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Public Policy, Industrial Innovation, and the Zero-Emission Vehicle

Matthew N. Eisler

MATTHEW N. EISLER teaches and researches the history of science and technology at the University of Strathclyde and is a cofounder and principal of the Centre for Doctoral Training in Interdisciplinary Sustainable Practices of Research in Energy (C-INSPRE). He is interested in the epistemology of research and development and the ways public policy informs the organization and material practices of industrial innovation.

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ABSTRACT

Regulating environmental outcomes without stipulating the technologies to accomplish them is a characteristically American form of governmental intervention. This approach aims to encourage industry to address public-policy concerns while minimizing interference in its affairs. However, California's zero-emission-vehicle mandate of 1990 implied the development of specific technologies with highly disruptive sociotechnical effects. The most practical zero-emission vehicle of the day was the all-battery electric vehicle, a technology characterized by the temporal mismatch of its components. Batteries have shorter life-spans than electric motors, a durability dilemma that rewards battery-making. In response, General Motors and Toyota devised strategies to mitigate this risk that involved mediating the technology of the Ovonic Battery Company.

Keywords

- electric car
- General Motors
- Matsushita
- nickel-metal hydride battery
- Ovonic
- Toyota

Over the last four decades, public interventions in response to market failure have become increasingly common in the United States, and in no arena have the results been more dramatic than automaking. In California, poor air quality justified a command-and-control measure known as the zero-emission-vehicle mandate, often credited with stimulating all-battery electric vehicles from around 2010. Regulation and support for basic science were long seen as appropriate roles for the state vis-à-vis civilian industry because, it was thought, such measures could not pick winners, taboo in American political culture.[1] First levied in the late 1960s, emission controls imposed limited industrial-technological burdens on automakers.

The mandate portended more onerous obligations. As conceived by the California Air Resources Board (CARB) in September 1990, this regulation required automakers with annual sales of at least thirty-five thousand units to deliver zero-emission vehicles amounting to 2, 5, and 10 percent of their car and light truck sales in 1998, 2001, and 2003 and subsequent years, respectively. In the zero-emission vehicle CARB specified an environmental outcome, not the technologies to achieve it, but this particular outcome implied a set of technologies highly disruptive to the status quo. In 1990, the only practical zero-emission vehicle was the all-battery electric vehicle, a system characterized by the temporal mismatch of its components. Batteries have shorter life-spans than electric motors, a durability dilemma with important implications for automaking. Over their service lives, all-battery electric cars might consume several power packs, a substantial hidden cost, as the sole CARB member to oppose the mandate noted.[2] The corollary was that much of the profit to be had in a commercial all-battery electric vehicle lay in battery replacement.

The mandate was a part of the Low Emission Vehicle (LEV) program of 1990, an air quality certification scheme that drew on CARB's experience of working with industry to adopt the catalytic converter, a rudimentary piece of hardware.[3] However, the technologies of zero-emission vehicles were totally dissimilar.[4] Automakers responded by lobbying against the mandate and adopting innovation initiatives that some sources argue were determined by research and development intensity, with "laggards" doing relatively less and "early movers" doing relatively more.[5] To be sure, the capacity of firms to perform research and development does not always correlate with a willingness or ability to commercialize new products.[6] In 1990, at any rate, no automaker had sufficient expertise to develop zero-emission vehicles on its own. National science and technology programs in both Japan and the United States made resources available for this purpose but automakers were reluctant to participate.[7]

In the context of mandate technopolitics, it is misleading to refer to laggards and early movers. I argue that in this context, automakers engaged in research and development primarily with a view to mitigate risk, and the efforts of General Motors (GM) and Toyota in this regard are exemplary. As large players in the California market, these companies had proportionately large mandate quotas and major stakes in the zero-emission vehicle. Their efforts converged on the Ovonic Battery Company, an R&D enterprise founded by the materials specialist Stanford Ovshinsky that dominated the intellectual property of the nickel-metal hydride battery, the most capable rechargeable of the day. Both GM and Toyota wanted to equip their advanced electric cars with this power source; however, Ovonic had developed the technology for consumer electronics, and adapting it for traction applications posed nontrivial challenges. More worrying for auto executives was that public policy bolstered Ovonic's ambitions to dominate the nascent electric vehicle market.

Accordingly, Ovonic was an important gatekeeper and GM and Toyota sought to control as much as to translate its technology. Efforts by GM centered on Impact, an all-battery electric car.[8] Much of what is known of this project comes from journalist Michael Shnayerson's *The Car that Could*, a semiofficial account published in 1996. Granted inside access by GM, Shnayerson recounts an industrial comedy of errors. In this narrative, Impact originated in chair and chief executive Roger Smith's wish to transfer technology from Hughes Aircraft in order to justify his purchase of the aerospace concern in 1985. Instead, Impact suggested the feasibility of the zero-emission vehicle and led CARB to create the mandate. Smith's successor, Robert Stempel, promoted Impact but Stempel's colleagues demurred at a time when GM was losing billions of dollars. In 1992, Stempel was deposed and replaced as chief executive by John (Jack) F. Smith, Jr., with John G. Smale serving as chair. Shnayerson concludes on an upbeat note, with Jack Smith's decision in 1995 to start limited production of the Impact as the EV-1.[9]

Historians of the recent past face many practical problems, not least the risk of becoming hostage to fortune. GM never commercialized EV-1 and canceled the program in the early 2000s. Clarifying the company's motives is complicated by the wall of silence that typically shrouds extant commercial concerns and the fact that many principals involved in the EV-1 are now deceased, including Ovshinsky, Smale, Roger Smith, and Stempel.

Fortunately, scholars have important resources in the personal papers of Ovshinsky and Stempel. These documents suggest that Jack Smith used the EV-1 program as a means of undoing the mandate. The idea was to partner with Ovonic in a way that allowed GM to monopolize knowledge claims for nickel-metal hydride batteries and then produce a small volume of sophisticated but costly all-battery electric cars as a way of demonstrating to regulators the intractability of the durability dilemma.[10]

The scheme also promised to hobble the competition. Knowledge of the deliberations of Toyota executives in this context comes largely from Hideshi Itazaki's *The Prius That Shook the World* (1999), a work that resembles *The Car that Could* as a semiofficial account based on inside access.[11] The archival record further illuminates this realm thanks to the fact that Matsushita, Toyota's battery supplier, was an Ovonic licensee. The Ovshinsky and Stempel papers indicate that the GM-Ovonic partnership tried to use Ovonic's patent portfolio to prevent the Japanese alliance from deploying nickel-metal hydride technology in electric vehicles in the United States. They also suggest that Toyota conceived the hybrid electric Prius as a technological means of addressing this obstacle as well as and the durability dilemma and U.S. environmental and fuel efficiency regulations.

In short, in their own ways GM and Toyota took advantage of the ambiguities of LEV nomenclature to undermine the equation between the zero-emission vehicle and the all-battery electric vehicle. This case revisits classic issues of emerging science-based industry in the context of environmental policy. As historians and sociologists have shown, innovation is a nonlinear process governed by a host of variables that cannot be anticipated or easily controlled.[12] Fresh problems arise in manufacturing, making factory floors as much a site of knowledge production as laboratories.[13] California air quality politics introduced automakers to this world by compelling them to cooperate with the consumer electronics industry. Rivals in commerce but united in their apprehension of the mandate and linked by their common bond with Ovonic, GM and Toyota engaged regulators by reinterpreting the meaning of the zero-emission vehicle.

