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Green principles for responsible battery management in mobile applications

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ABSTRACT

Vehicle electrification is expanding worldwide and has the potential to reduce greenhouse gas emissions (GHGs) from the transportation sector. Batteries are a key component of energy storage systems for electric vehicles (EVs), and their integration into EVs can lead to a wide range of possible environmental outcomes. These outcomes depend on factors such as powertrain type, electricity source, charging patterns, and end-of-life management. Given the complexities of battery systems, a framework is needed to systematically evaluate environmental impacts across battery system life cycle stages, from material extraction and production to use in the EV, through the battery's end-of-life. We have developed a set of ten principles to provide practical guidance, metrics, and methods to accelerate environmental improvement of mobile battery applications and facilitate constructive dialogue among designers, suppliers, original equipment manufacturers, and end-of-life managers. The goal of these principles, which should be implemented as a set, is to enhance stewardship and sustainable life cycle management by guiding design, material choice, deployment (including operation and maintenance), and infrastructure planning of battery systems in mobile applications. These principles are applicable to emerging battery technologies (e.g., lithium-ion), and can also enhance the stewardship of existing (e.g., lead-acid) batteries. Case study examples are used to demonstrate the implementation of the principles and highlight the trade-offs between them.

1. Introduction

Deployment of battery systems in both mobile and stationary (grid) applications has increased recently with the goal of reducing GHG emissions of the transportation and electricity sectors. In the transportation sector, development of a range of EVs, including battery electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid vehicles (PHEV) have driven battery development and production. In the electricity sector, batteries help integrate variable renewable energy sources and improve grid reliability and sustainability [1]. Each battery technology has specific operational characteristics, such as chemistry, round-trip efficiency, and service life that make it suitable for a particular application. Several studies have identified and compared the characteristics of various energy storage systems including batteries, demonstrating that key energy storage system parameters differ greatly across technologies [2–7].

Manufacturing, use, and end-of-life management of battery storage systems may lead to significantly different life cycle environmental impacts. Regarding battery production, Larcher and Tarascon argue that the only viable path towards more sustainable batteries is rooted in designing electroactive materials that release less CO_2 during production, while providing desirable performance [8]. Wang et al. conducted life cycle assessment to analyze and compare the production burden of lead acid, lithium manganese and lithium iron phosphate batteries [9]. Through life cycle assessment, Arvidsson et al. concluded that reducing electricity consumption of cell production, sourcing renewable electricity such as solar or wind power, improving the specific energy of the cell, and shifting to low-impact carbon materials improve the environmental impact of lithium sulfur batteries [10]. Several other studies have also analyzed the life cycle assessments of these batteries [11–13]. Ambrose and Kendall argue that charging of electric vehicles at high penetration rates increases demand for electricity, resulting in a change in utility GHG emission factor. This impact is dependent on location, local mix of energy sources, EV range, level of public charging deployment, charging schedules (daytime vs. nighttime), and charging rates [14]. A study on battery recycling by Argonne National Laboratory (ANL) indicates that recycling lithium, aluminum, and copper can reduce the energy intensity of battery production by approximately 40%–50% [15].

Green principles have been used widely by industry and practitioners, in both chemistry and engineering [16–18]. These sets of principles are generic by design and due to the unique challenges of energy storage systems, we developed a set of principles specific to green energy storage systems for grid applications [19]. The goal of this

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work was to improve environmental outcomes when integrating grid-scale energy storage into the electricity system. Battery design and life cycle management strategies differ somewhat between stationary and mobile applications. For example, battery weight is a key design parameter in mobile applications that strongly influences fuel economy and use stage impacts, but is generally not a significant criterion in stationary applications. Operational strategies (e.g., charging patterns) that can preserve battery health and limit degradation are also different between mobile and stationary applications and due to vehicle range requirements, degradation is a more critical concern in mobile applications.

Specific guidance is needed to elucidate tradeoffs (e.g., material production vs. use stage impacts) and quantify the environmental merit of vehicle battery design, manufacturing, use, and management. Use of stationary energy storage principles to guide development and deployment of mobile applications is inappropriate, will likely lead to sub-optimal outcomes, and does not best serve the target audience. We present here a set of ten principles to provide practical guidance on improving life cycle environmental performance of mobile battery systems. The goal is to promote sustainable life cycle management of battery systems in mobile applications. Targeted audiences for these principles include battery designers, suppliers, original equipment manufacturers (OEMs), and end-of-life managers.

We created an extensive list of concepts and potential principles through close interaction with stakeholders and review of existing literature on design, operation, and end-of-life of mobile battery systems, that we then condensed by combining principles with similar content or intent. We solicited feedback to refine these principles at several meetings with diverse stakeholders that included battery manufacturers, suppliers, OEMs, recyclers, and ANL. Based on this feedback, we further condensed the set to the current ten principles. The relative importance of any principle depends on the application and question being asked. We understand this set of principles is not immutable and recognize that not all principles will apply to a given question and, more importantly, that there will be tradeoffs between principles. We have produced a parsimonious set of principles that can guide analysis and inform decisions on development and deployment of battery systems for mobile applications.

