Introduction

We are at the start of a solar revolution. The solar energy industries have taken off in the past decade, growing forty-fold globally from 2008 to 2018 with few signs of slowing down.[1] More than 99.9% of all photovoltaic modules and concentrated solar power plants ever built were installed after 2008. That year the photovoltaic industry produced 170 megawatts' worth of modules, enough to power a quarter of a million homes on a sunny afternoon.[2] At the end of 2018, cumulative photovoltaic installations surpassed 500 gigawatts (GW), over a thousand times the annual production a decade earlier, and enough to power over two hundred million homes.[3] Solar power is no longer alternative energy. New records for solar generation are broken every month in California, Germany, and China, and headlines regularly announce the opening of the next largest solar power plant in the world.[4] Solar electric technologies—photovoltaic and concentrated solar power technologies such as parabolic troughs and solar power towers—are making meaningful contributions to electricity supplies in some places, albeit geographically unevenly across the globe. On sunny afternoons in 2017, solar provided over 50% of peak electricity in Germany and California.[5] These records will be broken repeatedly as more solar power is installed.

When solar power is measured in terawatts—a hundred times the annual production today—the industry will be making inroads as a major source of electricity. Today solar remains a small portion of the overall energy supply. In June 2015, solar surpassed 1% of total energy supply globally.[6] Solar triumphalists contend that solar power's biggest growth period lies in the future. Based on growth rates since 2009, that prospect is taking shape today. However, not all energy experts share this vision. Concerns about "value deflation"—the idea that increasing penetration of solar power becomes less valuable to the grid and to investors over time—could lock photovoltaics into low contributions of electricity.[7]

From the perspective of environmental studies, the ways that solar power development unfolds will transform society and the environment in different and important ways.[8] The net social and environmental benefits of solar power are well documented and generally uncontested—more jobs, higher quality of life, and much less air pollution and greenhouse gas emissions, compared to an equivalent energy supply from fossil fuels. Yet, all forms of energy development have impacts or pose new or different risks to specific communities, ecosystems, and landscapes. The transition to solar power will be no different, requiring greater land-use changes for solar energy landscapes, production of silica and various metals from mines, processing in smelters, blast furnaces, glass factories, chemical plants (with their effluents), and manufacturing facilities ("fabs") to fabricate components and assemble devices. Exploring the environmental challenges of scaling up photovoltaic manufacturing to the terawatt level can help society plan for the coming environmental impacts of the solar energy transition. Analysts with the SunShot Initiative, an effort led by the U.S. Department of Energy, estimate that to get photovoltaic module manufacturing levels to 20 GW per year, production of supply chain materials would need to increase 6% for glass, 520% for polysilicon, 38% for tellurium, 160% for indium, and 30% for silver, from current levels.[9] To bring solar power to terawatt levels implies a hundred-fold increase in these numbers. Environmental and energy justice outcomes are more likely if impacts can be identified and proactively governed.[10]

This book aims to identify the challenges facing a sustainable and just transition to solar power, and to inspire us to solve these challenges before they become problems. Much of the analysis will focus on the production of *photovoltaic modules* (or *photovoltaics*), which are devices that covert the energy of sunlight into electricity. Electric power generation currently contributes one-third of global greenhouse gas emissions,[11] but photovoltaics generate electricity with no emissions at all (putting aside the manufacturing process), making them key technologies for decarbonizing electricity.

Photovoltaics are manufactured with chemical feedstocks and processes similar to those used in electronics and semiconductor production.

This raises some concern, as the legacy of electronics and semiconductor industries in places like Silicon Valley left workers and communities around manufacturers like Fairchild Semiconductor and IBM exposed to toxic vapors and solvents and other wastes in groundwater.[12] Public health and occupational questions followed these semiconductor and electronics factories as they offshored to East Asia, Mexico, and other places in the global economy that attract chemical and manufacturing industries.[13] Scaling up photovoltaic manufacturing will raise environmental, health, and safety challenges that may require planning, management, and regulatory interventions, especially where some workers and communities might bear disproportionate burdens or risks.

