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From petroleum to power sources: Big Oil and the technopolitics of energy conversion

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ABSTRACT

This paper explores spillover into advanced energy conversion technologies as an oil industry response to US energy and environmental policies from the last third of the twentieth century. These policies initiated the 'quasi-planned' renovation of energy infrastructure through an uncoordinated mixture of regulation and innovation/industrial stimulus intended to develop all forms of primary energy and the technologies that could efficiently and cleanly convert that energy. Influenced by this sweeping public policy objective as well as the global consumer electronic industry's increasing demand for petroleum-derived inputs from the late 1970s, Western oil interests doing business in the US engaged the technoscience of advanced energy conversion. Big Oil researched, developed, and in some cases manufactured materials and components associated with power sources including fuel cells, galvanic batteries, and photovoltaic arrays in projects that illustrate the affinities and antagonisms between enterprises of naturally stored primary energy, energy conversion, and flows and carriers of energy. Case studies of Big Oil's involvement with these technologies illustrate how public policies supporting all-of-the-above energy and energy conversion limited the extent of oil spillover into advanced energy conversion systems and complicated the transition to a fossil fuel-free future.

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Introduction

In October 2019, the Royal Swedish Academy of Sciences (RSAS) awarded the Nobel Prize in Chemistry to three people (John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino) it credited with playing a leading role in the development of the lithium-ion rechargeable battery. In its press release, the RSAS held that this technology represented a major step towards a 'wireless, fossil fuel-free society', invoking an intriguing connection between technologies of telecommunication and clean energy that it did not elaborate. The press release did provide an obscure but tantalizing hint that fossil fuels were somehow implicated in the shift to the wireless fossil fuel-free society: the battery's electrode, invented by Yoshino, was made of petroleum coke.[1]

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RSAS did not mention other important linkages between the petroleum sector and the development of the lithium-ion battery. Yoshino had worked for Asahi Kasei, a multinational chemical concern and a leading manufacturer of a petroleum-based polymer applied to the battery as a crucial safety component. And Whittingham had made his contributions to lithium-ion battery technology in the employ of oil giant Exxon in the early 1970s. Exxon promoted this connection from the mid-2010s, long after Whittingham had left the company, and it also supplied important material inputs for commercial lithium-ion cells.[2]

The case of the lithium-ion battery seemingly problematizes the trope of oil companies as technologically conservative guardians of the fossil fuel order. It represents an instance of multi-pronged petroleum spillover into consumer electronics and clean energy, fields of technoscience whose linkages might not be immediately apparent. Their common denominator is advanced energy conversion and storage (defined here as non-internal combustion/non-nuclear technology), a set of objects, material practices, and ways of knowing that enable a host of other advanced technologies ranging from wireless telephony to automobile traction to renewable energy systems. Understanding how the oil industry intersects with the interests around these technologies has the potential to reveal much about the capacity of Big Oil to facilitate the transition to a fossil fuel-free society, a question of high relevance in the era of climate change and efforts to mitigate it.

Scholars of mixed-method approaches in the environmental and energy humanities informed by science and technology studies (STS) who engage this question must first consider the implications of the realist turn in discussions of social construction and causality in human affairs provoked by the public health crises of climate change and the covid pandemic.[3] In response to these crises, STS thought leaders cautioned against critical inquiry devolving into radical scepticism and suggested the scholarly community ‘do its part’ to resolve them.[4] The turn to realism diminished the tension in STS between analysis and norming without erasing it completely and moreover swung the pendulum of agency toward the non-human. Many who would vocally note that the debate around anthropogenic climate change has long since closed while perhaps accepting that questions of how climate change manifests remain open, also assume that the debate around remediating climate change is also closed while perhaps accepting that questions of precisely how remediation will be operationalized remain open. The corollary assumption is that renewable energy represents a key if not the primary means of resolving the climate crisis, a view present even in studies that acknowledge the primacy of human agency and predict that social factors will replicate the same social inequities in the notional future low-carbon society that are currently present in high-carbon society unless corrective action is taken.[5]

And so while few if any scholars in STS and its allied fields would claim technology as the chief causal agent of history, there is some willingness to entertain energy determinism thanks to the seemingly strong correlation between energy and climate change.[6] In 2014, the philosophers Robert-Jan Geerts, Bart Gremmen, Josette Jacobs, and Guido Ruivencamp outlined the implications of this sort of thinking. Renewable energy determinism, they suggested, has had the effect of eliding flows of energy with stocks of stored energy, blurring distinctions between the various forms of primary energy and the energy conversion and carrier technologies that enable useful work to be derived from them.[7] This mindset, accentuated by normativity, fosters a sort of conceptual cognitive dissonance that dematerializes renewable energy. On the one hand, there is a presumption that because renewables do not yield emissions at point of use they must somehow be distinct and separate from the materiality of fossil energy. On the other, representations of renewable energy tend to depict not wind, falling water, and sunlight so much as highly visible objects like turbines and photovoltaic arrays that mediate and convert that energy. And while in the distant past energy conversion technologies (like windmills) were constituted of non-fossil fuel resources, in the recent past, an era sometimes referred to as high-energy modernity, such technologies were heavily constituted of fossil fuel resources at all points in their life cycle, what energy and environmental studies refer to as embodied or whole life carbon.[8]

I suggest that a way of resolving the tension around human versus non-human agency and the question of materiality in energy and environmental studies is through the frame of reference of the social relations of energy conversion. In essence, this is historical materialism applied to the era of high-energy modernity. Such a historical-sociological approach would center human agency in analyses of forms of primary energy and assume that these forms have physical properties that are not absolute but relative to human interpretation. It would also assume that as humans initiate relationships with non-humans, knowledge-gaps emerge around these relationships that social systems struggle to address. In such a framework, the scope of human agency is contingent on the provisional state of knowledge of a given instance of human/non-human interrelationship (what STS sometimes refers to as the sociotechnical and envirotechnical) at a given point in time.

In order to understand the timing and quality of the oil industry’s involvement in the materials and technologies of advanced energy conversion and contributions to fossil fuel-free society, we need to understand something of the industry’s social relations or political economy. Like all large-scale modern industrial enterprises, the oil industry is transnational in scope. Western oil interests have been strongly influenced by US oil interests, which asserted hegemony after World War Two and continued to exert a leadership role even as American petropower waned from the 1970s, and by US markets and energy and environmental policies. In this article, I focus on Western oil interests, often referred to collectively as ‘Big Oil’, primarily with a view to their operations in the US context but with an eye to the industry’s transnational reach. As with all capitalist industrial enterprises, the Western oil industry was fundamentally shaped by the tendency to overproduce.[9] Historically, petroleum producers managed abundance by creating scarcity, partly by destroying surplus resources but primarily through oligopolistic control of markets, often with the aid of the state, with varying degrees of success.[10]

A related aspect of the paradox of petroleum abundance is found in the history of petroleum refining. Petroleum is a complex compound and the oil industry perceived its constituent substances in dynamic sociotechnical, envirotechnical, and socio-economic conditions. When US entrepreneurs first began exploiting oil on a large scale in the mid-nineteenth century, they valued its heavier fractions for lubrication and lighting and intentionally destroyed the lighter fractions as waste byproducts until changing conditions caused them to reinterpret and reevaluate these substances.[11] Petroleum refiners seeking kerosene dumped energy-rich gasoline in vast quantities until the advent of the internal combustion-engined (ICE) passenger vehicle at the turn of the twentieth century led them to perceive gasoline as a fuel.[12] As the US ICE vehicle fleet scaled over the course of the twentieth century, eventually greatly surpassing the energy conversion capacity of US stationary generation plant, gasoline became the main refined petroleum product and a core business of the oil industry.[13]

