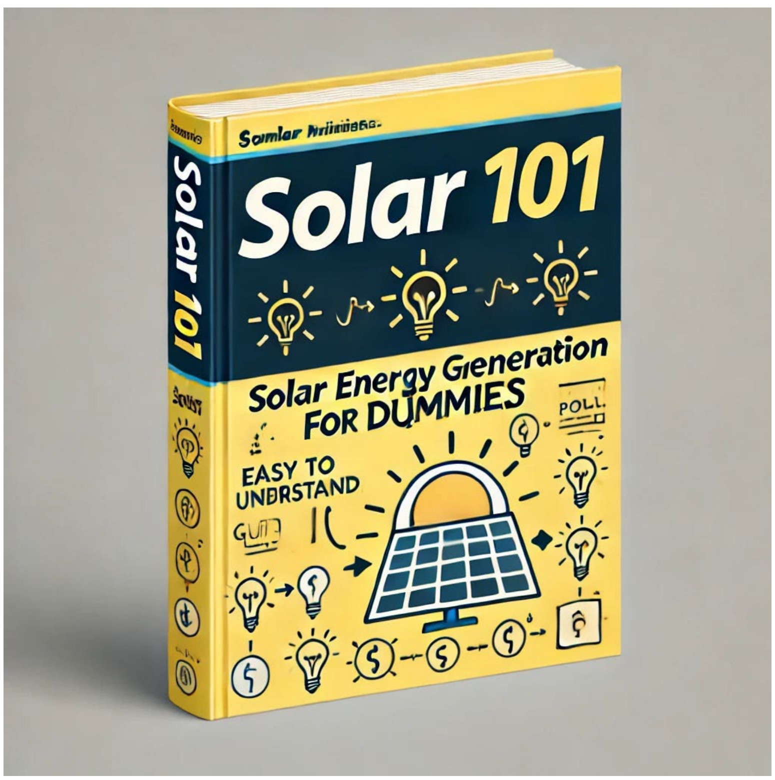
Solar Energy For Dummies - Solar 101

Although the post of this could cause some to be “triggered” (heaven forbid), the title merely references the self-help reference books of years past such as Computers For Dummies, DOS For Dummies, Windows95 For Dummies, and yes for us men… Making Marriage Work For Dummies. These reference books helped those who may have had zero understanding of the book’s subject matter, or at best was minimally familiar with it, but needed a detailed step-by-step instruction as to how to accomplish a desired task.

This will not be a comprehensive deep dive into solar, but intended to be a launching point for you to gain some general knowledge. The majority of the information within this chapter was taken from the US Department of Energy, Office of Energy Efficiency & Renewable Energy’s website (late summer of 2024) and admittedly some aspects likely were written years prior.



COMMON TERMS DEFINED

Utility-Scale Solar: or industrial solar, is a safe and reliable way to increase energy generated without increasing pollution or waste. To be considered utility scale, solar projects need to generate 50+ megawatts (MW) of electricity. [19] More specifically defined within Ohio Revised Code 4906.01(B)(1)(c) & (H).

Small-Scale Solar: means solar panels and associated facilities with a single interconnection to the electrical grid and designed for, or capable of, operation at an aggregate capacity of less than fifty megawatts (<50MW). Per Ohio House Bill 501 (134th General Assembly), signed into law on January 5, 2023 and effective as of April 6, 2023.

Community Solar: is an innovative approach to harnessing the power of the sun for electricity generation while ensuring that the benefits flow to multiple stakeholders within a specific geographic area. It allows individuals, businesses, nonprofits, and other groups to access clean and affordable solar energy, even if they are unable to install solar panels on their own properties. Instead, community solar subscribers either own or subscribe to a portion of the energy generated **by a solar array located off-site**, and they receive electric bill credits for the electricity generated by their share of the community solar system. [20]

Note: State Rep. Jim Hoops (R-District 81) and Rep. Sharon Ray (D-District 66) (135th General Assembly) introduced community solar legislation HB197 - Establish community solar pilot and solar development programs on June 6th of 2023 and as of September of 2024 this legislation still sits in committee.

This legislation's proponents, those in favor of its passage, obviously include the solar industry itself and it's advocates (such as Solar United Neighbors, IBEW, Momms Clean Air Force in Ohio, and others). This legislation seemingly is an attempt for commercial solar vendors, contractors, and/or developers to circumvent the provisions of HB501 which returned property rights to County Commissioners and/or Boards of Zoning Appeals to adopt zoning regulations governing Small Solar Facilities fifty megawatts (50MW) or less.

THE HISTORY OF SOLAR17

Solar technology isn't new. Its history spans from the 7th Century B.C. to today. We started out concentrating the sun's heat with glass and mirrors to light fires. Today, we have everything from solar-powered buildings to solar powered vehicles. Here you can learn more about the milestones in the historical development of solar technology, century by century, and year by year.

This timeline lists some of the milestones in the historical development of solar technology from the 7th Century B.C. to the 2002 A.D.

7th Century B.C. - Magnifying glass used to concentrate sun's rays to make fire and to burn ants.

3rd Century B.C. - Greeks and Romans use burning mirrors to light torches for religious purposes.

20 A.D. - Chinese document use of burning mirrors to light torches for religious purposes.

1767 - Swiss scientist Horace de Saussure was credited with building the world's first solar collector, later used by Sir John Herschel to cook food during his South Africa expedition in the 1830's.

1816 - On September 27, 1816, Robert Stirling applied for a patent for his economizer at the Chancery in Edinburgh, Scotland. In his spare time, he built heat engines in his home workshop. Lord Kelvin used one of the working models during some of his university classes. This engine was later used in the dish/Stirling system, a solar thermal electric technology that concentrates the sun's thermal energy in order to produce power.

1839 - French scientist Edmond Becquerel discovers the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution—electricity-generation increased when exposed to light.

1873 - Willoughby Smith discovered the photoconductivity of selenium.

1876 - William Grylls Adams and Richard Evans Day discover that selenium produces electricity when exposed to light.

1883 - Charles Fritts, an American inventor, described the first solar cells made from selenium wafers.

1887 - Heinrich Hertz discovered that ultraviolet light altered the lowest voltage capable of causing a spark to jump between two metal electrodes.

1891 - Baltimore inventor Clarence Kemp patented the first commercial solar water heater.

1904 - Wilhelm Hallwachs discovered that a combination of copper and cuprous oxide is photosensitive.

1905 - Albert Einstein published his paper on the photoelectric effect (along with a paper on his theory of relativity).

1908 - William J. Bailley, of the Carnegie Steel Company, invents a solar collector with copper coils and an insulated box—**roughly, it's present design**.

1918 - Polish scientist Jan Czochralski developed a way to grow single-crystal silicon.

1932 - Audobert and Stora discovers the photovoltaic effect in cadmium sulfide (CdS).

1947 - Passive solar buildings in the United States were in such demand, as a result of scarce energy during the prolonged W.W.II, that Libbey-Owens-Ford Glass Company published a book entitled Your Solar House.

1954 - Photovoltaic technology is born in the United States when Daryl Chapin, Calvin Fuller, and Gerald Pearson develop the silicon photovoltaic (PV) cell at Bell Labs—the first solar cell capable of converting enough of the sun's energy into power to run everyday electrical equipment. Bell Telephone Laboratories produced a silicon solar cell with 4% efficiency and later achieved 11% efficiency.

Note: Today, nearly 70 years later, commercial solar panels have only succeeded in doubling efficiency as today's solar panels, on average, range from 15% to 20%. Canadian Solar currently tops the industry with 22.8% efficient panels.

1956 - William Cherry, U.S. Signal Corps Laboratories, approaches RCA Labs' Paul Rappaport and Joseph Loferski about developing photovoltaic cells for proposed orbiting Earth satellites.

1957 - Hoffman Electronics achieved 8% efficient photovoltaic cells.

1958 - Hoffman Electronics achieves 9% efficient photovoltaic cells.

1959 - Hoffman Electronics achieves 10% efficient, commercially available photovoltaic cells.

1960 - Hoffman Electronics achieves 14% efficient photovoltaic cells.

1963 - Japan installs a 242-watt, photovoltaic array on a lighthouse, the world's largest array at that time.

1972 - The Institute of Energy Conversion is established at the University of Delaware to perform research and development on thin-film photovoltaic (PV) and solar thermal systems, becoming the world's first laboratory dedicated to PV research and development.

1973 - The University of Delaware builds "Solar One," one of the world's first photovoltaic (PV) powered residences. The system is a PV/thermal hybrid. The roof-integrated arrays fed surplus power through a special meter to the utility during the day and purchased power from the utility at night.