1.1. Elements of green principles for sustainable battery management in mobile applications

Fig. 1 shows three main system components that shape the development of the green principles. These components are the battery (e.g., Li-ion, lead-acid), vehicle (ICEV, BEV, PHEV, and HEV), and grid electricity source (including fossil fuels, nuclear, hydro, and renewables). The battery life cycle can be condensed into three main stages: material production and manufacturing; use; and end-of-life (EoL). During the use stage, the battery is integrated into and operated in a vehicle, and is charged by electricity from the local utility. Fig. 1 highlights key parameters in each battery life cycle stage that are emphasized in the principles. For example, type of chemistry influences battery cycle life and thermal stability, which ultimately drive its sustainability performance [14]. Degradation of battery capacity during use results in a reduction in round-trip efficiency and environmental performance.

2. Green principles for responsible battery management in mobile applications

2.1. Principle #1: choose battery chemistry to minimize life cycle environmental impact

Develop and select battery chemistry that enhances operational and broader life cycle performance, which ultimately drive sustainability.

Chemistry type affects important parameters of the battery system, and therefore influences the system's technical and sustainability performance. For example, the amount of electrical energy per mass or volume that a battery can deliver is a function of cell voltage and energy capacity, which are both dependent on chemistry [20]. Battery power, which depends partly on the battery's engineering, also depends fundamentally on its chemistry [20].

The aging mechanism and cycle life of different battery types are very complicated, depending on parameters such as cathode and anode materials and electrolyte composition. Currently, cathode materials for commercial lithium-ion (Li-ion) batteries include $LiFePO_4$ (LFP), $LiMn_2O_4$ (LMO), and $LiNi_xCo_yMn_{1-x-y}O_2$ (NCM), and anode materials include $Li_4Ti_5O_{12}$ (LTO) and graphite (C) [21]. Among cathode materials, spinel lithium manganese oxides (LMO) are receiving wide attention due to their low price, high energy density, and nontoxicity [21,14]. LMO, LFP, NCA and NCM have been successfully adopted by automakers including Tesla, BMW, BYD, Chevrolet, Mercedes Benz-Daimler, Volkswagen, and Nissan [22]. It is expected that by 2025, NMC battery technology will increase its market share owing to its higher energy density than LFP, while NCA and LMO will keep stable shares of the total market [22]. Tesla uses mainly NCA technology, while most other carmakers use LFP, NCM, LMO or blended NCM and LMO technology [22]. Li-ion batteries are also characterized by large power/weight ratio as well as good energy density [23].

There has been concern regarding scarcity of some materials, such as cobalt, used in electrodes [8]. Cobalt is costly, and manufacturers are moving toward lower cost and higher energy density materials to reduce the cost of battery manufacturing, while also seeking to improve safety and performance. Therefore, cobalt-free materials will be more attractive and cost-competitive eventually [22]. On the other hand, recovering cobalt at end-of-life and returning it to new battery production has the potential to reduce battery life cycle impact [22,24].

Since each battery type uses different materials, their masses and production burdens are different [14]. Majue-Bettez et al. compared the production burden of nickel metal hydride (NiMH), nickel cobalt manganese Li-ion (NCM), and iron phosphate Li-ion (LFP) batteries and showed that, except for ozone depletion potential, the NiMH battery performed significantly worse than the two Li-ion batteries in all impact categories [25]. These reasons are the greater charge-discharge efficiency of Li-ion relative to NiMH, the fact that each kilogram of Li-ion battery stored 2–3 times more energy over its lifetime, and also that NCM and LFP batteries contained less nickel and virtually no rare earth metals. Based on their results, among Li-ion batteries, LFP had more environmental benefits relative to NCM, due to a greater lifetime and the use of less environmentally intensive materials. Zackrisson et al. concluded that using water as a solvent instead of N-methyl-2-pyrrolidone (NMP), led to lower environmental impacts in the slurry for casting the cathode and anode of Li-ion batteries [26].

These examples illustrate that the materials and chemistries used in batteries and their compositions influence battery performance, aging mechanisms, and environmental sustainability.

2.2. Principle #2: minimize production burden per energy service

Minimize the production burden per energy service provided by the battery system. Production burden includes material production, manufacturing, and associated infrastructure.

Battery system material production and manufacturing stages account for a significant environmental burden, resulting in an increase in the total vehicle production burden. In general, production of the traction battery accounts for the highest energy demand and GHG emissions of the components in an electric powertrain [27]. For example, Kim et al. compared the production burden of a Ford Focus BEV and Ford Focus ICEV, and their results showed a 39% increase in cradle-to-gate GHG emissions of the Focus BEV compared to the ICEV, within the range of literature estimates of 27–63% increases for hypothetical nonproduction BEVs [27]. They assume that cell mass is 55%–60% and

