# Harnessing the sun: A critical look at the feasibility of solar energy

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## Introduction

As part of the Next Generation Science Standards, students look at the effect of humans on the environment, as it applies to the atmosphere, hydrosphere, geosphere, and biosphere. Energy is a big part of our ecological footprint, both in how we obtain it and the pollutants we create. As students become more aware of the problems involved in using fossil fuels like coal, oil, and natural gas, they become more interested in learning about other energy sources with solar energy being at the top of the list. After all, at first glance, the sun is free and seemingly limitless. In this unit, my objective is for students to think more critically about solar energy. I want them to consider its benefits and its drawbacks both in terms of feasibility and cradle to grave environmental cost. Although this unit is designed to be part of a high school Environmental Science class, discussion of the role of the sun in meeting our needs runs through the K-12 curriculum.

One of the challenges in discussing solar energy is understanding the limitations of photovoltaic cells. Prior to my current placement, my science teaching experience had been limited to sixth grade and below. My knowledge of solar cells was basically as magic black boxes: sunlight in and electricity out. Through my participation in the seminar and my research in creating this unit, I've developed a deeper understanding of the mechanics of photovoltaics and how the cost per kilowatt relates to both composition and placement.

## Rationale

In designing this unit, I was guided by the Next Generation Science Standards for high school with an emphasis on incorporating the eight Science and Engineering Practices. A secondary focus was on increasing access to content and providing multiple ways to demonstrate understanding. I am currently working in a setting where all my students have individual education plans, principally for other health impairments. Our minority population represents 87% of our student body, with 68% of the students falling into the low socio-economic status. Because of medical issues, there is a higher absenteeism rate than average. In addition, all students are pulled throughout the day for a variety of nursing needs, and therapies which may include speech, physical, occupational, and counseling. Due to its location inside a hospital, there is no real schoolyard, and any outside activities need to be done in a nearby public park. There are also restrictions on the use of certain common science materials, such as open flame, due to health or facility concerns. Although designed for a high school audience, my lessons also includes material at the middle school level as many of my students have major gaps in their science background knowledge due to their chronic illnesses.

## The Objectives:

In this unit, my objective is for students to think more critically about solar energy, its benefits, and its drawbacks both in terms of feasibility and cradle to grave environmental cost.

As part of feasibility, students will investigate how solar energy is being used today. They will consider passive and active uses in private and commercial settings. Students will discover that geography plays a huge role in determining the amount of available sunshine, within a day and within a year. They will discover that there is a sizable power loss in the conversion of solar energy to other forms of energy. They will also discover that present technology limits the ability to store energy from even the best sites.

For a cradle to grave evaluation, students will investigate the cost of using solar energy both in terms of initial outlay in dollars and in environmental production to create the solar panels. They will look at the changing efficiency rates over the life of a solar cell and also what is involved in safely disposing of the materials, some of which are quite toxic.

## Background Research

### The History of Solar Energy

Using the power of the sun goes back as far as recorded history. As early as the 7th century BC, people used magnifying glass to concentrate the sun's rays as a fire starter. Greeks and Romans used burning mirrors in the 3rd century BC to light ceremonial torches and there are even stories of Archimedes, a famous Greek scientist, using the bronze shields to reflect sunlight and set fire to the Roman wooden ships attacking Syracuse.[1] Although there are no contemporary writings for substantiation, in 1973 the Greek navy did a version of the alleged event and successfully set fire to a wooden boat fifty meters away. The Mythbuster's gang, however, was not as successful in any of their three attempts so it may be just an apocryphal tale.

In the 1st to the 4th century AD, we start to find large south facing windows in Roman bath houses to let in the warmth. In the 6th century AD, the Justinian code references "sun rights" to insure individual access to the sun, because sunrooms on houses and public buildings had become so common. In North America, the Ananzi were building their cliff dwellings in the 1200s to maximize southern sun exposure in the winter months.

The 18th and 19th century saw solar energy starting to be harnessed as a power source to do a range of other things. In 1767, a Swiss scientist, Horace de Saussure is credited with building the first solar oven. In 1816, Robert Stirling applied for a patent for his economiser. It was a closed machine that depended on the temperature difference between sides. When one end is heated and the other kept cool, the difference in temperature produced air movement that turned a rotating shaft. It worked with any heat source, including the sun.[2] In 1839, the photovoltaic effect was discovered by Edmond Becquerel. When the electrolytic cell he was working with was exposed to light, the amount of electricity created was greater than just in the electrolytic solution. From the 1860s through the 1880s, French mathematician August Mouche and his assistant, Abel Pifre, constructed the first solar powered steam engine and then used it and variations for a wide variety of applications. Modern parabolic dish collectors are based on their models. The photoconductivity of Selenium was discovered in 1873 by Willoughby Smith with William Adams and Richard Day creating the first selenium solar cell in 1876. Although the photovoltaic effect they generated was not enough to power electrical equipment, they did show that light could be changed into electricity without heat or moving parts. Moving beyond visible light, in 1887, Heinrich Hertz discovered that the amount of voltage needed to cause a spark was decreased by exposure to ultraviolet light. The century closed with Baltimore inventor Clarence Kemp patenting the first commercial solar water heater in 1891.[3]