1977 - The U.S. Department of Energy launches the Solar Energy Research Institute "National Renewable Energy Laboratory", a federal facility dedicated to harnessing power from the sun.

1978 - NASA's Lewis Research Center dedicates a 3.5-kilowatt photovoltaic (PV) system it installed on the Papago Indian Reservation located in southern Arizona—the world's first village PV system. The system is used to provide for water pumping and residential electricity in 15 homes until 1983, when grid power reached the village. The PV system was then dedicated to pumping water from a community well.

1980 - At the University of Delaware, the first thin-film solar cell exceeds 10% efficiency using copper sulfide/cadmium sulfide.

1982 - Australian Hans Tholstrup drives the first solar-powered car—the Quiet Achiever—almost 2,800 miles between Sydney and Perth in 20 days.

1982 - The U.S. Department of Energy, along with an industry consortium, begins operating Solar One, a 10-megawatt central-receiver demonstration project. The project established the feasibility of power-tower systems, a solar-thermal electric or concentrating solar power technology. In 1988, the final year of operation, the system could be dispatched 96% of the time.

1985 - The University of South Wales breaks the 20% efficiency barrier for silicon solar cells under 1-sun conditions.

1986 - The world's largest solar thermal facility, located in Kramer Junction, California, was commissioned. The solar field contained rows of mirrors that concentrated the sun's energy onto a system of pipes circulating a heat transfer fluid.

The heat transfer fluid was used to produce steam, which powered a conventional turbine to generate electricity.

1986 - ARCO Solar releases the G-4000—the world's first commercial thin-film power module.

1992 - University of South Florida develops a 15.9% efficient thin-film photovoltaic cell made of cadmium telluride, breaking the 15% barrier for the first time for this technology.

1993 - Pacific Gas & Electric completes installation of the first grid-supported photovoltaic system in Kerman, California. The 500-kilowatt system was the first "distributed power" effort.

1994 - The National Renewable Energy Laboratory develops a solar cell—made from gallium indium phosphide and gallium arsenide—that becomes the first one to exceed 30% conversion efficiency.

1999 - Spectrolab, Inc. and the National Renewable Energy Laboratory develop a photovoltaic solar cell that converts 32.3 percent of the sunlight that hits it into electricity. The high conversion efficiency was achieved by combining three layers of photovoltaic materials into a single solar cell. The cell performed most efficiently when it received sunlight concentrated to 50 times normal. To use such cells in practical applications, the cell is mounted in a device that uses lenses or mirrors to concentrate sunlight onto the cell. Such "concentrator" systems are mounted on tracking systems that keep them pointed toward the sun.

1999 - The National Renewable Energy Laboratory achieves a new efficiency record for thin-film photovoltaic solar cells. The measurement of 18.8 percent efficiency for the prototype solar cell topped the previous record by more than 1 percent.

2000 - Sandia National Laboratories develops a new inverter for solar electric systems that will increase the safety of the systems during a power outage. Inverters convert the direct current (DC) electrical output from solar systems into alternating current (AC), which is the standard current for household wiring and for the power lines that supply electricity to homes.

2000 - Two new thin-film solar modules, developed by BP Solarex, break previous performance records. The company's 0.5-square-meter module achieves 10.8 % conversion efficiency—the highest in the world for thin-film modules of its kind. And its 0.9-square-meter module achieved 10.6% conversion efficiency and a power output of 91.5 watts — the highest power output for any thin-film module in the world.

2002 - ATS Automation Tooling Systems Inc. in Canada starts to commercialize an innovative method of producing solar cells, called Spheral Solar technology. The technology—based on tiny silicon beads bonded between two sheets of aluminum foil—promises lower costs due to its greatly reduced use of silicon relative to conventional multicrystalline silicon solar cells. The technology is not new. It was championed by Texas Instruments (TI) in the early 1990s. But despite U.S. Department of Energy (DOE) funding, TI dropped the initiative.

2002-2024 - Not included in the DOE document information was drawn from. My apologies.

HOW DOES SOLAR WORK?[1]

The amount of sunlight that strikes the earth's surface in an hour and a half is enough to handle the entire world's energy consumption for a full year. Solar technologies convert sunlight into electrical energy either through photovoltaic (PV) panels or through mirrors that concentrate solar radiation. This energy can be used to generate electricity or be stored in batteries or thermal storage.

Below, you can find resources and information on the basics of solar radiation, **photovoltaic** and **concentrating solar-thermal power technologies**, **electrical grid systems integration**, and the non-hardware aspects (soft costs) of solar energy.

Solar Energy 101 - Solar radiation is light – also known as electromagnetic radiation – that is emitted by the sun. While every location on Earth receives some sunlight over a year, the amount of solar radiation that reaches any one spot on the Earth's surface varies. Solar technologies capture this radiation and turn it into useful forms of energy. There are two main types of solar energy technologies—**photovoltaics (PV)** and **concentrating solar-thermal power (CSP)**. This document will concentrate on PV technology as it is the prominent type implemented in Ohio.

- **Photovoltaics Basics** - You're likely most familiar with PV, which is utilized in solar panels. When the sun shines onto a solar panel, energy from the sunlight is absorbed by the PV cells in the panel. This energy creates electrical charges that move in response to an internal electrical field in the cell, causing electricity to flow.
- **Concentrating Solar-Thermal Power Basics -** Concentrating solar-thermal power (CSP) systems use mirrors to reflect and concentrate sunlight onto

receivers that collect solar energy and convert it to heat, which can then be used to produce electricity or stored for later use. It is used primarily in very large power plants.

Solar Photovoltaic Technology Basics[2]

What is photovoltaic (PV) technology and how does it work? PV materials and devices convert sunlight into electrical energy.

- A single PV device is known as a cell. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. These cells are made of different semiconductor materials and are often less than the thickness of four human hairs. In order to withstand the outdoors for many years, cells are sandwiched between protective materials in a combination of glass and/or plastics.

To boost the power output of PV cells, they are connected together in chains to form larger units known as modules or panels.

- Modules can be used individually, or several can be connected to form arrays. One or more arrays is then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large.

PV modules and arrays are just one part of a PV system. Systems also include mounting structures that point panels toward the sun, along with the components that take the direct-current (DC) electricity produced by modules and convert it to the alternating-current (AC) electricity used to power all of the appliances in your home.

Solar Photovoltaic CELL Basics[3]

When light shines on a photovoltaic (PV) cell – also called a solar cell – that light may be reflected, absorbed, or pass right through the cell. The PV cell is composed of semiconductor material; the “semi” means that it can conduct electricity better than an insulator but not as well as a good conductor like a metal. There are several different semiconductor materials used in PV cells.

When the semiconductor is exposed to light, it absorbs the light’s energy and transfers it to negatively charged particles in the material called electrons. This extra energy allows the electrons to flow through the material as an electrical current. This current is extracted through conductive metal contacts – the grid-like lines on a solar cells – and can then be used to power your home and the rest of the electric grid.

The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell.

An important property of PV semiconductors is the bandgap, which indicates what wavelengths of light the material can absorb and convert to electrical energy. If the semiconductor's bandgap matches the wavelengths of light shining on the PV cell, then that cell can efficiently make use of all the available energy.

Below are the most commonly-used semiconductor materials for PV cells.

- **Silicon -** Silicon is, by far, the most common semiconductor material used in solar cells, representing approximately 95% of the modules sold today. It is also the second most abundant material on Earth (after oxygen) and the most common semiconductor used in computer chips. Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice provides an organized structure that makes conversion of light into electricity more efficient.