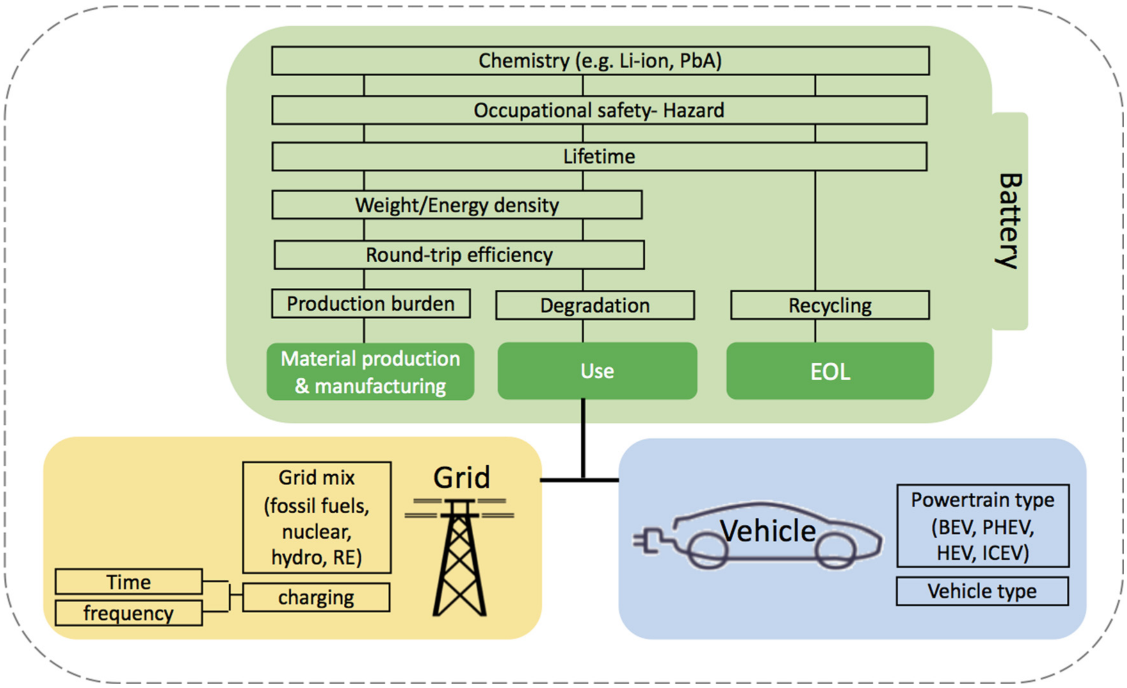

Fig. 1. Framework for developing green principles for mobile applications.

pack material mass (depending on materials used) is 40% of battery system total mass. Ambrose and Kendall showed that aluminum was responsible for approximately 40% of material production global-warming potential (GWP) for Li-ion batteries. Emissions associated with energy consumed for cell and pack assembly were 80% of total production emissions, or 157–475 kg CO_2e/kWh [14]. In a sensitivity analysis, Ellingsten et al. demonstrated that producing battery cells with electricity from a clean energy source was the most effective way to reduce emissions associated with battery production [28]. Combustion of hard coal and natural gas to supply energy for the manufacturing of battery cells made up 51% of the battery's total GWP, and extraction of hard coal and natural gas made up 32% of the battery's total fossil depletion potential. In an examination of selected air emissions beyond GHGs, Dunn et al. showed that copper and aluminum were the key contributors to emissions of SO_x and NO_x in the cradle-to-gate stages of the Li-ion battery life cycle [29].

Based on Notter et al., the major contributors to environmental burden for battery production are metal supply and process energy [30]. Metals are used in the production of the anode (copper collector foil), the cathode (aluminum collector foil), and the battery pack. The battery pack requires copper for cables, steel for the battery container, and copper, gold, and tin for battery management system [30,31].

The relative importance of the manufacturing stages increases with degree of vehicle electrification, due to the reduction of emissions from the well-to-wheel (WTW) life cycle of vehicle fuels and the increase in production of new electrical drivetrain components [31]. There are several other studies that review and compare the production burden of different battery chemistries and provide detailed life cycle impact from production of each battery component, including energy required for cell and pack assembly [9,32–34]. Wang et al. show that electrode manufacturing and assembly are the key processes that drive the environmental impact of lithium manganese and lithium iron phosphate batteries [9]. Yuan et al. show that 88.9 GJ of primary energy is needed to produce a 24 kW h LMO-Graphite battery pack, with 29.9 GJ of energy used for battery material processing, 58.7 GJ energy consumed in the battery cell production, and 0.3 GJ energy used in the final battery pack manual assembly [35]. In a review of Li-ion battery LCAs, Peters et al. conclude that on average, producing 1 Wh of storage capacity is associated with a cumulative energy demand of 328 Wh and produces 110 g CO_{2e} of greenhouse gas (GHG) emissions [34] Although the majority of studies focus on GHG emissions or energy, they show that other impact categories such as toxicity might be even more important. They also conclude that energy density, cycle life, and charge-discharge efficiency are key parameters that drive the environmental performance of Li-ion batteries.

Excluding the production-related emissions for electric vehicles (EVs) downplays tradeoffs between their production and operational emissions, so a life cycle approach for evaluating emissions is required to ensure that policies intended to reduce GHG emissions of vehicles are successful [14].

2.3. Principle #3: minimize consumptive use of critical and scarce materials

Design and production of batteries should minimize the consumptive use of scarce and critical materials, since depletion of materials can constrain continued deployment of these systems.

