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Review

On the State-of-the-Art of Solar, Wind, and Other Green Energy Resources and Their Respective Storage Systems

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Abstract: In this article, we provide a brief overview of solar photovoltaic and thermal energy, wind turbines with vertical and horizontal axes, and other sustainable energy production systems as well as energy storage systems. In some remote areas away from easy access to electricity and fresh water, a self-contained and self-sustainable off-grid energy production and storage farm is very much needed. In this so-called sustainable energy farm, solar photovoltaic and solar thermal energies along with wind energy can be harvested and stored in a secured battery warehouse with mobile wireless surveillance systems with unpredictable coherent motions. In this battery-based energy storage system, special fire protection measures must also be employed with heat sensors and early detection and alarm systems. The alarm system will be connected to both local fire stations and automated fire extinguishing systems. A subsequent paper will present the details of this wireless fireproof alarm powered by sustainable energy resources. The main purpose of this paper is to document, provide references, and inform about the state-of-the-art achievements in the field of renewable energies, particularly, solar, wind, and other green energy resources.

Keywords: wind; solar; green; storage; transmission; photovoltaic; fireproof

Citation: Wang, S.; Tonge, E.; Sekanyo, I.; Portmann, E.; Azzouz, S.M. On the State-of-the-Art of Solar, Wind, and Other Green Energy Resources and Their Respective Storage Systems. *Eng* **2023**, *4*, 857–883. https://doi.org/10.3390/eng4010052

Academic Editors: George Z. Papageorgiou, Maria Founti and George N. Nikolaidis

Received: 23 December 2022
Revised: 4 February 2023
Accepted: 27 February 2023
Published: 6 March 2023

1. Introduction

Solar energy refers to radiant light and heat from the Sun that could be harnessed as one of the main green energy resources, as shown in Figure 1. On average, 173,000 terawatts (TW) of solar radiation continuously strike the Earth in daylight, while global electricity demand averages 2.7 TW [1].

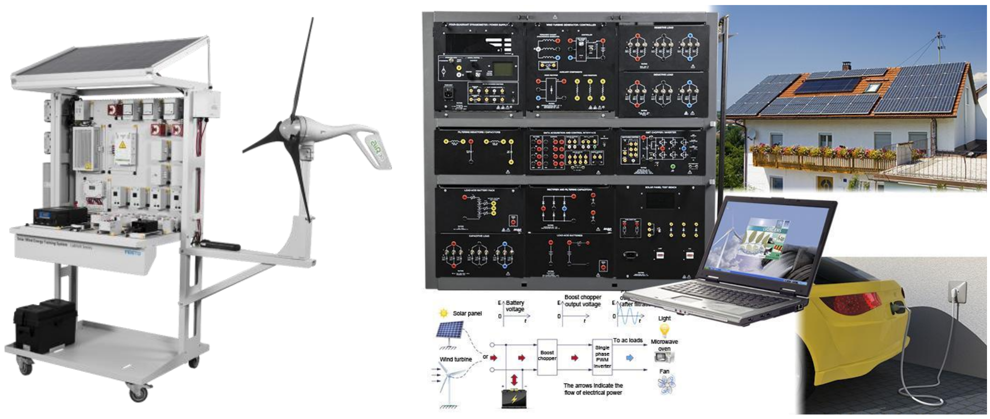

Figure 1. LabVolt Solar House similar to the University of North Texas (UNT) zero energy house model is a good maintenance house example for the energy production and storage farm [2].

As an essential source of renewable energy, solar energy systems are broadly characterized as either passive solar or active solar depending on how solar energies are captured and distributed. The solar photovoltaic portion can be directly converted into electricity, whereas solar thermal energy is traditionally harvested in water or air heating units or molten salt in large installations. Typical solar thermal systems include water heater thermosiphon, parabolic troughs, solar power towers, heliostat power plants, air heating solar units, solar dish engines, and solar thermoelectric units [1].

With respect to wind energy, as described in Ref. [3], nearly all of the wind turbines currently in use are horizontal-axis turbines. Horizontal-axis wind turbines have blades like airplane propellers. In general, they have two-blade, three-blade, upwind, and downwind installations. The largest horizontal axis turbines (Vestas V236-15MW) are taller than 70-story buildings, more than 900 feet, and have blades more than 700 feet long [4]. Taller turbines with longer blades generate more electricity. The specific kinetic energy is proportional to the square of the velocity. Moreover, the mass flow rate is also proportional to the product of the air density, the velocity, and the cross-sectional area of the horizontal-axis wind turbine which is proportional to the square of the blade radius. Therefore, the power generation will be proportional to the cube of the velocity, the air density, and the square of the blade radius.

Recently, vertical-axis windmills are getting more attention in practice and often have a comparable performance to horizontal-axis windmills. As described in Ref. [5], Savonius wind turbines have blades built around the vertical shaft in a helix form, which basically looks like the double helix of DNA or fusilli pasta. In Ref. [6], the system work function for power generation has been elaborated.

A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades which produce lift and function like airplane wings or helicopter rotor blades. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates the lift force or lift. In addition to the surface shear force, a typical source of drag, the cross-sectional geometries of the blades also produce the so-called form drag. This translation of aerodynamic forces to the rotation of a generator creates electricity. However, the effectiveness of a wind turbine in generating electricity also depends on the weather. When the wind is above 20 mph, for safety, many wind turbines are turned off. Needless to say, when there is no wind, the wind turbine will not be functional. In short, such an energy source is often intermittent. Moreover, for environmental reasons, more offshore wind turbines have been installed in addition to onshore ones.

2. Solar Energy

As an essential source of renewable energy, solar energy systems are broadly characterized as either passive solar or active solar depending on how they capture and distribute solar energy. Solar energy has two typical portions, namely, photovoltaic energy, which is directly converted into electricity and constitutes a smaller percentage, and thermal energy, which is harvested in water or air heating units and constitutes a much larger percentage [7]. Photovoltaic (PV) cells are made from semiconductor materials that eject electrons, when energetic light over a threshold strikes the surface, and produce electrical currents [1]. A wide variety of semiconductor materials can be employed for PV cells. A typical material is silicon. In addition, copper indium gallium diselenide (CuInSe2), cadmium telluride (CdTe), perovskites, and even some organic photovoltaic compounds (OPV) can be utilized [1]. Although PV conversion efficiency is an important metric, in engineering applications, cost efficiency measured by the cost per watt of power must also be considered. Solar PV capacity has grown by nearly 500 times since 2000. In 2020, global PV power capacity grew by over 138 GW and reached 773.2 GW. The top installers of solar power in 2022 were China (307.0 GW), the USA (95.2 GW), and Japan (74.2 GW) [8].

For most available commercial panels, the photovoltaic energy conversion rate is around 15% to 20%, although some researchers have developed photovoltaic (PV) cells with efficiencies near 50% for space applications [1]. However, even with intermediate efficiency, with 0.6% coverage of the land area, PV cells would generate enough electricity to meet the demand in the USA [1].

According to Ref. [9], active solar techniques include the use of photovoltaic systems, concentrated solar power, and solar heating systems; whereas passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces with more natural air circulations. According to Ref. [9], a photovoltaic solar panel produces electricity in direct proportion to the amount of exposed sunlight. As shown in Figure 2, the sun's angle in the sky influences the intensity of the light received by the Earth. Thus, the location of the sun directly affects how much energy a solar panel generates. Several factors such as time of day, season, and latitude also determine the sun's location relative to the panel.

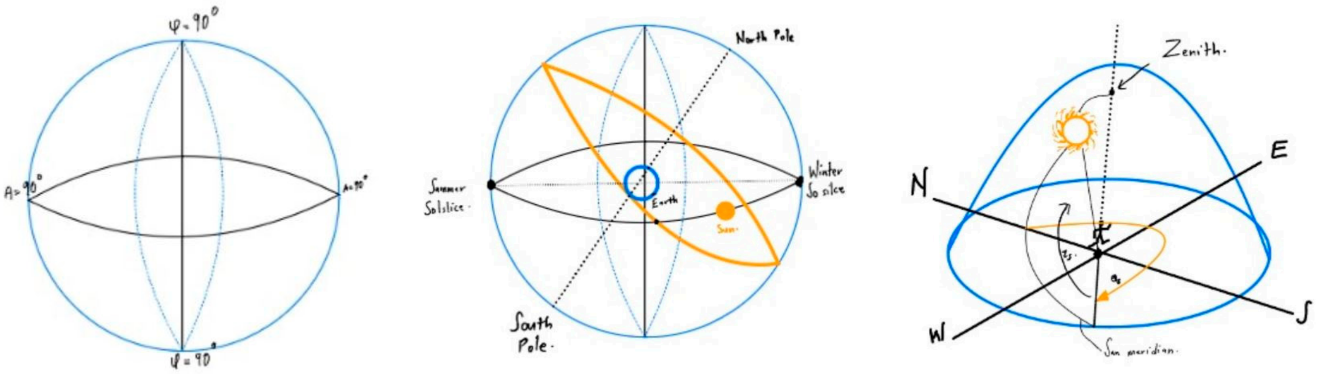

Figure 2. Position of the sun, latitude, and longitude [1,9].

As shown in Ref. [9], when the sun is overhead, its rays are the most direct and intense. As it moves lower in the sky, the same area of light from the sun covers a larger area of the Earth. As the area increases, intensity decreases. Consequently, the solar panel receiving this light produces less electricity. To partially compensate for the intensity reduction, a solar panel is often tilted to match the sun's angle [10], although the complexity and upkeep of mechanical tracking systems add considerable cost to a solar energy installation. In Ref. [11], a passive solar tracking system is utilized. This passive system developed by Zomeworks is based on the movement of the liquid within the canister-copper tube system and respective gravitational forces.

Of course, the light power and intensity measured by lumen, steradian, and candela can be easily mapped into the power unit Watt [12]. With respect to the latitude, the declination angle (δ) relates to the tilt of the earth's axis, which is 23.45°. Declination is the angle between an earth–sun line and the equatorial plane. The declination angle is measured north or south of the celestial equator, along the hour circle passing through the point in question. The declination angle varies from positive 23.45 degrees to negative 23.45 degrees as the earth rotates around the sun.

The latitude is an angular value, an expression of positioning north–south from any point on the earth. Longitude is an angular value, an expression of positioning east–west from any point on the earth. The optimum tilt angle of our solar system depends on the positioning of the sun and is defined by the height of the sun (zenith) and the sun's azimuth. The zenith is an angle between a line that points from the site toward the center of the sun, and the horizon. It is the opposite angle to the sun's height. The azimuth angle is measured clockwise, between the geographical north and the point on the horizon directly below the sun.

2.1. Solar Voltaic Portion of Energy

The subjects of the solar voltaic part of energy include photovoltaic (PV) cells, modules, panels, characteristic voltage (V)–current (I) curves, electric power output, efficiency, and DC to AC inverters along with respective advantages and disadvantages. As shown in Figure 3, a photovoltaic panel is a device that produces electrical energy when it is illuminated by a source of light. By placing a PV cell outside directly under the sun, it is possible to generate electrical energy through the use of sunlight. The basic component of a photovoltaic panel is the photovoltaic cell. A photovoltaic cell is primarily a P–N junction mostly made of silicon. A type N semiconductor is doped with Arsenic (As), Antimony (Sb), or Phosphorus (P) with free electrons with negative charges; whereas a type P semiconductor is doped with Gallium (Ga), Indium (In), or Boron (B) with so-called holes or vacancies with positive charges. However, the P–N junctions in PV cells are made up of thin slices of silicon so as to maximize its surface area, thereby allowing PV cells to intercept as much light as possible.

