Electric Vehicle Batteries

From Sourcing to Second Life and Recycling

Bob Galyen
Frank Menchaca
with Foreword by Sir M. Stanley Whittingham

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Edited by

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Foreword

This book differs dramatically from most texts on batteries, which predominantly focus on the chemistry and materials science of the active components. In contrast, here the authors focus on the engineering of batteries and the creation of a sustainable ecosystem, with a particular emphasis on electric vehicles. This book is essential reading if we are to have a sustainable planet, not one where it takes more than 40 kWh of energy to produce a 1 kWh lithium-ion battery and some materials traverse tens of thousands of miles from the mine to the finished product. Not one where we use toxic chemicals, like N-Methyl-2-Pyrrolidone (NMP)for coating the cathode material, that subsequently require the most energy to remove during the manufacturing process.

We need to relook at the whole manufacturing process, from mine to finished product. Instead we need to leapfrog today's methods to build the next generation factories that are sustainable and can use mostly recycled components. At the front end, we must use mining technologies that do not generate mountains of toxic solid waste and/or wastewater. An example might be the plans to drill for lithium as proposed in Arkansas, then separate the lithium from the other cations before pumping those other cations back into the same ground. At the backend, we have to get away from totally destroying old batteries into black mass, but rather get the materials back as far as possible in their virgin form and do it locally.

As we implement these changes, safety must always take first place. We cannot afford to have low-quality batteries enter the market, as this could damage the future market, particularly when human life is compromised. At the same time, it is crucial to remember that all forms of energy is inherently unsafe. Given today's safety standards, it is unlikely that internal combustion engines, where a20-gal fuel tank is located beneath the back seat (occupied by a 2-year-old child), can be considered a reasonable safe technology.

This book serves as a guided tour through all of these issues and more, written by experts practicing in the fields they discuss.

Sir M. Stanley Whittingham
Binghamton, NY

Preface

The first decades of the 21st century have been a period of profound change for engineering. The rapid development of technologies such as advanced manufacturing and artificial intelligence, alongside the post-pandemic onshoring of manufacturing, converged with a shift from fossil fuels to battery electric and renewable forms of energy. These factors have necessitated, if not a reimagining, then a significant revision of how vehicles, propulsion, and infrastructure are designed and built.

This is the first in a series of publications designed to identify, define, and implement these revisions. Each book in this series focuses on an area of critical importance to new transportation: batteries, metals, composite materials, and alternative fuels. It explores what engineers, aspiring engineers, and the instructors and leaders who support them, need to know about each of these topics.

These are not research endeavors, although heavily informed by research, but rather practical publications. The series is authored by industry experts who spend each day of their working lives to figuring out how to implement these profound changes in their practices.

In addition to in-depth discussions of key strategies for successfully and safely designing vehicles and putting them into use, each book offers case studies of businesses and organizations at the forefront of this new world. It also provides information on standards and regulations and profiles the kinds of jobs and skills that are emerging. The objective of the series is to help engineers work safely and effectively as they confront the new challenges associated with technology and the energy transition.

Frank Menchaca

Pittsburgh, PA

January 2025

Introduction

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What You Will Learn in This Chapter

This chapter introduces you to this book: why we wrote it and what sustainability has to do with engineering and batteries.

In this chapter:

- We describe the problems the book sets out to address and how we organize our approach.
- We explore the drivers of sustainability in transportation.
- We examine how those drivers affect the development of vehicles and the engineering practices that support them.
- We include terms to know, information on jobs that relate to the topics at hand, and resources for learning more.
- We use a real-world case study to illustrate our points, as with most topics in this book.

Case Study: Circular Economy for EV Batteries in Australia

In 2021, a team of researchers at the University of Melbourne set out to study the impact of reusing electric vehicle (EV) batteries.[1] Some projections had EVs accounting for 30 % of vehicles on Australia's roads by 2035. This growth was important to decarbonatization of transportation and to achieving net zero emissions, but it would not be consequence free for the environment.

