7

Economics of Photovoltaic Cells and Systems

7.1 The Basics of PV Economics

The economics of PV devices are also related to the optics. The cost of photovoltaic materials is often expressed on a per-unit-area basis, but the modules are often sold based on cost per peak watt potentially generated. To convert the cost per square meter to the cost per peak watt, the following equation is employed:

$$\$/W_P = \frac{\$/m^2}{\eta \cdot 1000\ W_P/m^2}, \tag{7.1}$$

where η is the conversion efficiency. A 12% efficient module with a cost of \$400/m^2 yields a cost per peak watt of \$3.30. In a simplified economic analysis, it is desirable to estimate the return on the investment made for a particular material used as part of the photovoltaic system. The time for an investment return (payback time) on the PV module, of cost \$/m^2, is related to its efficiency, and the cost at which electricity is sold on the market, in \$/kWh. The payback time is expressed as follows:

$$\text{Payback time} = \frac{\text{Cost } \$/m^2}{\eta \cdot \frac{5\,\text{kWh}}{\text{day} \cdot m^2} \cdot \frac{365\,\text{day}}{\text{year}} \cdot \frac{\text{electricity}\,\$}{\text{kWh}}}. \tag{7.2}$$

For example, the payback time for a \$75/m^2 module of 10% efficiency at an electricity-selling price of \$0.08/kWh is approximately 5 years. Commercial crystalline-silicon (c-Si) solar cells are currently produced by growing single crystal ingots using very pure materials. The silicon is sliced and processed with dopants and methods that are very similar to silicon technology used for making integrated circuits and computer chips. This process is not conducive to high-volume production rates or large areas per unit time. The c-Si costs are currently \$400–500/m^2. Newer thin-film technologies are based on materials such as (noncrystalline) amorphous-silicon (a-Si), or on polycrystalline CdTe or $CuInSe_2$. These thin materials can be directly deposited on glass and interconnected using laser or photolithography patterning (see Fig. 1.6).

7.2 Estimated Solar Module Cost

To estimate the costs of a PV module, consider how much a hypothetical thin-film solar cell material costs (see Table 7.1). In the production of a PV module, the materials, and the fabrication must be considered. Unlike crystalline solar cells such as c-Si, major costs for thin-film technology include the glass and the manufacturing and operation costs.

Table 7.1 The cost of the hypothetical PV module.

	Costs
Solar cell materials and glass	\$50.00
Production overhead: equipment depreciation, indirect and other direct materials	\$5.00
Labor: direct and indirect (including assembly and testing)	\$1.00
Encapsulant or sealant	\$2.00
Frame and electrical interconnects	\$2.00
Additional protective cover or Tedlar backing	\$2.00
Profit, Interest due on loans	\$2.00
Total module cost	**\$64/m²**

The direct costs, such as those for tools and labor, are related to the actual production of the module, while the indirect costs incurred for such things as accountants, rent, and computers are volume insensitive. This calculation assumes a 5–10 MW_p/year factory with 100 employees, and a capital cost of equipment of \$17,000,000, housed in a 2000 m^2 facility. The module costs are determined primarily by the cost of the conductive glass, and the production overhead. To estimate the cost per peak watt, one relates the cost per unit area with the power produced, which depends on the solar conversion efficiency and the peak solar illumination as described above. For a PV module at an efficiency of 8%, power would be produced at \$0.80/W_p if the module cost is \$64/m^2. For a 10% efficient cell, the cost would be approximately \$0.64/W_p. The estimated solar module production cost for a factory producing 10 MW_p per year of 10% efficient solar modules is found to be less than \$2/W_p if the module cost per square meter is less than \$100 As a comparison, the module costs for single crystal-silicon (c-Si) cells are now approximately \$5–8/W_p.