Integrating solar into electricity grids will require the deployment of new landscapes. Energy from the sun is diffuse compared to the concentrated forms of fossil and nuclear fuels, so solar power requires a lot of space.[14] New requirements for electric utilities and falling costs for utility-scale projects could provoke conflicts over land use in regions with rich solar energy resources.[15] And while they provide low-carbon electricity, utility-scale solar energy projects could negatively impact certain communities, workers, and ecosystems. Land-use changes for utility-scale solar energy development could permanently alter ecological communities, disturb cultural artifacts, and transform landscapes.[16] Conflicts over what the Nature Conservancy terms "energy sprawl" are already occurring, most prominently at a few sites in the California deserts.[17] The insolation that blankets southern Spain, China's Gobi Desert, the Atacama Desert of Chile and Peru, and Africa's Sahara, Kalahari, and Sahel deserts are starting to attract proposals and investments for utility-scale solar power plants.[18] Communities and land managers in these places will face tough decisions about how to resolve land-use conflicts over renewable energy development. But conflicts are not inevitable: future patterns of solar deployment can be guided to work toward climate adaptation and biodiversity conservation goals rather against them.[19] Photovoltaics can be readily integrated into the built environment, on abandoned agricultural or disturbed land, parking lots, landfills, and other landscapes where conflicts may be minimal. "Floatovoltaics" can be placed on reservoirs and other open water bodies.[20] Most fittingly, few electricity sources are so well suited for people to live under.

Energy justice aims for "a global energy system that fairly distributes both the benefits and burdens of energy services, and one that contributes to more representative and inclusive energy decision-making."[21] The aim of this research is to raise questions about solar power transitions: Who bears the burdens? Where might collateral effects manifest? How can these aspects be integrated into energy policy, planning, and practice?[22] Energy justice can inform energy policy by providing a framework capable of incorporating distributional, recognitional, and procedural tenets—these include accepting that impacts are unevenly distributed, representing silent or marginalized voices, and ensuring that processes are fair and democratic.[23] Attaining energy justice in solar energy transitions requires overcoming power asymmetries at several scales, from inequitably arranged political interests shaping regulation and legislation, to decisions embedded in our everyday routines.

How can this solar revolution be scaled rapidly and at the same time be kept *sustainable* and *just*? Identifying and resolving issues with solar power supply chains, construction activities, operation, decommissioning, and end-of-life management can ensure more sustainable and equitable outcomes. This requires building effective institutions to coordinate decision-making processes and planning efforts, and social movement engagement, as well as sustainability leadership from industry. Geographers and energy policy experts on the low-carbon energy transition note that energy justice needs sustained theoretical and empirical attention.[24]

Solar power is a term colloquially used to describe electricity generated from a photovoltaic module, by steam boiled by the sun, or even the solar heating of water. In electronics, power is the voltage times the electric current; it is the ability to do work with electrical energy. But power is also a social concept. Social scientists think of power operating in society in several ways, depending on the entry point of the respective research community. Power can describe control over others. People, communities, social movements, and nations are said to "have power over" or to "influence" outcomes. For other social scientists, no one holds power because power is a relational effect, produced through interaction.[25] Power is diffuse or discursive and a factor that conditions our everyday behavior and ways of thinking, or subjectivities. In this book, I point out how power structures shaped certain environmental outcomes, but also how discourses and subjectivities configured particular consequences in specific ways.

Anticipating future environmental justice issues is an emerging research theme in energy transitions research.[26] Political ecology is an area of inquiry in environmental studies and human geography that focuses on the multi-scalar and interconnected aspects of what humans make and use. Its roots are in disaster studies, cultural ecology, and development studies, and much of this research connects disparate places of production to sites of consumption, showing how decisions made in one part of the world might be connected to environmental problems somewhere else. Researchers in political ecology consider questions related to how landscapes and communities become vulnerable to environmental degradation from commodity production and how uneven power relations sustain these effects. Drawing from sociology, political ecologists have borrowed the "commodity chain" as a conceptual apparatus to connect raw material extraction, through supply chains, to sites of manufacturing, use, and eventual disposal. This allows the researcher to follow a commodity through the all the stages of production and use. The narratives taken from these commodity stories often focus on how political-economic factors and power structures shape nature–society relations in natural resource struggles or environmental change. This political ecology lens will help highlight potential frictions associated with scaling up solar technologies, as it will be attentive to the challenges associated with the political economy of solar energy development in an uneven world.

This book does not argue that solar power is in any way a poor technical choice or worse than conventional energy sources. The evidence emphatically points to the benefits of solar power.[27] The argument in the book does emphasize opportunities to make solar energy commodity chains more just and sustainable. Photovoltaic production has a green halo compared to other electronic and chemical industries, which means it sometimes escapes the scrutiny deserved by all systems of commodity production if the goals are sustainability and environmental justice. If few question the environmental bona fides of photovoltaics, opportunities to green design, production, and deployment along the life cycle will be missed. The following chapters take a closer look at solar power commodity systems and their implications for energy transitions. Solar power remains the most attractive and sustainable option to supply society with low-carbon energy, but it will require careful planning, assessment, and practice to ensure that socio-environmental impacts are minimized and equitably distributed.

