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ABSTRACT

Most buildings require power produced by fossil fuels, the extraction and consumption of which contaminate our environment. The Virginia Center of Basic and Applied Science (CBAS, INC) constructed a building in a remote forested area as a plant and fish nursery (and living space for staff) to be operated by solar electrical power. Comfortable summer interior temperature is facilitated by an open design, 15,000 cubic foot interior, ceiling fans, many large windows and doors, with a large sun-screen eave off the 1000 square foot south-facing roof. Comfortable winter temperature is possible because the building has no tree-shade, thick well-insulated walls and roof, a low number of air changes per hour, and when necessary the surrounding forest provides wood stove heat. The energy challenge of the research was to develop a system facilitating 24-hour and year-round use (primarily for lights, fans, pumps, heaters and staff living requirements) that did not need to be connected to the local electrical utility company. On average, the facility uses 3-4 kilowatt hours per day. The solar power is captured by 8 solar panels which charge a bank of deep-cycle batteries, which in turn generate the power for the facility. The complete system (solar panels, charge controller, batteries, DC-to-AC inverter, 110-to-220 transformer) cost about $10,000, about 5% of the total facility cost.

Keywords: photovoltaic, greenhouse, pollution

1. INTRODUCTION

Fusion reactions within the sun, most of which convert hydrogen to helium, produce heat so extreme that the nuclei of atoms in the sun's outer layer radiate energy, some of which is visible and infrared light. Much more than the earth's requirements for photosynthesis are met by this light, and it could supply all of our primary supply needs for electricity. The earth intercepts less than one-trillionth of the sun's light because of the great distance from the sun and the comparatively small size of the earth, yet capturing only 0.01% of the light striking the earth would satisfy all of earth's annual electrical needs. For the United States, capturing only 0.1% of its sunlight would satisfy its needs. Currently, in the United States, solar generated electricity contributes less than 0.1% of the energy consumed.

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Solar energy is the ultimate in terms of renewable energy, often defined as an energy source that will never run out and will not directly result in pollution of the earth's air, water and soil. In the natural world, the atmosphere, hydrosphere, biosphere and lithosphere trap solar energy. Winds in the atmosphere, currents and tides in the oceans, and biomass energy (carbon-based) all are indirect sources of energy created by the sun's light. However, in contrast to carbon-based and uranium-based fuels, the direct use of sunlight carries the possibility of being both an inexpensive and pollution-free energy (Kryza, 2003).

It has been said that fossilized sunshine, in the form of coal, oil and natural gas are finite resources. Estimates of the time until these carbon-based fuels will be exhausted are as high as 200 years, and are based on numerous assumptions and estimates. However, as time passes these fuels become increasing expensive to extract and refine, and more difficult to deliver without exceeding acceptable pollution levels.

The infrared component of sunlight that is captured on absorbing materials is often used to heat commercial buildings and homes with sunlight-facing circulating water heaters and with air heaters (commonly called heat exchangers). In some latitudes that receive above-average sunlight, sunlight concentrated by mirrors can be focused on tanks of water (or other liquid) to make high-pressure vapor used to turn electricity-generating turbines (Fahrenbruch and Bube, 1983).

Electricity directly from light uses the photovoltaic effect, discovered almost 200 years ago. The first silicon-based solar cells were made almost 100 years ago, and by 50 years ago the efficiency of solar cells was up to about 5%. Each solar cell provides a tiny electrical current, so many are formed together into a solar panel, and panels are joined into solar arrays.The first solar panels and arrays of solar panels were built for commercial use in the 1960's, and most notably were used in space to power satellites and NASA's Skylab. By the 1970's solar panel array costs were down to $30/watt. By the 1980's, corporate and governmental systems producing 100's of kilowatts (kW) down to remote location systems producing 100's of watts were being built. In the 1990's, solar cells of different designs with higher efficiencies of 10-30%'s were created and marketed, the power generated by the solar panels increased by almost 100%, the cost of the more commonly installed solar panels fell toward $10/watt, and systems producing close to a 100 million watts (100 MW) were constructed.

