IMPLEMENTING SOLAR ELECTRIC SYSTEMS ON SWINE FACILITIES

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Pork Production

On June 1, 2016, the United States hogs and pigs market possessed 62 million pigs (USDA 2016). In Minnesota alone, 7.44 million pigs were on the market on June 1, making Minnesota rank third for the number of pigs raised and second for the value of the pigs (USDA 2016). Not only is pork production essential economically, but the industry has made great steps in becoming environmentally progressive as well. In the past fifty years, the pork production industry in Minnesota has reduced water usage by 41%, land usage by 78%, and its carbon footprint by 35% overall (Minnesota Pork Producers Association 2016). Despite these advances, raising swine is still an incredibly energy intensive process, requiring a lot of electricity and fuel to transpire.

Facility construction, operation and management, grain cultivation, feed processing, breeding and birthing, and manure management are six processes that occur in swine systems (Gensch 2014). Grain cultivation uses almost half of the energy required in this system; however, many swine farmers are not involved in this process. Facility operation, which includes heating, cooling, and ventilation, is the second largest energy user at 25% (Figure 1).

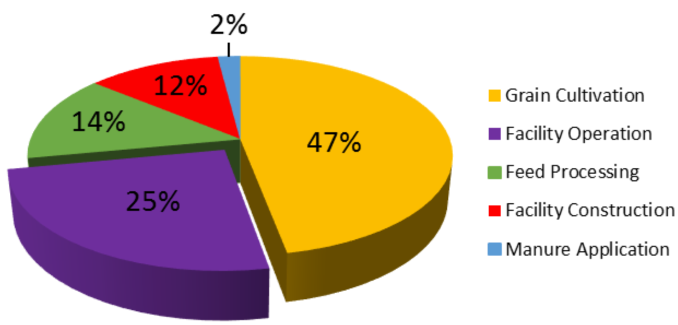


Figure 1: Percentage of Total Energy Used by the Main Processes in Pork Production (Gensch 2014)

Operation provides a great opportunity to start minimizing energy costs and usage due to the large amount of control a farmer has on building and barn design and operation (Gensch 2014). While one pig normally requires the equivalent of 7-12 gallons of gasoline, these values can be significantly reduced, but only after understanding how the fuel and electricity is being used (Gensch 2014).

There are four phases of swine production: gestation, farrowing, nursery, and finishing (Gensch 2014). In the gestation phase, pregnant sows are housed and develop their litters. Until weaning at about 11 lb., piglets are born and raised with their mother in the farrowing phase. The young pigs are then moved to the nursery phase where they are raised to approximately 55 lb. Lastly, in the finishing phase, the pigs are grown until they reach market weight, or approximately 250 to 300 lb.

Just because humans may be comfortable in the barn does not mean the pigs are. Although pigs are able to adapt to their environment within reason, swine tend to be very sensitive to the smallest of environmental stresses, which may cause depressed growth, reproduction, or lactation or impair disease resistance (Baker 2004). They give off heat, water vapor, urine, feces, and disease-causing organisms that impact their environment, and as the temperature difference between the body and cooler environment increases, so does a pig's heat loss.

The temperature of a barn must always be kept between the lower and upper critical temperatures, the effective temperatures below or above which swine are unable to maintain productivity (Baker 2004). These critical temperatures, between which is known as the thermoneutral zone, change with body weight, type of housing, amount and composition of feed, presence of bedding, and use of cooling systems. For example, John E. Baker at the Warrick Veterinary Clinic in Chandler, IN found that piglets have a lower critical temperature of 84°F as they are small and become cold easily (Baker 2004). Swine approximately 8 weeks old, or 40 lbs, have a lower critical temperature of about 63°F whereas finishing barn swine (>100 lb.) and breeding or gestating sow require a lower critical temperature of 54°F. Fortunately, temperature controls in barns do exist; unfortunately, heating and cooling depends upon a great deal of energy to use these necessary controls. Dr. Lee Johnston, Director of Operations at the WCROC and a professor of swine nutrition and management, has done considerable research on lowering the nocturnal temperature of swine facilities (Johnston and Li 2011). Specifically, in swine nurseries, extensive amounts of supplemental heating are required to keep pigs within their thermoneutral zone. By lowering the temperature for a portion of the day and allowing the pigs to huddle close together to conserve heat, the amount of energy required to operate the barn may be lowered significantly.

Another concern in raising healthy swine indoors is the production of more than 130 fixed gases and odorous vapors, especially as manure decomposes (Ni et al. 2000). Hydrogen sulfide, ammonia, and carbon dioxide are some of the most common gases that need to be properly exhausted from the pig space using ventilation, another environmental control system that depends on electricity to run. Hydrogen sulfide can be tolerated by swine up to 10 ppm but can be lethal at concentrations as low as 50 ppm. Ammonia can be present up to 100 ppm in a swine barn. At 50 ppm, ammonia hinders a young pig's ability to clear bacteria from its lungs; at 75 ppm, ammonia depresses pig growth (Kim et al. 2007). Carbon dioxide can be allowed up to 3,000 ppm for swine and often determines the minimum ventilation rate required for a barn (Ni et al. 2000). To prevent the buildup of noxious gases, two to four air changes are required per hour, varying from 1.5 ft^3/min per nursery pig to 3.5 ft^3/min per growing pig to 10 ft^3/min per sow and litter in a farrowing barn (Jones and Friday 1980).

Pork production is a large economic benefactor in Minnesota, but the amount of electricity or fuel required for operation can lead many farmers to seek supplemental sources of energy to offset costs of traditional fuel sources. Solar energy has become a leading solution, but it is important to understand how electric load (i.e. amount of electricity) is affected by the swine and their environmental requirements as well as how the amount of available solar energy changes with its own conditions. By first knowing what electric loads are required, the proper type of solar system can be chosen to fit those needs.

What is solar energy?

Without fail, the sun rises and sets whether we notice it or not. Earth receives about 1,366.1 watts per square meter of energy from the sun (Gueymard 2003). New technologies are being invented constantly with the sole purpose of harnessing the sun's power and turning it into electricity or heat. In fact, approximately the same number of solar systems was installed from 2012 to 2014 that had been implemented since its inception (Roney 2014). This makes solar technology the most rapidly growing energy technology by a wide margin.

Direct, diffused, and reflected are all types of solar energy (Kalogirou 2014). Direct radiation passes through the atmosphere and strikes the earth without being deflected and constitutes 85% of solar radiation. Diffused radiation means that water vapor, dust, carbon dioxide, or other compounds in the air are able to scatter the radiation, making it the only radiation able to reach the ground when skies are completely overcast. Unfortunately for those trying to harness solar energy, diffused radiation is comprised of significantly less energy than direct radiation. Finally, reflected radiation "bounces" off a surface, such as snow. Reflected radiation contains less energy than direct radiation but more than diffused radiation. As a result, cloud cover, air pollution, reflection, atmospheric absorption, and other atmospheric and weather conditions can greatly affect the amount of solar energy able to be received by a solar collector.

Another characteristic of solar energy that affects the amount of energy received is the angle of incidence, or the angle between the solar collector and the sun's rays (Kalogirou 2014). When the sun is directly above the solar collector (i.e. at noon above a horizontal panel), the sun's rays intercept the panel at 0°. The greater that angle becomes, the more radiation is reflected, and the less radiation is intercepted (Figure 2).

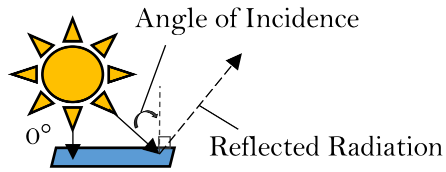


Figure 2: Sun's rays reflecting off of a horizontal panel (Made by author).

Despite the simplicity of the concept, the angle of incidence can significantly reduce the amount of energy received by a collector (Kalogirou 2014). Throughout the day, the sun is moving across the sky, constantly changing the angle at which its rays hit the surface. Longitude also plays a role on what angle and direction the sun is most efficient at. For example, the sun is directly above the equator. This means that a person in the northern hemisphere receives more solar radiation to the south, and someone in the southern hemisphere gets more solar radiation to the north. The final major consideration is the time of year as the sun is much lower in the sky in the winter when compared to summer.

When discussing solar energy, one of the most important concepts to understand is energy efficiency. Energy efficiency involves minimizing energy use while maximizing productivity (Brown and Elliott 2005). In regards to solar systems, efficiency is the effectiveness with which a solar collector absorbs and retains energy (Kalogirou 2014). Mathematically, energy efficiency is shown in Figure 3.

$$Efficiency = \frac{Solar\ energy\ collected}{Total\ solar\ energy\ striking\ collector\ surface} * 100\%$$

Figure 3: Equation to calculate efficiency of a solar system (Kalogirou 2014).

When choosing the size of a solar system for a swine barn, efficiency of the system is a major factor. Efficiency changes with the angle of incidence as well as type of solar radiation being received. As a result, time of day when a high electric load is required, longitude, and season all affect the type and size of the system needed to make a swine barn a net zero system. A net zero system means that no supplemental electricity would have to be purchased as the farm is self-sufficient and can produce the same amount of electricity as is being used at any point in time. In other words, a higher efficiency is desired when there is a greater need for electricity, such as a need for cooling at noon when the barn is hottest, and the system generally has a high efficiency due to the low angle of incidence. The type of solar system being used can also have an effect on when the electricity is being produced and how large the system may need to be.

Types of Solar Systems

As previously mentioned, solar systems transform solar energy into electricity or heat. There are two main kinds of solar collectors: passive, which has no separate solar collector or medium for the transference of heat, and active, which utilizes a collector unit and fans or pumps to push solar-heated air or liquid to where the heat is needed (Kalogirou 2014). Passive systems, such as a window, often take advantage of seasonal changes by letting little solar radiation in during the summer and a lot in during the winter. However, these same systems that let the heat in during the day tend to let heat out by night, resulting in a drastic cycling of temperatures. The drastic cycling can be reduced by adding insulation to the walls, ceiling, and/or roof, insulating glass to the windows, insulating covers to the windows overnight, or ventilation systems that are controlled by thermostats.

Another type of passive solar system is the transpired solar collector (TSC), which can be further separated into sidewall collectors (A.1a) and transpired solar ducts (A.1b). Sidewall collectors are typically attached on a south-facing wall, where a lot of sunlight is able to be absorbed. They are simple to install and maintain and have a high efficiency in winter, making them ideal for livestock with low tolerance for temperature fluctuations. In order to prevent overheating in the summer, some farms have white, hinged panels that swing up to cover the collector and reduce the amount of radiation able to get through. Similarly, transpired solar ducts use sunlight to heat the barn, but instead of letting the light directly into the barn, the sun's rays warm the air as it passes through a wall or duct (Love and Shah 2011). The air is then drawn through perforations in an unglazed metal sheet, transferring the air to the inside of the barn.

Despite the convenience of passive collectors, active systems are more often necessary to maintain a constant target temperature necessary for swine. A black-painted surface (i.e. the absorber plate) absorbs the sun's rays, causing an increase in temperature on the surface, which subsequently heats up an interlaying transfer medium, usually air or water (Kalogirou 2014). This medium can then be relocated to be used or stored.

More often than not, the absorber is protected by a cover plate so that heat is not lost as a result of wind convection or radiance. Cover plates are primarily made of glass, fiberglass, or plastic (Kalogirou 2014). Glass has a transmissivity of 87%; in other words, 87% of the radiation reaches the black absorber plate rather than being reflected or absorbed by the glass. Greenhouse-grade fiberglass is the most common material for cover plates in the Midwest. Although it has a slightly lower transmissivity of 80%, fiberglass is more resistant to breakage. Plastic often becomes brittle and discolored after only a year or two. Finally, plastic films or sheets have a high transmissivity (92%), but up to 30% of captured radiation can be lost by reflecting back through the cover.

There are three primary types of active collectors: bare plate, covered plate, and suspended plate (Turner et al. 1981). Bare plate collectors draw the transfer medium underneath the absorption plate (A.2a). Although the least efficient, bare plate collectors are also the most common. Covered plate collectors consist of a transparent cover over the absorption plate between which fluid is drawn (A.2b). Lastly, the suspended plate draws the medium between the transparent cover and from under the absorption plate, making it the most efficient but least practical in terms of swine farms due to the efficiency rarely being worth the high capital cost (A.2c).

Countless types of active collectors have been invented, including ground-mounted (A.3a), pole-mounted (A.3b), and roof-mounted (A.3c). Ground-mounted are attached to the ground at an angle, pole-mounted are held above ground by a rod, and roof-mounted are directly attached to a roof. Pole-mounted systems can also be tracking or fixed, meaning the system is able to follow the sun's trajectory throughout the day. While tracking increases the efficiency by 27% on average, they are significantly more complex and expensive (WCROC 2016). In addition, ground-mounted panels are often more efficient than roof-mounted due to a less efficient slope that generally is present on roof-mounted panels. For example, at the West Central Research and Outreach Center, the ground-mounted solar system is at 28°, but the roof-mounted system was installed on a 4/12 pitch roof, or only 18.5°. The steeper angle of the ground-mounted is able to collect solar radiation more consistently throughout the year. When the sun is lower during winter, a more horizontal panel is able to get very little of the radiation. Despite being more efficient, ground-mounted systems cover a lot of potentially valuable land, so roof-mounted is often more economical. Another consideration for choosing between roof- and ground-mounted is that roof-mounted systems are more difficult to access for removing snow or performing maintenance, which can sometimes result in a decrease in efficiency during those times.

One of the most common terms used when discussing solar energy is "solar photovoltaic (PV) systems" (A.4a). Solar PV systems use photons to knock electrons loose from semi-conductor materials and separate free positive and negative charges, which then form an electric field. The electric field pushes the charges toward a load, creating an electric current (Romich 2014). Essentially, solar PV systems convert light into electricity, giving the technology high potential for swine farmers who wish to supplement their electricity needs with an alternate source of energy.

