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Materials Research, Super Batteries, and the Technopolitics of Electric Automobility

ABSTRACT

The protracted commercialization of battery electric passenger vehicles is often ascribed to the failure of the automobile industry to embrace the latest power sources. In this article, I argue that the pace of progress in this context was instead dictated largely by the ways researchers constructed metrics of power source performance. Such processes can in turn be seen as issuing from the conflicting agendas of academic, industrial, and state research. Knowledge of advanced power sources historically tended to be generated not in the automobile industry but in the research laboratories of allied industries and especially in state-funded academic networks. Notable in this regard was materials science and engineering, which exerted an important

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The following abbreviations are used: BEV, battery-electric vehicle; CARB, California Air Resources Board; CSIR, Council for Scientific and Industrial Research (South Africa); DOE, Department of Energy (U.S.); ERDA, Energy Research and Development Administration (U.S.); HEV, hybrid electric vehicle; *JPS*, *Journal of Power Sources*; *MRB*, *Materials Research Bulletin*; MSE, materials science and engineering; NiMH, nickel metal hydride; PNGV, Partnership for a New Generation of Vehicles (U.S.); *SSI*, *Solid State Ionics*; ZEV, zero-emission vehicle.

epistemic influence on advanced power source and electric vehicle research and development. Materials researchers tended to select compounds for reactivity rather than safety and durability, giving rise to the idea of a super battery and leading them and others to treat power sources as essentially materials rather than parts of complex technological systems. This way of thinking prevented technologists from appreciating the physical limits of power sources in real-world applications, setting up crises of expectation at later stages of electric automobile research and development. In the gap between basic research and the exigencies of industrial technoscience, the imagined super-battery electric vehicle came to be mobilized for ends consonant with multiple entrenched interests.

KEY WORDS: electric vehicle, fuel cell, lithium ion battery, materials sciences and engineering, science and technology policy, solid-state ionics

Both popular and scholarly accounts tend to ascribe the long gestation of the modern electric passenger vehicle to the dilatory tactics of auto manufacturers, a sector often cast as a holdover from the golden age of heavy manufacturing. If the conspiratorial predilections of automakers have perhaps been overstated, this industry's antipathy and coordinated resistance to technology-forcing legislation, above all, the California Air Resources Board's Zero Emission Vehicle mandate, have been well documented.¹ One industry tactic, theorized the historian David A.

¹ See, for example, Daniel Sperling, *Future Drive: Electric Vehicles and Sustainable Transportation* (Washington, DC: Island Press, 1995); Michael Shnayerson, *The Car That Could: The Inside Story of GM's Revolutionary Electric Vehicle* (New York: Random House, 1996); Jack Doyle, *Taken for a Ride: Detroit's Big Three and the Politics of Pollution* (New

Kirsch in 2000, was to conjure an imaginary super battery as a way of indefinitely delaying commercial production of electric vehicles.² Indeed, the historical record indicates that many advanced power sources have had a difficult and protracted development.³ The chemist Johan Coetzer held that this was a consequence of the ways researchers defined performance, which prevented them from considering the physical limits of practical power sources in real-world applications. Writing in 1986 after a decade of work on the sodium metal chloride battery, he

York: Four Walls Eight Windows, 2000); Gustavo Collantes and Daniel Sperling, “The Origin of California’s Zero Emission Vehicle Mandate,” *Transportation Research Part A: Policy and Practice* 42, no. 10 (2008): 1302–13; Daniel Sperling and Deborah Gordon, *Two Billion Cars: Driving Toward Sustainability* (Oxford: Oxford University Press, 2009).

² David A. Kirsch, *The Electric Vehicle and the Burden of History* (New Brunswick, NJ: Rutgers University Press, 2000), on 206–07.

³ The term “advanced power source” generally refers to batteries that are rechargeable, powerful (defined as the rate of energy flow per unit of volume), and energetic (defined as the amount of stored energy per unit of volume or mass). Batteries are often considered “advanced” if they have energy densities greater than 30–40 watt hours per kilogram, the contemporary limits of classical battery chemistries such as lead-acid and nickel-cadmium. Notable advanced power sources include sodium sulfur, lithium titanium disulfide, sodium metal chloride, and lithium aluminum–metal sulfide batteries, as well as a range of fuel cells. See Chen-Xi Zu and Hong Li, “Thermodynamic Analysis on Energy Densities of Batteries,” *Energy and Environmental Science* 4 (2011): 2614–24, on 2615.

noted that electrochemical systems were often judged only by energy and power density, yet high cost and adverse safety characteristics often made them unviable.⁴

Kirsch and Coetzer's observations call attention to collaboration among the academy, state, and industry in constructing metrics of power source performance as a key determinant of the history of electric automobility. Quests for super batteries and their crises of expectation may be attributed largely to the belief that power sources were essentially materials rather than parts of complex technological systems.⁵ This belief can in turn be seen as a product of the conflicting agendas of academic, industrial, and state research.

An important reason automakers were reluctant to produce electric vehicles at the turn of the twenty-first century is that few possessed significant in-house expertise in anything other than the venerable lead-acid battery, a technology they claimed could not meet consumer expectations. Knowledge relevant to advanced power sources usually tended to be generated elsewhere, sometimes in the research laboratories of allied industries and especially in state-funded academic networks. Notably important in this regard was materials science and engineering (MSE). A boundary-straddling discipline originally built around metallurgy and, later, the study of ceramics and plastics, MSE was initiated by the federal government in the

⁴ Johan Coetzer, "A New High Energy Density Battery System," *JPS* 18, no. 4 (1986): 377–80, on 377.

⁵ I reference the actor's category of material-as-device from Christophe Lécuyer and David C. Brock's study of the early history of semiconductor research and development. See "The Materiality of Microelectronics," *History and Technology* 22, no. 3 (2006): 301–25, on 304.

wake of Sputnik on grounds that advanced materials constituted the basis of modern military and civilian industry.⁶

The equivalence of materials, technology, and economic growth increasingly influenced thinking in federal science policy circles from the 1970s as the energy and environmental crises generated pressure for alternative energy/transportation systems.⁷ Working at a remove from the

⁶ For an exemplary history of MSE, see Bernadette Bensaude-Vincent, “The Construction of a Discipline: Materials Science in the United States,” *Historical Studies in the Physical and Biological Sciences* 31, no. 2 (2001): 223-48. See also William O. Baker, “Advances in Materials Research and Development,” in *Advancing Materials Research*, ed. Peter A. Psaras and H. Dale Langford (Washington, DC: National Academy Press, 1987), 3–22.

⁷ For the historical progression of such thinking, see National Academy of Sciences, Committee on the Survey of Materials Science and Engineering, *Materials and Man’s Needs*, vol. 1: *The History, Scope, and Nature of Materials Science and Engineering* (Washington, DC: National Academy of Sciences, 1975); National Research Council, Committee on Materials Science and Engineering, *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials* (Washington, DC: National Academy Press, 1989); National Research Council, Committee on Condensed-Matter and Materials Physics 2010, *Condensed-Matter and Materials Physics: The Science of the World Around Us* (Washington, DC: National Academies Press, 2007); National Science and Technology Council, *Materials Genome Initiative for Global Competitiveness* (Washington, DC: Executive Office of the President of the United States, 2011). **re yellow: Pls confirm that a committee of 2010 can publish something in 2007,? That’s how this reads to me.—yes, this one is tricky, but I have double-checked it. The author of the document is CCMMP 2010, and the doc was published in 2007; see**

automobile sector, academic MSE researchers took energy and power to be the defining properties of batteries, in part because they were the traditional points of departure for battery technologists. Unlike improvements in safety and durability, improvements in energy and power could be quickly and dramatically demonstrated, thereby constituting valuable social capital for researchers beholden to demanding and fickle state and academic patrons. Quite naturally, and again emulating traditional practice, materials researchers sought powerful compounds as the means to this end. However, responsibility for integrating these components lay with industrial research communities with varying degrees of contact with automakers and often their own ideas about applications. Building practical power sources out of potent and volatile materials often proved difficult, and none of the resulting technologies could meet all the requirements of electric drive.

