Socio-environmental impacts of lithium mineral extraction: towards a research agenda

Datu Buyung Agusdinata1,3, Wenjuan Liu1, Hallie Eakin1 and Hugo Romero2

1 School of Sustainability, Arizona State University, Tempe AZ 85287, United States of America
2 Department of Geography, University of Chile, Av. Portugal 84 Santiago, Chile
3 Author to whom any correspondence should be addressed.

Abstract

The production of lithium-ion batteries (LIBs) has increased in capacity by almost eight fold in the past ten years due to growing demand for consumer electronics and electric-drive vehicles. The social and environmental implications of increased lithium demand is significant not only in the context of policy initiatives that are incentivizing electric vehicle adoption, but also because electric vehicle adoption is part of the vision of sustainability transitions that are being put forth in a variety of contexts. Any evidence that suggests that the externalities of the technology uptake are not being addressed would directly counter the intent of such initiatives. For LIBs to be fully sustainable, it is imperative that impacts along life cycle stages be adequately addressed, including lithium mineral extraction. This study investigates how the scope and focus of research in this area are changing and what drives their evolution. Based on a bibliometric analysis, we evaluate the state of research on the issues of lithium mineral extraction, use, and their impacts. The article identifies research hotspots and emerging research agendas by mapping the evolution of research focus and themes. Our analysis finds that research on the socio-environmental impacts of lithium extraction at local level has been very limited. We discuss some research directions to address the knowledge gaps in terms of specific research topics, methodologies, and broader system perspectives.

Introduction

Transportation activities, mostly associated with passenger cars, have been responsible for about a quarter of greenhouse gas (GHG) emissions in the US (EPA 2016). Almost 90% of auto fuels are from fossil fuels (i.e. gasolines and diesels). One of the most promising pathways to reduce GHG emissions is transitioning passenger cars to renewable energy sources such as low carbon electricity and biofuels. To this end, electric-drive vehicles (EDVs) powered by lithium-ion batteries (LIBs) have been considered as promising alternatives. Should there be a high level of EDVs adoption by 2050, the carbon intensity of car transport (CO2 equivalent per vehicle-kilometer-travel) would be reduced by 71% compared to 2013 levels (Scown et al 2013).

Increased demand for EDVs is driving the need for high-density energy storage, particularly through the use of LIBs (EPA 2013). The global electric car stock surpassed two million vehicles in 2016 and is projected to grow to between nine and 20 million by 2020, and between 40 and 70 million by 2025 (IEA 2017). This trend is partly responsible for the fact that the demand for the storage capacity of lithium batteries has increased by 790% and the market, as measured in US dollars, has expanded by 330% in the past ten years. The lithium consumed in battery production has increased from 5160 metric tons in 2007 to 19 780 metric tons in 2017 (Jaskula 2008, Jaskula 2018). In 2015, the largest sector of global LIBs demand is ‘consumer electronics’ (69%); the second is ‘automotive’ (28%). However, the compound annual growth rate forecasted for LIBs’ automotive market share ranges from 22% to 41% through 2020 (NREL 2015).

As a result of these trends, the demand for LIBs will increase lithium mining activities places such as ‘lithium
triangle': the arid territories of Bolivia, Chile, and Argentina where accessible and high-quality Lithium is largely concentrated. Together, the salt lakes of the lithium triangle contain about 75% of the world’s known lithium resources (Jaskula 2012). These areas, remote from the site of lithium-ion consumption, can be expected to experience some of the negative externalities of the growing market. In fact, the potential for such externalities has been anticipated by policymakers. The European Commission, for instance, stated that ‘deployment of “green” vehicles reduces the use of fossil fuels but increases the demand for electricity and certain raw materials, some of which are subject to supply restrictions and concentrated in a few geographical areas (e.g. rare earth elements for electronic components and fuel cells, lithium for batteries)’ (European Commission 2011).

To support robust public policy for sustainable low-carbon technologies, there is a need for greater attention to the socio-environmental impacts of lithium mining activities. There have been only few publications related to the topic. Peters et al. (2017) reviewed the LCA studies on Li-ion batteries with a focus on the battery production process and explored the role of key parameters used for life-cycle modeling, like ‘battery cycle of life’ or efficiency. Gruber et al. (2011) reviewed global lithium availability for supporting future development of electric vehicles, through compiling data from global deposits and assessing future demand under different scenarios. They found that lithium resources are sufficient to support the rapid increase of demand for lithium. Egbue and Long 2012a reviewed the critical issues in the supply chain of lithium for electric vehicle batteries through the state-of-the-art matrix analysis method. They identified the geographic location and geopolitical environment of reserves, competing applications of lithium, and supply capacity as critical concerns. Complementing this work, Olivetti et al. (2017) reviewed various Li-ion battery types and material supply risks in order to identify potential bottlenecks of critical materials in the LIB supply chain. None of these contributions to the literature, however, has addressed the social and environmental impacts of lithium extraction in any depth.

Based on this preliminary literature review, we present our research questions, focused on how the social and environmental externalities associated with the uptake of EDVs technology have been addressed in research and analysis to date. We ask: what are the trends in research and analysis of LIBs externalities and impacts? How are research trends associated with shifts in public policy related to EDV technology? Our hypothesis is that the evaluation of impacts of lithium extraction and use has been limited to issues of costs, technical performance, and a small set of environmental factors. We suspect that the full supply chain impacts have not been evaluated and that the implications of the technology for sites distant from the sites of consumption and manufacturing will be less understood than impacts closer to the sites of consumption.

To understand the drivers of LIBs demand, we will first look into the developments EDVs in the context of corporate and policy initiatives towards sustainable transportation systems. We then present the bibliometric study and findings. The last section discusses what we think may be a promising research agenda addressing the socio-environmental impacts of lithium mining.