Photoconversion is the absorption of sunlight on solid materials whose electrons are excited to a more energetic state, and that energy can then be captured as usable electricity. The photovoltaic effect occurs when separated positive and negative charges can be created in the solid material when it absorbs sunlight. That is, the sunlight simultaneously and continuously excites atoms in the material, and the excited atoms that have lost electrons become positively charged sites. Given the opportunity, such as connecting the material to a battery, the "liberated" electrons can move into one terminal of the battery (negative post) and the positive sites can be connected to the other battery terminal (positive post). In this configuration, as the electrons flow through the battery, they cause chemical changes required to recharge the battery, and then the electrons flow back into the light-sensitive material. Sunlight again liberates electrons which continue to flow through and recharge the battery (Komp, 1995).

The material most commonly used for photoconversion is silicon, which behaves as a semiconductor. The amount of silicon now used to produce solar electricity is more than the amount of silicon used to produce all other electrical components (e.g., computer chips). Semiconductors are weak conductors (half-way between a metal and an insulator) because the bonds linking the atoms are relatively weak and the energy required to excite and liberate electrons is relatively weak. Most photovoltaic cells or solar cells used to make electricity from sunlight are silicon semiconductors.

Experimental solar cells have been designed to utilize all of sunlight, but these types of cells are extremely expensive. In 2008, a multi-metal type of solar cell demonstrated an ability to convert over 40% of sunlight energy into electricity. Silicon solar cells also absorb all light, but only infrared light (which makes most of the light’s energy) is converted to electricity. The rest of the sunlight makes only heat in modern commercially available solar panels.

Some of the new installations are thin-film photovoltaic panels, not made of silicon, which are less expensive than silicon-based solar cells to manufacture. Thin-film solar cells were first created in the mid-1980’s, and now account for about 10% of the solar installations around the world. Thin-film panels are less efficient than the silicon panels (higher cost/watt), but they have enabled innovative applications. Large installations, such as on a building with a metal roof are being done, and the thin-film panels can also be used in unusual applications, such as electricity-generating window curtains and portable roll-up panels for campers (McCoy, 2008).

In commercially available silicon-based solar panels, the highest possible light-to-energy conversion occurs in crystalline solar panel cells (silicon atoms have a regular arrangement) and in silicon alloyed with metals (such as germanium, gallium, and indium) that strain the bonds between the silicon atoms and allows faster electron movement. However, most solar panels in use today, and most new installations, are made of amorphous silicon (silicon atoms in random arrangements). These panels, while having light-to-energy conversions of less than 10% and require perhaps hundreds of square feet coverage to collect enough sunlight, are much more popular because they have the lowest cost/watt ratio (Green, 2000).

Solar panel arrays produce direct current (DC), which is normally converted into alternating current (AC) for lighting, equipment and appliances. The greatest barrier to the widespread use of solar panels is their cost (currently almost $1000/panel), the cost of the panel-to-battery charge regulator (a few $100), the cost of the batteries used to store electricity for use at night (batteries cost about $100 each), and the cost of converting the DC to AC power (an adequate inverter costs about $1000). All these costs have declined markedly over the past 10 years, while the costs of electricity from fossil fuels have increased.

Power derived by using the photovoltaic effect has the best cost-to-benefit ratio in sunny locations, such as in the southern United States. It is also a good option in locations where conventional power grid lines are not available. In fact, the development of local solar power stations could reduce the need for creating power grids that carry electricity over long distances. In the United States, about half of the solar electricity systems are used to electrify homes and farms, about a third is used for communications and industrial applications, and about 15% is given back to electrical utility companies to send over power lines.

In recent years, the fastest increase in the use of home-site photovoltaic systems is in Japan and Europe, particularly Spain. In 2007, world photovoltaic installations amounted to almost 3000 MW of electrical capacity, which was over 50% higher than 2006 (Johnson, 2004; McCoy, 2008). However, while solar energy comes from the sun, so it is free, renewable and will never run out, and while solar panel systems are clean and silent, reliable and easy to install, have a low environmental impact and a very low operating cost, have essentially no components that can have mechanical failure, do not require centralized supplies and extensive distribution systems, and have high public acceptance, the United States government ended its subsidies in the 1980's, and most states (including Virginia) provide no tax or regulatory credit. A few states, most notably California, subsidize the cost of the photovoltaic system and buy back excess electricity at retail rates. In the United States, about half of the systems installed each year are in California (Tullo, 2006).

