Understanding the future of lithium
Part 2, temporally and spatially resolved life-cycle assessment modeling

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Abstract
An array of emerging technologies, from electric vehicles to renewable energy systems, relies on large-format lithium ion batteries (LIBs). LIBs are a critical enabler of clean energy technologies commonly associated with air pollution and greenhouse gas mitigation strategies. However, LIBs require lithium, and expanding the supply of lithium requires new lithium production capacity, which, in turn, changes the environmental impacts associated with lithium production since different resource types and ore qualities will be exploited. A question of interest is whether this will lead to significant changes in the environmental impacts of primary lithium over time. Part one of this two-part article series describes the development of a novel resource production model that predicts future lithium demand and production characteristics (e.g., timing, location, and ore type). In this article, part two, the forecast is coupled with anticipatory life-cycle assessment (LCA) modeling to estimate the environmental impacts of producing battery-grade lithium carbonate equivalent (LCE) each year between 2018 and 2100.

The result is a normalized life-cycle impact intensity for LCE that reflects the changing resource type, quantity, and region of production. Sustained growth in lithium demands through 2100 necessitates extraction of lower grade resources and mineral deposits, especially after 2050. Despite the reliance on lower grade resources and differences in impact intensity for LCE production from each deposit, the LCA results show only small to modest increases in impact, for example, carbon intensity increases from 3.2 kg CO₂e/kg LCE in 2020 to 3.3 kg CO₂e/kg LCE in 2100.

KEYWORDS
batteries, dynamic modeling, electric vehicles, life-cycle assessment (LCA), resource depletion, technology and environment

1 | INTRODUCTION

An array of emerging technologies, from electric vehicles (EVs) to renewable energy systems, relies on large-format lithium ion batteries (LIBs). Improving performance, increased production, and decreasing prices of large format LIBs has enabled remarkable growth in these clean energy applications. In response, global production capacity for LIBs is expected to triple in the next 5 years, exceeding 300 GWh by 2022 (Curry, 2017). This means that the constituent materials used in LIBs must be produced at increasing rates as well. By 2030, global demand for lithium in LIBs is expected to range from 300 to 600 thousand metric tons¹ of lithium per year, comprising more than three quarters of total lithium demand.

Two key issues for LIBs and emerging technologies that rely on lithium batteries are resource constraints and environmental impacts that occur during production. Growth in demand for LIBs across a number of sectors is already placing strains on current lithium production capabilities, and will likely move production to increasingly low-grade resources over time (Ambrose & Kendall, 2019; Helbig, Bradshaw, Wietschel, Thorenz, &

¹ 1 metric ton = 1000 kg; ≈1.102 short tons.
Previous research on LIB demand, lithium supply, and environmental impacts of lithium production

LIB demand is fueled in part by the falling price of LIBs; cost targets for LIBs set 10 and 15 years ago have already been met and exceeded; with costs now expected to fall below $80/kWh, enabling economic deployment in an increasing range of applications (Curry, 2017; Nykvist & Nilsson, 2015; U. S. Department of Energy, 2017). Falling prices for LIBs are not a consequence of falling lithium prices. In fact, demand for lithium for use in LIBs is likely insensitive to increases in the price of lithium (Ciez & Whitacre, 2016) because, despite their name, the actual content of lithium in LIBs is low, and relative to other costs in manufacturing, lithium costs are not large. Thus, significant increases in the price of battery-grade lithium carbonate may not slow adoption of LIBs and, thus, demand for LIBs.

Recent growth in the demand for critical energy materials, which includes lithium, is a concern for climate mitigation efforts and local environmental impacts (Bauer et al., 2010; Department of Interior, 2018). Previous studies have investigated the effects of increasing demand and decreasing resource quality on the environmental impacts of metal production. For example, production of copper has shifted to increasingly low-grade resources with lower yields over the last century (Crowson, 2012; Memary, Giurco, Mudd, & Mason, 2012). Studies have indicated the significant decrease in the average copper ore grade, from greater than 12% Cu to less than 1% Cu by mass, has been accompanied by an order of magnitude increase in energy required for mining and beneficiation (Northey, Mohr, Mudd, Weng, & Giurco, 2014). The grade of the deposit affects the design of the mine and processing facilities, as well as overburden, effluent and tailings generated, all of which influence the LCA of metals production (Durucan, Korre, & Munoz-Melendez, 2006). Average ore grade has been proposed as a characterization factor for comparing the life-cycle environmental impacts of metal extraction (Vieira, Goedkoop, Storm, & Huijbregts, 2012). Coupled with continued growth in demand for copper, these trends could result in a doubling of the climate impacts associated with the global copper cycle by 2050 (Kuipers, van Oers, Verboon, & van der Voet, 2018).