In this article, I explore the influence of the materials-technology equation in power source and electric vehicle research and development through the intertwined careers of key materials researchers, especially John B. Goodenough and Michael Thackeray. They are often credited as the intellectual authors of the contemporary revival in electric vehicles, thanks to their contributions to the invention of at least three of the most important lithium ion battery compounds in use in the mid-2010s.⁸ Revising accounts of the work of Goodenough and

[http://www.nap.edu/catalog/11967/condensed-matter-and-materials-physics-the-science-of-the-world}}](http://www.nap.edu/catalog/11967/condensed-matter-and-materials-physics-the-science-of-the-world)

⁸ See Seth Fletcher, *Bottled Lightning: Superbatteries, Electric Cars, and the New Lithium Economy* (New York: Hill and Wang, 2011); International Battery Association 2013, “Special Symposium to Honor Michael Thackeray;”

<http://congresses.icmab.es/iba2013/images/stories/PDF/mt.pdf> (accessed 13 Oct 2014);

Thackeray by rooting them in the overlapped yet disjointed realms of academic, state, and industrial research illustrates the unintended consequences of institutional and geographical distance from the realities of application. In the gap between basic research and the exigencies of industrial technoscience, the imagined super-battery electric vehicle came to be mobilized for ends consonant with multiple entrenched interests.

GENESIS OF SUPER-BATTERY TECHNOSCIENCE

For most of the twentieth century, the history of the research, development, and production of power sources for electric automobiles tracked broader trends in industrial battery technoscience. In the years following the disappearance of electric cars and trucks from American and European public roads in the 1920s and 1930s, automakers followed the preference of battery manufacturers for cheap, proven chemistries. They deemed the lead-acid rechargeable sufficient for the auxiliary role of starting and lighting internal combustion engine automobiles. For decades afterward as a result, noted the historian Richard Schallenberg, civilian power source technoscience stagnated in the United States.⁹

University of Texas at Austin, “UT Austin’s John B. Goodenough Wins Engineering’s Highest Honor for Pioneering Lithium-Ion Battery,” 6 Jan 2014; <http://www.utexas.edu/news/2014/01/06/goodenough-wins-highest-engineering-honor/> (accessed 13 Oct 2014).

⁹ Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia: American Philosophical Society, 1982). See also Ralph J. Brodd, *Factors Affecting US Production Decisions: Why Are There No Volume Lithium-Ion*

In the Cold War era, only U.S. state institutions were willing to fund and procure powerful advanced batteries, mainly for specialized military roles.¹⁰ Nevertheless, the emergence of the conjoined energy and environmental crises in the last quarter of the twentieth century periodically compelled civilian industry to experiment with electric traction. Sometimes these enterprises were given impetus by governmental regulatory interventions and often were linked with state-funded research networks. Thanks to the cyclic nature of petroleum markets and electoral politics, as well as disputes between industry and government over how best to configure sustainable energy systems, however, such projects generally lacked coordination and continuity.

It was through academic and state MSE networks that Goodenough and Thackeray helped shape the field of advanced power sources. Claims for Goodenough's role in these developments rest on his status as a founder of solid-state ionics, the technoscience of moving, inserting, and storing ions inside solids without changing their fundamental structures. It is the branch of MSE relevant to lithium ion batteries. Unlike his contemporary Stanford Ovshinsky, often credited with inventing the landmark nickel metal hydride (NiMH) rechargeable battery,

Battery Manufacturers in the United States? (Working Paper 05-01, ATP Working Paper Series, 2005).

¹⁰ In this period, a number of U.S. federal agencies directly researched or supported research in specialized power sources, including the Army (nickel-zinc batteries, fuel cells), NASA (zinc/silver-oxide batteries, fuel cells, radioisotope thermoelectric generators, photovoltaic arrays), the Atomic Energy Commission and National Institutes of Health (radioisotope thermoelectric generators), and the Department of Energy (lithium-alloy/metal sulfide batteries and fuel cells).

Goodenough was not a technologist, strictly speaking. Possessing a doctorate in theoretical solid-state physics earned at the University of Chicago in 1952, he professed himself motivated by both materials design and basic questions of solid-state science.¹¹ Over the years, Goodenough developed a research agenda and an interdisciplinary style of work based on solving problems arising from devices. Guided by what he referred to as “engineering targets,” he designed experiments for chemists to execute.¹²

Such work sometimes brought Goodenough into contact with battery interests, including some linked with the electric automobile. When this happened, and because he straddled the boundaries of basic and applied science, he tended to focus not on complete power source systems but on materials for particular components, mainly electrodes.¹³ The first such episode had formative consequences for solid-state ionics and power source design. Goodenough spent his early career at Lincoln Laboratory, where he worked on projects of his own choosing, following his contribution to the ceramic memory unit for the Whirlwind II air defense computer as part of the Air Force’s Project Lincoln in the late 1950s. He had become an authority on the class of gem-like minerals known as spinels by the time the Atomic Energy Commission (AEC)

¹¹ John B. Goodenough, interview by Bernadette Bensaude-Vincent and Arne Hessenbruch, March 2001, Caltech Library, http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/Goodenough/Goodenough_interview.htm (accessed 28 Jan 2015).

¹² John B. Goodenough, interview by author, Austin, Texas, 11 Jul 2013.

¹³ Goodenough, Bensaude-Vincent and Hessenbruch interview (ref. 11).

seconded him to evaluate a battery utilizing such substances invented by members of the Ford Research Laboratories in the late 1960s.¹⁴

Inverting the traditional battery configuration of liquid electrolytes and solid electrodes, Joseph T. Kummer and Neill Weber's sodium-sulfur system had serious practical problems relating to its volatile materials and high operating temperature of 350°C. Foremost among these was how to maintain heat during shutdown to prevent the electrodes from freezing and the risk of explosion if their molten materials breached containment and contacted each other. In the late 1960s, Ford had no plans to commercialize the technology.¹⁵

Nevertheless, the sodium-sulfur battery aroused great scientific interest because it utilized a hitherto unknown property of its solid electrolyte, a prosaic ceramic known as beta-alumina. Commonly used as industrial furnace insulation, this material also efficiently conducted ions when applied in a power source. The historians Hervé Arribart and Bernadette Bensaude-Vincent held that the sodium-sulfur system stimulated study of the reversible insertion of ions inside solids, a major shift in thinking at a time when electrochemists believed that reactions occurred primarily on electrode surfaces in relation to liquid electrolytes.¹⁶ Goodenough reported that his

¹⁴ Goodenough, interview by author (ref. 12).

¹⁵ Michael H. Westbrook, *The Electric Car: Development and Future of Battery, Hybrid and Fuel-Cell Cars* (London: The Institution of Electrical Engineers, 2001), 22–23, 67, 79–80.