The process of waste revaluation stimulated by industrialization stimulated the refining and petrochemical wings of the oil industry.[14] This chemical manufacturing complex eventually came to commodify all fractions of petroleum in materials applied in everything from pavement to packaging to clothing and electronics. The contingent value-identity of petroleum-derived materials as waste/feedstock and their production both by oil and non-oil industrial interests meant that these materials were never subjected to cartel control. Where the political economy of oil was characterized by periods of relative stability afforded by global oligopoly, the political economy of petrochemicals was characterized by fierce competition and instability.[15]

Big Oil's engagements with advanced energy conversion technology were determined by shifting valuations of materials (petroleum-derived and otherwise) informed by changing sociotechnical and envirotechnical conditions co-produced with changing US public policies intended to address perceived problems of national security, pollution, and resource scarcity emerging around the last third of the twentieth century. These policies, which accreted over time, were loosely coordinated through a host of institutions of regulation and industrial stimulus and informed the 'quasi-planned' renovation of US energy conversion infrastructure around a dual imperative: the maximal exploitation of all forms of primary energy and the development of technologies that could efficiently and cleanly convert that energy.[16] Together with the global consumer electronic sector's demand for petroleum-derived inputs as it began scaling mobile devices and personal computers from the late 1970s, these policies incentivized US and Western oil interests to experiment and diversify. Big Oil researched, developed, and in some cases manufactured materials and components associated with power sources including fuel cells, advanced batteries, and photovoltaic arrays, all key enablers of low- and zero-emission energy conversion and the subject of intense public policy interest and investment. Oil companies engaged these technologies roughly sequentially from the 1950s, 1960s (fuel cells), and 1970s (advanced batteries and photovoltaic arrays) and then concurrently from around the 1990s.

Case studies of these enterprises illustrate the oil industry's limited capacity to adapt to changing circumstances and to reconcile its core business of naturally stored primary energy with the businesses of technologically stored energy (batteries, hydrogen), materials and technologies of energy conversion (ICE, fuel cells, batteries, photovoltaic arrays), and flows or carriers of energy (utility liquids, gases, and electricity). These cases reveal the collaboration between Western oil and US national security interests in innovating advanced technologies, a theme also explored by Owen Marshall and Cyrus Mody in articles in this issue.[17] These cases also illuminate connections between advanced energy conversion and electronics and between petroleum and consumer electronics interests as well as the petroleum dependence of key aspects of high-technology industrial manufacturing more broadly. They further problematize the idea of the linear clean energy transition by casting into relief the complexities of contemporary US energy infrastructure, not only in terms of the heterogeneous sources of primary energy it consumes, as scholars have pointed out, but also in terms of the heterogeneous forms of energy conversion technology it employs.[18] The commitment of economic and political elites to energy and energy conversion diversity ultimately limited the extent of oil spillover into advanced energy conversion technology and infrastructure and complicated the transition to a fossil fuel-free future.

Petroleum and electrochemical energy conversion

Big Oil's involvement in advanced energy conversion technology can be traced to experiments in electrochemical power sources from the late 1950s, a time when the US federal government encouraged industry to develop advanced materials in support of the arms and space races.[19] An important part of this work related to the fuel cell, an energy conversion device that bridges the sociotechnical regimes of stored energy and electricity. Fuel cells (actually a family of devices with different operating systems) produce electricity by electro-oxidizing hydrogenous gases and liquids. The basic physical principle was established by the scientists William Robert Grove and Christian Friedrich Schönbein, who independently used platinum foil to catalyze a reaction between pure hydrogen and oxygen in experiments conducted in the late 1830s and early 1840s. Fuel cells operate best on pure hydrogen, a carrier of energy and a medium of energy storage that can also be applied as a liquid or gaseous fuel. Hydrogen is a costly substance that is difficult to manage, so fuel cell technology was not practically applied for many years after its discovery. In principle, however, fuel cells can utilize hydrogen bound up in carbonaceous fuels, and the possibility of a carbonaceous fuel cell attracted periodic interest in the succeeding century. From the 1880s, researchers began studying the possibility of fuel cells operating on coal and coal-derived gases, but such technologies faced serious engineering challenges.[20] The first practical fuel cells were not built until the 1960s, and they operated on pure hydrogen for use in NASA spacecraft.[21]

Encouraged by progress in aerospace hydrogen fuel cells, Royal Dutch Shell and Standard Oil of New Jersey's Esso Research and Engineering division began studying fuel cells that could use cheap common fuels like diesel, kerosene, and alcohol, technologies that in theory would enable electric vehicles (EVs) to operate within the existing fossil fuel infrastructure. This research was motivated mainly by US military interest and was organized and funded by the Department of Defense's fledgling Advanced Research Projects Agency (ARPA) as Project Lorraine from 1958 to 1966.[22] Esso Research and Engineering's fuel cell program mainly sought to understand fuel dynamics so that suitable formulas could be prepared in the event the federal government procured carbonaceous fuel cells at scale.[23] Initial research yielded some progress but no breakthroughs in catalyst and electrolyte materials and suggested that the carbonaceous fuel cell was impracticable given the current state of the art. By the late 1960s, oil companies were shelving the technology, but they would revisit it in the 1990s when public policy created new justifications for it.[24]

Meanwhile, the energy crisis of the 1970s and public policy pressure for alternative energy conversion technologies prompted oil companies to consider another kind of electrochemical power source in the form of the rechargeable battery. Rechargeables have less direct relevance to oil's core interests than fuel cells because they store electricity converted from any source of primary energy. One spillover axis into rechargeables came through hydrogen, a substance that some experts had long believed could supplement electricity as an energy carrier and that could also serve as a storage medium.[25] In the late 1970s, the Atlantic Richfield Company (ARCO) began collaborating with Energy Conversion Devices (ECD), a Detroit-based research laboratory founded by the self-taught scientist Stanford Ovshinsky, to commercialize amorphous or disordered materials, a class of nanomaterial possessing very high surface area that imparted useful electronic and catalytic properties to prosaic, cheap substances. These investigations, enabled by ARCO research grants and contracts to ECD, began with a study of metal hydrides, a medium for hydrogen storage. The German automaking giant Daimler-Benz was then studying metal hydrides for use in hydrogen-fueled ICE-powered automobiles, but researchers at ECD applied these materials as the negative electrode of an electrochemical couple equipped with a nickel hydroxide cathode. The resulting device electrolyzed water on charging and oxidized hydrogen on discharging and was known as a nickel-metal hydride battery (NiMH).[26]

General Electric and Philips had patented NiMH battery technology in the early 1970s but the version developed by ECD became widely recognized as the first practical such battery, largely because the company was able to exploit the additional surface area of amorphous materials to enable extra hydrogen storage.[27] In 1982, Ovshinsky set up the Ovonic Battery Company as a wholly owned unit of ECD, developing NiMH compounds and licensing the technology for consumer electronics applications to a host of manufacturers including Varta, Hitachi Maxell, Gold Peak, and Matsushita.[28] Nickel-metal hydride batteries were relatively safe and more energetic and durable than the nickel-cadmium rechargeable battery and helped enable parallel developments in hand-held consumer electronics.[29]