2. SOLAR ELECTRICITY IN THE UNITED STATES

In the southwestern United States (mainly California, Arizona and Nevada, but also in Utah, Colorado, New Mexico and Texas), a "solar land rush" has been happening. Large and small companies are buying and leasing land that has little worth except for the sunlight. The already purchased and leased land (over one million acres) could, in theory, produce more energy than is consumed by California. The amount of solar radiation is considerably less elsewhere in the United States. For example, in Virginia the average annual solar radiation is about 50% of the radiation in California.

In Virginia (and elsewhere), solar installation companies are contracting with the operators of stores, warehouses and factories to at no cost install and maintain solar panel systems on the roofs, requiring a 10- to 20-year contract with the building owner to purchase solar generated electricity at close to or less than utility company rates. This arrangement seems likely to continue, since time has shown that as the industry capacity to manufacture solar panels rises, the cost of the panels fall.

Over the past 10 years, worldwide manufacture of solar panels (mostly Japan and Germany, followed by the United States) has almost doubled and the cost/panel has fallen almost 50%. In the mid-1990's, after the United States had ended its solar power subsidy program, Japan's government began a "solar roof" program (advertising, education, low-interest loans, and rebates). In the subsequent 10 years, the annual number of installations in Japan grew by over 40% each year, and now the cost that is charged to customers by the generators of solar electricity is less than the cost charged by electrical utilities using atomic power or other sources.

Photovoltaic systems are initially expensive, but the costs are very low after the installation, and in a few years, the savings from not paying an electrical utility bill pays for the system. The cost for solar panel systems that can completely power a home depends on the size of the home. While smaller homes need fewer panels, they normally have much smaller monthly electrical bills. The system in a small home now takes about 15 years to pay for itself, in terms of utility bill savings.

While an office complex might require a system that produces 100's or 1000's of kW's when the sun shines, a small size off-the-grid all-electric home or other similar size building might require only a 1 kW system. The area to be covered by solar panels can be compared to the quantity of electrical power generated by the system. In very approximate terms, 100 square feet of solar panels of medium generating ability generates about 1000 watts (1 kW) in full sunshine. Assuming the equivalent of 5 hours of full sunlight/day, this would be a 5 kWHrs/day, or about 150 kWHrs/month (e.g., a small home in Virginia). Off-the-grid electricity from solar energy now costs less than ten dollars per watt (includes all components, batteries and installation), so the solar electricity system for a small home (a 1 kW system) will cost about $10,000.

Multiples of these approximations can serve to predict the requisite size and cost of larger photovoltaic systems. A modest size home needs a 4 kW system, making 600 kWHrs/month, which now costs about $40,000. This could be compared to the home's $400/month electricity bill (includes electricity, various service charges and taxes). It would take about 10 years for the solar power system to pay for itself.

While some home owners plan to stay in their home, other home owners might not anticipate being in their present home for 10 years, but they can anticipate offering a potential home buyer an off-the-grid home. In any event, the number of photovoltaic solar installations in the United States is up 50% compared to two years ago. This is probably because as time passes, the systems are becoming less expensive. It has been speculated in 10 years from now, the costs will fall another 50% due to competition, increased production and availability of solar panels, and the decreased cost of installation.

The following is research directed toward the owner of a home or other building that cannot, or does not want to be connected to the electrical grid of a utility company. In particular, we wanted to operate the requisite air, water and light systems for a greenhouse which, for whatever the reason, is an off-the-grid operation.

3. CONSTRUCTION OF THE EXPERIMENTAL BUILDING

Builders of homes designed to operate on solar electricity should ensure that the building has adequate insulation, "tight" doors and windows, and efficient lighting and HVAC systems. If the building is constructed with a proper size photovoltaic system, the building can have a zero electrical bill, and the buyer has a slightly greater mortgage.

More commonly, the approach is to "retrofit" a building and then install a photovoltaic system.