The LIBs-based sustainable transportation systems

Electric vehicle technologies have evolved significantly over the past 20 years. The range of EDV products offered in the market can be characterized as in terms of hybrid vehicles (e.g. Toyota Prius, the first to have a commercial success) and all electric vehicles (e.g. Nissan Leaf and Tesla Model S). In between the two, plug-in hybrid electric vehicles are variants of traditional hybrid vehicles and can be recharged using the main electricity grid (e.g. Chevrolet Volt).

All EDVs technologies rely on batteries to provide power. Lithium is currently the preferred element for use in high-energy-density rechargeable batteries. Compared to other battery technologies, LIBs have the highest charge-to-weight ratio, a desirable property for batteries in transportation applications. Since the first commercial release in 1991, LIBs have become instrumental technologies for achieving low-carbon transportation systems.

Demand projections for lithium minerals

The demand for EDVs will drive the demand for lithium minerals. The current EDVs demand projections vary depending the assumptions used. Some of the key factors affecting projections include assumptions about public acceptance and competitiveness of EDVs (Lane and Potter 2007, Egbue and Long 2012b, Järvinen et al. 2012, EDVs policy incentives (Shepherd et al. 2012, Sierzchula et al 2014), and lithium recycling rates and capacity (Gruber et al. 2011, Speirs et al. 2014).

Figure 1 shows how market shares of EDVs have evolved globally and the influence of policy incentives on this evolution. China is currently the world’s biggest market for EDVs, where more than 500 000 of all EVs were sold in 2016 (Cheng and Tong 2017). Norway leads globally in terms of EDVs’ market share. In 2017, more than half of new cars sold in Norway were EDVs, and EDVs made up a third of total vehicle market shares in the country (Norwegian Road Federation 2018). The US has also been seeing a growing demand for EDVs, where market share has reached over 9% of the total vehicles sold in 2017 (figure 2).

Sales of EDVs directly translate into demand for batteries and in turn lithium minerals. In terms of power capacity, to travel a 40 mile trip in an electric vehicle using a single charge would require 1.4–3.0 kg
of lithium equivalent (i.e. 7.5–16.0 kg of lithium carbonate) (Gaines and Nelson 2009). The amount of lithium in the batteries of current EDVs ranges from 4 kg in a compact Nissan Leaf’s battery to 63 kg in in Tesla Model S battery pack. To meet the current demand, the market share of lithium in rechargeable batteries has gone up from zero in 1991 to 80% in 2007. The projection is that in the US alone, annual demand for electric vehicles might require as much as 22 000 ton of lithium (i.e. 117 000 ton of lithium carbonate) by 2030, and as much as 54 000 ton (287 000 ton of lithium carbonate) by 2050, (Gaines and Nelson 2009). The annual demand might increase by 420 000 ton annually under a scenario in which all new vehicles produced are EDVs, each having a 5 kw battery (requiring about 1.40 kg of lithium carbonate) (Tahil 2007, Tahil 2008).

Supply aspect of lithium minerals

The supply of lithium mainly comes from two sources: (1) spodumene, a hard silicate mineral found in pegmatites (13% of worldwide reserves in 2009) and (2) lithium chloride in brine lake deposits (87% of reserves). The third possible source, seawater, is currently deemed infeasible (Stamp et al 2012). Australia is the main producer of lithium from hard rock whereas the lithium recovered from brine comes mostly from Chile. In particular, the Salar de Atacama in Chile, with the highest brine concentration, holds almost 30% of the world’s known lithium resources and in 2009 accounted for 65% of the world lithium market (Goonan 2012).

Timeline of corporate and policy initiatives

The dynamics of lithium demand and supply needs to be interpreted with respect to the influence of policy initiatives that affect lithium production and use. We provide a timeline analysis of milestones in corporate decisions on EDVs and relate them with relevant sustainable transportation policy initiatives in the US, Europe, China, and Japan (figure 3). In the US, the State of California has been leading the policy initiatives by
enacting stringent emissions standards, and establishing the target of selling 3.3 m EDVs in the state by 2025. The EU carbon standard is expected to become more restrictive (from 130 to 68 g km$^{-1}$) by 2025, which might provoke additional demand for EDVs (Erbach 2014). China’s New Energy Vehicle (NEV) Mandate Policy requires that EDVs achieve 4% of the share of new passenger vehicle sales by 2020, and reach 5 million in cumulative sales by 2020 (China Ministry of Industry and Information Technology 2017).

The automotive industry has been ramping up their EDVs portfolios in response to the policy incentives. Ford Motor Company, for instance, plans to introduce 13 new EDVs in the next five years (Ford Motor Company 2016). Volkswagen, the world’s biggest carmaker, plans to launch 30 new battery-powered models by 2025. Daimler Company aspires to a target of having EDVs account for 20% of its sales by 2025. As a result, models of EDVs could outnumber the conventional internal combustion engine-powered cars within 15 years (The Economist 2017).

In this very fast-moving and dynamic industry, it can be difficult to monitor and account for potential externalities of production and technology use, particularly if the supply chain spans large geographies and multiple political jurisdictions. Research initiatives and the academic community can play a key role in bringing the full impact of the Lithium supply chain into the realm of public and corporate scrutiny. In many complex and geographically dispersed supply chains, a lack of data and evidence can result in unpleasant surprises to corporate actors. Anticipatory governance of sustainability challenges—in this case, lithium mining, processing and use—requires continual learning, assessment and monitoring, and the research community can play an important role in providing information to stakeholders (Miller et al 2014, Kemp et al 2005). What knowledge is being put forward, and where there may be knowledge deficits, can be revealing. Evaluating the state of the existing literature is a first step in this regard.

**Methodology**

We conducted a bibliometric analysis to help better understand (1) interactions between policy and corporate action and the research focus in academia, (2) research tendencies in terms of what themes may be the focus of future research and (3) thematic evolution of scientific papers published in this research field.