  Solar cells made out of silicon currently provide a combination of high efficiency, low cost, and long lifetime. Modules are expected to last for 25 years or more, still producing more than 80% of their original power after this time.
- **Thin-Film Photovoltaics -** A thin-film solar cell is made by depositing one or more thin layers of PV material on a supporting material such as glass, plastic, or metal. There are two main types of thin-film PV semiconductors on the market today: **cadmium telluride (CdTe)** and **copper indium gallium diselenide (CIGS)**. Both materials can be deposited directly onto either the front or back of the module surface.
  - Cadmium is recognized as a toxic substance by the United States Environmental Protection Agency (EPA), which set a maximum contaminant level (MCL) for cadmium (Cd) of 0.005 mgL-1 in drinking water. Tellurium (Te), while not regulated by the EPA, has also been shown to have the potential to cause kidney, heart, skin, lung, and gastrointestinal system damage in rats and in humans.[4]
    - Main Findings - Leaching of Cd and Te[4]: The potential release of the toxic compounds from a CdTe thin-film solar panel under conditions simulating those prevailing in young- and a mature municipal mixed solid waste landfills was assessed in this work. The most important effect was observed in the acidic column in

which a remarkable release of Cd was observed (ca. 73% of the Cd supplied as CdTe). **The maximum concentration of Cd in the leachate was 3.24 mg L-1, which is 3-fold higher that the TCLP limit for Cd, and 650-fold higher than the U.S. federal MCL in drinking water (0.005 mg L-1)**. Comparison of Cd levels in the leachate with MCL values provides information on the required attenuation to ensure that MLC levels are not exceeded in drinking water resources impacted by landfill leachate. The maximum concentration of dissolved Te measured in this leachate was 1.1 mg L-1. In contrast, the release of dissolved Cd and Te species was negligible in the methanogenic column. **To the best of our knowledge, this study represents the first attempt to comparatively assess the leaching behavior of a CdTe solar panel by considering both simulated acidic and methanogenic landfill conditions in a continuous flow fashion.**

- Implications[4]: The evidence found in this work indicates that the standardized TCLP and WET leaching tests might underestimate the leaching of Cd and Te from disposing decommissioned CdTe solar panels in landfills. Although some previous works have stated that CdTe is an insoluble form of Cd and that CdTe is expected to have low bioavailability in the environment, the results obtained in the present study as well as another related investigation indicate that a high fraction of the Cd and Te in CdTe panels could be potentially released if non-encapsulated CdTe solar panels are discarded in municipal landfills. Leaching of Cd and Te is expected to occur mainly during the acidic phase of a landfill in which low pH values are dominant.

  The risk that leachate impact groundwater is minimized in modern MSW landfills that are designed with daily cover of the waste, storm water management, use of liners at the bottom of the landfill, and a leachate collection system. Releases into groundwater are, thus, particularly a problem in landfills that were not originally designed to prevent migration of the leachate (unlined landfills). Elevated concentrations of metals and metalloids have been measured in samples of groundwater collected in locations close to landfills receiving electronic waste.

  The significant leaching of toxic Cd demonstrated in the present study under simulated, acidic landfill conditions indicates the

    need for further investigation of the leaching potential of decommissioned CdTe PV panels, and suggests the need for measures to minimize their disposal in MSW landfills.
    - Conclusions[4]: Given the high toxicity of Cd, these results suggest the need for measures to minimize the disposal of decommissioned CdTe PV panels in MSW landfills.
- Copper indium gallium diselenide (CIGS) is a new efficient thin film used in some types of solar cell. Indium is a constitutive element of CIGS thin-film solar cells. It was thought that indium compounds were not harmful until the beginning of the 1990s because there was little information regarding the adverse health effects on humans or animals arising from exposure to indium compounds. After the mid-1990s, data became available indicating that indium compounds can be toxic to animals. In animal studies, it has been clearly demonstrated that indium compounds cause pulmonary toxicity and that the dissolution of indium compounds in the lungs is considerably slow, as shown by repeated intratracheal instillations in experimental animals. Thus, it is necessary to pay much greater attention to human exposure to indium compounds, and precautions against possible exposure to indium compounds are paramount with regard to health management.[5]
- Abstract[6]: Thin-film technologies have been part of the rapidly-expanding solar photovoltaics (PV) market for many years, led by cadmium-telluride (CdTe) and copper-indium-gallium-selenide (CIGS). However, their environmental impacts remain largely unknown, particularly considering state-of-the-art CIGS manufacturing techniques.

  However, their environmental impacts remain largely unknown, particularly considering state-of-the-art CIGS manufacturing techniques. This study estimates the life cycle environmental impacts of CIGS PV installations in the UK and Spain, including balance-of-system components, using real manufacturing data.

CdTe is the second-most common PV material after silicon, and CdTe cells can be made using low-cost manufacturing processes. While this makes them a cost-effective alternative, their efficiencies still aren't quite as high as silicon. CIGS cells have optimal properties for a PV material and high efficiencies in the lab, but the complexity involved in combining four elements makes the transition from lab to manufacturing more challenging. Both CdTe and CIGS require more protection than silicon to enable long-lasting operation outdoors.

- **Perovskite Photovoltaics -** Perovskite solar cells are a type of thin-film cell and are named after their characteristic crystal structure. Perovskite cells are built with layers of materials that are printed, coated, or vacuum-deposited onto an underlying support layer, known as the substrate. They are typically easy to assemble and can reach efficiencies similar to crystalline silicon. In the lab, perovskite solar cell efficiencies have improved faster than any other PV material, from 3% in 2009 to over 25% in 2020. To be commercially viable, perovskite PV cells have to become stable enough to survive 20 years outdoors, so researchers are working on making them more durable and developing large-scale, low-cost manufacturing techniques.
- **Organic Photovoltaics -** Organic PV, or OPV, cells are composed of carbon-rich (organic) compounds and can be tailored to enhance a specific function of the PV cell, such as bandgap, transparency, or color. OPV cells are currently only about half as efficient as crystalline silicon cells and have shorter operating lifetimes, but could be less expensive to manufacture in high volumes. They can also be applied to a variety of supporting materials, such as flexible plastic, making OPV able to serve a wide variety of uses.
- **Quantum Dots -** Quantum dot solar cells conduct electricity through tiny particles of different semiconductor materials just a few nanometers wide, called quantum dots. Quantum dots provide a new way to process semiconductor materials, but it is difficult to create an electrical connection between them, so they're currently not very efficient. However, they are easy to make into solar cells. They can be deposited onto a substrate using a spin-coat method, a spray, or roll-to-roll printers like the ones used to print newspapers.

  Quantum dots come in various sizes and their bandgap is customizable, enabling them to collect light that's difficult to capture and to be paired with other semiconductors, like perovskites, to optimize the performance of a multijunction solar cell.
- **Multijunction Photovoltaics -** Another strategy to improve PV cell efficiency is layering multiple semiconductors to make multijunction solar cells. These cells are essentially stacks of different semiconductor materials, as opposed to single-junction cells, which have only one semiconductor. Each layer has a different bandgap, so they each absorb a different part of the solar spectrum, making greater use of sunlight than single-junction cells. Multijunction solar cells can reach record efficiency levels because the light that doesn't get absorbed by the first semiconductor layer is captured by a layer beneath it.

  While all solar cells with more than one bandgap are multijunction solar cells, a solar cell with exactly two bandgaps is called a tandem solar cell. Multijunction solar cells that combine semiconductors from columns III and V in the periodic table are called multijunction III-V solar cells.

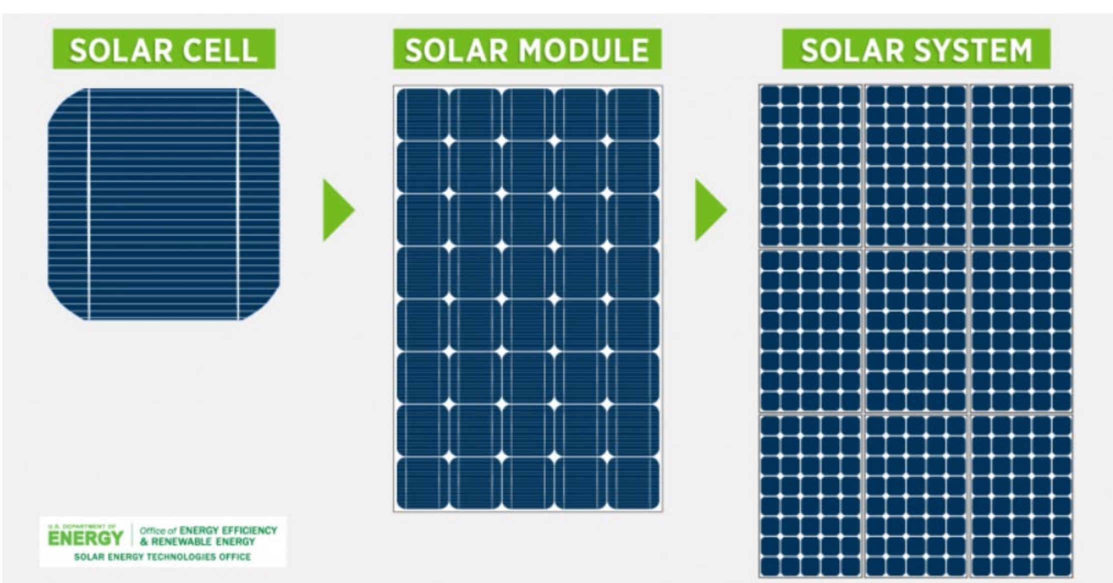
Multijunction solar cells have demonstrated efficiencies higher than 45%, but they're costly and difficult to manufacture, so they're reserved for space exploration. The military is using III-V solar cells in drones, and researchers are exploring other uses for them where high efficiency is key.