OVERVIEW OF THE CHAPTERS

Chapter 1 introduces the synergies and tensions between solar power innovations, green jobs, and environmental justice. In the United States, a "green jobs" discourse emerged starting around 2005 and manifested in government investments in economic stimulus through the American

Recovery and Reinvestment Act (ARRA) several years later. Tens of billions of dollars in ARRA investments went toward renewable energy technologies and projects, and this created thousands of jobs during a time of recovery from a global economic calamity. Rust Belt communities embraced the idea of reinventing the economy around renewable energy, as it was an opportunity to retrain skilled workers in industries experiencing automation or offshoring. Urban communities saw opportunities to employ people in traditionally underserved communities. Silicon Valley was flush with a new round of semiconductor industries, as solar equipment and thin-film photovoltaic manufacturers numbered in the dozens in the late 2000s. Federal investments in a green jobs workforce led an early wave of the solar energy transition in the U.S.

Several environmental justice organizations began to focus on green jobs training in the installation of photovoltaic modules. However, very few were asking if the green jobs being created would be linked to other jobs that exhibit patterns of environmental inequality. Other electronics and semiconductor manufacturers are frequently in the news for chemical contamination or worker health and safety issues.[28] Would the growth in green jobs be linked to environmental inequality elsewhere in the commodity chain? Several organizations, including the Silicon Valley Toxics Coalition, led an effort to investigate the risks new semiconductor manufacturers posed to communities. Critical approaches like these are important to energy justice research related to the solar energy transition because the lessons learned can shape policy and practice. Chapter 1 introduces the primary environmental, health, and safety issues in solar power commodity chains against the backdrop of green jobs.

Chapter 2 describes in more detail the investments in solar innovations made through ARRA—the policy architecture that helped invest $90 billion in renewable energy. A set of institutional forces set into motion by the U.S. Departments of Interior, Energy, and Treasury would provide inertia to projects that transformed landscapes and commodity chains, with implications for socio-ecological systems. Starting with activities initiated for energy development on public lands by the Department of the Interior in 2001 on the recommendations of vice president Richard Cheney's Energy Task Force in president George W. Bush's administration,[29] the three agencies all implemented incentives that would favor developers of large-scale solar power projects, including power plants and manufacturing facilities. This chapter describes the important changes in governance that aided solar deployment. One key set of policies were state-level renewable energy portfolio standards, requiring investor-owned utilities to acquire greater amounts of electricity from renewable sources every year until they hit some predefined target percentage (20%, 33%, 50%, etc.). This effectively created guaranteed markets for renewables, making long-term investments less risky, as the most economically viable projects were offered power purchase agreements by investor-owned utilities. The Energy Policy Act of 2005 asked the Bureau of Land Management (BLM) to develop 10 GW of renewables on public lands (expanded to 20 GW in 2015). This opened over 33,000 square miles (about 22.5 million acres, or 87,336 km^2) of public land to solar energy development across the American Southwest.[30] These federal decisions about public lands enabled the expeditious processing of ARRA expenditures within the short window that they were available, but also led to a series of what some might call rash or hasty decisions. Finally, a set of programs to subsidize the risks of solar energy finance and investment made it possible to leverage more capital from firms that otherwise would not fund such endeavors. These policies helped reduce costs for solar and allowed several large-scale projects to access capital that would otherwise not be available, particularly at the height of a global financial crisis. One of these projects would be the largest photovoltaic installation in the world for a few years.

Chapter 3 explores some of the environmental, health, and safety impacts of innovations in the life cycle of thin-film photovoltaics. As innovations in solar technologies make it cost-competitive with conventional energy sources, they introduce new manufacturing risks that deserve consideration. The ARRA investments in thin-film photovoltaics, for example, relied on semiconductors containing cadmium compounds. Sometimes these new risks take the form of unknown impacts of novel materials, such as carbon nanospears or cadmium quantum dots. Other new risks emerge from innovations in social organization. For example, contract manufacturing could be seen as an innovation in production, but also as a new environmental health risk, as accountability shifts and social distance is increased between sites of production and consumption.[31] Life-cycle-assessment experts at the Photovoltaic Environment Research Assistance Center at Brookhaven National Laboratory and the National Renewable Energy Laboratory have developed a comprehensive literature on the environmental, health, and safety hazards of photovoltaics.[32] The chapter describes how these risks are articulated through environmental performance metrics produced through life cycle assessment. While the framework offers much in telling stories about systems of production, the construction of performance metrics can often obscure or silence other ways of understanding environmental impacts, particularly ones that are unevenly distributed.

