Agrisolar Fundamentals

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Supported by DOE Foundational Agrivoltaic Research for Megawatt Scale (FARMS) Program through Grant No. DE-EE0010439.0000

Preface

Agrivoltaics, or agrisolar, is the simultaneous use of land for both agricultural production and photovoltaic solar electricity generation. This symbiotic system integrates solar power with agriculture, creating renewable energy and providing space for crops, grazing, and native habitats under and between solar panels. Agrivoltaics enables the joint development of the same land area simultaneously for both agriculture and renewable solar energy, promoting land use efficiency, climate change mitigation, sustainable food, and local economies.

This brochure entitled "Agrisolar fundamentals" is developed with the financial support from the U.S. Department of Energy (DOE) Foundational Agrivoltaic Research for Megawatt Scale (FARMS) Program through Grant No. DE-EE0010439.0000 to educate students and the general public with the basic science of photovoltaics and the emerging practices of agrivoltaics. Fundamental topics and technical aspects of agrivoltaics introduced in the brochure are as follows:

1. Energy and energy efficiency
2. Renewable energy technologies
3. Solar energy and common utilities
4. Principles of photovoltaics
5. Photovoltaic systems for solar electricity
6. Performance and economics of photovoltaic systems
7. Agrivoltaics: concept and development
8. Benefits and challenges of agrivoltaics
9. Agrivoltaic system designs
10. Technoeconomic analysis of agrivoltaics

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1. Energy and Energy Efficiency

1.1 Energy fundamentals

Energy is the capacity of a physical system to perform work, while work is to move a physical object against a force over a distance. To do work requires energy, the capacity to overcome the resistant forces from moving physical objects (Fig. 1-1). Energy is invisible, though the "work" process and results may be visible. When work is done, energy is consumed. Energy, however, cannot be created or destroyed, it is just being transformed from one form to the others during "doing work."

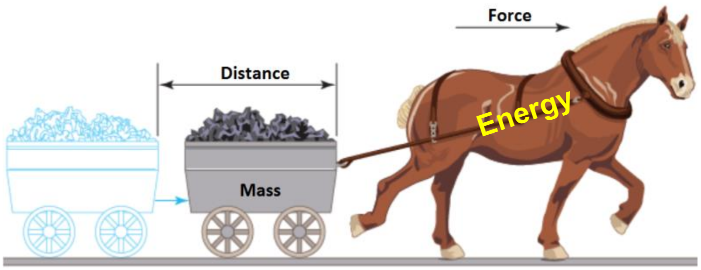


Fig. 1-1. Energy is consumed while a horse works to pull a coal cart from one place to a new location

There are two types of energy in various forms: Kinetic energy and potential energy. Kinetic energy includes electric energy, thermal energy, radiant energy, and motion energy while potential energy covers chemical energy, nuclear energy, mechanical energy, and gravitational energy (Fig. 1-2). When an apple high in the tree falls to the ground, its gravitational energy is transformed to motion energy. The motion energy is transformed to thermal energy upon the apple reaching the ground. The thermal energy is then absorbed by the ground and the apple, causing them to become "hotter." A coal-firing train carrying cargos from one city to the other involves transformation of the chemical energy in coal to the motion energy of the moving train and to the thermal energy absorbed by rails and wheels. Eventually, the rails and wheels become hotter.

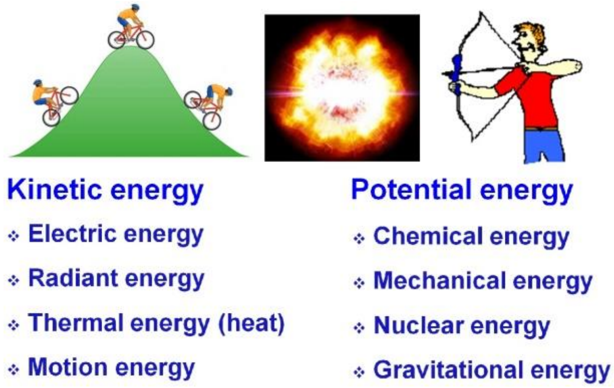


Fig. 1-2. Various forms of kinetic energy and potential energy

The First Law of Thermodynamics, so-called the Law of Conservation of Energy, states that the energy of the universe remains the same; energy cannot be created or destroyed, but can be transferred from one location to another or converted from one form to other forms. Work is always required to transfer or transform energy and therefore, the capacity of energy to do "work" decreases during transfer or transformation, and the energy consumed for doing "work" becomes heat that can only be transferred from a higher temperature body to a lower temperature body. Both work and heat are involved in energy transfer and conversion. As energy is transferred or transformed, more and more of it is "wasted."

Energy is measured in **J**oule (the amount of work done when a force of 1 newton is exerted over 1-m distance) or **Cal**orie (the energy required to raise 1 g of water by 1°C; 1 Cal = 4.186 J). The unit **Btu** (British Thermal Unit) is defined as the amount of heat required to raise 1 pound of water by 1°F; 1 Btu = 1055.06 J). For example, 1 gallon of gasoline will release approximately 1 million Btu of thermal energy upon complete combustion. The term **power** describes how fast (the rate at which) work is being done and energy is being converted or transferred. The unit of power is **W**att, equivalent to Joule per second (J/s). Another power unit is Horse Power (HP), referring to raising 550 pounds of weight over 1 foot in one second (1 HP = 746 W). The commonly mentioned term kilowatt hour (kWh; 1 kW = 1000 W; 1 h = 3600 s) measures each unit 3,600,000 J of electrical energy (electricity) generated or used.

All materials on the Earth contain chemical, gravitational, and thermal energies. The energy usable for human purposes, however, can only be obtained from limited sources, such as the Sun, wind, flowing water, fossil fuels, biomass, geothermal heat, battery, and radioactive matter (Fig. 1-3). The sources fossil fuels, battery, and radioactive matter are not renewable, while the others are renewable and can be continuously replenished by natural processes.

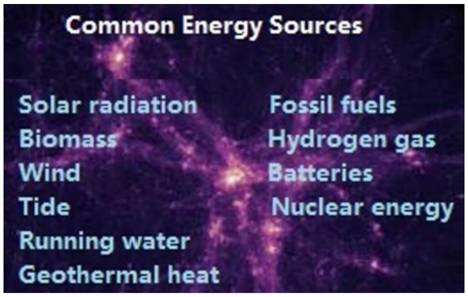


Fig. 1-3. Ten common energy sources

1.2 Energy efficiency

To perform the same amount of work, more or less energy in a particular form may be taken, depending on the technologies used. **Energy efficiency** is defined as the ratio between the useful output and input of an energy conversion process. The energy efficiency of a system refers to the ratio of desirable energy output to total energy input. Energy efficiency is commonly measured as the amount of desirable energy output for a given energy input and listed as a percentage between 0% and 100%.

Energy efficiency generally pertains to the technical performance of energy conversion and energy-consuming devices and to building materials. To improve the energy efficiency means using less energy to perform the same task or produce the same result or provide the same service – that is, reducing energy waste (in heat dissipation). For example, 1300–1500 lumen of bright light may be generated using a 100-W incandescent bulb, a 70-W halogen bulb, a 20-W compact fluorescent lamp (CFL), or an 18-W light emitting diode (LED) bulb, indicating the energy efficiency of LED bulbs is more than 5 times higher than incandescent bulbs for converting electricity to visible light (Fig. 1-4). The average efficiency of commercial solar panels is between 15% and 20%, meaning only 15–20% of the solar energy received by a solar panel is converted into electricity.

Fig. 1-4. Different types of light bulbs showing significantly increased energy efficiency from incandescent bulbs to halogen bulbs to compact fluorescent lamps (CFL) to light emitting diode (LED) bulbs

Potential benefits of improving energy efficiency include:

- **Economic**: Improving energy efficiency can lower individual utility bills and help stabilize electricity prices and volatility.
- **Environmental**: Increased efficiency can lower greenhouse gas (GHG) emissions and reduce generations of wastes (e.g., wastewater and waste gas) associated with energy production.
- **Utility system benefits**: Improved energy efficiency can provide long-term benefits by lowering overall electricity demand, thus reducing the need to invest in new electricity generation and transmission infrastructure.

1.3 Energy conservation

Energy conservation refers to implementation of actions that can reduce the amount of end-use energy consumption. The National Energy Conservation Day is celebrated annually on December 14th to raise awareness about the importance of energy conservation and efficiency (Fig. 1-5).

Fig. 1-5. National Energy Conservation Day

Improving energy efficiency is a particular effort of energy conservation. In general, energy efficiency and energy conservation are related and serve often as complimentary or overlapping ways to reduce energy consumption. For example, installing energy-efficient lights is an efficiency measure. Turning lights off when not needed, either manually or with timers or motion sensor switches, is a conservation measure.

Efficiency and conservation measures can help to directly lower consumers' energy bills and potentially reduce GHG emissions associated with energy use. Consumers also benefit indirectly when reducing their electricity consumption helps reduce demand on the electric system. High electricity demand often results in higher costs for generating and transmitting electricity that may be passed on to utility customers.