While EVs produce no tailpipe emissions, their batteries require impactful processes such as mining to reach underground reservoirs of brine and other materials. Refining brine produces lithium, a chemical element critical to power in EV batteries. This involves large quantities of pumped water, which also means producing wastewater. Besides, emissions associated with mining equipment, transportation, and manufacturing and EV batteries threaten to neutralize the gains made by the vehicles they power.

Research has already established that an EV battery, once it serves the vehicle's 8 to 10-year average lifespan, could retain as much as 80% of its capacity.

(continued)

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[1] Nicholas Wilson. Resources, Conservation & Recycling 174 (2021) 105759.

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Harnessing that capacity without dismantling the battery and interacting with its potentially toxic contents, known as black mass, became the goal of the Melbourne team and to achieve it, they conducted what is referred to as a Lifecycle Assessment (LCA). An LCA is the study of a product or procedure's environmental impact – a codification of the steps that go into manufacturing something and quantification of their consequences: the energy they use, the emissions they produce, and more. LCAs constitute a critical tool in identifying where environmental tolls are heaviest and how to reduce them.

The researchers defined and assessed not only the creation of EV batteries but, just as important, their use as storage devices when their service in the EV ended, known as their second life. This meant mapping out any remanufacturing and transportation, assessing their impact, and establishing how much energy the repurposed batteries could store as offset.

This EV battery lifecycle consists of five phases in two cases of reuse, one as a home energy storage system (HESS) and one as home energy battery pack (HEBP):

1. Minerals extraction and manufacture, in which lithium and other natural materials are mined and refined, occurring in China and the Rest of the World (ROW).
2. EV use, in which the battery powers the car over its 8- to 10-year life span.
3. Repurposing, in which the battery is remanufactured so that it can be reused. Because the study assumes the battery was produced with the intention of being reused, it allocated 25% of the emissions generated in its production to reuse. In the study, as in other LCAs, energy use and emissions must always be accounted for; in this case, allocation was done over the period of initial use and reuse.
4. Use, in which the battery is put to reuse in a HESS and HEBP.
5. End of Life, in which the battery is dismantled and its constituent units are recycled.

By assessing each step in the repurposed EV battery's initial and second life, the Melbourne team was able to draw some important conclusions about the environmental benefit of recycling – or creating a circular economy – for batteries and their contents. "The repurposed battery has a smaller footprint across all eight environmental impact categories, provided it operates for a minimum of six years[2]," they wrote. The environmental categories on which the team studied the battery's impact included:

- Global warming potential (GWP)
- Terrestrial acidification potential (TAP)
- Surplus ore potential (SOP)
- Fossil resource scarcity potential (FFP)
- Water consumption (WCP)

These are important areas that directly affect human health, biodiversity, and the economy, among other things. Understanding the impact of manufacturing on these areas, and finding means of limiting that impact constitutes the essence of a sustainable engineering practice. That is the focus of this book.

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[2] Wilson, p.

A New Age in Engineering

The Melbourne case illustrates several important transformations the field of mobility engineering is undergoing. One is a commitment to sustainability. A term used frequently and in a wide variety of contexts, sustainability can seem general and vague. Our use of the term derives from the 1987 United Nations Brundtland Commission's definition: “meeting the needs of the present without compromising the ability of future generations to meet their own needs.”[3] Natural resources are finite, says this definition, and we must use them in a way that does not damage the world and its people and prevent future generations from enjoying their benefits, thriving, and leading prosperous lives.

Sustainability has become critical to mobility because transportation accounts for an estimated 20% of global greenhouse gas (GHG) emissions – second only to electricity generation.[4] These are the emissions, produced by burning fossil fuels burned in cars, airplanes, ships, and other forms of transportation. Their accumulation in the atmosphere causes global warming. Governments and businesses throughout the mobility industry have committed to transfer to electric and renewable energy sources as a means of reducing GHGs. For many, this is to comply with the Paris Agreement,[5] a 2015 international agreement to limit global warming to less than two degrees centigrade by 2050 – a threshold at which climate scientists project the impact of climate change to be manageable – by reaching net zero GHG emissions.