¹⁶ Hervé Arribart and Bernadette Bensaude-Vincent, “Beta-Alumina,” 16 Feb 2001, Caltech Library, <http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/Beta-alumina.htm> (accessed 12 Aug 2013). **[[a] URL didn't work with “Fletcher 2011” attached. — [b] Did you mean to include Fletcher from n.8 here?—yes, it is Fletcher from n.8, I should have cited it first to avoid snafu-ing the URL}}**

investigation of sodium-sulfur technology led him to help bring about the convergence of solid-state ionics and electrochemistry, introducing to him to associates including Robert A. Huggins of Stanford University and M. Stanley Whittingham of the Exxon Corporation, whose work would importantly influence his own.¹⁷

OPPORTUNITY COSTS AND CONSEQUENCES

The sudden rise in the cost of petroleum and increasing public awareness of environmental despoliation from the early 1970s provided economic and political incentives for industry and government to revisit electric automobility. In this period, the federal energy establishment underwent a major reorganization, resulting in the breakup of the AEC and the consolidation of all energy-related research and development in the Energy Research and Development Administration (ERDA) in 1974 and then the Department of Energy (DOE) in 1977. As these events unfolded, Goodenough began to consider power source technology, including work Whittingham performed with electric traction in mind.¹⁸

Both researchers adopted a reductive approach, focusing on particular components. One problem that Goodenough considered involved the limitations of water-based electrolytes, the solvent into which ionic charge carriers are dissolved. Water decomposes into oxygen and hydrogen at 1.23 volts, limiting batteries employing aqueous electrolytes to relatively low power. Goodenough was attracted by the potential of a zirconia-based solid electrolyte as the basis of a fuel cell, a device that directly electro-oxidizes hydrogenous fuels.¹⁹ Ever since the invention of

¹⁷ Goodenough, interview by author (ref. 12).

¹⁸ Goodenough, interview by Bensaude-Vincent and Hessenbruch (ref. 11).

¹⁹ Goodenough, interview by author (ref. 12).

the fuel cell in the mid-nineteenth century, researchers had imagined the technology as a combination of heat engine and galvanic battery without their respective shortcomings.²⁰

In practice, most fuel cell systems proved complex and fragile, incapable of rapid power delivery and prone to damaging side reactions when using anything other than pure or nearly pure hydrogen. To be sure, the solid oxide fuel cell (SOFC) obviated the electrolysis problems experienced by low-temperature storage batteries using aqueous electrolytes. It was also capable of directly using the cheapest and dirtiest carbonaceous fuels, at least in theory. However, the SOFC had severe practical problems, including severe corrosion, owing to its extremely high operating temperature of around 1,000°C. It was also totally unsuited for vehicular applications.

Aware of the shortcomings of high-temperature electrochemical systems, Whittingham considered chemistries that operated at low temperature with nonaqueous electrolytes.²¹ In the 1970s, he was employed by the research and engineering division of the Exxon Corporation, a company synonymous with the fossil fuel transportation order but with some interest in electrochemical technology, likely as a hedging strategy. In the late 1950s and early 1960s, the company (then Standard Oil of New Jersey, through its Esso Research and Engineering division) studied fuel cells in hopes of supplying specialized fuels in case the U.S. Army decided to adopt the technology for electric drive.²² As the price of petroleum skyrocketed from October 1973,

²⁰ Matthew N. Eisler, *Overpotential: Fuel Cells, Futurism, and the Making of a Power Panacea* (New Brunswick, NJ: Rutgers University Press, 2012).

²¹ M. S. Whittingham, “Electrical Energy Storage and Intercalation Chemistry,” *Science* (New Series) 192, no. 4244 (1976): 1126–27.

²² “Proposal for the Continuation of Government Contract Research on Fuel Cells; Program Period-Calendar Year 1965,” 24 July 1964, Esso Research and Engineering Company, Box 2,

Exxon had to consider the possibility that automakers would be forced to commercialize electrics. In September 1976, Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Act, authorizing ERDA to promote electric vehicle technologies and demonstrate their commercial feasibility.²³ Start-ups including Sebring-Vanguard in the United States and Electraction in the United Kingdom were producing small batches of short-range city electrics well prior to this legislation, and most established automakers conducted experiments with electric drive in this period, all using lead-acid batteries.²⁴

It was in this context that Whittingham invented the lithium–titanium disulfide battery in 1976. With this device he succeeded in demonstrating the insertion and extraction of lithium ions, a major milestone in power source technoscience.²⁵ At the time, Whittingham suggested that he had developed a practical rechargeable battery, but this was not quite the case. In fact, he had focused his energies on the titanium disulfide cathode, pairing it with an interim test anode

AO 247-Esso Research and Engineering Company, 1958–1966 Official Correspondence Files—Materials Sciences Office, Advanced Research Projects Agency, Accession Number 68-A-2658, Record Group 330, National Archives and Records Administration, College Park, MD.

²³ *Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976*, Public Law 94-413, *US Statutes at Large* 90 (1976): 1260–72.

²⁴ Westbrook, *The Electric Car* (ref. 15), 24–25.

²⁵ John B. Goodenough, “Rechargeable Batteries: Challenges Old and New,” *Journal of Solid State Electrochemistry* 16, no. 6 (2012): 2019–29, on 2022; John B. Goodenough and Youngsik Kim, “Challenges for Rechargeable Li Batteries,” *Chemistry of Materials Review* 22, no. 3 (2010): 587–603, on 592.

made of metallic lithium, a dangerous combination when the cell was subject to repeated recharging.²⁶ In such circumstances, recollected Goodenough, the lithium–titanium disulfide battery became an incendiary.²⁷

As with the sodium-sulfur battery, this failed technology would supply Goodenough with timely engineering targets. In 1976, the federal government suddenly transferred all of Goodenough’s fuel cell research to ERDA. With his program at Lincoln Laboratory “dead in its tracks,” Goodenough accepted an offer from Oxford University to chair its Inorganic Chemistry Laboratory.²⁸ In England, the physicist regained the latitude to research spinels and metal oxides on his terms.

The story of how Goodenough helped invent the lithium cobalt oxide cathode as a consequence of his analysis of the lithium–titanium disulfide battery illustrates how his use of engineering targets informed his definition of power source performance. Goodenough reasoned

²⁶ Whittingham, “Electrical Energy Storage” (ref. 21).

²⁷ Over time, lithium ions plated unevenly on the anode owing to the creation of a “passivation” layer, an interaction between the lithium metal anode and the ethylene carbonate in the liquid electrolyte. Repeated cycling at high voltage promoted lithium dendrites (encrustations) that, as they grew between the electrodes, created a short circuit that often ignited the flammable electrolyte; see Goodenough, interview by author (ref. 12); Goodenough, “Rechargeable Batteries” and Goodenough and Kim, “Challenges for Rechargeable Li Batteries” (ref. 25).

²⁸ According to Goodenough, his new employers assumed that because he had headed a ceramics laboratory engaged in solid-state chemistry, he must have been a chemist. Goodenough claimed his success annoyed English inorganic chemists who had coveted the position. See Goodenough, interview by author (ref. 12).

that a layered sulfide cathode mated to a metallic lithium anode could yield no more than 2.5 volts. Using a safer anode, he recalled, would have lowered voltage to the point that the device would not have been competitive with existing rechargeables using nonflammable aqueous electrolytes. An abstraction in this context, given that Goodenough seems to have had no intention of designing a complete battery for a specific application, this comparison privileged the quality of power over safety, cost, and durability.