It is essential that increased adoption of EVs does not cause adverse consequences, such as unsustainable consumption of metals (lithium, cobalt, manganese) in addition to energy-intensive or high-impact steps in battery production [29,33,36]. Battery systems are material-intensive and if they are to be widely deployed, their constituent materials will be needed in large quantities. In an assessment of the resource potential of Li-ion batteries, Peter and Weil conclude that cobalt and nickel used in battery chemistry, and copper and the (semi-) precious metals required for the battery electronics (e.g. gold and silver) are critical substances [36]. Another example is the high resource depletion impact from tantalum, which is required for electronic components [36].

The U.S. Department of Energy assesses the criticality of materials in the energy sector in two dimensions: importance to clean energy and supply risk [37]. Graedel et al. identify criticality of metals in three dimensions: supply risk, environmental implications, and vulnerability [38]. The world's largest known lithium reserves exist in Bolivia, which is not among the largest lithium producers. Bolivia's undeveloped infrastructure, its unpredictable regulatory environment and uncertain security of mining investments continue to present obstacles to investors [39]. High magnesium concentration in Bolivian brines is another reason that the lithium market is not more well developed, as a high Mg/Li ratio makes it more difficult and expensive to extract lithium [40,41]. This type of contradiction and the factors behind it have caused anxieties among EV manufacturers and lithium-producing countries.

Considering the criticality dimensions in material selection for vehicle battery systems is crucial to enhance their environmental performance and make batteries sustainable, efficient, and reliable [42]. One option is to make electrodes from renewable sources. In addition, organic materials have been used in the semiconductor industry recently and are expected to make progress in energy storage in the coming decades. However, organic materials currently have several disadvantages such as limited thermal stability and significant solubility in electrolytes [20].

A material selection strategy for energy storage systems acknowledges that cost reduction is highly important and material costs have the biggest share in the cost of these systems, but emphasizes that it is necessary that both abundant and low-cost materials are used in energy storage devices [43].

Consumptive use of scarce and critical materials changes them in such a way that they are no longer available for their first use, limiting future generations' access to them [44]. While batteries can have a beneficial application in EVs, their production should minimize the consumptive use of scarce and critical materials; otherwise, depletion of materials can constrain their deployment.

2.4. Principle #4: maximize battery round-trip efficiency

Maximize battery round-trip efficiency to minimize energy losses during vehicle charging and operation.

Round-trip efficiency is one of the most important parameters of battery energy storage systems, ranging between 75% (for zinc-bromine batteries) and 90% (for Li-ion batteries) [45,46]. Round-trip efficiency is defined as the ratio of energy delivered by the storage system to energy input [45]. Round-trip efficiency is one of the main factors in use stage emissions during vehicle operation, so increasing round-trip efficiency leads to more environmental benefits during EV operation. In addition, vehicle electrification enables energy recovery through regenerative braking, which increases vehicle energy efficiency. Fast charging can also increase EV efficiency [47], but the focus of this principle is on battery round-trip efficiency.

Zackrisson et al. investigated the impact of round-trip efficiency on use stage emissions of a PHEV, modeling the use stage as electricity losses during the PHEV lifetime and the extra energy needed to carry the battery weight. Their results showed that the dominant impacts in the use stage came from electricity losses in the battery and that environmental impacts related to round-trip battery efficiency were two to six times larger than the impact due to battery weight in PHEVs (assuming 90% round-trip battery efficiency) [26].

Temperature conditions have a direct effect on battery efficiency [48]. At cold temperatures, battery efficiency, discharge capability, and available energy decrease, while battery internal resistance increases, reducing the power that can be drawn from the battery. Battery performance improves with temperature, but batteries also degrade faster at high temperatures, increasing thermal management requirements [48].

It is very important to design and deploy batteries with maximum round-trip efficiency, as the use stage burdens decrease when battery efficiency is increased.

2.5. Principle #5: maximize battery energy density to reduce vehicle operational energy

Design battery storage with maximum energy density to minimize mass-related fuel consumption.

Reducing vehicle mass is a key strategy to achieve significant reductions in life cycle energy consumption and emissions [49]. The high energy efficiency (conversion of fuel to vehicle motion) of EV powertrains is due to the high efficiency of an electric motor compared with an internal combustion engine, and also the ability to capture energy via regenerative braking in EVs. An et al. found that the benefit of mass reduction is less for a hybrid electric vehicle (HEV) than for an ICEV due to the higher efficiency of HEV powertrains and their ability to capture kinetic energy through regenerative braking [50].

Manzetti et al. suggest that the highest energy density batteries are preferred for electric vehicles, and research to increase energy density is of immediate importance and a significant factor in raising the number of EVs on the road [23].

Luk et al. showed that the multi-material lightweight vehicle (MMLV) glider could reduce life cycle GHG emissions across different powertrain types despite its use of lightweight materials, which can be emissions intensive to produce, since it enabled a decrease in fuel cycle (production and use) emissions. Fuel savings, and thus life cycle GHG emission reductions, vary significantly across different powertrain types [51].

The masses of vehicle components by vehicle type are shown in Fig. 2 and fuel consumption values and fuel reduction values quantifying marginal fuel savings from lightweighting are shown in Fig. 3. The high efficiency of HEVs and BEVs decreases the potential fuel savings from lightweighting compared to ICEVs. BEVs are more efficient than HEVs, though they require more battery mass to provide an acceptable driving range. A lightweight glider can use a smaller battery for a given driving range. Battery downsizing is another option for mass reduction that further decreases fuel consumption and use-stage GHG emissions [51]. Previous work has also shown that powertrain re-sizing can significantly increase fuel economy [52].