While several studies have considered the environmental impacts of lithium used in cathode materials and batteries (Grosjean, Miranda, Perrin, & Poggi, 2012; Li, Gao, Li, & Yuan, 2014; Notter et al., 2010; Speirs, Contestabile, Houari, & Gross, 2014; Swart, Dewulf, & Biernaux, 2014; Yu et al., 2014), only one study has considered potential variability in impacts resulting from the different resources that can supply lithium. Stamp, Lang, and Wäger (2012) modeled the production of lithium carbonate from generic brine and rock (i.e., pegmatite) sources, and considered potential implications for the environmental impacts of LIBs. They found that carbonate from rock deposits generally have higher impacts than those from brine production, but that heating brines to accelerate the removal of water can quickly increase energy inputs and, thus, emissions related to lithium production (Stamp et al., 2012).

While previous studies focused on issues and dynamics of lithium supply and demand with respect to the rapidly increasing demand for LIBs, no studies combined this modeling with quantitative assessment of environmental impacts from lithium production at different sites and from different resources. Thus, the relationship between the environmental intensity of lithium production and increasing demand over time has not been previously explored. In addition, the projections of LIB demand for EVs have been highly variable across studies. Here, we investigate the temporal dynamics of environmental impacts of lithium carbonate used for LIBs in the context of increasing demand and the need for expansion of production to new sites.

To estimate environmental impacts dynamically, we undertook the following research steps (steps one and two were completed in part one of this article series, while step three was completed here in part two):

1. Provide a novel forecast for demand for battery-grade lithium carbonate to 2100 based on capacity for lithium battery manufacturing.
2. Develop a resource model to link forecasted demand to global lithium resources, development of known reserves, and the relative costs of dispatching new lithium resources to yield estimates of lithium production over time differentiated by the source deposit, which determines location and ore type of source.
3. Develop LCA models founded on regionalized background data and engineering-based models for mining and refining of different resource types and resource qualities to evaluate the effects of expanding the supply of lithium on the environmental impacts of lithium for the battery market.

Two scenarios for lithium production, an optimistic (high demand) and a conservative (low demand) scenario, were developed. Under the optimistic forecast, demand continues to increase steadily after 2050, to 7.5 million t LCE per year in 2100. In the conservative scenario, global
production increases from 237 thousand metric tons LCE in 2018, to 4.4 million metric tons LCE/year by 2100. The results of the resource model suggest that production from high-grade brines could be sufficient to satisfy the majority of demand through 2035, but sustained future demand will require the development of lower grade and unfavorable deposits (Ambrose & Kendall, 2019).

2 | METHODS

This study undertakes a temporally dynamic (considering an annual time step each year between 2018 and 2100) LCA of battery-grade lithium carbonate, tracked in units of lithium carbonate equivalent (LCE). The scope of the LCA includes energy consumption, chemicals, blasting and other site emissions to air and water, but excludes land transformation and some impacts from tailings (e.g., processing wastes). Regional energy inventory data were also used to reflect differences in primary energy sources and conversion technologies. The study provides a novel set of life-cycle inventories (LCIs) for lithium carbonate used for large format LIBs (such as those used in EVs). Contributions of this study to the existing body of work include several factors that either are absent in previous studies or have been identified as requiring additional research. These include:

- Inclusion of demand for large format LIBs sectors other than light-duty passenger vehicles (i.e., heavy-duty vehicles and stationary applications).
- Changes in production sources (i.e., expansion of existing sites and development of new deposits) over time.
- Variability in energy requirements and efficiency of lithium carbonate production across lithium deposits.
- Regional availability of primary energy sources and electricity generation technologies.