- **Concentration Photovoltaics -** Concentration PV, also known as CPV, focuses sunlight onto a solar cell by using a mirror or lens. By focusing sunlight onto a small area, less PV material is required. PV materials become more efficient as the light becomes more concentrated, so the highest overall efficiencies are obtained with CPV cells and modules. However, more expensive materials, manufacturing techniques, and ability to track the movement of the sun are required, so demonstrating the necessary cost advantage over today's high-volume silicon modules has become challenging.

PV Cells 101: A Primer on the Solar Photovoltaic Cell[7]

You've seen them on rooftops, in fields, along roadsides, and you'll be seeing more of them: Solar photovoltaic (PV) installations are on the rise across the country—but how do they turn sunshine into energy? Simple answer: with semiconductors. Of course, there's more to it.

But before we explain how solar cells work, know that solar cells that are strung together make a module, and when modules are connected, they make a solar system, or installation. A typical residential rooftop solar system has about 30 modules.



How a Solar Cell Works - Solar cells contain a material that conducts electricity only when energy is provided—by sunlight, in this case. This material is called a semiconductor; the "semi" means its electrical conductivity is less than that of a metal but more than an insulator's. When the semiconductor is exposed to sunlight, it absorbs the light, transferring the energy to negatively charged particles called electrons. The electrons flow through the semiconductor as electrical current, because other layers of the PV cell are designed to extract the current from the semiconductor. Then the current flows through metal contacts—the grid-like lines on a solar cell—before it travels to an inverter. The inverter converts the direct current (DC) to an alternating current (AC), which flows into the electric grid and, eventually, connects to the circuit that is your home's electrical system. As long as sunlight continues to reach the module and the circuit is connected, electricity will continue to be generated.

A module's ability to convert sunlight into electricity depends on the semiconductor. In the lab, this ability is called photovoltaic conversion efficiency. Outside, environmental conditions like heat, dirt, and shade can reduce conversion efficiency, along with other factors. But researchers are coming up with solutions, such as backsheets that are placed on the panels to reduce their operating temperature, and new cell designs that capture more light.

Capturing more light during the day increases energy yield, or the electricity output of a PV system over time. To boost energy yield, researchers and manufacturers are looking at bifacial solar cells, which are double-sided to capture light on both sides of a silicon solar module—they capture light reflected off the ground or roof where the panels are installed. The jury is still out on how bifacials will affect a system's energy yield, but some SETO-funded projects are working to reduce this uncertainty by establishing baseline metrics to quantify and model bifacial efficiency gains.

Silcon: The Market Leader - The main semiconductor used in solar cells, not to mention most electronics, is silicon, an abundant element. In fact, it's found in sand, so it's inexpensive, but it needs to be refined in a chemical process before it can be turned into crystalline silicon and conduct electricity.

The maximum theoretical efficiency level for a silicon solar cell is about 32% because of the portion of sunlight the silicon semiconductor is able to absorb above the bandgap. **The best panels for commercial use have efficiencies around 18% to 22%,** but researchers are studying how to improve efficiency and energy yield while keeping production costs low.

PV Cells 101: Solar Photovoltaic cell research directions8

Silicon cells have a maximum theoretical efficiency of about 32%, so researchers are exploring new materials and cell designs that can improve conversion and performance. Here are the most promising ones:

- **Layering Up with Multijunction Solar Cells -** Some researchers are working to improve cell efficiency by layering multiple different semiconductors to make multijunction solar cells. These cells are essentially semiconductor stacks, as opposed to single-junction cells, which have only one semiconductor. Each layer absorbs a different part of the solar spectrum, making greater use of sunlight than single-junction cells do.

  Multijunction solar cells have demonstrated efficiencies higher than 45%, but they're costly and difficult to manufacture, so they're reserved for space exploration. The military is using III-V solar cells in drones, and researchers are exploring other uses for them where power conversion efficiency is key.

- **The Skinny on Thin-Film Solar Cells -** Silicon may be the most common type of solar cell, but thin-film solar cells generally cost less and can be easier to fabricate. T**hin films make up 3% to 5% of the global market but are usually less efficient than silicon.**

  Thin-film solar cells are made by coating a thin layer of a highly absorptive semiconductor material on a sheet of glass, plastic, or metal foil called a substrate rather than creating a crystal wafer. This material can be deposited on flexible surfaces, which keeps costs down and the solar cells versatile. Thin films are typically dark or partially transparent, so the modules look more uniform than the speckled, blue or black crystalline-silicon modules. **The record high thin-film cell efficiency is 22.1%, while monocrystalline-silicon cells have reached 25%, and polycrystalline, over 20%.**

  - Three types of thin-film solar cells are on the market:
    - cadmium telluride (CdTe)
    - copper indium gallium diselenide (CIGS)
    - amorphous thin-film silicon (a-Si)

      CdTe and CIGS have reached gigawatt-scale production. CdTe is more commercially successful and has reached efficiency levels comparable to crystalline-silicon modules in the lab.

- **Perovskite -** Perovskite solar cells are a type of thin-film cell and are named after the eponymous ABX3 crystal structure, with the most studied PV material being methylammonium (MA+) lead (Pb+2) iodide (I-), or MAPbI3. Perovskite cells are built with layers of materials that are printed, coated, or vacuum-deposited onto a substrate. **They are typically easy to fabricate and can reach solar conversion efficiencies higher than 20%.** In the lab, perovskite solar cell efficiencies have improved faster than any other PV absorber material, from 3% in 2009 to over 24% in 2019. **But to be commercially viable, perovskite PV cells have to become more stable and durable enough to survive 20 years outdoors**, so researchers are working on that—and developing large-scale, low-cost manufacturing techniques.

Solar performance and efficiency[9]

The conversion efficiency of a photovoltaic (PV) cell, or solar cell, is the percentage of the solar energy shining on a PV device that is converted into usable electricity. Improving this conversion efficiency is a key goal of research and helps make PV technologies cost-competitive with conventional sources of energy.

Factors Affecting Conversion Efficiency - Not all of the sunlight that reaches a PV cell is converted into electricity. In fact, most of it is lost. Multiple factors in solar cell design play roles in limiting a cell's ability to convert the sunlight it receives. Designing with these factors in mind is how higher efficiencies can be achieved.

- Wavelength—Light is composed of photons—or packets of energy—that have a wide range of wavelengths and energies. The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.
- Recombination—One way for electric current to flow in a semiconductor is for a "charge carrier," such as a negatively-charged electron, to flow across the material. Another such charge carrier is known as a "hole," which represents the absence of an electron within the material and acts like a positive charge carrier. When an electron encounters a hole, they may recombine and therefore cancel out their contributions to the electrical current. Direct recombination, in which light-generated electrons and holes encounter each other, recombine, and emit a photon, reverses the process from which electricity is generated in a solar cell. It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an

impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.

- Temperature—Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes. Since much of the sunlight shining on cells becomes heat, proper thermal management improves both efficiency and lifetime.
- Reflection—A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti-reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

Determining Conversion Efficiency - Researchers measure the performance of a PV device to predict the power the cell will produce. Electrical power is the product of current and voltage. Current-voltage relationships measure the electrical characteristics of PV devices. If a certain "load" resistance is connected to the two terminals of a cell or module, the current and voltage being produced will adjust according to Ohm's law (the current through a conductor between two points is directly proportional to the potential difference across the two points). Efficiencies are obtained by exposing the cell to a constant, standard level of light while maintaining a constant cell temperature, and measuring the current and voltage that are produced for different load resistances.

- **Maximum Theoretical Efficiency (Shockley–Queisser) -** Shockley–Queisser limit[21] or detailed balance limit refers to the calculation of the maximum theoretical efficiency of a solar cell made from a single pn junction. It was first calculated by William Shockley and Hans Queisser.