Chapter 4 tackles the important questions around disposal and end-of-life management accompanying the widespread adoption of photovoltaics. The rare and precious materials in photovoltaics are compounded with or embedded in more toxic ones, the same recipe that fuels the global trade in e-waste that poses public health problems in West Africa and Southeast Asia. Separating the cadmium from tellurium and the lead from silver in end-of-life photovoltaic modules might be done by artisan e-waste collectors with crude tools, raising concerns about occupational exposures and public health.[33] The top manufacturer of thin-film photovoltaics from 2005 through 2017 has a "filter cake" recycling system able to recover 95% of the tellurium from processed modules. The narrative here explains the background that led to this arrangement and identifies best practices to increase the recyclability and recycled content of photovoltaics. Other environmental benefits of recycling photovoltaics include avoided mining and obtaining a secure supply for rare substances that could be subject to price volatility or material scarcity.[34] There are already viable recycling schemes, based on extended producer responsibility, throughout Europe.

Chapter 5 describes controversies involving public lands, managed by the BLM across six states in the American Southwest, that were offered to solar energy developers in the name of climate protection. Several utility-scale projects in California that received loan guarantees were sited on lands that many viewed as having important conservation value and biological and genetic significance, and as habitat for threatened and endangered species. A species facing severe habitat loss, Agassiz's desert tortoise (*Gopherus agassizii*), was at the center of many of these controversies. With 80% of desert tortoise habitat on public lands in the U.S., the BLM plays a special role as steward for this species. Opening large swaths of habitat to leasing for solar development put ecological considerations into direct conflict with climate change mitigation strategies, putting the BLM in the familiar position it is in elsewhere across western public lands, where it balances domestic oil, gas, and coal production against ecosystem conservation. Solar energy policies were intended to create opportunities for solar development, but also created several intractable conflicts and deep rifts among environmental groups over land use across the Southwest.

Chapter 6 describes new planning institutions, policies, and practices put in place in reaction to early ecological and cultural resource controversies. After an overview of the socio-ecological impacts of utility-scale solar power plants and proposed mitigations, public policymaking processes are described that sought a framework to resolve some of the land-use conflicts between renewables and ecosystems. The first is the Western Solar Plan, a public process initiated by the BLM via Secretarial Order 3285A1, which set the policy goal of identifying and prioritizing land for solar energy development. With the help of several agencies and national energy labs, the BLM proposed Solar Energy Zones, where development would be incentivized because they were deemed to have fewer ecological and cultural resource conflicts. The process through which Solar Energy Zones were proposed and reshaped is an example of how public participation can have meaningful impacts on energy landscapes. From the time the assessment was initiated in 2008 until 2014, tens of thousands of public comments led to the elimination of several proposed Solar Energy Zones. The Desert Renewable Energy Conservation Plan (DRECP) is a framework to guide solar development to focused areas on public lands in California with minimal land-use conflicts and will extend the analysis to private lands. The public participation and extensive agency coordination required to work through the DRECP make it one of the most comprehensive planning analyses for solar energy transitions ever prepared. But the impact of this planning effort is now up in the air because in early 2018 interior secretary Ryan Zinke announced plans to dismantle the DRECP.

Chapter 7 explores the challenges to public policies designed to foster innovation through case studies of loan guarantees to venture capitalists in the solar space. By establishing the industry context for the investments made through the Department of Energy loan guarantee program to solar power startups like BrightSource, Solyndra, Abound Solar, and SoloPower, the chapter explains why particular projects were believed to represent "breakthrough technologies"—the term that framed the Department of Energy loan program's mission. Many of these investments became controversial, because the innovation process for venture capital has certain tendencies and logics that make for politically vulnerable public policy bets. The public has a different perspective on risk from a venture capitalist or a hedge fund manager. After a description of the trends in the venture capital sector around clean technology, the issues related to the bankruptcies of thin-film photovoltaic manufacturers Solyndra and Abound are detailed. Overproduction of photovoltaics in China and crony capitalism were common explanations for the projects' failure. And tensions between thin-film manufacturing and justice were highlighted when cadmium compounds were left behind after the bankruptcies. The chapter documents the rapid ascendance of the Chinese photovoltaic industry, which sparked several ongoing trade disputes. Starting in 2010, the U.S. and Europe engaged in retaliatory trade measures with China over solar industry subsidies. The accusation made by the U.S. Department of Commerce was that China was illegally subsidizing its solar energy industry, allowing Chinese manufacturers to sell photovoltaic modules below cost in foreign markets. U.S. policymakers claimed that these subsidies had led to the downfall of several ARRA investments in thin-film technologies.[35] The eventual outcome would be a significant tariff on modules imported into the U.S. from China, and soon after that, from Taiwan; and eventually the tariffs would be proposed for all photovoltaic module and cell imports to the U.S.