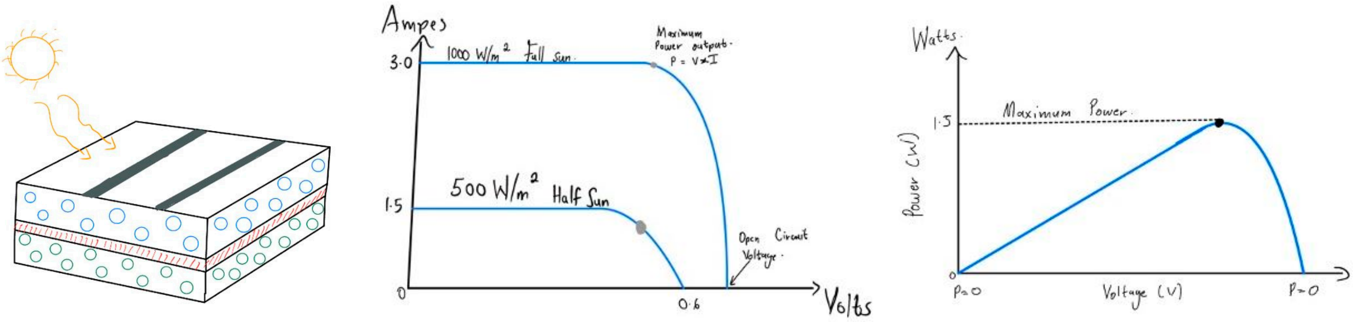

Figure 3. Solar voltaic power output and principles [1,9].

The PV panels usually consist of PV modules fastened to a common frame. Most PV solar cells have a solar rating for the maximum deliverable solar power produced by the cell in watts which is equal to the product of the cell voltage multiplied by the leading cell current. For instance, if the maximum output current output of a single 0.5 Volt silicon photovoltaic cell with a maximum rated power output of 1.75 Watts at the full sun, the maximum current can be easily estimated as 3.5 Amps. Note that the maximum theoretical current as the confirmed or real current is determined by the rate of the incoming solar photons. Moreover, the amount of electrical power generated by the photovoltaic cell depends on solar irradiance and environmental conditions such as temperature and cloud cover. The power rating of a solar cell is expressed in Watts (W), which refers to the maximum or peak power delivered by one cell at the full sun with full exposure to sunlight.

PV cells, when illuminated, are equivalent to a source of current parallel with diodes. In order to produce more electrical power from photovoltaic solar cells, we need to either increase the photovoltaic effect and the energy of photons or produce a different type of cell that is more efficient at converting solar energy into electricity. The amount of electric power provided by a PV cell depends on the point on the V–I curve at which the PV cell operates. The point on the V–I curve where the photovoltaic cell output power is maximum is referred to as the maximum power point (MMP). It is important that the PV panels operate at maximum power point in order to maximize the amount of energy produced. Notice, however, only a small portion of the energy from the incident light could be converted into electrical energy whereas the majority of the energy is locked in the so-called solar thermal energy part. The more productive or efficient the PV cells in the PV module or panel are, the higher the amount of electric power would be produced. The efficiency of PV modules or panels is usually calculated using the characteristic E–I curve under standard test conditions. The formula is given below as

$$\eta = [(\text{MPP})/(\text{Irradiance} \times \text{A})] \times 100,$$

in which η is the efficiency of the PV module, MMP stands for the maximum power point of the PV module, A represents the surface area of the PV module, and Irradiance refers to the energy density when PV cells are illuminated by sunlight and measured in W/m^2.

The three most commonly used SI radiometric units describe the effectiveness of radiation coupling between a light source and an optical system, namely, (1) Radiance; (2) Irradiance; and (3) Radiant Flux. Radiance is often casually called “brightness”, a term used in photometry to describe the perception of human eyes looking at a light source. Irradiance is the radiometry term for the power per unit area of electromagnetic radiation incident on a surface. Irradiance is sometimes called intensity with a unit watts per square meter (W/m^2), or milliwatts per square millimeter (mW/mm^2); whereas Radiant Intensity is measured in watts per steradian (W/sr). Irradiance is the amount of light energy from one emitting object hitting a square meter of another each second. Photons that carry this energy have wavelengths from energetic X-rays and gamma rays to visible light to infrared and radio. Solar irradiance is the output of light energy from the entire disk of the Sun, measured at the Earth [13].

An inverter is a device that changes direct current (DC) power stored in a battery to standard 120/240 VAC electricity. Most solar power systems generate DC which is stored in batteries. In an inverter, direct current (DC) is switched back and forth to produce an alternating current (AC). Then, it is transformed and filtered into an acceptable output waveform such as a sine wave. The final product becomes a waveform that is acceptable to all loads without sacrificing too much power in the conversion process. Solar panel specifications include KC50TM high efficiency multi-crystal photovoltaic module with an efficiency of over 16%, maximum power of 50 Watts, the voltage at a maximum power of 17.9 Volts, current at a maximum power of 2.80 Amps, open circuit voltage of 21.8 Volts, short circuit current 3.35 Amps, series fuse rating 6 Amps, dimension 25.2 by 25.7 by 2.1 inches, and weight 16 lbms.

A bank of solar voltaic panels is normally wired in either series or parallel settings, as shown in Figures 4 and 5. If we wanted to wire the solar panel banks in series, a few assumptions had to be made. The first assumption is that each individual solar panel will be producing the same voltage and current. Secondly, we assume that solar panels act like batteries; thus, if we were each individual solar panel in the panel bank in series, we can add the voltage produced by each panel together. Total voltage is equal to the number of solar panels multiplied by the voltage being produced in each panel, but current, on the other hand, will not be multiplied. Current is the same total output of the solar bank as each individual solar panel. For the wiring of the solar panel bank in parallel, we still have the same assumptions, that solar panels are acting like batteries for a solar panel bank and each individual solar panel is producing the same voltage and current. Hence, for a bank of solar panels connected in parallel instead of in series, the total voltage being produced would be equal to the voltage output of an individual solar panel, whereas the total current will be the product of the number of solar panels and the current produced by each panel in the bank.

Figure 4. Solar voltaic panels in a series configuration [9].

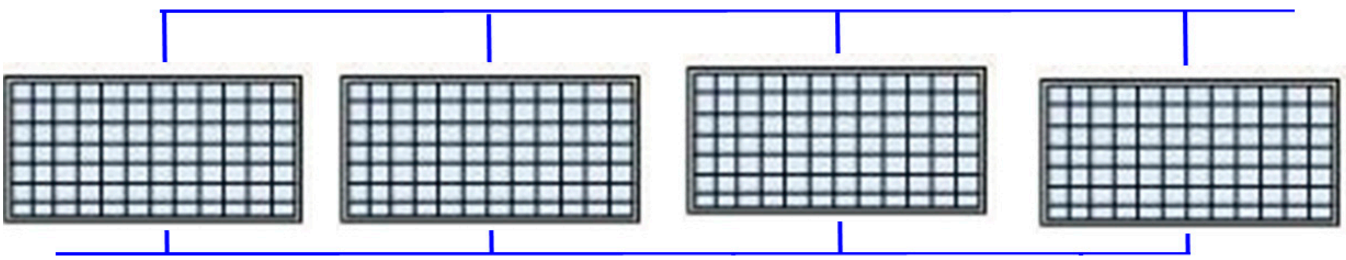

Figure 5. Solar voltaic panels in a parallel configuration [9].

2.2. Solar Thermal Portion of Energy

Another more significant portion of solar energy is in the thermal energy form. A solar thermal system is designed to capture the Sun's radiant energy and convert it into heat (thermal energy) by transferring or exchanging the heat to and from a fluid (liquid or gas). In practice, water and air are the two most commonly used fluids in existing solar thermal systems. It is worth noting that nearly fifty years ago, amid the Arab oil embargo, which had caused a national energy crisis during President Jimmy Carter's administration, thirty-two solar panels were installed on the White House roofs for thermal solar energy [14]. Regrettably, they were removed in the next administration. One route for harnessing solar thermal energy to produce electricity is to use concentrated solar power (CSP). The world's first commercial solar thermal power plant came online in Spain in 2007. Projections from the International Energy Agency are that the share of renewable electricity generation from solar energy will increase from 0.3% in 2011 to almost 0.6% in 2018 and 17% in 2021, of which about one-tenth will be from CSP [15].

All concentrating solar power (CSP) technologies use a mirror configuration to concentrate the sun's light energy onto a receiver and convert it into heat. The heat can then be employed to create steam to either drive a turbine to produce electrical power or directly serve as process heat in manufacturing for heavy industries [16]. In most solar thermal energy collectors, sunlight shines through the glass or silicon panels. Some of the light, in particular, longwave radiation, is reflected or refracted. However, most of the light, in particular, shortwave radiation, passes through the glass and onto the dark-colored collection material where a large portion of the radiant electromagnetic energy is absorbed and converted into thermal energy or heat. In practice, heat is thermally transmitted from the absorber material to the copper tubing via physical contact, conduction, or convection. Notice that the copper thermal conductivity is much higher than aluminum, steel, or PVC-type materials. The collected heat conducts through the copper tubing to the fluid inside the pipe system. As the fluid (water or air) moves through the tubing, the conducted heat is transmitted to other parts of solar thermal systems, as shown in Figure 6.

Figure 6. Different LabVolt solar thermal energy collectors [2].

The clear glass panels are often double-glazed and manufactured with a minimum amount of iron content in order to pass a larger spectral portion of infrared energy. In addition, thermal insulation placed below and on the sides of the absorber material helps to minimize thermal losses or the inadvertent heat transfer to the ambient air that surrounds the solar collector enclosure. Moreover, baffles and manifolds are used to increase surface area and to control the flow of fluid through the solar collector in such a way as to improve thermal transfer efficiency. There are many different types of solar collectors in use today. In general, we have passive air collectors and active water collectors which can also be connected in parallel and series, as shown in Figure 7.

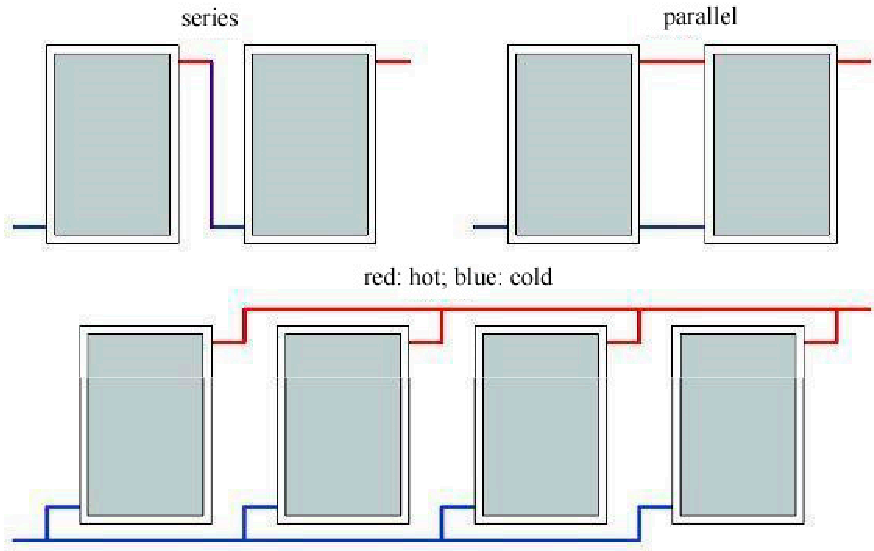

Figure 7. Solar thermal panels are connected in series and parallel [2].

The integrated collector storage or solar batch heater is suitable for moderate climates; this simple collector uses its internal water tank or multiple tanks for both collection and storage of solar heat. Each tank is coated to absorb solar energy, and the entire assembly is enclosed in a thermally insulated and glazed box. One such system is the so-called thermo-siphoning water panel, essentially a flat-plate type of convection heat storage system that requires storage tank placement above the collector. Similarly, a thermos-siphoning air panel is a glass window upon a vertically positioned and well-insulated box with a dark-colored interior that allows the air inside to become heated by the sun. Natural convection causes the air to flow from bottom to top. The evacuated tube is another convection heat storage system that also requires storage tank placement above the collector. The heat pipe style uses long borosilicate glass tubes with pure copper tube absorbers called heat pipes inside to indirectly heat an insulated copper manifold at the top of the unit by way of evaporated heat pipe fluid. The purified water with additives boils at only 86°F due to an internal vacuum. The cooled vapor forms back into a liquid by way of condensation and such heating processes repeat continuously. A vacuum between the clear outer glass and an aluminum nitride-coated inner glass absorber tube virtually eliminates heat loss by natural convection, so these units are highly efficient. The vacuum is maintained by a barium coating at the bottom of each tube normally silver in color; a cloudy white coloring at the tube end indicates a loss of vacuum.