Contributions to the development of materials relevant to rechargeable batteries were also made by Exxon, the former Standard Oil of New Jersey, again motivated by the energy crisis. In the wake of the 1973 oil embargo, Exxon worried about the possibility that automakers might build EVs and saw research into energy storage materials as a wise hedge.[30] It was in the employ of Exxon Research and Engineering that Whittingham devised the lithium titanium disulfide formula, a rechargeable chemistry of unprecedented power and energy. At the time, Whittingham suggested that he had developed a practical power source but the device proved too volatile for commercial use, in large measure because it used a metallic lithium anode. With repeated recharging of the cell, this highly reactive substance induced growth of uneven deposits of lithium that bridged the electrodes, causing a short circuit that could ignite the device's highly flammable organic electrolyte.[31]

Nevertheless, Whittingham's technology demonstrated the principle of intercalation, the reversible storage of ions in a layered structure, as the basis of a rechargeable lithium battery. This work inspired further research in the emerging field of solid state ionics and lithium insertion compounds, most notably by the physicist John Goodenough on lithium cobalt oxide, a highly energetic formula that would change perceptions of what was possible in hand-held electronics and, later, battery electric vehicles (BEV).[32] Goodenough's contributions to the invention of the lithium cobalt oxide battery would earn him the honor as co-laureate of the 2019 Nobel Prize in Chemistry alongside Whittingham and Yoshino.

Electronics and the carbon industrial complex

Exxon did not immediately follow up its pioneering research in lithium compounds for commercial gain. Commercialization of the lithium-ion rechargeable battery instead occurred in the 1980s at the intersection of the carbon industrial complex adjacent to the petrochemical industry and the consumer electronics sector, the latter an important arena of spillover, as Mody and Marshall observe.[33] Carbon-based materials have been used in electrochemical devices since the mid-1840s and are valued for their good electrical and thermal conductivity, resistance to corrosion, light weight, abundance, malleability, and non-toxicity. By the late 1980s, carbon materials were being widely used as structural components, electroconductive supports, and electrocatalysts in batteries and fuel cells.[34] Of particular importance were the carbon blacks, a family of nanoscale-particle materials produced annually in the millions of tons through the incomplete combustion of coal tar, biomass, and heavy petroleum products. Carbon blacks are vital industrial substances, used in everything from rubber to ink to conductive agents. Only a few varieties conduct electricity, including materials (Ketjenblack and Philblack) that became available in the mid-1970s as the byproducts of a Shell gasification process.[35]

Efforts to commercialize a lithium-ion rechargeable battery centered on the development of a safe carbon anode for the lithium cobalt oxide cathode, one that would allow lithium ions to evenly and thus safely intercalate with and plate on the anode. This requirement necessitated the development of sophisticated engineered carbon materials, efforts pioneered by Sony and Asahi Kasei. Akira Yoshino, who took BS and MS degrees in the Department of Petrochemistry at Kyoto University, is widely credited with pairing a lithium cobalt oxide cathode with a carbon anode. Yoshino recalled that he initially selected polyacetylene, an electroconductive polymer derived from the hydrocarbon acetylene and invented in the early 1980s by the chemist Hideki Shirakawa, in part because Asahi Kasei envisioned a market for the new material as a battery component.[36]

Yoshino subsequently used a different anode material, usually described as ‘petroleum coke’, a soft carbon, in a basic design for a lithium rechargeable cell that he patented in 1985 and that Asahi Kasei licensed to other companies including Sony. Yoshino later claimed that he used vapor grown carbon fiber (VGCF, or synthetic graphite, popularly known as carbon nanotubes), a then-experimental and costly material created by heat-treating a soft carbon precursor, produced by a research unit at Asahi Kasei.[37] Sony’s battery team, led by Yoshio Nishi, developed a series of anodes using more conventional compounds made of petroleum coke and later graphite, and in 1991, Sony brought the world’s first lithium rechargeable to market, initially for the Kyocera cellular telephone. The next year, Asahi Kasei set up a joint venture with Toshiba to manufacture lithium-ion batteries.[38]

Commercialization of the lithium-ion battery in turn opened parallel markets for feedstocks and components that overlapped the petrochemical complex. Despite Yoshino’s contributions to carbonaceous anode design, Asahi Kasei did not manufacture this component. Carbonaceous anodes for lithium-ion batteries were instead produced mainly in the carbon industrial complex, a network of multinational chemical operations optimized for products made from elemental carbon derived from petrochemical feedstocks. Much of this complex consisted of Japan-based enterprises including Hitachi Chemical, Showa Denko, and Tokai Carbon. This complex embraced both legacy and high-technology manufacturing and produced materials ranging from commodity carbon blacks to batches of expensive engineered carbon-based nanostructured materials like VGCF and synthetic graphite for electronics applications.[39]

However, Asahi Kasei did produce a carbon-based polymer membrane that served as a crucial safety component of lithium-ion cells. The lithium cobalt oxide battery is composed of volatile flammable materials including metal oxides and organic electrolyte. If a cell in such a battery ignited, it could trigger an uncontrollable chain reaction called thermal runaway, a sudden release of chemical energy that could spread to other cells and create a fire that, fed by the oxygen in its metal oxides, cannot easily be extinguished. Separator membranes insulated cell electrodes and inhibited short circuits while offering minimal resistance to ionic transport. In the event of a heat spike, separator micropores expand and cut off current.[40]

The separator market became attractive to Exxon partly because separators were derived from polyolefins, a cheap and abundant petrochemical byproduct. In the mid-1980s, the oil company developed a polyethylene-based polymer separator in a part of the petrochemical complex co-located with Japan's industrial carbon and consumer electronics complexes. The material was produced by Exxon Chemical affiliate Tonen Chemical, part of TonenGeneral, one of the largest Japanese oil refiners, then also controlled by Exxon. As we have seen, Exxon would later claim that it had invented separator technology.[41] However, some industry insiders indicate the basic chemical formula for polyethylene and polypropylene-based polymers dated to the late 1960s and had been developed for application in filtration equipment and breathable garments, including surgical gowns and recreational clothing popularized in the Gore-Tex brand.[42]

Whether novel or repurposed, such materials were important enablers of the commercial rechargeable lithium-ion battery and the revolution in mobile electronics from the late 1980s. As the market for separators expanded with the burgeoning demand for lithium-ion batteries for mobile electronics, Exxon became a major supplier along with Asahi Kasei and Polypore, supplying around 35 percent of the market.[43]

Battery materials, mobile computing, and the EV quandary

Exxon's involvement in the battery separator market was precipitated by the shift from desktop to handheld computing and complicated by two sequential sociotechnical developments: the integration of electronics and power sources in the consumer electronics sector and the emergence of the EV market. Exxon's commercial calculations in these contexts were informed by consideration of systems integration problems issuing from these emerging and converging industrial-technological sectors and of the implications of the EV market on the company's primary business of stored primary energy. The appearance of commercial NiMH and lithium-ion rechargeable batteries enabled the practical use of microprocessors in handheld devices, yet pressure for increased device functionality, the availability of increasingly powerful chips, and rising demand for power created cascading systems problems in integrated battery-chip devices that the relevant research communities (petrochemicals, electronics, and power sources) were ill-equipped to address owing to disciplinary and institutional siloing.[44]

By the 1990s, vertical disintegration in the US consumer electronics sector was well under way, manifesting in offshoring, outsourcing, the fabless foundry, and the idea that components could be seamlessly integrated in novel configurations.[45] Michael Dell, a leading commodifier of the Wintel personal computer, referred to this process as 'virtual integration', a management model that emphasized marketing and logistics over research and development and took the trend in vertical disintegration to its logical conclusion.[46] The idea of virtual integration was informed by experience with the desktop personal computer, an object whose three basic components (monitor, case, and keyboard) were available as discrete retail items.