Trade disputes in the solar industry are not limited to China. Japan sued Canada over Ontario's domestic sourcing requirement, which required a specified portion of the module to be made or assembled within the Canadian province to take advantage of a feed-in-tariff—a valuable consumer incentive that usually rewards a solar-producing customer with a high rate for electricity delivered to the grid. The U.S. is calling on India to repeal its domestic sourcing requirement for similar reasons. India argues that the requirement is critical to developing its own photovoltaic manufacturing capacity. These trade conflicts add cost and shape where solar manufacturing capacity will take root and expand. The solar trade war remains active on all these fronts. In February 2018, the U.S. commerce secretary under President Donald Trump declared that all imports of crystalline silicon photovoltaics (with a handful of exceptions) would have a 30% tariff levied on them. Anticipation of the tariff led to a massive increase in imports prior to the ruling; Bloomberg New Energy Finance reported an eleven-fold increase in photovoltaic imports to the U.S., which will be warehoused until needed, defying the administration's ruling.[36]

Chapter 8 outlines a vision for a solar energy transition that simultaneously promotes decarbonization, environmental justice, sustainability, and community resilience. There are opportunities to improve community livelihoods, reduce chemical exposures in the workplace, and eliminate solar waste by pursuing innovations in green chemistry, worker health and safety, industrial ecology, and design for recycling. This chapter draws from experiences with efforts to establish a sustainability leadership standard for photovoltaics through a stakeholder-led process. Developing any system of industrial production around principles of sustainability and environmental justice will be challenging, especially as efforts continue to prioritize measures that drive down the cost of solar electricity. All energy sources have impacts, and there is ample evidence that the social and environmental costs of fossil fuels are significantly greater than the impacts of solar power. For example, the fossil fuel industries have significantly higher rates of occupational injury and death than renewable energy industries.[37] Keeping with the themes of the book, the goal of this chapter is to offer a vision for a more just and sustainable solar power in policy and praxis. Taking stock of the full picture of all of the environmental and energy justice impacts we have learned about and can foresee now, hopefully brings us closer to that objective.

SOLAR POWER TECHNOLOGIES

The Earth is bathed in electromagnetic radiation—that is, light from the sun, often called *insolation* or *solar radiation*—which can also be thought of as a stream of packets of energy called photons. Going back to the start of sedentary civilization, humans have developed numerous contraptions to harness power from the sun. Many point to the "solar death ray" designed by Greek inventor Archimedes as an early instance of a technological device specifically designed to harness solar energy for human use. The device may be mythical rather than historical, but according to some Greek historians, it used mirrors to concentrate sunlight—enough to burn the masts and sails of incoming warships at the battle of Syracuse in 212.[38] Other early uses of the sun include drying crops, which was probably done even before sedentary agriculture, and which is critical for storing food.[39] Efforts to harness solar energy in human civilization are nothing new.

The solar energy technologies addressed in this book are those that generate electricity, with photovoltaics being the most widely featured in the case studies. Photovoltaics use semiconductors to directly generate electric current in response to photons collected from sunlight. Recall from chemistry and physics that the electrons that surround atoms represent quantities of energy. In a solar cell, the photons carrying some portions of the spectrum of solar radiation deliver enough energy to raise an electron's energy level from the valence band to the conduction band. Electrons in the conduction band are free to move within the material, which means that a current can flow. The solar cell architecture allows electrons to flow from a layer with extra electrons toward a layer that loses electrons when exposed to light. There are many variations on these basic principles, with different devices constituted by different semiconductor materials (sometimes in combination with an electrolyte).

French physicist Edmond Becquerel built the first photovoltaic cell in 1839, an electrolytic solution that generated electric current proportional to light exposure. Becquerel learned that electric current could be generated across plates of platinum submerged in a solution of silver chloride in acid when exposed to sunlight. Hence, the photovoltaic effect is sometimes referred to as the "Becquerel effect." In 1873, while evaluating materials for the trans-Atlantic underwater telegraph wire, English electrical engineer Willoughby Smith discovered that selenium was photoconductive.[40] The physical properties of selenium were deemed excellent in the lab, but in the field, where they were exposed to variations in sunlight, the selenium equipment did not perform as expected. Smith would later realize that the resistance of selenium changed with incident light. In 1883, inventor Charles Fritts made the first solid-state photovoltaic device, a selenium-based solar cell with gold conductors. At the turn of the century, Wilhelm Hallwachs started making solar cells of copper and cuprous oxide, and what he would learn would evolve into the foundational principles for making CIGS (copper indium gallium diselenide) thin-films. Scientists had very little understanding of the mechanism behind the photovoltaic effect (in which photon energy is absorbed and an energized electron is drawn into a circuit, creating voltage) until 1905, when Albert Einstein described the the first part of the effect (where a photon's energy is transferred to an electron, but no circuit is present). Robert Millikan, the University of Chicago physicist whose famed oil-drop experiment verified the charge of the electron, would provide an experimental apparatus for the photoelectric effect in 1916. This experimental proof resulted in Einstein winning the Nobel Prize in 1921 (the prize was not given, as many people assume, for his special theory of relativity, also published in 1905).