The methods used to develop the resource model are available in part one of this article series (Ambrose & Kendall 2019); here, we discuss the development of the LCA model.

2.1 | Life-cycle assessment model

2.1.1 | Goal and scope

The goal of the LCA model is to estimate the life-cycle impacts for producing LCE from available primary resources. The scope of the LCA is from mine to processor or refining gate and reflects specific resource conditions (e.g., the concentration of lithium in the ore), and differences in background systems (namely national-level energy systems). The functional unit selected is 1 kg of battery grade LCE (≥99% Li$_2$CO$_3$ by content). Figure 1 provides a summary of the key processes and inputs included in the LCA model, and highlights the stages at which dynamic inventory modules have been developed to reflect local environmental conditions, regional availability of primary energy sources, electricity generation technology, and the effects of resource quality on material extraction, transportation, and refining processes. Future technological developments in production machinery or electricity generation (e.g., increased renewables deployment) were not included in the scope. Potential implications and limitations of these assumptions are briefly summarized in the discussion section.

2.1.2 | Life-cycle inventory model

The lithium production process can vary from deposit to deposit, and many of the specifics regarding lithium processing are proprietary. Compounding the potential variability across production sites, many companies use different techniques for lithium processing depending on the desired outputs. Influencing factors include the concentration and distribution of lithium minerals within the deposit, the overall grade of the deposit, the presence of contaminants (such as magnesium), and the location of the deposit (Garrett, 2004). Production system design may also vary by estimated returns on different grades of output, for example, low-grade hydroxides versus high-grade carbonate for LIBs, in addition to loss of product (e.g., tailings and slimes). The LCI model differentiates based on resource type and resource quality. Separate production models were developed for each of the two resource types, classified as other minerals (mostly pegmatites) or brines, and then tailored to specific deposit conditions based on ore grade and background systems (namely the fuel source and electricity grid).

For pegmatite resources, the first stage in production includes mining and raw ore recovery, which is affected by ore grade and depth of the deposit. The major processing steps for these hard-rock minerals involve screening, comminution, magnetic separation, froth flotation (FF), and drying (King, 2001). Screening is the initial step to separate inputs based on particle size, followed by crushing. There are many different methods to achieve crushing based on the inputs, desired outputs, and rate of production. Aside from the grinding, power supply for conveyors is also required to transport materials. Magnetic separation is used to remove any magnetized contaminants (such as iron). Although requirements range depending on the field strength needed, low intensity magnets can be used to generate up to a 15-kG field with only 16 kW of energy per pole needed (King, 2001). The largest energy inputs directly associated with pegmatite processing are heating and comminution (Garrett, 2004).
After recovery, raw ore is processed through one or more additional circuits: dry material separation and recovery, heavy liquid material separation including FF, and hydrometallurgical recovery (HMR). FF is a widely used technique in mineral processing to separate materials based on the ability of air bubbles to attract and remove certain particles while other particles remain behind (Kawatra & Eisele, 2002). The process is a highly variable step in pegmatite processing, primarily due to the unique physical and chemical properties of processing inputs depending on the location of mineral extraction (Menéndez, Vidal, Toraño, & Gent, 2004). FF involves dewatering, the production of a rougher float and a cleaner float, and thickening with a goal of maximizing a high degree of recovery and meeting market specifications. FF of lithium spodumene can be achieved through anionic or cationic flotation. Anionic flotation typically provides high-recovery rates, but lower purity concentrates, and vice versa for cationic flotation.

In terms of energy inputs, FF does not require a significant amount of direct energy, but that does not account for any energy inputs for producing chemicals used in FF. Additional processing also increases production costs, and energy inputs increase across the three processes. For FF and HMR, reagent inputs are also extensive. Reagent costs can represent 50% or more of average production costs, and additional FF and HMR processing may be required to concentrate and refine lower grade mineral deposits (Staiger & Rödel, 2017).

For brines, extraction begins with drilling to pump lithium brines to the surface, which are then often collected in solar evaporation pools. Impurities in the final brine include boron, magnesium, and calcium. Unless processing facilities are located on-site or close to the evaporation ponds, the brine must be shipped via truck or rail to a processing plant. The major processes involved in the production of commercial-grade lithium products from brine sources are impurity removal, settling, filtering, pressing, heating, precipitation, and thickening/drying (King, 2001).