Thusly motivated, Goodenough looked to oxides. He devised an experiment to establish how much lithium could be reversibly extracted from cathodes made of layered lithium nickel and lithium cobalt oxides. He and his team showed that about 60 percent could be reversibly extracted from the latter when paired with a metallic lithium anode, generating 4 volts. They extracted even more (80 percent) from the nickel compound, but this material was unstable and difficult to prepare.²⁹

Goodenough and Whittingham's approach to basic science as an early-stage process of technology development had important unintended consequences, both professionally and for the future of lithium ion battery and electric vehicle development. Despite his stated interest in basic research, Goodenough wanted to sell his component. But battery manufacturers were not interested for lack of a suitable, safe anode. With little money despite support from the European Energy Commission—and, interestingly, the United States Air Force, which continued to fund

²⁹ See Goodenough, "Rechargeable Batteries" (ref. 25) and interview by author (ref. 12). See also K. Mizushima, P. C. Jones, P. J. Wiseman, and J. B. Goodenough, "Li_xCoO₂: A New Cathode Material for Batteries of High Energy Density," *MRB* 15, no. 6 (1980): 783–89; J. B. Goodenough, K. Mizushima, and T. Takeda, "Solid-Solution Oxides for Storage-Battery Electrodes," *Japanese Journal of Applied Physics* 19 (1980): 305–13.

his work at Oxford—Goodenough patented through the United Kingdom’s Atomic Energy Research Establishment (AERE).³⁰

Goodenough had to relinquish all his rights in an arrangement that haunted him in later years. Lithium cobalt oxide was not ideal for commercial electric drive, not least because cobalt was too expensive in the quantities this role called for. But the chemistry was suited for consumer electronics. From 1985, Sony’s Energytec division sought to integrate the lithium cobalt oxide cathode with a graphitic anode in a project to replace the nickel-cadmium battery, one that owed a good deal to the contributions of Akira Yoshino and the Asahi Kasei Corporation.³¹ Licensing generated vast royalties for AERE, of which Goodenough received nothing. Nevertheless, Goodenough’s work on battery materials helped him become perhaps the world’s foremost expert on spinels and lithium insertion compounds. In the early 1980s, Goodenough attracted the attention of Michael Thackeray, a young South African chemist whose search for a better battery for electric automobiles would become his life’s work.

ENGINEERING TARGETS IN AN ERA OF ENERGY PLENITUDE

³⁰ See Goodenough, interview by author (ref. 12); Fletcher, *Bottled Lightning* (ref. 8).

³¹ Goodenough, “Rechargeable Batteries” (ref. 25); Yoshio Nishi, “My Way to Lithium-Ion Batteries,” and Masaki Yoshio, Akiya Kozawa, and Ralph J. Brodd, “Introduction: Development of Lithium-Ion Batteries,” in *Lithium-Ion Batteries: Science and Technologies*, ed. Masaki Yoshio, Ralph J. Brodd, and Akiya Kozawa (Springer: New York, 2009), v–vii, xvii–xxvi; Kazunori Ozawa, “Lithium-Ion Rechargeable Batteries with LiCoO₂ and Carbon Electrodes: The LiCoO₂/C System,” *SSI* 69, nos. 3–4 (1994): 212–21, on 212.

For proponents of the electric automobile, the return to cheap oil in most of the developed world from the early 1980s deprived them of an important justification. The Reagan administration was hostile to alternative energy technologies, although not as uniformly as sometimes suggested. It did not support renewable energy.³² However, the DOE (the successor of ERDA) did invest in high-temperature electrochemical devices, both fuel cells (which had political cover owing to their theoretical ability to use common carbonaceous fuels), and lithium batteries. Although these programs did not ignore electric traction, they emphasized stationary power systems.³³

³² David Biello, “Where Did the Carter White House’s Solar Panels Go?” *Scientific American*, 6 Aug 2010, <http://www.scientificamerican.com/article/carter-white-house-solar-panel-array/> (accessed 5 Mar 2014).

³³ For a brief history of Argonne National Laboratory’s involvement with hot lithium power sources, see G. L. Henriksen and D. R. Vissers, “Lithium-Aluminum/Iron Sulfide Batteries,” *JPS* 51, nos. 1–2 (1994): 115–28. In this period, the Department of Energy’s Office of Fossil Energy extended a good deal of aid to the United Technologies Corporation in a project to commercialize phosphoric acid fuel cells. See U.S. Department of Energy, *Onsite 40-Kilowatt Fuel Cell Power Plant Manufacturing and Field Test Program* (Washington, DC: U.S. Department of Energy, 1985), 1–1, 1–2, 2–4; A. J. Appleby and F. R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989). From around 1980, the DOE also began to support electric vehicle demonstration programs. See J. Byron McCormick and James R. Huff, “The Case for Fuel-Cell-Powered Vehicles,” *Technology Review* (Aug/Sept 1980): 54–65; D. A. Freiwald and W. J. Barattino, “Alternative Transportation Vehicles for Military-Base Operations,” *International Journal of Hydrogen Energy* 6, no. 6 (1981): 631–36; Pandit G. Patil, “Prospects for Electric Vehicles,” *IEEE AES Systems Magazine* 5, no. 12 (1990): 15–19.

Conditions in South Africa, however, were importantly different. There the energy crisis had severe long-term effects compounded by the country's growing political and economic isolation.³⁴ In response, policy makers linked national science institutions with a semi-autarkic industrial policy emphasizing energy and transportation.³⁵ From around 1977 and for the next fifteen years, these considerations drove efforts by South Africa's Council for Scientific and Industrial Research (CSIR) to develop commercial electric vehicle batteries in the so-called ZEBRA project.

As a doctoral student of Johan Coetzer at the National Physical Research Laboratory in Pretoria in the mid-1970s, Thackeray, like Whittingham, had begun his career investigating materials problems of high-temperature advanced batteries. As Coetzer searched for alternative electrodes for the lithium aluminum-iron sulfide battery then being researched at Argonne National Laboratory, Thackeray contemplated metal oxides. He believed iron oxides were less corrosive than both Argonne's iron sulfide cathode and the iron chloride electrode Coetzer had considered as a possible replacement. Attention at CSIR then shifted to sodium-metal chloride

³⁴ Barbara Rogers has pointed out the often-overlooked breadth of the 1973 oil embargo.

Coordinating with the nonaligned movement, OPEC's Arab states targeted not only Western allies of Israel, but South Africa, Rhodesia, and Portugal as well. Waxy Angolan and Mozambiquan oil was considered unsuited for South African refineries and was in any case largely contractually obligated to Gulf Oil. See "Southern Africa and the Oil Embargo," *Africa Today* 21, no. 2 (1974): 3–8.

³⁵ D. G. Kingwill, *The CSIR: The First 40 Years* (Pretoria: CSIR, 1990), 6–9, 32.

chemistries utilizing beta-alumina as the electrolyte. It was in the course of this project that Thackeray noted the potential of certain spinels to absorb and release lithium ions.³⁶

With this realization, Thackeray made contact with Goodenough at Oxford and arranged to work with him as a postdoctoral fellow. Supported by the CSIR, its affiliated South African Inventions Development Corporation (SAIDCOR), and mining giant Anglo American, Thackeray demonstrated the insertion of lithium into magnetite and another spinel known as hausmannite between the fall of 1981 and the end of 1982. This work informed Thackeray's subsequent demonstration of lithium insertion and extraction in a lithium manganese oxide cathode.³⁷ In 1985, Goodenough and Thackeray patented their work (assigned to SAIDCOR) on the metal oxide spinel frameworks for use as battery components.³⁸

The knowledge that these materials provided three-dimensional interstitial space for mobile lithium ions did not have immediate practical consequences. Sony conducted research on

³⁶ Michael Thackeray, "20 Golden Years of Battery R&D at CSIR, 1974–1994," *South African Journal of Chemistry* 64 (2011): 61–66, on 63.