Although there had been some work on solar energy previously, the twentieth century would see it take greater prominence. In 1904, Wilhelm Hallwachs discovered that a mixture of copper and cuprous oxide was photosensitive. In 1905, Einstein published the paper on the photovoltaic effect, which would be the basis of his winning the Nobel Prize in 1921. In 1908, a version of the modern solar collector, copper coils and an insulated box, was invented by William J. Bailley of the Carnegie Steel Company. In 1918 Polish scientist Jan Czochralski developed a way to grow single-crystal silicon. His discovery would become extremely important as silicon is the basis of most solar cells today. Bell Labs took center stage in 1954, with the first solar cell capable of powering everyday low wattage equipment. Employees Daryl Chapin, Calvin Fuller, and Gerald Pearson were the first to develop the silicon photovoltaic (PV) cell with an initial 4% efficiency, later to reach 11%.[4]

We speak of an energy crisis now but it hasn't been the first in our nation's history. WWII really taxed the home resources with the result being a demand for architecture that incorporated passive solar heating.

Yet it would be in space where solar technology first too off. In 1958, The Vanguard I space satellite, Explorer III, Vanguard II, and Sputnik-3 were all launched with PV-powered systems on board. It became the accepted energy source for space applications and remains so today. Seventy years later and solar energy is still key to extra-terrestrial applications. In 1962, Bell Telephone Laboratories launches the first telecommunications satellite, Telstar with an initial power of 14 watts. In just a few years, power production jumps by orders of magnitude. In 1964, NASA launches the first Nimbus spacecraft—a satellite powered by a 470-watt photovoltaic array. This was quickly followed by the first orbiting astronomical observatory launched by NASA in 1966, which was powered by a 1-kilowatt photovoltaic array.[5]

The move to terrestrial based systems became a reality through the work of Dr. Elliot Berman, with help from Exxon Corporation. His redesign of the solar cell dropped the cost of energy from $100 a watt to $20 a watt. At this reduced price, solar energy started to be seen as an option in remote locations, such as offshore gas and oil rigs, lighthouses and railroad crossings where grid connected utilities were prohibitively expensive.[6]

My home state took the lead in 1972 when The Institute of Energy Conversion was established at the University of Delaware (UD), as the world's first laboratory dedicated to thin-film photovoltaics and using solar for heating. A year later, UD unveiled "Solar One," one of the world's first photovoltaic (PV) powered residences. It was a PV/thermal hybrid. The roof-integrated arrays sent surplus power to the local utility during the day and purchased power from it at night. The system also provided heat with the cells acting almost as heat sponges. Fans then blew the warm air to bins where the heat was stored through phase changes.[7]

Over an almost two decade period from 1976 through 1995, NASA installed 83 photovoltaic systems on every continent except Australia. These systems met a variety of needs including vaccine refrigeration, room lighting, medical clinic lighting, telecommunications, water pumping, grain milling, and classroom television in areas lacking access to power grids. Attempts were also made to use solar technology in transportation. In 1981, Paul MacCready built the Solar Challenger. With over 16,000 solar cells mounted on its wings, it flew over the English Channel from France to England. On land, in 1982, Australian Hans Tholstrup drove the Quiet Achiever, the first solar-powered car, between Sydney and Perth, a distance of almost 2,800 miles. Tholstrup is also the founder of the "World Solar Challenge", one of the oldest and best known of the solar powered car racing events that recently celebrated its 30th anniversary in 2017.[8]

In 1982, The U.S. Department of Energy, began operating Solar One, a 10-megawatt central-receiver to demonstrate the feasibility of concentrating solar power. In 1996, Solar Two was opened. It focused on showing how solar energy could be stored efficiently and economically producing power even when the sun isn't shining. Its construction involved a field of mirrored heliostats focusing sunlight on a 300-foot (91 meter) tower, filled with molten nitrate salt. The salt flowed like water and could be heated to 1050 degrees F. Once heated, the liquid salt was used to produce electricity by way of a high efficiency steam turbine.[9]