The experimental building used in this study is located on a 100 acre farm near the town of Culpeper, in central Virginia. The building was initially constructed without a photovoltaic system, so various photovoltaic size, components and efficiency factors could be evaluated. The building is a one-story 30 by 50 foot "ranch house" of wood construction, with a 10 foot ceiling (15,000 cubic feet of air). The longest sides of the building face south (toward the sun) and north. The building is on a hilltop in a field, with no tree shade for most of the day. The walls are 6 inches thick and well insulated (R-19), as is the roof. To facilitate access and summer cross ventilation, both of the 30 foot end walls have single 3 foot wide doors, and the 50 foot south and north walls have 6 foot double doors. The south-facing wall has the most of the UV-protected (argon filled) double-pane windows, but on average about 30% of the walls are windows.

The roof on the experimental building has a 30 degree pitch (with light-colored shingles), and extends beyond the north and south walls. The eave off the north side roof is primarily for shelter and only extends 6 feet beyond the north wall. The eave off the south side extends 12 feet out from the south wall, so it is 10 feet high along the south wall and only 8 feet at the end of the eave. Consequently, the winter sunshine can reach the windows as the sun traverses the sky at a comparatively low angle, but the higher summer sun cannot shine into the windows.

To moderate the interior temperature, the floor is a 10 inch thick cement slab covered by ceramic tiles. To maximize the work space, the slab floor of the building extends 5 feet out from the north wall and 10 feet out from the south wall.

Because the building is to function as a greenhouse and fish nursery, the southern half of the building (an open 15 by 50 foot floor space) is the work area. This single work room has 14 ceiling lights (1 per 50 square feet), 2 ceiling fans, and many wall electrical outlets for maintenance equipment. The northern half of the building is the living space for the building operator, and is divided into a workshop, wet room, study, bedroom, kitchen, and bathroom.

Power to the experimental building was assembled to ensure satisfactory year-round energy. Available are a 200 amp (110 and 220 volt) local energy utility line, a 3500 watt (110 and 220 volt) gasoline electrical generator, a blower-equipped 20,000 Btu/hour wood stove (and surrounding forest), kerosene and propane heaters and lamps, and the experimental photovoltaic system.

The incandescent lights in the building have not yet been replaced. Incandescent lights require 5 to 10 times more electricity and have a 10-30 times shorter lifespan than compact fluorescent lights and light emitting diode lights.

4. CALCULATIONS FOR THE SOLAR ARRAY SYSTEM

For the following commentary, several definitions and analogies are useful. Voltage is a force, electrical potential or potential difference, expressed in volts. The analogy for water could be the distance the water falls over a dam. Amperage is the strength or intensity of an electrical current, expressed in amps. For water, it could be considered the amount of water flowing over a dam. Wattage is a power, expressed in watts. For water, it could be considered the ability of moving water to carry a weight or volume of material.

The important major components for any off-the-grid system are the batteries and the solar panels. Calculations to determine the requisite number of each begin with the estimated amount of electricity needed each month, usually determined by looking at a bill from the electrical utility company. Based on estimates, it was hypothesized that the electricity to operate the greenhouse and nursery space would be about 100 kWHrs/month (as in a very small home), or about 3.5 kWHrs/day, to be provided by batteries that are charged as needed by the solar panel array.

The deep-cycle 12 DC-volt batteries used in this experiment are each rated at 70 amp-hours. This means, for example, they can each provide 1 amp (the amperage used by one light bulb) over 70 hours. Using [volts][amp-hours] = [watt-hours], when fully charged each battery holds [12 volts][70 amp-hours] = [840 watt-Hrs] or 0.84 kWHrs. To provide 3.5 kWHrs/day, it requires [3.5/0.84] = 4 batteries.

Based on the preceding calculations, the solar array could, in theory, provide the batteries with 3.5 kWHrs/day, which would fully recharge the batteries each day. With careful use of the building, it would be possible, in theory, to avoid taking too much power out of the batteries. This is necessary, because if the voltage from the batteries drops significantly below 12 volts, the system stops providing 110 AC voltage.

As discussed above, the “small home” calculation assumed a need for 100 kWHrs/month, which could be provided by 4 deep-cycle batteries, if they were recharged during the day. Each battery requires about 840 watt-Hrs to be recharged in one day. Each of the solar panels used in this experiment produces 62 watts, 22 DC-volts and 4 amps at full sunlight. In mid-latitude states like Virginia, compared to “full-sunlight” states like California, there are about 6 hours/day of full-sunlight in the summer (2 hours/day of full-sunlight in the winter). In the summer, each panel provides [6 hours][62 watts] = 360 watt-Hrs, so in one day two panels should, in theory, be almost enough to recharge one battery in a day. Another approach, which reduces the calculations to a simple ratio, is that each battery in an off-the-grid system can be recharged by 125 watts of the solar panel energy (e.g., 4 batteries can be recharged by a solar panel array producing 500 watts).