Examples of energy efficiency and conservation measures for consumers include:

- Biking and car pooling
- Using programmable thermostats to control heating and cooling systems
- Setting a lower temperature (e.g., ~65°F) of room thermostats in the winter time and a higher temperature (e.g., ~76°F) in the summer time
- Buying energy-efficient products including high-fuel-economy vehicles
- Installing energy management and control systems in commercial and industrial facilities
- Turning off lights and electric appliances when not in use

2. Renewable Energy

2.1 Renewable energy resources

Renewable energy is the energy generated from natural resources that are continuously replenished on the human timescale. Such natural resources include sunlight, geothermal heat, wind, tides, running water, and biomass (Fig. 2-1). **Renewable energy extends commonly to solar energy (heat and electricity), geothermal heat, wind power, hydropower, and bioenergy**. Renewable energy resources are constantly renewed by natural processes and cannot be exhausted. Fossil (coal, petroleum, and natural gas) energy and nuclear energy are non-renewable energy, as the energy resources (fossil fuels and nuclear materials) are not renewable.

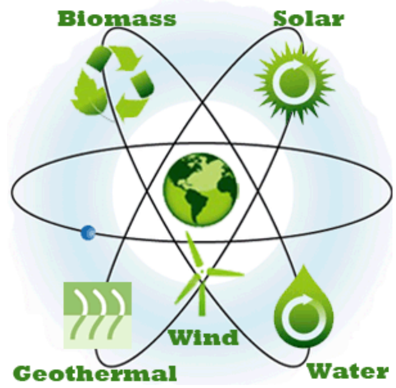


Fig. 2-1. Renewable energy sources

Renewable energy plays an important role in enhancing the energy independence and security of a nation and in reducing the global emission of greenhouse gases (e.g., CO_2, CH_4, and N_2O). Unlike consumption of fossil fuels that releases CO_2 and other greenhouse gases into the atmosphere, the use of hydropower, geothermal heat, wind electricity, and solar energy does not directly emit greenhouse gases. The use of bioenergy does not additionally introduce CO_2 to the atmosphere, as biomass is originally synthesized from the atmospheric CO_2.

2.2 Renewable energy technologies

1) Bioenergy

Each year terrestrial plants produce approximately 120 billion tons of dry vegetative biomass via photosynthesis, storing 2.2×10^{15} MJ of chemical energy (Fig. 2-2). This amount of bioenergy is 3–4 times of the current human energy demand.


Fig. 2-2. Plant mass as a major bioenergy source

Upon combustion, biomass releases its chemical energy in heat and light. Direct combustion is the most efficient way to utilize the energy in biomass. Nevertheless, raw biomass has a relatively low energy density and is not convenient to use. To improve the energy usability, raw biomass is usually processed with physical, chemical, and biological technologies into different fuel products. Through chipping and palletization, for example, firewood can be transformed into chips and pellets, respectively and used as convenient fuels for heating (**bioheat**) and electricity generation (**biopower**).

Biomass is the only renewable resource for liquid fuels. Sugar, starch, and (hemi)cellulose in biomass can be converted via *fermentation* into **bioethanol** to power gasoline engines; vegetable oils, algal lipids and animal fats can be transformed via *transesterification* into **biodiesel** to fuel diesel engines; raw biomass can be changed via *pyrolysis* and *gasification* into **charcoal** (a solid fuel), **bio-oil** (a liquid fuel), and **syngas** (a gaseous fuel). Another gaseous fuel **biogas** (mainly CH_4) can be produced by *anaerobic digestion* of animal manures, food waste, and plant residues and used as a natural gas substitute.

2) Hydropower

Flowing water carries motion energy that can be harnessed to generate electricity (so-called hydroelectric power or simply hydropower). In a hydropower plant, flowing water turns a turbine and the spinning turbine activates a generator to produce electricity (Fig. 2-3).

To create and control adequate flowing water for utility-scale electricity generation, a dam is typically needed to form a reservoir to store water and raise the water level (i.e., to increase the gravitational energy of the water). The Hoover Dam, for example, is 221.4 m in height and 2.48 million m^3 in volume. With the installed capacity of 2.1 gigawatts, it generates annually 4 billion kWh of electricity.

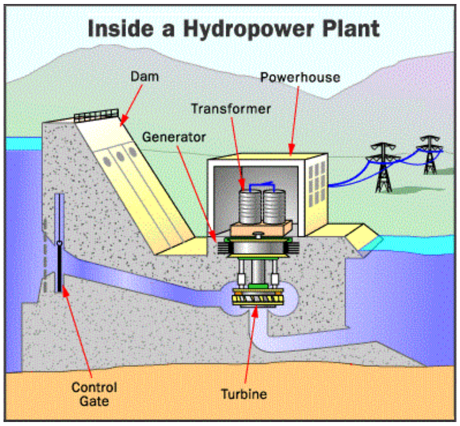


Fig. 2-3. Structure of a hydropower plant

3) Geothermal heat

From the surface to the deep of the Earth, the temperature is getting higher and higher. The heat carried by the underground earth materials is called geothermal heat. Geothermal heat can be utilized for generating electricity, heating water, and conditioning room air.

A geothermal power plant generates electricity from geothermal heat. Such a facility is often built in areas with hot springs, geysers, or volcanic activities, where the Earth is particularly hot near the surface (Fig. 2-4). Deep wells are installed to withdraw pressurized hot water or steam. At the surface, depressurized hot water becomes steam to spin a turbine for generating electricity. The steam then condenses to liquid water after passing through a cooling tower. The cool water is injected back to the Earth to start a new cycle.

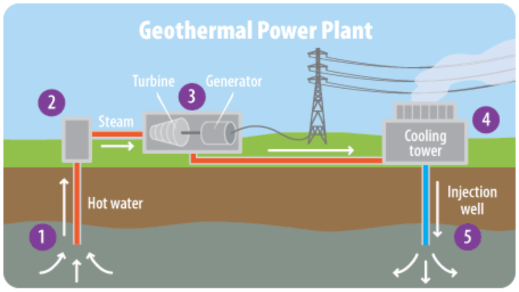


Fig. 2-4. Structure of a geothermal power plant

Meters under the Earth surface, the temperature is relatively constant, not fluctuating as the surface air temperature. This feature has been utilized for home heating, ventilation, and air conditioning (HVAC). In practice, water or refrigerant is pumped through a loop of pipes buried underground (<300 m). The circulating fluid releases heat in the winter and absorbs heat in the summer when passing through a building (Fig. 2-5).

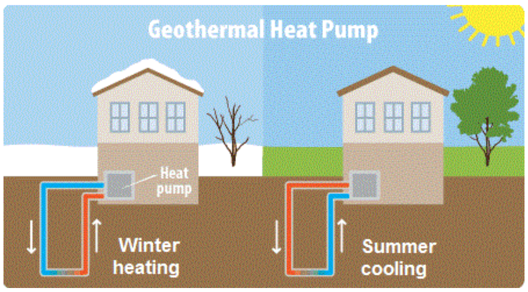


Fig. 2-5. Geothermal heating and cooling

4) Wind power

Wind is flowing air. The moving air mass carries motion energy that can be harvested using a wind turbine to generate electricity. A wind turbine is composed of blades, a rotor, a shaft, a gearbox, an electric generator, a supporting tower, and electrical cables. Wind turns the blades, which spin the shaft connecting to an electric generator to produce electricity (Fig. 2-6).

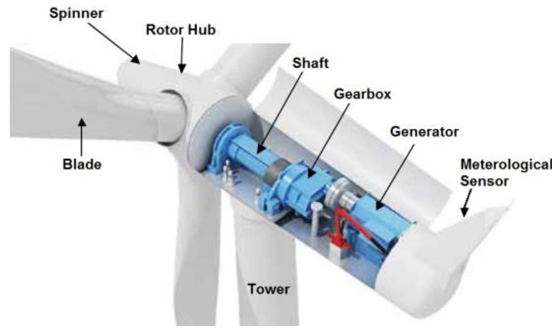


Fig. 2-6. Structure of a wind turbine

Wind turbines can be small or big. A small backyard turbine can produce enough electricity for a single home, while a big turbine can generate electricity adequate for powering 600 U.S. homes. The power of a wind turbine can be estimated by the equation: $P = \frac{1}{2}\rho A v^3$, where ρ is the density of air, A is the area covered by rotating blades, and ν is the wind velocity. A utility-scale wind farm may have tens to hundreds of wind turbines (Fig. 2-7).

Fig. 2-7. A utility-scale wind farm

5) Solar electricity and heat

The Sun is the primary energy source of the Earth system. Solar radiation energy can be collected to produce electricity (solar power) using photovoltaic panels or prepare hot water (solar heat) using specially designed heating systems.