One of the ongoing issues has been efficiency. In 1999, an industry breakthrough occurred when Spectrolab, Inc. and the National Renewable Energy Laboratory developed a photovoltaic solar cell that converted 32.3 percent of the sunlight that hit it into electricity. This feat was achieved by combining three layers of photovoltaic materials into a single solar cell and then exposing it to sunlight concentrated 50 times its normal strength using lenses and mirrors. In order to compensate for Earth's movement, "concentrator" systems were mounted on tracking systems that keep them aimed toward the sun.[10]

Although there had been some earlier isolated attempts, photovoltaic systems didn't really take hold in the non-commercial sector until the 21st century. In 2000, a 12 kilowatt solar electric system installed by a family in Morrison, Colorado, demonstrated that it was possible to meet the needs of a family of 8 in a 6,000 square foot home. In 2001, Home Depot begins selling residential solar power systems in three of its stores in San Diego, California and a year later expanded its sales to include 61 stores nationwide.[11]

Fast forward almost twenty years, and where do we stand today? In the U.S., our facilities can harness enough solar energy to produce an estimated 62.5 gigawatts, or put another way, enough to power 12 million average homes. In addition, in the last five years alone, the average cost of solar photovoltaic (PV) panels has decreased by nearly 50%. Unfortunately, even as hardware costs have gone down, individual consumer costs have risen due to the expiration of several energy grant and rebate programs. 74% of the total cost of a residential system now goes for permitting, financing, and installation.[12]

Worldwide, the picture is even better. Overall there has been a steady growth in the use of renewable energy. According to IRENA, the International Renewable Energy Agency, solar energy capacity increased by 94 GW in 2018, up 24% from the previous year. The majority of growth was in Asia, about 70%, primarily from China, India, Japan, and the Republic of Korea. Other major increases included the US (+8.4GW), Australia (+3.8 GW) and Germany (+3.6 GW). Brazil; Egypt; Pakistan; Mexico, Turkey and the Netherlands also significantly expanded their use of solar.[13]

**Solar Energy Usage**

At its core, non-passive solar energy uses captured sunlight to create photovoltaic power (PV) or concentrated solar power (CSP) for solar heating. With production increasing, both in the U.S. and internationally, how is all that power being used? Energy Sage listed the five most popular current non-passive uses as transportation, wearable personal technology, outdoor lighting, heating, and home energy use.[14] In transportation, railroads, subways, buses, planes, cars and even roads can all be powered by solar (PV). China is using solar buses on a large scale to help reduce the country's carbon footprint while maintaining efficient mass transit in densely populated cities through the use of lithium ion batteries. Boating is another area where solar technology is taking hold.

Personal technology that incorporates solar power includes cell phones, wearables (such as watches and fitness trackers), speakers, camping gear, flashlights, radios, speakers, calculators, electronic devices such as iPads and tablets, and portable charging stations. I, myself, carry an all-in-one portable solar, kinetic powered flashlight and charging station, in my car or in my backpack, so I never have to worry about my cell phone being out of a charge. Outside lighting is a natural fit. Solar cells absorb the energy during the day and then come on automatically at dusk without any additional wiring needed. More industrial uses include road signs and traffic lights. Heating is another area where solar energy shines. Systems can either be passive or active, using water or air as the medium and convection or pumps as the circulation method. Lastly, there is the concept of whole house integration using photovoltaics to generate electricity. Solar energy which comes in as direct current is transformed (inverted) to alternating current. This current is then available for property/household use. Any surplus is then sent through a net metering device which sends it back to the utility provider, if on a grid.

The term photovoltaic cell (PV) has been used a great deal in this paper but what is it actually and how does it work? To answer that question involves a little chemistry and starts with Silicon, the most common element in PV cells. Discovered in 1824, Silicon has an atomic number of 14, which means that it has 14 protons and 14 electrons, causing it to have 4 valence electrons. It is in the same family as Carbon. Silicon is both ordinary and unique. Ordinary because it is the 8th most common element in the universe and the 2nd most common element found in Earth's crust. It is usually found combined with other elements in sand. Purified is when it becomes unique. It is a hard, brittle, dark colored crystal that acts as a metaloid, which means it has properties between metals and non-metals and can act as a semiconductor. When exposed to sunlight, it produces an electrical current.

By itself, silicon is fairly stable, but when doped i.e. have other materials such as phosphorous deliberately added, it increases the conductivity. Phosphorous has 5 valence electrons. Four pair up with Silicon and one is left unattached, only being held by the positive charge of the proton in the nucleus. The extra electrons cause the silicon ion to have a negative charge. A second element added is Boron which bonds with Silicon to create a positive ion. When the two plates are put together, the free electrons on the negative ion side, move to fill the “holes” on the positive ion side. In doing so, a barrier is formed with an electric field separating the two sides. The electrons move from the negative side to the positive side. When a photon, light in the form of electromagnetic waves, hits the solar cell, that energy is absorbed by an electron which moves it into a higher energy state. It is the moving of the electrons which provides the current. The cell’s electric field causes the voltage. Multiplying the two, gives you the power.