³⁷ Thackeray and Goodenough's work aroused some interest in state research and development circles. In addition to SAIDCOR, the researchers had financial support from the United States Air Force Office of Scientific Research, the Commission of European Economic Communities, the U.K. Ministry of Defense, and the Admiralty Marine Technology Establishment. See M. M. Thackeray, W.I.F. David, and J. B. Goodenough, "Structural Characterization of the Lithiated Iron Oxides $\text{Li}_x\text{Fe}_3\text{O}_4$ and $\text{Li}_x\text{Fe}_2\text{O}_3$," *MRB* 17, no. 6 (1982): 785–93; M. M. Thackeray, W.I.F. David, P. G. Bruce, and J. B. Goodenough, "Lithium Insertion into Manganese Spinel," *MRB* 18, no. 4 (1983): 461–72.

³⁸ Goodenough "Rechargeable Batteries" (ref. 25); Thackeray, "20 Golden Years" (ref. 36).

lithium manganese oxide and lithium nickel oxide chemistries before choosing lithium cobalt oxide.³⁹ On his return to South Africa, Thackeray set up a group to explore the properties of metal oxide electrodes in room-temperature lithium cells. In the succeeding years, however, the ZEBRA project seems to have absorbed much of his energy.⁴⁰ In 1986, with basic research completed, the CSIR transferred sodium metal chloride technology, and most of its staff, to Anglo American. Shortly thereafter, the mining firm partnered with Daimler-Benz, which began testing sodium nickel chloride batteries in electric vehicles.⁴¹

ON THE THRESHOLD OF A SALTATION

The agenda of the German automaker was less straightforward than its partners. Daimler-Benz had long experimented with alternative propulsion systems for a variety of reasons including, by

³⁹ Sony preferred lithium cobalt oxide because it offered superior cycling, discharge capacity, and charge/discharge efficiency (at the cost of lower stability and voltage) than lithium manganese oxide, and had higher voltage, better charge/discharge efficiency, and better stability and cycling than lithium nickel oxide at the cost of lower discharge capacity. See Yoshio Nishi, “Lithium Ion Secondary Batteries: Past 10 Years and the Future,” *JPS* 100, nos. 1–2 (2001): 101–06, on 102.

⁴⁰ Most of Thackeray’s key papers and patents for lithium manganese systems date from the early 1990s. See “20 Golden Years” (ref. 36).

⁴¹ J. L. Sudworth, “Zebra Batteries,” *JPS* 51, nos. 1–2 (1994): 105–14; Thackeray, “20 Golden Years” (ref. 36).

the 1970s, public relations at a time of rising environmental consciousness.⁴² By the late 1980s and early 1990s, Daimler-Benz had become interested in another advanced power source, the proton exchange membrane (PEM) fuel cell developed by a little-known Canadian R&D start-up known as Ballard Power Systems.⁴³

In general, however, interest in super-battery electric vehicles (BEVs) remained tepid through the 1980s. Power sources no longer supplied Goodenough's primary engineering targets, and his interests in this period were eclectic.⁴⁴ He ascribed his role in the discovery of lithium iron phosphate, the last of the three lithium insertion compounds he had a hand in creating, as motivated by fundamental curiosity in three-dimensional, sodium ion–conducting structures.⁴⁵

⁴² See Peter Hoffmann, *The Forever Fuel: The Story of Hydrogen* (Boulder, CO: Westview Press, 1981); Helmut Buchner, "The Hydrogen/Hydride Energy Concept," *International Journal of Hydrogen Energy* 3, no. 4 (1978): 385–406; Helmut Buchner and R. Povel, "The Daimler-Benz Hydride Vehicle Project," *International Journal of Hydrogen Energy* 7, no. 3 (1982): 259–66.

⁴³ Tom Koppel, *Powering the Future: The Ballard Fuel Cell and the Race to Change the World* (Toronto: John Wiley & Sons Canada, 1999), 115–16.

⁴⁴ In 1986, Goodenough and his postdoctoral fellow Arumugam Manthiram decamped Oxford for the Center for Materials Science and Engineering at the University of Texas at Austin. There they succeeded in inducing high-temperature superconductivity in a copper oxide material in 1987, a period when this phenomenon was stimulating much interest in materials and popular science circles.

⁴⁵ Goodenough, "Rechargeable Batteries" (ref. 25), 2026.

On the other hand, Thackeray and his coworkers at the CSIR's Division of Materials Science and Technology made a series of improvements to lithium manganese oxide electrodes in the early 1990s with practical power sources very much in mind, even as South African government support waned for a lack of industrial interest. With apparently limited means, Thackeray's team managed to stabilize the four-volt lithium manganese oxide cathode, which experienced structural distortions under conditions of deep discharge, by doping it with a variety of metals. They also developed a spinel anode (lithium–titanium oxide) suitable for the stabilized cathode.⁴⁶ In 1992, the CSIR left the field entirely, and in January 1994, Thackeray accepted a position at the Chemical Technology Division of Argonne National Laboratory, where he performed some of this work.

DEFINING THE ZERO-EMISSION AUTOMOBILE

In the 1990s, regional air quality politics triggered a major resurgence of interest in electric drive. In its Zero Emission Vehicle (ZEV) mandate, part of a larger Low Emission Vehicle program created in 1990, the California Air Resources Board (CARB) created a fertile environment for materials approaches to power source research and development, and for super-battery ideation as a key element in the ensuing technopolitics of alternative automobility. On its face, the mandate promised to revolutionize the ways industry built and marketed automobiles. It required automakers with the largest shares of the California market (the seven major American

⁴⁶ R. J. Gummow, A. de Kock, and M. M. Thackeray, "Improved Capacity Retention in Rechargeable 4V Lithium/Lithium-Manganese Oxide (Spinel) Cells," *SSI* 69, no. 1 (1994): 59–67; E. Ferg, R. J. Gummow, A. de Kock, and M. M. Thackeray, "Spinel Anodes for Lithium-Ion Batteries," *Journal of the Electrochemical Society* 141, no. 11 (1994): L147–50.

and Japanese companies) to produce a rolling quota of ZEVs as a percentage of overall sales: 2 percent in 1998, 5 percent in 2001, and 10 percent in 2003 and subsequent model years.⁴⁷

Yet the mandate was ambiguous, for CARB could only specify air quality outcomes, not the technologies that would achieve them. The result was a protracted negotiation on the definition of a ZEV, one in which state research and development agencies played an important role. A number of scholars concur that CARB drew inspiration for the mandate from the Impact, a lead-acid concept BEV developed by General Motors, which the company's chief executive officer, Roger Smith, suggested might be commercially produced.⁴⁸

But automakers were unanimously opposed to the legislated production of BEVs. They considered existing batteries inadequate and sought to convince CARB and the federal government that a commercial lead-acid BEV would be a market fiasco. They also supported advanced power source research and development. With the help of the DOE, American automakers formed the United States Advanced Battery Consortium (USABC) in 1991 to coordinate public and private work to this end.⁴⁹ The White House reinforced the industry agenda with its Partnership for a New Generation of Vehicles (PNGV). Launched in 1993, this collaborative research and development program was intended to encourage American automakers to develop non-BEV advanced technologies, especially the hybrid electric vehicle

⁴⁷ CARB, "Proposed Regulations for Low-Emissions Vehicles and Clean Fuels: Technical Support Document," 13 Aug 1990.