We hypothesize that (a) there exists a coupling of the policy environment, actions taken by industry, and the research focus of academics, (b) there will be an expansion/diversification of themes in the literature over time as industry gets a better handle on what the issues are, and academia responds.

According to the timeline analysis of policy initiatives (figure 3), we break down our analysis of research themes into four time segments: prior to and including 2008, 2009–2011, 2012–2016, 2017 and beyond. The period before 2008 represents a period in which the development of EDVs had just begun and there were only a few policy incentives and regulations related to EDVs. With the introduction of the new CAFE standards in 27 March 2009, a phase of new policy incentives, regulations and government funded research programs supporting the development of EDVs technologies began (2009 to 2011). The US National Program was established in 2009 and finalized in 2010, serving as the new national automobile standard of fuel efficiency and global warming pollution in the United States. The first phase of the National Program regulates model year 2012–2016 vehicles, and the second phase regulates model year 2017–2025 vehicles. Thus, the period 2012–2016 and 2017 and beyond stand for the first and second phase of the national new automobile standards on GHG emissions, respectively.

We used two databases for our analysis: ISI Web of Science and SCOPUS. We desired databases that would include interdisciplinary research in order to address both social and ecological components of the lithium-ion technology. We used the following Boolean search terms: (i) environment “impact” AND

---

**Figure 3.** Milestones: corporate decisions and policy initiatives related to electric vehicles and sustainable transportation.

---

![Figure 3](image-url)
lithium∗ battery/lithium mining, (ii) social∗ AND lithium∗ battery/lithium mining.

We searched only for peer-reviewed journal articles, and returned 195 and 434 results, respectively, for each database. After eliminating repetitive references, we had a sample of 395 articles. We used the Software SciMAT (Cobo et al 2012) to analyze the title, abstract and authors of literature. The bibliometric results are based on science mapping analysis, which is widely used to detect the hidden key elements (documents, authors, institutions, topics, etc) and how key elements are related to one another in different research fields (Small 1999). To analyze this research field, and detect and visualize its conceptual thematic area and thematic evolution, we used a bibliometric approach developed by Cobo et al (2011). The approach is based on (1) a co-word analysis (Callon et al 1985) and the h-index (Hirsch 2005, Alonso et al 2009) to represent the productivity and citation impact of a research theme, (2) the equivalence index (Callon et al 1991) to represent the similarity between keywords and (3) the inclusion index (Callon et al 1986, Sternitzke et al 2009) to represent the similarity of the conceptual nexus between research themes in different periods. A summary of scientific papers published over time in this field and the detailed methodology is provided in the supporting information (SI) is available online at stacks.iop.org/ERL/13/123001/mmedia document.

Each identified research theme will be characterized by how important (centrality) and how-well developed (density) it is. Given the measurements of centrality and density, the identified research themes can be classified into four thematic groups (Callon et al 1991, Courtial 1994, Couler et al 1998, He 1999, Cahlik 2000, Bredillet 2009, Cobo et al 2011): (a) motor, (b) basic and transversal, (c) emerging or declining, and (d) highly developed and isolated theme. The characteristics of each thematic group are summarized in table 1.

### Results and discussion

The following sections present and discuss the results in terms of the geographic distribution of publications, the temporal evolution of research themes, the connection of research themes with the evolution of EVBs technology and policy, and gaps in analytical coverage and thematic areas of research.

**Geographical distribution of research**

Figure 4 shows the geographical distribution of the total publications of each country from 1974 to present. This distribution identifies the national affiliation of article’s authors and the thematic focus of the academic contributions. We divide the literature into contributions from authors primarily associated with a lithium-producing country, LIBs-consuming country, or both, anticipating that the thematic focus of the literature will differ according to these categories. Countries that both consume LIBs and produce lithium, such as United States and China, contribute 44% of publications. The remaining literature is primarily from LIBs consumer countries, such as Korea, Japan, and European countries, constitute 54% of the publications. The publications from lithium-producing countries only account for 2% of the total publications.

Of the research coming out of the US and China, only 4% and 1% address socio-environmental impacts of lithium production, respectively. Only two publications from Germany study the socio-economic impacts of lithium extraction issues in production countries (Wanger 2011, Reuter 2016). Contributions from the Czech Republic and Finland also address socio-environmental issues in producing countries (Vuori et al 2008, Jetmarová 2012). There are far fewer publications from lithium producing countries such as Australia, Portugal, Argentina and Brazil. However, these latter studies were not disproportionately focused on the social and environmental issues driven by resource extraction. Only publications from Australia address future management and sustainable governance of lithium resource, taking into consideration the native environment and social justice (Prior et al 2013, Wang et al 2018). In short, there is a deficit of research contributions from lithium producing nations, and the geographic origin of the research authors does not appear to be associated with the thematic focus of the research.

| Research theme | Characteristics |
|----------------|-----------------|
| Motor themes   | Featured by high density and centrality values, usually contain highly-associated keywords in their clusters, implying that motor themes are internally well-developed and central for the structuring of a research field. |
| Basic and transversal themes | Having high centrality but low-density values. It includes keywords that are very different from each other. This thematic group is still central and important for a research field, although may not yet be fully developed or may remain generic; promising or past themes are always located here. |
| Emerging or declining themes | Poorly developed and marginal to the research field given the low values of density and centrality. Themes found in this group are always at the early stage of new trends within the research field. |
| Highly developed and isolated themes | Usually have high values of density and low values of centrality, indicating that themes in this group are peripheral and unimportant for the field even if they are well developed. Very specialized themes and themes from other disciplines can be found in this group. |
Structural and conceptual analysis of the thematic evolution of research themes

Our results indicate that the core research topics being studied in this research field are stable, although new topics have emerged over time. Prior to 2012, the impact-related themes are mainly focused on Environmental Impact, Greenhouse Gas and Energy Efficiency. After 2012, the impact-related themes become more diverse. New themes like Toxicity, Sustainability, Environmental-Friendly Technology appear. A detailed analysis of research themes in each study period can be found in supporting information.

