CHAPTER ONE

The History of Solar Energy

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About 4.5 billion years ago, Earth's Sun was born. It sits at the center of our solar system, 93 million miles away from Earth. It's also about 30,000 light years away from the center of the Milky Way galaxy. Our solar system is located in one of the Milky Way's spiral arms. Just as all of our planets rotate around the Sun, our solar system rotates around the center of the galaxy. It takes a mere 250 million years to do so.

Unlike the earth, the sun is entirely gaseous. It's approximately 74 percent hydrogen, 25 percent helium, and 1 percent other. A constant nuclear chain reaction produces the light and heat given off by the sun's layers. The sun's luminosity, or brightness, is the same as that produced by four trillion-trillion (4,000,000,000,000,000,000,000,000) 100-watt lightbulbs. The sun will continue to get brighter and larger for another five billion years.

In the meantime, humanity benefits from the solar energy that reaches the earth. We receive just one-billionth of the total energy generated by the sun. About 174,000 terawatts (TW) of radiation hits the earth's upper atmosphere. It reflects roughly 30 percent back into space. Oceans, landmasses, and clouds absorb the rest. The wavelengths of the solar radiation we receive are in the visible, ultraviolet, and near infrared spectrums. To put the amount of solar energy the earth gets into perspective, we receive more energy from the sun in one hour than the world uses in an entire year. It's roughly two times as much as all the energy that we will ever get from all of the oil, coal, natural gas, and uranium combined.[1]

However, the amount of energy actually available to generate electricity is less than what reaches the earth's surface. This is due to limiting factors such as cloud cover and geography. Landmasses closer to the equator receive far more solar radiation (called insolation) than lands closer to the polar regions.

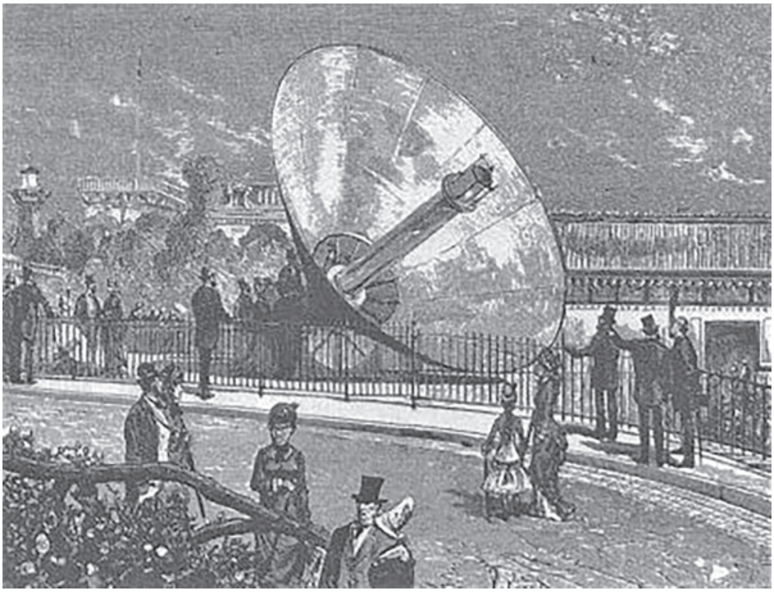
THE MAGIC OF THE PHOTOVOLTAIC EFFECT

The French physicist A. E. Becquerel observed the photovoltaic effect for the first time in 1839. A voltage or electric current is created when various materials are exposed to light. It is both a chemical and physical phenomenon. When the light is absorbed, it causes the excitation of an electron to a state of higher energy. A voltage or electric potential is created by the separation of charges. The light hitting the material has to contain enough energy to surpass the potential excitation barrier. In the case of the sun, this isn't a problem.

Back in 1839, Becquerel's first experiment used an electrochemical cell to create the photovoltaic effect. But today we can observe the photovoltaic effect in solid-state semiconductor devices. These are either **photodiodes** or devices commonly called solar cells. When sunlight strikes the surface of a photodiode, electrons on the surface of the material absorb **photons** from the sunlight. The excited electrons jump to the conduction band and become free. They then diffuse into the material. Some will reach what is known as a rectifying junction (commonly called a **p-n junction**). The Galvani potential accelerates these into a different material. This process generates an electromotive force, thereby converting some of the original sunlight into electricity.