Applying this philosophy to the innovation of the integrated battery-microprocessor of the handheld device induced a host of unintended sociotechnical consequences. Faster processors generated more heat and required more power, and for developers of battery cells, the cheapest solution was to make room for more reactive material in the cell casing by thinning the separator. Thinned separators often failed to provide sufficient thermal insulation, but manufacturers were concerned mainly with battery performance over the short life cycle of consumer electronics.[47] Hardly any research was devoted to battery reliability and safety, and thinned cell separators in lithium cells factored in a spate of fires in notebook and laptop devices through the 2000s and 2010s.[48]

The potential for trouble was even greater in the large lithium-ion battery packs being planned for EVs in this period. These packs contained much larger volumes of combustible material than their consumer electronics counterparts, and the vehicle duty cycle placed that material under much greater stress and generated more heat. Separators in EV cells had to cope with that stress and heat, creating a demand for new and more robust polymer materials.[49]

In the mid-2000s, ExxonMobil Chemical committed to meeting this demand. The company was particularly interested in the market for separators in lithium-ion cells for the plug-in hybrid EV (PHEV), a class of EV that US automakers were developing with the encouragement of the federal government in order to compete with Toyota's Prius, a successful non-plug-in hybrid EV whose first-generation iteration used a NiMH battery pack.[50] Unlike the all-battery EV (BEV), hybrid EVs of all types directly use carbonaceous fuels and in principle represent a balancing of environmental and fossil energy interests, a calculus that appealed to the US national security establishment.[51] ExxonMobil Chemical and its Tonen Chemical affiliate worked to develop advanced heat-resistant separator material and, in late 2009, announced a joint venture with Tonen and Japanese multinational Toray Industries to produce it.[52]

Two years later, however, Exxon pulled out of the joint venture, directing Tonen to sell its stake to Toray.[53] The oil giant left the separator market at a time when margins were shrinking as cell manufacturers scaled production and dramatically cut costs from the turn of the millennium. As yields and prices on first-generation separator material declined through the 2000s and 2010s, exacerbated by separator-thinning, the prospect of protracted research and development and a long lead time for commercial advanced separator material likely did not appeal to oil executives.[54] With the departure of Exxon, the battery separator market became dominated by large chemical companies including Toray, Asahi Kasei, and ENTEK, as well as the petrochemical concern SK Innovation.

Commodifying the sun

In some ways, the oil industry's involvement with photovoltaic power resembled its engagement with fuel cells and batteries in that all these technologies were solutions seeking problems until perceived national security crises precipitated state market-making around them. Prior to the 1970s, energy was cheap, and there was little demand for commercial-scale photovoltaic power, an enterprise that promised to be highly capital-intensive at the outset. Like so many other hallmark advanced technologies, the photovoltaic cell was invented by Bell Laboratories in the 1950s, and like the fuel cell, the technology had a military connection, one that overlapped consumer electronics. The basic raw material of contemporary commercial photovoltaic power is crystalline silicon, a substance that from the late 1950s served as the basis of solid-state electronics in the form of transistors and semiconductors, technologies initially used mainly in military applications like missiles.[55] Similarly, the first notable application of silicon photovoltaic cells in the US was in spacecraft, a market pioneered by semiconductor maker Hoffman Electronics from the late 1950s.[56] As semiconductor manufacturers led by Intel scaled production from the late 1960s, cheap chips were applied in consumer electronics and, from the mid-1970s, personal computers, stoking demand for crystalline silicon.[57]

Aerospace remained the primary market for photovoltaic power when the federal government initiated large-scale experiments in terrestrial applications of the technology as part of its response to the energy crisis. In 1974, Congress passed the Solar Energy Research, Development, and Demonstration Act, and in 1978, it passed the Public Utility Regulatory Policies Act (PURPA) requiring utilities to sell and purchase electricity generated and co-generated from non-utility decentralized small plant using biomass, waste, or renewables.[58] In theory, PURPA stimulated photovoltaic power and its inputs.

However, utility-scale photovoltaic power still faced important barriers in cost, demand, and, relatedly, institutional sponsorship. As with nuclear power, there was no private sector leadership on these questions, so the state filled the vacuum. Solar energy was only one of several energy initiatives the federal government launched in response to the oil price shocks, and policymakers were not then prepared to plan and subsidize its commercial lifecycle as they had with nuclear power.[59] In the 1970s and early 1980s, quasi-planned federal support for photovoltaic power was confined to research and mild stimulus and left the various industrial enterprises with relevant technology and experience to foster their own collaborative arrangements. Electric utilities as businesses of energy conversion and flows were the primary notional users of photovoltaic power but had no capacity to fabricate crystalline silicon and confined their activities in this field to monitoring and assessing photovoltaic cell research through their collective non-profit Electric Power Research Institute (EPRI)[60] The chemical and semiconductor sectors were the main producers of crystalline silicon, and the latter was the main user, but did not have direct interests in photovoltaic power and did not play a direct role in its development.[61] The oil industry neither manufactured crystalline silicon nor had an interest in photovoltaic power. But because the energy crisis was an oil crisis, and because oil was the single largest source of primary energy consumed in the US, and because the oil industry hence dominated the US energy industry, Big Oil by default became the major private sector player in the terrestrial photovoltaic research project.[62]

In this enterprise, oil companies had little choice but to collaborate with electronics and materials companies, where expertise in the technologies of photovoltaic power resided. Petroleum interests initially focused on established single-crystal silicon technology, with ARCO and Mobil joining power source-maker Westinghouse and several start-ups in this field.[63] In 1973, Exxon created Solar Power, an entity that the business historians Geoffrey Jones and Loubna Bouamane characterized as the first US enterprise established expressly to manufacture terrestrial photovoltaic cells.[64] Solar Power was managed by the industrial chemist Elliot Berman and used silicon wafers rejected by the semiconductor industry as a feedstock for cells initially employed in remote applications, including offshore oil rigs. In 1974, Mobil began working with semiconductor maker Tyco in a photovoltaic cell fabrication venture.[65]