5. CONSTRUCTION OF THE SOLAR ARRAY SYSTEM

The eight panels that form the solar panel array used in this experiment were made by SOLAREX (type MSX64). Each 20 x 43 inch panel produces direct current (DC) and is rated at 21.5 volts, 3.91 amps, and 62 watts. This is 75% of the theoretical 85 watts, calculated using the electricity [volts][amps] = [watts] equation. The eight panels are wired in parallel in a 50 square foot array, so the array produces 488 watts, 22 DC-volts and 32 amps. On a summer day with average sunlight (6 full-equivalent sunlight hours), in theory the system can produce about 3 kW-hours (kWHrs). Over a month of average sunlight, the system can in theory produce almost 100 kWHrs. As discussed earlier, this was hypothesized as being adequate to support the operation of a greenhouse and nursury, which in this case also has a small living area (kitchen, bedroom, bathroom, and study) for the facility operator.

A XANTREX (Model C-60) Controller is used to change the 22 DC-volts from the panels into12 DC-volts, to charge the batteries. This controller charges the batteries at an operator determined voltage (e.g. 14 volts) until they are fully charged, and then allows the voltage in the batteries to drop to 12 volts where they are maintained. This cycle is repeated whenever the battery voltage drops below 12 volts. As noted earlier, the solar panel array can produce up to 32 amps, but this controller will accept a current from a solar array of up to 60 amps. If that amperage were exceeded, the extra energy is converted to heat and dissipated by a heatsink on the controller. At night, the solar panel array is disconnected from the batteries by the controller (prevents reverse leakage of power from the batteries).

Only 70 (or more) amp-hour deep-cycle batteries are used because they will have a longer life than normal automobile-size batteries. In theory, it was found that two solar panels could adequately maintain the charge in one battery on a day with average sunlight. The solar array now has 8 panels, one charge controller and five (one extra) deep-cycle batteries, wired in parallel. Although connected to the batteries, the controller (and the inverter) cannot be in a compartment with the batteries, because batteries vent hydrogen-sulfide gas, which corrodes electronic equipment.

The DC current provided by the battery pack goes through an inverter to provide AC voltage to the experimental building. The smallest inverters commonly used in buildings provide 1 kW (small home size). However, on occasion the building may require greater electrical flow, and as long as the batteries have sufficient charge, more than 1 kW can only be provided with larger inverters. For example, a 1 kW inverter (using the [110 volts][amps] = [watts] equation) can provide a 10 amp flow, while a 3 kW inverter can provide a 30 amp flow.

The 12 DC-volt power produced by the batteries is changed to 110 AC-volt power by an inverter. Most inverters provide a sine wave or a modified sine wave voltage. Pure sine wave voltage is required for specialized equipment, such as life support medical devices. Pure sine energy is provided by electrical utility companies, and allows electrical equipment and appliances to run longer, cooler and more efficiently. However, most solar energy applications use a modified sine wave inverter, which is adequate for most motors, which does not produce much interference in devices like a television, radio and computer, and which is much less expensive.

An inverter has two ratings, a constant wattage, and peak wattage which is about twice the constant watt rating. The peak wattage cannot be maintained for long, but it allows extra power to start electric motors. Motors require about twice as many peak watts (often called “surge watts”) to start as they do to run.

A 1000 constant watt inverter is most commonly used for lighting (e.g., several 60 watt bulbs), and for devices like refrigerators, radios and televisions, computers and coffee makers, each of which require only a few hundred constant watts. However, in many applications, a 1000 watt constant watt inverter is not sufficient, because some devices cannot be started and operated unless other devices are turned off. A larger (e.g., 3000 watt rating) inverter can allow more devices to be simultaneously operated, and a large inverter is required to start and operate devices like larger power tools, microwave, well pump, and window air conditioners. Still larger inverters are required to start and operate devices like a cloths washer/dryer, dish washer and central air conditioner.