Solar thermal panels or arrays can be configured or connected in series or in parallel as illustrated in Figure 7 to increase volume or flow rate, respectively. Although series configuration is not normally used in residential applications due to the high-temperature elevation through the sequential heat from the solar thermal energy, the high water temperatures from series-connected arrays are sometimes required for commercial installations. Moreover, for systems in series or parallel, basic plumbing techniques are used to interconnect the solar collector panels. The use of brass unions permits easy collector replacement and can minimize rooftop soldering. Several key factors determine the required size or capacity of a solar collector array for any given thermal system, which includes the required solar power, the available space, and the collector orientation. In general, the array must have a large enough surface area to capture the required solar power for a particular geographical location. In addition, unless a ground installation is planned, the entire array must be sized correctly to fit properly on the building's roof. The space required to mount the solar collector array on a roof also depends upon the roof pitch versus the tilt angle required for each solar collector. The site latitude essentially equals the optimal solar collector tilt angle for year-round operation with about 10° subtracted to compensate for weather variations. In the Northern Hemisphere, for winter operation only, add 15°, or for summer operation only, subtract 15°. The rise and run ratio depends very much on the roof pitch angle. In general, the 20 to 12 ratio is set for 60°; the 12 to 12 ratio is set for 45°; the 7 to 12 ratio is set for 30°; the 4 to 12 ratio is set for 18°; and 0 to 12 ratio is set for 0°.

Heat pipes require a minimum tilt angle of 25° to operate properly. The direct flow style heats liquid directly inside the inner glass tube, which contains a long copper feed tube that forces the liquid up through the glass tube. This style is not normally passive in operation. It typically requires an active circulator pump. Unlike heat pipe designs, if the glass tube breaks due to freezing conditions, the thermal transfer fluid can escape and drain the system. These units, and similar devices, called U-tube/U-pipe collectors can be positioned between 0° and 90°. In a U-pipe design, a U-shaped copper tube inside the inner glass tube contains the thermal transfer fluid. No liquid enters the glass vacuum tube, so breakage is less common and not as critical. A window box is a flat-plate type of collector, it is a smaller version of an air panel that fits inside a window exposed to the sun. Matrix is also similar to the flat plate; this collector uses an absorber material with a large amount of total surface area, such as expanded metal lath or fiberglass fibers within an insulated enclosure. A glass window on the box top exposes the dark-colored material inside to heat the internal air. Designs that restrict airflow should only be used in active systems. A solar chimney is a large structure that uses sunlight and natural convection to heat and move the inside air.

A flat-plate active water collector is very common for residential and commercial buildings, due to their high efficiency and low cost. It uses a grid of copper tubing inside a thermally insulated enclosure. A glass window on the top exposes dark-colored copper fins or aluminum sheeting as an absorber plate that is thermally connected to the flow tubes. Water flow is forced through the tubing by a motorized electric pump. The flat-plate active air collector uses baffles to direct airflow through a grid within a thermally insulated enclosure.

Glazing is not required for the low-temperature rises typically needed to warm swimming pools, hot tubs, and spas. The water is commonly pumped between the pool and the collector via the water filter system. The total collector area is typically sized to half of the pool surface area for the purpose of heating the entire pool. A rock box is a glass window upon an insulated and stone-filled box that allows the air flowing inside to become heated by the sun-warmed rocks. Airflow is forced by an electric blower fan. This collector uses an absorber material with a large amount of total surface area, such as expanded metal lath or fiberglass fibers within an insulated enclosure. A glass window on the box top exposes the dark-colored material inside to heat the internal air. Designs that permit plenty of airflows can also be used in passive systems. During radiant-to-thermal energy conversion, the amount of surface area exposed to the sun is the largest single contributor to solar collector efficiency. In addition, high flow rates that keep low-temperature differentials between the solar fluid and ambient air are usually more efficient than low flow rates and high-temperature differentials. For larger industrial operations, solar thermal energy can also be collectors with parabolic troughs or parabolic dishes. In the largest installation so far, a combined unit with parabolic dish-shaped individual mirrors or silicon panels is introduced with the tower full of salt to be melted by the solar thermal energy and eventually used to power the steam engine for the production of electricity. In this combined form, both solar voltaic energy and thermal energy are harvested.

There are a few mechanisms based on which the solar system can generate power. Concentrating solar power (CSP) plants typically integrate thermal energy storage systems in order to generate electricity during cloudy periods or for hours after sunset or before sunrise. This ability to store solar energy makes CSP a flexible and dispatchable source of renewable energy [17].

CSP plants can be broken down into two groups, based on whether the solar collectors concentrate the sun rays along a focal line or on a single focal point with much higher concentration factors. Line-focusing systems include parabolic trough and linear Fresnel plants along with single-axis tracking systems. Point-focusing systems include solar dish systems and solar power plants along with two-axis tracking systems to concentrate the power of the sun [18]. The earliest CSP technology in use is a parabolic trough, and the fastest-growing technology is the tower with concentrating mirrors and molten salt, as shown in Figure 8. Molten salt is employed because its specific heat is much higher than water or air [17].

Figure 8. Various solar thermal energy collectors with concentrating mirrors [17,18].

Power towers or central receiver systems utilize sun-tracking mirrors called heliostats to focus sunlight onto a receiver at the top of a tower [10]. A great deal of research has been conducted in exploring various heat transfer or energy storage materials ranging from air to alternative mixtures of chemicals to attain higher temperatures which gain higher efficiency and yield lower costs.

In a parabolic trough CSP system, the sun's energy is concentrated by parabolic curved, trough-shaped reflectors onto a receiver pipe, namely, the heat absorber tube running along about a meter above the curved surface of the mirrors. The temperature of the heat transfer fluid flowing through the pipe, usually thermal oil, is increased from 293 °C to 393 °C, and the heat energy is then used in the thermal power block to generate electricity in a conventional steam generator.

A trough solar collector field comprises multiple parabolic trough-shaped mirrors in parallel rows aligned to enable these single-axis trough-shaped mirrors to track the sun from east to west during the day to ensure that the sun is continuously focused on the receiver pipes as shown in Figure 9. As of 2018, 90% of the concentrating solar power (CSP) in commercial operations is generated through trough-shaped mirrors.

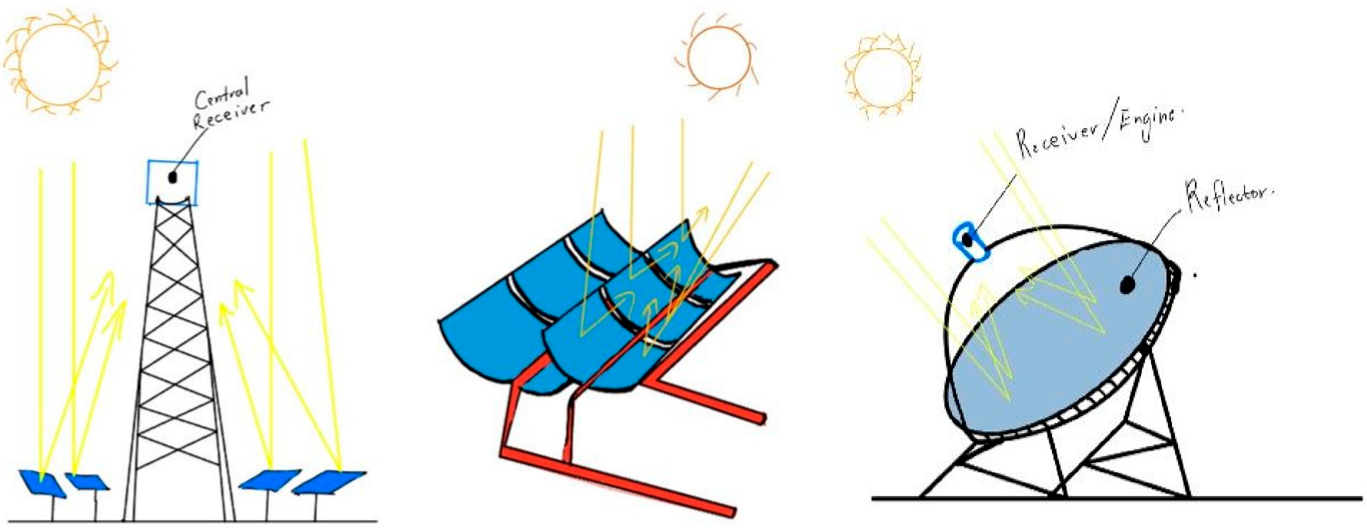

Figure 9. Parabolic trough and parabolic dish solar thermal energy collectors [17,18].

Like troughs and towers, the key operating parameters of which are listed in Table 1, the so-called Fresnel system, a parabolic dish system consisting of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point, can also be incorporated to generate steam for direct use. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun. The collected heat is typically utilized directly by a heat engine, with either a Stirling or Brayton power cycle, mounted on the receiver moving with the dish structure. The dish can attain extremely high temperatures and holds promise for use in solar reactors for making solar fuels which require very high temperatures.

Table 1. Specific energy and storage requirements for different green energy systems [7].

	Parabolic Trough	Solar Tower
Typical Capacity (MW)	10–300	10–200
Tech Development Risk	Low	Medium
Operating Temp (°C)	350–550	250–565
Plant Peak Efficiency (%)	14–20	23—35
Annual Net Efficiency (%)	11–16	7–22
Storage System	Indirect or Direct	Direct
Grid Stability	Medium to High	High
Storage with Molten Salt	380 °C or 550 °C	550 °C

To be economic, this solar thermal electricity (STE) or concentrating solar power (CSP) installations require abundant direct solar thermal radiation. In fact, only strong direct sunlight can be concentrated to the temperatures required for electricity or heat generation, which limits STE or CSP to hot and dry regions with direct normal irradiance levels (DNI) of 2000 kWh/m^2/year or more [18]. STE or CSP plants in areas with higher DNI will have a lower levelized cost of electricity (LCOE). There are a number of global regions with excellent solar resources that are suitable for STE or CSP plants, which include North Africa, the Middle East, Southern Africa, Australia, the western United States, and parts of South America [19]. In practice, the long-range transmission system must be used to transport clean STE from favorable production areas to large consuming areas [12]. Nevertheless, off-grid energies in developing countries, such as solar PV and STE, can transform the lives of those 1.4 billion people currently deprived of access to electricity, and those who can barely rely on their electric grids. Furthermore, solar cooking, solar crop drying, and solar water heating can significantly improve living standards in developing economies. In fact, even in countries with well-developed energy systems, solar technologies can help ensure greater energy security and sustainability [19].

According to Ref. [20], the largest solar farm in the world, Bhadla solar park, which is under construction since July 2015 with a total estimated investment of around 1.4 billion dollars, will be a 2.25 GW solar complex in Bhadla village in Jodhpur district of Rajasthan, India. As shown in Figure 10, the entire solar park spreads over 17 square miles of hot and dry area with an average temperature of around 116 degrees Fahrenheit. As mentioned, too, in Ref. [20], Ecoppia will install approximately 2000 solar panel cleaning robots in the solar park. The first phase of the solar park has seven solar power plants with a combined capacity of 75 MW, which was completed in October 2018. For the next few years, phase two has ten solar power plants with a combined capacity of 680 MW, and phases three and four will have capacities of 1000 MW and 500 MW, respectively. As one of the world's largest solar farms, Topaz Solar Farm has a 550 MW photovoltaic power station in San Luis Obispo County, California, United States [21].

Figure 10. Bhadla solar park in India [20].

According to Ref. [22], the Australia–Asia Power Link combines the world's largest solar farm and battery storage facility in the Northern Territory, as shown in Figure 11, with a solar array spread over 120 square kilometers and a power capacity of 3.2 GW. With a 5000 km transmission system, renewable electricity is supplied to Darwin, Singapore, and Asian markets at reliable and competitive prices. Based on Ref. [23], Quaid-e-Azam Solar Park in Pakistan has dedicated the land of over 6500 acres in Lal Sohnra, Cholistan, Bahawalpur, as shown in Figure 12, with over 400,000 solar modules and a total solar energy capacity of 1 GW.

Figure 11. The Australia–Asia Power Link [22].

Figure 12. Quaid-e-Azam Solar Park in Pakistan [23].