Solar electric systems (e.g. PV systems) contain three components: a solar module, inverter, and Balance-of-System (BOS) (Romich 2014). Solar modules are what actually collect solar rays and are comprised of a number of cells. Furthermore, modules are combined to create a rigid frame called a panel, which can be further adjoined to form an array. This solar array can be connected to an inverter, which converts electricity from direct current (DC) to alternating current (AC). Direct current is generally used for long distance travel, but alternating current is what most equipment, such as lights, ventilation fans, and heating and cooling equipment, requires to operate. Finally, BOS, also referred to as Balance-of-Plant (BoP), includes any meters, safety equipment (e.g. disconnect switches), conduits, cables, combiner boxes, and racking and tracking gear that may be required for the system to operate properly.

Solar thermal collectors are the second most common type of solar system and can be active or passive (A.4b). However, when discussing applications in agriculture, solar thermal collectors are often active. These devices collect heat by absorbing the radiation and distributing it into a transfer liquid, commonly water or air. Sensors that measure the temperature differential between the transfer liquid and the liquid being heated determine when a pump should be turned on, making it more efficient and, by definition, an active system. Active solar thermal systems are common in ventilation systems and/or hot water heaters and can prove to be very useful on swine farms.

Why Should Solar Be Placed on Swine Farms?

Society is very familiar with rising gas and electricity prices, uncertainty about access to fossil fuels in the future, and concern about the implications of fossil fuel use for the global climate (Lammers et al. 2012). The United States spends $9 billion per year, or 13% of all farm expenses, on energy used in agricultural applications (Brown and Elliott 2005). Electricity prices vary widely, but the average was 6.4 cents per kWh in 2013 and is projected to double by 2040 (Romich 2014). As electricity prices increase, the cost of generating agricultural products tends not to be far behind. With an increase in the production costs, farm income generally decreases. As a result, solar energy provides an invaluable opportunity for swine facilities as it has the ability to stabilize energy costs, minimize fossil fuel use, and decrease pollution and greenhouse gas emissions (Xiarchos and Vick 2011).

Solar panels are the most common way to produce on-farm renewable energy (Vilsack and Clark 2011). Often power fences, water pumps, and irrigation systems are built in locations where it is either too costly or not possible to build power lines. Solar power has been historically found to be a great solution for low power needs in these remote locations (Romich 2014). More recently, solar energy has also been used for systems with greater energy demand, such as grain drying or ventilation and cooling systems in livestock production facilities. In 2011, 78 Minnesota farms were equipped with solar systems, which included 51 farms with PV and 34 with thermal systems (Vilsack and Clark 2011). The entire United States has 7,968 farms using solar panels. Ninety-two percent of these systems are PV, and 28% are thermal. The average generating capacity is 4,449 W with an average installation cost of $31,947 per farm; however, there are a wide variety of costs and sizes of solar panels, so it is important to fit the system to the farm.

The growing popularity of solar systems on farms is not unfounded. Rural areas tend to lack in natural gas, and propane is expensive. When using propane for swine barns, carbon dioxide gets trapped in the building even if the combustion is perfect (Figure 4).

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + 50.36\ MJ/kg$$

Figure 4: Combustion reaction using propane (Godbout et al. 2004)

More carbon dioxide is produced from using propane over using a solar thermal system. As carbon dioxide can greatly reduce air quality, using propane instead of solar thermal requires greater ventilation, more air changes per hour, and more heating for the new air, requiring even more propane to heat (Godbout et al. 2004). By using solar thermal, less propane can be used, improving air quality and reducing the production of greenhouse gases.

Another benefit to solar is that electric grids are aging and may not be available in remote areas. Encouraging efficiency and renewable energy options is often less expensive than improving on the current grid infrastructure (Brown and Elliott 2005). Solar can also act as a backup in the case of an electrical outage instead of using kerosene, diesel, or propane (Xiarchos and Vick 2011).

In addition to lack of natural gas and aging electric grids, agricultural areas have more options for where to build solar systems than is available in the city. Solar arrays can be placed on marginal land (if available) or rooftops to avoid competing with valuable land. In some cases, solar arrays can be built on floating structures over water. For example, at the Far Niente Winery in Oakland, CA, almost 50% of a 400 kW system floats on a single acre gray water retention pond (Boyd 2008).

If building the solar arrays on land is not an option, these systems can also be placed on a barn's roof. Orientation of a building can help determine if solar is feasible. As wind pressures result in reduced exhaust fan efficiency and improper ventilation, large tunnel fans should be facing east rather than towards the often south-facing summer winds in the Midwest (Jacobson 2011). As a result, swine facilities in the Midwest are often built in an east to west configuration for better ventilation. This also provides a south-facing roof, which is ideal for the installation of solar collection systems.

Other advantages of using solar energy are that solar collectors have no moving parts and as a result, low operational and maintenance costs (Romich 2014). They also provide the ability to harness a free renewable fuel source.

Sometimes the significant initial capital investment stops farmers from looking into it any further. However, there are a vast amount of subsidies and programs that can help recover the cost (Xiarchos and Vick 2011). One such program in Minnesota is net metering. Once the system is installed, net metering provides financial compensation to customers who produce excess electricity using an on-farm solar electric system (Romich 2014). Excess electricity is then diverted back to the grid to be used by other consumers. The Minnesota Revisor of Statutes describes this program in 216B.164, "Cogeneration and Small Power Production". Any system below 40 kW can sell excess electricity back at the "average retail utility energy rate", received in the form of a check or a credit on the customer's bill. If the system is between 40 and 1,000 kW, electricity can be sent to the utility for an "avoided cost rate". Regardless, the net metering program substantially improves the return-on-investment (ROI) and payback period for a solar system. Other federal incentives are available as well, such as the USDA REAP grant, loans, and investment or production tax credit (DSIRE 2016). The SunShot Initiative is a program developed by the U.S. Department of Energy with the goal of reducing solar expenses to $1 per Watt by 2020 (U.S. DOE 2016). In 2010, the average cost of solar energy was $3.80/W, and already costs have gone down to $1.64/W (U.S. DOE 2016).

Energy Use on Swine Barns

The first step in identifying how solar energy can be implemented is to understand how a farm's strategies to raise swine affects its energy use. One such study was conducted in Iowa (Lammers et al. 2012). Six different facility types, diet formulations, and cropping sequence scenarios were examined in relation to energy use. The baseline system produced 15,600 pigs annually using confinement facilities and a corn-soybean cropping sequence and required 206.8 kWh per 300 lb. market pig, similar to most pork production facilities in the upper Midwest. The bedded hoop barn for grow-finish pigs and gestating sows used 3% less energy (200.2 kWh). Diet type alone accounted for 61 and 79% of total energy in conventional and hoop barns respectively. When averaging all size pigs, hoop barns generally used 64% less energy than conventional but 2.4% more feed. Operation of conventional swine buildings make up 25% of the total cost of energy, suggesting that the best way to minimize energy expenditure is by developing strategies to minimize or supplement energy use for heating and ventilation while maintaining pig performance.

Brown and Elliott (2005) attempted to characterize usage patterns of fossil fuel-based energy on farms. However, they concurred that there is not enough information to come to a conclusion and suggested that the state and/or utilities collect data on the amount of energy used for each application, such as drying and curing, heating, cooling, and ventilation, and water heating. This displays a need for knowledge of how and where supplemental energy is needed.

In Athens, Greece, Panagakis and Axaopoulos (2014) were interested more in how building materials affect cooling in Greece's hot and humid climate. Microclimate control was used to maintain air temperature and relative humidity in the area surrounding the swine. Traditional materials, such as fired brick or cement blocks without insulation, provided buildings that needed 18.2% more daily energy than prefabricated cement panels with insulation. Animal weight, housing density, type of floor, and feed energy content all influenced the total annual cooling energy requirements, but no published information could be found on specific or estimated values.

Regardless of location, the information on where and how swine farms are using energy is just not available. In order for farmers to feel they can install solar collection systems on their farms, they first need to know where the energy is needed most, whether on a specific type of barn (e.g. finishing, nursery, gestation, or farrowing) or on a specific application (e.g. ventilation fans or heating or cooling systems). By knowing where the solar system is most needed, the system can be efficiently used, and the farmer can feel more secure about their investment.

Testing Solar Technology on Swine Barns

Once energy use is determined, a properly fitted solar system can be chosen for a particular swine barn. Using solar technology on swine barns is not all that new but has historically been too expensive or impractical to install. However, pork producers are finding themselves more inclined to install them as electricity and propane costs go up and the cost of solar systems go down. As a result, studies and tests have been growing in popularity to determine how solar energy can be utilized on different types of barns with varying needs all around the world.

Weaning typically occurs from three to five weeks of age and demands a suitable environment for young pigs to remain productive (Bodman et al. 1989). This can be done by heating the entire volume of air between 80 and 95°F or by using hovers, infrared heating, and floor heating to create less energy intensive microenvironments. Bodman, Kocher, and DeShazer studied two modified-open-front (MOF) non-mechanically-vented nurseries in Nebraska: one consisted of 22 pens plus an equipment area and a capacity of 550 pigs and the other barn consisted of 12 pens with a capacity of 300 pigs (A.5d). Construction of the facilities cost approximately 2/3 that of conventional nurseries with heating at 1-2% the cost to operate during winter. Despite the lower cost, solar energy was considered to be a beneficial and effective way to heat in the winter. As a result, the two nurseries were fitted with a mono-slope roof design and passive collector panels for warm weather ventilation panels. In addition, a ground-mounted solar collector provided in-floor heat distribution and storage. Between October 1980 and January 1982, an average of 19% of the solar energy was transferred to the floor surface. After thirteen years of operation, the two facilities showed that the passive and ground-mounted solar panels together could be used effectively. However, there was some uncertainty regarding if the reduced heat loss was due to floor heating, solar energy, or some combination of the two.

Another attempt to modify MOF nurseries in Nebraska occurred in the winter of 1988 (Song 1989). A naturally-ventilated, solar-assisted (NVS) swine nursery and a mechanically-ventilated, solar-assisted (MVS) nursery both held up to 96 pigs and installed active solar collectors for in-floor heating and hovers in the sleeping areas (A.5e). The NVS nursey also utilized solar-preheated ventilation while the MVS nursery had double-glazed solar windows for passive solar heating. Unlike the 1980 study, Song compared building environment, energy efficiency, pig performance, and pig behavior during the experimental process. Finally, the NVS nursery was found to use 72% as much energy as the MVS and required 0.60 kWh less energy per pig. In fact, the MVS required 45% more energy than the NVS in winter because of the need for excess ventilation. Also, a conventionally heated nursery was modeled and found to spend 15.2 to 18.2 kWh per pig compared to 1.4 to 2.2 kWh per pig used by either the NVS or MVS barn.

Solar walls have been of particular interest to many swine farmers. In St-Sylvestre de Beaurivage outside of Quebec City in Canada, a solar wall was installed on the south-southeast wall of a 1,000 piglet space that was 28.6 m long and 14.6 m wide (A.5a; Godbout et al. 2004). The Marisol farm consisted of four rooms with twelve stalls each and kept swine from 11.7 to 55.8 lb. For six months, the energy used for heating was measured, varying between 450.8 kWh and 2389.4 kWh monthly; each month, 12.2-47.4% of that was contributed by the solar wall. If the farm had previously used propane as a fuel source and then replaced it with the solar wall, the energy bill would be reduced by as much as 31%.

A swine nursery in eastern North Carolina implemented a transpired solar wall (TSW) for heating in the winter (A.5b; Shah et al. 2016). The building was equipped with a curtained sidewall, which can be lowered for emergency ventilation but can lose a lot of heat in winter. TSWs have the ability to recover heat by acting as a barrier over the wall and absorbing the heat that tries to escape. This was shown in the fact that 50% of the energy collected by the TSW was actually collected at night between 18:00 and 08:00 when normally the most heat would be escaping due to the large temperature differential between the air inside and outside of the barn. However, in this particular facility, the ventilation fans were not normally operating during the day, so a majority of the heat energy being collected by the TSC in the day had no application to be used on and thus was released as waste. With the TSW, the air temperature was able to be increased up to 95°F, and propane use was reduced by 8.5%; however, the system may have caused unwanted heat gain in the summer had it been tested during those months. Regardless, the conclusion was that the TSW was "technically feasible for use" based on energy output, time of energy output, temperature variation, and animal performance. Economics were not really discussed.

In eastern North Carolina, a swine barn and turkey brooder were both analyzed to determine the practicality of TSC ducts on the barns (Love and Shah 2011; A.5c). PV systems were considered to have too high of an installation cost and too low of an efficiency for these barns whereas TSC ducts could convert up to 80% of solar radiation into heat energy that could be easily retrofitted to a swine barn and turkey brooder. The swine barn was made up of two rooms, 7.6 m x 30.5 m each. One room was fitted with a TSC duct; one was not. The barn had a capacity of 950 pigs raised from about 18 days to 8 weeks old and included a thermostatically-controlled insulated drop ceiling (i.e. a secondary ceiling built below the structural ceiling) and curtains on one side, six ventilation fans, and heating via a propane-fired forced-air furnace. From the fall of 2010 to the spring of 2011, the amount of propane replaced with the energy collected from the TSC ducts was recorded, and analyses of animal performance and carbon dioxide levels were continuous. Propane use was reduced by an average of 34% for the two swine herds in the room with the TSC duct; the first herd was placed in the room with the TSC duct from 11/19/2010 to 1/4/2011 and used 65% less propane than the first herd in the room without the duct in the same period of time, and the second herd was placed in the room with the TSC duct from 1/15/2011 to 3/1/2011 and used

12% more than the second herd in the room without the duct in that period of time. The higher usage in the second herd was more than likely due to management error. During the coldest week of the testing period, the minimum ventilation fans were set to run far longer than necessary, and the solar fan was activated before the TSC duct was able to warm the air, resulting in cold air being pushed into the room. Despite this, the TSC duct showed potential for providing supplemental heat to the swine barn. Unfortunately, tests with the turkey brooder showed the amount of heat supplemented by the TSC duct was inconsequential as the brooder used approximately the same amount of propane as it did prior to installation of the duct.