  The calculation places maximum solar conversion efficiency around 33.7% assuming a single pn junction with a band gap of 1.4 eV (using an AM 1.5 solar spectrum). Therefore, an ideal solar cell with incident solar radiation will generate 337 Wm-2. When the solar radiation is modelled as 6000 K blackbody radiation the maximum efficiency occurs when the bandgap energy Eg=1.4 eV. [22]

Trade/Industry magazine, PV-Magazine, pushed an article in April 2024 in which states that “Researchers at Lehigh University (US) has developed a new thin-film solar cell absorber material **that reportedly** features an average photovoltaic absoption of 80% and and external quantum efficiency (EQE) of 190%.” The article goes on to state, “Looking forward, the research group said new research is required to identify a practical way to embed the novel material in real solar cells. However, they also noted that the experimental techniques used to create these materials are already “highly advanced.”

As the current efficiency of solar panels is somewhere between 23%-25%, or only an 11%+/- in the past 70 years, I believe it may be equally as long to get solar panel efficiencies to a point where they are economically viable without significant financial government incentives.

Solar Photovoltaic System Design Basics[10]

Solar photovoltaic modules are where the electricity gets generated, but are only one of the many parts in a complete photovoltaic (PV) system. In order for the generated electricity to be useful in a home or business, a number of other technologies must be in place.

- **Mounting Structures -** PV arrays must be mounted on a stable, durable structure that can support the array and withstand wind, rain, hail, and corrosion over decades. These structures tilt the PV array at a fixed angle determined by the local latitude, orientation of the structure, and electrical load requirements. To obtain the highest annual energy output, modules in the northern hemisphere are pointed due south and inclined at an angle equal to the local latitude. Rack mounting is currently the most common method because it is robust, versatile, and easy to construct and install. More sophisticated and less expensive methods continue to be developed.

  For PV arrays mounted on the ground, tracking mechanisms automatically move panels to follow the sun across the sky, which provides more energy and higher returns on investment. One-axis trackers are typically designed to track the sun from east to west. Two-axis trackers allow for modules to remain pointed directly at the sun throughout the day. Naturally, tracking involves more up-front costs and sophisticated systems are more expensive and require more maintenance. As systems have improved, the cost-benefit analysis increasingly favors tracking for ground-mounted systems.

- **Building-Integrated PV -** While most solar modules are placed in dedicated mounting structures, they can also be integrated directly into building materials like roofing, windows, or façades. These systems are known as building-integrated PV (BIPV). Integrating solar into buildings could improve material and supply chain efficiencies by combining redundant parts, and reduce system cost by using existing building systems and support structures. BIPV systems could provide power for direct current (DC) applications in buildings, like LED lighting, computers, sensors, and motors, and support grid-integrated efficient building applications, like electric vehicle charging. BIPV systems still face technical and commercial barriers to widespread use, but their unique value makes them a promising alternative to traditional mounting structures and building materials.

- **Inverters -** Inverters are used to convert the direct current (DC) electricity generated by solar photovoltaic modules into alternating current (AC) electricity, which is used for local transmission of electricity, as well as most appliances in our homes. PV systems either have one inverter that converts the electricity generated by all of the modules, or microinverters that are attached to each individual module. A single inverter is generally less expensive and can be more easily cooled and serviced when needed. The microinverter allows for independent operation of each panel, which is useful if some modules might be shaded, for example. It is expected that inverters will need to be replaced at least once in the 25-year lifetime of a PV array.

  Advanced inverters, or "smart inverters," allow for two-way communication between the inverter and the electrical utility. This can help balance supply and demand either automatically or via remote communication with utility operators. Allowing utilities to have this insight into (and possible control of) supply and demand allows them to reduce costs, ensure grid stability, and reduce the likelihood of power outages.

- **Storage -** Batteries (or Battery Energy Storage Systems – BESS) allow for the storage of solar photovoltaic energy, so we can use it to power our homes at night or when weather elements keep sunlight from reaching PV panels. Not only can they be used in homes, but batteries are playing an increasingly important role for utilities. As customers feed solar energy back into the grid, batteries can store it so it can be returned to customers at a later time. The increased use of batteries will help modernize and stabilize our country's electric grid.

Getting the Most out of Solar Panels[11]

Here’s something to consider: figuring out the real cost of solar energy is about more than just the price tag on the panels and their rated power output. For example, there’s the lifespan of the panels to take into account. And then there’s the system’s “solar energy yield” -- or how much electricity it will actually generate over the course of the year.

Solar panels are rated on efficiency and the power output under standard laboratory conditions. Of course, your solar energy system isn't being installed in a lab. It's going outside, where all kinds of things can change its actual solar energy yield.

Man, it's a hot one, High temperatures reduce the voltage of a solar cell - which, as you might guess, is a bad thing. Conventional rooftop solar modules can lose as much as 30 percent of their electricity output on hot summer days. Researchers at Arizona State University are trying to address this problem by improving the backsheet -- or bottom layer -- of a solar PV module, which serves as an electrical insulator and protects the module from moisture and other environmental damage. By studying backsheets with different heat-conducting properties, the team hopes to keep solar panels cooler and improve performance in hot weather.

- **Less impact from high temperatures**[18] - All solar panels suffer a small loss in wattage as they heat up. This effect is temporary — panels recover the lost productivity once they cool down. However, when you constantly expose solar panels to hot weather, the loss of production can add up over time. As a result, hot temperatures can result in a 10% to 25% decrease in solar panel efficiency.
- **Solar panels have a metric called the temperature coefficient**, which describes the negative effect of heat. For example, **a panel with a coefficient of -0.40% per Celsius degree will lose 8% productivity with a temperature rise of 20°C**. On average, monocrystalline panels have lower temperature coefficients than polycrystalline panels, which means they are less affected by heat. This is a major advantage in warm regions where hot temperatures can impact solar panel performance over time.

Dirt does hurt - Another way panels lose power is simply that they get dirty. The effects of "soiling" (as it's known in the solar industry) vary widely by location, but energy yield losses of 10 percent are not uncommon. Research on environmental conditions and panel maintenance procedures could help us better understand how and why panels lose power to dirt, which in turn could lead to better prediction of soiling from one solar energy system to another and more effective dirt-resistant treatments for PV module glass.

- *Note: Typically, renewable energy developers apply anti-soiling, and/or anti-glare, coatings to panels to help minimize the effects of dirt, pollen, dust, snow, etc.*

Shady Situations - While heat and dirt reduce solar panels' energy yield in a pretty straightforward way, shadows are a bit more complicated. In instances when a faint cloud goes over the solar module, the power levels are simply reduced. However, sometimes the light is completely or regularly blocked by a permanent structure -- like a utility pole that shades just one part of the module -- which can actually cause "hot spots" that can damage the module over time.

What is Solar Panel Efficiency?[18] - Solar panels consist of modules or photovoltaic (PV) cells. You can measure the efficiency of a PV cell based on the percentage of light energy it converts into electricity. Alternatively, solar cell efficiency is the ability of a panel to capture energy from photons or light particles. When light hits a solar panel, it releases electrons that start moving and create an electrical current.

For example, a solar panel with a 20% efficiency can convert 20% of sunlight into usable energy. **Most commercially available solar panels have an efficiency of less than 23%, with an average range of 15% to 20%. Canadian Solar currently top the industry with 22.8% efficient panels.**

Common Misconceptions About Solar Panel Efficiency?[18] - There is a common misconception that solar panel efficiency equates to product quality. Efficiency is simply a product feature, like power rating and module dimensions, and you can find high-quality panels of all efficiency levels.

The main factor that determines efficiency is a solar panel's material:

- Monocrystalline silicon panels have a typical efficiency of over 20%.
- Polycrystalline silicon panels have a typical efficiency below 20%.
- Thin-film panels are generally the least efficient, but new materials such as perovskite can match the efficiency of silicon cells.

As you can see, monocrystalline solar panels are the most efficient type of solar panel compared to other options. The main advantage of high-efficiency panels is generating more electricity using less surface area — but they are also more expensive. If you have plenty of space for your PV system, using a higher number of less efficient panels is also a viable option.

Qualify for Higher Solar Incentives[18] - Many solar benefit programs calculate financial incentives by the per-watt capacity of your solar system. Since high-efficiency panels have a higher wattage, they can qualify for higher incentive amounts. However, this does not apply to incentive programs with fixed rebates.

The federal solar tax credit is a nationwide incentive that allows you to claim 30% of your solar system costs as a tax credit for the year you install panels. Since monocrystalline panels cost more, your total system cost will likely be higher than if you used polycrystalline panels. As a result, you will see a higher tax incentive per panel.

ANTI-SOILING COATINGS

Anti-soiling coatings are applied to solar panels and mirrors to reduce the amount of dust and dirt that sticks to them. The coatings can be applied during production or after the panels are installed.