2.3 Renewable energy status

Today, the annual global energy demand has been escalating to nearly 600 quadrillion (10^{15}) Btu, of which ~12% is met by renewable energy and ~88% by non-renewable (fossil and nuclear) energy. Overall, fossil energy dominates the energy source, accounting for 79% of the U.S. energy demand and 83% of the global energy demand (Fig. 2-8). Development of renewable energy significantly reduces the consumption of fossil fuels, the primary cause for the on-going climate change. In the past three decades, the global production and utilization of renewable energy has been increasing steadily. According to Renewables 2023 Global Status Report, renewable energy shared 12.1% of the global energy consumption in 2022. In the U.S., renewable energy capacity has been expanding by 3–4% each year and reached 13.2 quadrillion in 2022, meeting 13% of the nation's total energy demand.

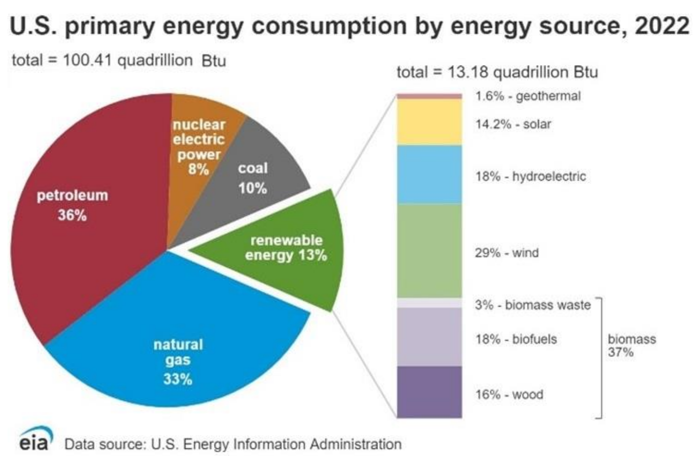


Fig. 2-8. The 2022 US consumption of energy by sources

3. Solar Energy and Utilization

3.1 Solar radiation

The **Sun** is a star 150 million km away from the Earth. It is spherical with a diameter 1,392,000 km, 109 times that of the Earth. It is composed mainly of hydrogen and helium, at mass 330,000 times that of the Earth. In the Sun's interior, a **thermonuclear fusion reaction** converts the hydrogen into helium ($_1^1H + _1^1H + _1^1H + _1^1H \rightarrow _2^4He + _{2+}^{0}e + energy$), releasing huge amounts of thermal energy (heat) and positrons. The heat generated from the fusion reaction raises the temperature of the Sun to above 5500°C at the surface. At such a high temperature the Sun glows and radiates, enabling the solar heat energy to travel through space in the form of **electromagnetic waves** by ***radiation*** (the process in which energy is transferred in electromagnetic waves from a radiating or emitting body).

Solar radiation occurs over a wide range of wavelengths, covering ultraviolet radiation (UV, 0.2–0.4 µm), visible light (Vis, 0.4–0.7 µm), and infrared radiation (IR, 0.7–4 µm). However, the energy of solar radiation is not divided evenly over all wavelengths but is rather sharply centered on the wavelength band of 0.2–2 µm and maximizes at a wavelength of about 0.5 µm (Fig. 3-1). Overall, ~5% of the solar energy is at UV radiation, ~43% at visible light, and ~52% at IR radiation.

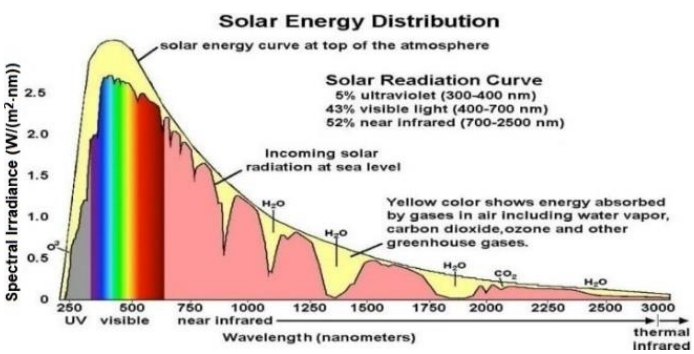


Fig. 3-1. Energy distribution of solar radiation over the wavelength band of 0.2-3 µm

Solar irradiance in W/m^2 is used to measure the energy flux or the surface power density of solar radiation. Solar irradiance decreases with increasing distance from the Sun. At the surface of the Sun it is approximately **63 × 10^6 W m^{-2}**. As the Sun's energy spreads through space its spectral characteristics do not change because space contains almost no interfering matter. When the solar radiation energy travels to reach the orbit of a planet, the large spherical surface over which the energy is spread has a radius, **d_P**, equal to the distance from the Sun to the planet. The energy flux at any place on this surface, **S_P**, is less than what it was at the Sun's surface (**S_S**) (Fig. 3-2). But the total energy spread over this large surface is the same as the total energy that left the Sun, thus:

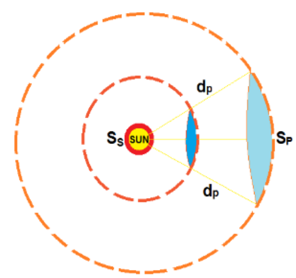


Fig. 3-2. The solar irradiance decreasing as increasing the distance from the Sun

$$S_S 4\pi r_s^2 = S_P 4\pi d_P^2$$

$$S_P = S_S (r_s/d_P)^2$$

where r_s is the radius of the Sun. Accordingly, when the radiation reaches the outer limit of the Earth's atmosphere, several hundred kilometers over the Earth's surface, the radiative flux is **~1360 W m^{-2}**.

When radiation from the Sun reaches the Earth, however, it does not strike all surface areas at the same angle. It strikes directly near the equator, but more obliquely near the poles. The total amount of radiation incident on the Earth is equal to the amount the Earth intercepts to cast the imaginary shadow (Fig. 3-3). That is, $S_P \pi r_P^2$ (r_p is the radius of the Earth). If the average energy flux over the area of the Earth is **S_{ave}**, the total energy for the Earth is $S_{ave} 4\pi r_P^2$.

$$S_{ave} 4\pi r_P^2 = S_P \pi r_P^2$$

$$S_{ave} = S_p/4$$

Therefore, the average solar irradiance at the Earth's atmosphere is 1360/4 = 340 W m^{-2}.

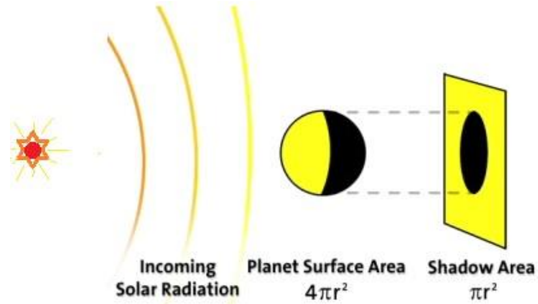


Fig. 3-3. The surface area of the Earth globe receiving solar radiation

The Earth axis tilts at an angle of 23.5° with respect to its plane of orbit, pointing towards a fix point in space as it travels around the Sun (Fig. 3-4). Once a year, on the Summer Solstice (about the 21st of June), the North Pole points most closely towards the Sun and the South Pole is entirely hidden from the incoming radiation. On the Winter Solstice (about the 21st of December) the North Pole points away from the Sun and does not receive any sunlight while the South Pole receives 24 hours of continued sunlight. During Solstices, incoming radiation is perpendicular to the Earth surface on either Tropic of Cancer (latitude 23.5°N) or Tropic of Capricorn (23.5°S). At the poles, the Earth is either exposed to sunlight over the entire (24-hours) day or is completely hidden from the Sun throughout the entire day. On the Equinox days (the 21st of March and 23rd of September), the Earth's axis tilts in parallel to the Sun and both Polar Regions get the same amount of light. At that time the solar irradiance is largest at the true equator.

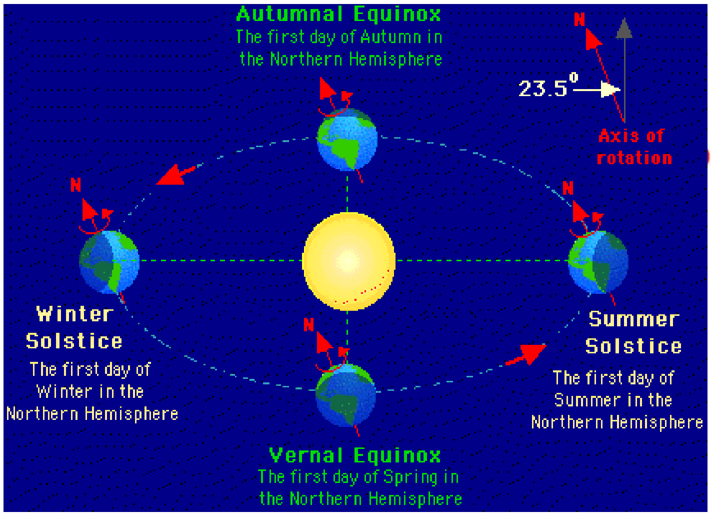


Fig. 3-4. Formation of four seasons from Earth's axis tilting toward its plane of orbit around the Sun

The quantity of solar radiation striking the Earth varies by region, season, time of the day, climate (especially the cloud cover), and air pollution in the region. **Insolation** is used to indicate the cumulative solar radiation energy received per unit area of a region over a defined period of time (e.g., annual, monthly, daily, etc.). The common unit of insolation is kilowatt hours per square meter (kWh/m^2) with a time interval specification. In a year, the areas near the equator receive more solar radiation than anywhere else on Earth. The amount of solar energy falling per square meter on Yuma, Arizona, in June, for example, is typically about nine times greater than that falling on Caribou, Maine, in December. These climatic factors all affect the amount of solar energy that is available to different uses. The yearly average solar radiation flux at different locations of the continental U.S. is shown in the following graphs (Fig. 3-5).