A few other things go into making a solar cell. To start, silicon is shiny so an antireflective coating is needed to keep the light from reflecting. Secondly, the cells need to be protected from weather, usually in the form of a glass plate. In addition, to maximize output, cells are usually connected in arrays and mounted in frames that include positive and negative terminals which provide a path for electricity to leave the device.[15]

Not all photovoltaic cells are made the same though most types do use silicon in one form or another. One of the most efficient modules is made from monocrystalline or single crystal silicon. The silicon is purified, melted, and then crystallized into ingots, which are then cut into thin wafers to produce individual cells. The typical color of monocrystalline PV module is black or iridescent blue. They are generally used for large scale applications and offer efficiency (15-24%) and longevity as selling points. On the con side, they are fragile and are more expensive to produce.

The next step down are polycrystalline or multi-crystalline panels that are made from multifaceted silicon crystals. Instead of the solid color of single crystal cells, they display a random pattern of crystal borders. Since a low-cost silicon is used to make the polycrystalline cells, efficiency is typically in the range of 12%-14%, a value slightly less than the monocrystalline cells, but much higher than solar technologies such as thin film. Polycrystalline cells lower cost and ease of production are two reasons they are currently the most used PV panels on the Earth. They are used in both residential and commercial buildings and come in power ratings from 5 W to 250 W or more.

In an effort to increase flexibility and decrease cost, thin film solar panels were developed. Unlike in molding or slicing crystalline silicon, the silicon material used in thin film panels does not have a crystalline structure. Instead, thin layers of semiconductor materials are applied to different surfaces. There are four major types of thin films: amorphous silicon; copper, indium, gallium, selenide (CIGS); cadmium telluride (CdTe); and organic photovoltaic cells (OPC) currently in use. Pros include their low manufacturing cost and their versatility. Drawbacks include low efficiency (8-10%) and life span as they degrade faster than mono- and polycrystalline solar panels. Currently, the panels are mainly used in electronic powering circuits, home light applications, and in solar fields. One unusual feature is that they can be made transparent so that they could be incorporated in skylights and windows.[16]

As important as solar panel construction is to efficiency, so is placement. When I think of solar cells in terms of large scale collection, I think of ones that are ground or roof mounted but other options are being investigated. One way is to modify existing infrastructure such as roads or artificial waterways. In the Netherlands, where open space is at a premium, research on solar roads is well underway. The SolaRoad pilot cycle path, near Krommenie, opened in October 2014. At 90 m long and 3.5 m wide, it is a bike path with integrated solar panels. It was designed with the idea that the green energy generated could be used for public lighting, traffic lights, household use and electric cars. The challenge of course was to maintain the road's primary function while also maximizing its solar energy collection.

Over the life of the SolaRoad project, three different versions of the road were tested. Engineers looked at the composition of the top layer, solar panel design, and solar cell technologies. In the end, they concluded that the composition of the top layer was the most crucial. The more transparent to sunlight, the more energy the road surface could absorb. Yet the top layer also had to be skid resistant to allow the surface its primary function of being a road. In addition to maintaining the feel of the road, the engineers also wanted the surface to not require any more cleaning than a regular road.

In some ways, the project exceeded expectations. Originally, an energy yield of between 50 and 70 kWh/m2/year was expected. The first year 73 kWh/m2/year was reached (first version, built in 2014) and 93 kWh/m2/year (second, improved version, built in 2016). However climatic influences affect yield and subsequent years more closely matched the predictions as there was less light transmission due to a buildup of pollutants not washed away by the rain. In addition, the top layer showed some delamination where small pieces had chipped off. As part of the project, two sections were replaced with thin film solar cells. The upside was that they are less likely to break than the brittle silicon cells initially installed. The downside is that their efficiency is lower, averaging 41 kWh/m2/year. The next step is to see if the success on the bike trail can be translated to roads carrying cars, trucks and busses. The plan is to incorporate the Solaroad technology into the existing roadway at Haarlemmermeer in stages, to allow the testing of different materials.[17]

Another way to address land use concerns associated with wide scale solar is to erect solar plants on the water, since over 70% of the Earth's surface is covered in water.
Floating Solar arrays are not new. Back in 2008, the Far Niente Winery in Napa California was interested in adding solar to offset energy costs but space for the panels meant less acreage for grapes. In the end, the compromise was to install more than 2000 solar panels, almost half are located on floating platforms anchored to the bottom of the winery's pool, making it the world's first non-experimental floating solar array. Since then, both Japan and China have capitalized on the technology, with the United States definitely lagging behind. Japan has more than 60 installations and China claims the largest at 166,000 panels which produces enough electricity to power about 15,000 homes. In a bit of irony, that facility near Huainan, floats on an artificial lake created from a collapsed coal mine. Putting aside natural water sources, the World Bank in 2018 estimated that floating solar arrays could generate more than 400 gigawatts if implemented worldwide.