7.3 Economics of Photovoltaic Systems

To produce useful power in a commercial application, one must consider the average illumination, instead of the peak, as well as the additional costs of land, batteries, support structures, *and* the lifetime of the panel. If these "balance of systems" (BOS) costs are considered, the cost of power produced with thin-film solar cells would be $0.08–0.11/kWh, assuming a 10% efficient module which lasts at least 15 years under the illumination found in the western United States. Note that this cost lies in the range of electricity for conventional fossil-fuel-based systems. Thus, the above analysis demonstrates that the thin-film solar cells, if proven stable over 15 years, could represent a viable solar energy option. There is more to a photovoltaic system than just the module. Balance of systems costs such as the mounting, wiring, and power conditioning must be considered, as well as the operating and maintenance costs. When these factors are taken into consideration, a rough cost per generated kilowatt hour can be estimated. The cost of electricity generated by solar cells can be estimated from the equation:

$$\frac{\text{Cost}}{\text{kWh}} = \frac{\left(\text{Cost of system } \$/\text{m}^2\right) \cdot \text{amortization}}{\text{kWh produced each year}} + \text{O\&M}. \tag{7.3a}$$

Putting in all the relevant terms, Eq. [7.3(a)] becomes

$$\frac{\$}{\text{kWh}} = \frac{\text{Module } \$/\text{m}^2 + \text{Mount } \$/\text{m}^2 + \left(\text{PC } \$/\text{kW}\right) \cdot \eta \cdot 1\,\text{kW/m}^2}{\eta \cdot \dfrac{5\,\text{kWh}}{\text{day} \cdot \text{m}^2} \cdot \dfrac{365\text{day}}{\text{year}}} \cdot \text{amortization}\left(1 + \text{Indirect}\right) + \text{O\&M}. \tag{7.3b}$$

One should note that if a concentrator is used, the module cost is divided by the concentration ratio, and the mount costs, O&M costs, and input kWh are adjusted accordingly. The per-unit-area cost of solar cells seems to be the largest and most variable cost item in a photovoltaic system. For a relative comparison, one can use the following numbers that are believed to be reasonable for near-term thin-film PV technologies:

(1) a module cost of $\$75/\text{m}^2$,
(2) a mounting cost of $\$50\text{–}75/\text{m}^2$ (mount, land, wiring),
(3) PC cost of $170 per peak kW
(power conditioning, battery storage, and dc-ac inverter), and
(4) an indirect cost of 30% for architect and engineer fees, along with interest during construction.

The costs of the PV system are paid off over the lifetime of the project. The amortization rate is calculated from the real discount rate of *i*, and a PV lifetime, N:

$$\text{amortization} = \frac{i}{\left[1-(1+i)^{-N}\right]}. \tag{7.4}$$

The amortization rate is 0.07–0.1 for N = 15–30 years and a discount of 6–12%. For a solar insolation of 4.4–5 kWh/day/m^2 (1600–1800 kWh/year/ m^2), and an operating and maintenance (O&M) cost of \$0.005/kWh, the electricity costs can thus be estimated. The cost of conventional electricity in U.S. dollars is \$0.06–0.12/kWh. Table 7.2 shows the results of this simplified analysis and indicates that although solar cells of 15% efficiency that last for 15 years can be competitive with fossil fuels, cells of less than 8% efficiency with lifetimes of under 15 years will probably not be economical. To compare present costs and future needs for PV, see Table 7.3.

Table 7.2 Cost of a photovoltaic system.

Electricity cost as $/kWh				
PV efficiency, η	8%	10%	15%	20%
N=30 years	0.093	0.077	0.056	0.045
N=15 years	0.13	0.108	0.078	0.062

Table 7.3 Present and future PV system cost breakdown.

Aspect of PV system cost	Now	Needed
Module cost	\$450–\$500/m^2	\$150–\$75/m^2
Area-related BOS	\$135/m^2	\$150–\$75/m^2
Power conditioning	\$200/kW (\$20/m^2)	\$100/kW (\$14/m^2)
Module efficiency	10–15 %	15 %
Cost of DC electricity	\$0.20/kWh	\$0.04/kWh
AC cost with storage	\$0.30/kWh	\$0.07/kWh
Module cost/W$_p$	\$5–\$7/W$_p$	\$2–\$3 /W$_p$

The analysis in Table 7.3 outlines the basic factors involved in the costs of both the PV cells and the PV systems and illustrates the areas for improvements. This analysis does not include the cost of capital in the form of loans, nor does it include the social and environmental benefits of solar energy converters compared to conventional power sources such as fossil fuels or nuclear power.