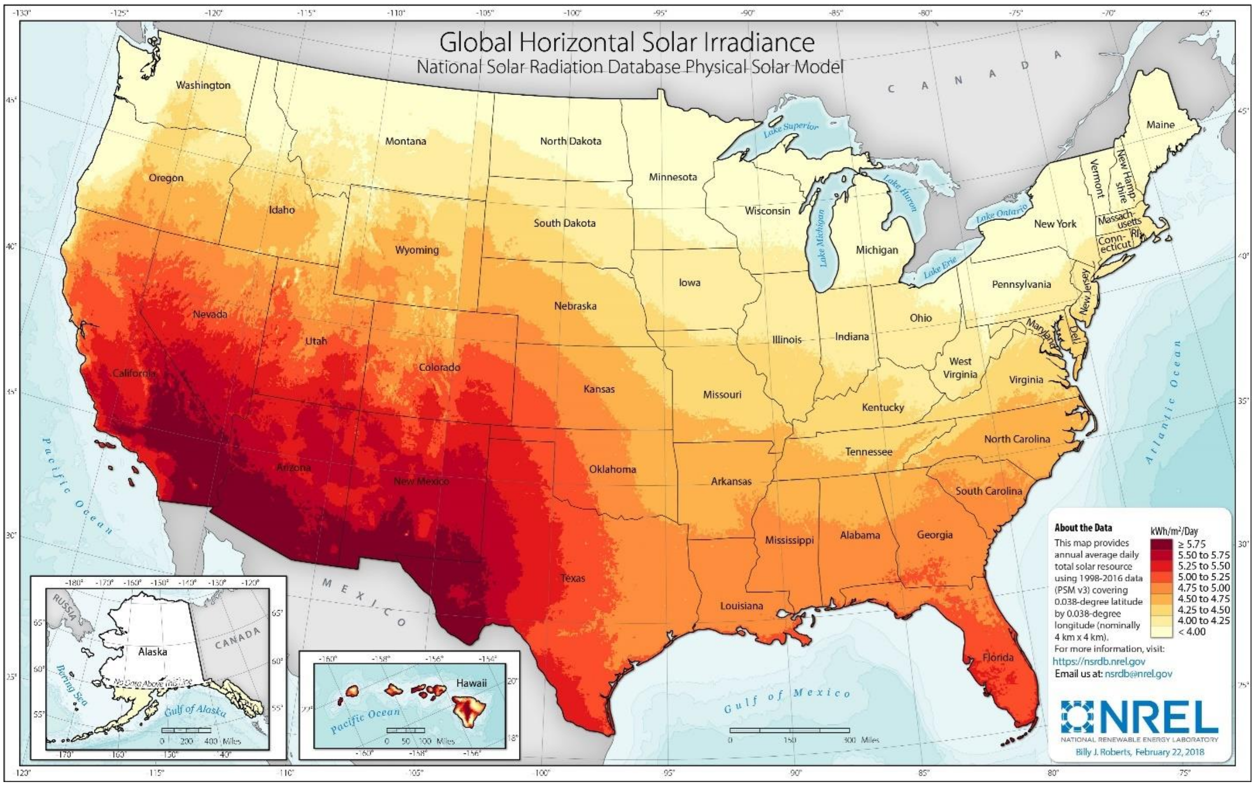


Fig. 3-5. Annual average solar insolation of the continental US

3.2 Utilization of solar energy

The solar energy flux on the Earth surface is averaged at 340 W/m^2. The solar radiation received on the Earth surface supports plant growth and biomass production. The solar energy can also be captured and used for heating and electricity generation.

Solar heating systems can be installed to prepare hot water or warm buildings. Such systems use sunlight to heat a fluid — water, glycerol, air — and convey the solar heat to the interior space or to a storage tank for later use. A solar water heater or a solar room heater typically consists of a solar collector, a storage tank, a circulating pump, and controls (Fig. 3-6). Three types of solar collectors are available: flat-plate, evacuated-tube, and parabolic-trough-solar-concentrating collectors. The dark surface of the collector absorbs sunlight and converts it to heat. A pump circulates water, air, or other heat transfer fluids through the collector. The heated fluid flows to a storage tank, a heat exchanger, or directly to a room. Hot water is then prepared for end use, or rooms are warmed by distributing the heat through a radiant floor, hot water radiators, or a central forced-air system. An

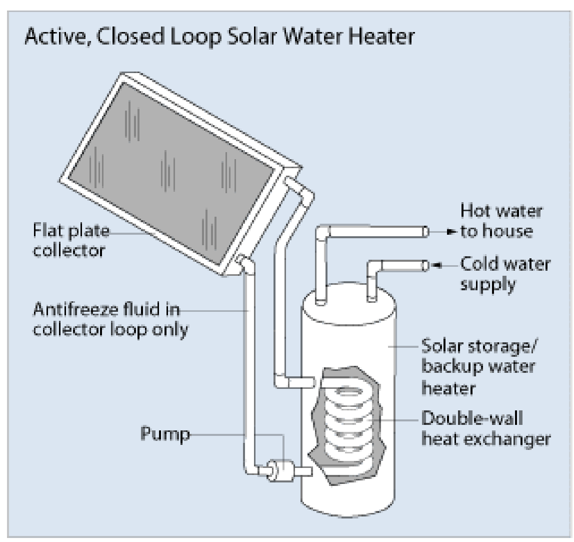


Fig. 3-6. Structure of a solar water heater

appropriately designed solar heating system will last decades and can provide 40–80% of the home's heating needs. In 2022 the global solar heating capacity reached 540 gigawatts (GW).

Electricity can be produced from solar radiation using solar cells made of **photovoltaic** (PV), semiconducting materials such as silicon. Under direct sunlight, photovoltaic materials are ionized, causing outer electrons to break free of their atomic bonds. The electrons are forced to flow in one direction due to the semiconductor nature of the solar cell materials, forming direct current (DC) electricity (Fig. 3-7). The sunlight-to-electricity efficiency of a solar cell ranges currently from 6% to 30%, depending on the material and design of the cell. In 2023, the global grid-tied solar power (electricity) production capacity reached 417 gigawatts.


Fig. 3-7. A commercial photovoltaic solar power farm

Concentrating solar-thermal power (CSP) technologies convert sunlight to thermal energy (heat) and use the heat to generate electricity by powering a turbine. The same basic technologies can also be used to deliver heat to a variety of industrial applications, like water desalination, enhanced oil recovery, and food processing. For example, the 195-m tall Crescent Dunes solar tower in the Nevada desert is a 100-MW concentrating solar-thermal power plant (Fig. 3-8). The solar tower is surrounded by >10,000 billboard-size mirrors focusing the sunlight on the tower tip to heat up a massive tank of Na/KNO_3 salts to melt at 565°C. When electricity is needed, the hot salt is used to boil water and produce high-temperature, high-pressure steam, which turns turbines that generate electricity.


Fig. 3-8. The first utility-scale, 110 MW concentrating solar plant Crescent Dunes Solar Tower in Nevada

Solar desalination is a thermal distillation process using solar radiation to evaporate saline water and generate potable water.

Solar fuels are fuels (e.g., H_2, hydrocarbon, and ammonia) made from common substances like water, carbon dioxide, and nitrogen using the energy of sunlight.

4. Photovoltaics

Photovoltaics are the technologies and systems converting light (photons) directly to electricity (voltage) using semiconducting materials that exhibit photovoltaic effect (generation of electric voltage in semiconducting materials upon exposure to electromagnetic radiation).

4.1 Photovoltaic effect

Photovoltaic (PV) effect is a physical phenomenon that occurs when semiconducting materials generate electricity (voltage) upon exposure to light (photons).

All matter is composed of atoms. An atom is composed of a nucleus in the center and a number of negatively charged electrons revolving around the nucleus. An atomic nucleus is further composed of a certain number of positively charged protons and neutral neutrons. The silicon atom, for example, has 14 electrons. Their natural orbital arrangement allows the outer four electrons to be given to, accepted from, or shared with other atoms. These outer electrons are called valence electrons. Large numbers of silicon atoms can bond together through sharing their valence electrons to form a crystal. In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms. The solid, then, consists of basic units of five silicon atoms: the original atom plus the four other atoms with which it shares its valence electrons.