3. Wind Energy

A wind turbine, as shown in Figure 13, turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, both lift and drag are produced. In general, the effect of the lift is stronger than that of the drag which causes the rotor to spin. The rotor connects to the generator, either directly (if it is a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator [6]. Contemporary designs of wind turbines are becoming more and more cost-effective and reliable. In addition, wind turbine sizes have scaled up to multi-megawatt power ratings. According to Betz's law [24], no turbine can capture more than 16/27 or 59.3% of the kinetic energy of the wind. In reality, wind turbines achieve a peak of 75% to 80% of the so-called Betz's limit. Nearly all of the wind turbines currently in use are horizontal-axis turbines with blades similar to airplane propellers. Taller turbines with longer blades generate more electricity. The largest horizontal-axis turbines are taller than 70-story buildings and have blades more than 700 feet long.

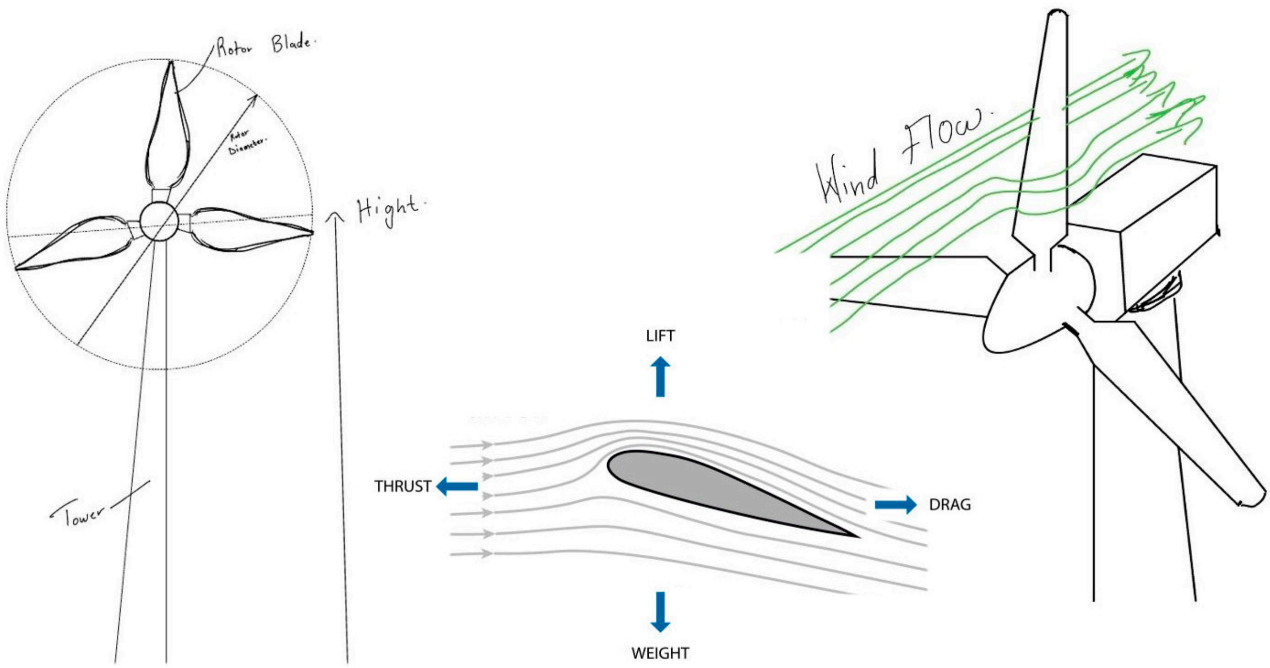

Figure 13. Typical horizontal axis wind turbine (HAWT) [25].

With respect to efficiency, according to Ref. [25], for commercially available wind turbines with around 5 kW for small residential turbines and 5 MW for large-scale utilities, the wind turbine efficiencies are 20% and 40%, respectively, measured by the percentage of wind kinetic energy into electrical energy. Note that these efficiencies are lower than 59.3%, the so-called Betz's limit. Moreover, with respect to the amount of energy typically produced for various applications, according to Refs. [3,6], residential-scale onsite energy use is typically less than 10 kW, small commercial-scale onsite energy use is between 10 and 50 kW, commercial onsite energy use is between 50 and 250 kW, large commercial or industrial energy use is between 0.5 and 1.5 MW, and utility-scale energy use is from 1.5 to 7.5 MW. One of the largest wind farms is the Horse Hollow Wind Energy Center in Texas, which, at the end of 2021, has 422 wind turbines spread over about 47,000 acres. At the moment, the largest wind farm in the USA is the Alta Wind Energy Center in California with a power capacity of 1548 MW. The project has a combined electricity-generating capacity of about 735 megawatts. As pointed out in Ref. [26], wind energy harvesting has its limitations. First of all, it is intermittent. It can be difficult to predict exactly how much electricity a wind turbine will generate over time. If wind speeds are too low on any given day, the turbine's rotor will not spin. This means wind energy is not always available for dispatch in times of peak electricity demand. In order to use wind energy exclusively, wind turbines need to be paired with some sort of energy storage technology. Tesla is working with the world's largest wind turbine manufacturer to deploy battery packs at wind farms. Currently, Tesla has provided 4.3 GWh of clean energy storage, including 256 Megapacks with roughly 3 MWh each and a total of up to 730 MWh with power output up to 182.5 MW at Moss Landing in Monterey, California, United States [27]. One of the largest projects of this nature is the Neoen's Hornsdale Wind Farm in Australia with a power pack capacity of 100 MW and 129 MWh.

Wind energy causes noise and visual pollution along with some negative impacts on the surrounding environment. Wind turbine blades are very large and rotate at very high speeds. Unfortunately, their blades can harm and kill species that fly into them, like birds and bats. The construction of wind farms can also disrupt the natural habitats of local species if not conducted in a sustainable manner. However, these problems can be solved to some extent with technological advancements. Moreover, wind energy also requires transmission systems. In many cases, turbines and generation sites may be located quite far from population centers where electricity is needed. Therefore, transmission systems as additional infrastructure must be built. Wind energy is typically used to directly add electricity to the energy grid which is then used in homes and businesses however there are many off-grid wind farms with energy storage, typically battery packs. Naturally, when the electricity is produced in DC, proper AC conversion must also be considered.

3.1. Horizontal Axis Wind Turbine

A typical upwind horizontal-axis wind turbine (HAWT) has an operating wind speed of 7 to 30 mph. An upwind turbine faces into the wind with the turbine blades in front of the Nacelle, which is located at the top of the mast and contains the rotor and generator, and sometimes a gearbox. Upwind HAWT needs to be designed so that the blades are positioned at a good distance from the mast. Although Downwind HAWT can tolerate more blade deformations, thus requiring less room for installation, it is generally noisier, and the blades are subject to more forces than those of upwind turbines. In practice, the process of forcing, or furling, is implemented.

In typical wind turbines, as shown in Figure 14, there are different regions of operation. In Region 2, below the so-called rated wind speed, the goal is to maximize turbine power. In Region 3, above the rated wind speed, the goal is to maintain turbine power at a constant level with rated power, to limit turbine loads. Other regions of operation include startup, namely, Region 1 and machine shutdown [28].

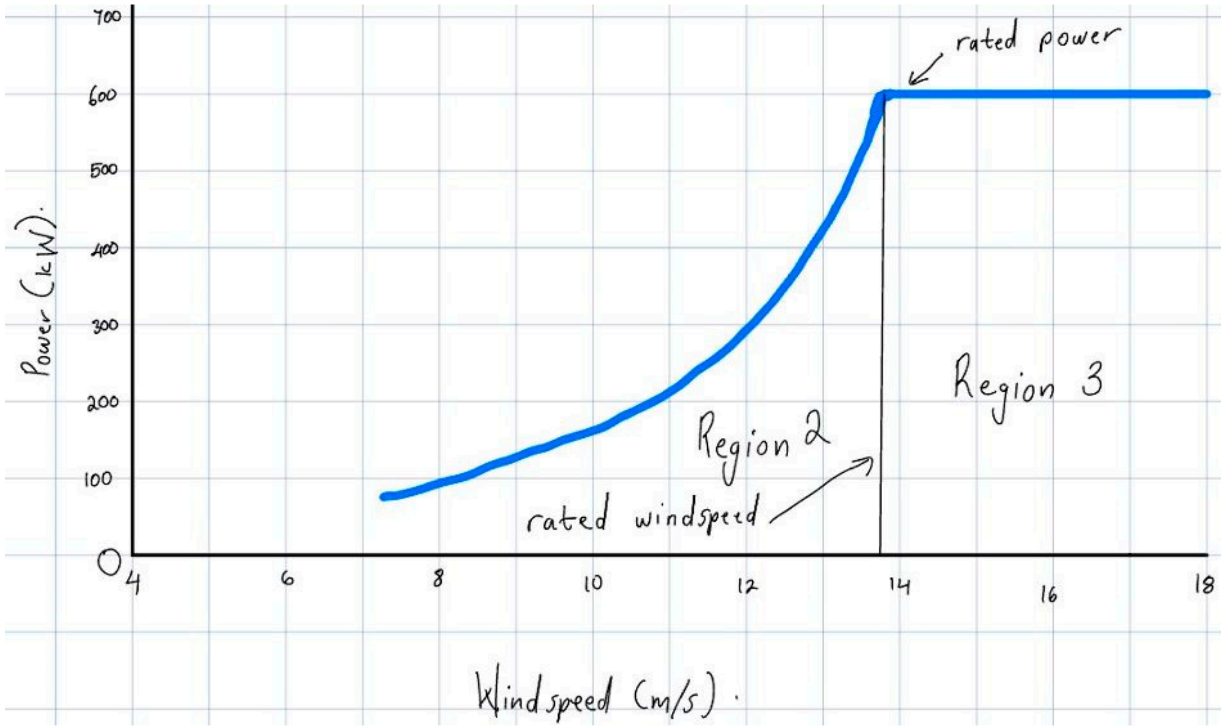

Figure 14. Power vs. wind speed graph showing the different regions of operation [28].

In practice, different actuation and control strategies are designated for wind turbines. Passive control means include fixed-pitch and stall control mechanisms in which the blades are designed to limit the power supply in Region 3. In addition, the generator speed is fixed in Region 2. Moreover, through the use of synchronous or induction generators, power electronics, and other mechanical variable speed transmissions [29–32], the constant turbine rotational speed can be maintained in Region 2. In order to maximize power output, the rotational speed of the turbine must vary with wind speed to maintain a constant tip-speed ratio (TSR) and a maximum power coefficient.

Typical variable-speed wind turbines have different operation regions, also depicted in Figure 15, with generator torque as a function of generator speed measured on the high-speed end of the gearbox. Turbine start-up occurs in Region 1 with generator speeds between 0 and 430 revolutions per minute (rpm), during which the generator torque is zero. In general, once the turbine supervisory control system detects a suitable wind speed for a startup, the pitch angle of the blades is changed from the full feather to a pitch angle with the help of pitch actuators or motors. When the turbine operates in Region 2, it is the so-called run-pitch position, during which the small pitch angle results in sufficient aerodynamic torque to overcome bearing friction and start the rotor motion. Furthermore, once the generator speed has accelerated to 430 rpm, the generator torque is switched on and power is then produced.