7.4 Economics of Solar Energy in the World Economy

Energy policy often neglects to consider the complex interplay between science, technology, and history. Once a set of technologies is chosen (e.g., fossil-fuel energy sources), it is difficult to move to more attractive, newer technologies without large investments and efforts. Scientists and engineers often do not see the economic and policy aspects of their new developments. Conflicts in the Middle East and elsewhere will continue to emphasize the disadvantages of reliance on nonrenewable energy resources. As concerns over energy resources and the consequences of pollution become more important internationally, the use of renewable energy will be increasingly important. Alternative energy technologies alone cannot ensure sustained economic development and growth. Likewise, policies that do not consider energy sources in their technical, historical, environmental, and economic contexts are doomed to fail in the end. Many questions exist as to whether renewable energy is up to the task of supplying a significant fraction of the world's energy needs. The question becomes how to promote renewable energy, and how to use both technology and policy to ensure that growth in energy supplies can meet future demand in a sustainable way. Discussions on renewable energy often focus on two questions: (1) can renewable energy supply our energy needs, and (2) can it be done economically? There is ample evidence that the answer to both of these questions is "yes."

On the exterior glass of a 48-story building located at 4 Times Square in New York City, 15 kW are being generated from sunlight using photovoltaics, otherwise known as solar electric panels. On the fourth floor, two 200-kW fuel-cell generators silently and efficiently provide energy for the entire building. The state-of-the-art building is also equipped with many other renewable energy and energy efficient technologies. In an article entitled "A realizable renewable energy future," by Dr. John Turner of the U.S. Dept. of Energy's National Renewable Energy Laboratory in Golden, Colorado, it is stated that, "PV technology has the ability alone to provide all of the energy needs of the United States." His calculation assumes a 10% solar-to-electrical-system efficiency, well within the efficiency capacity of today's technology and the use of fixed flat-plate collectors that are now the PV industry standard. Dr. Turner's conclusion has been asserted several times before but is nonetheless noteworthy. Using standard PV technology, a square 161 km (100 miles) on a side, in 1 year, would produce the energy equivalent to that used annually in the entire United States. Although 25,921 km^2 (10,000 square miles) is a large area, it is less than one quarter of the area that the U.S. has covered with roads and streets, and is much smaller than the area in the U.S. devoted to cropland. This area could be located in one place (e.g., a desert area), or distributed on every suitable roof or area. It should be noted that if wind power is added to a country's energy mix, the required area for PV is reduced. For example, the San Gorgonio pass in southern California has the wind energy equivalent of seven nuclear power plants. Wind power is now cost competitive with electricity generation from fossil fuels in several areas, and the installed wind-turbine capacity is expected to grow by more than 25% per year over the next few decades.

The cost of solar photovoltaics has dropped from over $100 per peak watt in the 1970s to under $6 per peak watt in 2002. Types of solar panels have diversified and now include 100–200 W modules of crystalline silicon, amorphous silicon, cadmium telluride, copper-indium diselenide, and others. The light energy to electrical-energy-conversion efficiency of these panels typically ranges from 10% to 15%, with steadily increasing values over the last 20 years. With continued interest and investment, the trend in increasing efficiency and decreasing costs is expected to continue. Applications of PV include satellite power, power for small consumer appliances, remote residential and industrial power, telecommunications, cathodic protection, water pumping and treatment, military and grid connected systems. Markets have grown at rates in excess of 15–20 % per year, and are expected to continue to grow at these rates or higher in the foreseeable future. The growth of energy markets in the developing world has prompted energy giants such as British Petroleum, Kyocera, Siemens, and Shell to purchase PV manufacturers. According to the PV industry analysts, more than 100 MW of solar panels are produced and shipped worldwide each year. Still, this puts the cost at several times the cost of conventional energy sources. Solar power and the other renewable energies are now cost competitive in many locations. Unlike conventional energy sources, these resources do not need to follow price spikes that have plagued the consumers of conventional energy sources. Once the initial cost of the installation is financed, the energy flows constantly and reliably. When the wind is not blowing or the sun is not shining, energy customers can buy energy from their local utilities. When the renewable resource (e.g., sun or wind) is available, however, excess energy can be put back into the grid for other customers to use. This storage concept is called “net metering” or “distributed generation,” and is possible because of efficient dc-to-ac converters (electronic inverters) that allow the small residential renewable energy systems to be “in phase” with the ac electricity on the transmission lines. Many utility companies give their customers full credit for the energy they generate. This could turn every building into a mini-power plant. The point is clear: we can collect and convert more than enough renewable energy to power our society. So if technology alone is not limiting the use of renewable energy, then what is? Perhaps it is the economics or the way we view the economics.