The Purdue University Cooperative Extension Service provided advice on solar heating in homes, farms, and businesses (Turner et al. 1981). With a farrowing house maintained at about 60°F, heating is essential, especially in winter. Turner et al. discussed various methods on when and how to implement solar systems on a farm. However, they come to no clear conclusion on whether solar is the way to do that as the practicality of the system must be determined on a case-by-case basis.

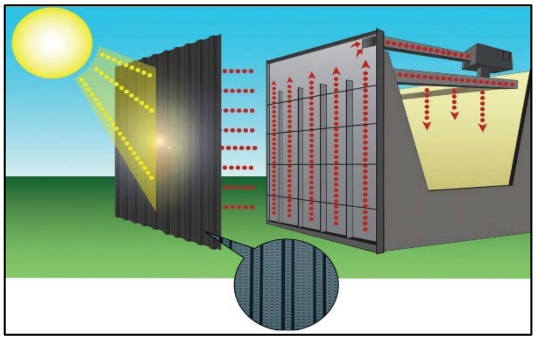
Lastly, a thesis was written in Iowa regarding the economic viability of solar (Sloth 1980). The R factor (e.g. the resistance of structural materials to heat loss) and type of flooring affected heat loss in a swine barn greatly; however, ventilation was by far considered the highest heat loss. The swine act as humidifiers and add moisture to the air, which collect on cold surfaces, reducing the life of the building and its equipment and increasing maintenance costs. As a result, ventilation is essential in maintaining a constant relative humidity and removing any dangerous gases, which is more difficult with solid floors rather than slatted. In this study, Sloth assumed the electrical requirement was solely from ventilation in farrowing and nursery barns. One-cover covered plate collectors were found to be best for swine systems with slatted floors or that are idle for part of the year, and two-cover suspended plate collectors with storage were considered best for systems requiring large amounts of heat or continuous use. Generally, increasing the size of the collector appeared to be more beneficial than improving its efficiency. If dealing with a farrowing and nursery unit, increasing the size of the farrowing unit collector and using any surplus heat in the nursery is more beneficial than using a collector on a nursery with slatted floors. Overall, it was determined that while solar systems are feasible, more work needs to be done to ensure its practicality in the swine industry. While this study was a good comparison among some solar systems in various types of barns, the study did not take into account heating, cooling, or other miscellaneous loads, further emphasizing the need for a better understanding of where energy is being used and can be improved.

Conclusion

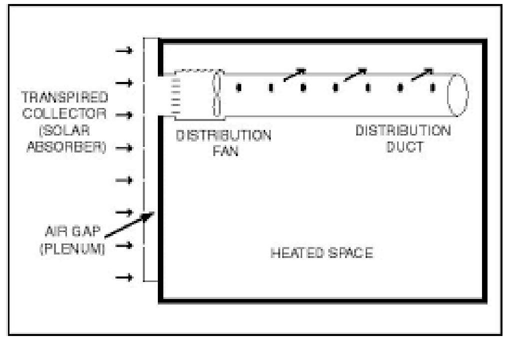
Pork production benefits the economy greatly yet the amount of energy required to operate these systems can be a burden on swine facilities. As a result, some farmers are looking towards the sun as an unlimited source of fuel and way to supplement their energy usage. There are numerous studies and implementations of solar technology and energy that provide information about specific applications and the means to advance solar in the agricultural industry. However, many have found that there just is not enough information out there to make an educated decision on where and how much energy is needed, a crucial first step in deciding if solar energy is the right solution. The WCROC has made steps in determining how best to implement solar on their farm and have found ways to inform pork producers of their findings. By first determining the specific applications of the energy being used, the WCROC was able to choose a suitable roof-mounted solar PV system for their finishing barn and further recommend systems to two other barns in the area. Through this process, solar energy can continue to grow and help farms diminish their electricity bill, reduce their carbon footprint, and overall make their farm a more sustainable and successful business.

Appendix

1. Examples of Passive Solar Systems

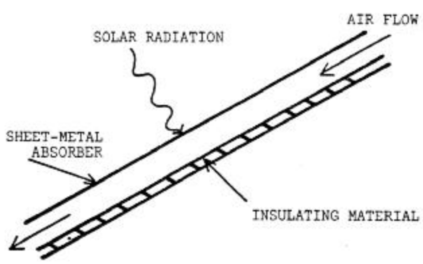


(a) Sidewall collector (Slattery 2014)

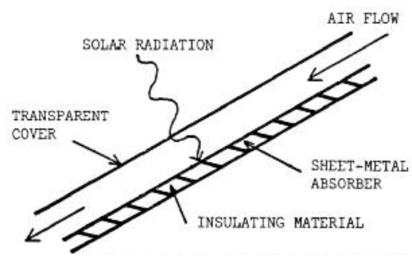


(b) Transpired solar duct (Maurer 2004)

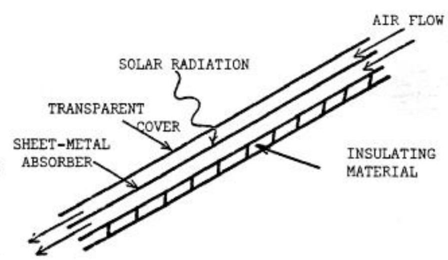
2. Types of Active Solar Systems



(a) Bare plate (Turner et al. 1981)



(b) Covered plate (Turner et al. 1981)



(c) Suspended plate (Turner et al. 1981)

3. Ways to Install Active Solar Systems

(a) Ground-mounted system at University of Minnesota: Morris (Taken by author 2016)

(b) Pole-mounted system at University of Minnesota: Morris (WCROC 2016)

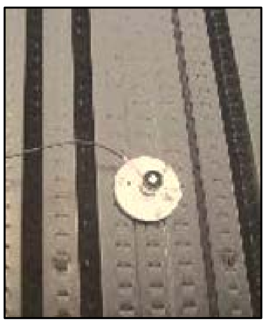
(c) Roof-mounted system on a swine barn at WCROC (Taken by author 2016)

4. Common Types of Active Solar Systems

(a) Solar PV System (Renu News 2015)

(b) Solar Thermal System (YouGen 2016)

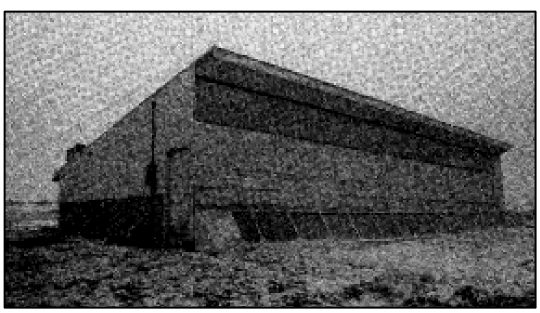
5. Solar Technology Tested on Swine Facilities



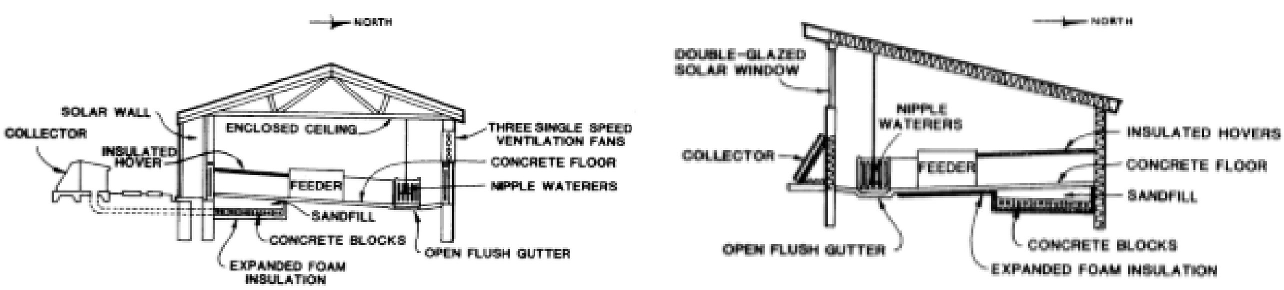
(a) Solar wall and radiation sensor in Quebec, Canada (Godbout et al. 2004)

(b) TSW in Clinton, NC (Shah et al. 2016)

(c) TSC ducts at a turkey brooder in Snow Hill, NC (top) and swine nursery in Roseboro, NC (bottom) (Love and Shah 2011)



(d) MOF Solar Nursery near Ceresco, NE (Bodman et al. 1989)



(e) Cross-section of an MVS nursery (left) and NVS nursery (right) (Song et al. 1989)

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TRANSITIONING MINNESOTA FARMS TO LOCAL ENERGY

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Abstract

The purpose of this study was to determine if solar photovoltaic (PV) systems are feasible options for swine barns to use as a source of electricity and have the ability to produce as much electricity as a swine barn is using at any given time. A 26.88 kW Heliene 60M280 system with three SE9K inverters from SolarEdge Technologies, Inc. was installed in June 2015 on the roof of the West Central Research and Outreach Center (WCROC) swine finishing barn. The system was fully operational in October 2015, at which point the electricity production was recorded. Solar irradiation, or the total solar energy available in a point of time, was measured with a pyronometer at the WCROC weather station and compared to the energy actually being converted into electricity by the solar PV system. In addition, the overall electricity usage in the finishing barn was recorded using the utility meter, and specific applications' electricity usage (e.g. from the pit fans, feed augers, lights, et cetera) was measured with Campbell Scientific CR800 data loggers. The PV system did not provide enough electricity to match the electric load in winter, largely due to snow covering the panels from mid-December through the majority of January, but produced more electricity in summer than the barn was using. Similarly, the system produced more electricity in the middle of the day than was being used, but there was a small load at night that had to be drawn from the grid. Nevertheless, generally the PV system did produce as much electricity as was being used by the finishing barn and proved to be a feasible option for the WCROC swine barn.

Contents

1. INTRODUCTION

The Earth receives about 1,366.1 watts per square meter from the sun (Gueymard 2003). This vast amount of energy can be harnessed using solar technology that can convert the solar radiation into electricity or heat. With the ability to harness this virtually unlimited power source, solar technology is the most rapidly growing energy technology by a wide margin (Roney 2014). The aim of the project, "Transitioning Minnesota Farms to Local Energy", was to determine the viability of using solar photovoltaic (PV) systems on swine farms to supplement or entirely replace electricity usage from the utility grid.

Solar PV systems use photons (i.e. particles of light from the sun) to knock electrons loose from the semi-conductor materials that make up the panels. This separates any free positive and negative charges and allows the formation of an electric current. Through this process, solar PV systems are able to convert light into electricity, which can then be used as an alternate source of electricity for swine barns. Solar PV systems consist of three main components: solar modules, inverters, and Balance-of-System (BOS) components. Solar modules are comprised of numerous cells which collect solar energy. Furthermore, several solar modules can be adjoined to compose a solar array. The array is connected to an inverter, which converts electricity from direct current (DC) to alternating current (AC). Direct current is generated by solar PV panels, but alternating current is what most equipment, such as lights, ventilation fans, and heating and cooling equipment, requires to operate. Finally, BOS components, also referred to as Balance-of-Plant (BoP) components, include any meters, safety equipment (e.g. disconnect switches), conduits, cables, combiner boxes, and racking and tracking gear that may be required for the system to operate properly.

There are numerous benefits to using solar as a source of electricity on a swine barn. First, gasoline, natural gas, and other fuel source prices are unpredictable with a general upward trend. In addition, there is uncertainty surrounding fossil fuels in regards to their availability in the future. In rural areas, natural gas availability is often lacking. Power lines may be failing or non-existent, particularly in remote areas where installing new lines or fixing old ones does not benefit utilities enough to warrant the cost. Using solar energy also reduces greenhouse gas emissions, provides the ability to harness an unlimited and free source of energy, and requires little or no maintenance because PV systems do not need moving parts to function. Finally, there are many programs and grants that give financial support to those installing on-farm solar energy systems. For example, net metering is a Minnesotan program that provides financial compensation to customers who produce excess electricity with a solar PV system (Minnesota Legislature 2015). Any system smaller than 40 kW can sell excess electricity back at its current retail rate, received in the form of a check or a credit on the customer's bill. If the system is between 40 and 1,000 kW, electricity can still be sent to the utility for an "avoided cost rate", or reduced retail rate. Other federal incentives include the Made in Minnesota Solar Incentive Program, USDA REAP grant, investment or production tax credit, and loans (DSIRE 2016).

Solar systems are usually installed in one of three ways. Ground-mounted systems are attached to the ground, as the name suggests. They are easily accessible for doing repair work and removing snow from the panels and can be installed at any angle or direction. In Minnesota, more sun comes from the south at an angle approximately equal to the latitude, which is 45° in Minnesota; ground-mounted systems can always be south-facing and at an ideal angle, making them as efficient as possible. Pole-mounted systems are similar to ground-mounted in that they are attached to the ground, but instead of being low to the ground, they are mounted on poles and can have additional machinery attached, allowing the system to track the sun. Tracking makes the system more efficient, but generally these systems require regular maintenance on the moving components and are too expensive to make them a feasible choice for farms. Lastly, roof-mounted systems are the easiest to install and are most efficient on south-facing roofs with no obstruction (e.g. no trees, chimneys, and other buildings). However, access can be difficult, even dangerous, if snow removal or repair work is required.

In addition to installing the array in different locations, the system can be attached to the grid. If the system is off-grid, benefits include being self-sufficient and potentially being a cheaper option than extending power lines into remote areas. However, off-grid systems require solar batteries to store electricity, which usually makes the system more expensive than a system connected to the grid. Grid-tied systems allow the owner to save money by taking advantage of the net metering program by selling excess electricity back to the utility during times of high production. In addition, at times of low or no solar electricity production, the utility will provide access to back-up power.

Every barn has different electricity needs, meaning that each system requires a different size, location, and type of solar systems. The goal of this project was to determine if solar PV systems can provide as much electricity as a swine barn is using. Actual electricity usage of the WCROC swine finishing barn was compared with the solar production of the 26.88 kW system installed on the barn's roof. In addition, the data was used to help a farm choose what system would be best for them.