The Accidental Revolution

The mandate can be seen as symptomatic of a crisis in the relations between automakers and state and federal regulators around the policy of incrementally reducing the emissions of the gasoline vehicle. In 1967, the federal government empowered California to set its own emissions standards for new vehicles, and over the next two decades the state and the Environmental Protection Agency negotiated policies based on the capabilities of catalytic converter technology. Tom Cackette, a longtime CARB official who rose to direct mobile source emissions regulation operations in a career that spanned thirty years from the early 1980s, recalled that regulators worked with catalyst suppliers to assess feasibility, with a view to what automakers could accomplish in three to five years.[14] Automakers complied, yet air quality remained poor. Jananne Sharpless, CARB chair from 1985 to 1993, noted that by the late 1980s the federal government was threatening to withhold highway infrastructure funds unless California took action. In response, the air resources board drafted the LEV.[15]

Regulators interpreted Impact as the logical coda to that measure. Impact was a concept car, a device automakers used to demonstrate engineering principles and corporate vitality, something that was especially important to American companies as they lost market share throughout the 1980s.[16] Impact originated in a project that Roger Smith set into motion in the wake of the Hughes Aircraft acquisition. In late 1986, the Danish adventurer-environmentalist Hans Tholstrup informed Smith's office of his plans to stage a race of solar-powered cars across Australia in November 1987. Smith's office passed this information to Hughes vice president Howard Wilson, who enlisted Paul MacCready, the famed pioneer of human-powered flight and founder of AeroVironment, a builder of lightweight experimental aircraft, in a project to develop an entry for GM. Stempel, then serving as executive vice president of GM Truck and Bus, was also enthusiastic. A young AeroVironment engineer named Alec Brooks developed the proposal and GM executives approved it in March 1987.[17] In four and a half months of concentrated effort, a team drawn from the three companies built Sunraycer, a teardrop-shaped single-seater equipped with an exotic propulsion system that integrated silver-zinc batteries with solar cells.[18]

Sunraycer handily won the inaugural World Solar Challenge and admirably served Smith's goals. Basking in the favorable publicity, Smith made clear that the car was intended only to demonstrate GM's "expertise" in new technologies.[19] But Brooks, who had served as Sunraycer's project manager, wanted to create a practical battery electric car. He had the support of Wilson, who provided funds to keep the Sunraycer team together, as well as Stempel, who convinced Smith to buy in.[20] The result was Impact, a sleek electric two-seater introduced by Smith as a "producible" experimental car at the Los Angeles auto show in January 1990.[21] This episode is often interpreted as the proximate cause of the mandate, supplying regulators with proof of the technological feasibility of the zero-emission vehicle.[22]

Reinterpreting the Zero-Emission Vehicle

Impact divided GM leadership. Smith seemed unaware of the regulatory implications of the project at a time when CARB was drafting the LEV and, despite pouring cold water on Impact, he was in no position to roll it back. In July 1990, Smith retired and was succeeded by Stempel, whose efforts to commercialize Impact thrust the program further into the spotlight. To Jack Smith and John Smale, on the other hand, the project was anathema and sacking Stempel in 1992 did not make it disappear. Public policy gave Impact an additional boost through Stanford Ovshinsky. A self-taught materials scientist, Ovshinsky pioneered "disordered" materials, compounds that imparted useful electronic and catalytic properties to cheap prosaic substances. In 1964 he founded Energy Conversion Devices (ECD) to develop and license them. In the early 1980s, ECD researchers applied disordered materials to the nickel-metal hydride battery, greatly improving a technology invented by Philips and General Electric a decade earlier. In 1983, Ovshinsky spun off Ovonic Battery to develop the formula for consumer electronics applications and license its commercial production.[23] In 1992, Ovonic received the first grant awarded by the United States Advanced Battery Consortium (USABC), set up by the Department of Energy in the wake of the mandate to support research on electric vehicle batteries.[24] The award raised Ovshinsky's profile and when Stempel met the inventor shortly after leaving GM he arranged to secretly supply the Impact team with an Ovonic prototype battery pack. In a test at GM's Desert Proving Ground in Mesa, Arizona, in January 1994, the Ovonic Impact ran over two hundred miles on one charge, far more than what a comparable lead-acid rechargeable was capable of affording.[25] The two men became close allies and in 1995 Stempel became chair and executive director of ECD.

By then, support for the mandate was spreading across the country. Believing that lobbying had political limitations, Jack Smith approved a plan to contain Impact, one that turned on reinterpreting the zero-emission vehicle, casting doubt on all-battery electric power, and proposing alternatives. Kenneth Baker, the executive responsible for turning the Impact prototype into a manufacturable car, outlined the details to the GM president's council in February 1994. Impact would serve as a test bed, initially for hybrid battery electric and later for fuel cell electric propulsion, the basis of the ultimate zero-emission vehicle.[26] Fuel cells were believed capable of giving an electric car much longer range than any battery because they were thought to be limited only by how much fuel the car could carry. However, the technology needed much improvement before it could approach the practicality of all-battery electric drive. Automakers would later adopt this argument in negotiations with CARB, promising fuel cell electrics in exchange for smaller mandate quotas and deadline extensions. In the meantime, they met quotas with "compliance cars," money-losing all-battery electrics converted from gasoline models.[27]

In this way, automakers defined their mandate responsibilities in terms of R&D rather than manufacturing. GM constituted its partnership with Ovshinsky accordingly. The agreement took the form of a "joint manufacturing entity" called GM-Ovonic, of which GM owned 60 percent. Ovonic supplied materials and components and the automaker supplied start-up capital. But GM retained control over manufacturing. Ovshinsky would discover, to his dismay, that the deal compelled Ovonic to cut the costs of its battery formula, which had not been designed for automobiles, before production could take place.[28] In effect, the automaker controlled Ovonic's intellectual property as it related to electric cars.

Baker had the support of Harry J. Pearce. Pearce was a corporate lawyer, an unusual profession for an automobile executive of his stature, and something of an outsider. He joined GM in 1985 as associate general counsel and defended product liability cases before being promoted to executive vice president in the 1992 leadership shakeup. Pearce joined Smith and Smale in a triumvirate and possessed unusually broad powers. In addition to responsibility for GM's government and industry affairs, Pearce managed all of the corporation's nonautomobile assets, including Hughes. He had a mandate to transfer technologies to the main business if possible and, some observers thought, to liquidate these assets if necessary.[29] In effect, Pearce ran GM's electric car program. Under his watch, GM-Ovonic and Impact/EV-1 would become tools to limit CARB's ability to impose its will on industry.

Battery Economics and the Prius Principle

Japanese automakers closely monitored these developments. Toyota executives were concerned by what they saw as the contradiction between the rules governing fuel efficiency and the rules governing emissions in the U.S. automobile market, which they believed put them at a competitive disadvantage. In 1975, Congress created the Corporate Average Fuel Economy regulation to address the energy crisis. With the return of cheap oil in the early 1980s, the rationale for fuel efficiency waned. By the early 1990s, Detroit had made modest improvements in fleet efficiency, but Japanese automakers built the world's most efficient fleets and Toyota led the pack.[30]

Toyota interpreted the mandate as a threat to this investment. In response, its executives began promoting the idea that fuel efficiency had environmental consequences: as individual vehicles burned less fuel, less carbon dioxide was produced. The logic was specious from the perspective of environmental science but it had political advantages. Federal, state, and local air quality laws regulated specific pollutants, like oxides of sulfur and nitrogen, but not carbon dioxide. Not regulating carbon dioxide, an emission responsible for climate change, was the same as not regulating fuel efficiency, or so Toyota suggested.[31]