One important economic issue that is often neglected when formulating energy policy is the subsidization of energy production, whereby government action is taken to influence energy market outcomes, whether through financial incentives, regulation, research and development, or public enterprise. Consideration of subsidies, in general, is becoming increasingly important for international trade, and the World Trade Organization (WTO) is discussing it. Many regulations placed on power companies and energy providers often act as subsidies. In some cases, those regulations and certain subsidies actually protect the environment, and the consumer. Subsides can favor certain energy industries and skew the economics so that one energy source looks unfavorable when it actually may not be. Norman Myers and Jennifer Kent [27] claim that today, subsidies worldwide are strongly weighted against nonpolluting renewable energy sources. Many studies assert that continued investment in renewable energy, such as solar energy, could stimulate economic growth worldwide [24-26]. Subsidies and political factors, however, often hide the full costs of conventional sources of energy. In the U.S., it is estimated that energy subsidies total $32–36 billion, approximately 90% of which goes to fossil fuels and nuclear power [27]. Another example comes from the Dominican Republic, where grid-connected electricity costs to consumers are $0.11/kWh, typical of many developed nations. This cost does not, however, reflect cost (e.g. $11/kWh) to string the transmission wire needed to reach the rural villages, nor does it reflect the limited supply of government money needed to provide such grid connection service to only a few scattered villages. For coal alone, the most subsidized energy source, subsidies total somewhere between $37 and $51 billion worldwide, with $17 billion from the former Soviet Union and $6 billion in China and India [27].

Even in light of these subsidies, the prejudice often persists that solar electricity is expensive compared to that from fossil fuels and nonrenewable alternatives. This assumption is clearly not true in many developing nations. For example, a study conducted by researchers at Sandia National Labs concluded that in the Dominican Republic, PV is the logical choice for remote rural villages. People there use energy sources such as kerosene and candles for lighting, automotive batteries to run televisions, and dry cell batteries for radios and consumer electronics. Although the cost for the purchase of each of these energy sources may be low, the cost per unit of energy is, on average, as much as $2.00/kWh. In contrast, a small village photovoltaic system can reliably and consistently supply the same loads at costs less than $0.75/kWh, which is higher than grid connected electricity, but still lower than the villagers would pay otherwise. Unfortunately, most of the 2 billion or more people in the world who could benefit from solar PV technology cannot afford to pay the high up-front costs associated with it.

Although the fuel is free and the maintenance is minimal, one of the major limitations of solar energy technologies is the necessity for large capital investments to be made at the beginning of a project. This has discouraged its use in many small applications worldwide due to the lack of available initial funds. In addition, energy prices are often too low for solar (and other renewable) energy to compete on economic grounds, in part due to explicit or implicit subsidies for conventional energy. If risks are perceived as being too high, investments by local banks and institutions will not be made. Several organizations are meeting this challenge and raising awareness in lending practices. For example, the Solar Electric Light Fund (SELF) in Washington, D.C., has provided tens of thousands of low-cost loans to small PV projects in Vietnam, India, China, and other developing countries. The World Bank and the Global Environmental Facility (GEF) have encouraged many international renewable energy projects, including those using solar energy [26]. In 1992, the World Bank established the Asia

Alternative Energy program, which helps to bring renewable energy and energy efficiency practices into the forefront in lending programs in Asia. In China, a rural energy and greenhouse gas mitigation study conducted in 1994 led to the current Renewable Energy Development Project underway there. In India, a PV program for home and commercial use was started in 1992. In 1997, similar programs were started in Indonesia and Sri Lanka for PV home systems in rural off-grid applications. Argentina followed in 1998, with programs in Mexico and the Philippines starting in 1999 [26]. These programs are typically funded in the \$50–150 million range and provide a multitude of PV systems ranging from a few watts to 1–10 kW_p. This may not seem much, but a small outdoor lamp powered by a PV system in Rajasthan, India, for example, has allowed adult literacy classes to be held at night, and projects like this can change the lives of millions. In Kenya, more than 40,000 small PV systems have been installed, financed by a grass-roots private financing program. These projects, and many more not mentioned above, have resulted in increased confidence in, and experience with, PV systems [29].