In some ways, floating cell technology is very much like land based. Instead of being mounted to the ground or a roof, the panels are put on pontoons which are tethered to the bottom of a man made reservoir or retention pond. Artificial sources are easier to utilize than lakes. Underwater or floating cables carry the direct current generated by the solar cells to an inverter on land which converts it to alternating current before sending it to the grid. Some of the unique challenges associated with water include making sure that the panels are resistant to corrosion, the platforms and tethers can resist high winds and waves, due to changing atmospheric conditions and that the anchors will last at least 25 years.

The benefits of water versus land can outweigh the challenges. To start, it frees up acreage for other uses such as agriculture or development. The panels can be floated into place and anchored versus using heavy equipment. Even energy efficiency may be improved as much as 20 percent as the cooling effect of the water counteracts the drop in efficiency due to heat. An additional claim was made that the floating arrays could improve the environment by blocking sunlight from penetrating the water which would reduce evaporation and also decrease algae blooms. I'm less willing to accept the premise that the panels would be solely beneficial as the decrease in sunlight would also affect other aquatic plants and the organisms that are part of their food web. As much of a fan as I am about solar energy, I would need more environment impact studies before agreeing that it's a good use of our artificial waterways.

As a nation, we seem to be proceeding cautiously with only 14 floating facilities in the United States as of 2018. One reason may be that there are still large areas of land available. Robert Spencer, a data scientist and software developer at National Renewable Energy Laboratory (NREL), suggests that it might be due to the uncertainty of the technology. "We're going to need to have a few high-profile projects that really demonstrate that this can happen at scale and by major players," he says. In a study he co-authored in Environmental Science and Technology, December 2018, he postulated that just by covering 27 percent of the 24, 419 artificial water bodies in the continental United State, floating panels could produce almost ten percent of our current power generation.

There are currently a few city based sites that bear watching. Kelseyville County Waterworks District in California, installed a 720-panel array on its wastewater treatment pond in 2018 and anticipates that it will recoup its installation costs after eight years. Los Angeles is looking to develop a plant at the Van Norman Lakes Reservoir. On the opposite coast, the Tampa Bay Water authority has added a reservoir-based solar power feasibility project to its 2019 capital improvement program, pending approval.

When the country is ready, so will the solar cell providers be. Ciel & Terre, one of France's leading solar cell producers changed its portfolio from land- and roof-mounted solar to floating arrays in 2011.[18]

One interesting marriage of non-fossil fuel based energy generation methods is to combine floating solar cells with hydroelectric power. "The Floating Photovoltaic Solar Power Plant" in the Alto Rabagão reservoir in Portugal is the first in Europe to combine solar and hydro power. EBT, the company that built the plant, chose the site partly because of the extreme conditions. There is a deep valley with rocky soil and significant height variations, which meant that the mooring solutions could be tested. In its first year, it surpassed expectations by 5% and survived freezing temperatures, snow, and even 3 foot swells.[19]

For the most part, hydroelectric plants are very predictable producers of electricity due to a constant water source flow. In some areas however, water levels can be seasonal. By installing floating arrays on the reservoirs associated with most dams, during the day less water needs to be released due to the cells contribution. At night, when the cells are not producing, some of the extra stored water can be let through the hydropower facility to provide more than enough energy to make it through the night hours. This continuity of energy is especially important in areas of weak grids.[20]

**Space Based Solar**

Technology has expanded communication to all parts of the world. Thanks to satellites, even the most remote places have access to cell service. It's a feat that would be unthinkable if we still needed to rely on running telephone lines. Now imagine instead of cell service, it is electric power being wirelessly transmitted.