2. MATERIALS AND METHODS

a. Location

The West Central Research and Outreach Center (WCROC) in Morris, MN provides opportunities to rural areas by researching innovations or emerging trends in real life scenarios and advising agricultural producers about potentially using these innovations on their own farms. Morris is located in central western Minnesota and part of one of the richest agricultural lands in the country, making it a prime location for testing. The WCROC is specifically located at a latitude of 45 35' N and a longitude of 95 52' W and at an elevation of 1,141 feet above sea level. Currently, the WCROC possesses nursery, gestation, finishing, bedded farrowing, and hoop barns for swine. The focus of this project was on the 146' x 36' finishing barn. The barn consists of one eastern and one western room, housing up to 216 swine each. During this period, the swine were fed a diet mainly consisting of corn and soybean meal. From January 1, 2015 to December 31, 2015, the finishing barn used approximately 3,000 therms of natural gas and 28,000 kWh of electricity.

b. Auditing Electricity Consumption for Pork Production Systems

Swine facilities require large amounts of electricity to function. Up to this point, most research regarding energy consumption to produce pork has been theoretical. To determine the feasibility of solar energy as a source of electricity on a swine farm, actual electricity consumption must be analyzed on the farm in question. Using a Campbell Scientific CR800 data logger with a Campbell Scientific AM 16/32B Multiplexer (Fig. 1), wall ventilation fans, pit fans, heaters, power washer vent fan, feed auger, power washer, and lights (Fig. 2) were monitored at the WCROC finishing barn. The data logger reported the electricity production in electric current consumed by each load in Amperes every ten minutes, and the data of interest was recorded from June 1, 2015 through July 31, 2016. The power consumed, in kWh/day, was calculated using the measured current, voltage, and an estimated power factor.

Figure 1: Campbell Scientific CR800 Data Logger with Campbell Scientific AM 16/32B Muliplexer.

Figure 2: Devices with high electricity requirements at the WCROC finishing barn. From top left, a wall ventilation fan, a pit fan, feed augers, and a heater. From bottom left, the power washer/power washer vent fan and lights.

In addition to measuring the loads of specific applications, overall electricity consumption was measured through an electric meter installed by the electric utility. The Campbell Scientific data loggers were unable to measure some of the miscellaneous loads, so the electric meter gave a better representation of the total need for electrical energy in the barn.

The number of pigs in the barn between June 2015 and May 2016 was also recorded as the electricity consumption can be greatly affected by the amount of pigs. High numbers of pigs require more cooling and ventilation. As the WCROC farm is research-oriented, the finishing barn did not always have pigs, requiring minimal electricity usage.

c. Installing the Solar PV System

An objective of the study was to make the building approach net-zero, meaning the barn would produce as much electricity as the barn would use. By first determining the total electricity usage, PVWatts could be used to estimate the size of the system required to meet that goal of net-zero. PVWatts is a program developed by the National Renewable Energy Laboratory (NREL) that predicts the electricity production of solar PV systems and takes into consideration system size (kW), module type (e.g. standard, premium, or thin film), array type (e.g. open rack, roof mount, tracking, etc.), system losses, tilt (e.g. 4/12 pitch gives an 18.5° tilt), and azimuth (i.e. north, south, east, or west-facing). Finally, the system was sized so that the array could fit on the roof. Using this method, a 26.88 kW DC array was determined to produce about as much electrical energy as the barn required to operate, if not slightly more. As a result, a Heliene 60M280 fixed array comprised of 96 modules was installed on the WCROC swine finishing barn in June 2015 (Fig. 3). The system was roof-mounted at a 20° angle facing south.

Figure 3: Heliene 60M280 Solar PV System Mounted on the Roof of the WCROC Swine Barn.

Electricity from each of the three rows of panels was diverted through one of three inverters, SE9K three phase inverters from SolarEdge Technologies, Inc., and to a transformer for distribution.

Figure 4: SolarEdge SE9K Three Phase Inverters on the WCROC Swine Barn.

The inverters recorded the electricity output of the solar PV system every fifteen minutes, allowing for the daily and monthly kWh produced to be calculated.

d. Comparing Electricity Production to Irradiation and Electricity Usage

Every day a certain amount of irradiation, or power from the sun per unit area, is received in Morris, MN. Irradiation affects the amount of available energy for the solar PV system to collect; therefore, comparing electricity production to irradiation provides the efficiency of the system.

$$Efficiency = \frac{Solar\ PV\ Production\ (W)}{Irradiation\ Available\ \left(\frac{W}{m^2}\right) * Area\ of\ Solar\ System\ (m^2)}$$

Equation 1: Calculation for efficiency of a solar PV system.

Available irradiation was gathered by the pyronometer at the WCROC weather station, and the solar production was collected using the inverter. The area of the 26.88 kW system was known to be approximately 140 m^2, given the number and type of modules. Efficiencies could then be calculated for every hour during a "typical day" in a given month. The typical day was determined by calculating the average daily electricity production. For each month, the date with the production closest to that daily average was chosen as a typical day. The hourly electricity production for the typical day was then compared to the actual irradiation collected from the pyronometer that day. By choosing the production and irradiation from actual days instead of an average of all the days in a given month, the calculated hourly efficiencies were more realistic.

In addition to comparing production to irradiation, the times of electricity production was compared to times of electricity consumption. As described previously, data loggers measured the electric load every ten minutes from the fans, pit fans, heaters, power washer vent fan, feed auger, power washer, and lights in the finishing barn. The data could then be easily compared to the solar electricity production throughout the day as well as on a monthly basis.

e. Case Study

Two farms, Finisher 4 and 5, showed interest in using solar energy to mitigate their grid electricity usage. "Finisher 4" and "Finisher 5" were designations given to the barns by the WCROC to keep their anonymity intact while still allowing the WCROC to monitor their energy usage. Finisher 4 has a tunnel-vented, two room barn with a 2,400 swine capacity (1,200 in each room). The barn's roof has 4/12 pitch and faces east and west, making roof-mounted solar panels much less feasible than ground-mounted. Finisher 5 is a curtain-sided barn with two 530-head rooms. The roof has 4/12 pitch and faces north and south, ideal for a roof-mounted solar PV system. The electricity usage of both barns were being monitored so that a Heliene 60M280 roof-mounted or TenKSolar XT-A ground-mounted solar PV system could be assessed.

After analysis of the two farms' electricity usage, PVWatts was used to estimate what size ground-mounted or roof-mounted arrays would be required to provide Finisher 4 and 5 with a net-zero system. Finally, a report was provided to Finisher 4 and 5, giving them an idea of the solar PV system that would be most beneficial to each barn.

3. RESULTS AND DISCUSSION

a. Electricity Consumption at the WCROC Finishing Barn

First, total electricity consumption of the WCROC finishing barn was analyzed. The electricity usage in the swine barn was recorded by the utility meter (Fig. 5). The meter measured the entire barn's usage and is separate from the Campbell Scientific current sensors, which measured the electricity usage of only specific pieces of equipment.

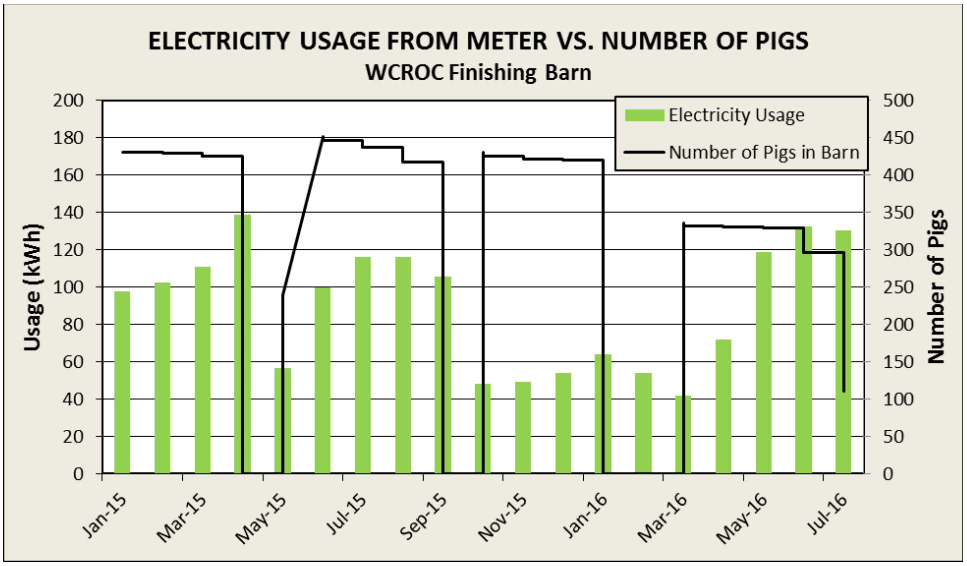
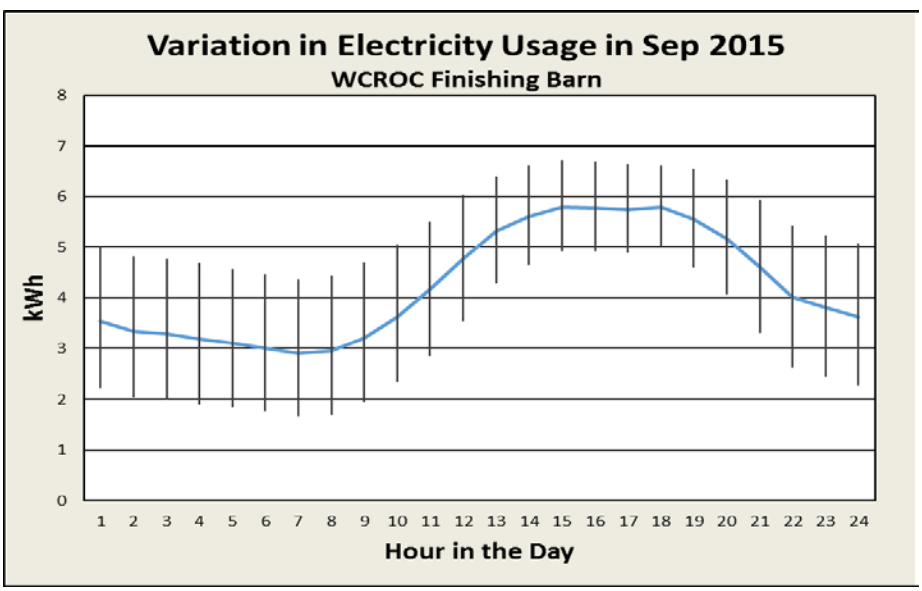


Figure 5: Amount of electricity used by the WCROC swine finishing barn, recorded using an electric utility meter, and the number of pigs in the finishing barn from January 2015 to July 2016.

As the WCROC finishing barn is primarily for research, pigs only resided in the barn during a study. The number of swine affected the load as more pigs residing in the barn required greater electricity usage. In addition, months with more extreme weather, such as January, May, July, and August, had a higher electric load due to higher heating, cooling, or ventilation. While the weather will still affect electricity usage in swine barns, commercial barns typically always have pigs in their barn, so data regarding energy usage in the WCROC finishing barn was only considered for months during which the barn had a significant number of pigs.

Naturally, there was some variation in the amount of electricity used throughout the day. Taken from the Campbell Scientific CR800 data logger with the Campbell Scientific AM 16/32B Multiplexer, the hourly electricity usage from the WCROC swine finishing barn could be shown in Figure 6.



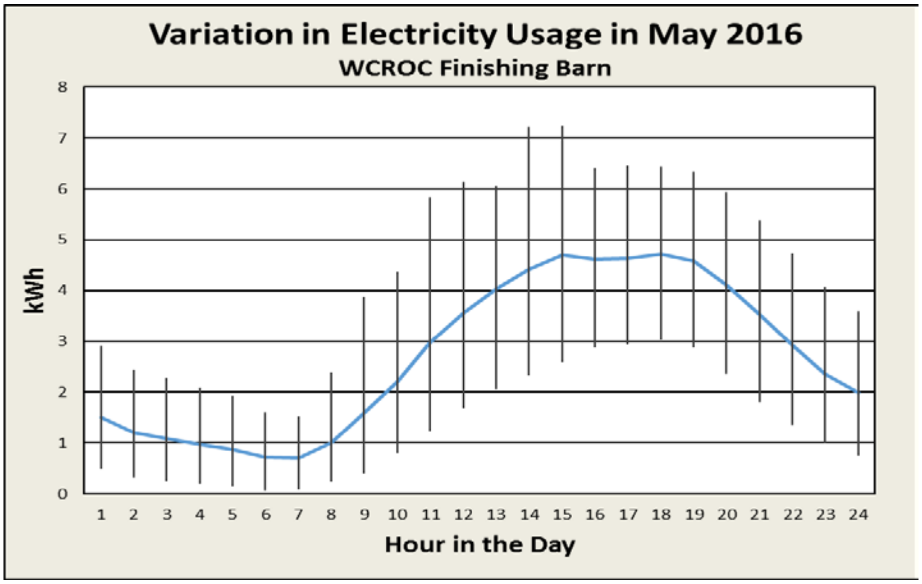


Figure 6: Variation in the total electricity used in an hour, measured using the Campbell Scientific data loggers.

Also, note that in September, the finishing barn had over 400 pigs. In May, there were approximately 330 pigs. Therefore, the barn had less electricity usage in May than it would have had there been seventy more pigs. More mild weather may have also had an effect on this.

Overall, there was a larger electricity usage in the middle of the day. For September, a high variation in electricity usage could be seen at night, and for May, the high variation was in the middle of the day. These high variations were in part due to weather; for example, in Minnesota, weather in May can be very warm, requiring electricity to keep the fans running. However, May weather can also be mild when the sun is high, requiring minimal cooling and some ventilation. This resulted in a high variation from 14:00 to 15:00 when the sun can make a large difference. For September, however, the weather was generally less unpredictable than for May, resulting in less variation in the middle of the day.

Next, average electricity usage and average solar production per month were evaluated (Fig. 7).