This energy transfer that supports this goal constitutes one of the largest – perhaps the largest – changes transportation has undergone since its beginning. Batteries play a central role. Let us examine how:

- Princeton University's Net Zero America study comprehensively calculates what will be required for the United States to achieve net zero emissions by 2050. It presents five scenarios and the backbone for all is a shift from fossil fuel-powered vehicles to EVs. The study projects a future in which electric vehicles replace internal combustion engine vehicles (ICEVs) in a vertiginous climb: 49 million in 2030, 204 million in 2040, and 328 million by 2050.[6] All of these vehicles will likely require batteries.
- In 2022, the United States passed the Inflation Reduction Act (IRA). Through a series of tax credits to businesses and individuals, the IRA is intended to attract EV buyers and accelerate battery production in the United States. The bill was accompanied by federal investments such as in 2023, when the U.S. Department of Energy loaned Ford Motor Company and Korean battery producer SK $9.5 Billion to build, among other things, a series of battery factories.[7] This enabled the automaker to make the largest financial investment in its history – in batteries.

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[3] **https://www.un.org/en/academic-impact/sustainability**

[4] **https://www.statista.com/topics/7476/transportation-emissions-worldwide/#topicOverview**

[5] **https://unfccc.int/process-and-meetings/the-paris-agreement**

[6] Net Zero America, p. 20.

[7] **https://news.yahoo.com/ford-just-got-loan-bigger-180**000907.html#:~:text = The%20Cool%20Down-,Ford%20just%20got%20the%20biggest%20U.S.%20investment%20%27since%20the%20advent,venture%20is%20spending%20it%20on&text = The%20U.S.%20Department%20of%20Energy,to%20build%20electric%20vehicle%20factories.

- In 2023, the European Union (EU) adopted a sweeping new regulation governing the production of batteries and the tracking of battery materials. Scheduled to go into effect in 2026, the legislation addresses the entire battery lifecycle. The law states:
  - In view of the strategic importance of batteries, to provide legal certainty to all operators involved and to avoid discrimination, barriers to trade, and distortions in the market for batteries, it is necessary to set out rules on the sustainability, performance, safety, collection, recycling, and second life of batteries as well as on information about batteries for end users and economic operators. It is necessary to create a harmonized regulatory framework for dealing with the entire life cycle of batteries that are placed on the market in the Union.[8]
- By the end of the 21st century's first decade, China had established itself as the global leader in both battery and EV manufacturing. Between 2009 and 2022, the Chinese government invested over 200 billion RMB, or $29 billion USD[9] in battery and EV technologies, with one Chinese company (CATL) emerging as the largest battery manufacturer in the world.

These are just a few examples of the centrality that batteries have attained within industry and government worldwide. This ecosystem is vast and dynamic. The Melbourne case study illustrates that this transition is complex and multifaceted and requires executives, engineers, designers, and technicians to do their work differently. Designing for reuse and understanding the impact of sourcing and production through LCAs are just a few of the many practices mobility professionals must learn and utilize. This change affects nearly everything: the structure of teams, manufacturing, profitability, professional development, and more. We are truly entering a new age of sustainable battery engineering, one that is critical to the future of mobility.

The purpose of this book and the series to which it belongs is to define and describe this new age in order to help businesses, government, and people thrive while supporting the goal of net zero emission transportation. We have chosen to begin with batteries because they are sustainable mobility's most significant and nearest-term power sources.

Our approach is very application oriented: we want to provide concrete guidelines that engineers and people who want to be engineers can follow in actual practice. Consequently, we engaged industry practitioners – people who are actually doing the work of manufacturing batteries and EVs – as authors. Getting working mobility professionals to contribute to a book had its challenges; at the same time, we genuinely hope this approach constitutes its distinguishing value.

How This Book Is Organized

Over seven chapters this book will explore every aspect of the battery ecosystem.