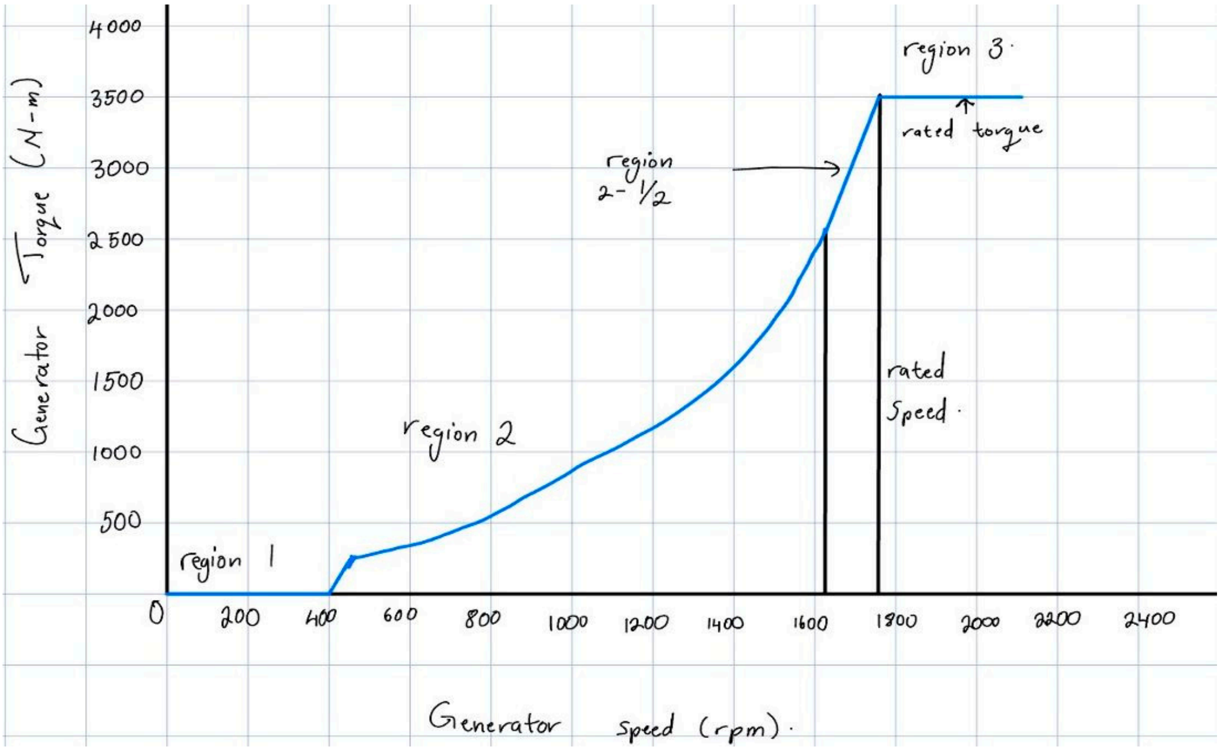

Figure 15. Regions of operation are shown in terms of generator torque vs. speed [28].

Power production in Region 2 continues as long as the generator speed is within the range of 430 to 1700 rpm during which the blade pitch is held constant at its run-pitch value, and generator torque control is used to vary the speed of the turbine to maintain constant TSR, thus maximizing energy capture.

3.2. Vertical Axis Wind Turbine

Currently, very few vertical-axis wind turbines (VAWT) are in use today because they do not perform as well as horizontal-axis turbines [3]. As shown in Figure 16, vertical-axis turbines have blades that are attached to the top and the bottom of a vertical rotor. As described in Ref. [33], Savonius wind turbines have blades built around the vertical shaft in a helix form, which basically looks like DNA or fusilli pasta. The wide, solid wind-receiving area of the blades is one of the most significant features of a Savonius wind turbine. When in operation, Savonius wind turbines rely on the flow resistance mechanism to turn their rotors. In addition, Savonius wind turbines can only turn as fast as the wind speed [5]. Savonius VAWT has an operating wind speed of 4 to 90 mph and is suitable for rooftop installations.

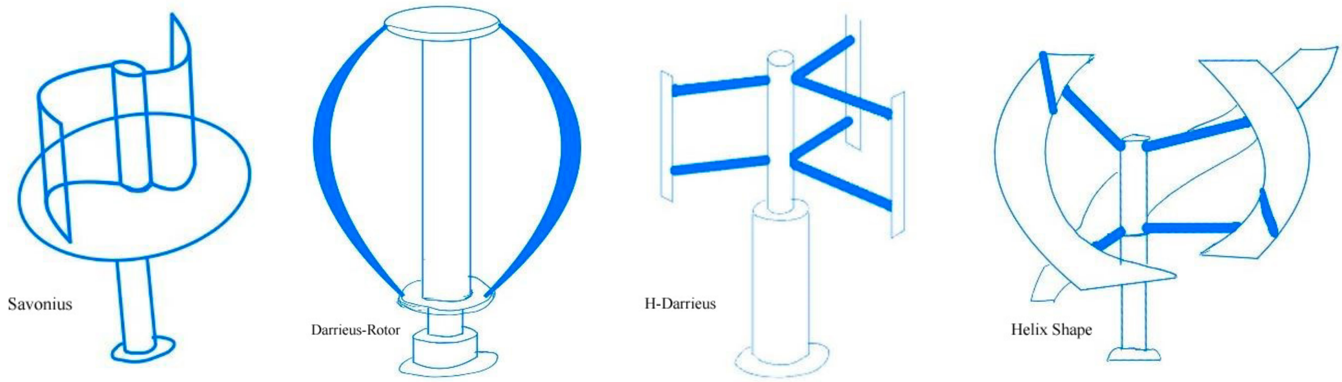

Figure 16. Darrieus and Savonius vertical axial wind turbine (VAWT) with some common designs [25,28,34].

The other common type of vertical-axis turbine, the so-called Darrieus wind turbine, named after the French engineer Georges Darrieus, who patented the design in 1931, looks like a giant, two-bladed egg-beater and has long, curved wings, each end of which is attached to the top and bottom of the rotor shaft. Another model of the Darrieus turbine has three straight wings connected to the parallel shaft, forming the "H" shape. In terms of operation, Darrieus utilizes the same "lift" aerodynamic force to rotate. By flowing around the structure, the wind creates a suction on the front side of the turbine, driving the wings to rotate. Because of the shape of the wings, they do not experience as much drag as Savonius turbines do. Once the rotation starts, Darrieus wind turbines are able to accelerate to rotate faster than the wind speed. Some versions of the vertical-axis turbine are 100-feet tall and 50-feet wide. The output of a wind generator is primarily a function of its swept area. Other features such as high-tech airfoils and more efficient generators will influence output [34]. Darrieus VAWT has an operating wind speed of 6 to 35 mph and is also suitable for rooftop installations.

To design a VAWT for education purposes, a mounting plate has to be introduced along with the capability for easy removal and replacement in the existing wind tunnel. Such a plate is designed to carry the entire load, which includes the weight of the generator and instrumentation as well as all static and dynamic loads [35]. A quick coupling design could be adapted to include a modular mounting plate to be replicated for the insertion of various VAWT prototypes. A generator will be specified and sized with variable load capability so that it can be matched to the possible output capability. The generator will be supported by the mounting plate and coupled to the main rotating shaft. There must be enough room inside the test throat assembly to mount a reasonably sized VAWT prototype in the wind tunnel. The standardized data sheet for prototype test covers mechanical vibration, power output, and characteristics at varying wind speeds. There must be enough redundancy and protection for surrounding equipment and operators in the event that the prototype disintegrates during testing [25,34].

WETO (Wind Energy Technology Office) facilitates research on wind energy as one of the reliable green energy resources, through the development of longer and lighter rotor blades, taller towers, and high-performance control systems [36]. WETO has been working with industry partners to improve the system's performance and reliability. Knight and Carver's Wind Blade Division in National City, California, United States has worked with researchers at the Department of Energy's Sandia National Laboratories to develop an innovative wind turbine blade that leads to an increase in energy capture by 12%. The most distinctive characteristic of the Sweep Twist Adaptive Rotor (STAR) blade is a gently curved tip, which, unlike the vast majority of blades in use, is specially designed to take maximum advantage of all wind speeds, including slower speeds [35]. More recently, to support the development of more reliable gearboxes, the program has worked with several companies to design and test innovative concepts. Through the support of 47 million US dollars, the Department of Energy (DOE) has established at Clemson University the largest and one of the most advanced wind energy testing facilities in North America.

One recent development for wind energy is the so-called bladeless turbine, as shown in Figure 17, which utilizes the aeroelastic resonance of the flexible structure with its interaction with the vortexes [37]. As a new area of research, there is not much research that has been conducted on these bladeless turbines [38,39]. According to current research, however, the results concluded that a single bladeless turbine is 30% less efficient than a HAWT due to its lack of ability to counter the high entropy of wind. Moreover, low-stress and high-cycle fatigue issues must also be considered along with endurance limits for different structural materials. However, due to their compact nature, bladeless turbines and VAWTs make better use of the area in comparison with HAWTs, and can be deployed in cities, on top of high-rise buildings or their surroundings.

Figure 17. New vertical rooftop windmills [35,39].

Although HAWTs are more efficient, components and moving parts of gearboxes and braking systems require regular maintenance whereas bladeless turbines have no such moving parts or connections, which greatly minimizes maintenance requirements. Furthermore, as shown in Figures 14 and 15, the greater the wind velocity acting on HAWTs, the greater the power output, whereas bladeless turbines work best when wind velocity is lower with more uniform vortices [37]. Notice that in addition to the traditional mechanical transmission systems as systematically studied in Refs. [29–32], power electronic systems employing the so-called insulated-gate bipolar transistor (IGBT) such as those from Infineon [40] are also available. According to Ref. [33], Alta Wind Energy Center (AWEC), also known as Mojave Wind Farm, is the third-largest onshore wind energy project in the world. As shown in Figure 18, with over six hundred wind turbines, the project will supply 1.55 GW of clean renewable energy to Southern California Edison (SCE) for more than 25 years under a 3 GW wind power development initiative commissioned in 2010. The entire wind farm costs about 2.9 billion US dollars and spreads over 3200 acres in the foothills of the Tehachapi Mountains.

Figure 18. Horizontal axial wind turbine (VAWT) large-scale land installations [36,39].

4. Energy Storage

In engineering practice, it is often the case that where the energy can be efficiently produced might not be the population center. Therefore, it is essential to have secure and effective energy storage systems for green energy resources, as shown in Figure 19.

In a subsequent paper, we will elaborate on two important issues related to energy storage units, namely, the fireproof and prevention mechanisms and the surveillance and security measures.

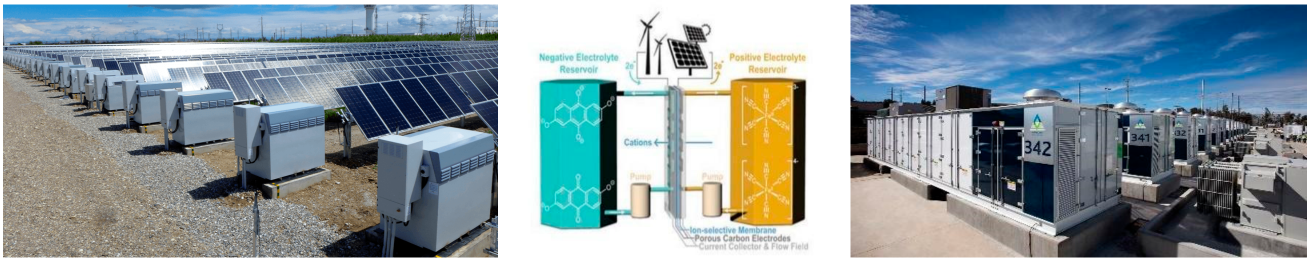

Figure 19. The largest battery storage facility in Texas [40].

As described in Ref. [16], a new non-flammable graphene-based battery was developed in lieu of a traditional lithium-based battery. This new Nanotech Graphene-Powered Lithium-Ion Battery with 18,650 cells was shot by a 4.5BRA bullet at a speed of 2917 feet per second. Despite the force of impact, the battery as shown in Figure 20 did not catch fire and even still held a charge. In contrast, a rival commercial battery with 18,650 cells shot by a 4.5BRA bullet at a speed of 2915 feet per second immediately burst into flames and no longer held a charge.

Figure 20. Non-flammable bulletproof graphene battery [16].

As illustrated in Figure 21 as well as Refs. [41,42], vanadium resources have been developed for efficient energy storage means. In the USA, a team at Lawrence Berkeley National Laboratory is deploying the phase-changing ability of vanadium to create a new energy-efficient roof coating. Researchers are also kicking around the idea of powering electric vehicles with flow batteries. As shown in Figure 21, a new flow battery for EVs is getting attention from the US Department of Defense through its cutting-edge technology funding office, Defense Advanced Research Projects Agency (DARPA), better known as the birth parent of the Internet. The US Air Force and NASA have also provided funding for the new battery. Finally, according to Ref. [43], replacing the conventional liquid electrolyte solution with a solid, hyper-compact solid battery. With zero wasted space and theoretically infinite energy density, this solid battery lasts far longer and charges far faster. Finally, a new candidate for reliable energy storage, a so-called liquid metal battery, despite its high operation temperatures, has also attracted the attention of investors and academics. The battery has electrodes based on common elements such as Calcium and Antimony and can have a capacity of 400 to 1000 kWh at a peak power of 250 kW. It also provides storage for up to 24 h and has a storage capacity ranging from 10 MWh to 2 GWh [44,45].