2.6. Principle #6: design and operate battery systems to maximize service life and limit degradation

Use charging patterns that minimize degradation by preserving battery capacity and round-trip efficiency. Temperature also impacts degradation.

The lifetime of a battery is dependent on several complex mechanisms relating to cell chemistry, charging and discharging conditions (e.g., fast charging and discharging cycles), maximum charge voltage, charging current, temperature, and cycle depth [31,53,54]. Battery service life is a function of battery degradation (or aging), which is characterized by a gradual decline of capacity and an increase in internal impedance (resistance) [14]. Degradation results in battery replacement or vehicle retirement [14].

Battery aging occurs due to the electrochemical degradation processes that take place during the operation and rest periods [55], and these processes are different across battery types. Large changes in state of charge, frequency of cycles, and thermal conditions accelerate loss of anode or cathode active material and increase in resistance, which

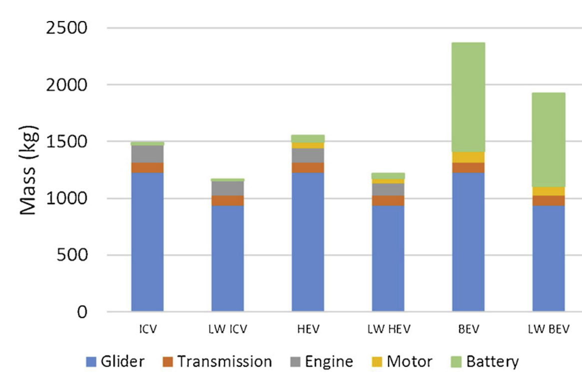

Fig. 2. Mass specifications of vehicle components [51].

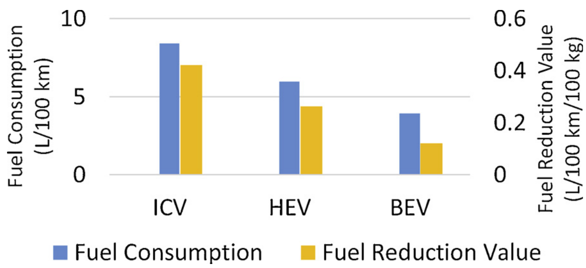

Fig. 3. Fuel consumption and fuel reduction values across powertrain types [51].

result in battery aging [14,21,56,57]. Physical degradation with cycling results in capacity fade and power fade. Capacity fade is a gradual loss in energy capacity that reduces vehicle range. It is mainly caused by formation of a solid electrolyte interface (SEI) passivation layer at the anode-electrolyte interface due to consumption of lithium ions (in the case of Li-ion batteries) [58]. Power fade is the increase in internal resistance (or impedance) of the cells. It limits the power capability of the system during acceleration, reduces ability to recapture energy during regenerative braking, and decreases the performance of the vehicle [56,58]. SEI also contributes to power fade by increasing resistance to ion transport [58]. At high temperatures, the formation of an SEI layer is accelerated [56]. Battery degradation also results in losses in battery charging (round-trip efficiency fade), affecting GHG emissions and energy consumption due to increased electricity use during battery operation in a vehicle [60]. These fading mechanisms affect pack lifetime and influence consumer acceptance of EVs.

Temperature also has significant impacts on degradation of batteries. High ambient temperatures increase battery performance degradation and consequently can affect vehicle lifetime [14]. In the case of Li-ion batteries, at extremely cold temperatures lithium metal deposition is the principal degradation mechanism [56]. It causes cathode breakdown, short circuits, and safety issues [14,53]. In addition, cold and hot ambient temperatures reduce EV range due to increased energy demand for auxiliary loads, such as cabin heating in winter and air conditioning in summer. Therefore, EVs may consume additional energy for each kilometer driven when operating in cold or hot temperatures, depleting the battery faster [61].

Current commercial Li-ion batteries are controlled by a battery management system [53]. The management system must include fault diagnosis functions to provide battery degradation information and give warnings of unhealthy batteries [53]. Thermal management can mitigate degradation caused by extreme thermal conditions and preserve battery health, though it typically increases vehicle energy requirements [14].

The coupling of high state-of-charge (SOC) and high temperature accelerates degradation [59]. Serrao et al. showed that battery life can be kept within an acceptable range in PHEV use if very deep cycles (< 60% depth-of-discharge (DOD)) are avoided, if temperatures are kept low (< 35 °C), and if average SOC is kept low (< 60%) [62]. Amiri et al. also recommended avoiding deep discharging and frequent charging to limit battery deterioration [63]. Hatzell et al. concluded that Li-ion batteries must operate within the desired temperature range of -30 °C and 52 °C for performance, efficiency, and health reasons. They showed that temperatures below -30 °C led to considerably increased cell impedance, temperatures above 60 °C led to severe capacity loss, and finally at temperatures more than 85 °C the SEI layer decomposed, which could cause rapid degradation and thermal runaway [64].