- High Capacity Battery Technology sets the stage by focusing on Lithium-ion batteries, which are the primary power and storage sources in EVs. David Howell and Tien Duong review the chemical and structural components of these batteries and provide insights on technical advances in energy density along with

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[8] **https://eur-lex.europa.eu/eli/reg/2023/1542/oj**

[9] Yang, Zeyi. "How did China come to dominate the work of electric casrs?" MIT Technology Revie. February 21, 2023. **https://www.technologyreview.com/2023/02/21/1068880/how-did-china-dominate-electric-cars-policy**

the trade-offs that come with each new change. In fact, trade-offs are a key topic our contributors focus on in this book. Technical change always comes with strings attached, whether those strings be in costs, power, or environmental impact. Informed choices are critical to commercial success and to sustainability and we have illuminated those choices wherever possible. This chapter provides readers with a foundation for understanding the subsequent topics.

- Sourcing addresses how the batteries introduced in the previous chapter begin their lifecycle. Austin Devaney and Bob Galyen review different types of sourcing with a specific emphasis on the environmental impacts of each. For example, lithium is sourced from brine which involves the resource-intensive process of pumping and evaporation. They guide the reader through the consequences of sourcing, highlighting opportunities for adopting sustainable material extraction practices.
- Joern Tinnemeyer's chapter on Battery Design clarifies the many trade-offs that come with design decisions. It foregrounds that discussion by differentiating between cell types and their characteristics. It examines the continual interplay between performance and cost. It also provides an understanding of battery cell composition in terms of safety, especially where it concerns thermal runaway. Designing for safety is critical to EV acceptance and this experienced professional guides the reader through the many decisions that underpin safe and effective performance.
- Oliver Gross provides a comprehensive discussion of Vehicle and Infrastructure Integration. He elucidates the challenges that go along with designing battery-powered vehicles for an infrastructure that is still emerging. Gross gives readers an understanding of the essential differences between EVs and internal combustion engine (ICE) vehicles and how they guide design decisions and affect costs and efficiency. An in-depth investigation of charging as a design also helps readers understand the new and important design considerations.
- In Steven Sloop's chapter on Recycling, readers will encounter a detailed discussion of battery chemistry and how it relates to recycling. Once again, an industry expert reviews the choices that designers make in battery composition and how they relate to establishing the all-important circular economy for power sources.
- Repurposing for the Second Life directly relates to the circular economy. As pointed out earlier in this chapter, EV batteries retain significant utility long after their use in EVs is complete. Drawing from the latest research in this burgeoning field, Apoorva Roy, Hamidreza Movahedi, and Anna Stefanopoulou provide an overview of the many new considerations that come into play when a vehicle's primary power source can be transitioned from propulsion to storage.
- What do engineers, managers, and other business professionals need to think about as they create and manage teams to work within this new and dynamic ecosystem? John Warner explores this in Designing New Engineering Teams and Practices. Building safe, cost-efficient, and reliable EVs is not just a technical matter. It is also a people matter. Resourcing, training, and managing those people are all critical to success. John Warner guides readers through the risks and options associated with EV and battery development.

At the very end of this book, we collect, expand, and organize the job roles mentioned in the previous chapters and serve as a guide to readers of the type of jobs in this field, the required skills, and training.

Words to Know

Black mass A waste product consisting of shredded ingredients such as lithium, cobalt, and other rare earth materials.

Brine The liquid materials containing lithium and other materials that can be refined for use in batteries. It is extracted from beneath the ground.

Circular economy A process that incorporates the reuse of materials, with the goal of producing as little waste as possible.

Energy transfer within the context of mobility The transition from fossil fuel-powered propulsion to electrification.

Lifecycle assessment (LCA) It codifies the steps in product manufacturing and quantifies their environmental impacts.

Paris Agreement An international treaty aimed at mitigating climate change and was signed in 2015.

Second Life within the context of battery development The use of the battery after it fulfills its primary use.

Sustainability Meeting a civilization's present needs without compromising the ability of future generations to meet their own needs, achieved through the responsible management of resources and social systems.

Further Reading

Here are publications we have found useful in building a general understanding of sustainability and its role in many aspects of mobility discussed in this chapter.