Here was the basis of a plan to reframe fuel efficiency as an environmental quality. It grew out of the G21 committee, struck in September 1993 by executive vice president of R&D Yoshiro Kimbara and so called because it was charged with determining the parameters of Toyota's commercial advanced propulsion vehicle of the twenty-first century. By privileging fuel economy, G21 ruled out all-battery electric drive. To be efficient, the car would have to be small, but to be marketable it had to have the same capabilities as an analogous gasoline car, identified as the Corolla. The G21 team thought that boosting efficiency by 50 percent was a realistic goal that could be accomplished using existing direct injection gasoline engine technology and an advanced transmission.[32] The G21's subsequent deliberations were influenced by the Clinton administration's decision to organize the Partnership for a New Generation of Vehicles (PNGV), a public-private R&D consortium designed to encourage Detroit to develop advanced fuel-efficient automobiles including hybrids, launched September 29.[33] In late 1994, executive vice president of development Akihiro Wada stipulated that the G21 car had to double the efficiency of the best gasoline engines. Now, only hybrid propulsion could tick all the boxes. The car was named Prius, derived from the Latin for "prior," in order to connote that commercialization would occur before the twenty-first century. Its identity as a hybrid electric passenger car would remain a closely guarded secret until its line-off, the start of mass production of a new model, a few years later. Toyota initially chose December 1998 as the production launch date but, in late 1995, company president Hiroshi Okuda inexplicably moved the date to December 1997.[34]

Toyota did not want its suppliers and affiliates to develop core competency in the relevant technologies of Prius and planned to develop most of them itself in parallel with its compliance car, a converted RAV4 sport utility vehicle.[35] The exception was the battery, which was the responsibility of the consumer electronics giant Matsushita, owner of the Panasonic brand. In May 1992, Matsushita announced that it had developed the world's first purpose-built nickel-metal hydride battery for electric vehicles and worked to adapt it to the requirements of the RAV4 EV. The vehicle's battery pack used twenty-four EV-95 modules of stacked flat cells, regarded as more suitable for electric traction than cylindrical commodity cells owing to their greater surface area and storage capacity.[36]

However, the RAV4 EV powerplant was far too large for Prius. Toyota and Matsushita might have built a pack around a smaller number of EV-95 modules but opted for a different approach. Toyota knew that for every electric vehicle it produced, the battery supplier was among the first to get paid. As long as vehicle production was low, battery costs would be high. Conversely, the battery supplier had to worry about the automaker's intentions. Purpose-built batteries could not make money if automakers produced only a few compliance cars. A commercial hybrid, however, might make it worth the trouble. In spring of 1995, Yuichiro Fujii, general manager of Toyota's Electric Vehicle Division, asked Matsushita if it could develop a hybrid battery by the end of the year. Matsushita said it could, using commodity cells.[37]

For both Matsushita and Toyota, this approach reconciled their interests. Matsushita already produced commodity cells for consumer electronics and they were proven, while the purpose-built electric vehicle modules were not. If commodity cells were used to build a battery pack and it turned out that Toyota was not serious or the hybrid did not sell, there was little loss. But if Prius was successful, Matsushita would have a vast new market.

Politics of Patent Monopoly

Another compelling reason for this approach was Ovonic's patent dominance. Matsushita began producing nickel-metal hydride commodity cells without obtaining a license from Ovonic and when it marketed them in the United States in 1992, the American company forced the Japanese company to terms. The parties also discussed the transfer of intellectual property relating to batteries for electric vehicles but the issue went unresolved because there was no scientific consensus on what defined such batteries at the level of cell chemistry. Ovonic's lawyers argued that Matsushita's claim to have invented the world's first nickel-metal hydride battery for electric vehicles was false. They held that the arrangement between the two companies restricted the licensee to patents relating to electronics applications.[38]

Matsushita viewed the agreement more broadly. Its lawyers argued that the deal simply covered small batteries and did not restrict how they might be applied. They believed the agreement gave Matsushita the right to license all patents owned by Ovonic and ECD covering inventions for small batteries conceived or developed prior to December 31, 1992. Moreover, Matsushita claimed Ovonic and ECD had agreed not to assert their rights on licensed patents they owned covering inventions conceived prior to May 4, 1992, relating to batteries of any size that also employed Matsushita's AB_5 metal hydride electrode.[39] Ovonic used AB_2, a vanadium-rich compound, selected because it enabled the highest possible storage capacity.[40] Vanadium is a relatively rare element that was not then expensive in the volume demanded by consumer electronics. In the electric vehicle application, however, that was not necessarily true.[41] In essence, Matsushita argued that a battery using a mix of Matsushita and Ovonic compounds was a novel thing for which it could claim legal ownership.

Ovshinsky hoped Matsushita might yet become a partner and maintained friendly relations with Shosuke Kawauchi, a senior managing director who would rise to become executive vice president of the corporation's battery division.[42] When GM and Ovonic joined forces in 1994, the prospects of an alliance with Matsushita became much less likely. Matsushita and Toyota faced the possibility that GM might use Ovonic's patent position to block import of electric vehicles equipped with nickel-metal hydride batteries into the United States. The RAV4 EV was vulnerable thanks to its large purpose-built battery, which potentially put Matsushita in violation of the 1992 agreement. Still, it suited the Japanese partnership to have this vehicle in the limelight. As a low-volume compliance car, the RAV4 EV was bound to lose money but it had value as a means of testing the U.S. reaction to Toyota and Matsushita's plans for the nickel-metal hydride battery and distracting attention from Prius.

In this sociotechnical context, the hybrid electric format had desirable qualities. In the Prius, Toyota also sought to foreclose the emergence of an automotive version of the consumer electronics market for disposable primary batteries, something Ovonic seeming to be aiming for. The all-battery electric car was a potentially open system. If a battery pack did not last the lifetime of the vehicle, it would have to be replaced and battery makers would reap the rewards. With the Prius, this could not happen because the battery pack was bundled into the propulsion system, from which it could not easily be removed, and was supposed to last the life of the vehicle. In short, Prius was a closed system. In its value chain there would be no battery market as such, only a long-term strategic relationship between two giant companies. Prius was an electric car that aged like a gasoline car and could be marketed like one.

The Discontents of Manufacturing

In contrast to Matsushita and Toyota, GM and Ovonic were not moving in lockstep. As the parties worked out terms through 1994, what emerged was a to-do list not so much for GM-Ovonic as for Ovonic itself. Ovonic was responsible for all battery research, development, design, and engineering, to ambitious performance goals set not by GM but by the USABC. The consortium wanted the cost of battery power cut to $150 per kilowatt hour at a time when Ovonic was charging around $6,000 per kilowatt hour for prototype batteries, amounting to well over $100,000 per pack. Ovonic also had to boost the energy density of its cells from around seventy watt hours per kilogram to the USABC target of around one hundred watt hours per kilogram.[43]

The partners were at loggerheads. Ovonic believed that it had sufficiently improved its battery by August 1994 to warrant manufacturing it as an important way of cutting costs but John W. Adams, president and chief executive officer of GM-Ovonic, was equivocal.[44] On the cost-cutting front, Ovonic was largely on its own.[45] Moreover, Ovonic would have to move from prototype to preproduction batteries while simultaneously resolving complications arising from the integrated propulsion system. Impact's first run on an Ovonic pack took place in a dry and cool Arizona winter, but like many battery chemistries the performance of nickel-metal hydride degraded in warm weather.[46]

A more serious problem was that charged packs lost charge when not in use. Charge depletion was a materials problem, and Ovonic was still perfecting the chemistry even as it worked to scale assembly. As problems with overheating and charge dissipation persisted into early 1995, cost targets were lost in a cascading series of trade-offs. Issues with charge depletion prevented Ovonic from freezing battery chemistry, and without a standardized chemistry it was impossible to fully understand cycle life. Not knowing how a battery pack aged, in turn, complicated the cost equation. By mid-1995, GM believed it would be difficult for Ovonic's first batteries to achieve even $500 per kilowatt hour, meaning that a thirty kilowatt hour pack could be worth an unacceptable $15,000. Automation was predicted to cut that figure but in 1995 production was still labor intensive.[47]