When a photon of sufficient energy strikes a valence electron, it may free it from its connection to the atom. This leaves a space in the crystal structure where an electron once resided (and bonded), called a "hole" (Fig. 4-1). The electron is now free to travel about the crystal lattice. The electron is now a part of the conduction band, so called because these free electrons are the means by which the crys*tal* conducts electricity. Meanwhile, the atom left behind by the freed electron contains a net positive charge in the form of the generated hole. This positive hole can move almost as freely about the crystal lattice as a free electron in the conduction band, as electrons from neighboring atoms switch partners. These light-generated charges, both positive and negative, are the constituents of electricity.

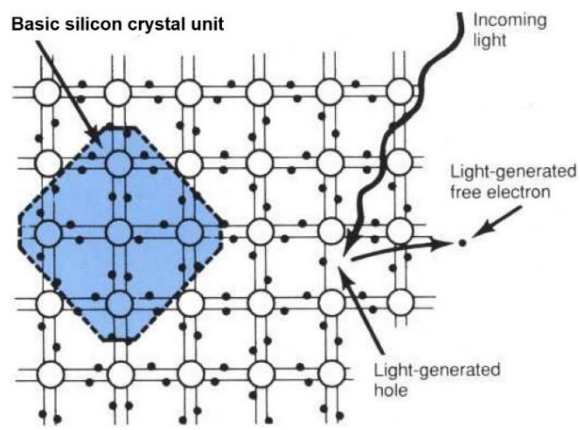


Fig. 4-1. Formation of electron holes in crystal silicon upon light exposure

4.2 Solar cell

A single solar cell, typically sized 6″×6″, is the smallest practical element that harnesses the photovoltaic effect to generate electricity (Fig. 4-2). A typical single-crystal silicon PV cell consists of several layers: a conducting grid on the top surface; an antireflective coating or treated surface layer; a thin layer (~1 μm) of silicon called collector; a very narrow electric field region at the

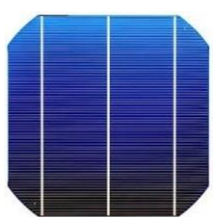


Fig. 4-2. A single silicon solar cell

junction that enables a current to be produced; a silicon base layer; and a back-contact electrode (Fig. 4-3). When photons strike a PV cell, they may be reflected *or* absorbed, or they may pass right through. It is the absorbed photons that generate electricity. When absorbed, a photon transfers its energy to an electron in an atom of the semiconductor device. With its newfound energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor, creating an electron-hole pair. Both the electron and the hole begin moving in the material, forming an electric field (voltage) at the interface. Attaching an external circuit allows the electrons to flow and form electrical current. If there is no external circuit, the charge carriers collect at the ends of the cell. This buildup continues until equilibrium voltage (called the open circuit voltage) is reached.

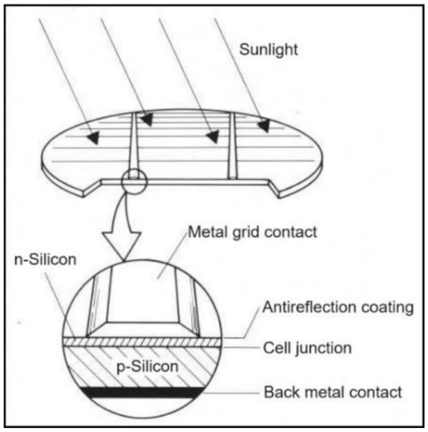


Fig. 4-3. Components of a typical silicon photovoltaic cell

The power from an electrical device such as a PV cell is equal to the product of the voltage (V) and the current (I). Under full sunshine, a single silicon solar cell generates 0.5-V electricity at 1-3 W power (1 W = 1 J/s).

4.3 Solar panel

A **solar panel (module)** is a single PV panel manufactured by connecting many solar cells in a separate assembly (Fig. 4-4). The number of cells in a solar panel can vary from 36 to 144. The two most common solar panel options on the market today are 60-cell (~65″×39″) and 72-cell (~80″×40″). A typical 200-W monocrystalline silicon solar module has six major components and weighs 15–28 kg (34–62 lbs):


Fig. 4-4. A typical solar panel

(1) extruded Al frame,
(2) 3.2-mm thick tempered glass cover,
(3) EVA encapsulation layers,
(4) solar PV cells,
(5) polymer rear back sheet, and
(6) a junction box containing bypass diodes and MC4 connectors.

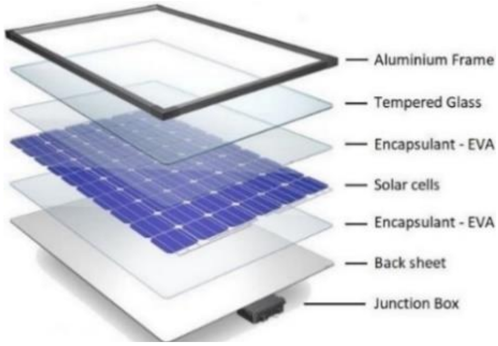


Fig. 4-5. A typical solar module design uses a substrate of metal, glass or plastic to provide back structural support; encapsulant material to protect the cells; and a transparent cover of plastic or glass.

4.4 Photovoltaic systems

The solar **cell** is the basic unit in a PV system. A **module** (**panel**) is formed when many cells are connected into a larger unit. Numerous modules can be connected to form even larger units known as **array**s and fastened to a rigid structure to produce solar electricity at utility scale.

A PV system comprises three subsystems: **PV devices** (modules, arrays, etc.) that convert sunlight into electricity; **the load**, the application for which the PV electricity is intended; and **balance-of-system** (BOS), a set of devices and structures that enables the PV electricity to be properly applied to the load (Fig. 4-6).

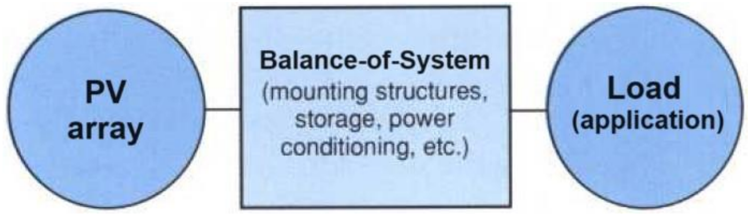


Fig. 4-6. Major components of a solar power system

The BOS components cover any elements necessary in a functioning PV system except for the actual PV panels, such as wires that connect modules, junction boxes to merge the circuits, mounting hardware, and power conditioning electronics like batteries, charge controllers, inverters, transformers, and other regulators (e.g., relays) that manage the PV array's output. Photovoltaic arrays have to be mounted on some sort of stable, durable structure such as pole, rack, or roof that can support the array and withstand wind, rain, hail, and other adverse conditions (Fig. 4-7). The mounting structure can either be stationary or it can track the sun. Stationary structures generally tilt the PV array at a fixed angle (so-called **fixed tilt**). Sun-tracking systems have the capability for tracking the Sun's position in the sky through a **solar tracker**, a device that orients solar panels toward the sun using different drivers (e.g., motor), controllers, and physics. By tracking the Sun, the power generation of a PV system may be doubled. Power conditioners process the electricity produced by a PV system to maximize power output, convert DC to alternating current (AC), match the AC electricity to a utility's network, and safeguard the utility network and its personnel from harm. For AC loads, power conditioning must include an **inverter** that converts the DC generated by the PV array into AC. For DC applications, power conditioning is often accomplished with regulators (batteries and charge controllers), which control output at some constant level of voltage and current to maximize output. For particular PV systems, batteries may be necessary to store excess electricity generated by solar arrays during the day and supply electricity at night and on cloudy days. Most batteries are protected by an electronic device **charge controller** that manages battery electricity storage from overcharge, excessive discharge, and back flow of electrical current.

Fig. 4-7. Pole-mounted, rack-mounted, roof-integral, and roof-standoff solar panels from left to right, respectively

Depending on whether or not connected with a power/electricity/utility grid (a network of components that generate, transmit, and deliver electricity to customers), a PV system can be <u>stand-alone</u> (off-grid) or <u>grid-tied</u> (Fig. 4-8). A stand-alone PV system is an off-the-grid PV system from which the generated solar electricity is not added to a power grid (e.g., unavailable in remote areas) but stored and used directly by local loads. Grid-tied PV systems, on the contrary, are those in human populated regions from which the generated solar electricity is added to and distributed via an electricity grid.