Ovshinsky's ECD served as an important contractor of oil industry-sponsored research in advanced photovoltaic materials, a role similar to the one it played in the realm of NiMH rechargeables. From the late 1970s through the mid-1980s, ARCO and then Standard Oil of Ohio (Sohio) funded ECD research in amorphous silicon, a technology that in theory offered certain advantages over crystalline silicon. Ovshinsky's biographer Lillian Hoddeson recorded that the inventor believed amorphous silicon solar cells could be efficiently and cheaply produced as a thin film 'by the mile' and thereby facilitate distributed electricity generation at home and in the developing world.[66] However, ARCO's solar division opted for crystalline silicon in its trials and subsequent production of photovoltaic cells, in part because thin-film amorphous silicon significantly degraded with exposure to sunlight.[67] In 1977, ARCO acquired crystalline silicon through the purchase of Solar Technology International, an enterprise founded by Bill Yerkes, a former employee of Spectrolab, an electronics contractor that developed photovoltaic systems for the US space program.[68]

By the early 1980s, technology for fabricating photovoltaic cells at scale had been developed, not by an established electronics concern or oil company but by Spire, a research and development start-up founded in the shadow of Route 128, Massachusetts' technology corridor.[69] By then, however, the oil price shocks had abated, resolved through diplomacy and the exploitation of reserves in Alaska, Mexico, and the North Sea.[70] When the Reagan administration decided to phase out subsidies for photovoltaic power and price controls on oil and gas, demand for photovoltaic power evaporated.[71]

Nevertheless, the oil crisis served to embed solar energy in the research agenda of US public policy and Big Oil. Through the 1980s into the early 1990s, oil companies continued to explore photovoltaic technology, with some players dropping out and others taking their place. Sohio's relationship with ECD helped develop thin-film photovoltaic technology but ended in 1986, when British Petroleum (BP) acquired Sohio and terminated the program in favor of crystalline silicon cells. Thin-film solar cells were first applied in consumer electronics.[72] In 1984, Exxon sold Solar Power to Solarex, a start-up acquired by Amoco the previous year and that later became a joint venture between Amoco and Enron. ARCO operated several demonstration-scale photovoltaic power plants in California until liquidating these assets in 1990.[73]

Around the turn of the millennium, intensifying public policy pressure for renewables, motivated by concern not so much with energy supply as with environmental issues, led some oil interests to reconsider photovoltaic power as a vertically integrated industrial enterprise.[74] Shell and BP led the oil industry's return to solar energy, building on their reputations as the petroleum concerns most sensitive to the risks that climate change posed to Big Oil's 'social legitimacy'.[75] Both companies invested in materials research and development, cell and panel fabrication, and the construction and operation of generation plant, with BP further concentrating Big Oil's activities in the field with its acquisition of Solarex in 1999 following its purchase of Amoco in 1998.[76]

Over the course of the 2000s, state support stimulated a photovoltaic boom that had the unintended consequence of disrupting the oil industry's efforts to control the photovoltaic supply chain. Despite investing in the production of photovoltaic feedstock material, Shell and BP had a relatively small share of this market. At the turn of the millennium, both companies committed resources to weighing the advantages of first-generation conventional crystalline silicon technology against second-generation thin films that were believed to have very high energy conversion efficiencies.[77]

However, the photovoltaic boom unfolded initially around polycrystalline silicon, with photovoltaic cells surpassing semiconductors as the largest application of this material by 2006.[78] In turn, the photovoltaic boom precipitated a global shortage of polysilicon, causing market turbulence that inhibited the ability of petroleum interests to control and compete in the value chain.[79] High polysilicon prices incentivized new producers, swinging the pendulum towards overproduction exacerbated by falling demand with the advent of the global recession in 2007. The recession triggered a restructuring of the photovoltaic sector, concentrating polysilicon production in a few multinational chemical companies led by Wacker and Hemlock and the manufacturing of solar cells in China.[80]

In 2006, Shell dropped crystalline silicon in favor of advanced thin film, an approach supported by the US federal government and proponents of a US high-technology riposte to China's growing dominance in photovoltaic power production. Sustained federal investment in thin-film photovoltaics produced mixed results thanks in part to the availability of cheap polysilicon and polysilicon solar cells from the late 2000s, which made it difficult for thin-film enterprises to compete. In 2011, two high-profile US thin-film start-ups (Solyndra and Evergreen Solar) went bankrupt.[81] Federal aid eventually enabled Tempe-based First Solar to scale thin-film cadmium-telluride photovoltaic technology for the 550-megawatt Desert Sunlight installation in Southern California, a project completed in 2015 and jointly owned by NextEra, General Electric, and Sumitomo of America.[82]

Foreign dominance in manufacturing and the US federal government's policy of stimulating advanced but costly new photovoltaic technologies seem to have disincentivized Western oil companies from continuing vertically integrated operations in this sector. Where BP Solar and Shell Solar had been the world's second- and fourth-largest producers of solar cells in the early 2000s, respectively, their share of this market steadily eroded thereafter. Both companies left the field around the turn of the decade.[83]

Conclusion

The terms of Big Oil's involvement in the research, development, and manufacturing of materials and technologies of advanced energy conversion were governed by the relative tension between those enterprises and the oil industry's traditional business of stored primary energy. Spillover here was determined by oil industry interpretation of wastes, feedstocks, and materials markets in the context of shifting public policy priorities and emerging industrial-technological sectors around consumer electronics and EVs. Some of these projects reinforced the oil industry's traditional interests while others did not but in general, oil companies regarded advanced energy conversion technologies with ambivalence.

Of these technologies, the fuel cell had the greatest direct relevance to the business of stored primary fossil energy. From the late 1950s, the federal government periodically stimulated research in carbonaceous fuel cells as an alternative to the galvanic battery in the EV application, supporting diesel, kerosene, and alcohol fuel cell technology for the military from the late 1950s to the mid-1960s and gasoline and alcohol fuel cells for civilian use in the later 1990s at a time when California had compelled the auto industry to produce all-battery EVs through its zero-emission vehicle (ZEV) mandate.[84] When these efforts failed to yield results, the state of California and the federal government began supporting hydrogen fuel cell technology, enlisting automakers and oil companies around the turn of the millennium in what former assistant secretary of the Department of Energy Joseph J. Romm interpreted as a cynical exercise in greenwashing designed to delay the commercialization of the BEV.[85]

Indeed, oil companies were widely perceived as hostile to EV battery technology owing to the threat the commercial BEV posed to their core interests. However, Exxon was willing to supply inputs for advanced rechargeables, as long as this did not undermine the core business. The company sold separators for lithium-ion cells from the early 1990s but left this market in the early 2010s as cell production scaled and profits shrank. Exxon initially planned to develop advanced new separator material for cells in batteries for the plug-in hybrid EV, a class of EV that used fossil fuels and that also represented a growing market for separator material, one potentially much larger and more profitable than the one around consumer electronics cells. In short, the commercial PHEV (along with the carbonaceous fuel cell EV) was a type of EV that an oil company could live with, as it benefitted both the main business of fossil fuels and the secondary petrochemical business around energy conversion-enabling materials.