Lunz et al. show that high battery SOC causes battery degradation, whereas the cycling of batteries at medium SOC has a minor contribution to their aging [65]. SOC impacts the stability of electrode and electrolyte: high electrode potentials (high SOC) cause electrolyte decomposition in the surface region of a cell's anode and cathode, consuming active Li-ions and causing growth of SEI on the electrodes' surfaces [65]. This leads to capacity and power fade, as well as impedance rise. Battery lifetime can be increased by reducing the target charge SOC to lower values, or by minimizing the rest periods at high SOC. Therefore, battery charging should occur immediately before departure [65]. Lunz et al. explain that since standby times dominate battery operation, battery lifetime can be significantly increased by implementing smart charging strategies (in terms of frequency and time of charging) [65]. Hoke et al. conclude that if the next day's battery energy requirement is known, the battery can be charged only to the extent required, rather than charging to a nominal maximum SOC as is typical. Spreading charging over time also reduces very high temperatures associated with fast charging [66]. These strategies minimize battery degradation and increase lifetime. High SOC and current exponentially increase capacity fade (since the anode side reaction takes place at high potentials corresponding to high SOCs), but degradation is also high at low SOC because of the cathode side reaction [67]. A high value of Δ SOC, the change in SOC during a charge or discharge, is related to battery power loss and the undesirable development of SEI [68]. Degradation causes more frequent battery replacement, resulting in additional environmental burdens associated with production and processing of new materials [69]. Detecting degradation (known as health monitoring [70]), and preventing catastrophic failures improve battery life and avoids these adverse environmental impacts.

2.7. Principle #7: minimize hazardous material exposure, emissions and ensure safety

Exposure to, and emission of, hazardous materials should be minimized during production, use (operation and service), and end-of-life stages of the battery system in order to provide a safe environment for communities, workers, and users.

Battery system safety is critical and must be emphasized during all battery life cycle stages. There are risks arising from the basic electrochemistry of batteries and if they are misused or face abnormal environments, these inherent hazards can lead to accidents [71,72]. In Li-ion batteries, the presence of combustible material and an oxidizing agent increases the risk of run-away reactions resulting in fires or explosions [20]. Some Li-ion batteries can also be categorized as hazardous waste due to high levels of lead, cobalt, copper, and nickel [73]. Improvements in Li-ion battery health monitoring are essential to address customer concerns regarding safety if these batteries are to fulfill their potential in the transportation sector [20,70]. Improvements in electrolyte composition could make the chemistry safer, but accidents are mainly due to attempts to package more active material in the same volume, resulting in internal short-circuits [20].

Policy-makers and the automotive industry should understand that resource use and toxicity associated with mining have significant adverse impacts on the environmental performance of EVs [31]. In an analysis of the production burden of different batteries, Majue-Bettez et al. indicated that, for NiMH batteries, mining and metallurgy activities required for the production of the nickel in the electrodes and the current collectors were responsible for more than 70% of the human toxicity and ecotoxicity impacts. These activities also contributed more than 80% of particulate matter formation, terrestrial acidification, and resource depletion potential impacts [25].

Fault mechanisms that influence safety include thermal runaway resulting from exothermic electrochemical reactions, mass and thermal transfer processes, and mechanical faults (e.g., stress deformation or delamination). Thermal runaway, the most dramatic event potentially occurring in a battery system, results from abnormal conditions of use or manufacturing defects. Triggering events for thermal runaway include internal or external short-circuits, overcharge, overdischarge, or overheating [74].

Battery end-of-life managers have found higher profits in places where workers have low wages and environmental/workplace regulations are not strong or are weakly enforced. This has resulted in excessive and uncontrolled air and water releases of lead [75]. The United Nations Environment Programme labels lead a “potent neurotoxin” and a “nerve poison” that is capable of causing serious and, in some cases, irreversible neurological damage and that threatens the health and intellectual development of millions of children and adults [76]. China has faced significant public health issues, with millions of children currently at risk of lead poisoning. The rapid increase in production and recycling of lead-acid batteries in China is the main source of lead exposure and may be a reason for high blood lead levels there [76]. Average blood lead levels in children living near battery factories in developing countries are four times the current level of concern established by the World Health Organization [76].

2.8. Principle #8: market, deploy, and charge electric vehicles in cleaner grids

Charge EVs with cleaner electricity to lower life cycle emissions. Any grid-vehicle interaction should result in lower emissions, and cause minimum battery degradation.

While electric powertrains are more efficient, their adoption does not necessarily lead to reduced life cycle GHG emissions. Tailpipe emissions are reduced in EVs, but are at least partially shifted to electricity generation units, meaning that the fuel used to generate electricity and EV performance under real-world conditions influence the life cycle GHG emissions of the EV [30,61]. Only if electricity generation is free from emissions of fossil carbon can adoption of EVs contribute to global warming mitigation [31,33]. Estimates of emissions performance based exclusively on fuel cycle or tailpipe emissions miss structural shifts in emissions between production and use [14], highlighting the need for life cycle GHG accounting.