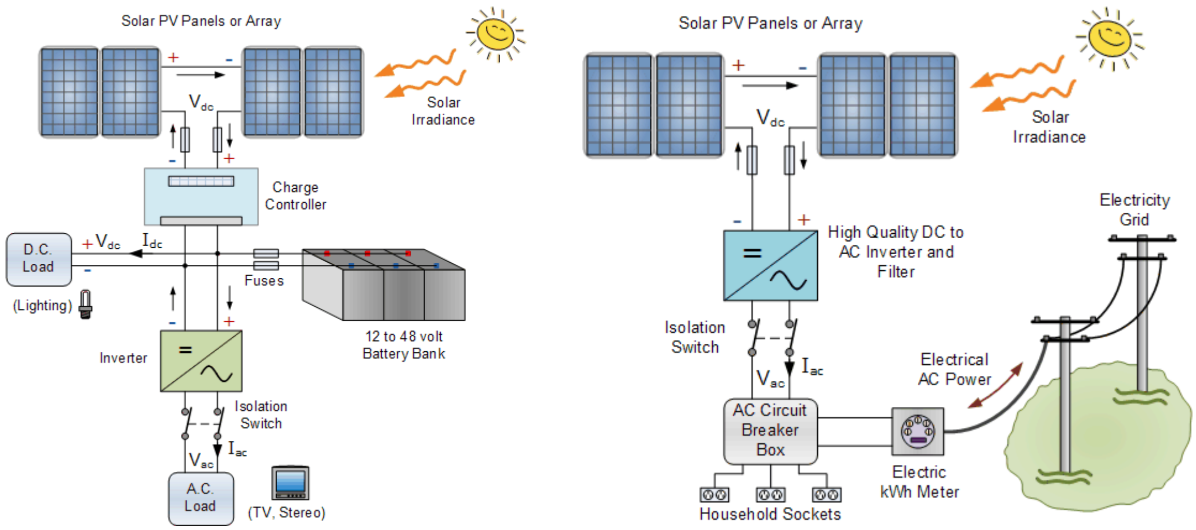


Fig. 4-8. A simplified stand-alone PV system (left) and a simplified grid-tied PV system (right)

4.5 Solar efficiency and system performance

Solar efficiency, defined as the amount of electricity produced by a solar cell or PV panel relative to the sunlight energy striking the device, indicates how efficiently a PV device converts solar radiation into electricity.

The theoretical efficiency limit of silicon solar cells is 33%. Field-installed silicon solar panels demonstrate typically a solar-to-power efficiency in the range of 10–20%. Solar cells with efficiency approaching 50% are being developed by researchers. Solar cells made of silicon currently provide a combination of high efficiency, low cost, and long lifetime. In a sunny day at 9:00 am–3:00 pm without shade, a silicon solar cell generates 0.5-V electricity at 1-3 W power (1 W = 1 J/s). The solar efficiency of silicon cells in a solar panel decreases slowly over time of field exposure to sunlight. The solar efficiency remains commonly more than 80% of the original level after 25 years of expected panel lifespan.

The rated (specified) capacity of a solar panel indicates the maximum power in watts (W) it can produce under standardized test conditions. The specified power of a solar panel is measured under the standard test condition (25°C, **1 sun = 1 kW/m^2 irradiance** of full solar noon sunshine, and a sea level air mass of 1.5).

The actual performance of a PV system can be estimated from the **IV curve** (or current-voltage characteristic curve) of the installed solar arrays. The IV curve is a graph exhibiting the relationship between the electrical current and voltage output of a solar array under given sunlight (irradiance) and temperature conditions (Fig. 4-9). It is obtained by measuring the electrical current and voltage output of a solar

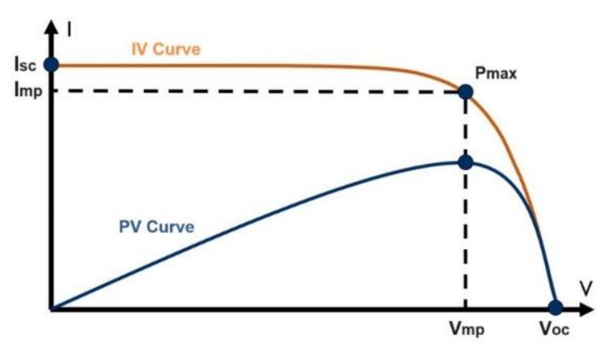


Fig. 4-9. Current-voltage (IV) curve of solar panels

array while varying the load. The main parameters in an IV curve include the open-circuit voltage (V_{OC}, the maximum voltage that can be obtained from a PV array when there is no load connected), the short-circuit current (I_{SC}, the maximum current that a PV array can produce when its output is shorted), the maximum power (P_{max}), the maximum power point voltage (V_{mp}, the voltage at which resulting in P_{max} in combination with I_{mp}), the maximum power point current (I_{mp}, the current at which resulting in P_{max} in combination with V_{mp}), and the fill factor [$FF = P_{max}/(V_{OC} \times I_{SC})$]. A higher fill factor indicates a more efficient solar array.

Solar panels can underperform and even fail over the expected 25-year life of uses. Solar panels slowly lose the power generation capacity by averagely 0.5% per year due to light-induced degradation. This slow degradation is often not noticeable, and most solar panels will still perform at 80% or higher of the original rated capacity after 20 years.

The amount of energy produced by a PV device depends both on available solar energy (insolation) of the installation site and the solar efficiency of the device. **Solar generation hours,** the daily times when installed solar panels generate the most electricity, range typically from 10:00 am to 4:00 pm. The daily solar insolation varies with location, season, and weather, but can be indicated by a **peak sun hour** (PSH) number (Fig. 4-10). One PSH equals 3,600 kJ/m^2 (or 1 kWh/m^2), defined as the solar energy received in one hour on 1-m^2 surface at **1 sun** or 1000 W/m^2 solar irradiance (i.e., 1 sun = 1000 W/m^2). For example, if a location receives sunlight at 500 W/m^2 between 8 AM and 10 AM, those two hours combined would be considered one PSH. The annually-averaged PSH numbers can help estimate the solar electricity output of specific PV systems.

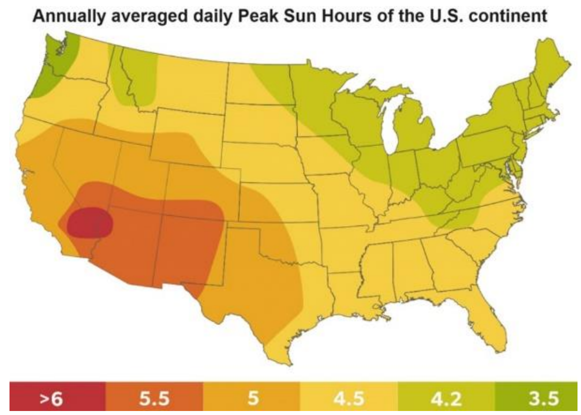


Fig. 4-10. Annually averaged peak sun hours of the U.S. continent

The actual power of a solar panel changes with the Sun's position in the sky. The Sun travels through 360° **east to west** every day in 24 hours. The Sun's position in the sky for a particular geographic location at any time of a year can be calculated and plotted on a **Sun Chart** in Cartesian (rectangular) or Polar coordinates (a free sun chart calculator is available at sunearthtools.com/dp/tools/pos_sun.php) (Fig. 4-11).

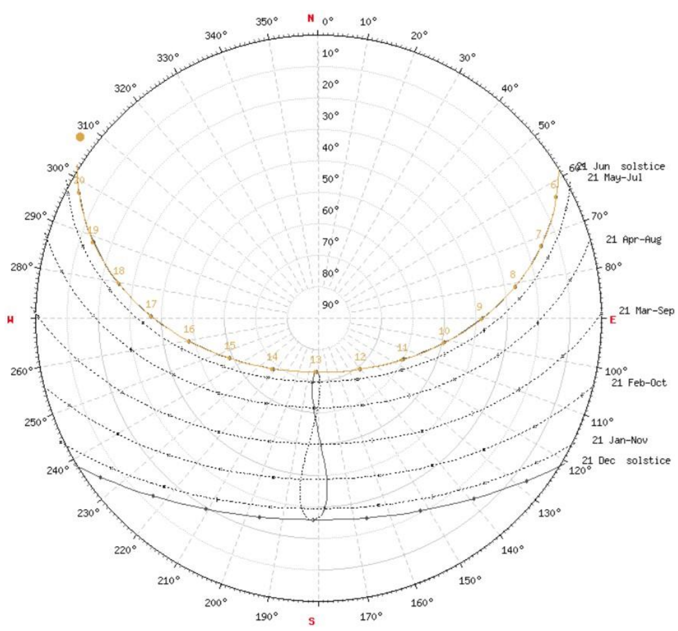


Fig. 4-11. Sun charts showing the Sun's path through sky on particular days

The orientation of solar panels influences the amount of solar radiation received and thus, impacts the PV system performance. In the northern hemisphere, solar panels should always installed facing the true south and in the southern hemisphere facing the true north. For fixed-tilt PV systems, the panel tilt angle should be close to the latitude of the location.

In addition to the solar panel orientation toward solar radiation, temperature, shades, and dust deposits all influence the performance and electricity yield of PV systems. Solar cells are sensitive to temperature. In general, solar cells love cold, sunny environments. In Antarctica, for example, solar arrays demonstrate greater electricity generation efficiency.