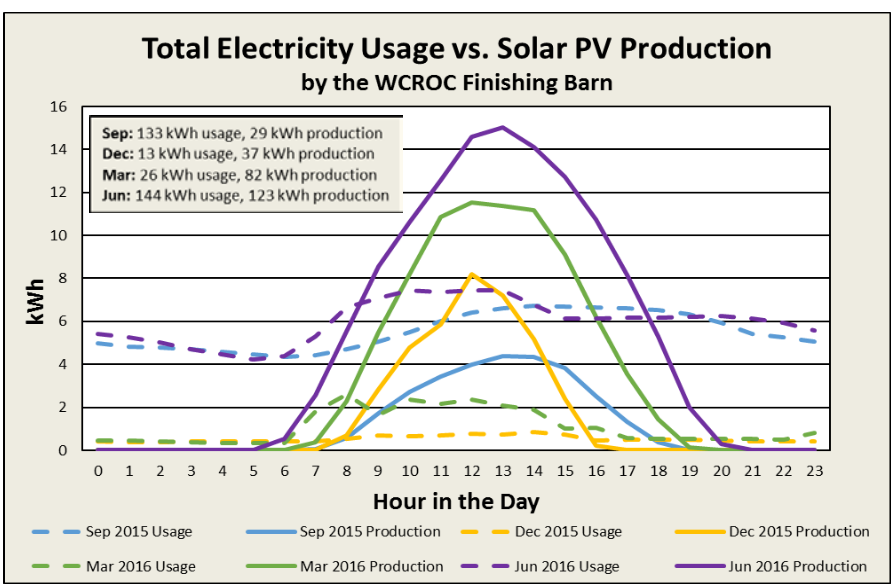


Figure 7: The average hourly electricity usage and solar PV production at the WCROC finishing barn.

Because the solar PV system produced the most electricity during the middle of the day when there is the greatest load, solar energy was a good fit for the swine barn. However, Minnesota winters have a lot of weather variability. When a large amount of heating was required, the weather may have been overcast, preventing enough electricity from being produced. Regardless, there appeared to generally be more production in the middle of the day. Despite this variability being a problem in winter, this trend was beneficial in summer as high ventilation and cooling was required when solar radiation was greatest. The large amount of solar radiation would be able to be converted into a large amount of electricity through the solar PV system, making solar energy ideal in the summer.

Despite the higher load and production in the middle of the day, a small load was typically required at night. In September and June, this average load was actually fairly significant, emphasizing the fact that solar PV systems must either be connected to the grid or attached to a solar battery in order to provide a back-up source of electricity in times of little or no production.

Knowing these trends is important when determining if solar was suitable for use in swine barns. With the WCROC finishing barn, a 26.88 kW roof-mounted system was believed to generally balance the electricity usage and production on an annual basis, but electricity was still required to be purchased from the utility at night and sold to the utility during the day using the Minnesota net metering program.

b. Electricity Production Using the 26.88 kW Solar PV System

Next, monthly production was analyzed. Electricity production from the solar system installed on the roof of the finishing barn was monitored using an online connection with the SolarEdge inverters, where the monthly production and usage were compared (Fig. 8).

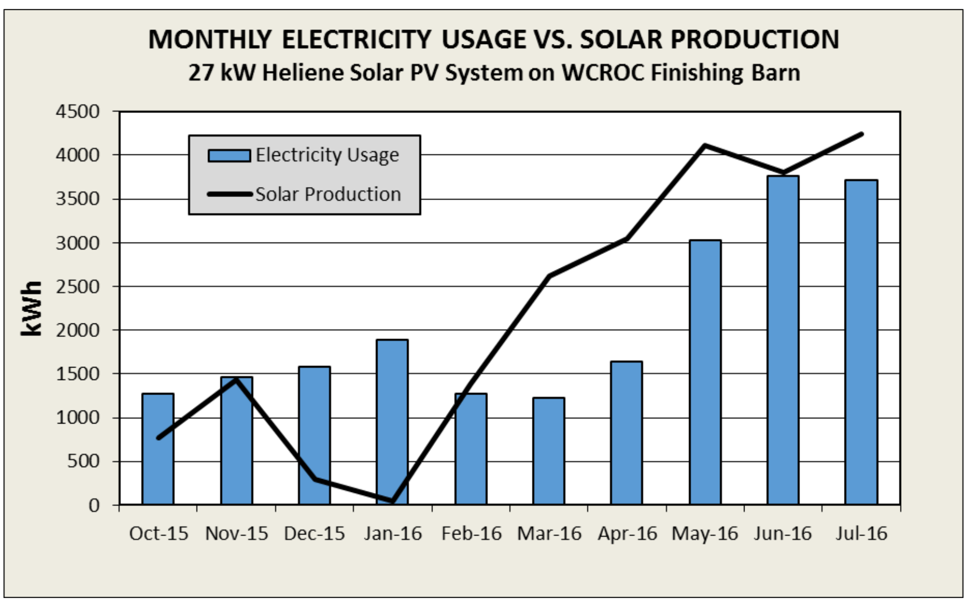


Figure 8: Comparison between the electricity used in the swine barn and produced by the 26.9 kW solar PV system each month.

First, note that the solar system electricity production was much higher in spring than fall. In addition, the load was higher in the late spring than fall. This demonstrates the fact that in the finishing barn, the monthly load was greater during months of high production. However, as the WCROC swine finishing barn is a research barn, the number of pigs residing in the barn fluctuates, another important consideration when looking at the electricity usage. From October

2015 through late January 2016, the barn was almost at full capacity with 212 pigs in each room. On January 26, 2016, the barn was completely emptied until March 11, 2016, explaining why the electricity usage in February and March are so low. The barn was then filled with 167 pigs in each room on March 11.

Another observation is how low solar production was in December and January. This was due to snow covering the panels from December 16, 2015 to January 27, 2016. As a result, about a month and a half of potential production time was lost. While a roof-mounted system was ideal for the finishing barn, cleaning snow off of the panels would be difficult and potentially dangerous. Despite the difficulty, removing the snow regularly is important. In fact, the system was supposed to be able to keep snow off by using solar radiation to melt the snow upon contact. Nevertheless, snow was able to cover the panels quickly enough that all the snow was not able to melt, preventing further heating and electricity production.

Despite the roof-mounted system balancing the annual electricity usage and production, the balance was not as great on a monthly basis. During months of low production, additional electricity needed to be purchased from a utility. During months of high production, the excess electricity was released to the grid. In other words, annual reconciliation is a good goal, but that does not mean no electricity goes into or out of the system on a monthly or even daily basis.

Another way to look at how much electricity being consumed and produced is to look at the daily electricity balance, here defined as the excess electricity being produced by the solar PV system or the total electricity consumption subtracted from the total production (Fig. 9).

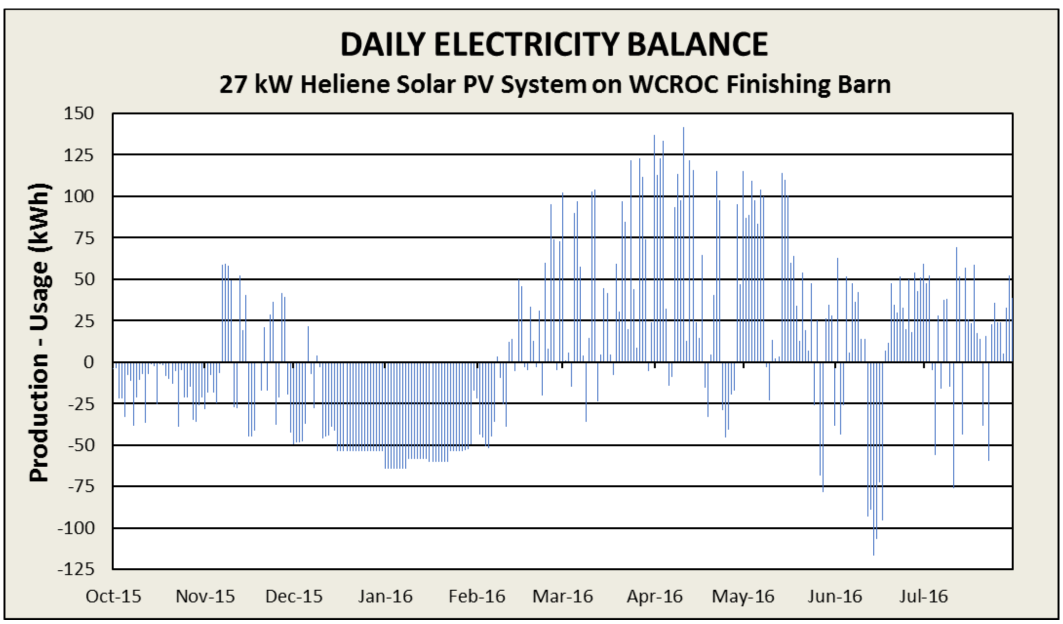
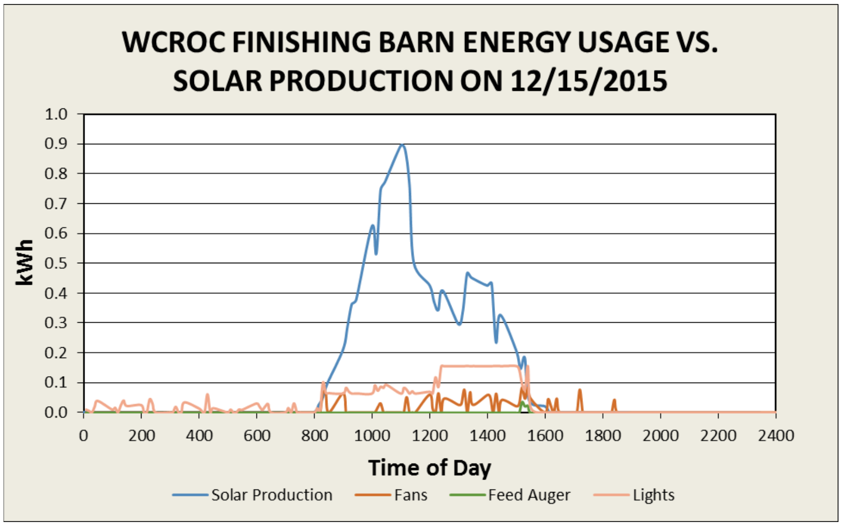
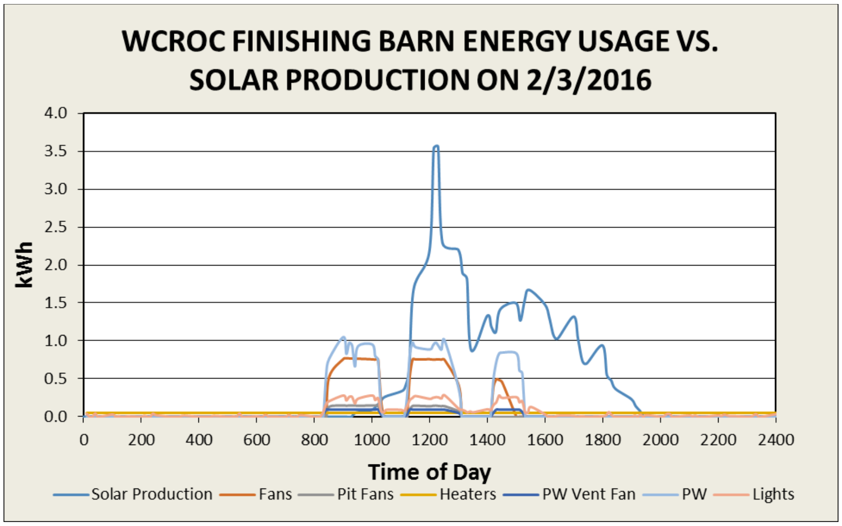


Figure 9: Amount of excess electricity produced from the WCROC solar PV system.

From October 2015 to February 2016, the net electricity balance was negative, meaning that the barn was using more electricity than the PV system was producing. The highly negative section from mid-December through January was explained earlier as being due to snow covering the panel. There was a highly positive net balance from February 2016 through July 2016 with a peak in April. From June 12-17, 2016, there is another very negative balance due to having an exceptionally cloudy week and very low levels of irradiation. Weather fluctuates, and as a result, solar production fluctuates as well. This cannot be prevented, but solar batteries or having a grid connection ensures that the barn will still have a source of electricity despite there being little to no production.

In addition to the total electricity usage, specific applications were measured using data loggers. Hourly electric loads from the ventilation fans, pit fans, heaters, power washer vent fan, feed auger, power washer, and lights were compared to the amount of electricity being produced by the solar PV system during a typical day (Fig. 10).





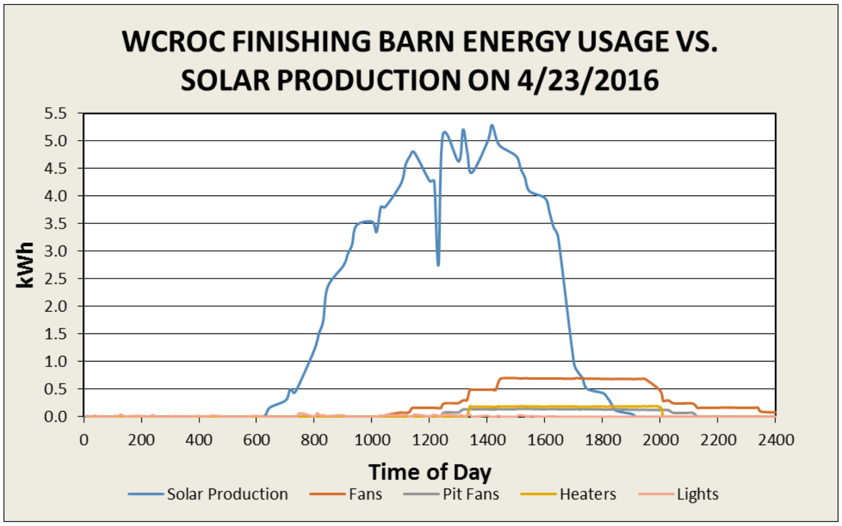


Figure 10: Electricity usage from ventilation fans, pit fans, heaters, power washer (PW) vent fan, feed auger, power washer (PW), and lights compared to the solar PV system's electricity production throughout a typical day in December and April. If the specific application is not shown in a given day, the total load that day from that device was 0 kWh. See the text after Equation 1 for the method for determining the "typical day".