Electric vehicle charging at high penetration rates would significantly increase demand for electricity, which will alter local utility grid emission factors based on: local and regional mix of energy sources, EV range, level of public charging deployment, charging schedules (daytime versus nighttime charging), and charging rates [14,77]. Fig. 4 shows annual GHG emissions of a Ford Focus BEV by eGRID subregion across the U.S. This map uses eGRID2016 emission rates (lb/MWh) and EPA fuel economy data for the Ford Focus BEV (31 kW h/100 mi and 15,000 mi/yr) [78,79]. An equivalent Ford Focus ICEV (289 g/mi and 15,000 mi/yr) would generate 9557 lb/yr of GHG.

In addition to location and timing of charging, temperature effects on EV performance can also be an important determinant of GHG emissions [61,80]. The effect of cold temperatures on EV performance leads to much higher GHG intensity during EV operation in cold regions of the country, which is compounded by high coal generation during winter months in the Midwest [61]. On the other hand, in states with warm weather and low-carbon electricity generation, such as California and Florida, EV adoption leads to emissions reduction compared to ICEVs [61]. These results demonstrate that emissions reduction benefits of electric powertrains depend on marginal electricity generation and ambient temperature. This is an important implication for policymakers seeking to incentivize EVs in specific regions. Another sustainability implication of vehicle electrification is that EVs shift the location of emissions from the tailpipe to the power plant, where they are easier to treat. This can lead to health benefits to society if the former is in a dense urban area and the latter is in rural area, though this can have negative health impacts adjacent to the electricity generating facilities [61].

2.9. Principle #9: choose powertrain and vehicle types to maximize life cycle environmental benefits

Increasing degree of electrification from ICEV to PHEV to BEV should result in lower life cycle emissions, depending on the grid mix.

Vehicle energy and GHG emissions associated with material production and manufacturing increase as degree of vehicle electrification increases. This is a result of changes in the vehicle powertrain (addition of a battery) and powertrain-dependent subsystems, including body structure, suspension, and fuel and exhaust [52]. Lewis et al. estimated that addition of a traction battery increases vehicle production GHG emissions by 2.5 g GHG/mi (78% of the total increase) for an HEV compared to an ICEV [52]. Of the remaining increase (0.7 g GHG/mi), 40% is a result of other changes in the powertrain and 60% is related to increased structural support. As degree of vehicle electrification increases, energy and GHG emissions from battery production increase, but are not larger than the savings due to reduced operation of the internal combustion engine. However, this does not necessarily mean that an all-electric vehicle would have the least life cycle impact, because upstream burdens could be very significant, depending on material and energy sources used [52]. Zackrisson et al. showed that production phase impacts for a PHEV were almost always larger than use-phase environmental impacts, except when the vehicle was being driven in countries with coal-dependent electricity generation [26].

Studies show that driving behavior and traffic intensity are important in determining fuel and energy used for transportation. Electric powertrains are best in congested traffic where the low speed and stop-start driving allow for energy recovery through regenerative braking and reduction of tailpipe emissions [26,31]. This is important for shaping transportation policies and strategies and for understanding which market sectors benefit most from incentives and investments [31].

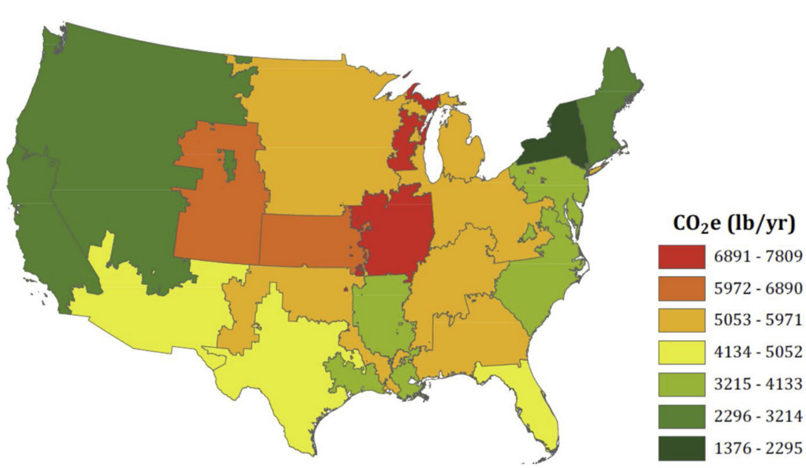

Fig. 4. Annual GHG emissions of Ford Focus BEV. The comparison value for a Focus ICEV is 9557 lb/yr [78,79].

2.10. Principle #10: design for end-of-life and material recovery

"Circular economy" end-of-life approaches (reuse, remanufacturing, and recycling) can significantly reduce environmental impacts and global demand for extracted materials.

Environmental impacts at the end-of-life of battery systems is a major concern, one that has received increased attention [81]. Reuse, remanufacturing, disassembly, and recycling of batteries are strategies that can reduce environmental impacts, demand for extracted materials, and cost.

One example of vehicle battery reuse is grid-scale stationary applications, such as peak shaving [82]. Due to the complexity of battery degradation, a dedicated analysis is necessary to evaluate the capabilities of batteries to fulfil the power and energy demands of any given second life application [83]. Secondary use of batteries has both financial and environmental benefits. From an economic perspective, extended use of expensive materials and distribution of battery costs over two different uses are both positive. Environmental benefits of reuse include decreasing waste and reducing demand for production of new batteries [84].