Frankopan, P. (2023). *The Earth Transformed: An Untold Story*. New York: Random House A comprehensive history of how Earth's climate has changed since pre-history, providing valuable context for the changes we are undergoing.

Henderson, R. (2020). *Reimagining Capitalism in a World on Fire*. New York: PublicAffairs An excellent examination of business and leadership in the context of sustainability with in-depth examinations of companies, such as Unilever, that have succeeded in balancing financial growth with social responsibility.

McKibben, B. (2020). *Falter: Has the Human Game Begun to Play Itself Out?* New York: Holt The founder of the influential 360.org examines the best and worst case scenarios in global warming.

Meadows, D. (2008). *Thinking in Systems: A Primer*. Junction, VT: Chelsea Green Meadow's overview of system thinking as a means solving problems in both social and physical infrastructure has influenced approaches to sustainability.

Pohlman, P. and Winston, A. (2021). *New Positive: How Courageous Companies Thrive by Giving More than They Take*. Cambridge, MA: Harvard Business Review Press The former president of Unilever and how to lead a sustainable company.

Sachs, J. (2015). *The Age of Sustainable Development*. New York: Columbia University Press An overview of the subject of sustainable development by the director of the Earth Institute.

Smil, V. (2022). *How the World Really Works*. New York: Viking Offers excellent examples of how quantifying the environmental impact of a product, such as tomatoes, can lead to unexpected insights. Also conveys the complexity behind terms like decarbonization.

Von Bertalanffy, L. (2015). *General System Theory Revised Edition*. New York: George Braziller A revision of the foundational work that established systems thinking, a holistic view of the interactions between systems in nature and society that informs sustainability.

Wallace-Well, D. (2020). *The Uninhabitable Earth: Life After Warming*. New York: Crown A stark look at the facts of global warming and their potentially dire consequences.

Yergin, D. (2021). *The New Map: Energy, Climate and the Clash of Nations*. New York: Penguin Books An examination of how power generation – particularly in the transportation industry – drives geopolitics.

CHAPTER 1

High-Capacity Battery Technology

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Introduction

Lithium batteries have come to dominate the battery market powering devices ranging from cell phones to electric vehicles (EVs) and becoming the linchpin to ensure the reliability of the increasing renewable grid. The lithium-ion (Li-ion) battery (LIB) is a platform technology, with many different anodes, cathodes, and electrolyte combinations that change the fundamental characteristics of the electrochemistry and lead to different performance metrics.

This chapter describes the various battery component active materials that are currently used in commercial LIBs and their characteristics. In addition, emerging Li-ion concepts are examined with an eye on the advantages and challenges that need to be solved for adoption into EVs. The chapter also covers the emerging Lithium metal-based battery materials and sodium-ion battery technology, that offer a variation to Li-ion but with significantly better supply chain security.

What You Will Learn in This Chapter

The most important learning from this chapter is that the diversity of lithium battery materials has led to variants for EVs and grid storage applications, with some chemistries promising long driving ranges while others lead to lower costs. The reader will also learn:

- The basic construction of LIBs.
- About the trade-offs that exist in energy density, cost, and commercial availability.

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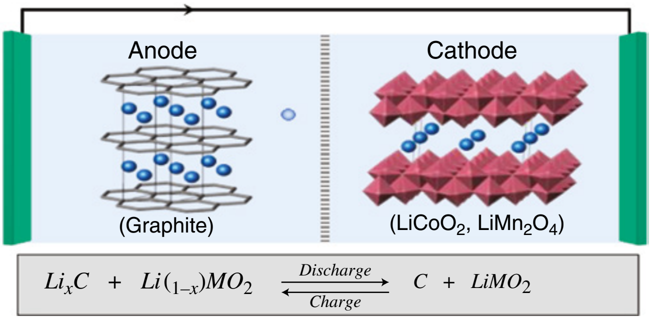
- About the supply chains associated with specific battery components.
- About the latest research trends to find sustainable, energy-dense alternatives to more traditional rare earth materials.