Anti-soiling coatings can

- Improve self-cleaning: Some coatings can help the surface clean itself through rain.
- Reduce cleaning needs: Anti-soiling coatings can reduce the number of times a solar installation needs to be cleaned, which can save on labor and consumables.
- Increase power output: Anti-soiling coatings can help solar panels maintain their optimal performance for longer, which can increase power output.

There are different types of anti-soiling coatings, including

- Hydrophilic coatings - These coatings have a high surface energy, which helps form thin films of water when it rains or when the panels are washed. This makes it easier to remove dirt.
- Hydrophobic coatings - These coatings have a low surface energy, which causes water to form into small droplets that roll off the surface, taking dirt with them.
    - Although hydrophobic coatings hold out great promise, outdoor has testing revealed degradation that occurs surprisingly quickly.[16]
- Titania-based coatings - These coatings often use a photocatalytic effect to break down organic matter when exposed to UV radiation

Solar Systems Integration Basics12

What is solar systems integration and how does it work? Solar systems integration involves developing technologies and tools that allow solar energy onto the electricity grid, while maintaining grid reliability, security, and efficiency.

- **The Electrical Grid -** For most of the past 100 years, electrical grids involved large-scale, centralized energy generation located far from consumers. Modern electrical grids are much more complex. In addition to large utility-scale plants, modern grids also involve variable energy sources like solar and wind, energy storage systems, power electronic devices like inverters, and small-scale energy generation systems like rooftop installations and microgrids. These smaller-scale and dispersed energy sources are generally known as distributed energy resources (DER).

The electrical grid is separated into transmission and distribution systems. The transmission grid is the network of high-voltage power lines that carry electricity from centralized generation sources like large power plants. These high voltages allow power to be transported long distances without excessive loss. The distribution grid refers to low-voltage lines that eventually reach homes and businesses. Substations and transformers convert power between high and low voltage. Traditionally, electricity only needed to flow one way through these systems: from the central generation source to the consumer. However, systems like rooftop solar now require the grid to handle two-way electricity flow, as these systems can inject the excess power that they generate back into the grid.

- **Power Electronics -** Increased solar and DER on the electrical grid means integrating more power electronic devices, which convert energy from one form to another. This could include converting between high and low voltage, regulating the amount of power flow, or converting between direct current (DC) and alternating current (AC) electricity, depending on where the electricity is going and how it will be used. By 2030, as much as 80% of electricity could flow through power electronic devices. One type of power electronic device that is particularly important for solar energy integration is the inverter. Inverters convert DC electricity, which is what a solar panel generates, to AC electricity, which the electrical grid uses.
- **Solar Plus Storage -** Since solar energy can only be generated when the sun is shining, the ability to store solar energy for later use is important: It helps to keep the balance between electricity generation and demand. This means that developing batteries (BESS) or thermal storage is key to adding more solar.
- **Grid Resilience and Reliability -** The electrical grid must be able to reliably provide power, so it’s important for utilities and other power system operators to have real-time information about how much electricity solar systems are producing. Increasing amounts of solar and DER on the grid lead to both opportunities and challenges for grid reliability. Complex modern grids with a mix of traditional generation and DER can make responding to abnormal situations like storms or blackouts more difficult. However, power electronics have the potential to collect real-time information on the grid and help to control grid operations. In fact, special “grid-forming” inverters could use solar energy to restart the grid in the event of a blackout.

Solar Integration: Solar Energy and Storage Basics[13]

Sometimes two is better than one. Coupling solar energy and storage technologies is one such case. **The reason: Solar energy is not always produced at the time energy is needed most. Peak power usage often occurs on summer afternoons and evenings, when solar energy generation is falling. Temperatures can be hottest during these times, and people who work daytime hours get home and begin using electricity to cool their homes, cook, and run appliances.**

Storage helps solar contribute to the electricity supply even when the sun isn't shining. It can also help smooth out variations in how solar energy flows on the grid. These variations are attributable to changes in the amount of sunlight that shines onto photovoltaic (PV) panels or concentrating solar-thermal power (CSP) systems. Solar energy production can be affected by season, time of day, clouds, dust, haze, or obstructions like shadows, rain, snow, and dirt. Sometimes energy storage is co-located with, or placed next to, a solar energy system, and sometimes the storage system stands alone, but in either configuration, it can help more effectively integrate solar into the energy landscape.

- **What Is Energy Storage? -** "Storage" refers to technologies that can capture electricity, store it as another form of energy (chemical, thermal, mechanical), and then release it for use when it is needed. Lithium-ion batteries are one such technology. Although using energy storage is never 100% efficient—some energy is always lost in converting energy and retrieving it—storage allows the flexible use of energy at different times from when it was generated. So, storage can increase system efficiency and resilience, and it can improve power quality by matching supply and demand.

  Storage facilities differ in both energy capacity, which is the total amount of energy that can be stored (usually in kilowatt-hours or megawatt-hours), and power capacity, which is the amount of energy that can be released at a given time (usually in kilowatts or megawatts). Different energy and power capacities of storage can be used to manage different tasks. Short-term storage that lasts just a few minutes will ensure a solar plant operates smoothly during output fluctuations due to passing clouds, while longer-term storage can help provide supply over days or weeks when solar energy production is low or during a major weather event, for example.

- Advantages of Combining Storage and Solar
  - Balancing electricity loads – Without storage, electricity must be generated and consumed at the same time, which may mean that grid

operators take some generation offline, or "curtail" it, to avoid over-generation and grid reliability issues. Conversely, there may be other times, after sunset or on cloudy days, when there is little solar production but plenty of demand for power. Enter storage, which can be filled or charged when generation is high and power consumption is low, then dispensed when the load or demand is high. When some of the electricity produced by the sun is put into storage, that electricity can be used whenever grid operators need it, including after the sun has set. In this way, storage acts as an insurance policy for sunshine.

    - "Firming" solar generation – Short-term storage can ensure that quick changes in generation don't greatly affect the output of a solar power plant. For example, a small battery can be used to ride through a brief generation disruption from a passing cloud, helping the grid maintain a "firm" electrical supply that is reliable and consistent.
    - Providing resilience – Solar and storage can provide backup power during an electrical disruption. They can keep critical facilities operating to ensure continuous essential services, like communications. Solar and storage can also be used for microgrids and smaller-scale applications, like mobile or portable power units.
- Types of Energy Storage - The most common type of energy storage in the power grid is pumped hydropower. But the storage technologies most frequently coupled with solar power plants are electrochemical storage (batteries) with PV plants and thermal storage (fluids) with CSP plants. Other types of storage, such as compressed air storage and flywheels, may have different characteristics, such as very fast discharge or very large capacity, that make them attractive to grid operators. More information on other types of storage is below.
    - **Pumped-Storage Hydropower** - Pumped-storage hydropower is an energy storage technology based on water. Electrical energy is used to pump water uphill into a reservoir when energy demand is low. Later, the water can be allowed to flow back downhill and turn a turbine to generate electricity when demand is high. Pumped hydro is a well-tested and mature storage technology that has been used in the United States since 1929. However, it requires suitable landscapes and reservoirs, which may be natural lakes or man-made by constructing dams, requiring lengthy regulatory permits, long implementation times, and large initial capital. Other than energy arbitrage, pumped hydro's value of services to integrate variable renewables are not fully realized, which can make the financial payback period long. These are some of the reasons pumped hydro has not been built recently, even though interest

is evident from requests to the Federal Energy Regulatory Commission for preliminary permits and licenses.

- **Electrochemical Storage** - Many of us are familiar with electrochemical batteries, like those found in laptops and mobile phones. When electricity is fed into a battery, it causes a chemical reaction, and energy is stored. When a battery is discharged, that chemical reaction is reversed, which creates voltage between two electrical contacts, causing current to flow out of the battery. The most common chemistry for battery cells is lithium-ion, but other common options include lead-acid, sodium, and nickel-based batteries.
- **Thermal Energy Storage** - Thermal energy storage is a family of technologies in which a fluid, such as water or molten salt, or other material is used to store heat. This thermal storage material is then stored in an insulated tank until the energy is needed. The energy may be used directly for heating and cooling, or it can be used to generate electricity. In thermal energy storage systems intended for electricity, the heat is used to boil water. The resulting steam drives a turbine and produces electrical power using the same equipment that is used in conventional electricity generating stations. Thermal energy storage is useful in CSP plants, which focus sunlight onto a receiver to heat a working fluid. Supercritical carbon dioxide is being explored as a working fluid that could take advantage of higher temperatures and reduce the size of generating plants.
- **Flywheel Storage** - A flywheel is a heavy wheel attached to a rotating shaft. Expending energy can make the wheel turn faster. This energy can be extracted by attaching the wheel to an electrical generator, which uses electromagnetism to slow the wheel down and produce electricity. Although flywheels can quickly provide power, they can't store a lot of energy.
- **Compressed Air Storage** - Compressed air storage systems consist of large vessels, like tanks, or natural formations, like caves. A compressor system pumps the vessels full of pressurized air. Then the air can be released and used to drive a turbine that produces electricity. Existing compressed air energy storage systems often use the released air as part of a natural gas power cycle to produce electricity.
- **Solar Fuels** - Solar power can be used to create new fuels that can be combusted (burned) or consumed to provide energy, effectively storing the solar energy in the chemical bonds. Among the possible fuels researchers are examining are hydrogen, produced by separating it from the oxygen in water, and methane, produced by combining hydrogen and

carbon dioxide. Methane is the main component of natural gas, which is commonly used to produce electricity or heat homes.