As I read this, I asked myself: is this science fact or science fiction? The answer is a little of both. As early as 1941, Isaac Asimov, the famous Science Fiction writer, set one of his robot stories Reason in an environment where energy needs were met by collecting solar power in space and then wirelessly transmitting it to other planets. A little more than twenty five years later, Peter Glaser, an American aerospace engineer, published *Power From The Sun: Its Future* in the November 22, 1968 issue of the journal *Science.* He saw a space based system as a way to get around the limitation of terrestrial based panels which can't produce any power at night. Consequently, potential power is already reduced and that is before taking into account anything lost due to the inefficiencies of the cells or the conversion from DC to AC. Putting the panels in space also restores the 29% of Solar radiation that is normally reflected back into space by clouds, other bright surfaces and the atmosphere itself. This raises the available power per square meter from 1000w/m2 to 1367 W/m2.[21]

Glaser's idea was to mount the panels on a satellite that would stay in geosynchronous orbit at around 35,000 km above the Earth's surface. Due to the Earth's tilt, the satellite would almost never be in total darkness. In spite of the early interest, the technology wasn't there and Space Solar Power Systems (SSPS) languished for several decades.
Recently there has been a resurgence. In reaction to the nuclear accident at Fukushima, the Japanese Aerospace Exploration Agency (Jaxa) is currently at work as part of a twenty year plan to develop a workable SSPS. They are looking at two different ways to transmit the energy: microwaves and lasers.

Microwaves offer two advantages in that they can penetrate cloud cover and rainfall and they are safer than lasers. To start, solar DC current would be converted to microwaves aboard the satellite and then those microwaves would be converted back to DC current on the ground. The present thought is to use vacuum tubes, such as magnetrons, klystrons, or traveling wave tubes because of their cost and their high power conversion rate of 70% or better. The next step is to choose the correct frequency as microwaves cover the electromagnetic spectrum from .1 mm to

10 cm (frequencies between .1 and 10 GHz). Lower frequency microwaves pass through the atmosphere easily but at a cost of needing very large antennas. Looking at the range of 1 to 10 gigahertz seems the best compromise. Another consideration is the need to choose a bandwidth that won't interfere with other signals. Within this range, 2.45 and 5.8 GHz qualify because they are in the bandwidth set aside for industrial, scientific, and medical uses. The goal of a smaller transmitting antenna seems to make 5.8GHz the best choice.

The second technological hurdle is to design a system that can steer a microwave beam in any direction with high accuracy. It is a daunting task when you consider that more than a billion antenna may be installed on a single panel. The sticking point is that to transmit the microwave energy safely, it has to be done with extremely precise accuracy. To be successful will require controlling and synchronizing billions of antenna.[22]

Lasers, (Light Amplification by Stimulated Emission of Radiation), are a form of artificial light that has a uniform wavelength and phase. Two things that make them ideal for energy transmission is that they have a low divergence angle and they are compact. Jaxa is currently looking at wavelengths of about 1070nm (near-infrared) and a continuous wave. Two significant drawbacks are that lasers are susceptible to atmospheric disturbances and they cannot penetrate clouds or rainfall. In addition, they require strict safety protocols as they are very dangerous to human vision. Lasers also carry a negative connotation having been associated with weapons. Creating the collector itself has challenges as Jaxa anticipates that it would need to be several kilometers in order to have the necessary equipment for the collection, conversion and transmission of solar energy. To date, the largest artificial structure in space is the International Space Station (ISS) which is 100 meters wide, 340 tons and operates at an altitude of 400 kilometers. The ISS was too big to be launched as one piece. Instead the component pieces were hauled by Russian Proton rockets and American Space Shuttles. Once there, they were assembled by ISS crewmen using a robotic arm. Since the solar collector assembly would be bigger, heavier, and need to be taken to a much higher altitude it too would have to be assembled in space. However, for cost and safety reasons, an alternative to human resources is needed. Jaxa's plan is to develop a robotic system that could autonomously assemble the SSPS.

As of 2014, there were two designs under consideration. The simpler of the two is a huge square panel, 2 km per side, covered with photovoltaic cells on the top and transmission antennas on the base. The panel would hang from 10-km-long tether wires from a small bus, which holds the satellite's controls and communication systems. The benefit of this configuration is that the bus acts as a counterweight to the panel. The panel, being closer to Earth, experiences more gravitational pull down and less centrifugal force away. At the same time, the opposite effects are operating on the bus, pulling it upward. Known as gravity gradient stabilization, this balance of forces could keep the satellite in a stable orbit, thus saving the need for any propulsion to maintain altitude. The benefit of a fixed orientation is also a drawback as the amount of sun exposure will vary as the geosynchronous satellite and the Earth spins.

A more sophisticated SPS uses two huge free flying reflective mirrors. They would be positioned so as to constantly direct light onto two photovoltaic panels. Since they would not be attached to the solar panels or the transmission unit, they would require some ongoing guidance system. Additional requirements of this system would include very light materials for the mirror structures and extremely high voltage power transmission cables to channel the power from the panels to the transmission unit with minimal resistance losses.[23]

While China is also planning to install extraterrestrial solar arrays, they are on a different time schedule. The first phase, beginning in 2021 centers on launching small and medium electricity generating satellites in the stratosphere. The next goal is to have a system in place by 2030 that can generate at least a megawatt with the ultimate goal being a commercial scale plant by 2050. One of the more interesting aspects of China's space plans involves not only having assembly take place off world but also manufacturing the components in space.[24]

## Teaching Activities

### Strategies:

The unit will begin with two pictures; a coal burning plant and a solar array. From there, students will be asked to generate questions on each. Questions will be shared anonymously and then grouped according to type. These questions will be part of our student driven investigations with more added throughout the unit. In anticipation that students may struggle to form questions, question cubes will be available.