Now that we've established the vast potential of the sun's radiation, let's delve into man's quest to harness that radiation to produce useful energy. It all started in a small town in France, more than 150 years ago. Augustin Mouchot, a nineteenth-century French schoolteacher and inventor, was concerned about his country's increasingly dependent use of coal. He astutely believed that this natural resource would eventually run out, bringing the world's booming Industrial Revolution to a grinding halt. So, he began to investigate alternative energy

FIGURE 1.1 AUGUSTIN MOUCHOT AND ABEL PIFRE'S PARABOLIC SOLAR-POWERED STEAM GENERATOR



Source: https://commons.wikimedia.org/wiki/File:Mouchot1878x.jpg.

sources that could replace the dirty fossil fuel. This ultimately led him to conduct experiments in solar energy.

His first experiments involved cooking with solar energy. He then demonstrated the ability to produce steam from a water-filled glass cauldron. He used this to power a small steam engine. Mouchot postured that if he could concentrate solar energy, he could produce even more steam. In 1866, he successfully designed the first parabolic solar collector (Figure 1.1). In 1869, he published his book *Solar Heat and Its Industrial Applications*.[2] That same year, Mouchot displayed the largest solar-powered steam engine he had ever built.

Mouchot's solar "motor" was a big hit. He worked for six years to improve his invention. He added a solar tracking mechanism that enabled the mirror to continually adjust to the sun's azimuth and altitude. This provided him with virtually uninterrupted and maximum reception of the sun's radiation. In 1872, he displayed his newly updated machine at his home in Tours. At this point, his solar motor was capable of producing one-half horsepower.

Mouchot tabulated his findings and results and reported them to the French Academy of Science. The French government was excited about Mouchot's invention. They decided that the best place to make the best use of it would be in the extremely hot and tropical climate of Algeria, which was a French protectorate at the time. Their reasoning was simple. Algeria had nearly constant sunshine, the perfect location for Mouchot's solar-powered steam motor. Before Mouchot's invention, steam engines in Algeria were entirely dependent on imported coal, a commodity that was prohibitively expensive in North Africa.

In 1878, Mouchot had yet again redesigned his solar steam motor. He attached this version to a refrigeration device. To an amazed audience, Mouchot demonstrated that it was possible to make ice using solar power. The French government awarded Mouchot a medal for his efforts. In 1881, it dispatched two commissioners from the French Ministry of Public Works to assess the cost efficiency of Mouchot's machine. They reported it was a technical success, but a failure in practice.

Unfortunately, for Mouchot, something else happened that was the deathblow for his invention. The French and English governments had vastly improved their working relationship. That meant that English coal, upon which the French were entirely dependent, became more readily and cheaply available. Mouchot, convinced this was a fool's errand, expressed his opinion in 1880 after one of his demonstrations of solar thermal energy: "Eventually industry will no longer find in Europe the resources to satisfy its prodigious expansion . . . Coal will undoubtedly be used up. What will industry do then?"[3] The French government decided energy alternatives were no longer required and dropped Mouchot's research funding. Unable to find anyone else to fund his research and development, a frustrated Mouchot returned to teaching.

Mouchot had a young partner by the name of Abel Pifre. Upon returning to teaching, Mouchot sold Pifre his patents. Pifre perfected Mouchot's original designs and increased their performance. In 1882, Pifre tested one of his improved generators at the Tuileries Gardens in Paris. It generated enough steam to power a Marinoni printing press that printed 500 newspapers per hour.

At this point, Pifre's solar-powered steam motor caught the attention of an Englishman by the name of William Grylls Adams, a professor of natural philosophy at King's College in London. Adams was convinced he could make improvements to Pifre's design that would greatly increase its power. He changed out Pifre's original parabolic dish-shaped reflector for 72 individual 10-inch by 17-inch flat mirrors. He aimed each one individually toward the central boiler. Adams' design produced enough steam to run a 2.5 horsepower steam engine, five times as big as Pifre's design.

Shortly thereafter, Adams's experimentation ended. Historians believe Adams lacked the enthusiasm to pursue further commercialization of his machine. But his design is the same basic concept used in today's **concentrated solar power** tower systems. The only difference is that the steam produced from today's systems powers a turbine shaft that connects to an electrical generator.