Based on the analysis of themes detected in each time period, their keyword compositions, and their evolution across the consecutively defined periods of time, we detected four thematic areas in the research field of ‘Socio-Environmental Impacts of Lithium Extraction and Use’: (1) Environmental Concerns; (2) Battery Chemistry and Materials; (3) Socio-economic Concerns; (4) Battery Performance and Design.

These thematic areas and their evolution across the four defined periods are shown in figure 5. In this map, the solid lines represent a conceptual nexus, meaning that both of two linked themes share the same name or one theme is part of the cluster of the other theme. For example, the theme ‘Lithium-ion Battery’ in 2012–2016 and the theme ‘Lithium-ion Battery’ in 2017–Beyond share the same name. The dotted lines refer to a non-conceptual nexus, which means that the linked themes have common keywords but the name of shared keywords are different to the name of the themes. For instance, the theme ‘Greenhouse Gas’ in 2009–2011 and the theme ‘Environmental Assessment’ in 2012–2016 share the same keyword of ‘Human Health’ in their cluster of keywords, as shown in figure 6. The thickness of the edge is proportional to the inclusion index, a measure of commonality of elements between two themes (see SI), and the sphere size is proportional to the number of published documents in each theme. The different color shading indicate the themes that belong to the same thematic area. The thematic area Environmental Concerns is highlighted in green, Battery Chemistry and Material is in purple, and Battery Performance and Design is in yellow. The thematic area Socio-economic Concerns is highlighted in the color of red transitional to green to represent its conceptual shift from social-economic focus to environmental focus across the last two periods.

Analyzing the thematic evolution map for each thematic area allows for several observations regarding the structural and conceptual aspects of each thematic area. The thematic area Environmental Concerns is mainly composed of motor themes and basic themes, and includes the most important theme in each time period. This thematic area started in the period 1974–2008 with qualitative research on the broad environmental impacts caused by industrial development and mass transportation. In the next period, the thematic area is primarily shaped by policies and specific to topics related to electric vehicles and GHG emissions. In the third period, the thematic area broadened to incorporate multiple aspects, covering research focused on quantitative assessment of environmental impacts, the environmental performance of Li-ion battery, fossil fuel conservation, and even the application of Li-ion batteries to broader vehicle types. Finally, in the last period, this thematic area evolved from impact assessment towards an analysis of existing studies. Also, it reflected a new research trend focused on the environmental concerns of utility-scale batteries. It is noteworthy that the theme performance, which refers to the comprehensive performance of batteries (including not only environmental aspects

Figure 4. Geographical distribution of lithium-related publications (1974–present).
but also material endurance, safety, etc), is shared by two thematic areas, and indicates the integration of two thematic areas to some extent.

The thematic area **Battery Chemistry and Material** originated from one motor theme and one emerging theme, and then develops to one motor theme and one basic theme in the last period. The general trend of this thematic area is one of increasing productivity. The strong linkage between themes in the consecutive periods implies that there is no gap in its evolution. This thematic area started with a focus on battery chemistry, and kept this same focus in the first three periods, covering topics related to material selection and innovation for battery components. In the last period, this thematic area evolved to focus on narrower topics such as nanomaterials and the comprehensive performance of batteries.

The thematic area **Battery Performance and Design** began with one motor theme (energy-efficiency), one isolated theme (measurement), and one basic theme (technology), and evolved to one declining theme (battery-model), even as an important new motor theme (temperature-management) emerged in the third period. While there is an overall shrinking trend for this thematic area, over the first three periods there was an increase in the number of themes included in this thematic area. This thematic area started with a broad focus that included battery technologies, energy transmission efficiency of batteries, and measuring physical and electrochemical characteristics of battery cells. Then in the third period, this thematic area evolved to highlight one specific topic, temperature-management. Finally, in the last period, this thematic area shrank to one declining theme related to modeling batteries from multiple scales.

The thematic area **Socio-economic Concerns** emerged in the third period (2012–2016) with one motor theme (sustainability) and one emerging theme (toxicity), but the research topics covered by this thematic area partially transformed to focus on environmental concerns in the fourth period. In comparison with the number of themes and the duration of other thematic areas, this thematic area implies that there has been a lack of research related to socio-economic aspects. The thematic area formed in the period 2012–2016, with the focus on the sustainable governance of rare metals and human toxicity, which represented the emerging trend of social-economic research in this field.
In the last period, this thematic area has taken two directions: the first still focuses on social impacts like battery safety issues, while the second demonstrates a shift to focus on environmental toxicity and sustainability. It is also notable that over time the thematic area Socio-economic Concerns appears to be merging into the thematic area of Environmental Concerns. This trend implies a declining interest in research focused on the socio-economic concerns of lithium batteries, since Socio-economic Concerns may no longer continue to develop as a thematic area but rather diminish into a research theme within the thematic area of Environmental Concerns in the future.

Research on Socio-economic Impact of lithium extraction and use

The relative paucity of research on socio-economic impacts of lithium extraction and use makes it challenging to assess the evolution of themes in this domain over time. However, by illustrating the clusters containing keywords related to socio-economic impacts in each period of time (figure 6) we can show what keywords are emerging in the discourse about the topic. In each cluster represented in figure 6, the size of the sphere is proportional to the number of documents corresponding to each keyword, and the thickness of the link between two spheres is proportional to the equivalence index, a measure of similarity between keywords (see SI). The figure shows increasing interconnections among key words, with both an increasing number of themes as well as an increase in the diversity of types of themes across the consecutive periods.