Impurity removal is done as an initial step to remove contaminants, including but not limited to boron, magnesium, and calcium. Boron is removed through solvent extraction. Magnesium and calcium are removed with lime and soda ash, respectively. The percentage of these contaminants in the brine directly affects the amount of solvents or chemicals and processing needed to remove a given impurity (Garrett, 2004). Accordingly, the value of a given brine source will range depending on the percentage of contaminants it contains. After the initial impurity removal, the remaining mixture progresses through a settling, filtration, and pressing process. Settling can be achieved via gravitational forces. Filter pressing requires pumps that vary in power use and efficiency depending on the inputs and rates of production. The goal of these processes is to increase the concentration of solid matter in the brine and remove unnecessary water and liquids.

The most energy intensive step to lithium brine processing (not including energy for chemical additives) is the thickening and drying processes. Settling and filtering require very low-energy inputs and can rely mostly on gravitational forces. After heating and precipitation of lithium carbonate, the resulting solution must be thickened. Sedimentation uses cycles and vacuum belts for the thickening process. The heating and drying is
FIGURE 2  Impact assessment of lithium production pathways (AP, acidification potential in g SO$_2$-eq; ETP, ecotoxicity potential in CTU; EP, eutrophication potential in g N-eq; GWP, global warming potential in kg CO$_2$-eq; HHP, human health particulate in g PM$_{2.5}$-eq; HHC, human health cancer in CTUh $\times$ 10$^8$; HHNC, human health noncancer in CTUh $\times$ 10$^7$; ODP, ozone depletion potential in mg $\times$ 10$^7$ CFC-11-eq; SFP, smog formation potential in kg $\times$ 10 O$_3$-eq). Underlying data used to create this figure can be found in Supporting Information S2.

usually achieved through a rotary steam tube. These machines typically operate with a combustion chamber to achieve temperatures of approximately 980°C. Lithium chloride and the concentrate is then made into lithium hydroxide or treated with sodium carbonate to produce lithium carbonate. Additional thermal energy is often required for concentrating brines, which may rely on locally available primary energy sources such as geothermal resources (Yu, Zheng, Wu, Nie, & Bu, 2015).

Though ore grades and geologic conditions are continuous variables, to make engineering model development and LCI model development manageable, all deposits are modeled as one of six hypothetical lithium production routes, three designations in descending order of preference for each of two categories of deposits; brines and other minerals. Brines are grouped as high-grade brine, low-grade brine, and low-grade brine with low solar evaporation potential. Other mineral deposits are grouped as high-grade pegmatite, low-grade pegmatite, and low-grade lithium minerals (i.e., those where the main lithium mineral is not identified, and/or is not a pegmatite or spodumene). Throughput, efficiency, and material and energy inputs are estimated based on company reporting, patents, and prior studies (An et al., 2012; Garrett, 2004; Laferriere et al., 2012; Stamp et al., 2012). Reference LCI datasets for subprocesses and production inputs were taken from the Ecoinvent Database Version 3.3 (Ecoinvent Centre, 2017). To represent variability in energy generation, inventories for grid electricity were selected based on the region of the deposit. A full list of reference LCI datasets, as well as graphical descriptions of the process models, is provided in Section S1 of Supporting Information S1.

2.1.3  Life-cycle impact assessment

The LCA model applies the US Environmental Protection Agency’s Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) impact assessment model (Bare, 2011). The following impact categories were considered: global warming potential (GWP), acidification potential, ozone depletion potential, eutrophication potential, photochemical smog formation potential, human health—particulate, human health—cancer, and ecotoxicity. Additional information on the selected impact categories and the indicators used to represent them is provided in Section S2 of Supporting Information S1.