⁴⁸ See Shnayerson, *The Car That Could* (ref. 1); Doyle, *Taken for a Ride* (ref. 1); Collantes and Sperling, "The Origin of California's Zero Emission Vehicle Mandate" (ref. 1); Sperling, *Future Drive* (ref. 1).

⁴⁹ "3 Auto Makers in Battery Plan," *The New York Times*, 1 Feb 1991.

(HEV), as a substitute for technology-forcing legislation like the Corporate Average Fuel Economy.⁵⁰

Hybrid electric drive implied that practical electric automobility could only be realized by coupling extant less-than-super batteries with existing (internal combustion) and experimental (fuel cell) power plants. If the global auto industry was of one mind where the BEV was concerned, it was not so united on the question of the HEV. To a degree, this divergence reflected distinct national approaches to industrial research, development, and production. Like U.S. federal agencies, Japan's Ministry of International Trade and Industry (MITI) had supported BEV research and development since the 1970s. To be sure, MITI played a much more overt role coordinating industrial planning, but the automobile sector was an important exception. More independent than other parts of the Japanese economy, it rejected MITI's initiatives.⁵¹

It is ironic, then, that Japanese automakers found themselves subject to state-backed, technology-forcing measures in the United States, a society nominally committed to free market

⁵⁰ Brent D. Yacobucci, "The Partnership for a New Generation of Vehicles: Status and Issues," *Congressional Research Service Report RS20852*, 22 Jan 2003, <http://wikileaks.org/wiki/CRS-20852> (accessed 2 Feb 2009). **URL no longer yields functional page. Do you have another URL for this source? —if you pop this URL into Google, it links to a Wikileaks site, where a PDF of the report can be downloaded; I've included the URL for the site:**

<https://wikileaks.org/wiki/CRS: The Partnership for a New Generation of Vehicles: Status and Issues, January 22, 2003>

⁵¹ Max Åhman, "Government Policy and the Development of Electric Vehicles in Japan," *Energy Policy* 34, no. 4 (2006): 433–43, on 435, 439.

principles. Facing California's ZEV mandate, they warmed to the HEV as a less risky industrial response to U.S. environmental politics. In the wake of the PNGV, which was restricted to American manufacturers, and independently of MITI, Honda and Toyota initiated hybrid electric projects in the early 1990s. They looked to the NiMH battery, technology pioneered by Stanford Ovshinsky with the aid of a USABC grant and intended for use in a pure BEV. Ovshinsky used relatively cheap and safe materials, including an aqueous, nonflammable electrolyte, to achieve energy density of up to 80 watt hours per kilogram, considerably higher than the 30–40 watt hours per kilogram of the best lead-acid traction batteries of the day.⁵²

Toyota adopted NiMH technology in a relatively short time. Having no expertise with prime mover electrochemical systems, like all automakers, it partnered with Matsushita, creating the joint venture Panasonic EV Energy in 1996. One year later, this enterprise introduced a cylindrical NiMH battery for the Prius passenger automobile.⁵³ Although MITI had not initiated the HEV projects, the analyst Max Åhman argued that the ministry nevertheless played an important supporting role by transferring to industry drive train and power source technology derived from its BEV effort.⁵⁴

⁵² S. R. Ovshinsky, M. A. Fetcenko, and J. Ross, "A Nickel Metal Hydride Battery for Electric Vehicles," *Science* (New Series) 260, no. 5105 (1993): 176–81; Zu and Li, "Thermodynamic Analysis" (ref. 3).

⁵³ See Yasuyuki Motoyama, *Global Companies, Local Innovations: Why the Engineering Aspects of Innovation-Making Require Co-Location* (Surrey, UK: Ashgate, 2012), 59–64; Akihiro Taniguchi, Noriyuki Fujioka, Munehisa Ikoma, and Akira Ohta, "Development of Nickel/Metal-Hydride Batteries for EVs and HEVs," *JPS* 100, nos. 1–2 (2001): 117–24.

⁵⁴ Åhman, "Government Policy" (ref. 51).

In contrast, Detroit's approach to the hybrid electric, through the PNGV, was to treat it as a kind of supercar. The industry-government partnership insisted that the HEV battery have two operating modes: power assist and pure electric. The former required only a battery of high power and modest energy, since the average depth of discharge would be comparatively shallow, depending on whether the battery was coupled to a prime mover that responded quickly (internal combustion) or slowly (fuel cell) to demands for power. The dual-mode hybrid electric, on the other hand, required a larger battery that had high power *and* energy and that was robust enough to deep-discharge repeatedly in providing electric-only transport.⁵⁵

With this decision, planners contradicted the premise of the hybrid electric as an interim technology. In essence, the dual-mode HEV was a near-BEV, a second-generation hybrid requiring precisely the super battery that U.S. industry insisted could not be quickly developed for the pure BEV, at a time when Japanese manufacturers were well on their way to commercializing a first-generation hybrid electric using first-generation NiMH technology. The PNGV identified NiMH and lithium-ion as the two candidate chemistries for this role, making France's SAFT the sole contractor for the latter. The contractor selected lithium nickel oxide on grounds of high power and energy, good cycle life, and low cost.⁵⁶

⁵⁵ Michael Saft, Guy Chagnon, Thierry Faugeras, Guy Sarre, and Pierre Morhet, "Saft Lithium-Ion Energy and Power Storage Technology," *JPS* 80, nos. 1–2 (1999): 180–89, on 185.

⁵⁶ National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Third Report* (Washington, DC: National Academy Press, 1997), 71–73; M. Broussely, J. P. Planchat, G. Rigobert, D. Virey, and G. Sarre, "Lithium-Ion Batteries for Electric Vehicles: Performances of 100 Ah Cells," *JPS* 68, no. 1 (1997): 8–12; M. Broussely, "Recent Developments on Lithium Ion Batteries at SAFT," *JPS* 81–82 (1999): 140–43, on 141.

But in longer-term tests of individual lithium nickel oxide cells, SAFT could not meet cycle-life targets. Perhaps predictably enough, given Goodenough's experiences, these tests revealed that the compound became dangerously unstable as it aged, resulting in some cases in cell combustion.⁵⁷ Researchers had rediscovered the dangers of electrode interaction with flammable organic electrolytes in abuse conditions such as overcharge, overdischarge, and vibration.

Because the PNGV partners agreed that adopting a new chemistry was akin to starting from scratch, the DOE created the Advanced Technology Development (ATD) program in 1998 to support manufacturers in characterizing the failure mechanisms of lithium nickel oxide.⁵⁸ Teams of researchers worked to correct the compound's inherent instability using a variety of ordering elements that kept nickel in the nickel layer, including cobalt, cobalt and aluminum, manganese and cobalt, and nickel-cobalt-aluminum (NCA). In the following decade, the ATD

⁵⁷ National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Fourth Report* (Washington, DC: National Academy Press, 1998), 43–44; National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report* (Washington, DC: National Academy Press, 1999), 7, 38–39.