As students deepen their knowledge on solar energy, the emphasis will be on the following Next Generation Science Standards (NGSS) Science and Engineering Practices. As they move through the unit, they will be asking questions and defining problems as part of both designing their solar ovens and evaluating site suitability. They will be obtaining, evaluating and communicating information as part of researching photovoltaic cells and through their work with pyranometers. They will be developing and using models as they extrapolate from their work with small solar cells to considering much larger arrays. They will plan and carry out investigations as they try and determine which materials will make their solar ovens more efficient. They will analyze and interpret data gathered from both real and virtual use of the Solar Pathfinder. They will use mathematics and computational thinking in comparing solar irradiance and also cost per kilowatt hour for different energy sources. They will be constructing explanations and designing solutions in determining the best location for a fixed solar array based on available sunlight during the peak solar window. In addition, they will be challenged to design and build their own solar powered device using small solar cells commercially available. Lastly, they will have multiple opportunities to engage in argument from evidence throughout the unit during justification of solar oven design, defending placement and angle of solar panels, and conducting a claims, evidence and reasoning argument regarding the feasibility of solar energy replacing fossil fuels as the main energy source within the next twenty years.

The unit will have three main components: obtaining content knowledge on the use of solar energy and its pros and cons, and looking toward future developments; planning and carrying out investigations that look at which factors affect active and passive solar energy collection and creating their own solar powered device using commercially available solar cells.

### Engineering a Solar Oven

Before moving into photovoltaic cells, students will start with something much simpler: solar ovens. I'm choosing to start this way as part of building knowledge and making connections to prior learning. As part of the 6-8th grade curriculum, students look at heat transfer from areas of higher heat to areas of lower heat. They also begin to look at the conductivity of different materials. In this bridge activity, students design a solar oven and then refine their designs based on experimental data. This initial lesson and the one that follows it are both freely available from Teach Engineering, a free for educational use site that provides stem lessons for K-12. Sponsored by the University of Colorado at Boulder, it provides background information for both teachers and students regarding the three types of heat transfer: conduction, convection and radiation. It then presents a partial engineering challenge as students work in groups to construct solar ovens using the same basic plan. Although I love the thoroughness of the teacher instructions, I prefer the lower tech version of modifying pizza boxes. Both resources can be found in the teacher resource section.

Several of the activities that follow come from the Center for Renewable Energy Advanced Technological Education Site. The material is free for educators and carries a copyright release for its modification and non-commercial use. The link can be found in the teacher resources.

**Determining Solar Irradiance and the Factors that Influence it**

Students will use a pyranometer to measure the amount of solar irradiance outside in a variety of settings. They will discover how angle and cover affect the amount of solar energy a panel can receive. In conjunction, they will look at the differences between fixed and tracking solar photovoltaic arrays. If pyranometers are not available, there are a number of different smart phone apps, while not rated for commercial use, are sufficiently accurate to be used in this investigation.

Working in pairs, students will take six readings and record the data in a table. They will then share their data to arrive at class averages. The six conditions include vertical (90 degrees) shaded and non-shaded, normal (135 degrees) horizontal (180 degrees) and reflected (225 degrees) off both a light and a dark surface. As part of sharing data, students should discuss any experimental notes that affected their data collection such as a change in cloud cover. Discuss with students how including data from other classes might affect their averages based on time of day. Ask whether time of year has any effect. The overall goal is for students to determine the factors that affect how much solar irradiance the solar panels can absorb before looking at feasibility in terms of placement and efficiency.

Formative assessment is a set of short answer questions that can be done individually or with a partner. As written, students will also need internet access or printed materials to help them investigate the benefits and drawbacks of fixed versus tracking systems. As a special education teacher, I would also allow my students to use both text to speech and speech to text to access the new material and to demonstrate their understanding. The assessment could also be modified to use the student picture with students putting in numbers on a scale of 1-6 (low to high) to show highest irradiance. As to listing the different factors such as season (both as to number of daylight hours and possible cover from deciduous trees), cloud cover, night, and time of day, students could be given a word bank or a series of pictures from which to choose.