3  RESULTS

3.1  LCA results by production pathway

While there are significant differences in energy inputs and throughput efficiencies across production pathways, impact assessment results do not show dramatic differences in most environmental impact categories (Figure 2). Figure 2 uses the weighted average region for each production pathway to estimate impacts from electricity consumed. In general, high- and low-grade brines show the most favorable results (i.e., lowest results) for toxicity-related impact categories and human health impacts from air emissions. High- and low-grade pegmatites show more favorable results for GWP, smog formation, and acidification. These results are primarily explained by differences in the chemical flows between brine and hard-rock mining and extraction processes. We find moderate variation between the most favorable and least favorable potential brine production pathways, with additional fuel use for drying in the “Unfavorable Conditions” brine scenario driving significantly higher toxicity-related air, water, and human health impacts.
3.1.1 | Impacts over time

Combining the impact analysis with the resource projection, we observe the potential changes in impacts over time under the optimistic scenario (Figure 3). Increasing impacts on fresh water, local air quality, and human health are likely to be concentrated around smaller deposits, which are likely to be developed after 2050. Notably, global warming impact intensity from LCE production does not change significantly over time, however, given significant growth in LCE production, total CO\textsubscript{2}e emissions from the lithium production sector will increase significantly. There can be significant interannual variations in production share across lithium resources due to overall market expansion, production capacity increases, and climate conditions for brine production. These effects are observable in Figure 3 as rapid shifts between years when new deposits are brought online. As the market for lithium continues to grow after 2050, these shifts are less noticeable as fewer new deposits with significant production potential come online. A shift in future supply toward lower grade resources did not translate to significantly higher environmental impacts for lithium carbonate on average.

Under the optimistic scenario, a larger share of production is supplied from lower-grade mineral deposits after 2080, but high- and low-grade brines continue to be the largest source of supply. This is due to both the increased demand for lithium, as well as the limits on potential production from lower cost brines. Comparing the average impacts per kg LCE over 2, 10-year periods, beginning in 2020 and 2080, significant increases in production from low-grade pegmatite and brine resources leads to only small increases in environmental impacts. For example, GWP increases by 3% from 3.2 to 3.3 kg CO\textsubscript{2}e/kg LCE. This translates to an increase of 0.14 to 0.16 kg CO\textsubscript{2}e/kWh of cathode material, assuming a nickel cobalt aluminum or manganese cathode precursor and a cathode energy density of 0.25 to 0.27 kWh/kg (Ciez & Whitacre, 2019). Changes to water, toxics and particulate matter were larger than GWP, increasing by 11, 12, and 15%, respectively. While the impact intensity (i.e., impact per kg of LCE) does not change significantly over time, given significant growth in LCE production, total impacts from the lithium production sector will increase significantly. For example, sector-wide CO\textsubscript{2}e emissions increased by at least two orders of magnitude between 2020 and 2080 (Figure S3-2 of Supporting Information S1).

Under the conservative demand scenario, there is no significant future development of low grade, hard-rock sources of lithium. This result in a 48–64% reduction in sector-wide environmental impacts from global LCE production in 2100 compared with the optimistic demand scenario (Figure S3-4 of Supporting Information S1). In addition, significant increases in the average impacts on ecotoxicity, eutrophication, and human exposure to particulates per kg of LCE after 2080 did not occur (Figure S3-5 of Supporting Information S1). An expanded description of results, including global sector-wide results, and data tables are provided in Section S3 of Supporting Information S1.

4 | DISCUSSION

Uncertainty in the results of an LCA can result from a number of sources: variability in assumed values, lack of knowledge, measurement errors, and choices related to model design and specification. We considered the impacts of parametric uncertainty on model findings, specifically discount rate, production costs, reagent use, production energy inputs and sources, and mineral grade/type. Changes to discount rate and production costs did not cause significant changes in the overall production forecast, but did affect year-to-year variation in estimated impacts. This is also due to assumptions around the rate of potential production capacity expansion at existing and new lithium deposits. Estimated production impacts are highly sensitivity to the extent of HMR processing, while the impacts of HMR processing are primarily due to consumption of reagents for collection and dispersion.

For brine production, two primary sources of uncertainty are variability in the effective evaporation rate of solar ponds and the use of external energy sources to dry aqueous brines. Small increases in annual precipitation can cause months-long disruptions in the production of solar evaporated brines, as was experienced in the Atacama region in 2015 (Abad, Rolando, & Izquierdo, 2017). The use of natural gas for drying in the worst-case scenario for brine production was the key factor driving increased impacts.