In the first period (1974–2008), socio-economic keywords were interconnected with two motor themes and one basic theme. The studies represented by these keywords are focused on the socio-economic concerns of lithium batteries, since Socio-economic Concerns may no longer continue to develop as a thematic area but rather diminish into a research theme within the thematic area of Environmental Concerns in the future.

In the second period (2009–2011), most of the socio-economic keywords are interconnected with one motor theme (material), which indicates that the concentration of research topics is on the socio-economic concerns of battery materials, especially metals. Some specific issues are addressed, such as impacts on the health of the local populations near mining sites, and the responsible extraction of metal resources.

In the third period (2012–2016), socio-economic keywords are connected with three motor themes, and two keywords develop to themes in this period. The topics represented by socio-economic keywords in this period diverge into three major categories: (i) socio-ecological consequences of mining activities and social justice issues on the local society; (ii) human health and potential toxicity concerns of battery cells for society generally; and (iii) socio-economic benefits...
from government subsidies of electric cars. In the fourth period (2017–now/present), socio-economic keywords are interconnected with five themes; only three themes are motor or basic themes. In addition, socio-economic related themes disappear in this period, which shows a shrinking pattern of the studies on socio-economic topics in this research field. The research focus also largely shifts from a focus on impacts to one of economic and social gains from lithium recycling and economic opportunities for improving the energy system.

Results from studies related to socio-economic Impacts of lithium mining

The impacts of lithium mining on socio-economic well-being can be assessed across different aspects using various indicators for different stakeholders (Egbue 2012c). A social life cycle assessment approach (UNEP 2009) covers workers’ well-being including their working hours, salary, freedom of association, and occupational health and safety. The rights of the local communities have been very relevant for the indigenous communities who have lived in the Andean region of Chile, Bolivia and Argentina for many centuries. These rights cover basic human rights, access to communal land and water (Romero et al 2012), and freedom from racial discrimination. With respect to society more generally, indicators are used to gauge the level of the industry’s commitment to sustainability (e.g. existence of a legal obligation on public sustainability reporting), economic development (e.g. contribution of the product to economic progress) and the level of corruption in countries associated with the supply chain (e.g. risk of corruption in the country).

From a sustainability perspective, lithium mining presents environmental justice issues (Romero et al 2012). The Chilean Atacama region has been exploited for its rich mineral deposits, including copper, gold, silver, molybdenum and lithium. On one hand, lithium mining brings revenues to the State coffers and profits for national and foreign companies. On the other hand, these economic benefits have come with social and environmental costs. The mining industry is extracting a large amount of groundwater in one of the driest desert regions in the world. As the mining sites overlap with nature conservation areas, mining activities have been responsible for ecosystem degradation. The process of forced migration of populations from villages and the abandonment of ancestral settlements has been precipitated by water scarcity and an increasingly erratic water supply.

In terms of environmental impacts, the literature is mostly focused on the impacts of production and end-of-life of LIBs (Peters et al 2017). Most assessments have been limited to the production of LIBs used for EDVs, and focus on GHG emissions or energy consumption. Environmental impacts are primarily driven in these analyses by the process of manufacturing battery electrodes (i.e. cathodes and anodes) (Notter et al 2010, Ellingsen et al 2013). On average, about 110 g CO₂ equivalent of GHG emissions are emitted for producing 1 Watt hour of LIB storage capacity.

The environmental and occupational health and safety risks related to lithium in brines are comparatively higher than for other sources of lithium, but the potential health effects are currently poorly understood. Of most concern is the fact that the mining practice uses evaporation ponds, exposing the products to the elements (e.g. wind and storms). Since geochemically lithium is a highly mobile element, there is a high chance that lithium will be released into the environment and potentially affect nearby communities (Figueroa et al 2013). The processing of lithium mining involves evaporation of brines and washing the mineral with sodium carbonate in large-scale polyvinyl chloride (PVC)-lined shallow ponds. A failure in of PVC barriers may leak chemical substances such as softeners into the environment and cause water pollution (Wanger 2011). The consequences for human health and native biodiversity may be severe, although ingested lithium is not expected to bioaccumulate. However, a concentration of lithium in blood greater than 20 mg l⁻¹ poses a risk of death (Aral and Vecchio-Sadus 2008).

Research themes reflecting policy evolution

International and national policy/regulation changes, largely associated with the countries of lithium technology adoption and use, appear to have largely shaped the research tendencies and characteristics in this field. The Environmental Impact theme is the most important and well-developed motor theme in the 1974–2008 period. Studies represented by this theme during this period cover a broad research scope in environmental impact, including environmental pollution caused by industrial development, Li-ion battery/hydrogen fuel cell/nanotechnology as cleaner alternatives to traditional energy sources, comparing environmental impacts across different battery types, and the mitigation of battery impacts through end-of-life recovery. Greenhouse gas appears in 2009–2011 as a new basic and transversal theme, which indicates a shift of research focus to greenhouse gas emissions during this period. The focus on addressing environmental impacts may have to do with the adoption of the Kyoto Protocol in 1997 and its entry into force in 2005.

Furthermore, the appearance of electric vehicle, energy consumption, and greenhouse gas as important new themes can be associated with the new CAFE standard proposed in 2009, and the Clean Energy Act in 2009. The development and consolidation of themes related to battery technology and electric vehicle technology (i.e. material, chemical compound, electric vehicle), can be supported by the fact that
many financial programs and initiatives were actively supporting innovation on vehicle and battery innovation over this period. These results may suggest that academic research is following trends in the regulatory environment and resulting corporate responses, instead of defining and leading such trends.