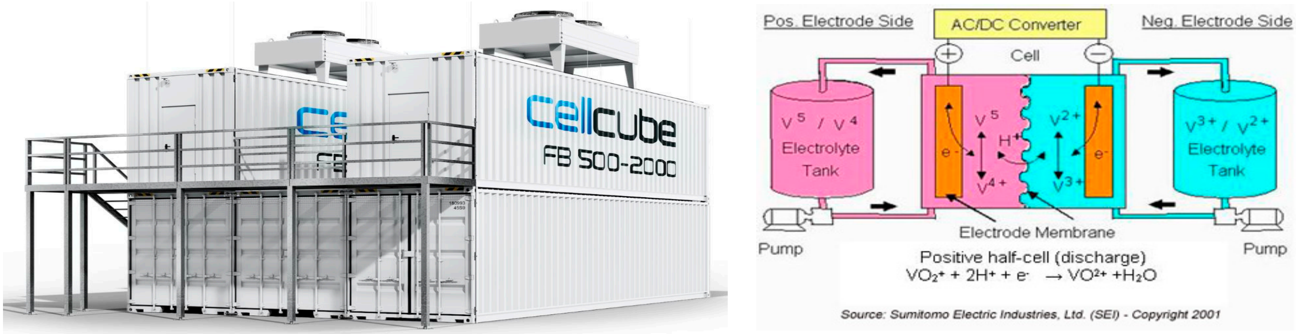

Figure 21. A better vanadium flow battery [41,42].

5. Hydrogen Fuel Cells, Bioenergy and Biomass, and Other Renewable Energy

5.1. Hydrogen Fuel Cells

Chemical (Hydrogen) is another type of renewable energy that we have looked into, and it can be produced from diverse, domestic resources [46,47]. Currently, most hydrogen is produced from fossil fuels, specifically natural gas. Electricity from the grid or from renewable sources such as biomass, geothermal, solar, or wind is also currently used to produce hydrogen. In the longer term, solar energy and biomass can be used more directly to generate hydrogen as new technologies make alternative production methods cost-competitive. The chemical (Hydrogen) is also most related to fuel cells. A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions. The first fuel cells were invented by Sir William Grove in 1838. The first commercial use of fuel cells came more than a century later following the invention of the hydrogen–oxygen fuel cell by Francis Thomas Bacon in 1932. The alkaline fuel cell, also known as the Bacon fuel cell after its inventor, has been used in NASA space programs since the mid-1960s to generate power for satellites and space capsules. Since then, fuel cells have been used in many other applications. Fuel cells are also used for primary and backup power for commercial, industrial, and residential buildings and in remote or inaccessible areas [48]. They are also used to power fuel cell vehicles, including forklifts, automobiles, buses, trains, boats, motorcycles, and submarines. For example, nearly half of the railroad lines in Europe are not electrified [49,50]. The diesel-powered trains that run on these tracks produce emissions. Switching to hydrogen would eliminate these emissions. Siemens Mobility is equipping trains with hydrogen fuel cells as shown in Figures 22 and 23. According to De-Niang Maria Peymandar, who is responsible for integrating fuel cells in the system, the cells are used to support the onboard power systems and have a range of up to 1000 km.

In the German state of Lower Saxony, we also have the world's first network with trains powered by hydrogen fuel cells in a passenger service that has now gone into operation [51]. On the route between Cuxhaven, Bremerhaven, Bremervörde, and Buxtehude, 14 hydrogen-powered Coradia iLint regional trains are now in operation, replacing 15 diesel trains [51]. A hydrogen filling station was built in Bremervörde for the H_2 trains, which are operated by Linde. The facility has a storage capacity of 1800 kg of hydrogen, distributed over 64 500-bar high-pressure storage tanks. Six hydrogen compressors supply the two dispensers where the trains can refuel with hydrogen around the clock. For the time being, hydrogen will be supplied. However, in the near future, hydrogen will be produced on-site by means of electrolysis. Since the trains have a range of 1000 km with one tank of hydrogen, they can cover their daily mileage without the refueling stop which takes place once a day outside operating hours. In this way, 1.6 million liters of diesel could be saved per year [52–55].

Another example, we have China's electric, zero-emission ferry, as shown in Figure 22, and the hydrogen fuel cell, zero-emission trolley, as shown in Figure 23, that began service in October 2022 [56,57]. In addition, according to Ref. [58] endorsed by *Trucking World*, Toyota's hydrogen-powered heavy trucks are also swinging into operation along with the hydrogen charging stations as illustrated in Figure 24. In general, hydrogen has a specific energy of 40 kWh/kg, which is about three times that of current jet fuels. According to a new zero-emission concept for aircraft ZEROe, recently released by Airbus, hydrogen can also be used to power aircraft. Although it is challenging to attach a high-pressure tank to an airplane, Airbus is planning to design and build a sustainable propulsion engine by 2035.

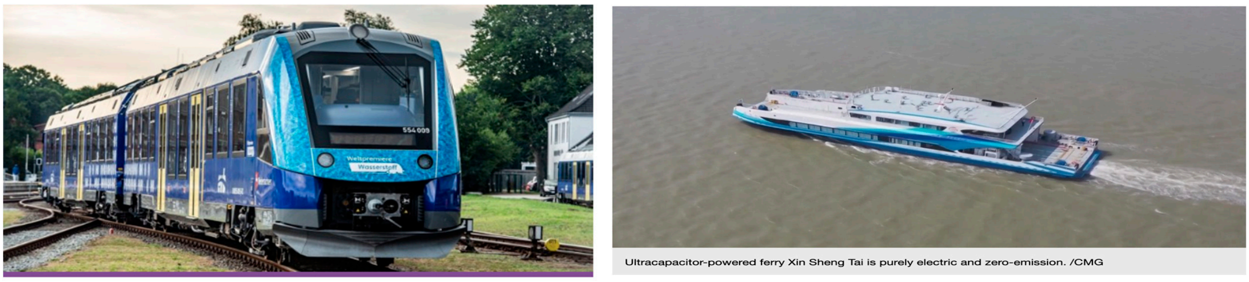

Figure 22. Train/ferry powered by Hydrogen fuel cells in German/China [51,57].

Figure 23. China's hydrogen fuel cell zero-emission trolley in service in 2022 [57].

Figure 24. Hydrogen-powered trucks and charging stations [58].

The ferry is 65 m long, 14.5 m wide, and 4.3 m deep, in which it can carry a maximum of 165 passengers and 30 cars at a time [59]. The ferry is also equipped with full rotation thrusters and supercapacitor power; the vessel has a power output of 2000 kilowatts and a speed of 12 knots. Due to the use of supercapacitors for charging, which enables the ship to sail for an hour only on a 15 min charge, about 500 tons of fuel can be saved every year [57]. This supercapacitor has four groups of batteries and is composed of 60 capacitor modules combined. Each module has 360 single capacitor cells, and there are 21,600 single cells in total [59]. This system can realize intelligent management and remote monitoring. If a fault occurs, the service provider can obtain data remotely, communicate with us in time and guide us to correct the fault. The ferry will boost Shanghai's green transportation development system and provide a new pathway to achieving new energy-powered development for inland vessels [57]. Some pros of fuel cells are high efficiency, good reliability, and less noise; they are also environmentally beneficial; and size reduction. Some of the cons when it comes to fuel cells are that they are very expensive to manufacture due to the high cost of catalysts, and there is a lack of infrastructure to support the destruction of hydrogen; hydrogen is also expensive to produce and not widely available.

As presented in Ref. [60], researchers from the National University of Singapore (NUS) have made a serendipitous scientific discovery of the unique performance of a nickel oxyhydroxide-based material in the water electrolysis experiment, which could potentially revolutionize the way water is broken down to release hydrogen gas, an element crucial to many industrial processes [61,62]. Since hydrogen can potentially be used as a fuel and is long touted as a sustainable fuel, hydrogen fuel produces no emissions as it burns upon reacting with oxygen, and no ignition is needed, making it a cleaner and greener fuel source. It is also easier to store, making it more reliable than solar-powered batteries.

5.2. Bioenergy and Biomass

Bioenergy is often produced from traditional renewable biological substances or biomass. As one of the green energy resources and one of many diverse resources depicted in Figure 25, it can be converted into liquid transportation fuels that are equivalent to fossil-based fuels, such as gasoline, jet, and diesel fuel. As a form of green energy resource derived from living organic materials, biomass can be used to produce transportation fuels, heat, electricity, and other commercial products. Moreover, proper handling, with contemporary technologies, of biomass as a versatile renewable energy source enables the reuse and recycling of carbon from farming and waste streams and reduces emission. The burning of biomass for electrical power and heat generation can also be competitive with coal. In addition, a byproduct of biomass can be used as fertilizer or construction materials. The main concern with biomass is the availability of distribution and collection infrastructure for a sustainable large-scale utilization. In many parts of the world, growing crops dedicated to biomass production can lead to higher net carbon emissions than fossil fuel burning because of the emissions associated with land clearings. There also are concerns about the impact of biomass production on agriculture, water use, and food prices. Finally, with a proper combination of aquafarming for the recycling of nutrients, anaerobic digestion of livestock manure for the recovery of methane, and fertilizer production, bioenergy has demonstrated its potential as one of the sustainable and renewable energy sources.

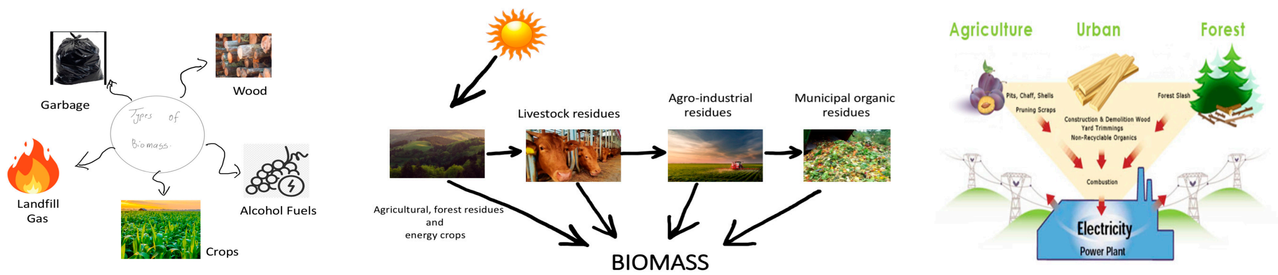

Figure 25. Solar energy-based processes for biomass production [60].

The longest biomass plant in the USA belongs to Nacogdoches Generating Facility of Southern Power, a subsidiary of the Southern Company in Sacul, Texas, which has a net capacity of 115 MW with a bubbling fluidized-bed boiler, a condensing steam turbine generator with an evaporative cooling tower, wood fuel handling system, and auxiliary support equipment fueled with non-merchantable wood biomass materials.

The other important area is reforestation. With more forests and less desert, humanity is finally incorporating its delicate ecosystem as the key consideration in sustainable and renewable development. In the past agrarian economy with low levels of industrialization, methane production was inefficient and limited to individual households. In concert with abundant solar thermal, solar photovoltaic, and wind energy along with modern storage systems, through burning or converting biomass into a gas or liquid at an industrial scale with proper recycling systems, bioenergy, and biomass are becoming more accessible for effective and efficient production of electricity and heat, just like fossil fuels and other renewable energy sources. This is, in particular, true when biomass and bioenergy productions are combined with a variety of other tasks such as poultry production, fertilizing, aquaculture, and aquaponics.

5.3. Other Renewable Energy

Virtually in all countries in Africa, the Americas, Asia, Europe, and Oceania, the importance of renewable energy sources has been established. In fact, the total energy production in China from renewable energy resources is quickly approaching the total energy production in the USA [63]. According to Ref. [64], as one of the world's biggest single geothermal fields, the geothermal field in California's Mayacamas Mountains, also called the Geysers, approximately 115 km north of San Francisco, as shown in Figure 26, has an installed capacity of nearly 1.52 GW. More than 350 steam production wells over 30 square miles of the area have been drilled within the Mayacamas Mountain region, some of which are as deep as three kilometers. The steam is brought overland through pipe systems that interconnect power plants and conventional steam turbines are employed for the production of green electricity.