A limitation of this study is the use of temporally static LCIs for regional electricity generation and processing technologies that may not reflect changing energy sources for electricity generation (e.g., decreased consumption of coal and increased use of renewables), or advances in machinery (e.g., improved heat rates for drying machinery). While impacts of regional electricity and natural gas sources were included, this did not result in significant differences across regions under current conditions. Given the large contribution of a single-brine deposit to global supply, development of local renewable resources, including geothermal and solar energy, could likely reduce the emissions associated with overall lithium production (Lahsen, Muñoz, & Parada, 2010; Parrado, Girard, Simon, & Fuentealba, 2016).

The results of this study generally agree with existing estimates of life-cycle impacts from LCE production. Figure 4 shows the average results for impacts across rock and brine resources from 2020 to 2100, with error bars indicating the minimum and maximum values observed across production pathways, compared with the inventories for LCE production from Ecoinvent for spodumene and brine, respectively.

Other life-cycle based studies have also reported results that can be compared to findings from this study. Gaines and Nelson (2010) estimate that 163 MJ are required per kg to process ore into lithium hydroxide at a marketable condition. For the processing of brines into lithium carbonate, they estimated 44.7 MJ per kg were required, with 78% of that energy coming from fuel oils, 4% coming from propane, and the remainder
FIGURE 3  Impact assessment of production weighted lithium production over time (AP, acidification potential in g SO$_2$-eq; ETP, ecotoxicity potential in CTUe; EP, eutrophication potential in g N-eq; GWP, global warming potential in kg CO$_2$-eq; HHP, human health particulate in g PM$_{2.5}$-eq; HHC, human health cancer in CTUh $\times 10^8$; HHNC, human health noncancer in CTUh $\times 10^7$; ODP, ozone depletion potential in mg $\times 10^7$ CFC-11-eq; SFP, smog formation potential in kg $\times 10$ O$_3$-eq). Underlying data used to create this figure can be found in Supporting Information S2.
coming from coal. The present study found energy inputs for producing LCE from pegmatites to range from 72 to 230 MJ/kg, while energy inputs from brines ranged 31 to 89 MJ/kg. In comparison to Gaines et al.’s findings, the present study found that energy inputs were lower for high-grade resources, but significantly higher for low-grade resources in unfavorable conditions. The scope of the current environmental assessment is limited in that it did not include site impacts including land transformation for solar evaporation ponds, or site impacts to air and water from the storage/disposal of mining wastes. While energy sources were estimated for deposit regions, these values were treated as static. Changes to the primary energy sources (i.e., a shift from coal to gas or renewables), or improvements in the efficiency of generation technologies could reduce the impacts of producing a kg of LCE. In addition, the reference data used may not accurately reflect the impacts associated with a particular source or supply for reagents or energy sources.

4.1 Recycled batteries, recovered lithium, and unconventional resources

Though excluded from the resource model in this analysis, recycling of batteries could be an important source of future lithium supply (Gruber et al., 2011; Pehken, Albach, & Vogt, 2015). Some previous studies have assumed widespread and effective recycling of LIBs as a major source of future lithium. Mohr, Mudd, and Giurco (2012) estimated recycled lithium could represent 50% or more of lithium demand by 2050. While there has been a proliferation of methods for recovering cathode materials, many developments remain at the laboratory scale, which is a challenge for prospective analysis of environmental impacts (Zeng, Li, & Singh, 2014; Zhang et al., 2018). Conventional material recycling processes can generally be divided into two categories: hydrometallurgical and pyrometallurgical. With the exception of some experimental in situ recycling processes, conventional pyrometallurgical recovery of high-value metal alloys, like nickel and copper, from spent LIBs does not produce lithium as a coproduct. The focus of most existing recycling efforts for LIBs has been on recovering cobalt, due to both the quantity of cobalt in the cathode of batteries for consumer electronics (i.e., LCO), and the high value of recovered cobalt (Zhang et al., 2018). Attention has shifted to recovering other high-value materials, like nickel, copper, and aluminum, as battery systems have increased in size and cobalt content has fallen (Gaines, 2018). For large-format LIBs, widely expected to drive demand for lithium in the future, coprecipitation of lithium–nickel cathode materials combined with reutilization, sometimes called direct cathode recovery, is a promising pathway. Ciez and Whitacre (2019) recently examined the environmental impacts and costs of recycling processes for LIBs including resynthesis of cathodes through direct cathode recovery at high-cathode recovery rates (Ciez & Whitacre, 2019). The authors found limited to insignificant benefits for battery GHG emissions from cathode recycling through hydrometallurgical or pyrometallurgical processes. The limited studies available suggest that recovery of lithium from spent cells provides no clear environmental or economic benefit. Recovery of aluminum, the largest contributor to energy for cell materials and material-related GHG emissions, and copper collector foils could reduce energy for cell material production by 70 to 80 MJ/kg of battery cells, or 34–69% (Dunn, Gaines, Kelly, James, & Gallagher, 2015; Gaines, 2018). The cost of leaching chemicals for lithium carbonate from recycled batteries could be more than the $8 per kg or $8000 per metric ton LCE (Gratz, Sa, Apelian, & Wang, 2014). This suggests the price of recycled lithium carbonate would be significantly higher than the average cost of production of lithium from primary sources.