Lithium-Ion Battery Technology

The remarkable success of the LIB is a result of simultaneously achieving high-energy density, reasonable power density, and long cycle and calendar life. This success is due to the reliance on the concept of intercalation, with lithium ions stored in the host lattice leading to minimum transformation of the structure and achieving long cycle life. Since the commercialization of the LIB started three decades ago, the materials used for the anode, cathode, and electrolyte have evolved in response to the need for higher-performance batteries for consumer electronics, EV, and grid storage applications. Figure 1.1 illustrates the material structure of a graphite-transition metal oxide battery popular in many applications.

Present Status of Li-Ion Battery-Active Materials

Many different anode and cathode materials have been examined aimed at enhancing the various performance metrics in the battery. Higher energy density requires materials that operate at high cell voltage along with high capacity. However, the choice of such materials needs to be balanced with the elevated risk of side reactions as cell voltage increases and possible structural changes in the material with increasing lithium content (i.e. capacity). Electrolytes play an important role because most battery materials operate above the thermodynamic limit of the electrolytes. Battery R&D aims to develop or discover new materials that increase energy density without compromising on other metrics, such as cycle life and safety.



$$Li_xC + Li_{(1-x)}MO_2 \underset{Charge}{\overset{Discharge}{\rightleftarrows}} C + LiMO_2$$

FIGURE 1.1 Schematic of a typical Li-ion battery with the electrode reactions

TABLE 1.1 Status of Various Li-ion Materials and Their Suitability Across Different Metrics

Couple	Cell Voltage (V)	Specific Energy (Wh/Kg)	Cycle Life	Fast Charge	Thermal Stability	Representative Manufacturer	Application
Graphite$\|$ $LiFePO_4$	3.2	180–200	Excellent	Good	Excellent	CATL, BYD	Tesla Model Y
Graphite$\|$ LMFP ($LiMn_{1-x}Fe_xPO_4$)	3.8–4.0	220–230	Good	Good	Excellent	Saft, CATL, BYD	EVs and others
Graphite$\|$ $LiMn_2O_4$ + NMC	3.7–3.75	220	Fair	Fair	Good	LG-Chem	Chevy Volt
Graphite$\|$ NCA	3.65	200–260	Good	Fair	Good (gassing)	Tesla	Tesla Model S, X, 3 and Y
Graphite$\|$ NMC	2.4	90–100	Excellent	Excellent	Good	Microvast	Buses
Graphite$\|$ NMC (Various Composition of Ni)	3.6	220–260	Good	Fair	Good (gassing)	LG-Chem, Samsung, SK	Chevy Bolt, Match-E
Graphite + Silicon Composite $\|$ NMC (High Nickel)	3.5	260–320	Fair	Good	Good (gassing)	Gotion, Zenlabs	Drones

Cathode materials: While a similar interplay between voltage and cyclability also plays into the choice of cathode material, an additional consideration is the need to minimize the use of critical elements that suffer from insecure supply chains. While the layered lithium cobalt oxide dominates the consumer electronics market, the high price of cobalt has led to the commercialization of nickel–manganese–cobalt oxides and nickel–cobalt–aluminum oxide for electric vehicle applications. Recently, there has been a push toward using the olivine, lithium iron phosphate, and variants that incorporate manganese, as an alternative to cathodes with nickel and cobalt. The cathode has an advantage in high stability and safety, owing to its lower voltage, but suffers from lower energy density compared to the oxide analogies. Table 1.1 tabulates the status of the different cathode materials used in commercial LIBs across the different metrics along with representative manufacturers that have commercialized the technology.

With the increasing concern over critical material use in batteries, R&D efforts have focused on reducing, and ultimately eliminating, cobalt and possibly nickel in next-generation batteries. The present focus is on reducing cobalt content by adding more nickel to the cathode along with other substitutions such as iron and aluminum. This trend is part of the movement from 33% cobalt (NMC-333 cathodes) to 20% (NMC-622) to the latest generation of cells that aim to use 10% or less cobalt (NMC-811 and NMC-90505) by substituting more nickel to the lattice. While higher nickel content promises higher capacity and thereby higher energy density, it comes at the expense of increased reactivity and lower thermal stability due to more propensity for oxygen release during thermal events. Differential scanning calorimetry data (Figure 1.2) shows the trend toward lower temperatures for the release of heat as the nickel content increases accompanied by higher heat release. NMC-811 cathodes are also prone to particle cracking at higher voltages due to the molar volume change in the lattice, resulting in a movement toward single-crystal cathodes.