The battery pack and BMS recovered from an EV, along with logistics and maintenance services for ensuring proper battery system operation, must match the requirements of the second life application [85]. Performance degradation will have an impact on the efficiency of the re-purposed pack, and thus on the economic viability of a secondary application [58]. It is also crucial to consider that the re-use of vehicle batteries in secondary applications can delay the return of materials for recycling [86].

The growing volume of Li-ion batteries reaching the end of first vehicle use requires a well-functioning collection and recycling infrastructure to maximize battery reuse potential and minimize environmental impacts associated with disposal [87,88]. Control of hazardous substances, safety, and resource recovery are important criteria for battery collection and recycling infrastructure [88]. Improvements in cell design and construction could make Li-ion batteries safer for extended applications beyond use in a vehicle [60]. However, there are potential challenges and barriers to EV battery reuse, which include regulatory, risk, and safety issues in addition to business feasibility of EV battery collection [60]. The quality of each used battery pack needs to be evaluated as it is removed from vehicle service. If a battery pack is close to new in quality, it can be reused in another vehicle. A pack that has experienced degradation up to 80% can still be suitable for stationary re-purposing. If vehicle OEMs implement design for disassembly, the repurposing process would be more efficient [60].

Achieving the desired benefit from cascaded use of EV Li-ion batteries requires policies and economic incentives to promote cascaded use before recycling [60]. Material recovery by recycling is essential to closing the loop on battery materials, and growing this nascent industry requires policy and economic incentives in addition to technology development to create collection programs and improve recovery efficiencies. Policies may be needed to ensure safe transport and promote the health and safety of workers [88]. While traditional policy approaches might intuitively use battery landfill bans as a strategy to minimize eco-toxicity, an alternative approach is to promote reuse, cascaded use, and recycling combined [89].

Recycling reduces the use of virgin materials, water, and energy, as well as reducing waste, air, and water pollution [90,91]. Recycling of lithium from Li-ion batteries is a critical step in balancing the supply of lithium with future demand [92]. Economically and technically mature disassembly systems are necessary for the end-of-life of Li-ion batteries, as the demand for these systems increases [93]. The elimination of landfilling due to recent disposal bans on rechargeable batteries increases the need for recycling [24], but recycling becomes less attractive if the energy required to recover battery materials via recycling is more than the energy required to produce them from virgin raw materials [29].

Preliminary analyses at ANL revealed that recycling lithium, aluminum, and copper could reduce the energy intensity of battery production by approximately 40% to 50%. This reduction was mainly from recycled aluminum, when energy for melting, casting, sheet production, rolling, and stamping of the recovered aluminum were included [15]. However, energy benefits from recycling may not be this great, given the contribution of cell manufacturing to energy consumption [27].

3. Discussion

Design and operation of battery systems differs between mobile and stationary applications. This new set of ten principles differs from those previously published for stationary grid applications [19]. For example, battery mass is a key design parameter that influences vehicle fuel economy and overall life cycle performance and is included in the current set of principles. Also, this new set highlights key parameters across battery life cycle stages from material production to use to end-of-life.

While the goal of each principle is to provide guidance to achieve improved environmental outcomes, there will be trade-offs between principles. For example, the relatively large battery in a BEV compared to an internal combustion engine vehicle can increase total vehicle production burden, as explained in Principle #2, but the potential reduction in emissions during EV operation (Principle #8) can offset this increased manufacturing burden. NCM chemistry has higher energy density [14], which is promoted by Principle #5, but this chemistry also has lower cycle life [14], which is in conflict with Principle #6 that focuses on maximizing battery service life. Other trade-offs emerge when cost objectives are considered. For example, while NCM chemistry has higher energy density than LMO, its higher material costs may be an obstacle to wide deployment [14]. While Principle #6 highlights the importance of charging an EV before departure, this might lead to charging during a peak electricity demand period and therefore increase emissions, conflicting with Principle #8, which focuses on reducing life cycle emissions. Another trade-off occurs when oversizing a vehicle battery, which provides longer cycle life while leading to additional environmental impacts associated with the production and lifetime transportation of the larger battery.

These principles serve to highlight trade-offs such as these when they are taken as a set – individual principles have more limited value on their own. The goal of this work is to present a robust set of green principles to raise awareness and guide environmental improvement of battery systems in mobile applications, as well as identifying areas of conflict where further assessment is needed. Life cycle assessment (LCA) is a comprehensive method to quantify the sustainability of battery systems and to evaluate and resolve trade-offs between impact categories. LCA models should address policy and market drivers. Depending on the goal and scope of the study, the system boundaries should be defined by considering a range of spatial scales from battery materials to vehicle fleets and from local charging stations to regional grids and temporal coverage spanning from battery charge-discharge cycles and degradation to renewables deployment and EV adoption rates.

One of the sustainability implications of increasing the deployment of EVs is to shift the location of emissions from the ICEV tailpipe to the power plant, potentially leading to reduced air pollution and human health impacts if ICEVs are in a dense urban area and the power plants are in rural area. This is especially important for heavy duty vehicles such as buses and trucks.

The principles also offer a framework to encourage designers, suppliers, original equipment manufacturers, and end-of-life managers to collaborate to develop innovative solutions that maximize environmental benefits while meeting cost and performance objectives.

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