The impacts being studied are largely concerned with battery production and manufacturing impacts. These impacts are occurring in the sites of battery manufacture and consumption. On the other hand, social impact topics, including socio-economic effects, human health effects, and the implications of lithium technology for developing countries, are diversely studied and connected with other research themes, have not evolved and become major research themes themselves. These findings suggest that it is the consuming countries’ regulatory environment that produces a demand for research and knowledge and speaks to inequities in the supply chain governance. Places like Chile and Bolivia may not have the resources or capacities to encourage the scientific attention necessary to create a thematic research focus on socio-economic and environmental issues pertinent to the sites of lithium production.

Towards a research agenda
The bibliometric analysis we present here not only reveals the evolution of research on social and environmental impacts of lithium-ion activities, but also provides some insight into the interaction of policy, industry and academia in defining knowledge trajectories that deserves further examination. While it is difficult to demonstrate causality or even directionality in the association of research themes with changes in the policy and regulatory context, the data does suggest that research themes evolve with policy/ regulation directions and initiatives. For example, the increased interests in various aspects of LIBs has been due to policies that incentivize new low carbon transportation technologies. The new CAFE standard that was introduced in 2009 spurred car companies’ decisions to produce various types of electric vehicles. Research first focused on battery technologies and performance, but since then has moved to the sustainability of battery production and use. In the context of increased investment in greenhouse-gas mitigation policy, research on environmental impacts are mostly focused on GHG emissions and energy use. Differences in the regulatory environments, policy discourse and governance capacities across countries involved in the lithium-ion supply chain also likely affect the trends observed in the literature. We note that existing studies are largely focused on impacts associated with battery technologies, rather than impacts of local mining activities. The impacts of the former issue are likely to be felt in relatively industrialized countries where electric vehicle demand is high; the latter impacts occur in geographic contexts where regulation may be less well enforced and the populations affected less able to bring attention to their concerns. Overall, studies on social impacts are much less developed than environmental impacts in general. In particular, impacts on local communities and indigenous groups have been rarely studied.

The lithium-ion supply chain exhibits many features of the geographically dispersed, multi-stakeholder supply chains that have been the subject of analysis in research on ‘telecoupling’. Telecoupling refers to the idea that impacts in one geographic location or social-ecological system may be distally associated with actions, policies, behaviors in another system (Liu et al. 2013). Because causality is difficult to demonstrate and quantify, governing such distant impacts can be challenging (Eakin et al. 2017). In these circumstances, intangible ‘flows’, such as information and knowledge that bring distal connections to the attention of decision-makers, can be instrumental (Eakin et al. 2014, Moser and Hart 2015). Academics and scientific research can play a key role in raising awareness about impacts, documenting causality and attracting attention to particular concerns that would otherwise be ‘off the radar’ of decision-makers in industry and government (Eakin et al. 2017).

In this light, the thematic focus and methodologies applied in research on the impact of lithium-ion technology can be particularly important. In this section, we will discuss the implications of the findings and discuss some of directions for research agenda. Specifically, we argue for filling the current gaps in addressing the local socio-environmental impacts due to lithium mining in terms of: (i) focused research topics/themes, (ii) methodologies and (iii) broader system perspectives. We supplement our analysis with preliminary interviews and interactions with the local communities in the Atacama region of Chile.

Neglected thematic areas
Research on establishing a baseline for water carrying capacity
In order to assess the impact and contribution of lithium technology on the environmental conditions of a particular system, it is important to assess baseline conditions. To our knowledge, no study has established a baseline to assess socio-environmental impacts of Lithium mining. One approach is to conduct a timeline analysis on various data, including hydrology, land use, mining activities, socio-economic conditions, and policy development. Water consumption is particularly important, given the water intensity of lithium mining. One estimate is that it requires 1 liter of brine water to produce 0.05–1 mg of lithium (Friends of the Earth Europe 2013). This translates into as much as half a million gallons to produce 1 ton of lithium. In the case of the Lithium Triangle in South America, competition for water is exacerbated by the
fact that the area is a major tourist destination (Aitken et al 2016, Segura et al 2018). Dynamical modeling, such as the one that has been used to assess water carrying capacity in East Africa (Gies et al 2014), could be a constructive approach. Statistical analyses based on the data would allow an estimation of how much change in water resources have been due to lithium mining or due to other factors such as climate change, other mining activities, and tourism. With such baselines, more reliable projections can be made of mining impacts on land use, food production, and the well-being of local communities.

Potential impacts on wildlife and ecosystem

The ecosystems in the lithium triangle region have extremely low precipitation, averaging 100–200 mm yr$^{-1}$ and evaporation rates of 1300–1700 mm yr$^{-1}$, with intermittent seasons of rainfall in La Nina years. Runoff from the mountains is the only source of water, and the livelihoods of local communities depend on the ecosystem services provided by the resulting wetlands. The region has a rich avifauna (e.g. three of the world’s six flamingo species) and vegetation cover (pastures and Marshes). In this global biodiversity hotspot, plant species are particularly sensitive to water availability, and a slight change in the water budget can greatly affect vegetation cover and plant diversity (Arroyo et al 1988).

Despite increasing attention in the press and among NGOs (Lombrana 2016, Corporación Nacional Forestal (CONAF) 2017), there is, as yet, limited attention in the scientific community to these issues. Theoretically, growing attention in the popular media and press can shift public opinion and add to pressure on industry to address these emerging concerns (Eakin et al 2017); scientific attention often accompanies these emerging discourses with more documented evidence.

Addressing knowledge asymmetries among stakeholders

What research themes achieve attention in media and in the research community, and thus contribute to shifting or shaping policy, is not arbitrary. Knowledge networks are politically and socially situated (Muñoz-Erickson et al 2017). In the case of complex supply chains such as those that characterize lithium technology, there are multiple interest groups and political administrations that are concerned about distinct outcomes from the technology production and use. Which voices are able to articulate their knowledge and values to others, and thus have agency in shaping the governance of the technology, depends on longstanding historical, political and economic dynamics in specific localities, nations and among countries in the international community. More research is needed on how these asymmetries affect what knowledge is produced and how it is used, and what methodologies and approaches might ensure more equitable and sustainable supply chain governance.