⁵⁸ Raymond A. Sutula, *Progress Report for the Advanced Technology Development Program* (Washington, DC: U.S. Department of Energy, 2000). Although the ATD program was designed to aid U.S. battery manufacturers, many PNGV subcontractors were foreign and ATD researchers depended heavily on materials and cathode chemistries developed by Japanese firms such as Fuji and Hitachi.

would constitute an important part of the federal advanced battery program.⁵⁹ It also influenced Panasonic in its efforts to develop the NCA battery, a technology the Japanese firm would produce for the Tesla Motors Model S luxury BEV from 2012.⁶⁰

PERFECTING THE ENEMIES OF THE GOOD

Even prior to this initiative, PNGV planners were becoming enamored with another super power source as the basis of the ultimate ZEV. This was the proton exchange membrane (PEM) fuel cell. A low-temperature (below 100°C) design that utilized a polymer electrolyte and a platinum-laced anode, it seemed to offer a number of advantages over conventional storage battery technology. Citing rapid improvements in the current density of PEM fuel cells in the 1990s, developers held that the technology reconciled high-performance electric drive with political and economic realities. Electric vehicles equipped with fuel cells, they claimed, would have much

⁵⁹ See, for example, K. Amine et al., “Factors Responsible for Impedance Rise in High Power Lithium Ion Batteries,” *JPS* 97–98 (2001): 684–87; R. B. Wright et al., “Calendar- and Cycle-Life Studies of Advanced Technology Development Program Generation 1 Lithium-Ion Batteries,” *JPS* 110, no. 2 (2002): 445–70; I. Bloom et al., “Effect of Cathode Composition on Capacity Fade, Impedance Rise, and Power Fade in High-Power Lithium-Ion Cells,” *JPS* 124, no. 2 (2003): 538–50; D. P. Abraham et al., “Performance Degradation of High-Power Lithium-Ion Cells: Electrochemistry of Harvested Electrodes,” *JPS* 170, no. 2 (2007): 465–75.

⁶⁰ Shoichiro Watanabe, Masahiro Kinoshita, and Kensuke Nakura, “Capacity Fade of $\text{LiNi}_{(1-x-y)}\text{Co}_x\text{Al}_y\text{O}_2$ Cathode for Lithium-Ion Batteries During Accelerated Calendar and Cycle Life Test. I. Comparison Analysis Between $\text{LiNi}_{(1-x-y)}\text{Co}_x\text{Al}_y\text{O}_2$ and LiCoO_2 Cathodes in Cylindrical Lithium-Ion Cells During Long Term Storage Test,” *JPS* 247 (2014): 412–22.

longer range and offer greater convenience than battery electrics because they would use common liquid fuels stored in conventional tanks. In this manner, fossil fuel infrastructure would be made sustainable.⁶¹

Such were the claims, at any rate, for fuel cell power. Beginning in early 1996, in response to heavy pressure from automakers, CARB modified the ZEV mandate accordingly. In exchange for an industry promise for early deployment of a much smaller number of BEVs, the air quality regulator eliminated its quotas from 1998 to 2002 and began to identify non-BEV technologies for which automakers could gain partial ZEV credit, including the dual-mode hybrid electric and the methanol fuel cell electric vehicle.⁶² From 1997, PNGV spending on fuel cells grew rapidly, supplanting hybrid systems as the DOE's top priority in the partnership by mid-1998.⁶³ Japanese automakers also began their own fuel cell electric research and development programs in this period.

In effect, the fuel cell electric had become the PNGV's politically correct hybrid electric. In the late 1990s, however, mounting problems with carbonaceous fuel cell systems, notably the

⁶¹ Between 1989 and 1997, Ballard Power Systems dramatically boosted fuel cell current density from 85 to 1200 watts per liter, after which progress quickly plateaued. See Charles Stone and Anne E. Morrison, "From Curiosity to 'Power to Change the World®,'" *SSI* 152–53 (2002): 1–13, on 7–8.

⁶² Deborah Salon, Daniel Sperling, and David Friedman, *California's Partial ZEV Credits and LEV II Program* (Davis, CA: Research Report UCD-ITS-RR-99-14, Institute of Transportation Studies, 1999), 4–8.

⁶³ National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Sixth Report* (Washington, DC: National Academy Press, 2000), 76.

inability of on-board converters to quickly crack gasoline or methanol into hydrogen, led government and industry researchers to focus on pure hydrogen fuel cell systems.⁶⁴ These technologies were the chief preoccupation of FreedomCAR, the successor of the PNGV during the George W. Bush administration.⁶⁵

If the idea of the hydrogen fuel cell vehicle helped kill the pure BEV, as some critics suggested, it did not stop the proliferation of HEVs powered by NiMH batteries.⁶⁶ As hybrid electrics became a familiar sight on U.S. roads, American manufacturers and the federal government belatedly realized there was in fact a lucrative market for the technology. In 2006, General Motors initiated the Chevrolet Volt project in what the company's vice-chair Robert Lutz characterized as a response to the commercial success of Toyota's Prius and the emergence

⁶⁴ Christopher E. Borroni-Bird, "Fuel Cell Commercialization Issues for Light-Duty Vehicle Applications," *JPS* 61, nos. 1–2 (1996): 33–48, on 42; Richard K. Stobart, "Fuel Cell Power for Passenger Cars: What Barriers Remain?" in *Fuel Cell Technology for Vehicles*, ed. Richard Stobart (Warrendale, PA: Society of Automotive Engineers, 2001), 14.

⁶⁵ Jeffrey Ball, "Bush Shifts Gears on Car Research Priority," *The Wall Street Journal*, 9 Jan 2002; George W. Bush, "Hydrogen Fuel Initiative Can Make 'Fundamental Difference:' Remarks by the President on Energy Independence," 6 Feb 2003, <http://www.whitehouse.gov/news/releases/2003/02/20030206-12.html> (accessed 16 June 2006). **URL diverts to current White House Briefing Room. Do you have a URL for the Bush document?—here is the new URL: <http://georgewbush-whitehouse.archives.gov/news/releases/2003/02/20030206-12.html>**

⁶⁶ Chris Paine made this claim in his 2006 film, *Who Killed the Electric Car?*

of BEV start-up Tesla Motors.⁶⁷ Sometimes referred to as an extended-range electric vehicle, the Volt was essentially a dual-mode hybrid utilizing a large and powerful battery. Whereas Tesla Motors equipped its Roadster with packs of lithium cobalt oxide electronics commodity cells, an expensive and problematic application of this technology, GM wanted a lithium battery pack designed expressly for electric traction.

Once again, the company had to rely on external expertise. The results fell far short of expectations, in large measure due to the impulse to make perfection the enemy of the good. Chevrolet selected a lithium manganese oxide system developed by LG Chem over a less powerful but safer lithium iron phosphate system developed by Massachusetts-based start-up A123. A vindication of Thackeray's work, this decision also validated U.S. federal science because the Volt battery pack used components licensed from Argonne National Laboratory.⁶⁸ Yet GM's quest for a super HEV delayed the company's entry into the market by a crucial decade. Demand for the Volt was low in the recessionary late 2000s and early 2010s, and the

⁶⁷ See Keith Naughton, "Bob Lutz: The Man Who Revived the Electric Car," *Newsweek*, 22 Dec 2007, <http://www.newsweek.com/2007/12/22/bob-lutz-the-man-who-revived-the-electric-car.html> (accessed 8 Jan 2014). Lutz also claimed he had supported BEV technology as early as 2003, and implied that he had been overruled by fuel cell enthusiasts within GM.