  - **Virtual Storage** - Energy can also be stored by changing how we use the devices we already have. For example, by heating or cooling a building before an anticipated peak of electrical demand, the building can "store" that thermal energy so it doesn't need to consume electricity later in the day. The building itself is acting as a thermos by storing cool or warm air. A similar process can be applied to water heaters to spread demand out over the day.

Solar-Plus-Storage 101[14]

Solar panels have one job: They collect sunlight and transform it into electricity. But they can make that energy only when the sun is shining. That's why the ability to store solar energy for later use is important: It helps to keep the balance between electricity generation and demand. Lithium-ion batteries are one way to store this energy—the same batteries that power your phone.

- **Why lithium? -** There are many ways to store energy: pumped hydroelectric storage, which stores water and later uses it to generate power; batteries that contain zinc or nickel; and molten-salt thermal storage, which generates heat, to name a few. Some of these systems can store large amounts of energy.

  Lithium is a lightweight metal that an electric current can easily pass through. Lithium ions make a battery rechargeable because their chemical reactions are reversible, allowing them to absorb power and discharge it later. Lithium-ion batteries can store a lot of energy, and they hold a charge for longer than other kinds of batteries. The cost of lithium-ion batteries is dropping because more people are buying electric vehicles that depend on them.

  While lithium-ion battery systems may have smaller storage capacity in comparison to other storage systems, they are growing in popularity because they can be installed nearly anywhere, have a small footprint, and are inexpensive and readily available—increasing their application by utilities

What's a solar-plus-storage system? - Many solar-energy system owners are looking at ways to connect their system to a battery so they can use that energy at night or in the event of a power outage. Simply put, a solar-plus-storage system is a battery system that is charged by a connected solar system, such as a photovoltaic (PV) one.

Solar plus Storage System - In an effort to track this trend, researchers at the National Renewable Energy Laboratory (NREL) created a first-of-its-kind benchmark of U.S. utility-scale solar-plus-storage systems. To determine the cost of a solar-plus-storage system for this study, the researchers used a 100 megawatt (MW) PV system combined with a 60 MW lithium-ion battery that had 4 hours of storage (240 megawatt-hours). A 100 MW PV system is large, or utility-scale, and would be mounted on the ground instead of on a rooftop.

Stop right there. What is a megawatt-hour?

A megawatt-hour (MWh) is the unit used to describe the amount of energy a battery can store. Take, for instance, a 240 MWh lithium-ion battery with a maximum capacity of 60 MW. Now imagine the battery is a lake storing water that can be released to create electricity. A 60 MW system with 4 hours of storage could work in a number of ways:

- So, you can get a lot of power in a short time or less power over a longer time. A 240 MWh battery could power 30 MW over 8 hours, but depending on its MW capacity, it may not be able to get 60 MW of power instantly. That is why a storage system is referred to by both the capacity and the storage time (e.g., a 60 MW battery with 4 hours of storage) or—less ideal—by the MWh size (e.g., 240 MWh).
- **How much utility-scale lithium-ion energy storage is installed in the country?** From 2008 to 2017, the United States was the world leader in lithium-ion storage use, with about 1,000 MWh of storage, and 92% of it, or about 844 MWh, is deployed by utilities, according to the benchmark report. **The average duration of utility-scale lithium-ion battery storage systems is 1.7 hours, but it can reach 4 hours.** Batteries account for the biggest share of a storage system's cost right now—a storage system contains an inverter and wiring in addition to the battery—and utilities will need big battery packs if they're going to provide backup power for all of their customers.
- **OK, but how many PV-plus-storage systems are installed in the country? -** According to NREL, there's only one utility-scale PV system in the United States connected to storage, and it's a 13 MW PV plant with 52 MWh of storage in Kauai, Hawaii. There are more systems that have storage co-located with a solar array, but those batteries can be charged by other sources of power on the grid. According to GTM Research's "U.S. Energy Storage Monitor 2017 Year in Review," more than 5,500 energy storage systems are installed in the U.S., in the residential and commercial sectors with over 95% connected to PV in the residential sector at the end of 2017, which amounts to about 4,700

systems. By the end of 2018, GTM estimates that solar-plus-storage will have accounted for about 4% of distributed PV and could reach 27% by 2023.

- **So, what will it cost to build a solar-plus-storage plant? -** That depends on how long you want your storage to last and how much power you want to use.

  A standalone 60 MW storage system will decrease in cost per megawatt-hour (MWh) as duration increases. Meaning, the longer your storage lasts, the lower the cost per MWh. That's because the cost of inverters and other hardware account for more of the system's costs over a shorter period.

  The system costs range from $380 per kWh for those that can provide electricity for 4 hours to $895 per kWh for 30-minute systems.

- **All right, so what will a 100-megawatt PV system with a 60-megawatt lithium-ion battery with 4 hours of storage cost?**
- Well, we have some options there too:
  - Putting a PV system and a storage system in the same place, known as co-location, enables the two systems to share some hardware components, which can lower costs. Co-location can also reduce costs related to site preparation, land acquisition, labor for installation, permitting, interconnection, and developer overhead and profit.

    When PV and battery storage are co-located, they can be connected by either a DC-coupled or an AC-coupled configuration. DC, or direct current, is what batteries use to store energy and how PV panels generate electricity. AC, or alternating current, is what the grid and appliances use. A DC-coupled system needs a bidirectional inverter to connect battery storage directly to the PV array, while an AC-coupled system needs a bidirectional inverter and a PV inverter. Various factors figure into the choice of system, and it's up to the owner to decide which would work best.

    When choosing between DC and AC, the technical factors that affect the system's performance must be considered, as well as costs. The cost of the co-located, DC-coupled system is 8% lower than the cost of the system with PV and storage sited separately, and the cost of the co-located, AC-coupled system is 7% lower. NREL's new cost model can be used to assess the costs of utility-scale solar-plus-storage systems and help guide future research and development to reduce costs.

Where is this all going? - As solar energy becomes cheaper and more widely used, the market potential for energy-storage devices grows. The challenge is making storage affordable too, with cheaper batteries while improving management and integration techniques. The goal, of course, is to make sure the U.S. electric grid can deploy enough energy to accommodate everyone during peak times at an affordable cost, ensuring the reliability of the grid.

Solar Integration: Inverters and Grid Services Basics[15]

What are Inverters? - An inverter is one of the most important pieces of equipment in a solar energy system. It's a device that converts direct current (DC) electricity, which is what a solar panel generates, to alternating current (AC) electricity, which the electrical grid uses. In DC, electricity is maintained at constant voltage in one direction. In AC, electricity flows in both directions in the circuit as the voltage changes from positive to negative. Inverters are just one example of a class of devices called power electronics that regulate the flow of electrical power.

Fundamentally, an inverter accomplishes the DC-to-AC conversion by switching the direction of a DC input back and forth very rapidly. As a result, a DC input becomes an AC output. In addition, filters and other electronics can be used to produce a voltage that varies as a clean, repeating sine wave that can be injected into the power grid. The sine wave is a shape or pattern the voltage makes over time, and it's the pattern of power that the grid can use without damaging electrical equipment, which is built to operate at certain frequencies and voltages.

The first inverters were created in the 19th century and were mechanical. A spinning motor, for example, would be used to continually change whether the DC source was connected forward or backward. Today we make electrical switches out of transistors, solid-state devices with no moving parts. Transistors are made of semiconductor materials like silicon or gallium arsenide. They control the flow of electricity in response to outside electrical signals.

If you have a household solar system, your inverter probably performs several functions. In addition to converting your solar energy into AC power, it can monitor the system and provide a portal for communication with computer networks. Solar-plus–battery storage systems rely on advanced inverters to operate without any support from the grid in case of outages, if they are designed to do so.