In February, the power washer was in use. The average electricity usage indicated that the power washer was being used a lot due to no pigs residing in the barn; therefore, a day with the power washer and power washer vent fans on was determined to be a good representation of that month. Incidentally, the power washer peaks are relatively in line with the solar production peak. While not necessary, ensuring that high loads, such as the power washer, is used at the same time as high production in the on-farm solar system is one way to ensure the electricity usage is as close to net-zero as possible at any given time.

Overall, specific applications were being used around the same time as electricity was being produced, indicating that solar energy was a good choice for the finishing barn. In December and April, the highest load was slightly later in the day than the greatest production but still usually requiring less electricity than being produced. The same held true in February if the power washer had not been used outside of high production times. A concern with using solar energy would be any loads outside of daylight hours. In this case, there are numerous loads outside of daylight hours, such as the wall ventilation fans, pit fans, heaters, and feed augers; generally, these loads are relatively small and as such do not affect the validity of using a solar PV system to supplement the WCROC finishing barn's electricity usage. However, a grid connection or solar battery is essential to ensuring that electricity is still available during times of no production.

Lastly, a comparison between the actual electricity production of the 26.88 kW Heliene solar PV system on the finishing barn and output predictions from a program called PVWatts was executed (Fig. 11). The goal was to validate this program and determine its practicality for use on a pig farm.

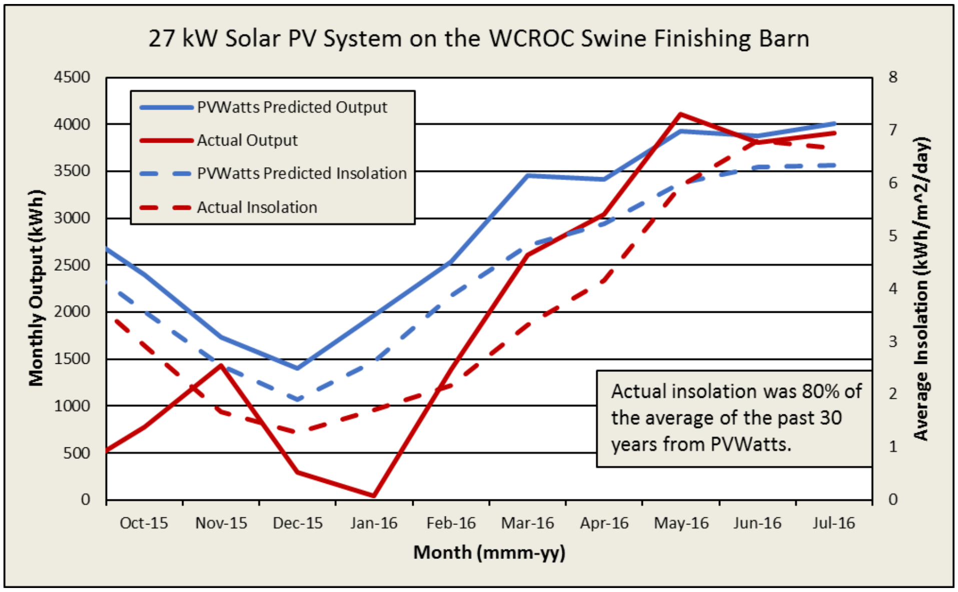


Figure 11: Actual electricity production from the WCROC solar PV system and average monthly insolation from the pyronometer at the WCROC weather station compared with predicted output and insolation from PVWatts.

Overall, PVWatts predicted more output than was actually produced. Specifically, the 26.88 kW Heliene solar PV system produced 74.5% of the electricity production estimated by PVWatts. While the prediction was fairly accurate, remember that December and January had a lack of production due to snow covering the panels, which PVWatts does not take into consideration. Not including these months, the system produced 83.0% of the predicted production from October 2015 to July 2016. However, PVWatts' prediction is based off an average of the solar insolation (i.e. energy received from the sun in a day) over 30 years. As shown in Figure 11, the actual amount of sunlight being received throughout this time period is 80% lower than the 30-year average. As PVWatts does not have the capability to input actual insolation values, a ratio of the average insolation given from PVWatts and the actual insolation in Morris was calculated. By multiplying the actual production by this ratio, the amount of electricity that would have been produced if the actual and predicted insolation were equal was estimated.

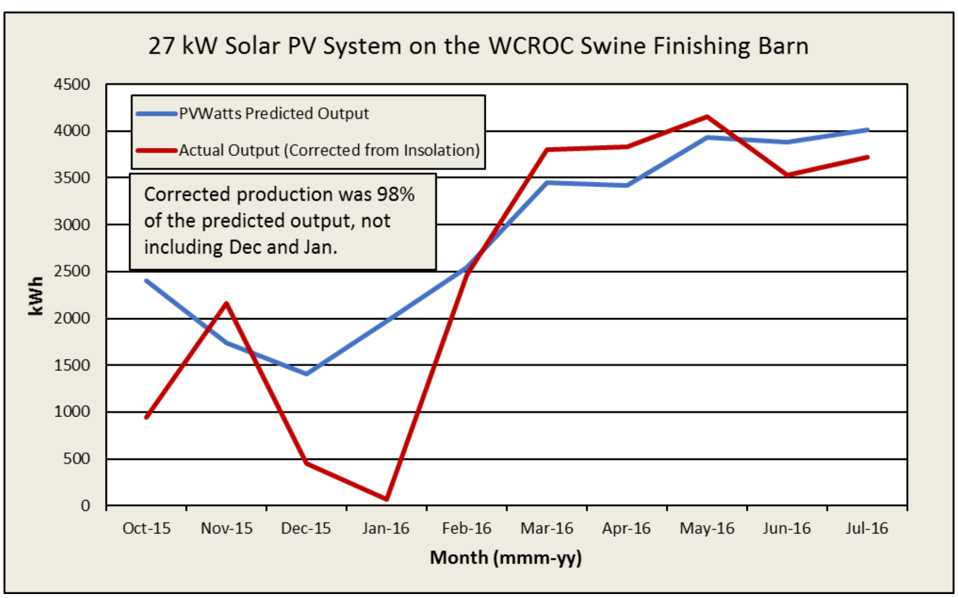


Figure 12: Corrected electricity production from the WCROC solar PV system.

The general trend predicted by PVWatts was much closer when taking into consideration the lower insolation. The actual production was 97.7% of the predicted output without January and December, showing that annual weather variation does occur but can be accounted for. In addition, while PVWatts is not perfect, the program can provide a reasonable estimate of a solar PV system's annual production. By validating this program, farmers can feel more confident about using the program to estimate the size of the array required to produce enough electricity to support their barn while understanding that weather may cause a variation in electricity output within ±10-15% annually.

c. System Efficiency

The efficiency of the solar PV system was calculated using the solar irradiation available as measured by the pyronometer at the WCROC weather station and the solar energy collected by the system (Eq. 1).

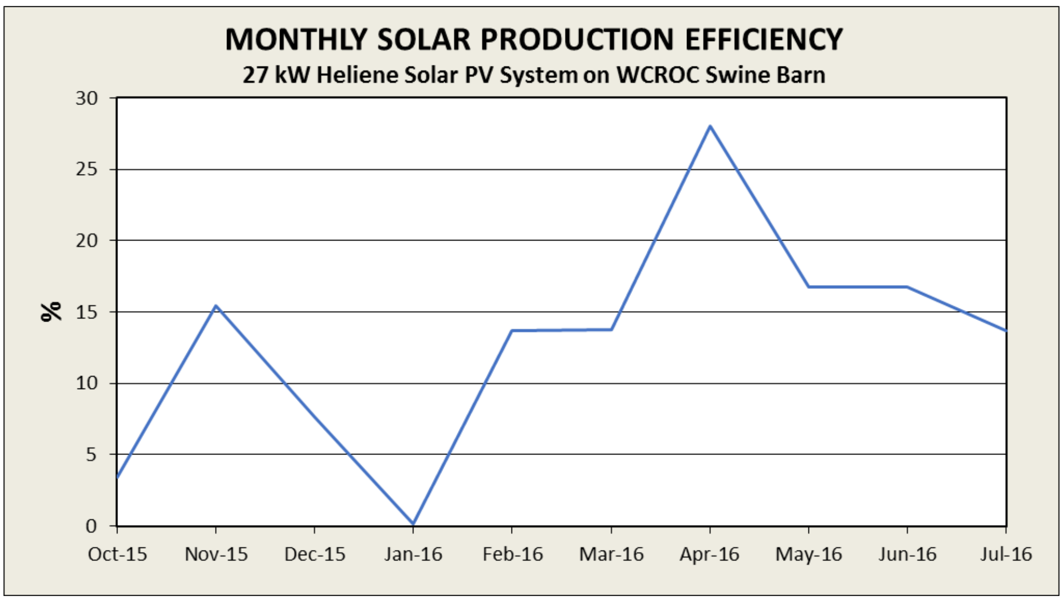


Figure 13: Monthly efficiency of the 26.9 kW solar PV system.

April was the most efficient month. There is a very distinct climb going from October to April as winter is generally less efficient than spring. However, note than January is near zero due to snow covering the panel.

The WCROC solar PV system ranged from an efficiency of 0.17% in January to 28.0% in April with an overall efficiency of 11.9% from September 2015 to June 2016. If snow had been properly removed, the overall efficiency may have been around 13.0%. In addition, one of the theoretically most efficient months, August, was not included in this average as a full year has not yet passed since installation. The average solar PV system typically possesses an efficiency between 11 and 15% (Pure Energies 2014), so this system worked as expected.

d. Determining Solar Options for Finisher 4 and 5

The 26.88 kW solar PV system at the WCROC finishing barn demonstrated the practicality of solar energy as a supplemental source of energy on a farm. Next, two swine barns, Finisher 4 and 5, expressed interest in implementing solar on their farms. PVWatts was used to model several solar PV systems that would fit their electric needs.

Finisher 4 was found to have an electricity need greater than a 40 kW system could provide. Because of this, if the farm were to sell the excess electricity back to the utility, they would receive a reduced compensation, currently around 4 cents per kWh, due to net metering policies. As a result, installing a 40 kW system and purchasing any additional energy from the utility or installing a system slightly larger than 40 kW that does not require Finisher 4 to sell back electricity at any point in time could be more financially beneficial than installing a system that would make the barn net-zero. In addition, due to the roof's orientation, a roof-mounted array would not be economically feasible. A 65 kW ground-mounted array would make the system as close to net-zero as possible but would be much larger than the 40 kW system required by net metering to sell excess electricity at the full retail rate. Therefore, in addition to the net-zero system, a 40 kW ground-mounted system was analyzed as well as one sized to never produce more electricity than needed (Fig. 14).

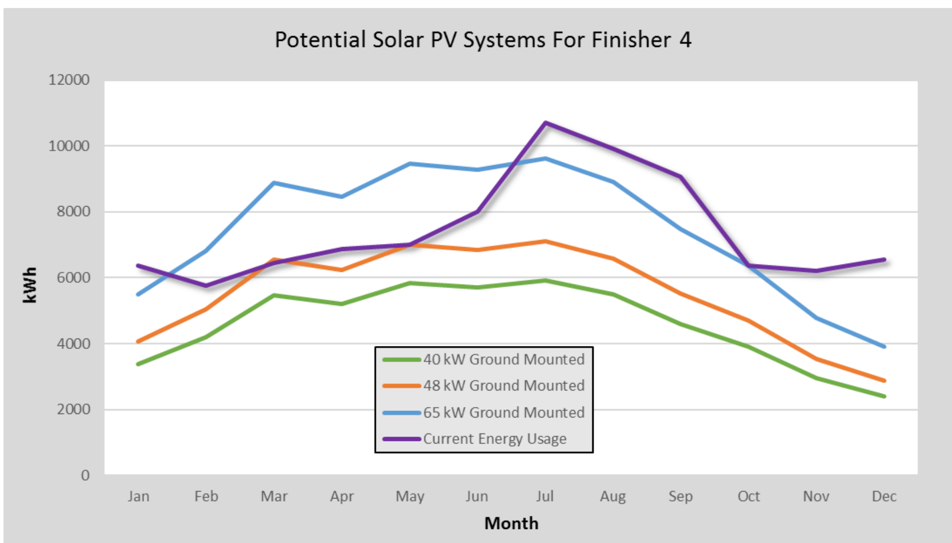


Figure 14: Electricity usage of Finisher 4 and the electricity production of several potential systems to supplement their usage.

All three systems were thought to be good options for Finisher 4 and as such were presented to the owners.

The second set of solar PV systems that were fitted to a swine barn was at Finisher 5. The barn load was small enough that net metering policy was not a concern. In addition, the roof orientation was such that a roof-mounted array was an option. Therefore, a roof-mounted and ground-mounted system were sized such that Finisher 5 would be as close to net-zero as possible.

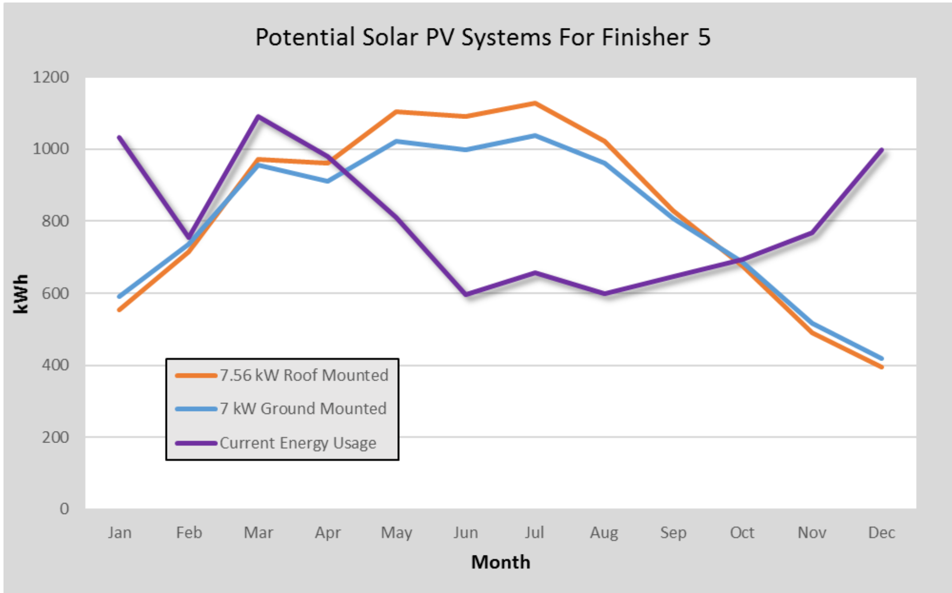


Figure 15: Energy usage of Finisher 5 and the electricity production of several potential systems to supplement their usage.