But while the PHEV market expanded through the 2010s, an increasingly large proportion of EVs were all-battery EVs (BEV), a type of electric vehicle that did not directly use fossil fuels.[86] Because cells in battery packs for PHEVs and BEVs used essentially the same material inputs, Exxon likely reasoned that any short-term gains to be had in supplying the PHEV market were not worth the risk of enabling the development of the BEV market and undermining the fuel business around ICE vehicles. Exxon's relatively liberal attitude to EV batteries contrasted with certain of its peers. In 2000, GM sold large-format NiMH technology jointly developed with ECD/Ovonic to Texaco, which was shortly thereafter acquired by Chevron, which then exerted a notorious patent encumbrance on this rechargeable chemistry.[87]

For a time, some petroleum interests seemed to perceive solar energy as having more commercial potential than either fuel cells or rechargeable batteries, despite the sociotechnical conundrums this enterprise implied. Solar energy has some affinity with stored fossil energy in that it is a primary energy resource, a parallel that may have appealed to oil executives. In every other way, these energy forms are utterly dissimilar. Converting solar energy to useful power required techniques, materials, and technologies that historically lay outside the ambit of the oil industry. Scholars have ascribed the exit of BP and Shell from vertically integrated photovoltaic cell manufacturing to a lack of expertise and the absence of complementarity with core activities in stored fossil energy and the inability to dominate the supply chain, a highly decentralized complex spanning the consumer electronics industry and non-petroleum chemical interests.[88] After oil companies abandoned efforts to manufacture materials and technologies of solar energy conversion, the only other possible enterprise of solar energy open to them was the business of energy flows, which is to say the business of electricity, a field historically dominated by utilities. While most Western oil majors had built photovoltaic plants by the mid-2020s, most of these were for demonstration purposes, with Total showing the greatest willingness to pursue utility-scale photovoltaic power.[89]

Big Oil's direct role in the development of advanced energy conversion technology hence should not be overstated.[90] These systems were products of protracted collaboration between myriad players in several industrial sectors in many countries over many decades. Where basic research was concerned, petroleum's contributions came largely in the form of patronage, often of independent innovator-entrepreneurs like Berman, Ovshinsky, and Yerkes. Spillover in this context linked electronics and energy conversion and stimulated certain lines of materials research the electronics industry itself might not have otherwise undertaken. Petroleum interests also played a major indirect role in stimulating the photovoltaic boom of the 2000s through their vertically integrated operations in this field, activities that ironically helped precipitate the silicon price boom and bust that was a key factor in their withdrawal from this manufacturing sector.

In 2004, the business management analysts Ans Kolk and David Levy held that it was unclear whether the oil and gas industry could successfully engage with renewable energy thanks to managerial inertia and incompatible supply chains.[91] The history of spillover in advanced energy conversion confirms this view but also cautions against framing the question as a matter of industrial-technological compatibility. Like other fabulously successful enterprises, the oil industry faced the problem of how to manage its surplus capital, a problem that it periodically tried to resolve through industrial diversification.[92] That problem, together with energy and environmental policy pressures, motivated tentative adventures in fuel cells, galvanic batteries, and photovoltaic arrays.

These factors, in concert with declining reserves of recoverable fossil energy resources, will likely compel the oil industry to continue engaging the technoscience of advanced energy conversion in one way or another. Big Oil's long experience with commodity liquid and gaseous fuels informed a preference for biofuels among renewable energy forms and public policy pressure caused the industry to reappraise hydrogen.[93] Since the early 1960s, oil companies used petroleum-derived hydrogen as a refining feedstock to strip out impurities from a variety of fuels including gasoline and to improve yields.[94] Protracted public policy fascination with pure hydrogen as a fuel for ICE vehicles and fuel cell-powered EVs and as a storage medium for renewable energy coupled with tightening environmental regulations led the oil industry to deepen experiments with 'green' and 'blue' fuel and feedstock hydrogen derived from renewables and natural gas, respectively, in a way that recalled the industry's hedging research on batteries and photovoltaics at the height of the 1970s oil price shocks.[95]

In the interim, the most important oil spillover into the clean energy economy of the near future will likely occur in the form of embodied or whole life carbon. Oil and natural gas are the most highly calorific forms of stored energy, but they are also mineral resources that along with coal constitute an important part of the materiality of a host of engineered substances used in a host of technologies including advanced energy conversion. One might expect the absolute proportion of fossil resources used as fuels to decline as reserves are depleted and as highly efficient low- and zero-emission energy conversion technologies proliferate, although predictions of the exact timeline of resource depletion historically have a poor shelf life.[96] What can be said with certainty is that for the foreseeable future, fossil resources will continue to be indispensable both as fuels and as material inputs in fabricating and manufacturing processes. Public policy restrictions on how fossil resources may be used will not by themselves seriously alter the oil industry's core business of natural resource commodities.

Indeed, quasi-planned reform of the US energy conversion complex since the 1990s had the paradoxical effect of deepening fossil fuel dependence even as it stimulated clean and green energy systems. At first glance, these policies can be interpreted as yielding some positive environmental results. From the mid-2000s, average per capita and aggregate primary energy consumption in the US declined and renewable energy capacity increased, trends some analysts attributed to the willingness of US policymakers to correct their failure to ratify the Kyoto Protocol.[97]

When US energy conversion systems are considered in the context of the deepening asymmetrical co-dependency between the West and the Global East and South, however, a different picture emerges. From the turn of the millennium, quasi-planning stimulated the concurrent scaling of the EV fleet and renewable energy capacity from components fabricated largely in Asia.[98] At home, petroleum consumption peaked in 2005 and declined thereafter, a trend that some analysts ascribed to the demand destruction wrought by the recession of the late 2000s and early 2010s and the covid pandemic of 2020–2021.[99] From the early 2010s, however, US hydrocarbon production sharply increased thanks to the exploitation of oil and gas shales by means of horizontal drilling and hydraulic fracturing technology developed with the support of the Department of Energy.[100] This project vaulted the US past Russia and Saudi Arabia to reclaim the title of the world's largest producer of crude oil and intersected with the federal government's geopolitical instrumentalization of US oil and gas resources, facilitated by the 2015 Congressional repeal of the 1975 ban on exports of crude oil.[101] Trends in US energy policy mirrored the long-term shift of industrial manufacturing and waste from the West to the Global South and East and served to even more deeply entrench the US petroleum industry as an enterprise of stored energy commodities in global systems of energy conversion and manufacturing.[102] The 'viscosity' of petroleum spillover into advanced energy conversion technology and infrastructure was hence ultimately determined by the US quest to maximally exploit all forms of energy, a policy the Obama administration dubbed 'all-of-the-above'.[103] In a society where policy elites have committed to diversity of energy and energy conversion technology, the idea of a discrete renewable energy industry performs the important work of sustaining belief in the linear clean energy transition.[104]

Acknowledging the pervasive effects of oil interests on contemporary social relations need not be interpreted as energy determinism or 'petromyopia'.[105] As Mody suggests, the frame of reference of spillover connotes the totalizing sociotechnological character of the petroleum energy regime and the panoply of ideas, material practices, and social activities it makes possible.[106] Contributors to this special issue show how spillover stimulated innovation within (Odinn Melsted), astride (Beatriz Martínez-Rius and Owen Marshall), and without the energy sector (Hannah Rogers). Rogers notes that Big Oil furnishes not only the patronage that extends into many walks of creative life but, for artwork critical of the oil industry and its social and environmental impacts, the 'feedstock' of critical inquiry through the industry's peculiar organization of the world.[107] Petroleum as a set of ways of knowing and ordering nature and society is indeed so deeply entrenched that it will be very difficult to undo or even substantially modify without drastic changes in social relations. As this special issue suggests, the capital reified from petroleum may have a social 'half-life' as least as durable as oil's environmental legacy by sustaining assumptions around the dominion of nature and human beings within the clean energy transition well into the foreseeable future.