However, Adams had another experiment unrelated to his experiments on improving Pifre's solar steam-powered motor. In 1876, Adams, teamed with one of his students, Richard Evans Day, discovered that when light struck one of two metal plates immersed in a dilute acid, it produced a weak electrical signal. The two plates were selenium and platinum, and illuminating their junction produced a photovoltaic effect, a chemical and physical phenomenon.

Werner von Siemens, one of the nineteenth century's greatest experts in the field of electricity, said Adams and Day's discovery was "scientifically of the most far-reaching importance." The selenium/platinum "solar cell" was far from efficient. Nevertheless, this was the very first demonstration that a junction of two metals, exposed to light, could directly produce electricity.

Albert Einstein was the first to explain the **photoelectric** effect in 1905. Einstein postulated that a new quantum theory of light explained the effect. He wrote an extensive paper on the subject and received the 1921 Nobel Prize in Physics for his efforts. In 1913, William Coblentz, a research scientist at the National Bureau of Standards, received the very first US patent (no. 1077219) for a "solar cell."

It would be almost 70 years after Adams's and Day's early experiments with selenium and platinum cells before scientists would discover the modern silicon solar cell, also known as the silicon photovoltaic (PV) cell. In 1954, three Bell Laboratory scientists, D. M. Chapin, C. S. Fuller, and G. L. Pearson, demonstrated the first silicon-based solar cell. Their paper, "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power," appeared in the May 1954 issue of the *Journal of Applied Physics*.

The initial silicon solar cells produced by the trio were only 6 percent efficient. After their unveiling to the public, the *New York Times* proclaimed the discovery was "the beginning of a new era, leading eventually to the realization of harnessing the almost limitless energy of the sun for the uses of civilization."[4] A year later, AT&T's manufacturing arm, the Western Electric Company, licensed the technology. In 1956, the first commercial solar cells became available. At $300 for a 1-watt cell, the cost was prohibitively expensive for most applications. Another company, Hoffman Electronics, created a commercial silicon-based PV cell with an efficiency of 2 percent. Each cell cost $25, and 71 of them were required to produce 1 watt of power.[5]

At this point, the only customers for those expensive solar cells were companies building satellites for communications and military purposes. In 1958, the US Signal Corps Laboratory developed a silicon solar cell design that was highly resistant to radiation damage in space. Later that same year, the United States launched the Vanguard I, the very first solar-powered satellite. Its solar panel was just 100 square centimeters, or about 2.5 inches on a side. It produced just 0.1 watts of power.[6]

The 1960s and 1970s saw continued improvements in solar cell efficiency and use. By 1960, Hoffman Electronics created a silicon solar cell with 14 percent efficiency. In 1962, the United States launched the Telstar communications satellite, powered by solar. In 1967, the Soviet Union launched Soyuz 1, the first solar-powered, manned spacecraft. A year later saw the introduction of a solar wristwatch and in 1973, the United States launched Skylab, the first US-manned orbiting spacelab powered by solar cells.[7] Finally, in the late 1970s, in addition to solar-powered calculators, solar got a big boost in public interest as a result of the "energy crisis." The Iran-Iraq war triggered it, and it led to a significant drop in Iran's oil output.

The 1980s and 1990s saw even more interest and improvements in solar technology. In 1982, Kyocera Corporation was the first company to mass-produce silicon solar cells. It used the casting method, a manufacturing technique that is still today's industry standard. By 1983, the worldwide cumulative PV production had reached 21.3 megawatts and sales hit $250 million.[8]

In 1984, the very first rooftop PV installation sat on the roof of the Intercultural Center at Georgetown University. The rooftop array totaled 30,000 square feet and to this day produces an average of 1 megawatt-hour of electricity daily. By 1985, solar was under development around the world. At the University of New South Wales School for Photovoltaic Engineering, researchers created the first solar cells to reach 20 percent efficiency.[9]

In 1991, solar energy in the United States got a big boost. President George H. W. Bush announced the creation of the National Renewable Energy Laboratory (NREL) under the US Department of Energy. In 1993, the NREL established the Solar Energy Research Facility. By the end of the decade, worldwide PV installations reached a cumulative 1 gigawatt (1,000 megawatts). Solar was well on the way to becoming more than just a science experiment.