Figure 26. The Geysers geothermal field in California [64].

In addition, according to Ref. [65], the Sihwa Lake project, the world's largest operating tidal power station, with a capacity of 254 MW, is located on the west coast of South Korea, with its winding rias, many-sized inlets, and wide tidal range. Sihwa Lake is an artificial lake with over 17 square miles of area and a nearly 8 miles long seawall at Gyeonggi Bay as shown in Figure 27. It was created by the South Korean government to provide reclaimed land for the nearby metropolitan area, flood mitigation, and secure irrigation water by converting the coastal reservoir to fresh water.

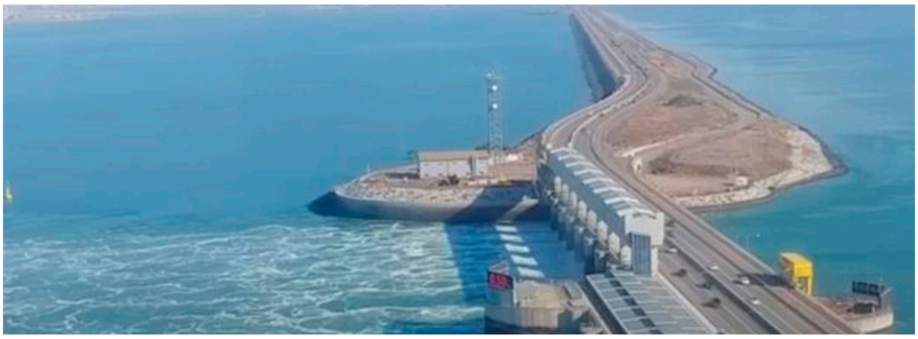

Figure 27. The Sihwa Lake tidal power station in South Korea [65].

Based on Ref. [66], a new renewable energy based on tidal wave mechanical energy with an efficiency as high as 80% is being considered. The oldest system was built in La Rance France in 1966 and since then, 240 MW of energy is steadily produced for nearly 250,000 homes. The man-made dam will hold the water generated at the high tide which is used to generate electricity during the low tide. The only tidal power plant in North America is located in Annapolis Royal, Nova Scotia, Canada with a power capacity of 20 MW. In addition, as suggested in Ref. [14], the majority of the installations utilize the tidal stream, as shown in Figures 28 and 29. In the USA, nuclear energy production is about 25 to 30 cents per kilowatt hour, hydroelectric power is about 5 cents per kilowatt hour, wind power is about 2 to 6 cents per kilowatt hour, and solar voltaic power is about 6 cents per kilowatt hour. The overall tidal power is about 66 cents per kilowatt hour, with special care and innovations, the tidal power can be dropped to about 4 to 12 cents per kilowatt hour.

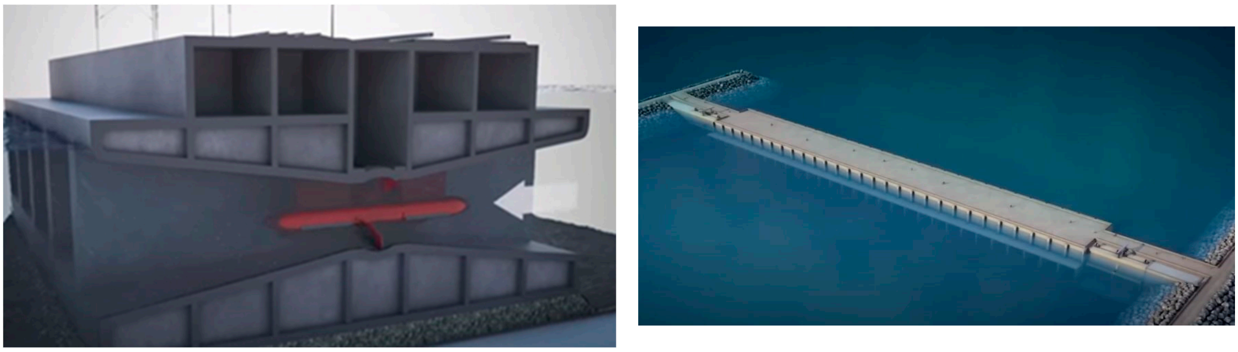

Figure 28. Tidal reservoir installation [66].

Figure 29. Tidal stream installation [66].

As described in Ref. [67], the Three Gorges Dam is located on the Yangtze River (Chang Jiang) just west of the city of Yichang in Hubei province, China. As shown in Figure 30, the Three Gorges Dam is 2335 m long with a maximum height of 185 m along with a straight-crested concrete gravity structure. With all of the dam's 34 turbine generator units operating, the dam generates 22.5 GW of electricity, making it the most productive hydroelectric dam in the world. Moreover, according to Ref. [68], Globeleq has signed a framework agreement with the Egyptian authorities for a green hydrogen facility in the Suez Canal Economic Zone, with operations expected to start by 2026–27. The project will develop 3.6 GW of electrolyzers in three phases over the next 12 years, powered by up to 9 GW of solar and wind. The first-phase pilot project will produce green ammonia from hydrogen, mainly for export to Asia and Europe, said the London-based company. Egypt signed several framework agreements at COP27 for hydrogen projects in the Suez Canal Economic Zone.

Figure 30. Three Gorges Dam in China [67].

According to Ref. [69] and illustrated in Figure 31, surface wave energy can also be harvested for power production through different flexible large surface structures. Moreover, based on Ref. [70], the International Thermonuclear Experimental Reactor (ITER) located in southern France is one of the most ambitious energy projects in the world today with over 100 fusion reactors built since the 1950s. In this international collaboration, 35 nations, through a partnership among the United States, Europe, Russia, India, Japan, China, and South Korea, are working together to build the world's largest tokamak, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large-scale and carbon-free source of energy based on the same principle that powers our sun and stars. As shown in Figure 32, the experimental campaign that will be carried out at ITER is crucial to advancing fusion science and preparing the way for the fusion power plants of tomorrow. In addition, as described in Figure 32, according to Ref. [71], 54 of the 440 panels required for the reactor are being made by China, one of the seven participants in the ITER project. The panels are composed of over 1 square meter layers of beryllium, copper alloy, and stainless steel which can withstand a heat load of over 4.7 MW.

Figure 31. Surface wave energy systems [69].

Figure 32. ITER nuclear fusion reactor (**left**) and comparable Chinese system (**right**) [70].

The other direction of the application of renewable energy resources is in concert with the development of electrical vehicles (EV) and the affiliated charging stations. Finally, as shown in Figure 33, according to articles in CarbonRecall (CR) and Electrek [72,73], the off-grid, 100% solar-powered EV chargers are extremely helpful to vulnerable grids of areas under the rising threat of natural disasters. The US Department of Homeland Security (DHS) is funding the EV ARC infrastructure from Beam Global.

Figure 33. Off-grid solar-powered EV charger [71,72].

6. Conclusions

This review is based on senior design projects as documented in Refs. [10,11,29–32,74–80] in the McCoy School of Engineering, MSU Texas, a member of the Texas University System. Over the past decade, many senior design projects in our ABET-accredited BS Mechanical Engineering Program were focused on green energy resources such as solar voltaic and thermal energies as well as wind energies from both vertical axis and horizontal axis turbine installations. Moreover, other popular sustainable energy resources such as biomass and hydrogen fuel cells along with energy storage systems have also been summarized. This overview will follow with focused research on the design of a fireproof and secure energy farm with a wireless robotic surveillance robot programmed with coherent yet unpredictable motion equipped with an infrared camera. The envisioned model of this off-grid energy farm will be solely powered with solar and wind energies along with other renewable energy resources and an efficient and secure energy storage system.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank all senior students who have graduated from our ABET-accredited BS Mechanical Engineering Program and faculty members in the McCoy School of Engineering at MSU Texas, a member of the Texas Tech University System. This review paper is in large part based on their senior design projects.

Conflicts of Interest: The author declares no conflict of interest.

References and Notes

1. Center for Sustainable Systems, University of Michigan. Photovoltaic Energy. 2022. Available online: https://css.umich.edu/sites/default/files/2022-09 (accessed on 11 October 2022).
2. FESTO Didactic. 2022. Available online: https://labvolt.festo.com/about_us (accessed on 28 February 2023).
3. U.S. Energy Information Administration (EIA). Wind Explained: Types of Wind Turbines. 2022. Available online: https://www.eia.gov/energyexplained/wind (accessed on 29 January 2023).
4. Electrek; Lewis, M. World's Most Powerful Wind Turbine's Blades Arrive for Installation. 2022. Available online: https://electrek.co/2022/12/22 (accessed on 29 January 2023).
5. LUVSIDE. What Is Vertical Axis Wind Turbine and How Does It Work? 2020. Available online: https://www.luvside.de/en (accessed on 29 January 2023).
6. Office of Energy Efficiency & Renewable Energy. Energy.gov. WindExchange. 2023. Available online: https://windexchange.energy.gov (accessed on 29 January 2023).
7. Total Energies Fondation. Planete Energies. The Two Types of Solar Energy. 2022. Available online: https://www.planete-energies.com/en/medias/close/two-types-solar-energy (accessed on 11 October 2022).
8. Solar Power by Country. 2022. Available online: https://worldpopulationreview.com/country-rankings/solar-power-by-country (accessed on 11 October 2022).
9. Seattle, P.I. Does the Location of the Sun Affect the Amount of Energy Solar Panels Collect? 2022. Available online: https://education.seattlepi.com (accessed on 14 September 2022).
10. MSU Texas BS Mechanical Engineering Program Senior Design Project. Portable Solar Tracker, Matt Capps, Clide Cadette, Leron Marrast, Laura Wittle. Faculty Advisor Dr. Salim Azzouz. 2010.
11. MSU Texas BS Mechanical Engineering Program Senior Design Project. Dalquest Water System. Aaron Smith, Nick Moore, Tony Burson, Karu Anto, and Philip Ray. Faculty Advisor Dr. Idir Azouz, 2010.
12. Zhu, H.; Blackborow, P. ENERGETIQ. A HAMAMATSU Company. Technical Note: Understanding Radiance (Brightness), Irradiance, and Radiant Flux. 2022. Available online: https://www.energetiq.com/technote-understanding-radiance-brightness-irradiance-radiant-flux (accessed on 30 September 2022).
13. Solar Dynamics Observatory. NASA. Solar Irradiance. 2022. Available online: https://www.nasa.gov/mission_pages/sdo/science/Solar%20Irradiance.html (accessed on 30 September 2022).
14. Murse, T.; ThoughtCo. A Brief History of White House Solar Panels. 2021. Available online: https://www.thoughtco.com/history-of-white-house-solar-panels-3322255 (accessed on 30 September 2022).
15. Yang, F.; Xu, M.; Bao, S.-J.; Wei, H.; Chai, H. Self-assembled hierarchical graphene/polyaniline hybrid aerogels for electrochemical capacitive energy storage. *Electrochim. Acta* **2014**, *137*, 381–387. [CrossRef]
16. Energy. Manufacturing.NET. Nanotech Shows Off 'Bullet-Proof' Graphene Battery. Energy Manufacturing. 2022. Available online: https://www.manufacturing.net/energy/news/22552437 (accessed on 10 November 2022).