On the other hand, the deepening geopolitical rift between the West, Eurasia, and the Global South is disrupting the asymmetrical global network of energy conversion and manufacturing infrastructure that has hitherto supported the interests of Western oil capital. Study of spillover and the history of the social relations of energy conversion it illuminates helps ground normative energy and environmental studies in an understanding of changing states of sociotechnical and envirotechnical systems and how these dynamic systems can facilitate as well as complicate the transition to the fossil fuel-free future.

Notes

1. RSAS, "The Nobel Prize in Chemistry 2019."
2. ExxonMobil, "Pioneers of Innovation."
3. For an exemplary review of the debate around human and non-human agency and social construction as it stood in the mid-1990s, see Pickering, "The Mangle of Practice."
4. See, for example, Latour, "Is This a Dress Rehearsal?"; Latour, "Why Has Critique Run out of Steam?"; De Vrieze, "Bruno Latour"; and Lynch, "We Have Never Been Anti-Science."
5. See, for example, Sovacool and Dworkin, "Energy Justice"; Jenkins et al., "Energy Justice"; and Healy and Barry, "Politicizing Energy Justice."
6. For an exemplary critique of energy determinism in the humanities, see Turnbull, "Energy, History, and the Humanities." For historical accounts that ascribe casual power to energy, see Nye, *Consuming Power*; Pomeranz, *The Great Divergence*; Podobnik, *Global Energy Shifts*; Mitchell, *Carbon Democracy*; Jones, *Routes of Power*; and Smil, *Energy and Civilization*.
7. Geerts et al., "Towards a Philosophy of Energy."
8. Love and Isenhour, "Energy and Economy"; Peters, "Carbon Footprints"; and Hamot et al., "Whole Life Carbon."
9. By the early 1970s, the dominant Western oil enterprises were British Petroleum, Chevron, Exxon, Gulf, Mobil, Texaco, and Shell, then colloquially known as the "Seven Sisters."
10. The economists A.F. Alhajji and David Huettner argued that the petroleum industry had relatively less control over prices than other commodity cartels and that the degree of control fluctuated over time; see Alhajji and Huettner, "OPEC."
11. From the inception of the oil industry, oilfield managers destroyed vast quantities of natural gas in regions that lacked local markets for this resource and the infrastructure to capture, store, transport, and convert it to useful heat or work, a practice that continued into the

twenty-first century. The energy historian David Breen held that the most extensive flaring of natural gas in North America took place in the isolated oilfields of southern Alberta in the first decades of the twentieth century; see Breen, *Alberta's Petroleum Industry*, xlix, 52–63.

12. By the 1940s, gasoline had supplanted kerosene as the main refinery product. The advent of the Jet Age in the 1950s revived demand for kerosene in the form of aviation fuel, which was deemed more suitable for operation in jet turbines at altitude than light distillates; see Maurice et al., "Advanced Aviation Fuels," 749.
13. One estimate held that by the 1990s, the US light duty fleet had around 16 times more energy conversion capacity than US stationary plant (12,000 gigawatts versus 750 gigawatts); see Kempton and Letendre, "Electric Vehicles," 159; for historical trends in refining and petroleum use in the US, see US DOE, *February 2024*, 63–4.
14. On the flexible interpretation of waste, see, for example, Thompson, *Rubbish Theory*; and O'Neill, *Waste Trading*.
15. Clews, *Project Finance*, 187–8.
16. Eisler, *Age of Auto Electric*.
17. Mody, "The Oil Spillover"; and Marshall, "The Oleaginous Voice."
18. Nye, "A Model"; and Sovacool, "How Long Will It Take?"
19. Baker, "Advances in Materials Research and Development," 5.
20. For a history of a fuel cell developed to operate on coal-derived gas, see Cassidy, *The Promise of Power*.
21. Eisler, *Overpotential*; and Wallace, "Fuel Cells."
22. US DOD, ARPA, "Project Lorraine Summary."
23. Esso Research and Engineering Company, "Proposal for the Continuation of Government Contract"; for a review of US Army fuel cell research and development in the 1960s, see Huff and Orth, "The USAMECOM-MERDC Fuel Cell."
24. Eisler, *Overpotential*; and Wallace, "Fuel Cells."
25. See Hoffmann, *Tomorrow's Energy* and *The Forever Fuel*; and Eisler, *Overpotential.*
26. Hoddeson and Garrett, *The Man Who Saw Tomorrow*, 144–5, 187–92.
27. Ovshinsky, Fetcenko, and Ross, "A Nickel Metal Hydride Battery"; Fetcenko et al., "Recent Advances in NiMH Battery Technology," 545–6.
28. Hoddeson and Garrett, *The Man Who Saw Tomorrow*, 192.
29. Ouchi, Young, and Moghe, "Reviews on Japanese Patent Applications"; and Chang et al., "Reviews on the US Patents."
30. In the mid-1970s, General Motors planned an electric conversion of the Chevrolet Chevette as an interim solution in the event of a catastrophic rise in oil prices. The Electrovette used nickel-zinc batteries, a cheap chemistry originally invented by Thomas Edison that had high power density but short lifetime; see GM Heritage Center, "GM Vehicle Technologies."
31. Whittingham, "Electrical Energy Storage"; and Goodenough, "Rechargeable Batteries," 2022.
32. John B. Goodenough, interview by the author, July 11, 2013.
33. Mody, "The Oil Spillover"; and Marshall, "The Oleaginous Voice."
34. Kinoshita, *Carbon*, 1–3.
35. Spahr, Gilardi, and Bonacchi, "Carbon Black," 385; and Spahr, "Carbon-Conductive Additives," 140, 145.
36. Matsuoka, "How Chemistry Nobelist Akira."
37. Yoshino, "From Polyacetylene to Carbonaceous Anodes," 449; and Sawai, "The Invention of Rechargeable Batteries." The discrepancy between petroleum coke and VGCF/synthetic graphite is notable. Neither the RSAS's 2019 press release nor the Asahi Kasei press release honoring Yoshino as a Nobel laureate mentioned VGCF.
38. Nishi, "The Development of Lithium Ion Secondary Batteries," 410; and Brodd, "Chapter 1," 1.
39. Long, Nascarella, and Valberg, "Carbon Black"; *Japan Chemical Daily*, "Hitachi Chemical Sets Sight"; *Japan Chemical Daily*, "Tokai Carbon"; *Japan Chemical Daily*, "Showa Denko"; and *NS Energy*, "Showa Denko."