In addition, successful recycling programs for e-wastes are an issue, as current collection rates for LIBs are approximately 3% (Swain, 2017). While collection rates might be significantly improved for large-format LIBs over those in the general e-waste stream, a confounding factor for
battery recycling economics is the potential for second-use applications of large-format LIBs in stationary applications. The primary determination of LIB service life in vehicles is power fade, and LIBs employed in high-power vehicle applications are likely to still have considerable capacity when retired. A growing body of research has pointed to the technical and economic feasibility of LIB reuse or second life (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2017; Martinez-Laserna et al., 2018; Richa, Babbitt, Nenadic, & Gaustad, 2017). To the extent batteries could be employed in secondary applications, batteries may remain in service longer. The value of recovered materials from recycled batteries may also be too low to motivate sufficient development of recycling infrastructure or to compete economically with second-life applications (Ambrose, Gershenson, Gershenson, & Kammen, 2014; Ciez & Whitacre, 2019).

Part one of this study assessed the potential for secondary lithium from recycled LIBs using a stock and flow model. Assuming a high rate of LIB collection at end-of-life (85%), and assuming approximately half of all vehicle LIBs find secondary uses, the model showed the total stock of LCE in waste batteries awaiting recycling could approach 25% of global primary reserves by 2100. The potential stock of LIB materials in retired LIBs could also grow as improvements to recycling technologies increase recovery rates. As LIB recycling processes and their technical, economic and environmental performance become clearer, future research could explore the effect of secondary lithium flows on the environmental intensity of average global lithium production.

5 | CONCLUSIONS

Despite differences in impacts by production pathway and a changing mix of resources being dispatched over time, the average impact intensity of a kg of LCE changes very little even out to 2100, though some impact categories (including eutrophication, ecotoxicity, and human health particulate) do show nontrivial increases around 2080 corresponding with new capacity from low-grade mineral ores. Examining results on a per-kg basis can be somewhat misleading, however, because the total quantity of lithium produced is increasing rapidly, meaning that total impacts from the sector will be much larger than today. Moreover, the impacts experienced by the communities that host lithium mining and processing sites may change dramatically when capacity is expanded or a new mine is opened. In addition, the significant variability in environmental protections and enforcement in different regions over the world means that the estimates provided here probably underestimate the variability across production sites. Thus, the industry (or the industries reliant on lithium) should consider focusing on reducing impacts per unit of lithium production to prevent significant increases in the total burden of pollution from lithium production and to protect the communities where lithium is produced.

Given these findings, future work might consider assessments that evaluate local conditions of production on a site-by-site basis to capture the variability in environmental impacts, not to mention the socioeconomic impacts, caused by expanding capacity at current sites and exploitation of new deposits. Given the significance of other constituent cathode and electrode materials, future resource analysis could also focus on cobalt (and to a lesser extent nickel). The underlying resource model used to develop this temporally and spatially resolved LCA could facilitate site-specific assessment of impacts likely to be experienced by communities under different demand forecasts, which could be important for understanding which communities may be disproportionately impacted.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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