PV systems are not limited to developing countries. In Dartmount, Devon, UK, for example, a grid-connected roof-top PV system supplies 900 kWh per annum—about 40% of the homes' requirements. In Berlin, at the German nation's leading financial institution, the Berlin Bank, a 50-kW_p system is being tested. In Amersfoort, Netherlands, a 180-KW_p system is being used in a 500 home development. A 4.2-kW_p PV tracking system is installed in Geest in Northern Germany, and in Karlsruhe, the Art and Media Technology building has a PV system that produces 90,000 kWh per year for a DC Tram (transportation) system. In Lausanne, Switzerland, as part of the European Heliotram project, 32 PV modules generate more than 7,800 W_p, which is fed into the DC line of the trolley-bus line. Near the Swiss Alps in Chur, grid-connected PV panels have even been installed on the sound barriers on the motorway N13. Although there are thousands of PV systems in the U.S., one clearly illustrates future trends. In Santa Cruz, California, 224 photovoltaic panels (approx. 12 kW) have been installed at the city hall. A state-sponsored subsidy paid approximately half of the cost of the system. Thanks to the rebates and grants, this PV system, which provides about 7% of the building's power, will pay for itself in fewer than 4 years. These subsidies were needed to make the system attractive compared to conventional energy sources, which are themselves subsidized by government expenditures.

Paradoxically, there is often much talk at the local and national levels about lowering environmental standards so that conventional generators can lower operating costs and pass these saving on to customers. This represents further subsidies to fossil fuels, and distorts the markets away from investments in renewable energy and energy efficiency. In fact, it is the promotion of renewable energy, energy efficiency, and the continuation of current environmental regulations that can benefit the economy in the end. For example, Myers and Kent describe that the U.S. Clean Air Act has produced net direct monetary savings during the period 1970–1990 averaging \$1.1 trillion per year. This is due to the cost of health care associated with pollution and the loss of productivity of people and crops. These are called "external costs," because if the environmental regulations were less restrictive, these costs would be paid by the consumer or society rather than by the energy producer.

In addition, the Kyoto Protocol and related international agreements attempt to limit carbon dioxide emitted during fossil-fuel energy utilization (i.e., coal, oil, natural gas). The concern is that greenhouse gases such as CO_2 will change the balance between incoming solar and outgoing thermal radiation from Earth, and thus the temperature of the planet will be raised. This could lead to climate changes that are difficult to predict. As greenhouse gases are increasingly viewed as a pollutant, there will undoubtedly be increased interest and investment in renewable energy. A popular myth to be dispelled is that c-Si PV modules generate more CO_2 than they offset. Although they do generate CO_2 via the fossil fuels used to make them, they generate approximately 3 times less per unit energy than fossil fuel sources over their 20–30-year lifetime. [25, 28] Changes in energy need not come at the expense of promoting economic growth and development. A Union of Concerned Scientists report asserted that actions to curb global warming are feasible and affordable. Many studies assert that there are many other benefits from renewable energy technologies, including cleaner air and water, the creation of jobs, and the promotion of new technologies and businesses. A switch to renewable energy may also be necessary from an ethical standpoint.

The United States possesses only 4% of the world's population, but it consumes 25% of its energy. The U.S. consumes roughly twice as much energy per person and per unit of GNP as do Western Europeans and the Japanese. By increasing the efficiency with which Americans use energy so that it is equivalent to Western European and Japanese levels, the country could save over $100 billion per year. The U.S. also emits 22% of carbon dioxide accumulating in the global atmosphere (a global common resource). In per-capita terms, it emits twice as much carbon dioxide as Germany, Russia, or Japan, almost three times as much as Italy, and ten times as much as China. Fossil fuels contribute 90% of the United States' greenhouse gas emissions. They also account for 90% of local air pollution and acid rain, and the great majority of gases leading to smog. A United Nations Environment Program study shows that not taking action to curb carbon emissions could lead to more than $300 billion (worldwide) in annual reductions in Gross Domestic Product (GDP) in the future. Many cite the "precautionary principle," which states that in the absence of full understanding of the scientific evidence for an effect with dire, unpredictable, and far-reaching consequences, it is best to err on the side of caution.