Anode materials: The most prevalent type of LIB anode is a carbon graphite anode and can be produced from natural graphite, synthetically produced graphite, or a mix of both. Optimized graphite anode materials typically have a capacity of >350 mAh/g (close to the theoretical value of 372 mAh/g for LiC_6). While current LIBs are cathode limited, improvements in anodes continue to drive up energy

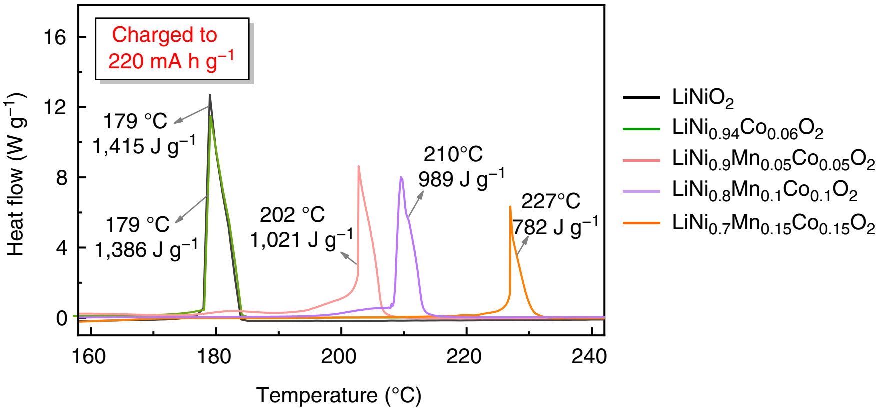
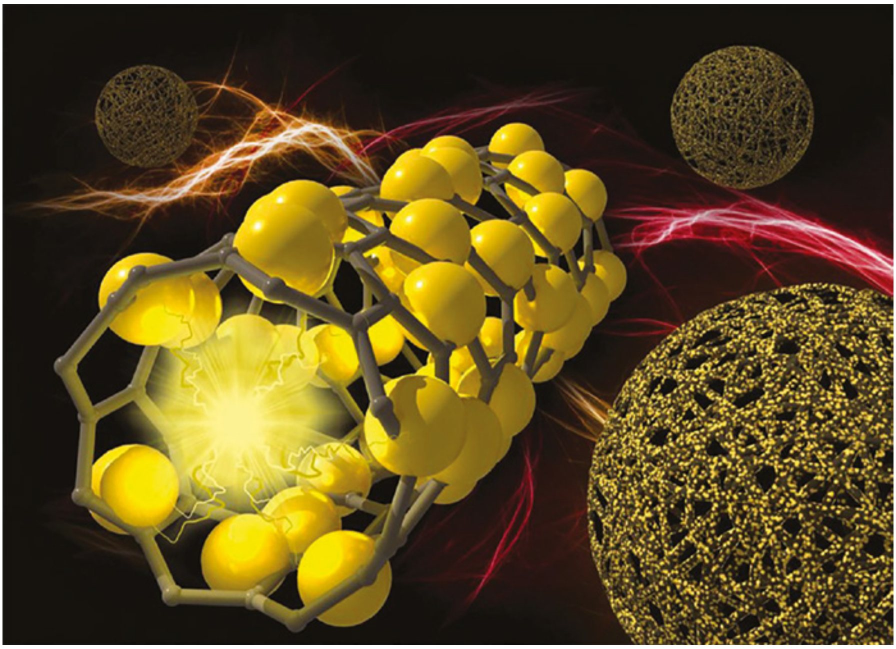


FIGURE 1.2 Differential scanning calorimetry (DSC) data on various TM cathodes with changing Ni content. *Source: Figure provided by Prof. Arumugam Manthiram, U. of Texas at Austin.*

density and aid in decreasing cost. Silicon composite anodes have improved significantly in the last decade. Commercial cells now blend low amounts of silicon with graphite (typically <10%), resulting in enhanced capacity and performance.