40. Nishi, "The Development of Lithium-Ion Secondary Batteries," 411–12.
41. See note 2 above.
42. I thank the chemists Mark DeMeuse and Michael Jaffe for these insights. DeMeuse and Jaffe were involved in polymer membrane development at the Celanese corporation in the 1980s and in the 2000s pursued this work at Celgard, a major producer of battery separators, and at the New Jersey Institute of Technology, respectively; Mark DeMeuse, interview by the author, October 10, 2016; and Michael Jaffe, interview by the author, January 24, 2017.
43. Gold, "Guess Who Hopes," B1.
44. Pillai and Shin, "Real-Time Dynamic Voltage"; Mudge, "Power"; and Magklis et al., "Dynamic Frequency"; see also Brodd, "Factors Affecting US Production"; and Eisler, "Exploding the Black Box."
45. For classic accounts of the historical development of Silicon Valley as a manufacturing district, see Saxenian, *Regional Advantage*; Bassett, *To the Digital Age*; and Lécuyer, *Making Silicon Valley*. For analyses of Silicon Valley that address vertical disintegration and de-industrialization, see Brown and Linden, "Offshoring"; and Brown and Linden, *Chips and Change*.
46. Magretta, "The Power of Virtual Integration."
47. Pecht, "Editorial"; and Cringely, "Safety Last."
48. Kanellos, "Can Anything Tame the Battery Flames?"
49. See note 16 above.
50. Erman, "Exxon Develops Technology"; Gold, "Guess Who Hopes to Help Power New Hybrid Cars," B1.
51. According to the journalist Sherry Boschert, one of the main advocates of PHEV technology in the 2000s was former CIA director R. James Woolsey, a primary source for Boschert's 2007 book on the subject; see Boschert, *Plug-in Hybrids.*
52. "ExxonMobil Chemical"; and McCoy, "ExxonMobil, Toray."
53. Tullo, "ExxonMobil Casts Off"; and *Reuters*, "Exxon Japan Group."
54. Ziegler, Song, and Trancik, "Determinants of Lithium-Ion Battery Technology."
55. Lécuyer and Brock, "The Materiality of Microelectronics," 310; and Ceruzzi, *Computing*, 87–90.
56. Jones and Bouamane, "Power from Sunshine," 14–6.
57. Berlin, *The Man Behind the Microchip*, 183–99.
58. *Solar Energy Research, Development, and Demonstration Act of 1974*; and *Public Utility Regulatory Policies Act of 1978*, 3134, 3144
59. Arguably the most important federal subsidy of nuclear power was the 1957 amendment to the Atomic Energy Act of 1954 that provided limited insurance indemnity for nuclear accidents. This provision, commonly known as the Price-Anderson Act, was extended and amended several times, most recently through the Energy Policy Act of 2005, which extended coverage through the year 2025; *Energy Policy Act of 2005*, 779–82.
60. Whitaker, DeMeo, and Taylor, "New Promise," 7.
61. Leslie Berlin, biographer of Intel co-founder Robert Noyce, did not record Noyce showing interest in photovoltaic power as a crossover business; see Berlin, *The Man Behind the Microchip*.
62. Petroleum constituted about 47 percent of US primary energy consumption in 1975; see US DOE, *February 2024*, 6–7.
63. Whitaker, DeMeo, and Taylor, "New Promise," 10.
64. Jones and Bouamane, "Power from Sunshine," 22–4.
65. Ibid., 22–4.
66. Hoddeson and Garrett, *The Man Who Saw Tomorrow*, 171–86.
67. Ibid., 143, 176.
68. Jones and Bouamane, "Power from Sunshine," 28.
69. *Chemical Week*, "A Shakedown."
70. See Yergin, *The Prize*, 630–32, 667–73.
71. *Chemical Week*, "A Shakedown."

72. Hoddeson and Garrett, *The Man Who Saw Tomorrow*, 178; and Jones and Bouamane, “Power from Sunshine,” 36, 52.
73. Jones and Bouamane, “Power from Sunshine,” 22; and Lee, “Arco Sells.”
74. See Miller, “Why the Oil Companies Lost Solar,” 54–5, 58; and Pinkse and van den Buuse, “The Development and Commercialization.”
75. Kolk and Levy, “Winds of Change,” 504.
76. Dow Jones, “BP Amoco”; and Ibrahim, “British Petroleum.”
77. Cunningham et al., “Reaching Grid Parity”; and Tarrant et al., “CIS Thin-Film Development”; see the National Renewable Energy Laboratory’s historical timeline of solar cell development (US DOE, “Best Research Cell Efficiencies”).
78. Fisher, Seacrist, and Standley, “Silicon Crystal Growth,” 1455.
79. Lewis, “Silicon Shortage.”
80. Yu, Li, and Bao, “Price Dynamics.”
81. For an analysis of the idea of economic dominance through technological superiority in this context, see Biello, “How Solyndra’s Failure.”
82. US DOE, “Desert Sunlight”; and US DOE, “Cadmium Telluride Accelerator Consortium.”
83. Miller, “Why the Oil Companies Lost Solar,” 53–4.
84. Borroni-Bird, “Fuel Cell Commercialization.”
85. CAFCP, “‘About Us’ and ‘Member Organizations’”; Romm, *The Hype About Hydrogen*.
86. Alsauskas et al., *Global EV Outlook 2023*, 14.
87. See Boschert, *Plug-in Hybrids*. In an October 2004 letter, Stanford Ovshinsky’s attorney Chester Kamin warned of Chevron’s seeming desire to “take over, neutralize, or destroy ECD”; Kamin to Stempel and Ovshinsky, “Re.”
88. For the argument on expertise, see, for example, Miller, “Why the Oil Companies Lost Solar”; for the argument on supply chains, see, for example, Pinkse and van den Buuse, “The Development and Commercialization.”
89. Miller suggests that Chevron’s involvement in photovoltaic plant in the 2010s was entirely predicated on public relations; Miller, see “Why the Oil Companies Lost Solar,” 54–55; also see Stromsta, “Chevron to Build 500 MW”; Shell, “Solar.” Total created the impression of interest in the business of photovoltaic utility electricity by virtue of a large investment in Adani Green Energy, a major builder and operator of renewable energy in India; see McFarlane, “Oil Giant”; and TotalEnergies, “Our Expertise.”
90. For an example of overstatement in this context, see Hsu, “How Big Oil.”
91. Kolk and Levy, “Multinationals and Global Climate,” 186.
92. In 1963, Standard Oil of New Jersey formed what would later be known as Exxon Enterprises, a platform for investing in emerging technology fields including nuclear fuels, exotic high-strength metals, and later, semiconductors and consumer electronic office equipment in addition to photovoltaic power; see Petty, ”Automating the Office.” I thank Cyrus Mody for this document.
93. Krishna and Sanicola, “Chevron Raises Clean Energy Bet.”
94. Gary, Handwerk, and Kaiser, *Petroleum Refining*, 5, 33.
95. McFarlane, “Big Oil Companies”; Shell, “Hydrogen”; Linde, “Meeting Refinery Needs for Hydrogen”; and Shearer, “Oil and Gas Companies.”
96. See Priest, “Hubbert’s Peak,” 42.
97. US DOE, *February 2024*, 6–7, 18; Nye, “A Model,” 46–7.
98. See note 16 above.
99. US DOE, *February 2024*, 7; BP, “Recession”; Feng et al., “Drivers of the US CO_2 Emissions”; Jiang, Fan, and Klemes, “Impacts of COVID-19.”
100. Fri et al., *Energy Research at DOE*, 55, 193–4.
101. US DOE, “The United States”; US DOE, *February 2024*, 3–4; and US GAO, *Crude Oil Markets*.
102. Brownell, “Negotiating the New Economic Order.”

103. Obama, “Remarks by the President on Energy.”
104. See, for example, Motyka et al., “2024 Renewable Energy Industry Outlook.”
105. Jones, “Petromyopia,” 36.
106. Mody, “The Oil Spillover”; and Mody, “Spillovers.”
107. Rogers, “What Art Can Show STS About Oil.”

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