Problems did not end there. In a painful lesson in industrial cross-training, engineers discovered that pack design and cell production interacted dynamically. Most automakers wired packs of cells in series, connecting unlike terminals of each successive cell (cathode to anode)—a more efficient arrangement than parallel wiring (anode to anode, cathode to cathode) and one that produced higher voltage. However, series-linked batteries are only as good as the least reliable cell and hence are more prone to failure. To maximize the lifetime of a battery pack it was essential to equalize the state of charge of its cells, but that required sophisticated battery management, a technology then in its infancy.[48]

Sudden failures of series-wired packs were common in the early mandate years and there were many causes.[49] Cell quality control was foremost among these. John Adams came to GM-Ovonic from GM's AC Delco Systems, where he had served as chief engineer of manufacturing and begun his career working with auxiliary lead-acid rechargeables for gasoline vehicles. Cells for such batteries were produced by batch processing, a start-and-stop method that tended to induce variations in cell quality. That did not matter in auxiliary batteries for gasoline cars, observed Adams, but it mattered a great deal in large series-wired battery packs for electric cars. In this application, all cells had to work with 100 percent reliability and continuous processing was the best way to reduce cell variation.[50] However, continuous processing was more complex and costly than batching and could not easily be stopped once initiated, as Ovshinsky learned, to his chagrin.[51]

Matsushita and Toyota selected commodity cells partly to avoid such problems but discovered that this was not the off-the-shelf solution they had assumed it was. Through 1996, Toyota was stumped by sudden failures of its hybrid pack, and it fell to Fujii, appointed executive vice president of Panasonic EV Energy, the partnership's joint battery production venture, to solve the mystery. In commodity cell-making, quality control occurs at the back end. Freshly made cells are aged and defective ones slowly discharge over time. Sometimes, however, proofed cells fail. [52] Fujii found that contaminants such as metal dust and lint at Matsushita's Tsujido plant were often the cause. If just one of the Prius pack's 240 cells was bad, the hybrid system would not work. To bring failure rates to zero, rigid quality control had to be enforced at the front end of the process. If the revamped line was not exactly at the standard of the semiconductor clean room, Toyota had moved it a step in that direction.[53]

Industrial Tradecraft

As the engineers tackled these problems, the respective alliances were reconnoitering each other. Matsushita and Toyota needed information on the nature of Ovonic's patent claims and GM-Ovonic's intentions and used the RAV4 EV to broach a conversation. Frustrated by slow progress at GM-Ovonic, Ovshinsky and Stempel hoped this demarche meant that a production deal could be worked out with the Japanese alliance. This was in the interest of neither automaker, but GM encouraged negotiations, likely in order to surveil the opposition. Talks unfolding through 1995 and into 1996 precipitated legal maneuvers that turned on the difference between a consumer electronics battery and an electric vehicle battery, a science controversy that laid bare the American partnership's patent strategy to control nickel-metal hydride chemistry.

In the version of events told by Ovonic's lawyers, Matsushita informed Ovonic in February 1995 of its plans to develop the RAV4 EV battery, ostensibly to sort out licensing terms. In a May meeting in Tokyo, Ovonic averred that it had said it would license production for the U.S. market but only through GM-Ovonic, "consistent with its commitments to GM." It also claimed Matsushita had said it preferred to join GM-Ovonic outright but talks were inconclusive. In August, Ovonic learned that Matsushita had approached Ford, and negotiations between Ovonic and Matsushita broke down. They resumed in the fall at the request, said Ovonic lawyers, of GM.[54]

Then, in the summer of 1995, Matsushita's lawyers asked Ovonic to specify the patents Matsushita would be violating if its nickel-metal hydride batteries for electric cars did find their way to U.S. shores.[55] According to Matsushita, Ovonic did not respond. With no answer from Ovonic, Toyota and Matsushita made their move. On January 22, 1996, Toyota announced that a two-year research project involving the RAV4 EV and Southern California Edison that was to have used lead-acid batteries would instead employ nickel-metal hydride batteries. Suddenly, the RAV4 EV had become a means of testing GM-Ovonic's claim of legal rights to such batteries for electric vehicles in the United States. Ovshinsky learned of the switch through the Japanese media and reproached Kawauchi in a February 5 letter. He was still interested in collaboration, he wrote, but licensing would have to be settled first. Until Ovonic and Matsushita settled their differences, Ovshinsky wanted Toyota to delay its test.[56] But Matsushita wanted to know the legal basis for denying its electric vehicle batteries access to the U.S. market. On February 26, Chester Kamin, Ovshinsky's personal attorney, provided the answer: Matsushita was infringing on U.S. Patent 5,348,822, or the "822." Unless Matsushita gave written assurance that it would stop importing such batteries into the United States, wrote Kamin, Ovonic would take legal action.[57]

Two days later, Matsushita filed to invalidate 822, moving to preempt what it claimed was an imminent lawsuit from Ovonic. In Ovonic's ensuing countersuit, the scope of the American company's claims were laid bare. Patent 822 described bulk spherical powders of nickel hydroxide incorporating the same principles of disorder Ovonic applied in the hydride-based anode but applied to the cathode. Kamin noted that patent had been filed on March 8, 1993, and so was not protected by the 1992 agreement.[58] How did Ovonic know 822 had been infringed? It did not possess a Matsushita electric vehicle battery and so had no direct evidence. Ovonic worked by inference, testing a consumer cell cathode. Ovonic's lawyers claimed the test indicated the presence of the offending substance. Moreover, they held, Matsushita product literature indicated that the performance characteristics of its consumer cells and electric vehicle cells were similar, something Ovonic interpreted as establishing a reasonable claim of infringement.[59]

For its part, Matsushita did not deny that it had infringed 822. Instead, it called attention to the hydride materials comprising the anode and, in particular, to its own AB_5 alloy. Matsushita's lawyers claimed the company had been working on this substance with a view to applying it in electric vehicle batteries as early as 1990. Matsushita believed the 1992 agreement allowed it to make a nickel-metal hydride battery of any size if it contained AB_5, a claim Ovonic did not directly contest. Matsushita's lawyers appeared especially concerned about Ovonic's long delay in identifying 822. They were curious about what Kamin had meant in his February 26 letter when he indicated that 822 was merely one of a number of "other violations" of Ovonic's rights. Matsushita suspected that Ovonic had other patents it was in no hurry to identify and that it might later try to assert against it.[60] In effect, Matsushita accused Ovonic of being a patent troll.

In March, Ovonic lawyers filed a motion for preliminary injunction, a riposte that represented a case for the technological potential of basic science. A small American company supported by the federal government, they argued, had used disordered materials to make the world's first commercially viable rechargeable nickel-metal hydride battery. Matsushita and Toyota's plan to "infiltrate" infringing batteries into the United States without a license, held Ovonic lawyers, would cause irreparable harm to Ovonic, the only entity legally authorized to license or produce nickel-metal hydride battery technology for the electric vehicle market.[61]

In short, Ovonic claimed ownership of the nickel-metal hydride battery in the electric vehicle application through its claims for the nanotechnology of amorphous materials. Whatever the scientific and legal merits of the case, however, the market as Ovonic imagined it did not then exist because automakers were unwilling to create one. In early 1996, the car companies convinced CARB to eliminate the quotas from 1998 to 2002 and worked out a Memorandum of Agreement to build a total of only eighteen hundred zero-emission vehicles between 1998 and 2000. In exchange, automakers had to meet stricter emission standards and continue the research and development of zero-emission vehicles.[62]