The roof-mounted array usually produced slightly more over a year than the ground-mounted, but the system was also 7.5 kW compared to 7 kW. As the roof-mounted system was mounted at a lower angle, 18.5°, than the ground-mounted system, the roof-mounted array was less efficient and had to be larger to produce about the same amount of electricity.

Another important step when choosing between roof-mounted and ground-mounted is to ensure that the required roof-mounted system would actually fit on the roof. Finisher 5's roof was measured to be about 6 m tall and 57 m wide. The array required to make the barn net-zero would be comprised of 27 modules, which would require only one row that is 1.65 m tall. Fortunately, the roof-mounted system would fit on the roof, meaning that both the roof-mounted and ground-mounted systems provided opportunities for Finisher 5 to become net-zero, so both were presented to the interested parties.

4. IMPLICATIONS

The objective was to confirm whether or not solar PV systems would be able to provide enough electricity to be a good option for swine barns to supplement their energy usage. At the WCROC finishing barn, a 26.88 kW Heliene model system was installed and proved to be a decent fit for the barn. In winter, the system did not make enough energy, but in summer, there was excess electricity being produced. In addition, the system more than made up for the energy usage during the day throughout most times of the year. Nevertheless, any electric loads at night had to be drawn from the utility grid as well as throughout most of December and January due to snow covering the panels. Solar batteries may provide an alternate option for providing a source of electricity during times of low or no production but add cost to the system.

The agricultural industry should consider implementing solar systems on swine farms. Not only did the WCROC PV system show that enough electricity could be produced to support the barn's electricity usage, but solar PV systems require minimal maintenance costs due to no moving parts, reduce carbon dioxide and other greenhouse gas emissions, and provide the ability to harness an unlimited source of energy. Determining where and how much energy is being used is the first step to choosing a solar system that would best suit a farm. Consider roof-mounted systems as well as ground-mounted depending on cost, land and roof space, and efficiency. In Minnesota, roof-mounted systems are very efficient if facing south but significantly less so if facing east or west. In addition, making a barn net-zero may not always be as economically beneficial as a smaller system due to net metering policies. Larger systems are only able to sell excess electricity at a reduced cost whereas smaller systems will be using all their electricity or selling it back at the full retail price. PVWatts can provide a reasonable estimate of how large a system may need to be to provide a certain amount of electricity within 10-15% depending on the weather that year.

The study of the WCROC finishing barn solar PV system will continue such that more data can be collected. Further studies could involve panel efficiency in winter when snow is manually removed from the panels as well as how the number of pigs, type of barn, or weather fluctuations affect a swine barn's electricity usage and production.

5. ACKNOWLEDGEMENTS

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR). The Trust Fund is a permanent fund constitutionally established by the citizens of Minnesota to assist in the protection, conservation, preservation, and enhancement of the state's air, water, land, fish, wildlife, and other natural resources. Currently 40% of net Minnesota State Lottery proceeds are dedicated to growing the Trust Fund and ensuring future benefits for Minnesota's environment and natural resources.

I would also like to thank Eric Buchanan and Kirsten Sharpe for working with me so closely during the course of the study, Michael Reese for overseeing all tasks, and Lee Johnston for reviewing my papers and presentation.

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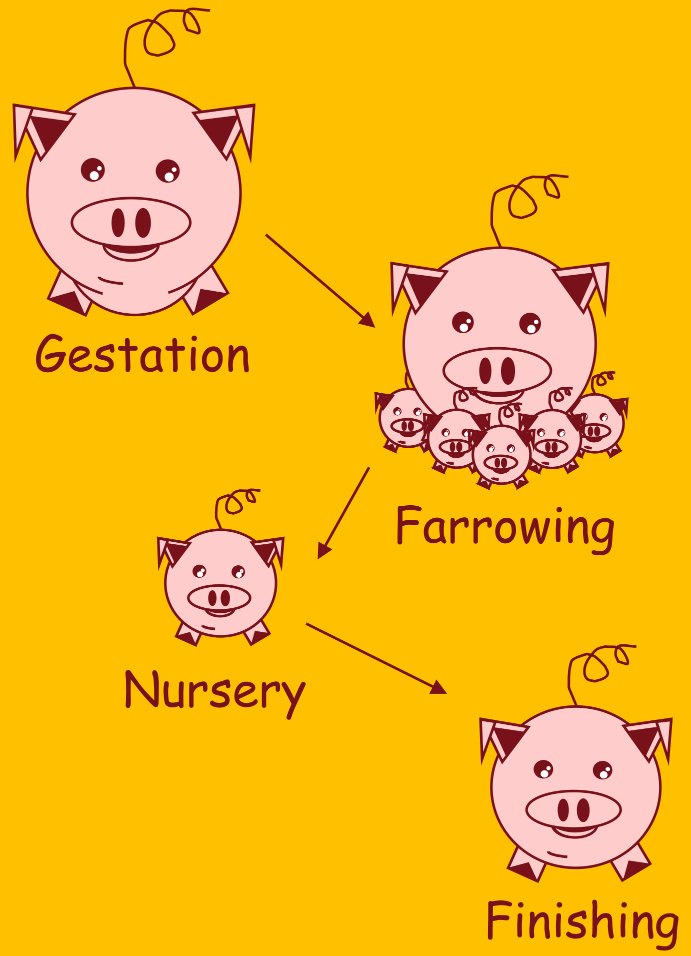
Transitioning Minnesota Farms to Local Energy

Presented by: Rachael Acevedo, Renewable Energy Intern
University of Minnesota West Central Research and Outreach Center

Objectives

- Determine if a solar PV system can provide as much electricity as a swine barn is using.
- Compare actual electricity usage with solar production for the WCROC solar PV system installed on the roof of a finishing barn.
- Use the WCROC data to help other farms choose what system would be best for them.



Installation Types

Pole-mounted at UMM

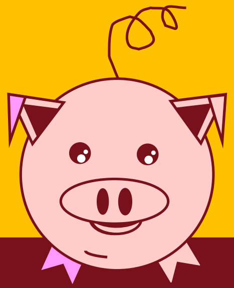
- Track sun
- More expensive

Roof-mounted PV system at WCROC swine barn

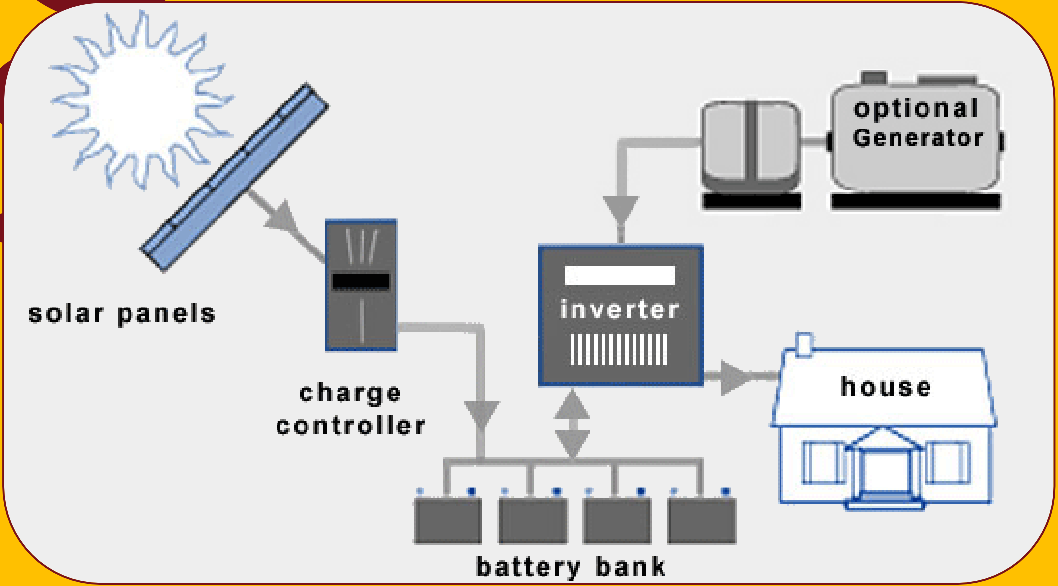
- Works best on south-facing roofs with no obstructions (e.g. no trees, chimneys, etc.)

Ground-mounted at WCROC

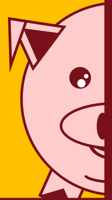
- South-facing
- Easier access for repairs



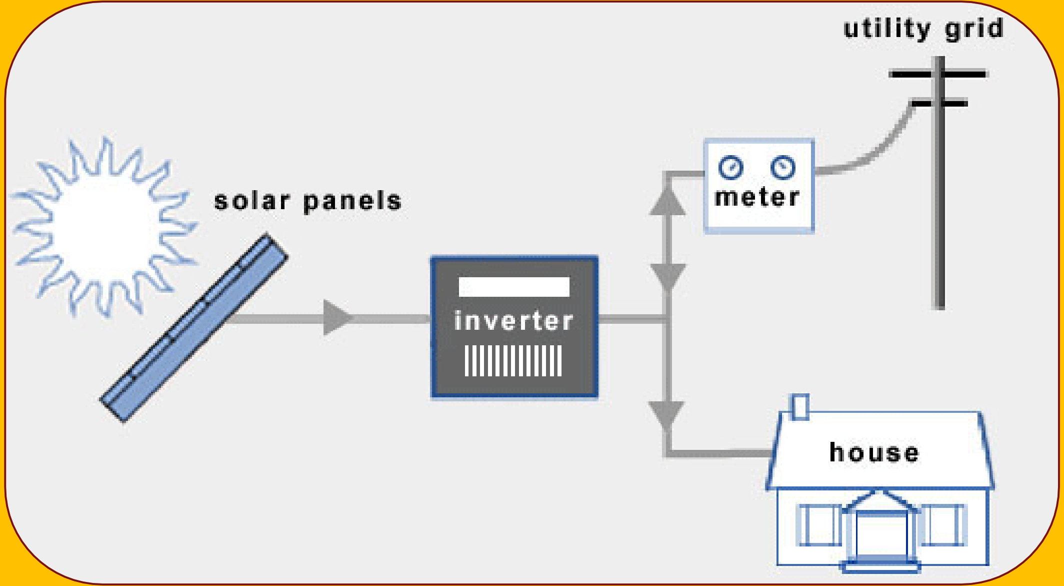
Off-Grid



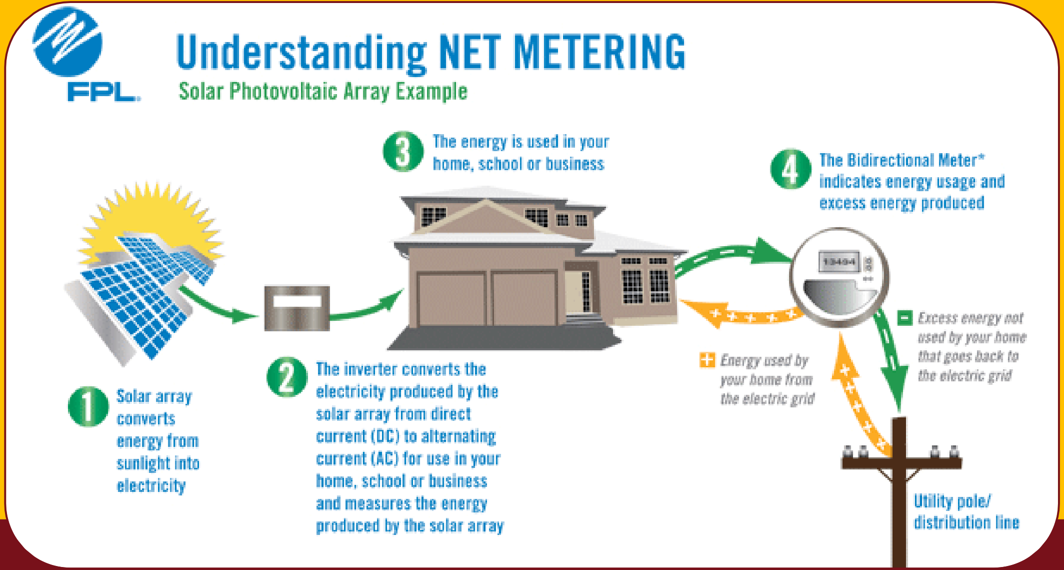
- Self-sufficient
- May be cheaper than extending power lines to remote areas
- Requires solar battery