At the experimental building, a XANTREX ProWatt, a 3000 watt modified sine wave inverter converts the 12 DC-volts from the batteries into 110 AV volts. Because the building was built to be powered by a 220 AC-volt gasoline powered electrical generator plugged into a 220 AC-volt port on the outside of the building, it proved useful to also produce 220 AC-volts by the solar array. Consequently, the 110 volts produced by the inverter is changed to 220 volts by a XANTREX (Model T240) 110-to-220 step-up transformer, capable of handling a constant 4 kW.

6. ANALYSIS OF THE SOLAR ARRAY PERFORMANCE

6.1 Sun’s Angle at Noon

The angle between the sun and the horizon, as seen at the location of the solar panel array in central Virginia, affects the intensity of the light striking the panels (Table 1). At locations farther north or south of the equator, the sun is farther away (which causes a neglible reduction in sunlight) and the sun passes through the atmosphere at a lower angle (which causes all the reduction in sunlight). When the summer begins, the noon time sun is almost directly overhead. The least amount of Earth’s atmosphere during the entire year is between the sun and the solar panels as the summer begins, so the intensity of light striking is more than at any other time during the year. When winter begins, the angle of the noon time sun is the lowest, and the distance of the sunlight travel through the atmosphere is the greatest, so the sun’s intensity is the least of the year.

Middle of Month	Sun's Angle at Noon
January	30 degrees
February	38
March	49
Spring Begins	
April	61
May	70
June	75
Summer Begins	
July	73
August	64
September	55
Fall Begins	
October	43
November	33
December	28
Winter Begins	

Table 1. Approximate mid-month noon-time angle between the sun and the horizon, in central Virginia (USNO, 2008).

6.2 Interval of Sunlight

The ratings shown in advertisements for solar panels are often in watts generated in "full sunlight." The "full sunlight" states are those close to the equator, like California. In Virginia, the number of "full sunlight" hours for any particular sunny day is less than in California, because sunlight's intensity and duration are less in Virginia. In short, the actual wattage of a solar panel when installed in Virginia is less than advertised.

The true number of "full sunlight hours" depends on the intensity of the light (Table 1), and the time interval over which the sun is visible (Table 2). It also depends on the number of hours it takes for the sun to appear over the morning tree line (about 2 hours) and the evening effect of the tree line (about 2 hours). In this fashion [(Table 1) x (Table 2 minus 4 hours)], estimates were made of the number of Full Sun Hours in central Virginia for each month. The Full Sun Hours data in Table 2 show that at the start of the summer, the days have almost 8 Full Sun Hours but at the start of the winter, this interval is down to about 2 hours/day.

6.3 Variation in the Relative Intensity of Sunlight

As the sun moves across the sky, the intensity varies in a pattern that is determined by the time of day, the inclination of the sun, and the amount of cloud cover. The Foot Candle (FC = light at a distance of one foot from a "standard candle") is often used to measure the intensity of light. The measurements in Table 3 were obtained with a calibrated Fisher Scientific Light Meter (Traceable Model).

Month	Average Sunrise	Average Sunset	Light Hours	Full Sun Hours
January	0728	1715	9.8 hours	1.7 hours
February	0703	1750	10.8	3.3
March	0624	1819	12.9	4.4
Spring Season Begins March 20				
April	0537	1848	13.2	5.7
May	0501	1916	14.3	7.2
June	0447	1938	14.8	7.8
Summer Season Begins June 20				
July	0500	1936	14.5	7.7
August	0526	1906	13.7	6.2
September	0700	1930	12.5	4.7
Fall Season Begins September 22				
October	0621	1734	11.2	3.1
November	0653	1659	10.1	2.0
December	0722	1652	9.5	1.5
Winter Season Begins December 21				

Table 2. Summary of the approximate number of daylight hours, and approximate number of equivalent full-sun hours, for central Virginia (USNO, 2008).