THE NEW MILLENNIUM USHERS IN RENEWABLE ENERGY

Since 2000, the continued development of solar cell efficiency and automated, high-speed manufacturing technology has enabled solar energy to flourish. It is now a mainstream energy source in the United States, and globally as well. In 2003, President George W. Bush had a 9-kW PV solar energy system and a thermal solar hot water system installed on the grounds-keeping building on the White House grounds.

However, what really got solar off the ground in the United States has been a continuing series of state mandates for renewable energy. These consist of an individual state requiring its electric utilities to have a given percentage of its generated power come from renewables by a certain date.

California has clearly led the US charge toward renewable energy. It started in 2004 with Governor Arnold Schwarzenegger. Through his Solar Roofs Initiative, he proposed that California have one million solar roofs by 2017. Through June 30, 2018, according to the Solar Energy Industries Association, the state led the nation with 863,266 solar projects installed. That equates to 22.77 GW of PV solar power.[10]

California recently approved a law that requires most new homes built in the state starting in 2020 have solar rooftop panels installed.[11]

Also in 2004, Governor Kathleen Sebelius issued a state mandate for 1 GW of renewable power in Kansas by 2015. Next came the Renewable Energy Standards Act, HB 2369, passed by the Kansas legislature in 2009, which created the state's first renewable portfolio standard (RPS). It required the state's investor-owned utilities to buy or generate at least 20 percent of its peak electrical demand from renewable sources starting in 2020.[12]

Then, in May 2015, the Kansas state legislature approved SB 91, which made the 2009 goal voluntary. This was somewhat ironic, because by 2014, wind power generation alone already accounted for 21.7 percent of the state's electricity mix. Regardless, SB 91 is viewed as a backward step for renewable energy in Kansas.

Polysilicon was primarily used in the fabrication of integrated circuits and other semiconductors until 2006, when the use of polysilicon for solar exceeded all other uses for the first time ever. That same year, the California Public Utilities Commission approved a program to keep polysilicon use for solar on the rise. The California Solar Initiative was a $2.8 billion, comprehensive program providing incentives for solar project development over the next 11 years.[13]

In 2007, the Vatican and Google both announced they would install solar energy systems to reduce their dependence on fossil fuel–generated electricity. That same year, the University of Delaware claimed it set a new world record in solar cell efficiency at 42.8 percent, although another laboratory has never independently confirmed this. In 2008, the NREL set a confirmed world record of 40.8 percent in solar cell efficiency, but it used a light concentrator to focus the equivalent energy of 326 suns on the solar cell.[14]

Even though some of the new techniques for improving efficiency were not cost-effective, it was clear that solar energy was on the rise. In 2010, President Barack Obama added additional solar panels and thermal solar water heating on the White House.

By 2011, a number of rapidly growing factories in China pushed PV solar panel manufacturing costs down to $1.25 per watt. By the end of the year, utilities and homeowners had installed roughly 70 GW of solar generating capacity worldwide. That was a 204 percent jump in just two years.[15]

By 2016, researchers at the University of New South Wales set a new world record for solar cell efficiency at 34.5 percent. Their cell was a single solar cell using unfocused sunlight embedded in a prism. That extracted the maximum energy from the sunlight by splitting it into four separate bands. Engineers used a four-junction receiver to capture and produce electricity from each band.[16]

In parallel to the development of silicon PV cells, **thin-film solar cells** were also under development. To make thin-film PV cells, engineers deposit one or more thin-film layers on a substrate of glass, metal, or plastic. There are three thin-film technologies. They are amorphous thin-film silicon (a-Si, TF-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). These technologies and their future applications are discussed in more detail in Chapter 5.