Moreover, Ovonic did not have an intellectual monopoly. As in other fields of science-based industry, there was constant traffic in ideas from the battery lab to the factory floor and back again. Knowledge of electric vehicle systems and cell manufacturing were all pertinent to developing production-grade nickel-metal hydride chemistry.[63] In these areas, Matsushita was more advanced than Ovonic, but it did not have all the answers either. In the 822 affair, Matsushita and Toyota accused Ovonic of interfering in research aimed at understanding electric cars in real-world conditions. Ovonic was not facing the prospect of imminent widespread use of an infringing battery, argued Matsushita lawyers, so its opposition to the RAV4 EV pilot study risked delaying the introduction of electric cars in the United States.[64] A self-serving claim, it contained a grain of truth. No one party held all the cards, as Stempel acknowledged in a note to the media: "This was a difficult decision for ECD to take since we are committed to support the developing electric vehicle market, and Toyota is a potential customer for some of our products."[65]

The Kyoto Car

Stempel and Ovshinsky continued to hope that a grand alliance could still be forged.[66] It was not to be, but the spring of 1997 brought seemingly good news for GM-Ovonic. The U.S. District Court for the District of Delaware moved to dismiss Matsushita's lawsuit and, in validating 822, to restrict the battery maker's technology to an earlier chemistry yielding only sixty-three watt hours per kilogram of capacity. As a result, the RAV4 EV would be no match in range for the Ovonic EV-1, whose battery pack was rated at about seventy watt hours per kilogram.[67] For Stempel, the legal process was doubly heartening because it caused GM to announce that the first module of production-intent equipment was operational, contradicting Matsushita's argument that GM-Ovonic was a joint venture in name only.

Ovonic used this information in its countersuit to claim that a manufacturing base for electric vehicle batteries in the United States was vital to the "overall EV strategy."[68]

Stempel hoped that competitive pressures accentuated by the court ruling would concentrate GM's mind on the Ovonic EV-1. But events were passing GM-Ovonic by. In March, Toyota announced that it would introduce a commercial hybrid electric for the model year 1997 and Detroit hitched its breath.[69] The American hybrid program lagged far behind. Unlike the Japanese manufacturers, Detroit and its federal partners in the PNGV treated the hybrid as a kind of supercar, aiming to triple the fuel efficiency of the average 1994 passenger sedan. This required precisely the sort of super battery that American automakers had long insisted could not be developed quickly for the all-battery electric car. Saft, Yardney, SRI, and Varta, the chosen hybrid battery contractors, had all failed to deliver one. Ovonic was unaccountably excluded from the PNGV but it developed its own hybrid electric battery with its own money that it now offered to GM.[70]

But GM was not interested. Over the course of 1997, Stempel surveyed global environmental politics with growing concern. Attending the Summit of Eight meetings in Denver in June, he was taken aback when energy secretary Federico Peña bluntly stated that the Clinton administration had no policy going into Kyoto. Stempel was finally grasping Toyota's strategy. In a meeting with Pearce on August 13, he presented his view of the situation. Toyota was going to use the Kyoto summit to position itself to dominate the global automobile industry by offering its commercial hybrid as the solution to the problem of climate change. The automaker's message would be that better fuel economy equated with less carbon, a substance that, unlike other tailpipe emissions, was not then subject to controls. Japanese and German automakers, noted Stempel, were lobbying hard against specific carbon reduction targets at Kyoto. In the technopolitics of local air quality, the balance of power favored the regulator; in the technopolitics of global climate change in the 1990s and early 2000s, the automaker held the upper hand. In building the market for the sustainable automobile, Toyota, Stempel observed, would rely on consumer acceptance, not public policy targets.[71]

Forcing the Future

Prius was a triumph of social as well as physical engineering. On December 10, the day before the climate treaty was signed in Kyoto, Toyota held a ceremony for the Prius line-off. As diplomats and officials gathered in the old imperial capital, Priuses were on hand to shuttle them between venues.[72] Jack Smith noted that Toyota had developed Prius with the help of a public subsidy, and it was true that Japan's Ministry of International Trade and Industry (MITI) offered financial assistance for first users. However, the automaker also benefited from the U.S. stimulus policies that were a major impetus for the electric vehicle revolution.[73] In Prius there was another, subtler connection between government and industry. Years later, G21 member Satoshi Ogiso revealed that the Prius production deadline had been moved up one year from December 1998 precisely so that the launch would coincide with signing of the climate treaty.[74] Toyota president Hiroshi Okuda made this decision nearly seven months before Kyoto was formally announced in July 1996 as the site of the Third Conference of the Parties of the UN Framework Convention on Climate Change, suggesting he had been privy to negotiations at the highest levels.[75]

Toyota's success is often ascribed to the Toyota Production System, a method of rigorous sequential planning wherein workers continually tested "hypotheses" of production, illuminating problems on which the system then focused resources.[76] The history of mandate politics suggests that Toyota also had a keener understanding than its competitors of how U.S. environmental regulations could be turned to commercial advantage. General Motors coped with risk in this context by investing resources in trying to prove the economic infeasibility of the all-battery electric format. In 2000, GM ended production of the EV-1 and sold its share of GM-Ovonic to oil giant Texaco, casting the knowledge of how to manufacture large nickel-metal hydride batteries into what amounted to an industrial limbo and marginalizing Ovonic.[77] A few years later, GM led its peers in recalling and disposing of all-battery electric cars, an act that delayed the mandate but did not kill it.[78]

In Prius, in contrast, Toyota had a means of convincing regulators to revise the rules in its favor. The hybrid electric car was an ingenious way of using patent-contested battery technology in a way that shared the rewards between automaker and battery maker and neutralized the durability dilemma. While hybrids did produce emissions, they were low in comparison with the cleanest all-gasoline cars. In November 1998, California air quality regulators amended the mandate to allow automakers to use hybrids, along with fuel cell electrics, to meet a portion of their zero-emission vehicle commitments.[79] In their own ways, both Prius and the EV-1 were highly sophisticated technologies. But where EV-1 was engineered at a scale sufficient to show regulators what was not possible, Prius was engineered at commercial scale with a view to reconciling all the challenges this class of consumer product faced in the U.S. market in the 1990s including fuel efficiency and environment regulations, patent obstructionism, and the riddle of battery economics. As a result, Prius became the first electric car for the masses.[80]

Conclusion

The story of the construction of the zero-emission vehicle is one of the unintended consequences and paradoxes of U.S. public policy. The mandate stimulated an emerging manufacturing sector with industrial-technological requirements that compelled a new level of interaction between automakers as nominal competitors, on the one hand, and between policymakers, automakers, and battery makers, on the other. Led by GM, Detroit cooperated with its Japanese peers and the rest of the global automaking establishment in exploiting the regulatory ambiguity of the zero-emission category to suppress the all-battery electric car, hoping also to suppress the incipient advanced battery research, development, and manufacturing base necessary for commercial electric propulsion in the process. General Motors enlisted Ovonic as a key instrument in this strategy. The automaking giant manipulated the small company's concentrated intellectual property around the nickel-metal hydride battery to limit its application in electric traction before abandoning its partner when the task was accomplished. In this manner, Ovonic became collateral damage in the Great Game of clean car technopolitics.