Examples of Indoor Lighting (normal distance to eyes)	
Normal Ceiling Lights (two 60 watt bulbs) =	5 FC
Bright Ceiling Lights (two 100 watt bulbs) =	25
Normal Desktop Lamp (one 60 watt bulb) =	50
Examples of Outdoor Lighting on a Cloudy Day	
Early Morning, in an Area With Shade =	1 FC
Early Morning, in Area Without Shade =	10
Noon Time, in an Area With Shade =	1,000
Noon Time, in Area Without Shade =	10,000
Examples of Outdoor Lighting on a Cloudless day	
Early Morning, in an Area With Shade =	5 FC
Early Morning, in Area Without Shade =	500
Noon Time, in an Area With Shade =	10,000
Noon Time, in Area Without Shade =	100,000

Table 3. Comparison of relative amounts of sunlight. Day-to-day outdoor measurements are variable, so approximations close to averages are presented for outdoor measurements.

Evidently, the operation of a solar panel array produces considerably less than its optimum if it is located where shade often covers the panels, and if the days of operation are often cloud covered. When these circumstances prevail, the assembly is often either relocated, or supplemented by other sources of electrical energy,

6.4 Operational Duration of the Electrical Power from the Solar Panel Array

As discussed earlier, it was estimated that the batteries could be fully charged in one day, and that this was done because the 0.5 kW power generated by the solar panels was sufficient to charge the batteries. Tests showed that this was correct, and on most days, with normal sunlight, the batteries became fully charged. It was also noted earlier that based on the past year of service by the local electrical utility company, the building required about 3.5 kW/day, mostly in the evening. In Table 4, the “Estimated Watts” are shown for each time interval (Estimated Watts = [3.5 kW/Service Interval]).The third column lists the Actual Watts that were required of the batteries in the solar power array, in tests to determine the actual Service Interval.

Service Interval	Estimated Watts	Actual Watts
14 hours	250 watts	
12		300 watts
10	350	
8		400
7	500	
6		600
5	700	
3		1200
2	1750	
1		2100

Table 4. Interval of electrical service at various amounts of electrical service..

Based on the experiments described in Table 4, the batteries provided electrical service to the building as anticipated. By inference, in fewer devices were used, the number of service hours increased. On average, the facility requires about 500-700 watts to operate adequately for approximately 5 hours after the sun sets.

6.5 Operational Capability of the Solar Panel Array

As discussed earlier, there is a limit to the amount of electrical lighting and electrical motors that can be driven by the electricity from the solar panel array. The inverter used in the array at the experimental building provides a constant wattage of up to 3000 watts, which at 110 AC-volts, provides an electrical service of almost 30 amps. When selecting the number of lights and other devices that can be operated, 3000 watts and 30 amps are the most that can be utilized. (Table 5).

Device	Watts	Amps
Incandescent Light	60 watts	0.6 amps
Radio/Television	100	0.9
Sewing Machine	100	0.9
Window/Ceiling Fan	230	2.1
Spotlight	250	2.5
Coffee Maker	300	2.7
Dishwasher	400	3.6
Shop Tools (e.g., jigsaw, drill, grinder)	400	3.6
Freezer	500	4.5
Kitchen Blender	550	5.0
Portable Vacuum	600	5.5
Furnace Fan	700	6.4
Refrigerator	800	7.3
Dishwasher	900	8.2
Cloths Washer/Dryer	1000	9.1
Microwave Oven	1000	9.1
Well/Sump Pump	1000	9.1
Computer System	1100	10.0
Window A/C	1200	10.9
Electric Air Heater	1500	13.9
Central A/C	3000	27.3
Water Heater	3000	27.3

Table 5. Approximate wattage and amperage required to operate devices. Not listed are the start-up (also called peak or surge) wattages and amperages, which may be twice the start-up wattage and amperage.

As shown in Table 5, when using the solar array system, which when fully charged can provide up to 3000 watts and 30 amps, not all of the devices can be operated simultaneously. Some attention must be paid to selecting the most necessary devices, because as more devices are used, the duration of operation decreases (see Table 4).

7. CONCLUSIONS

In central Virginia, an array of 8 solar panels was installed to provide electricity to a building constructed as a greenhouse and fish nursery, with attached living space. The building was designed using energy conserving techniques, and the solar panel array provides electrical energy at approximately 0.5 kW and 30 amps, which is more than enough to recharge four deep-cycle batteries each day. Through a 3 kW inverter and a 4 kW transformer, the batteries provide about 3.5 kWHrs/day which is more than enough to power the activities in the building.

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