery from its device prior to a refinement facility is not considered in a circular supply chains. Similarly, the effect of transporting only LIBs separated from the devices is not considered. Incorporating the domestic transport and separation operations can increase environmental impacts.

Refinement. Refinement data in conventional supply chains are limited to the country scenarios reported in GREET, and transport between refinement unit processes is not included. Ancillary processes (e.g., transport between unit processes) beyond direct refinement unit processes and embodied resources of the capital equipment used for material refinement are not considered for the circular supply chain. The chemical formats of output products differ between the conventional and circular supply chains, but converting them to the same products will not substantially change the results due to the similarity between the cathode salts of the two supply chains (**Note 3** in **Supplementary Information**).

References

1 Gielen, D. *et al.* World energy transitions outlook: 1.5° c pathway. (2021).

2 Office, V. T. National blueprint for lithium batteries 2021–2030. (Vehicle Technologies Office, 2021).

3 Agency, I. E. (International Energy Agency Paris, France, 2021).

4 Winslow, K. M., Laux, S. J. & Townsend, T. G. A review on the growing concern and potential management strategies of waste lithium-ion batteries. *Resources, Conservation and Recycling* **129**, 263-277 (2018).

5 Staub, C. *MRF operator: Lithium-ion batteries are 'ticking time bombs'*, <https://resource-recycling.com/recycling/2021/04/13/mrf-operator-lithium-ion-batteries-are-ticking-time-bomb> (2022).

6 Mayyas, A., Moawad, K., Chadly, A. & Alhseinat, E. Can circular economy and cathode chemistry evolution stabilize the supply chain of Li-ion batteries? *The Extractive Industries and Society* **14**, 101253 (2023).

7 Jacoby, M. in *Chemical & Engineering News* (American Chemical Society, 2019).

8 Ciez, R. E. & Whitacre, J. F. Examining different recycling processes for lithium-ion batteries. *Nature Sustainability* **2**, 148-156 (2019).

9 Gaines, L., Dai, Q., Vaughey, J. T. & Gillard, S. Direct recycling R&D at the ReCell center. *Recycling* **6**, 31 (2021).

10 Baum, Z. J., Bird, R. E., Yu, X. & Ma, J. Lithium-Ion Battery Recycling─ Overview of Techniques and Trends. *ACS Energy Lett.* (2022).

11 Crenna, E., Gauch, M., Widmer, R., Wäger, P. & Hischier, R. Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries. *Resources, Conservation and Recycling* **170**, 105619 (2021).

12 Wang, M. The greenhouse gases, regulated emissions, and energy use in transportation (GREET) 2021. *Center for Transportation Research, Argonne National Laboratory* (2021).

13 Steward, D., Mayyas, A. & Mann, M. Economics and challenges of Li-ion battery recycling from end-of-life vehicles. *Procedia Manufacturing* **33**, 272-279 (2019).

14 Kartini, E., Fakhrudin, M., Astuti, W., Sumardi, S. & Mubarok, M. Z. 1 edn 070001 (AIP Publishing LLC).

15 Yang, Y., Xu, S. & He, Y. Lithium recycling and cathode material regeneration from acid leach liquor of spent lithium-ion battery via facile co-extraction and co-precipitation processes. *Waste Management* **64**, 219-227 (2017).

16 Makuza, B., Tian, Q., Guo, X., Chattopadhyay, K. & Yu, D. Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. *Journal of Power Sources* **491**, 229622 (2021).

17 Kim, S. *et al.* A comprehensive review on the pretreatment process in lithium-ion battery recycling. *Journal of Cleaner Production* **294**, 126329 (2021).

18 Balachandran, S. *et al.* Comparative study for selective lithium recovery via chemical transformations during incineration and dynamic pyrolysis of EV Li-ion batteries. *Metals* **11**, 1240 (2021).

19 de Chalendar, J. A., Taggart, J. & Benson, S. M. Tracking emissions in the US electricity system. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 25497-25502 (2019).

20 de Chalendar, J. A. & Benson, S. M. A physics-informed data reconciliation framework for real-time electricity and emissions tracking. *Appl. Energy* **304**, 117761 (2021).

21 Grubert, E. & Sanders, K. T. Water use in the United States energy system: a national assessment and unit process inventory of water consumption and withdrawals. *Environ. Sci. Technol.* **52**, 6695-6703 (2018).

22 Bureau, U. S. C. <https://www.census.gov/data.html> (2022).

23 Energy, U. S. D. o. *Electric Vehicle Registrations by State*, <https://afdc.energy.gov/data/10962> (2022).

24 CalRecycle. *Where to recycle: Map of public recycling locations*, <https://www2.calrecycle.ca.gov/wheretorecycle/> (2022).

25 Roithner, C., Cencic, O. & Rechberger, H. Product design and recyclability: How statistical entropy can form a bridge between these concepts-A case study of a smartphone. *Journal of Cleaner Production* **331**, 129971 (2022).

26 Harper, G. *et al.* Recycling lithium-ion batteries from electric vehicles. *nature* **575**, 75-86 (2019).
27 Transportation, D. o. Hazardous Materials: Transportation of Lithium Batteries. (2014).
28 Sun, M., Yang, X., Huisingh, D., Wang, R. & Wang, Y. Consumer behavior and perspectives concerning spent household battery collection and recycling in China: a case study. *Journal of Cleaner Production* **107**, 775-785 (2015).
29 Daily, G. C. & Ruckelshaus, M. (Nature Publishing Group, 2022).
30 Berger, K., Schöggl, J.-P. & Baumgartner, R. J. Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production* **353**, 131492 (2022).
31 International Organization for, S. *Environmental management: life cycle assessment; Principles and Framework*. (ISO, 2006).
32 Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* **21**, 1218-1230 (2016).
33 Korolev, I. *et al.*
34 Brückner, L., Frank, J. & Elwert, T. Industrial recycling of lithium-ion batteries—A critical review of metallurgical process routes. *Metals* **10**, 1107 (2020).
35 Bae, H. & Kim, Y. Technologies of lithium recycling from waste lithium ion batteries: a review. *Materials advances* **2**, 3234-3250 (2021).
36 Solvay. Battery Recycling
. (Solvay, 2023).
37 Li-Cycle.