4.6 Solar power economics

Solar panels are highly reliable. They contain no moving parts and require minimal maintenance. According to the Solar Energy Industries Association (SEIA), solar panels can last 20–30 years, with an average lifespan of 25 years. A typical silicon crystalline solar panel will generate enough energy to repay the embodied energy within 2 years of installation. A PV system generates 3 to 6 times more energy than is required to produce the solar panels and BOS components. Reusing multi-crystalline cells can reduce manufacturing energy by over 50%.

Modern crystalline silicon solar panels contain only traces of lead in the solder used for the cell interconnections. Although pollutants and toxic substances are emitted during PV manufacturing, life cycle emissions are low. Furthermore, PV systems on average consume less water to generate electricity (26 gallons per MWh), compared to nonrenewable technologies such as coal (687 gallons per MWh).

Major disadvantages of photovoltaics: 1) no electricity generation at night; 2) lower electricity output when weather is unfavorable; and 3) relatively high installation costs. The cost of solar power has dropped over 80% since 2009. Today a 200-W, 12-V high efficiency monocrystalline solar panel costs ~$250 in the market. In 2023, global investment in solar power is estimated to be $380 billion. This accounts for 14% of the total amount invested in energy worldwide. Including sectors such as manufacturing, sales, distribution, and installation, there are over 231,000 U.S. solar jobs. The Inflation Reduction Act of 2022 expanded the federal Investment Tax Credit (ITC) to 30% until 2032 for the installation of a solar PV system, a savings of over $7,500 for an average system.

Currently, no data exist on the total flow and final disposal of PV modules reaching end-of-life. At the end-of-life, materials embodied in used PV modules can be recovered and used as virgin material replacements for new module manufacturing (Fig. 4-12).

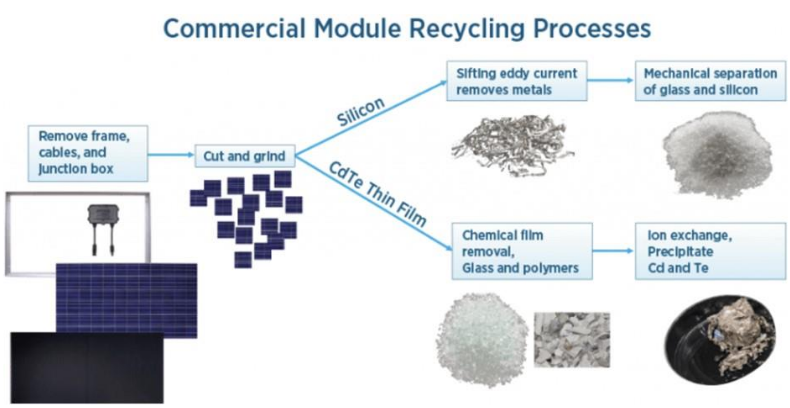


Fig. 4-12. Potential recycling processes of spent solar panels

5. Agrivoltaics

5.1 Concept

Solar power or photovoltaic electricity is a renewable, clean energy that has been increasingly produced and utilized in the past two decades to help meet the societal demands for energy. Solar PV arrays, however, take space to deploy. The space is mostly available in remote areas, where an established electricity grid does not exist and transmission of electricity to urbanized locations may be impractical due to the involved infrastructure costs and energy losses. Agrivoltaics may be a solution to the dilemmatic situation.

Agrivoltaics, or agrophotovoltaics or agrisolar, is the simultaneous use of land for both agricultural production and solar energy generation (Fig. 5-1). The symbiotic system integrates solar power with agriculture, creating energy and providing space for crops, grazing, and native habitats under and between solar panels. Agrivoltaics enables the joint development of the same land simultaneously for both agriculture and solar energy, promoting land use efficiency, climate change mitigation, sustainable food, and local economies. Extensive practice of agrivoltaics is expected to significantly enhance the resilience of the society to climate change.

Fig. 5-1. An agrivoltaic system concurrently growing crops and producing solar power on the same farmland

5.2 Development

To address climate change, the Biden Administration set a goal to decarbonize the electricity sector by 2035. Solar energy, which currently provides about 4% of U.S. electricity supply, has a key role in this decarbonization. According to DOE's *Solar Futures Study*, solar energy could supply as much as 40% of U.S. electricity by 2035. This level of solar deployment could require ~0.5% (5.7 million acres) of the U.S. contiguous land area.

As utility-scale PV systems must be located near a power grid or electricity transmission lines, relatively flat and sunny farmland becomes an ideal location for housing the PV systems. Nevertheless, dedicating farmland to solar electricity production may worsen the ongoing trend of converting farmland to non-agricultural uses and threaten the food security. Combining agriculture and solar on the same piece of land might be a strategic option (Fig. 5-2).

Fig. 5-2. An agrivoltaic system integrating sheep grazing and solar electricity production on farmland

Though the concept can be dated back to the 1980s, agrivoltaics is still a nascent business model. Based on data collected so far by the National Renewable Energy Laboratory, there are over 2.8 GW of agrivoltaic sites in the U.S., the majority of which involve sheep grazing and/or pollinator habitat. Growing crops under solar panels has been largely confined to research test plots, though this is beginning to change. At least five commercial solar-crop sites are operating in Colorado, Massachusetts, and Maine.

5.3 Agrivoltaic designs

In agrivoltaics, solar panels and crop plants (and grazing animals) co-exist and should benefit mutually. In practice, solar panels require special deployment and positioning to comply with farming operations and crop establishment. Solar panels are typically positioned about 7–10 feet (~2–3 m) above the ground, with some spacing to provide a mix of sun and shade to the plants below. This layout can offer compounding advantages such as shielding plants from excessive heat, cold and ultraviolet (UV) radiation, thereby increasing the yield of certain crops.

Agrivoltaic PV configurations can be broadly split into two categories: elevated and inter-row. Elevated systems feature PV modules sited directly above the vegetation. These heights are generally greater than 6 feet (1.8 m). Crops are grown underneath the PV modules and in inter-row space of PV arrays (Fig. 5-3). The modules can act as a protective barrier for the underneath crops against inclement weather, although there can be more substantial shading and reductions in sunlight. It is common to find higher-value crops, such as berries, grapes, short-stature fruit trees, and delicate vegetables, in elevated agrivoltaic systems.

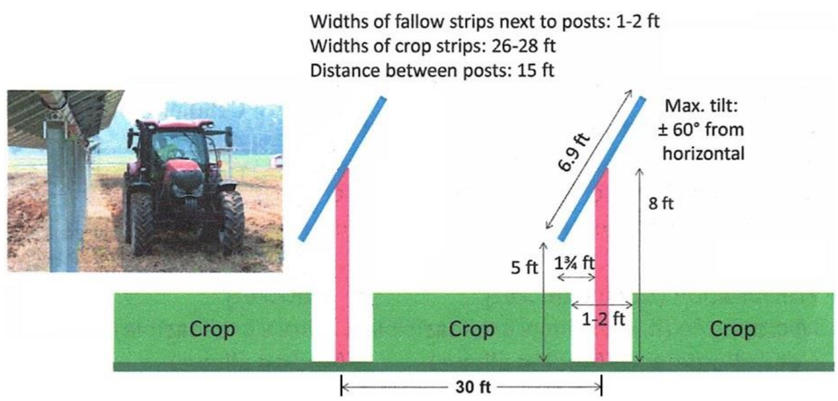
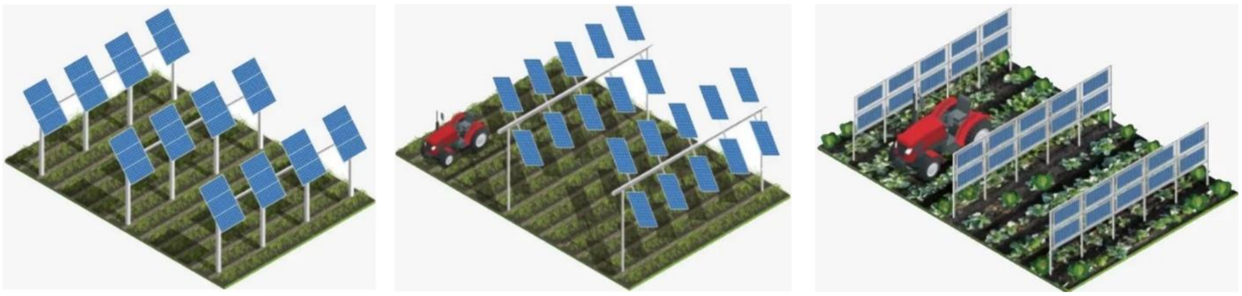


Fig. 5-3. An agrivoltaic system design employed in a research trial in Pittstown, NJ, USA

In inter-row agrivoltaic systems, vegetation is primarily grown in between rows of PV arrays rather than directly under them. To accommodate large farming machinery, the inter-row spacing of the PV arrays (e.g., ~10 m or 30 feet) is greater than conventional ground-mounted utility-scale PV projects. Compared to elevated agrivoltaic systems, the PV modules in inter-row agrivoltaics provide less physical protection for crops against the elements, though more sun is usually available to the vegetation. It is more common to find lower-value crops, such as grasses, grains, and hardy vegetables, in inter-row systems, and higher-value horticultural and specialty crops in elevated systems.