The next lesson involves taking a closer look at photovoltaic panels. There is an overwhelming amount of text available on the internet but I love the background material on this site. To start, it introduces students to the element silicon using a resume approach. The language is straightforward and there is strong picture support. Then it provides a short history and gives a surface explanation of the mechanism of electron excitation and movement in three short pages with diagrams. There are a series of short answer questions that follow. As mentioned previously, one modification would be to allow students to use text to speech and speech to text for their comprehension responses.

**Evaluating Site Suitability**

In evaluating a site, students will consider how much of the solar window is available. In astronomical terms, the solar window is defined as the area of the sky open to sunlight. The upper and lower limits are defined by the sun's path on the summer solstice to the first day of the winter solstice. The east and west edges are defined by the horizons.

Since sunlight is usually weakest in the early morning and late day due to the angle of the rays, those sections of the complete solar window are viewed as less important in site selection. In the photovoltaic (PV) industry, the three hours on either side of solar noon are considered the most important so students focus on the area between 9AM-3 PM. In the best case scenario, students will get to use an actual Solar Pathfinder. On the plus side, the device is very easy to use. The down side is that it retails in the low $200 range. Although a reasonable model can be constructed using a convex plastic produce lid, it would be much better to purchase a standard one or arrange to borrow one from a local university or solar energy company. This device is a low tech way to gather data on the feasibility of a site in terms of needed solar exposure by looking at any shadows that fall on the face during a proscribed period. The data can lead to good discussions as to aesthetics versus energy efficiency. In cases where house roofs don't have southern exposure, what are some other placement ideas? Do you take out mature trees in order to increase irradiance? How much physical ground are you willing to sacrifice to a land based solar array?

Prior to using the Solar Pathfinder, students build on background knowledge defining key terms such as latitude, longitude, solar azimuth, solar altitude, solar noon and solar window. To help them operate the device there are video tutorials and also a paper copy of the disc that comes closest to their latitude. The provided worksheet also provides a link to a site that allows students to find out key astronomical information about their local area.

Even if students are not able to have hands on experience, the CREATE site also offers a series of video examples. As part of my own drive to have students develop their arguing with evidence skills, I will be having them use the different examples as the basis of doing Claims, Evidence, and Reasoning mini paragraphs. So as to not overwhelm the students, I will set the individual images up as different stations that they will visit in mixed ability pairs.

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**Teacher Resources**

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Appendix

**Standards:**

HS-ESS 2-4 Use a model to describe how variations within the flow of energy into and out of Earth's systems can result in changes in climate. As part of investigating solar irradiance, students will analyze the uneven heating of the Earth.

HS-PS3-3 Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy. Students will be creating both a passive solar energy device in the form of a solar oven and an active solar device using a photovoltaic cell.

**Disciplinary Core Ideas:**

PS3.A: Definitions of Energy - At the macroscopic scale, energy manifests itself in multiple ways, such as motion, sound, light, and thermal energy. Students will discover that the sun's energy comes to us in different wavelengths with different properties.

PS3.D: Energy in Chemical Processes - Although energy cannot be destroyed, it can be converted to less useful forms, for example, to thermal energy in the surrounding environment. Students will discover why solar cells are only able to convert a fraction of the sun's energy to electric current.

ETS1.A: Defining and Delimiting an Engineering Problem - Throughout this unit, students will be considering the "cost" of implementing solar energy from an economic, environmental, and quality of life lens. They will also consider design parameters and constraints in creating their own solar powered devices.

**Cross Cutting Concepts:**

Changes in energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. As part of sharing their solar powered projects, students will describe the flow of energy.

Common Core Standards

Mathematics

**Reason quantitatively and use units to solve problems.**

CCSS.MATH.CONTENT.HSN.Q.A.1
Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.

CCSS.MATH.CONTENT.HSN.Q.A.2
Define appropriate quantities for the purpose of descriptive modeling.

CCSS.MATH.CONTENT.HSN.Q.A.3
Choose a level of accuracy appropriate to limitations on measurement when reporting quantities.

In this unit, students will be using mathematics as they collect and analyze data, either through their own investigations or through research, especially in the areas of cost, efficiency and solar irradiance.

Common Core Standards ELA

CCSS.ELA-LITERACY.RST.9-10.1
Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

CCSS.ELA-LITERACY.RST.9-10.2
Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.

CCSS.ELA-LITERACY.RST.9-10.3
Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks, attending to special cases or exceptions defined in the text.

In this unit, students will be working with multiple text sources to build background knowledge, to answer student generated questions, and as part of lab procedures.

CCSS.ELA-LITERACY.W.9-10.1
Write arguments to support claims in an analysis of substantive topics or texts, using valid reasoning and relevant and sufficient evidence.

In this unit, students will use the claims, reasoning and evidence format as part of the culminating project on site selection.

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