Electricity is also generated by concentrated solar power (CSP) plants, which rely on steam-powered electric generators. While photoconductivity was still being explored and tested in the early twentieth century, other engineers and inventors began to investigate harnessing the sun to drive steam engines. In the late 1800s, French inventor Augustin Mouchot and his assistant Abel Pifre used the sun to make steam and drive a motor for a printing press. One of the first CSP parabolic troughs was in built in Egypt, where it was used to make steam that powered irrigation systems.[41] Today, solar thermal energy is concentrated as solar flux, using mirrors or heliostats, primarily to make electricity. The solar flux heats a fluid, which then boils water to make steam, which turns a generator to make electricity. There are several types of CSP technologies, but each makes steam. The oldest, called solar parabolic troughs, uses large curved mirrors that track the sun, directing heat at a fluid carried in a pipe that runs down the center of the trough. Solar "power towers" like the Ivanpah Solar Electric Generating System use fields of heliostats, large mirrors that track the sun and direct solar flux toward a boiler atop a tall tower. Stirling engines are external combustion engines, where a dish of mirrors focuses solar power on a heating element that warms to create the temperature difference needed to drive a piston. More obscure is the solar chimney concept, where solar energy is directed toward heating air, which turns a turbine as it rises up the chimney.

Solar devices like solar hot water heaters, which collect thermal energy from the sun to warm water, are not much discussed in this book. Passive technologies like solar hot water heaters and passive solar design for interior living spaces were not the focus of ARRA support, despite their widespread use in some parts of the world, including China and Israel. The ARRA investments focused more on technologies that make electricity and infrastructure that would be integrated into the electricity grid. This should not be read as an indictment of the maturity of solar hot water heaters, as they have tremendous potential to displace natural gas and electricity used to heat water. But public policymakers did not see an opportunity to generate game-changing technologies out of solar hot water heater investments because the technology remains basically similar to the kinds that have been commercially available for over a century. Anaheim, California, for example, saw widespread solar hot water heating in the 1890s, and the U.S. saw growth in solar hot water heaters again in the late 1970s. Yet solar hot water heaters inexplicably remain a fringe technology for hot water in the U.S. today; they are far less common than photovoltaics atop residential rooftops.[42]

PHOTOVOLTAICS

Photovoltaic modules are colloquially called solar panels. A single photovoltaic device is referred to as a module and is made up of numerous solar cells. When several photovoltaic modules are interconnected, it becomes a photovoltaic or solar array. Some refer to it as a solar system, though this is obviously a confusing term given its more widespread astronomical use. Most photovoltaic modules are flat plates of silicon cells or thin films; flat plate means that the entire surface collects light. Concentrated photovoltaics use a glass or plastic lens to concentrate light on a much smaller, but expensive, semiconductor surface. Instead of silicon, these are typically several stacked p–n junctions made of gallium arsenide, indium phosphide, or similar compounds. Concentrated photovoltaics are mostly limited to specialized satellite, telecom, and military applications because they are expensive, although there have been several commercially available concentrated photovoltaics for utility-scale solar power plants.

The most common photovoltaics use crystalline silicon semiconductors. Pure crystals of silicon are sliced into thin wafers and made into solar cells by "doping" the crystal with small amounts of impurities on each side, one with extra electrons, the other devoid of electrons, to facilitate electron flow. The solar cells are most commonly sandwiched between a sheet of glass and a back cover, and encapsulated in a polymer to protect the module from the weather.

While a community of scientists sought to better understand the photovoltaic effect and the behavior of electrons, in 1916 a Polish materials scientist named Jan Czochralski developed an important understanding of how to make very pure silicon. Czochralski's key innovation took advantage of different ways to cool and crystallize silicon. The basic approach is still widely used to make the silicon chips in transistors, which made possible the twentieth-century revolution in electronics. Even into the twenty-first century, crystalline silicon remains the backbone of electronic devices. Photovoltaic manufacturing depends on experience, techniques, and knowledge developed to improve the transistors that underlie the computer revolution.