Knowledge of science and technology is needed to achieve sustainable development (Cash et al 2003). In the case of Chile, there are provisions in the agreement between mining companies and local communities to establish a community monitoring system (Cubillos 2018). Under the provision, communities can verify a company’s use of resources (e.g. water consumption). They also can check a mining company’s compliance with environmental regulations. Nevertheless, in many cases, local communities are left to make own arrangements and to recruit monitoring personnel. They are also often inundated with technical data that they have little expertise to interpret. Such asymmetries are important at local level, but also more broadly. There are knowledge asymmetries between countries that makes the regulatory environment uneven, and this then affects what issues receive attention and what do not.

Applications of impact assessments methodologies

Part of the challenge of documenting the full complexity of social and environmental impacts associated with a new technology is methodological. Social concerns are more likely to be assessed through qualitative data than more biophysical concerns (Barrow 2006). Methodological approaches and analytical tools that are flexible in the type of data used and that can integrate and synthesize social-ecological interactions can play critical roles in enhancing the knowledge base in Lithium ion technologies. Social-Life Cycle Analysis, for example, has been applied to assess the extraction and production impacts on workers, local communities, and the society in Chile (Egbue 2012c). The social and socio-economic impacts on workers, local community, and the society differ in the type of mining techniques and socio-economic status of countries, and thus the Social-LCA needs to be tailored to local contexts. Other promising methods and approaches involve ‘Consequential LCA’ (Ekvall 2002, Jørgensen et al 2010). To date, this approach is most associated with the assessment of GHG impacts (McManus and Taylor 2015, Arvidsson et al 2018), but it could be mobilized to address concerns in mining and battery use.

Reconsider the conceptual framing of research on impact assessment

Instead of having the technology and regulatory environment frame the research agenda, we can let the research agenda be framed by the values and norms of sustainable development. In addition, addressing
issues surrounding mining, livelihoods of communities, and development would benefit greatly by adopting broader system perspectives. These two conceptual framing frameworks articulated in the sustainable development goals (SDGs) and system-of-systems (SoS) approach respectively would in a sense ‘invert’ the way that it appears the research has evolved in lithium impacts and help drive the agenda with a more complete picture of impacts.

UN sustainable development goals (SDGs) is comprehensive list of 17 goals and 169 targets agreed by 193 participating UN member countries. SDGs are seen as the transformative pathway that will lead to a more equitable society. SDG 7 (affordable and clean energy), for example, sets a target for substantial increase in access to clean fuels and technology by 2030. Initiatives and efforts to meet this target will drive demand for clean electric vehicles technologies and as a result, LIBs.

In particular, two SDGs targets and indicators are related to the well-being of indigenous people. The first one is on SDG 2.3 (Zero Hunger) to ‘double the agricultural productivity and incomes of small-scale food producers…’. The second is SDG 4.5 (Quality Education) to ‘eliminate gender disparities in education and ensure equal access to all levels of education and vocational training.’ In addition, in 2007 144 countries have adopted the United Nations Declaration on the Rights of Indigenous Peoples. The non-binding resolution establishes a universal framework of minimum standards for the survival, dignity, and well-being of the world’s indigenous peoples. A forerunner of the declaration is a legally binding international convention concerning Indigenous and Tribal Peoples issued by the International Labor Organization (ILO) in 1989. It has been ratified by the three major Lithium producing countries: Argentina, Bolivia, and Chile. The so-called ILO-convention 169 (C-169) Article 6 (a) of the convention specifically mandate consultation: ‘consult the peoples concerned, through appropriate procedures and in particular through their representative institutions, whenever consideration is being given to legislative or administrative measures which may affect them directly.’

From an SoS perspective, mining activities, communities livelihood and regional development can be considered as a system in its own right (i.e. constituent system). An SoS of lithium mineral extraction and use spans different scales (e.g. individual, household, company, region, national and global) and aspects (e.g. resources, operations infrastructure, financial/economics, safety, policies and governance) of systems. SoS definition seeks to capture the competing interests and priorities of multiple actors across geographical boundaries (e.g. local indigenous communities and policymakers, mining companies, batteries and EDVs manufacturers, and consumers).

The traits of emergence and operational and managerial independence are the underlying characteristics of a system-of-systems (SoS) (Maier 1998, Agusdinata and DeLaurentis 2008). Each system is controlled by different actors with different and often conflicting priorities. Mining companies’ first priority is profitability and return to stakeholders (Cragg and Greenbaum 2002). On the other hand, governments’ priorities for development are more complex. Although each system operates and is managed independently, each system owner and elements will need to interact because they share physical space and compete for resources. They need to interact for two reasons: (1) need to address conflict and (2) achieve goals that are beyond the top priority of each actors (e.g. minimizing environmental impacts).

**Concluding remarks**

In this study, we investigated the state of literature using bibliometric approach with questions pertaining to the socio-environmental impacts of lithium mineral extraction and use. The reliance on LIBs by new low-carbon technologies such as EDVs demands that research holistically addresses the socio-environmental impacts in the supply chain of lithium batteries. In the past 40 years, research themes have evolved and covered a diversity of focus areas, but these are not necessarily inclusive enough to address the sustainability challenges stemming from increased technology adoption. In particular, the issue of lithium mining impacts on local communities needs to be urgently addressed.