Toyota and Matsushita were only too happy to see the demise of the all-battery electric car. In Prius, they elaborated a more expansive definition of what constituted a commercially-viable zero-emission vehicle, one that reinforced their sociotechnical agenda. But in commercializing this hybrid electric car, the Japanese partnership emerged from the green automobile wars of the 1990s into the new millennium in a position to dominate the core material content of electric cars of all types. By virtue of its supply monopoly for Prius, Matsushita (renamed Panasonic in 2008) became the world's largest producer of battery cells for electric vehicles. When electric vehicle enthusiasts and U.S. public policymakers revived the all-battery electric format over the course of the 2000s and thrust forward as their champion Tesla Motors, a company that used the lithium ion battery, a power source less constrained by patent claims than the nickel-metal hydride battery, Panasonic was in a position to reap many of the benefits. It expanded into lithium cells for electric vehicles, becoming Tesla's chief cell supplier and profiting from the U. S. stimulus measures that increasingly supported all- battery electric propulsion from the late 2000s. The saga of the EV-1 and Prius as contrasting responses to the zero-emission vehicle mandate hence illustrates the ambivalent effects of R&D in the context of technology-forcing public policy. It suggests that environmental, trade, and socio-cultural factors are all key determinants of how new knowledge is applied in industrial enterprise and points to opportunities for fruitful collaboration between historians of business, historians of science and technology, and environmental historians in grasping the latest unfolding chapter of the electric vehicle.

Footnotes

[1] For an excellent review of the assumptions of science policy in this context, see Ann Johnson, "The End of Pure Science: Science Policy from Bayh-Dole to the NNI," in *Discovering the Nanoscale*, ed. Davis Baird, Alfred Nordmann, and Joachim Schummer (Amsterdam, 2004), 217–30.

[2] During the September 1990 hearings, battery expert Andrew Wortman cited a study by the Department of Energy indicating that operators of electric cars equipped with standard lead-acid batteries would have to replace their packs every fifteen months at a cost of $3,000 to $4,000 for each replacement; see 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): 1308.

[3] Tom Cackette (former CARB chief deputy executive officer), interview by the author, 27 Sept. 2019; Jananne Sharpless (CARB chair, 1985–1993), interview by the author, 5 Sept. 2019.

[4] Collantes and Sperling, "Origin," 1312.

[5] J.H. Wesseling, J.C.M. Farla, and M.P. Hekkert, "Exploring Car Manufacturers' Responses to Technology-Forcing Regulation: The Case of California's ZEV Mandate," *Environmental Innovation and Societal Transitions* 16 (2015): 90.

[6] Compare, for example, the cases of AT&T/Bell Labs and Dell Technologies. Thanks to its market monopoly, AT&T did not have a pressing need to commercialize the innovations produced by Bell Labs. Its monopoly was tolerated and regulated by the federal government in exchange for a commitment to freely license Bell Labs patents, an arrangement that underpinned the intellectual basis of the semiconductor revolution. In contrast, Dell become one of the most successful commodifiers of the personal computer in part by outsourcing as much research and development as possible, a model its founder referred to as "virtual integration." See Jon Gertner, *The Idea Factory: Bell Labs and the Great Age of American Innovation* (New York, 2012), 183; Joan Magretta, "The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell," *Harvard Business Review*, Mar.–Apr. 1998, 72–84; Stefan Thomke, Vish V. Krishnan, and Ashok Nimgade, "Product Development at Dell Computer Corporation" (Harvard Business School Case 9-699-010, Aug. 1998), 1–21.

[7] Max Åhman, "Government Policy and the Development of Electric Vehicles in Japan," *Energy Policy* 34, no. 4 (2006): 433–43; United States Council for Automotive Research, "Who We Are," accessed 23 June 2013, https://www.uscar.org/guest/history.php.

[8] The expression "'pure' electric car" is sometimes used to refer to the all-battery electric car, as distinct from the hybrid battery electric and fuel cell electric formats. Strictly speaking, the fuel cell electric vehicle is also a kind of "pure" electric vehicle, including variants that integrate fuel cells and galvanic batteries in an all-electric hybrid configuration. To avoid confusion, I will not use the adjective "pure" in this context.

[9] Michael Shnayerson, *The Car that Could: The Inside Story of GM's Revolutionary Electric Vehicle* (New York, 1996).

[10] For classic studies of the public ratification of truth claims in science and engineering communities, see Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, 1985); and Stephen Hilgartner, *Science on Stage: Expert Advice as Public Drama* (Stanford, 2000).

[11] Hideshi Itazaki, *The Prius That Shook the World: How Toyota Developed the World's First Mass-Production Hybrid Vehicle*, trans. Albert Yamada and Masako Ishikawa (Tokyo, 1999).

[12] See, for example, David C. Mowery, Richard R. Nelson, Bhaven N. Sampat, and Arvids A. Ziedonis, "The Growth of Patenting and Licensing by U.S. Universities: An Assessment of the Effects of the Bayh-Dole Act of 1980," *Research Policy* 30, no. 1 (2001): 99–119; Mowery and Ziedonis, "Academic Patent Quality and Quantity before and after the Bayh-Dole Act in the United States," *Research Policy* 31, no. 3 (2002): 399–418.

[13] See, for example, Cyrus Mody, *The Long Arm of Moore's Law: Microelectronics and American Science* (Cambridge, MA, 2016); Hyungsub Choi, "The

Boundaries of Industrial Research: Making Transistors at RCA, 1948–1960," *Technology and Culture* 48, no. 4 (2007): 758–82; Christophe Lécuyer and David C. Brock, "The Materiality of Microelectronics," *History and Technology* 22, no. 3 (2006): 301–25; and Stuart W. Leslie, "Blue Collar Science: Bringing the Transistor to Life in the Lehigh Valley," *Historical Studies in the Physical and Biological Sciences* 32, no. 1 (2001): 71–113.

[14] Cackette interview.

[15] Sharpless interview.

[16] George Harrar, "Technology: The 'Concept Car' Pushes Change," *New York Times*, 1 July 1990, sec. 3, p. 5.

[17] Brooks, an avid enthusiast and participant in advanced-technology human-powered lightweight racing, learned independently about the Tholstrup race and was planning his own entry around the time MacCready was contacted by Hughes. Alec Brooks, interview by the author, 6 Dec. 2019.

[18] Two Sunraycer cars were built, with the second one incorporating improvements on the initial prototype. Hughes designed the power source system around specialized subsystems then mainly used in military applications, using its own gallium arsenide photovoltaic cells and silver-zinc batteries made by Eagle Picher. AeroVironment built Sunraycer's body and chassis and GM's Research Laboratories designed and built the motor. See Bill Tuckey, *Sunraycer* (Hornsby, NSW, 1989), 13–20, 43–9; and Shnayerson, *The Car That Could*, 14–15.

[19] Roger B. Smith, "A Message from the Chairman," in Tuckey, *Sunraycer*, 9.

[20] Brooks interview; Shnayerson, *The Car That Could*, 21.

[21] Roger B. Smith, "GM Impact (EV1) Intro at the 1990 LA Auto Show," speech given on 3 Jan. 1990, YouTube video, posted 7 Aug. 2008, https://www.youtube.com/watch?v=OjgbTdAiJE0.

[22] Collantes and Sperling contest this claim; see "Origin," 1306–7. It is likely that CARB was aware of Impact prior to conceiving the mandate. Cackette recalled that as his team was preparing the LEV in 1989, AeroVironment invited them to view the Impact prototype. Cackette interview.

[23] Lillian Hoddeson and Peter Garrett, *The Man Who Saw Tomorrow: The Life and Inventions of Stanford R. Ovshinsky* (Cambridge, MA, 2018), 187–208.

[24] S.R. Ovshinsky, M.A. Fetcenko, and J. Ross, "A Nickel-Metal Hydride Battery for Electric Vehicles," *Science* 260, no. 5105 (1993): 176–81.

[25] S.K. Dhar, S.R. Ovshinsky, P.R. Gifford, D.A. Corrigan, M.A. Fetcenko, and S. Venkatesan, "Nickel/Metal Hydride Technology for Consumer and Electric Vehicle Batteries: A Review and Update," *Journal of Power Sources* 65, no. 1–2 (1997): 5; see also Shnayerson, *The Car That Could*, 171–81.

[26] Shnayerson, *The Car That Could*, 187–90.