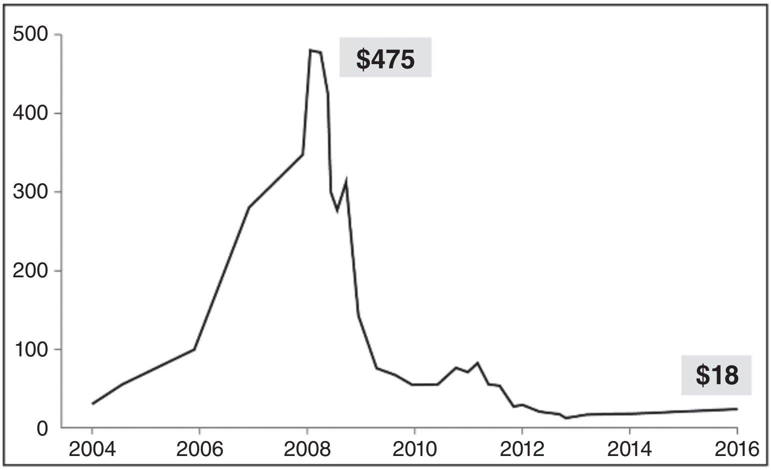
Cells made using thin-film technology are far thinner than cells made using crystalline silicon (c-Si). The advantage of thin-film, especially when using plastic substrates, is that the cells and panels can be flexible, semitransparent, and much lower in weight. Building integrated PV (BIPV) systems, where roof shingles and building siding can act as solar gathering devices, use thin-film technology. Given their transparent nature, thin-film solar can be laminated onto window glass.

But the thin-film technologies are mainly attractive because they are far less costly than conventional c-Si cells and modules. Today, some of the largest commercial, utility-scale power plants use thin-film solar panels. While cell efficiencies of thin-film have lagged those of c-Si, recent lab cell efficiencies for CdTe and CIGS are beyond 21 percent. Under accelerated life testing conditions, however, thin-film modules and panels seem to degrade faster than c-Si panels. Typically, c-Si panels come with a 25-year warranty, whereas thin-film panels have an expected lifetime of 20 years.[17]

During their heyday, thin-film solar panels commanded as much as 20 percent of the solar panel market but have now receded to about 9 percent of the overall solar panel market. The story of the rise and fall of thin-film solar technology is an interesting one. No history of solar energy would be complete without it.

It all started in 2007. The increasing demand for solar panels was straining the ability of crystalline silicon wafer manufacturers to keep up. While manufacturers of crystalline silicon ingots were building additional capacity, it was clear that it was lagging the exploding

FIGURE 1.2 THE HISTORY OF POLYSILICON SPOT PRICES IN DOLLARS PER KILOGRAM



Source: commons.wikimedia.org/wiki/File:Polysilicon_prices_history_since_2004.svg and: pv.energytrend.com/pricequotes.html.

demand for solar panels. As you can see from Figure 1.2, the cost for raw polysilicon hit $475 per kilogram ($1,045 per pound) back in early 2008.

Clearly, something had to be done. Enter a company called Solyndra. It offered what was then a novel, CIGS, thin-film solar panel. But Solyndra wasn't the only company betting on thin-film technology. In a presentation I gave in 2009, I said there were no less than 143 companies making or planning to make thin-film solar panels. Most are out of business today. What happened?

As you can see from Figure 1.2, the unthinkable, but in hindsight very predictable, thing happened. Manufacturing capacity for polysilicon crystal mushroomed. When that happened, prices for raw polysilicon fell dramatically. And that killed the economic models of nearly every would-be thin-film solar panel manufacturer. Their long-term viability was completely dependent on the price of raw polysilicon remaining high. Nonetheless, an increase in demand for any commodity is eventually met with an increase in supply. That's what happened a decade ago and it spelled the end for most thin-film manufacturers.

The case of Solyndra was notable for several reasons. Solyndra was founded in Fremont, California, in 2005. It designed, manufactured, and sold CIGS-based thin-film solar panels. But its panels were unique in the industry. Each 1 × 2 meter panel contained a rack of 40 cylindrical tubes. Each tube was actually a CIGS thin-film solar module containing up to 200 CIGS cells.[18] Solyndra believed its revolutionary cylindrical design could produce significantly more electricity than conventional panels. That's because Solyndra claimed its panels always had some of its face directly perpendicular to the sun's rays.

In September 2009, Solyndra received a $535 million loan guarantee from the US Department of Energy to build and equip a 450-MW thin-film panel-manufacturing factory. Known as Fab 2, this facility's total cost was $733 million. The remainder of its financing was put up by private investors. The plant was the size of five football fields, with a total of 300,000 square feet under roof. It was going to be highly automated with robotic assembly of individual panel assemblies. When completed in 2013, its projected annual production was 610 megawatts worth of panels.