All crystalline silicon photovoltaics are indebted to work at the iconic Bell Laboratories in Berkeley Heights, New Jersey, where important inventions such as the transistor were born. In 1954, three scientists—Daryl Chapin, Calvin Fuller, and Gerald L. Pearson—demonstrated a 6% conversion efficiency with a crystalline silicon photovoltaic device.[43] A year prior, Pearson had made solar cells of silicon better than those of selenium, the starting material, which the research team had found to be limited to 0.5% efficiency. Chapin and Fuller refined Pearson's work and made cells powerful enough to power small electrical equipment. Meanwhile, the university-military-industrial complex anchored by Stanford University and the University of California, Berkeley, was transforming the Santa Clara Valley into Silicon Valley. Among the major players in crystalline silicon, Hoffman Electronics produced solar cells at 8% efficiency in 1957, 10% by 1959, and 14% by 1960, mainly for NASA space and communications applications.[44] Today, premium-brand crystalline silicon photovoltaic modules routinely have conversion efficiencies better than 20%. With the help of several internal advocates of photovoltaic technologies, the U.S. military adopted solar power for satellites, culminating in the flight of the Vanguard 1 in 1958, a solar-powered satellite launched in reaction to the unexpected launch of the battery-powered and short-lived Sputnik satellite by the USSR in 1957. Federal government investments were instrumental in the development of crystalline silicon solar cells.

There are three kinds of crystalline silicon photovoltaics, which are produced by several hundred manufacturers and have over 95% of the photovoltaic market share.[45] *Monocrystalline* silicon is named for the ingot, made of a single crystal, that forms when using a process of heating and cooling polysilicon—the Czochralski method. The process requires placing a rod of pure silicon in the core of a reactor holding molten silicon. As the silicon is cooled, the crystalline silicon grows around the rod. In 2015, the Czochralski method was used to make roughly half of the volume of the silicon-based photovoltaics sold. Other processes that turn polysilicon into crystalline silicon include the fluidized bed process, which uses silane as the primary input. Silane is used in small quantities for doping crystalline silicon photovoltaic modules. But companies that use silane as their sole silicon source use very large volumes of the gas, which is responsible for more worker deaths than any other chemical in this industry, with twelve documented deaths (context matters here—this is orders of magnitude lower than worker death rates in other energy industries).[46]

Prior to casting in crucibles, small amounts of impurities like boron are added to the molten silicon, doping it to be intrinsically a positive layer, or p-layer, able to accept an incoming electron. The pure ingots of monocrystalline silicon, round when they are drawn out, are cut into rectangular bricks using diamond-bladed wire saws. They are then sliced into wafers. These silicon wafers are next cleaned, textured, and doped with a second impurity to form the negative layer (n-layer) that gives this part of cell its negative charge and makes it an electron donor. With the n-layer and p-layer now integrated into the solar cell, an antireflective coating is applied to maximize light absorption. Finally, the contact grid lines and busbar are added to the solar cell surface. These contacts harvest the electrons freely moving in the conduction band, drawing them into the circuit.

There are several other processes used to turn molten silicon into *multicrystalline* or *ribbon-crystalline* silicon photovoltaics. Whereas monocrystalline silicon is cooled into one single crystal, multicrystalline silicon (sometimes called polycrystalline silicon) is cast into crucibles and when it cools forms an ingot composed of many crystals. Ribbon-crystalline silicon is made by pulling wafers directly out of the molten silicon, as opposed to slicing wafers from ingots. In the 2000s, there were several companies exploring ribbon silicon, most notably a Massachusetts firm, Evergreen Solar, but it is no longer commercially produced. Evergreen Solar made headlines in 2008 when it was named by the *Boston Herald* as one of the major hazardous waste generators in the state and caused controversy when it moved its manufacturing to China shortly after taking several large local government grants to expand a factory in the U.S.[47]

Thin-film photovoltaics use semiconductor layers on the order of hundreds of nanometers in thickness that are applied to a substrate as it moves along the production line. The substrate is often glass, but these layers can also be applied to flexible materials like plastics and metal foils. Thin-films use less semiconductor materials and lower energy inputs, making them in principle less expensive to manufacture. They also can be made more rapidly in a continuous manufacturing process, which further reduces costs. The time from when a piece of glass starts down the production line until when the product is ready for inspection is on the order of hours, instead of weeks or months with silicon-based technologies. Common types of thin-film cells now in commercial production include cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous silicon (a-Si). Table 1 shows the major technologies used in the photovoltaics industry.