17. SolarPACES. How CSP Works: Tower, Trough, Fresnel or Dish. 2018. Available online: https://www.solarpaces.org/how-csp-works (accessed on 8 September 2022).
18. IRENA Working Paper. Renewable Energy Technologies: Cost Analysis Series. *Conc. Solar Power* **2012**, *1*, 1–48.
19. Solar Energy Perspectives. International Energy Agency. 2011. Available online: https://www.iea.org/reports/solar-energy-perspectives (accessed on 7 September 2022).
20. Bhadla Solar Park, Rajasthan. NS Energy. 2015. Available online: https://www.nsenergybusiness.com/projects/bhadla-solar-park-rajasthan (accessed on 25 October 2022).
21. Topaz Solar Farm. Wikipedia, the Free Encyclopedia. 2022. Available online: https://en.wikipedia.org/wiki/Topaz_Solar_Farm (accessed on 29 January 2023).
22. Power Technology. Alta Wind Energy Center (AWEC), California. 2014. Available online: https://www.power-technology.com/projects/alta-wind-energy-center-awec-california (accessed on 25 October 2022).
23. NDC Partnership. 1000 MW Quaid-e-Azam Solar Park in Pakistan. 2022. Available online: https://ndcpartnership.org/case-study/1000-mw-quaid-e-azam-solar-park-pakistan (accessed on 25 October 2022).
24. Betz's Law. Wikipedia, the Free Encyclopedia. 2022. Available online: https://en.wikipedia.org/wiki/Betz%27s_law (accessed on 29 January 2023).
25. United States Environmental Protection Agency (EPA). *Renewable Energy Fact Sheet: Wind Turbines*; United States Environmental Protection Agency (EPA): Washington, DC, USA, 2013; pp. 1–5.
26. Energy Sage. Smarter Energy Decision. Wind Energy Pros and Cons. 2022. Available online: https://www.energysage.com/about-clean-energy/wind (accessed on 29 January 2023).
27. INSIDEEVs; Kane, M. PG&E Commissions Its Moss Landing Elkhorn Battery: 256 Tesla Megapacks. 2022. Available online: https://insideevs.com/news/590551/pge-moss-landing-elkhorn-battery (accessed on 29 January 2023).
28. Wright, A.; Fingersh, L.; National Renewable Energy Laboratory. *Advanced Control Design for Wind Turbines. Part I: Control Design, Implementation, and Initial Tests*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2008; pp. 1–148.
29. MSU Texas BS Mechanical Engineering Program Senior Design Project. Gear Based Quasi Continuous Variable Transmission. Krista Duke, Dania Wilson, Kyle Ressel, Martin Soto, Justus Nwoke. Faculty Advisor Dr. Salim Azzouz. 2014.
30. MSU Texas BS Mechanical Engineering Program Senior Design Project. Rotational Speed/Displacement Motion Conversion Machine. Shawn Blackette, Yusuke Nakanishi, and Jason Meisel. Faculty Advisor Dr. Salim Azzouz. 2008.
31. MSU Texas BS Mechanical Engineering Program Senior Design Project. Variable Inertia Motion Control Flywheel/Shaft System. Donley Antoine, Brittney Franklin, Rayon Austrie. Faculty Advisor Dr. Salim Azzouz. 2009.
32. MSU Texas BS Mechanical Engineering Program Senior Design Project. Active Gearing System for Wind Turbines. Anh Dao, Daniel McMullan, and Daniel Brooking. Faculty Advisor Dr. Salim Azzouz. 2011.
33. Sun Cable. Australia-Asia PowerLink. Sun Cable's Vision Is to See the Indo-Pacific Region Powered by Renewable Energy Harnessing High-Quality Solar Resources. 2022. Available online: https://suncable.energy/australia-asia-power-link (accessed on 25 October 2022).
34. *Tangarie Alternative Power LLC Report 2011*; 12399 Hamp Naylor Drive: Vernon, TX, USA, 2011.
35. IEA. Wind Electricity. Tracking Report. 2022. Available online: https://www.iea.org/reports/wind-electricity (accessed on 29 January 2023).
36. Office of Energy Efficiency and Renewable Energy. Next-Generation Wind Technology. 2022. Available online: https://www.energy.gov/eere/wind/next-generation-wind-technology (accessed on 29 January 2023).
37. Bardakjian, A.; Mandadakis, P.; Tingle, A. Efficiency comparison of horizontal axis wind turbines and bladeless turbines. *PAM Rev. Energy Sci. Technol.* **2017**, *4*, 59–75. [CrossRef]
38. The Renewable Energy Hub UK. How a Wind Turbine Works. 2022. Available online: https://renewableenergyhub.co.uk/main/wind-turbines (accessed on 29 January 2023).
39. Darrieus Wind Turbine. Wikipedia, the Free Encyclopedia. 2022. Available online: https://en.wikipedia.org/wiki/Darrieus_wind_turbine (accessed on 29 January 2023).
40. Infineon. Electric Power Transmission, Distribution and Storage. 2022. Available online: https://www.infineon.com/cms/en/about-infineon/energy-efficiency-technologies (accessed on 24 November 2022).
41. Energy Storage. Solar-Estimate.org. Vanadium Flow Batteries Could Leapfrog over Pumped Hydro for Long Duration Energy Storage. 2022. Available online: https://cleantechnica.com/2022/11/25 (accessed on 24 November 2022).
42. Bellini, E. PV Magazine. Lithium-Vanadium Battery for Renewables Storage. 2022. Available online: https://www.pv-magazine.com/2022/11/23 (accessed on 24 November 2022).
43. Lango, L.; INVESTORPLACE. The Forever Battery That Promises to Change the EV Industry. 2022. Available online: https://investorplace.com/hypergrowthinvesting/2022/11 (accessed on 24 November 2022).
44. Thomson, E.; MIT News. Donald Sadoway Wins European Inventor Award for Liquid Metal Batteries. 2022. Available online: https://news.mit.edu/2022 (accessed on 29 January 2023).
45. Bradwell, D.; Kim, H.; Sirk, A.; Sadoway, D. Magnesium–Antimony Liquid Metal Battery for Stationary Energy Storage. *J. Am. Chem. Soc.* **2012**, *134*, 1895–1897. [CrossRef] [PubMed]
46. Office of Energy Efficiency & Renewable Energy. Hydrogen: A Clean, Flexible Energy Carrier. 2017. Available online: https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier (accessed on 7 September 2022).

47. Office of Energy Efficiency & Renewable Energy. Hydrogen Production: Microbial Biomass Conversion. 2022. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-microbial-biomass-conversion (accessed on 9 September 2022).
48. Lindorfer, J.; Rosenfeld, D.C.; Böhm, H. Fuel Cells: Energy Conversion Technology. *Future Energy* **2020**, 495–517. [CrossRef]
49. Office of Energy Efficiency & Renewable Energy. Hydrogen Storage Challenges. 2022. Available online: https://www.energy.gov/eere/fuelcells (accessed on 9 September 2022).
50. U.S. Energy Information Administration (EIA). Hydrogen. 2022. Available online: https://www.eia.gov/energyexplained/hydrogen (accessed on 9 September 2022).
51. Randall, C. Battery & Fuel Cell. Electrive.com. Hydrogen Train Network Goes Live in Germany. 2022. Available online: https://www.electrive.com/2022/08/25 (accessed on 9 September 2022).
52. White, L.; Oleksiewicz, A. Fuel Cells. Illinois.edu. Benefits and Disadvantages. 2023. Available online: https://publish.illinois.edu/fuel-cells (accessed on 9 September 2022).
53. Office of Energy Efficiency & Renewable Energy. Hydrogen and Fuel Cell Technologies. 2022. Available online: https://www.energy.gov/eere (accessed on 9 September 2022).
54. Kulikovsky, A.A. Fuel cell basics. In *Analytical Modeling of Fuel Cells*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 1–33.
55. Oneindia News. Hydrogen Fuel Cell Car: How Does It Work and Compare to Electric Car. 2022. Available online: https://www.bing.com/videos (accessed on 9 September 2022).
56. Anstrom, J.R. Hydrogen as a fuel in transportation. In *Advances in Hydrogen Production, Storage and Distribution*; Woodhead Publishing: Sawston, UK, 2014.
57. China Global Television Network (CGTN). China's Electric, Zero-Emission Ferry to Begin Service in October. 2022. Available online: https://news.cgtn.com/news/2022-09-27 (accessed on 9 September 2022).
58. Plungis, J. TOYOTANEWSROOM. Trucking World Endorses Toyota's Hydrogen-Powered Fuel Cells as a Step Toward a Cleaner Planet. 2022. Available online: https://pressroom.toyota.com (accessed on 30 November 2022).
59. Office of Energy Efficiency & Renewable Energy. How Do Wind Turbines Work? 2022. Available online: https://www.energy.gov/eere/wind (accessed on 29 January 2023).
60. National University of Singapore. PHYS.ORG. Revolutionary Technique to Generate Hydrogen More Efficiently from Water. 2022. Available online: https://phys.org/news (accessed on 10 November 2022).
61. Sequeira, C.; Pedro, M. Lead-Acid battery storage. *Cienc. E Tecnol. Dos Mater.* **2007**, *19*, 1–7.
62. Ragheb, M. Energy Storage with Wind Power. 2017, pp. 1–14. Available online: https://www.electricscotland.com (accessed on 29 January 2023).
63. EARTH.ORG. Top 5 Fastest-Growing Renewable Energy Sources Around the World. 2021. Available online: https://earth.org (accessed on 29 January 2023).
64. Power Technology. The Geysers Geothermal Field. 2012. Available online: https://www.power-technology.com/projects (accessed on 25 October 2022).
65. International Hydropower Association. Technology Case Study: Sihwa Lake Tidal Power Station. 2016. Available online: https://www.hydropower.org/blog (accessed on 25 October 2022).
66. Tidal Power Will Beat Wind and Solar Energy in No Time. 2022. Available online: https://www.youtube.com/watch?v=MFm-dvC8hvw (accessed on 21 November 2022).
67. Petruzzello, M. Britannica. Three Gorges Dam. 2022. Available online: https://www.britannica.com/topic/Three-Gorges-Dam (accessed on 25 October 2022).
68. Matalucci, S. PV Magazine. The Hydrogen Stream: Egypt to Host 3.6 GW of Electrolyzers at Suez Canal. 2022. Available online: https://www.pv-magazine.com/2022/11/22 (accessed on 24 November 2022).
69. YouTube.com Global Updat. This Spine Like Floating Device can Convert Wave Power into Electricity. 2022. Available online: https://www.youtube.com/watch?v=WytbO1OI_aM (accessed on 24 November 2022).
70. ITER Fusion World. 2023. Available online: https://www.iter.org (accessed on 24 February 2023).
71. Chinese State Media. Fusion Energy is One Step Closer Thanks to Developments in China. 2022. Available online: https://interestingengineering.com/science/china-and-iter-fusion-reactor (accessed on 24 November 2022).
72. Shahan, Z. CleanTechnica. CARS. Solar-Powered EV Charging for More Americans. 2021. Available online: https://cleantechnica.com/2021/07/01 (accessed on 24 November 2022).
73. Johnson, P. Electrek. EV Chargers. First Off-Grid Solar-Powered EV Charger Deployed in Puerto Rico in Wake of Rising Natural Disasters. 2022. Available online: https://electrek.co/2022/11/22 (accessed on 24 November 2022).
74. MSU Texas BS Mechanical Engineering Program Senior Design Project. Hybrid Open and Closed Loop Wind Tunnel. Stephen Albright, Lindy Hammon, Eurydice Kanimba. Faculty Advisor Dr. Sheldon Wang. 2014.
75. MSU Texas BS Mechanical Engineering Program Senior Design Project. Wind Turbine teetering Hub Damping System Design. Austin Smith, Ben Shields, Amanda Jinks, Haley Bragg. Faculty Advisor Dr. Sheldon Wang. 2015.
76. MSU Texas BS Mechanical Engineering Program Senior Design Project. Solar-Powered Steam Turbine. Kayode Crump, Zachary Skelton, Vjekoslav Stipanic, Khalid Walters. Faculty Advisor Dr. Idir Azouz. 2012.
77. MSU Texas BS Mechanical Engineering Program Senior Design Project. Mobile Wireless Surveillance System with Unpredictable Coherent Motion., Juwel Williams, Virgil Henry, Mamgoree Sock, Darrell Middlesworth. Faculty Advisor Dr. Sheldon Wang. 2019.

78. MSU Texas BS Mechanical Engineering Program Senior Design Project. Active Road Rumble Energy Harvest Panels. Robert Rorabaugh, Abhishek Chatterjee, and Chris Venegas. Faculty Advisor Dr. Salim Azzouz. 2013.
79. MSU Texas BS Mechanical Engineering Program Senior Design Project. Solar-Powered Stirling Engine. Rip Martin, Raul Hazel, and Dane Vincent. Faculty Advisor Dr. Salim Azzouz. 2013.
80. MSU Texas BS Mechanical Engineering Program Senior Design Project. Protective Solar Panel. Chukwudalu Mokah, Matt Mourning, Alex Petree, and Eguro Makeri. Faculty Advisor Dr. Sheldon Wang. 2014.