⁶⁸ Angela Hardin, "LG Chem, Argonne Sign Licensing Deal to Make, Commercialize Advanced Battery Material," 6 Jan 2011, <http://www.anl.gov/articles/lg-chem-argonne-sign-licensing-deal-make-commercialize-advanced-battery-material> (accessed 27 June 2013)

advanced battery plant built with Obama administration stimulus money initially operated at well below capacity.⁶⁹

Moreover, the latest advanced battery packs offered nontrivial performance trade-offs that had serious implications for the marketing of electric vehicles. Lithium ion batteries were by far the most potent of all electrochemical power sources, boasting an energy density of around 210 watt hours per kilogram by 2010.⁷⁰ But they did not perform well in very cold or very hot weather.⁷¹ Lithium ion batteries also had short shelf lives, which represented an unprecedented hidden replacement cost, especially for large batteries worth a large fraction of vehicle value. And their well-known safety issues persisted. Responding to a spate of fires in 2013, Robert Huggins held that lithium ion batteries were inherently dangerous owing to their flammable organic electrolytes and propensity to produce oxygen at high voltage.⁷² For these reasons, some analysts predicted that massive recalls of lithium ion traction packs were all but inevitable.⁷³

⁶⁹ U.S. Department of Energy, *Special Report: The Department of Energy's Management of the Award of a \$150 Million Recovery Act Grant to LG Chem Michigan Inc.* (Washington, DC: OAS-RA-13-10, 2013); Bernie Woodall, Paul Lienert, and Ben Klayman, "GM's Volt: The Ugly Math of Low Sales, High Costs," *Reuters*, 10 Sep 2012, <http://www.reuters.com/assets/print?aid=USBRE88904J20120910> (accessed 20 June 2013).

⁷⁰ Between the early 1990s and the late 2000s, researchers more than doubled the energy density of lithium ion systems. See Zu and Li, "Thermodynamic Analysis" (ref. 3), 2615.

⁷¹ Ronald K. Jurgen, "The Growing Surge in Electric Vehicle Activity," in *Electric and Hybrid-Electric Vehicles*, vol. 2 (Warrendale, PA: SAE International, 2011), 3.

⁷² Robert A. Huggins, "Do You Really Want an Unsafe Battery?" *Journal of the Electrochemical Society* 160, no. 5 (2013): A3001–05.

EPILOGUE

The equation of materials, technology, and industrial growth was a crucial (although by no means the sole) factor in the technopolitics of contemporary electric automobility. A way of knowing originating in academic and state research communities, it informed the construction of performance at every stage of the development of advanced power source technologies. It directed materials researchers in this context to seek substances yielding high power and energy density. Automakers later learned to exploit the resulting performance premium for their own agendas. Uncertain of the engineering and marketing implications of the commercial BEV, and resentful of state-mandated technological change, they made internal combustion performance the benchmark for battery electric performance, privileging the qualities of convenience, energy, and power over zero emissions and silent operation.

The denouement spoke to the paradoxes of industrial-state relations in the global market. Automakers had united in arguing for super batteries as the necessary condition for super-electric vehicles, convincing CARB to roll back the ZEV mandate in exchange for research and development commitments. Unlike their American counterparts, however, Japanese automakers opened a lucrative market for hybrids equipped with the less-than-super NiMH battery, a system that combined reasonably high-energy density and modest lifespan with low cost and excellent

⁷³ Jingliang Zhang, Linxia Liao, and Jay Lee, “Prognostics and Health Monitoring of Li-Ion Battery for Hybrid Electric Vehicle,” in *Electric and Hybrid-Electric Vehicles*, vol. 2 (Warrendale, PA: SAE International, 2011), 45.

safety. Moreover, critics pointed out that heavy federal investment in lithium ion battery technoscience and industry almost exclusively benefitted Asian power source manufacturers.⁷⁴

Yet it was far from clear whether this commitment would translate into commercial success in the automobile sector. As ever, market-leading Toyota was circumspect. It embraced the lithium ion battery but did not believe that the technology proved the economic feasibility of the pure BEV. Along with Daimler-Benz, Toyota was content to take a stake in Tesla Motors and let the Bay Area start-up, its battery supplier Panasonic, and the U.S. taxpayer bear the financial risk of pushing the physical envelope of large, powerful battery packs. The majors purchased batteries and drive trains from Tesla Motors/Panasonic for use in experimental BEV fleets, but high costs and slow sales led them to liquidate their shares in this venture in late 2014.⁷⁵

⁷⁴ See U.S. Department of Energy, *Special Report* (ref. 69); Brodd, *Factors Affecting US Production* (ref. 9); National Research Council, *Building the US Battery Industry for Electric Drive Vehicles: Summary of a Symposium* (Washington, DC: The National Academies Press, 2012). My thanks to Professor Bruce S. Dunn for his insights on this question; interview by author, Los Angeles, California, 7 Sep 2010.

⁷⁵ Mike Ramsey, “Toyota Steps Away From Tesla’s Batteries,” *The Wall Street Journal*, 11 Sep 2014; **I would never include a URL this cumbersome, and citation is complete without it.— sounds good**; Joseph B. White, “Toyota Confirms Sale of Part of Tesla Stake,” *The Wall Street Journal*, 24 Oct 2014, <http://www.wsj.com/articles/toyota-confirms-sale-of-part-of-tesla-stake-1414197536> (accessed 24 Oct 2014).

Wary of the manufacturing and marketing problems of BEVs, Toyota saw the hybrid electric as the future of electric automobility.⁷⁶ To be sure, the company did intend to replace NiMH with lithium ion systems. When this project encountered technical difficulties in 2009–2010, Toyota characteristically adopted a pragmatic approach. It retained the older, proven power source for the baseline Prius and used costlier lithium ion power for the plug-in version.⁷⁷

At the turn of the twenty-first century, electric drive had returned to public roads in the form of an ostensibly interim technological system.⁷⁸ But the quest for the super battery for the

⁷⁶ Mike Ramsey, “Toyota Calls Hybrids ‘Sturdy Bridge’ to Automotive Future: Chairman Uchiyamada Says No Major Market for All-Electric Cars,” *The Wall Street Journal*, 30 Sep 2013, <http://online.wsj.com/news/articles/SB10001424052702303918804579107213728805086> (accessed 11 Oct 2013).

⁷⁷ Toyota Motor Corporation, “2015 Toyota Prius Plug-In Hybrid is Evolutionary—and a Little Bit Revolutionary,” 26 Sep 2014, <http://toyotanews.pressroom.toyota.com/releases/2015+toyota+prius+plug+in+hybrid+revolutionary.htm>. **}}This URL is only the google search results (and it’s a cumbersome URL). Pls confirm the replacement is what you intended.—yes, this URL is the correct one}}**

⁷⁸ Toyota Motor Corporation, “Worldwide Sales of Toyota Hybrids Top 6 Million Units,” 14 Jan 2014, <http://corporatenews.pressroom.toyota.com/releases/worldwide+toyota+hybrid+sales+top+6+million.htm> (accessed 19 Feb 2015).

super-electric car remained a key justification of federal materials research.⁷⁹ That this all-or-nothing approach should have yielded so little for American industry to date reflects the remarkable persistence of the belief, despite all evidence to the contrary, that the benefits of national programs of science and technology necessarily accrued to domestic manufacturers.

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⁷⁹ See, for example, National Science and Technology Council, *Materials Genome Initiative* (ref. 7). The authors of this policy paper ascribed the slow development of lithium ion batteries for electric traction to insufficiently developed materials research programs.