After its peak in early 2008, however, the price of polysilicon, the raw material for Solyndra's competition, began dropping. By November 3, 2010, the writing was on the wall. Solyndra announced a layoff of 40 employees and the cancellation of contracts for 150 temporary workers. By mid-2011, the price of polysilicon had fallen 89 percent from its mid-2008 high. On August 31, 2011, Solyndra formally filed for Chapter 11 bankruptcy protection. It completely shut down all manufacturing and operations and laid off its remaining 1,100 employees.[19]

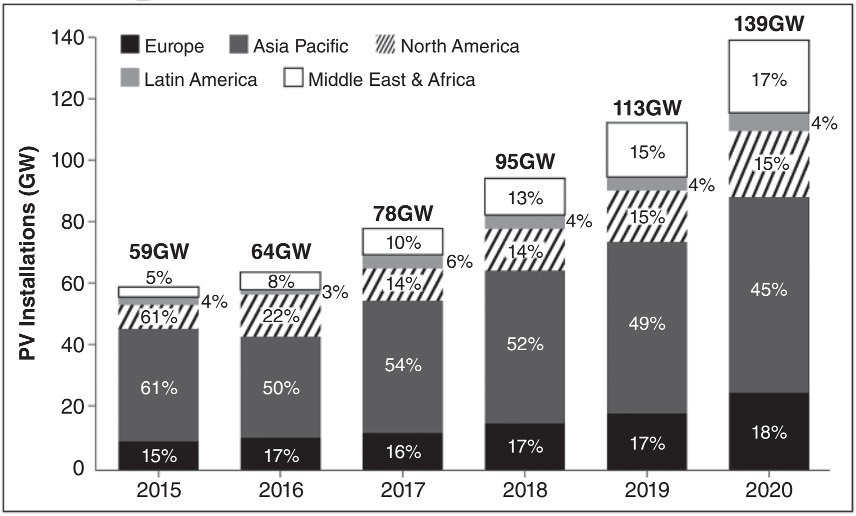
Given the amount of federal loan money involved, the US Treasury Department launched an investigation in September 2011. The FBI raided the company and the homes of Solyndra's CEO Brian Harrison, and its founder Chris Gronet. There was an immediate sense of company overspending.

An article originally published by *Bloomberg* reported that the Taj Mahal–like plant had robots whistling Disney tunes. The employee showers had "spa-like liquid crystal displays of the water temperature," and "glass-walled conference rooms."[20] It became obvious to investigators that Solyndra had designed and built a plant capable of building far more solar panels than it had orders for. Initially, it looked as though the Obama administration, and ultimately the US taxpayers, were going to be stuck with the defaulted loan. But by 2014, the US Department of Energy renewables loan program had recouped its losses, including Solyndra's $528 million blunder, and was profitable.

In 2018, demand for thin-film solar panels is a fraction of what it was during 2008, when polysilicon was in short supply. Currently, there is an oversupply of polysilicon for solar and semiconductor use, despite very strong demand in both semiconductor and solar markets. In January 2016, polysilicon prices hit near-record lows. Because of increased capacity built by existing manufacturers and Chinese capacity growth, the oversupply that was 7 percent in 2016 grew to 15 percent in 2018.[21] Based on the extension of the US renewables Investment Tax Credit, the Paris United Nations Conference on Climate Change (COP21) CO_2 limits, and higher solar growth in emerging markets, solar demand is outpacing even recent forecasts. You can clearly see this in Figure 1.3.