[27] Harold D. Wallace, Jr., "Fuel Cells: A Challenging History," *Substantia* 3, no. 2 (2019): 83–97; Matthew N. Eisler, *Overpotential: Fuel Cells, Futurism, and the Making of a Power Panacea* (New Brunswick, NJ, 2012). As a type of miniature chemical plant, fuel cells require physical plumbing to manage liquids and gases, making them more difficult to integrate into electric drivetrains than conventional galvanic batteries.

[28] Leon J. Krain to Stanford R. Ovshinsky, 4 Mar. 1994, box 47, ECD/Corporate Partners/Joint Ventures, 1971–2004, Stanford R. Ovshinsky Papers, Bentley Historical Library, University of Michigan at Ann Arbor (hereafter SROP).

[29] See Doron P. Levin, "Mr. Pearce's Growing Domain," *New York Times*, 15 Nov. 1992.

[30] Environmental Protection Agency, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2016* (EPA-420-R-16-010, Nov. 2016), 51.

[31] Itazaki, *Prius*, 107, 153–54.

[32] Itazaki, 19–21, 301.

[33] Former CARB member Daniel Sperling suggested that the PNGV inspired G21; see Sperling, "Public-Private Technology R&D Partnerships: Lessons from U.S. Partnership for a New Generation of Vehicles," *Transport Policy* 8, no. 4 (2001): 251. For a review of the founding of the PNGV, see National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles* (Washington, DC, 1994), 6–7.

[34] Itazaki, *Prius*, 71–73, 115–16, 319, 340.

[35] Itazaki, 75–76, 83, 94, 102.

[36] Akihiro Taniguchi, Noriyuki Fujioka, Munehisa Ikoma, and Akira Ota, "Development of Nickel/Metal-Hydride Batteries for EVs and HEVs," *Journal of Power Sources* 100, no. 1–2 (2001): 117–24; "Panasonic Battery History," Panasonic Global website, accessed 29 June 2020, https://www.panasonic.com/global/consumer/battery/about_us/history.html; Panasonic, "PEV: Battery for Pure Electric Vehicles," data sheet, 1998, accessed 28 Jan. 2018, http://www.evnut.com/rav_battery_data_sheet.html.

[37] Itazaki, *Prius*, 263–65; Taniguchi et al., "Development," 119–21.

[38] Thomas N. Young, "Civil Action No. 96-70919; Memorandum of Law in Support of Ovonic Battery Company Inc.'s Motion for Preliminary Injunction," 3 Mar. 1996, 5, box 32, untitled dustcover (Matsushita), Robert C. Stempel Papers, Bentley Historical Library, University of Michigan at Ann Arbor (hereafter RCSP).

[39] Morton Amster, Jesse Rothstein, and Daniel S. Ebenstein, "Civil Action No. 96-101: Matsushita Battery Industrial Co., Ltd., versus Energy Conversion Devices, Inc., and Ovonic Battery Company, Inc.," 28 Feb. 1996, 8-9, box 32, untitled dustcover (Matsushita), RCSP.

[40] Srinivasan Venkatesan, Michael Fetcenko, Benny Reichman, and Kuochih C. Hong, "Development of Ovonic Rechargeable Metal Hydride Batteries," *Proceedings of the 24th Intersociety Energy Conversion Engineering Conference* 3 (1989): 1659–64.

[41] Shiuan Chang, Kwo-hsiung Young, Jean Nei, and Cristian Fierro, "Reviews on the U.S. Patents Regarding Nickel/Metal Hydride Batteries," *Batteries* 2,

no. 10 (2016): 2–3.

42 In June 1992, Kawauchi wrote a short but warm letter to Ovshinsky that began with the following lines: "As you know, according to Buddhist philosophy, in our human life, we all have a unique occasion to meet the right person at the right time. I regard our meeting in Japan as one of those occasions." Kawauchi to Ovshinsky, 12 June 1992, box 8, Matsushita, 2007, SROP.

43 Krain to Ovshinsky, 4 Mar. 1994, 1–3; "OBC_PLN3.DOC 06/13/94," 13 June 1994, box 32, GM-Ovonic, USABC John Adams, 4, RCSP; GMO Battery Summary, 21–23 Sept. 1997, 1–3, box 32, GM-Ovonic Battery Summary, RCSP; Shnayerson, *The Car That Could*, 101, 204.

44 The contrast in the views of Ovonic and GM-Ovonic on the relationship between battery cost and manufacturing can be seen in a comparison of a draft and the final version of a press release announcing the formation of the GM-Ovonic management team. The draft, likely written by someone from Ovonic, quotes Adams as stating that GM-Ovonic's evaluation of the Ovonic battery was the "next logical step in the commercialization process…as you move from the laboratory to the marketplace." The draft also quotes Ovshinsky as stating that "opening the manufacturing facility" was necessary to achieve cost and production goals. The official GM press release omits any mention of Ovshinsky and includes only a more moderate claim from Adams that the automaker was encouraged by its technical evaluation and that GM-Ovonic was committed to moving the technology from the laboratory to the marketplace. See, respectively, "GM-Ovonic Forms Management Team, Readies Manufacturing Facility," 30 Aug. 1994, and "GM-Ovonic Forms Management Team, Names Board of Managers," 9 Sept. 1994, both in box 47, ECD/Corporate Partners/Joint Ventures, 1971–2004, SROP.

45 The initial business plan stipulated that GM would not fund Ovonic directly but instead facilitate resources from "organizations such as USABC." "OBC_PLN3.DOC 06/13/94," RCSP; see also Shnayerson, *The Car That Could*, 233.

46 The pack heated up when charging and when discharged in warm ambient conditions; see Shnayerson, *The Car That Could*, 233–35.

47 Shnayerson, 233–41.

48 A battery's state of charge is defined as the level of charge relative to battery capacity, ranging from empty to full. See Nasser H. Kutkut, Herman L.N. Wiegman, Deepak M. Divan, and Donald W. Novotny, "Design Considerations for Charge Equalization of an Electric Vehicle Battery System," *IEEE Transactions on Industry Applications* 35, no. 1 (1999): 28–35. A further complicating factor in battery pack management is that even cells from the same final assembly batch can develop different states of charge depending on their placement in the pack. Victor Tikhonov, "Simple Analog BMS for the Tinkerer, Part 1," *Current Events* 44, no. 12 (2012): 1–34.

49 Nickel-metal hydride cells were moderately tolerant of overdischarge because the reaction yielded hydrogen that, if not produced too rapidly, could be reabsorbed by the anode. Ovonic promoted this quality of its metal hydride materials as a way of dispensing with costly pack management technology. See Robert C. Stempel, Stanford R. Ovshinsky, Paul R. Gifford, and Dennis A. Corrigan, "Nickel-Metal Hydride: Ready to Serve," *IEEE Spectrum* 35, no. 11 (Nov. 1998): 29–34.

50 GM Advanced Technology Vehicles, "Manufacturing EV-1 and S-10 Electric NiMH Batteries," press release, 3 Dec. 1998, 1–3, box 31, Electric Vehicle Miscellaneous, RCSP.

51 Ovshinsky was accustomed to altering the chemistry of scaled-up cell prototypes and was annoyed when he learned that the GM-Ovonic production line would not be stopped to accommodate changes. Ovshinsky to Stempel, "Subject: GMO 3 Status," 24 July 1998, 4, box 50, Business Admin ECD/notes (includes org chart) 2005–2006, SROP.

52 I thank battery expert Jack Johnson, cofounder of Volta Power Systems, for these insights; Johnson, interview by the author, 26 Jan. 2017.

53 Itazaki, *Prius*, 274–78.

54 Thomas N. Young, "Complaint and Jury Demand," 29 Feb. 1996, 6–7, box 32, untitled dustcover (Matsushita), RCSP; and Young, "Civil Action No. 96-70919," 6.