While the debate continues over whether the switch to renewable energy is even feasible or possible, renewable energy systems are becoming more common worldwide. As in the skyscraper powered by renewable energy in Times Square, the promise of solar cells is reaching high. Nonpolluting renewable energy systems can continue to make a significant contribution to solving local and global problems. It is up to us to closely examine, and choose, those technologies, economic incentives, national and international policies, and local actions that will hasten the inevitable transition away from fossil fuels toward renewable and sustainable technologies. Solar cells and photovoltaic technologies can, and will, make an impact on the world's energy production. By understanding the basic operation of these remarkable devices, the impact can be made to occur sooner rather than later.

7.5 Conclusions and Further Study

This book has outlined a basic approach to understanding the optical basis of solar cells. The optical properties of solar cell materials, and how these properties relate to the creation of practical devices, have been examined. A simplified version of a generalized model has been outlined and can be used to understand existing quantum-solar-energy converters, as well as solar cells that will be developed in the future. With the completion of this text, the student is ready to go on to more detailed work on the subject. It is hoped that students will do so using the bibliography as a starting point. In many developing nations, and in remote (off-grid) locations, solar cells already provide a highly valued, low-maintenance and cost-effective alternative to fossil fuels and nuclear power. The challenge of the 21st century will be to use optical, electrical, and economic analyses of solar cells to effectively provide energy for a growing population.

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Preface

With concerns about worldwide environmental security, global warming, and climate change due to emissions of CO_2 from the burning of fossil fuels, it is desirable to have a wide range of energy technologies in a nation's portfolio. These technologies can be used in domestic markets, or exported to other nations, helping them to "leapfrog" to a cleaner, and less carbon intensive, energy path. Far from being an altruistic act, these energy technologies are lucrative businesses that will grow stronger in the global economy of the 21st century. According to U.S. DOE EIA, NREL U.S. PV Industry Technology Roadmap 1999 Workshop and Strategies Unlimited, photovoltaics (or PV) is a billion dollar a year industry and is expected to grow at a rate of 15–20% per year over the next few decades. Solar cells have already proven themselves a viable option as a nonpolluting renewable energy source in many applications. It is advantageous to optical engineers to have at least a basic knowledge of how these devices function, and of the important parameters that control their operation. This text is designed to be an overview for those in the fields of optics and optical engineering, as well as those who are interested in energy policy, economics, and the requirements for efficient photo-to-electric energy conversion.

Greg P. Smestad
April 2002

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A new scientific truth does not triumph by convincing its opponents, but rather because its opponents die, and a new generation grows up that is familiar with it.

Max Planck

There is one thing stronger than all the armies in the world: and that is an idea whose time has come.

Victor Hugo

A Basic Solar Energy Library for the Optical Specialist

The following is a partial list of the recommended references in the field of solar energy conversion and photovoltaics. These books and other sources can be explored for details on the topics introduced in this brief tutorial.

1. M. A. Green, *Silicon Solar Cells: Advanced Principles and Practice*, Bridge Printery, Sydney, 1995. This book (and any of Green's many articles found in the literature) is a must-read. It also contains useful constants and tables for silicon and a description of texturing the front of a solar cell.

2. American Society for Testing and Materials, *Standard for Terrestrial Solar Spectral Irradiance Tables at Air Mass 1.5 for a 37° Tilted Surface*, ASTM standard E 892, Vol. 12.02, West Conshohocken, Penn., 2002 Annual Book of ASTM Standards. This standard is equivalent to IEC 60904-3 and ISO 9845-1. ASTM standards E 948 and E 1021 are also useful for measurement of the I-V curve and Spectral Response curve, respectively.

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19. A. De Vos, *Endoreversible Thermodynamics of Solar Energy Conversion*, Oxford Univ. Press, Oxford, 1992. A mathematical treatment of the fundamental (thermodynamic) aspects of all solar converters. It covers thermal and photo-conversion, photosynthesis, and tandem systems; and it provides useful insights for those who wish to determine the limitations of a given approach.

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28. M. Oliver, T. Jackson, "The evolution of economic and environmental cost for crystalline silicon photovoltaics," *Energy Policy,* **28,** pp. 1011, 2000.

29. Useful websites:
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