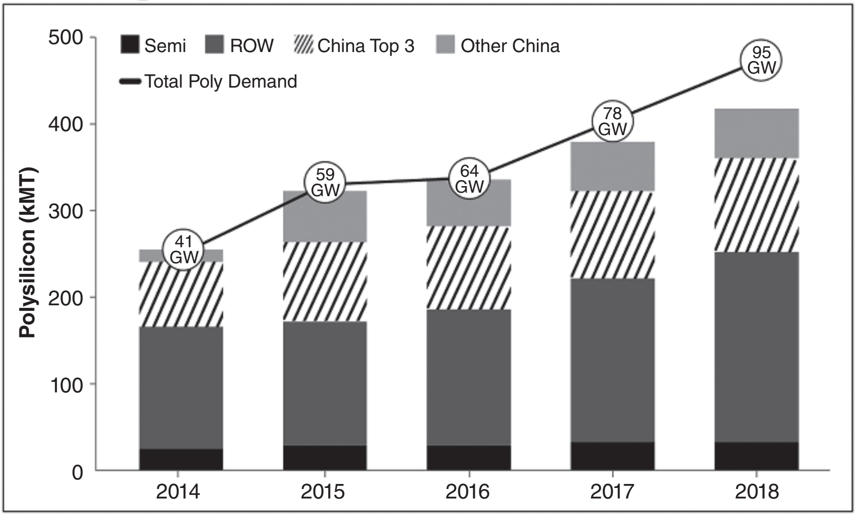
However, the ongoing trade war between China and the United States has affected the polysilicon market. Unfortunately, the United States has lost all access to Chinese polysilicon wafers. These are a key ingredient in the manufacture of solar cells, modules, and panels. In February 2016, polysilicon was selling for just $12 per kilogram,

FIGURE 1.3 PV DEMAND BY REGION



Data source: www.seia.org/research-resources/solar-market-insight-report-2015-q2.

FIGURE 1.4 POLYSILICON SUPPLY/DEMAND



Data source: www.seia.org/research-resources/solar-market-insight-report-2015-q2.

near historic lows. But by April 2016, prices had risen to $19 per kilogram, a 58 percent increase in just three months. It turns out, according to IHS Markit, that some, if not all, of the price increase is due to demand in China.

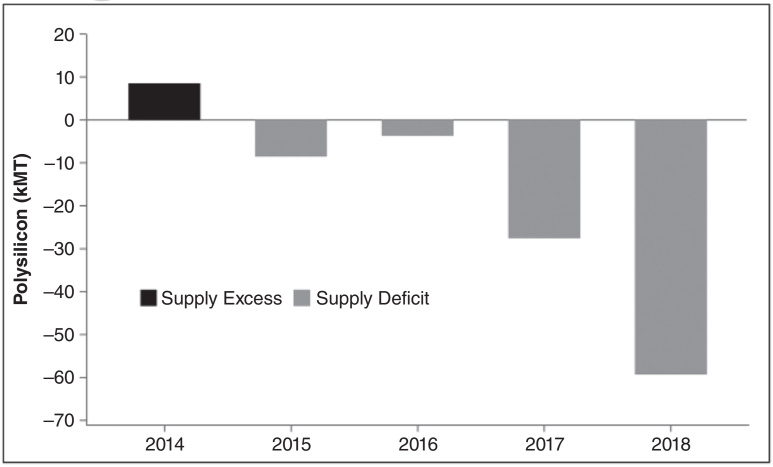
The Chinese imposed a June 30, 2016, deadline, after which it cut solar feed-in tariff levels to large-scale wind and solar developers in China. The intent was to focus future installations on commercial and industrial sites, on the distributed side of the network. That created a rush to install new systems before the deadline. That also created a big spike in the demand for polysilicon.

Figure 1.4 shows polysilicon supply/demand and Figure 1.5 shows the market balance for polysilicon through 2018. This is predicated on a global PV demand forecast hitting 95 GW for 2018.[22]

Resolving the trade dispute with China makes sense for both countries. China will have better access to the US panel market. This is even more desirable since the investment tax credit extension (see the Introduction). It will eliminate US duty hikes on Chinese panels. Finally, it will eliminate the blooming polysilicon shortage in China.

For the United States, the reopening of the China market will help alleviate any shortage of polysilicon in China. Since most of the new

FIGURE 1.5 POLYSILICON MARKET BALANCE



Data source: www.seia.org/research-resources/solar-market-insight-report-2015-q2.

polysilicon manufacturing capacity is being added outside of China, shortages for the rest of the world, including the United States are less likely to materialize.

The bottom line is solar energy is here to stay. While it took over 100 years to get to where we are today, it's clear that solar energy isn't just a science project anymore. Prices are competitive with conventional generation, and are already responsible for retiring fossil fuel-fired generating plants. Based on the above forecast from IHS, solar is set to pop 117 percent between now and 2020. Frankly, I believe that number could turn out to be conservative. We could see global demand come close to doubling by 2022.

NOTES

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