55 Morton Amster to Chester T. Kamin, 28 Feb. 1996, in Amster, Rothstein, and Ebenstein, "Civil Action No. 96-101," 12.

56 Ovshinsky to Kawauchi, 5 Feb. 1996, box 32, untitled dustcover (Matsushita), RCSP.

57 Kamin to Amster, 26 Feb. 1996, in Young, "Complaint and Jury Demand."

58 Kamin to Amster, 26 Feb. 1996 in Young, "Complaint and Jury Demand," and Amster, Rothstein, and Ebenstein, "Civil Action No. 96-101," 11–12.

59 Young, "Civil Action 96-70919," 11–12.

60 Amster, Rothstein, and Ebenstein, "Civil Action No. 96-101," 5–12.

61 Young, "Civil Action No. 96-70919," 2–8.

62 Deborah Salon, Daniel Sperling, and David Friedman, "California's Partial ZEV Credits and LEV II Program" (UCTC No. 470, University of California Transportation Center, Berkeley, 2001), 2; Brad Heavner, *Pollution Politics 2000: California Political Expenditures of the Automobile and Oil Industries, 1997–2000* (Santa Barbara, CA, 2000), 7–8.

63 A number of large manufacturing enterprises, mainly Japanese, had extensively patented nickel-metal hydride cell construction methods and components. See Chang et al., "Reviews," 7–9.

64 Amster, Rothstein, and Ebenstein, "Civil Action No. 96-101," 15; see also Thomas N. Young and Carl H. von Ende, "Civil Action No. 96-70919: Toyota Motor Sales U.S.A., Inc.'s Memorandum in Support of Motion to Stay This Proceeding Pending Decision of Delaware Court on Motion to Stay, Dismiss, or Transfer," 12 Mar. 1996, 9, box 32, Young, and von Ende, Miller, Canfield, Paddock, and Stone, 03.12.96, RCSP.

65 Stempel to Rich Piellisch, 6 Mar. 1996, 1, box 32, *Fleets & Fuels* inquiry, RCSP.

[66] "Potential Settlement Plan," 28 Jan. 1997, 1–3, box 50, Bus Admin ECD/Notes (includes org chart) 2005–2006, SROP.

[67] Ovonic claimed its second-generation battery pack (the GMO-2) had an energy density of eighty watt hours per kilogram and hoped to put it in production by the end of 1997. "Slide 48 MBI," Annual Meeting 1997, 58, box 96, ECD Annual Meetings, 1996–1998, SROP.

[68] Stempel made these assertions in a letter to Robert C. Purcell, executive director of GM's Advanced Technology Vehicles division. Stempel to Purcell, 14 Apr. 1997, box 32, GMR Meeting 7/23 Baker, RCSP. With the court victory all but certain, Stempel wrote Pearce: "Thank you for all your valuable help on the Matsushita-Ovonic matter...now that the MBI EV battery market position has been defined (and limited), it is clear that GM can be in a dominant, controlling position with NiMH EV batteries." Stempel to Pearce, 14 Apr. 1997, box 32, GMR Meeting 7/23 Baker, RCSP. The U.S. District Court for the District of Delaware formally dismissed Matsushita's lawsuit on 23 Dec. 1997. Energy Conversion Devices, "MBI Litigation Concluded in Favor of ECD," news release, Jan. 5 1998, 1–2, box 32, Black Folder (ECD/Ovonic/NiMH Update), RCSP.

[69] Valerie Reitman, "Toyota to Sell Hybrid Gas-Electric Car: Auto Maker Cites High Efficiency, Low Emissions," *Wall Street Journal*, 26 Mar. 1997, A12; "(Fairly) Clean Cars," *New York Times Sunday*, 30 Mar. 1997.

[70] Subhash K. Dhar to Ovshinsky, "Subject: Hybrid Electric Vehicle," 21 Mar. 1997, and Paul R. Gifford to Ovshinsky, "Meeting with GM Hybrid Vehicle Team," 21 Mar. 1997, both in box 32, HEV Batteries Ovonic, RCSP.

[71] Robert Stempel, "Trio Report: Summit of 8 Meetings, Denver, Colorado," 20 June 1997, 2–3, box 32, dustcover 3, unorganized/misc 1, RCSP; and Stempel hand notes, "H.J. Pierce [*sic*] Office, 9:30 AM 13 Aug. 1997," 1–3, box 32, unmarked folder 2, RCSP.

[72] Satoshi Ogiso, "The Story behind the Birth of the Prius, Part 2," Toyota Global website, 13 Dec. 2017, https://newsroom.toyota.co.jp/en/prius20th/challenge/birth/02/.

[73] On the MITI subsidy, see Itazaki, *Prius*, 381. The Prius also benefited from the Bush administration's Energy Policy Act of 2005, which provided a tax credit of up to $7,500 for conventional hybrid passenger vehicles up to a total of sixty thousand units until December 31, 2010. See Public Law 109-58, Energy Policy Act of 2005, 8 Aug. 2005, 1043, 1047, 1049; and Molly F. Sherlock, "The Plug-In Electric Vehicle Tax Credit," *Congressional Research Service*, 14 May 2019, https://fas.org/sgp/crs/misc/IF11017.pdf.

[74] Ogiso, "Story."

[75] Itazaki, *Prius*, 115, 270, 340; United Nations, *Report of the Conference of the Parties on its Second Session, Held at Geneva from 8 to 19 July 1996. Addendum. Part Two: Action Taken by the Conference of the Parties at its Second Session.* 29 Oct. 1996. 4, https://unfccc.int/documents/977.

[76] For an influential analysis of the TPS, see Steven J. Spear and H. Kent Bowen, "Decoding the DNA of the Toyota Production System," *Harvard Business Review*, Sept.–Oct. 1999, 96–106. For an example of the influence of the TPS in non-automobile fields, see Clayton M. Christensen, Steven King, Matt Verlinden, and Woodward Yang, "The New Economics of Semiconductor Manufacturing," *IEEE Spectrum* 45, no. 5 (May 2008): 24–29.

[77] Gregory L. White, "GM Stops Making Electric Car, Holds Talks with Toyota," *Wall Street Journal*, 12 Jan. 2000, A14; "Texaco to Acquire General Motors' Share of GM-Ovonic Battery Joint Venture," *Business Wire*, 10 Oct. 2000, 1. Shortly after Texaco acquired GM's stake in GM-Ovonic, Texaco was itself absorbed by Chevron; see Sherry Boschert, *Plug-In Hybrids: The Cars That Will Recharge America* (Gabriola Island, BC, 2006), 44–5, 82–3.

[78] The liquidation of the EV-1 took place in the context of GM's gradual divestiture of its electronics and parts empire. In 1997, the automaker sold Hughes to Raytheon and GM's Automotive Components Group (renamed Delphi Automotive in 1995) absorbed Delco Electronics in 1997 before GM spun off Delphi in 1999.

[79] Salon, Sperling, and Friedman, "California's Partial ZEV Credits," 3–5: CARB, "Fact Sheet: The Zero Emission Vehicle Program-2008," 6 May 2008; "California Cuts ZEV Mandate in Favor of Plug-In Hybrids," *Wired*, 27 Mar. 2008, http://www.wired.com/autopia/2008/03/the-california/.

[80] GM produced some 1117 EV-1s, most equipped with lead-acid battery packs and a few hundred with Ovonic packs. By 2017, Toyota had produced nearly four million Priuses; see Toyota Motor Corporation, "Worldwide Sales of Toyota Hybrids Surpass 10 Million Units," press release, 14 Feb. 2017, https://newsroom.toyota.eu/global-sales-of-toyota-hybrids-reach-10-million/.