PRACTICAL INSIGHTS | Using Silicon for Battery Anodes

The same material used in pencils (graphite) has long been a key component in today's lithium-ion batteries LIBs. As reliance on these batteries increases, however, graphite-based electrodes are due for an upgrade.



Silicon microspheres have extraordinary mechanical strength due to the addition of carbon nanotubes, which make the spheres resemble balls of yarn. In this representation, the image on the left illustrates a close-up of a portion of a microsphere made of silicon nanoparticles deposited on carbon nanotubes. *Source: Mike Perkins, Pacific Northwest National Laboratory*.

Silicon, used in computer chips and many other products, is appealing because it can hold 10 times the electrical charge per gram compared to graphite; however, silicon expands greatly when it encounters lithium and is too weak to withstand the pressure of electrode manufacturing. Researchers have developed a unique nanostructure that limits silicon's expansion while fortifying it with carbon. This work could inform new electrode material designs for other types of batteries and eventually help increase the energy capacity of LIBs in electric cars, electronic devices, and other equipment.

A conductive and stable form of carbon, graphite, is well suited to packing lithium ions into a battery's anode as it charges. Silicon can take on more lithium than graphite but it tends to balloon about 300% in volume, causing the anode to break apart. The

(continued)

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researchers created a porous form of silicon by aggregating small silicon particles into microspheres about 8 micrometers in diameter – roughly the size of one red blood cell.

The electrode with a porous silicon structure exhibits a change in thickness of less than 20% while accommodating twice the charge of a typical graphite anode. Unlike previous versions of porous silicon, the microspheres also exhibited extraordinary mechanical strength, thanks to carbon nanotubes that make the spheres resemble balls of yarn.

The researchers created the structure in several steps, starting with coating the carbon nanotubes with silicon oxide. Next, the nanotubes were put into an emulsion of oil and water. Then they were heated to boiling. The coated carbon nanotubes condense into spheres when the water evaporates. Then, aluminum and higher heat were used to convert the silicon oxide into silicon, followed by immersion in water and acid to remove by-products. What emerges from the process is a powder composed of tiny silicon particles on the surface of carbon nanotubes.

The porous silicon spheres' strength was tested using the probe of an atomic force microscope. One of the nanosized yarn balls may yield slightly and lose some porosity under very high compressing force but it will not break. Anode materials must be able to handle high compression in rollers during manufacturing.

The next step is to develop more scalable and economical methods for making the silicon microspheres so that they can one day make their way into the next generation of high-performance LIBs.

Source: "Using Silicon for Battery Anodes," Mobility Engineering, October 1, 2020.

Next Generation Li-Ion Cathode and Anode Research and Development

Next-generation Li-ion chemistries employ an alloy anode that is normally silicon-based and/or a high-voltage and high-energy cathode. These cells promise 20–40% higher energy density than today's cells, potentially lower cost, and reduced dependence on critical battery materials.

Manganese-rich NMC cathodes: Lithium- and manganese-rich (LMR) oxides promise several advantages over current state-of-the-art (e.g. Ni-rich) cathodes as they are typically made up of ~50% or more manganese. Specifically, manganese is known to enhance the stability of cathodes in terms of safety and is one of the world's most abundant, readily available (geographically diverse), and inexpensive transition metals. Data on these materials (see Figure 1.3) (Croy et al. 2021) suggests compelling performance compared to industrially prepared NMC-622 cycled under standardized, high-voltage protocols. Although promising, several challenges remain that inhibit large-scale adoption. These include (1) mitigating impedance at low states of charge, (2) enhancing surface instability over long-term cycling, (3) inhibiting or controlling local cation rearrangements, and (4) enabling particle and electrode designs that allow for higher volumetric energies.