Many scientists, investors, and technologists see thin-films as having the greatest potential for long-term, widespread adoption as they can be significantly cheaper to make, requiring less material and energy. But excitement about thin-films in the investment community seems to have waned since the 2006-to-2010 window. Some interest remains, but much of the enthusiasm has faded, because many of the cost reductions either did not come to fruition or were outpaced by the falling price of crystalline silicon (allegedly because Chinese manufacturers were dumping crystalline silicon photovoltaics onto the U.S. market below cost, according to the U.S. Department of Commerce). Since the time that thin-films spurred widespread investments in the mid-2000s, many of the thin-film companies that garnered support have folded, or were sold to larger firms; some have even switched to silicon-based technologies. The major exception to the decline in thin-film manufacturing is a major actor in many of the cases presented in this book, First Solar of Tempe, Arizona. It is one of the world's largest and most innovative players in photovoltaics. First Solar was the number-one photovoltaics manufacturer in 2010, and a top-five producer for several subsequent years.

TABLE 1

Crystalline silicon	Thin films	Crystalline gallium arsenide
Monocrystalline	Cadmium telluride	Monocrystalline
Multicrystalline	Copper indium gallium diselenide	Concentrator
Thick silicon film	Amorphous silicon	Thin-film crystal
Thin-film crystal	Nano-silicon	
Silicon heterostructures (HIT)		
Multi-junction cells	**Emerging**	
Three junction (concentrator)	Dye-sensitized solar cells	
Three junction (non-concentrator)	Organic cells	
Two junction (concentrator)	Organic tandem cells	
Two junction (non-concentrator)	Inorganic cells	
Four junction (non-concentrator)	Quantum dots	
Multijunction silicon	Perovskites	

Founded by inventor Harold McMaster and seeded by the National Renewable Energy Laboratory and True North Partners—an investment arm of the Walton family, owners of Walmart—First Solar receives many accolades for its environmental and sustainability policies around chemical handling and product stewardship, including an extended producer responsibility program.[48] But at times it has been embroiled in land-use controversy, including lawsuits from major environmental NGOs such as the Center for Biological Diversity, Sierra Club, and Defenders of Wildlife against projects proposed on public lands.[49]

The evolution of thin-film photovoltaic manufacturing is rooted in a separate line of semiconductor innovations. Scientists began to experiment with cadmium-based thin films in the 1930s. The most commonly explored materials for thin-film solar cells at the time included cadmium sulfide and cadmium selenide. Cadmium compounds are very good semiconductors for photovoltaics because the energy required to elevate their electrons to the conduction band—what physicists call the band gap—closely matches the energy found in the most powerful part of the solar spectrum. The availability of materials that produce the photovoltaic effect is quite limited by the laws of physics and the electromagnetic spectrum of the sun. By the 1950s, cadmium telluride specifically was garnering attention from solar researchers. Companies exploring cadmium-based photovoltaics as far back as that time include many household and Fortune 500 names, including General Electric, Kodak, Matsushita, and British Petroleum.

By the 1960s, the first commercial photovoltaics were coming to market, alongside other solid-state electronics powered by semiconductors. Space satellites and telecommunications equipment were among the first devices powered by photovoltaics. In the 1970s, a researcher named Elliot Berman, with support from major oil producer Exxon, made important innovations that led to a much less costly crystalline silicon photovoltaic module. Amorphous silicon thin-film photovoltaic technologies were also coming into commercial applications, most notably in consumer electronics. Companies were researching and investing in crystalline silicon, thin-films, crystalline gallium arsenide, and multijunction solar cells by the end of the decade. The key technologies undergirding the solar revolution were already being commercialized.

By the 1980s, photovoltaics were powering many devices too far from the electricity grid to warrant running copper wires. Photovoltaics were increasingly competitive and sometimes cheaper than running copper wire to remote places. Among the companies investing in photovoltaics were oil and gas companies, who were using photovoltaics to power small devices at remote or offshore drilling platforms. Oil companies would later embark on a buying spree of photovoltaic companies, sparking speculation about conspiracies to undermine the success of photovoltaics. Many began to question the motives of the oil and gas companies, noting that developing renewable energy was not in the interest of industries that derive their profits from fossil fuels. Some went so far as to suggest that the oil industry was buying up patents to prevent others from developing renewables. More likely is that the oil and gas industry viewed photovoltaics a way to diversify their energy product portfolio and control their supply chain, as photovoltaics were increasingly being installed in remote operations such as drilling platforms and pipeline compressor stations.

Today, photovoltaic and CSP technologies are competing with mainstream electricity technologies. Transitioning toward increasing amounts of solar power can have minimal impacts if planned well and deployed with environmental best practices. All energy technologies come with social and environmental externalities that can produce, maintain, or reproduce environmental inequality. Fossil fuels are widely documented to cause the most environmental harm. The following pages present some lessons learned from the early years of solar power deployment in the hopes that the benefits of these rapidly emerging technologies will foster positive social and environmental change.