Toward an Inverter-Based Grid - Historically, electrical power has been predominantly generated by burning a fuel and creating steam, which then spins a turbine generator, which creates electricity. The motion of these generators produces AC power as the device rotates, which also sets the frequency, or the number of times the sine wave repeats. Power frequency is an important indicator for monitoring the health of the electrical grid. For instance, if there is too much load—too many devices consuming energy—then energy is removed from the grid faster than it can be supplied. As a result, the turbines will slow down and the AC frequency will decrease. Because the turbines are massive spinning objects, they resist changes in the frequency just as all objects resist changes in their motion, a property known as inertia.

As more solar systems are added to the grid, more inverters are being connected to the grid than ever before. Inverter-based generation can produce energy at any frequency and does not have the same inertial properties as steam-based generation, because there is no turbine involved. As a result, transitioning to an electrical grid with more inverters requires building smarter inverters that can respond to changes in frequency and other disruptions that occur during grid operations, and help stabilize the grid against those disruptions.

Grid Services and Inverters - Grid operators manage electricity supply and demand on the electric system by providing a range of grid services. Grid services are activities grid operators perform to maintain system-wide balance and manage electricity transmission better.

When the grid stops behaving as expected, like when there are deviations in voltage or frequency, smart inverters can respond in various ways. In general, the standard for small inverters, such as those attached to a household solar system, is to remain on during or "ride through" small disruptions in voltage or frequency, and if the disruption lasts for a long time or is larger than normal, they will disconnect themselves from the grid and shut down. Frequency response is especially important because a drop in frequency is associated with generation being knocked offline unexpectedly. In response to a change in frequency, inverters are configured to change their power output to restore the standard frequency. Inverter-based resources might also respond to signals from an operator to change their power output as other supply and demand on the electrical system fluctuates, a grid service known as automatic generation control. In order to provide grid services, inverters need to have sources of power that they can control. This could be either generation, such as a solar panel that is currently producing electricity, or storage, like a battery system that can be used to provide power that was previously stored.

Another grid service that some advanced inverters can supply is grid-forming. Grid-forming inverters can start up a grid if it goes down—a process known as black start. Traditional "grid-following" inverters require an outside signal from the electrical grid to determine when the switching will occur in order to produce a sine wave that can be injected into the power grid. In these systems, the power from the grid provides a signal that the inverter tries to match. More advanced grid-forming inverters can generate the signal themselves. For instance, a network of small solar panels might designate one of its inverters to operate in grid-forming mode while the rest follow its lead, like dance partners, forming a stable grid without any turbine-based generation.

Reactive power is one of the most important grid services inverters can provide. On the grid, voltage— the force that pushes electric charge—is always switching back and forth, and so is the current—the movement of the electric charge. Electrical power is maximized when voltage and current are synchronized. However, there may be times when the voltage and current have delays between their two alternating patterns like when a motor is running. If they are out of sync, some of the power flowing through the circuit cannot be absorbed by connected devices, resulting in a loss of efficiency. More total power will be needed to create the same amount of "real" power—the power the loads can absorb. To counteract this, utilities supply reactive power, which brings the voltage and current back in sync and makes the electricity easier to consume. This reactive power is not used itself, but rather makes other power useful. Modern inverters can both provide and absorb reactive power to help grids balance this important resource. In addition, because reactive power is difficult to transport long distances, distributed energy resources like rooftop solar are especially useful sources of reactive power.

Types of Inverters - There are several types of inverters that might be installed as part of a solar system. In a large-scale utility plant or mid-scale community solar project, every solar panel might be attached to a single central inverter. String inverters connect a set of panels—a string—to one inverter. That inverter converts the power produced by the entire string to AC. Although cost-effective, this setup results in reduced power production on the string if any individual panel experiences issues, such as shading. Microinverters are smaller inverters placed on every panel. With a microinverter, shading or damage to one panel will not affect the power that can be drawn from the others, but microinverters can be more expensive. Both types of inverters might be assisted by a system that controls how the solar system interacts with attached battery storage. Solar can charge the battery directly over DC or after a conversion to AC.

References & Citations:

[1] US Department of Energy, Office of Energy Efficiency & Renewable Energy – How Does Solar Work? https://www.energy.gov/eere/solar/how-does-solar-work

[2] US Department of Energy, Office of Energy Efficiency & Renewable Energy –Solar Photovoltaic Technology Basics https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics

[3] US Department of Energy, Office of Energy Efficiency & Renewable Energy –Solar Photovoltaic Cell Basics https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics

[4] National Library of Medicine –Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5607867/

[5] National Library of Medicine –Health effects of solar cell component material. Toxicity of indium compounds to laboratory animals determined by intratracheal instillations https://pubmed.ncbi.nlm.nih.gov/23718969/

[6] National Library of Medicine –Environmental impacts of copper-indium-gallium-selenide (CIGS) photovoltaics and the elimination of cadmium through atomic layer deposition https://www.sciencedirect.com/science/article/abs/pii/S004896971932916X?via%3Dihub

[7] US Department of Energy, Office of Energy Efficiency & Renewable Energy – PV Cells 101: A Primer on the Solar Photovoltaic Cell https://www.energy.gov/eere/solar/articles/pv-cells-101-primer-solar-photovoltaic-cell

[8] US Department of Energy, Office of Energy Efficiency & Renewable Energy – PV Cells 101, Part 2: Solar Photovoltaic Cell Research Directions https://www.energy.gov/eere/solar/articles/pv-cells-101-part-2-solar-photovoltaic-cell-research-directions

[9] US Department of Energy, Office of Energy Efficiency & Renewable Energy – Solar Performance and Efficiency https://www.energy.gov/eere/solar/solar-performance-and-efficiency

[10] US Department of Energy, Office of Energy Efficiency & Renewable Energy – Solar Photovoltaic System Design Basics https://www.energy.gov/eere/solar/solar-photovoltaic-system-design-basics

[11] US Department of Energy, Office of Energy Efficiency & Renewable Energy – Getting the Most out of Solar Panels https://www.energy.gov/articles/getting-most-out-solar-panels

[12] US Department of Energy, Office of Energy Efficiency & Renewable Energy – Solar Systems Integration Basics https://www.energy.gov/eere/solar/solar-systems-integration-basics

[13] US Department of Energy, Office of Energy Efficiency & Renewable Energy – Solar Integration: Solar Energy and Storage Basics https://www.energy.gov/eere/solar/solar-integration-solar-energy-and-storage-basics

[14] US Department of Energy, Office of Energy Efficiency & Renewable Energy - Solar-Plus-Storage 101 https://www.energy.gov/eere/solar/articles/solar-plus-storage-101

[15] US Department of Energy, Office of Energy Efficiency & Renewable Energy - Solar Integration: Inverters and Grid Services Basics https://www.energy.gov/eere/solar/solar-integration-inverters-and-grid-services-basics

[16] Degradation of Hydrophobic, Anti-Soiling Coatings for Solar Module Cover Glass https://www.mdpi.com/1996-1073/13/15/3811

[17] US Department of Energy, Office of Energy Efficiency & Renewable Energy – The History of Solar https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

[18] MarketWatch – Solar Panel Efficiency Explained https://www.marketwatch.com/guides/solar/solar-panel-efficiency/#:~:text=Most%20commercially%20available%20solar%20panels,with%20zero%20emissions%20(sunlight).

[18] US Energy Information Administration - Record U.S. small-scale solar capacity was added in 2022 https://www.eia.gov/todayinenergy/detail.php?id=60341

[19] Ohio Citizen Action – Utility Scale Solar https://www.ohiocitizen.org/utility_scale_solar#:~:text=Utility%20Scale%20Solar%2C%20or%20industrial,megawatts%20(MW)%20of%20electricity.

[20] Ohio Citizen Action - Say YES to community solar https://www.ohiocitizen.org/community_solar

[21] William Shockley and Hans J. Queisser, "*Detailed Balance Limit of Efficiency of p-n Junction Solar Cells*", Journal of Applied Physics, Volume 32, pp. 510-519 (1961) http://metronu.ulb.ac.be/npauly/art_2014_2015/shockley_1961.pdf

[22] Queen Mary University of London – The Shockley-Queisser Limit https://ph.qmul.ac.uk/sites/default/files/u75/Solar%20cells_environmental%20impact.pdf

[23] Green Illusions, The dirty secrets of clean energy and the future of environmentalism – Ozzie Zehner