**ORCID iDs**

Datu Buyung Agusdinata @ https://orcid.org/0000-0003-4537-0446

**References**

Agusdinata D B and DeLaurentis D 2008 Specification of system-of-systems for policymaking in the energy sector Integr. Assess. J. 8 1–24
Aitken D, Rivera D, Godoy–Faúndez A and Holzapfel E 2016 Water scarcity and the impact of the mining and agricultural sectors in Chile Sustainability 8 128
Alonso S, Cabreroiz F, Herrera-Viedma E and Herrera F 2009 h-Index: a review focused in its variants, computation and standardization for different scientific fields J. Informetr. 3 273–89
Aral H and Vecchio-Sadus A 2008 Toxicity of lithium to humans and the environment—a literature review Ecotoxicol. Environ. Saf. 70 549–56
Arroyo M T K, Squeo F A, Armesto J J and Villagran C 1988 Effects of aridity on plant diversity in the northern chilean andes: results of a natural experiment Ann. Missouri Bot. Gard. 75 55–78
Ardisdsson R, Janssen M, Svanström M, Johansson P and Sandén B A 2018 Energy use and climate change improvements of Li/S batteries based on life cycle assessment J. Power Sources 383 87–92
Barrow C J 2006 Proactive assessment, prediction and forecasting Environmental Management for Sustainable Development ed C J Barrow (London, New York: Routledge) pp 204–34
Bredillet C N and Chaos O A 2009 Mapping the dynamics of the project management field: project management in action (Part 2) Proj. Manage. J. 40 2–6
Moser S C and Hart J A F 2015 The long arm of climate change: societal teleconnections and the future of climate change impacts studies Clim. Change 129 13–26

Muñoz-Erickson T A, Miller C A and Miller T R 2017 How cities think: knowledge Co-production for urban sustainability and resilience Forests 8 203

Norwegian Road Federation 2018 Car sales in 2017 (available from: (http://ovias.no/bilsales-i-2017/category/751.html) (in Norwegian)

Notter D A, Gauch M, Widmer R, Wäger P, Stamp A, Zah R and Althaus H J 2010 Contribution of Li-Ion batteries to the environmental impact of electric vehicles Environ. Sci. Technol. 44 6550–6

NREL 2015 Automotive Lithium-ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations NREL/PR-6A50-63354 (www.energy.gov/erci/cm/i/downloads/automotive-lithium-ion-battery-supply-chain-and-us-competitiveness)

Olivetti E A, Ceder G, Gaustad G G and Fu X 2017 Lithium-Ion battery supply chain considerations: analysis of potential bottlenecks in critical metals Joule 1 229–43

Peters J F, Baumann M, Zimmermann B, Braun J and Weil M 2017 The environmental impact of Li-Ion batteries and the role of key parameters—a review Renew. Sust. Energy Rev. 70 491–506

Prior T, Wäger P A, Stamp A, Widmer R and Giurco D 2013 Sustainable governance of scarce metals: the case of lithium Sci. Total Environ. 461–462 785–91

Reuter B 2016 Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles Int. J. Interact. Des. Manuf. 10 217–27

Romero H I, Smith P and Vasquez A 2009 Global changes and economic globalization in the andes. challenges for developing nations Alpine Space - Man & Environment 7: Global Change and Sustainable Development in Mountain Regions ed R Pienner et al (Innsbruck: Innsbruck University Press) pp 71–95

Romero H, Méndez M and Smith P 2012 Mining development and environmental injustice in the Atacama desert of northern Chile Environ. Justice 5 70–6

Sceown C D, Taptich M, Horvath A, McKone T E and Nazaroff W W 2013 Achieving deep cuts in the carbon intensity of US automobile transportation by 2050: complementary roles for electricity and biofuels Environ. Sci. Technol. 47 9044–52

Segura D, Carrillo V, Remonsellez F, Araya M and Vida G 2018 Comparison of public perception in desert and rainy regions of Chile regarding the reuse of treated sewage water Water 10 334

Shepherd S, Bonsall P and Harrison G 2012 Factors affecting future demand for electric vehicles: a model based study Transp. Policy 20 62–74

Sierzchula W, Bakker S, Maat K and van Wee B 2014 The influence of financial incentives and other socio-economic factors on electric vehicle adoption Energy Policy 68 183–94

Small H 1999 Visualizing science by citation mapping J. Am. Soc. Inf. Sci. 50 799–813

Speirs J, Contestabile M, Houari Y and Gross R 2014 The future of lithium availability for electric vehicle batteries Renew. Sust. Energy Rev. 35 183–93

Stamp A, Lang D J and Wäger P A 2012 Environmental impacts of a transition toward e-mobility: the present and future role of lithium carbonate production J. Clean. Prod. 23 104–12

Sternitzke C and Bergmann I 2009 Similarity measures for document mapping: A comparative study on the level of an individual scientist Scientometrics 78 113–30

Tahil W 2007 The Trouble with Lithium: Implications of Future PHEV Production or Lithium Demand (Martainville: Meridian International Research)

Tahil W 2008 The Trouble with lithium 2: Under the Microscope (Martainville: Meridian International Research)

The Economist 2017 The Economist 18 February Volts wagons (www.economist.com/business/2017/02/18/electric-cars-are-set-to-arrive-far-more-speedily-than-anticipated)

UNEP 2009 Guidelines for Social Life Cycle Assessment of Products UNEP-SETAC Life-Cycle Initiative (www.lifecycleinitiative.org)

UNEP 2009 Guidelines for Social Life Cycle Assessment of Products UNEP-SETAC Life-Cycle Initiative (www.lifecycleinitiative.org)

Vuori S et al 2008 Summary: Geological resources in Finland, production data and annual report 2007 (Geological Survey of Finland Report of Investigation 176) (Espoo: Geological Survey of Finland) (in Finnish)

Wang Q, Liu W, Yuan X, Tang H, Yang W, M, Zuo J, Song Z and Sun J 2018 Environmental impact analysis and process optimization of batteries based on life cycle assessment J. Clean. Prod. 174 1262–73

Wanger T C 2011 The lithium future-resources, recycling, and the environment Conserv. Lett. 4 202–6