Some overlap exists between these two broad categories, such as the example of agrivoltaic grazing operations in which ruminants graze on grass grown both below and between PV rows. Furthermore, the PV arrays may be elevated to allow cattle to pass under the panels or to accommodate taller vegetation growth. The posts may be strengthened against animal rubbing.

In agrivoltaics, solar panels are typically ground-mounted on poles or racks facing south at a fixed tilt angle. Single axis tracker systems are also practiced. Vertical bifacial PV systems are not uncommon (Fig. 5-4). Studies showed that vertical bifacial PV systems had comparable power generation, better crop yield, yet reduced panel soiling issues relative to fixed-tilt systems.



Reinforced regular mount Tracker stilt mount Vertical mount

Fig. 5-4. Pole-mounted (left), rack-mounted (middle), and vertical bifacial (right) solar arrays in agrivoltaic systems

5.4 Agrivoltaic applications

Agrivoltaic applications include 1) crop and food production, 2) livestock production, 3) provision of ecosystem services through vegetation management, and 4) solar greenhouses (Fig. 5-5).

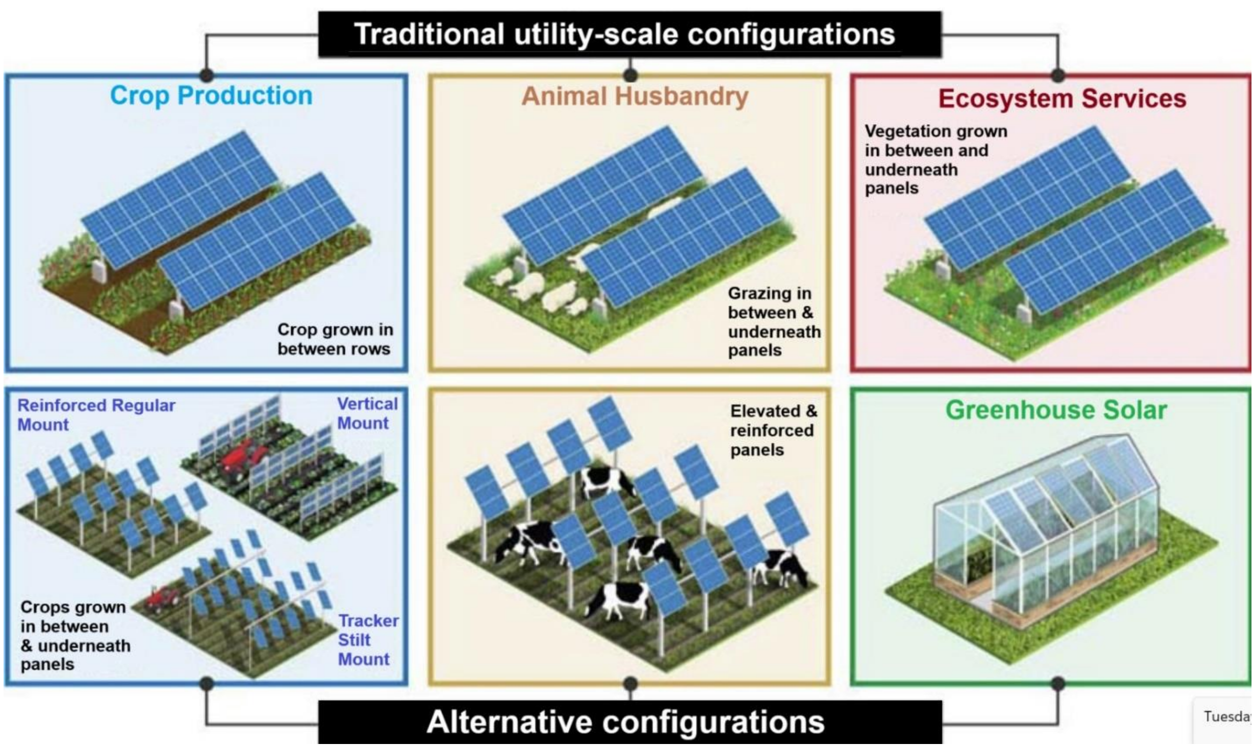


Fig. 5-5. A variety of agrivoltaic applications in crop production, livestock rearing, ecosystem service provision, and solar greenhouses

Crop production systems include the cultivation of annual and perennial food, fiber, or specialty crops underneath and around solar infrastructure. Crop production systems are affected by the partial shade of solar infrastructure; crops can be grown directly underneath panels and in between rows of panels. Crops can be managed manually or with mechanized equipment.

Livestock and animal husbandry agrivoltaics systems include the grazing and management of animals underneath, around, and directly adjacent to solar infrastructure. Animals including sheep, cattle, poultry, honeybees, and rabbits are all adaptable. Animals can be on-site year-round, seasonally, or on an as-needed basis, as determined by the animal manager and the needs of the solar site. Such agrivoltaic systems may need to include vegetation planting and management, fencing, water supply, and animal access to facilitate the compatibility with animal husbandry practices.

Ecosystem service agrivoltaic projects encompass installations that are designed to create or restore habitat, improve soil, and provide other ecosystem services. Ecosystem services can include supporting, provisioning, regulating, and sociocultural services.

5.5 Advantages of agrivoltaics

The global population continues to increase, so does the human competition for food, water, and energy. Agrivoltaics produces more renewable energy and more food whilst using less water, fortifying the security of all three of these critical natural resources and providing a rare chance for true synergy.

Agrivoltaics may serve as a holistic, integrated approach to the food-energy-water nexus that may enhance the resiliency of both food and energy systems (Fig. 5-6). The potential benefits of practicing agrivoltaics by co-locating agriculture and PV systems on food production, irrigation water requirements, and energy production are identified as:

Fig. 5-6. Agrivoltaic trials on production farmland

1) Maximizing land productivity
2) Enhancing the resilience of farmland ecosystems by reducing water budget, increasing crop yield, and preserving agricultural land. Agrivoltaics has the potential to help farmers adapt to climate change and diversify their income through land lease payments or other business structures. Landowners begin earning passive income once the equipment is installed and solar energy is generated. Solar panels provide protection to crops against extreme weather events.
3) For the solar industry, agrivoltaics has the potential to facilitate siting of solar installations, improve solar PV panel performance by cooling the panels from underneath and surrounding evapotranspiration, and lower operations and maintenance costs by limiting the need for mowing and sharing water between irrigation and panel cleaning.
4) For communities, agrivoltaics could help sustain rural farmland economies.

5.6 Challenges of agrivoltaics

The main disadvantage of agrivoltaics is the high upfront cost required. The capital costs of agrivoltaics tend to be higher than traditional solar development due to modified system structures and more complex design and installation. Compared to conventional roof mounted PV, dual use solar systems require a larger, more complex mounting systems which can cost up to triple the cost of the installation of flat roof PVs. Further to this, deeper steel foundations are required for the PVs to provide stability and resilience in adverse weather conditions; the embodied carbon emissions associated with this are high.

A Department of Energy (DOE) Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) research study categorized the agrivoltaics success factors in the U.S. into five primary themes:

1) Climate, soil, and environmental conditions: The ambient conditions (e.g., climate, surrounding land use, and water access) and factors (e.g., soil health, prior land use, grazing livestock pests and diseases) of the specific location that are beyond the control of agrivoltaic practitioners need to be examined and evaluated.

2) Configurations, solar technologies, and designs: The choice of solar technology, the site layout, and other infrastructure that can affect light availability and solar generation have to be carefully considered before the start of agrivoltaics projects. Project capacity, PV technology, panel height, panel spacing, row spacing, and racking system all deserve attentive designs and selection.

3) Crop selection, cultivation methods, and management approaches: Vegetation selection, vegetation establishment methods, and product markets and distribution all warrant evaluation and determination to secure agrivoltaic success.

4) Compatibility and flexibility: Sitewide operation and management plans, infrastructure placement, farm practice compatibility, and prescribed grazing plan all need to be examined and designed to achieve the compatibility of the solar technology design and configuration with the competing needs of the solar owners, solar operators, and agricultural practitioners.

5) Collaboration and partnerships: It is critically important to attain understandings and agreements across stakeholders and sectors on supporting agrivoltaic installations and operation, including community engagement, permitting, and legal agreements.

To make agrivoltaics a widely available option for developers, questions about cost, worker safety, liability, and other business, legal, and regulatory issues will need to be addressed. At the same time, questions remain for farmers about how to do agrivoltaics, including which crops are suitable in a shaded environment.

All agrivoltaic stakeholder groups – from developers to farmers to financiers and insurers – will need to understand each other’s priorities and establish common goals to realize the potential benefits. Communities will need to see tangible benefits from agrivoltaics.

Notes