Grid-Tied

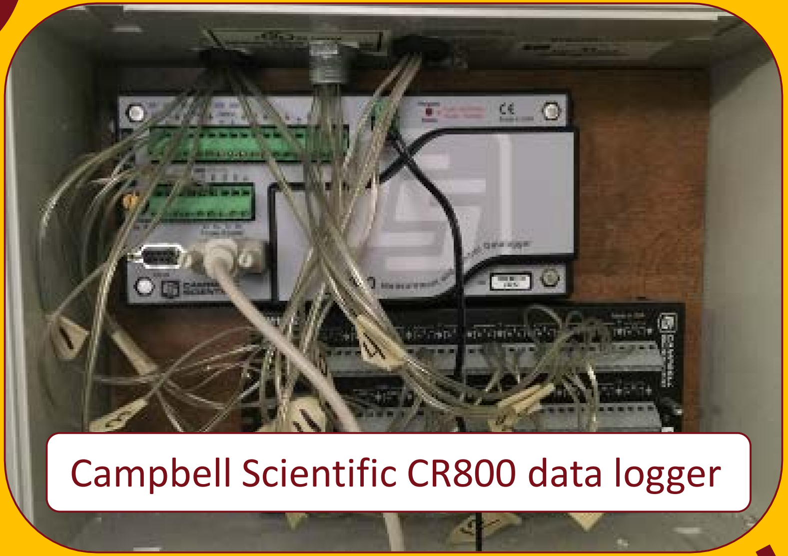


- Save money with net metering
- Access to back-up power



WCROC Finishing Barn

Auditing Energy Usage



Campbell Scientific CR800 data logger

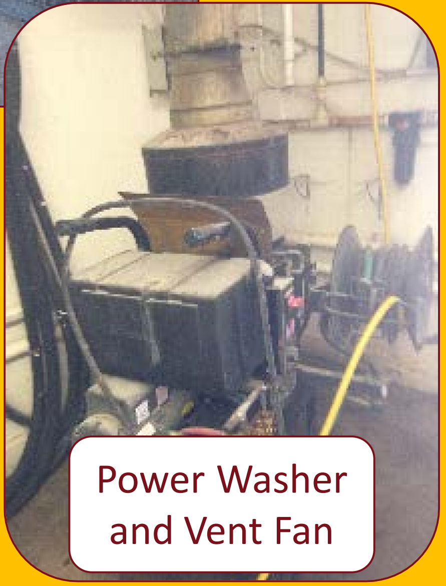
Feed Augers

Pit Fans

Lights

Fans

Heaters

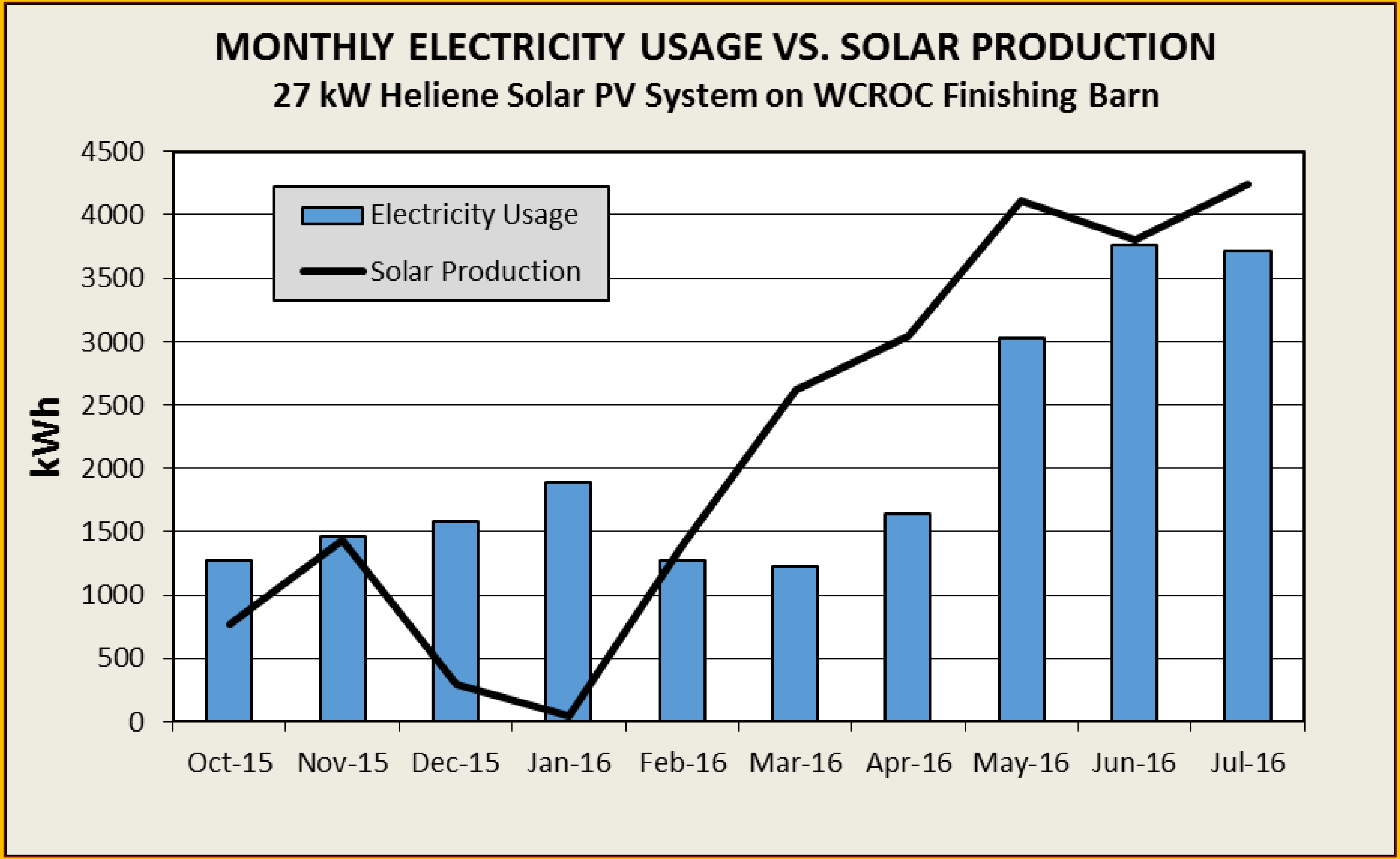


Power Washer and Vent Fan

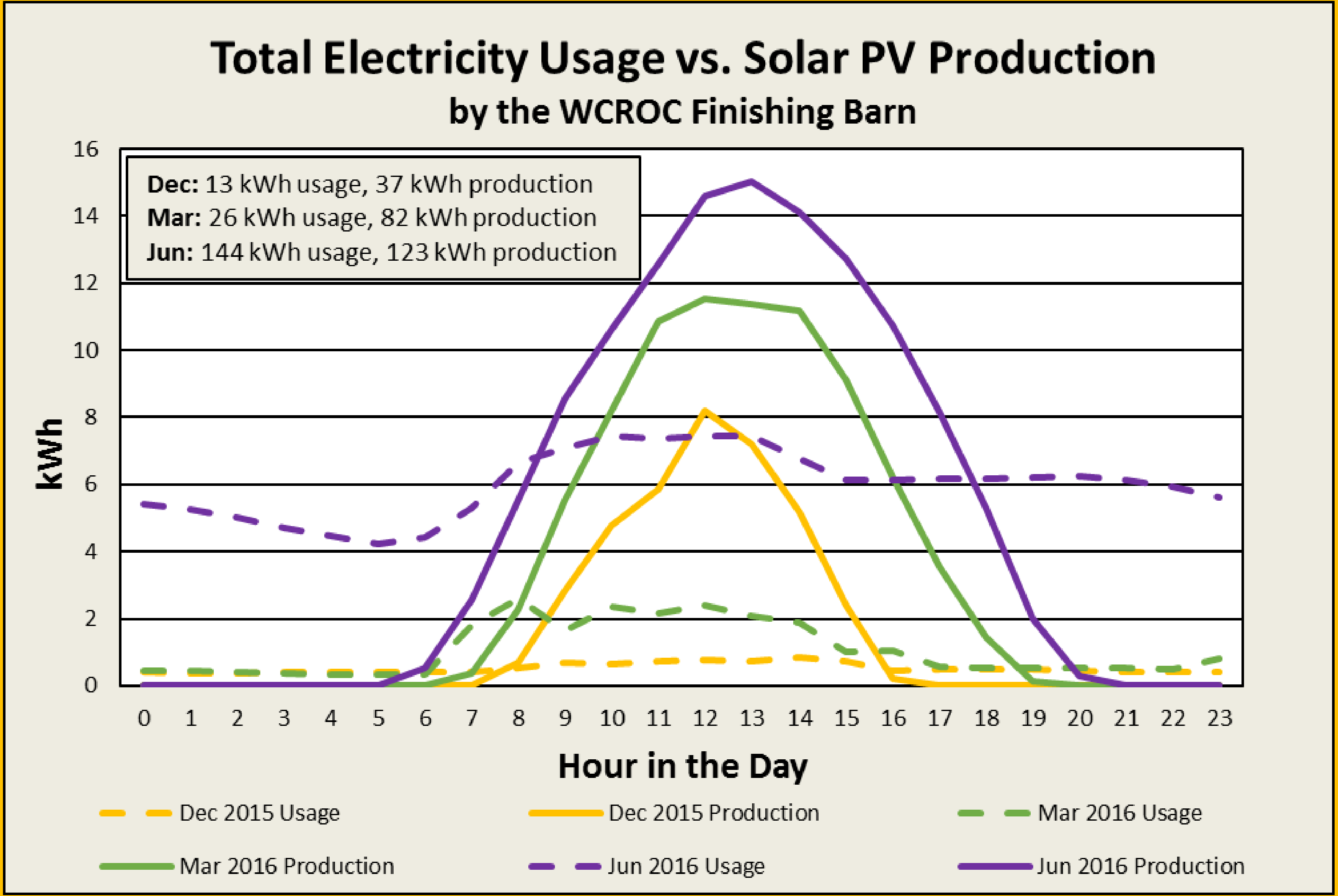
WCROC Solar PV System

- 26.9 kW Heliene 60M280 array installed in June 2015
- Roof-mounted facing south at 20° angle
- 3 SE9K inverters from SolarEdge Technologies, Inc. records power output

Energy Usage vs. Production



Energy Usage vs. Production (cont.)

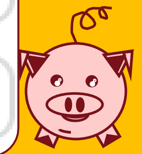


PVWatts Calculator by NREL

SYSTEM INFO

Modify the inputs below to run the simulation.

DC System Size (kW):	26.88
Module Type:	Standard
Array Type:	Fixed (roof mount)
System Losses (%):	14
Tilt (deg):	18.43
Azimuth (deg):	180



RESULTS

Print Results

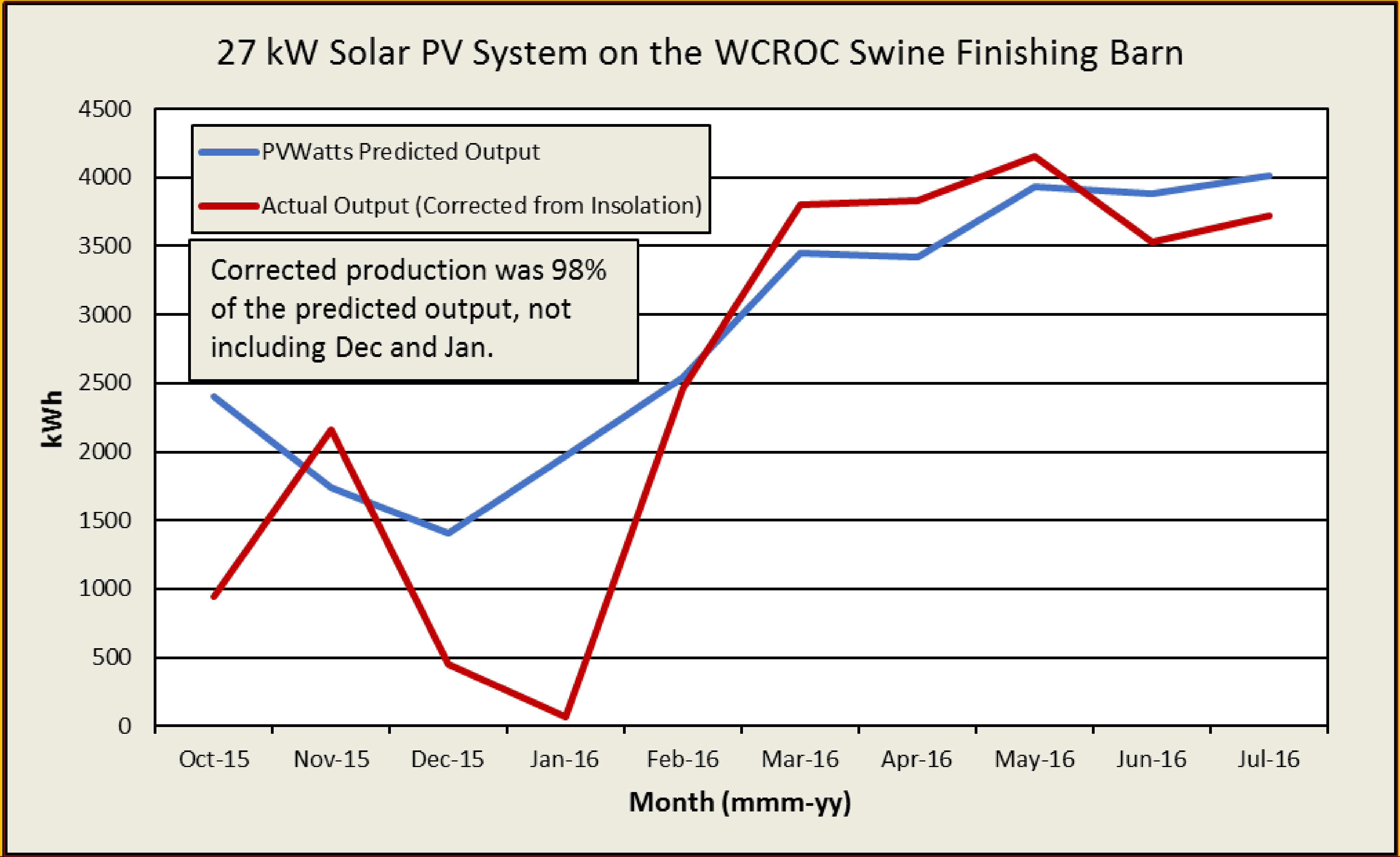
35,317 kWh per Year *

System output may range from 33,777 to 37,337kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Energy Value ($)
January	2.62	1,966	171
February	3.86	2,541	222
March	4.82	3,455	301
April	5.23	3,419	298
May	6.01	3,928	343
June	6.31	3,881	338
July	6.33	4,012	350
August	5.73	3,629	316
September	4.66	2,946	257
October	3.56	2,400	209
November	2.54	1,737	151
December	1.90	1,403	122
Annual	4.46	35,317	$ 3,078

PVWatts is used to determine the size of the ground or roof mounted arrays required to make these barns net-zero.

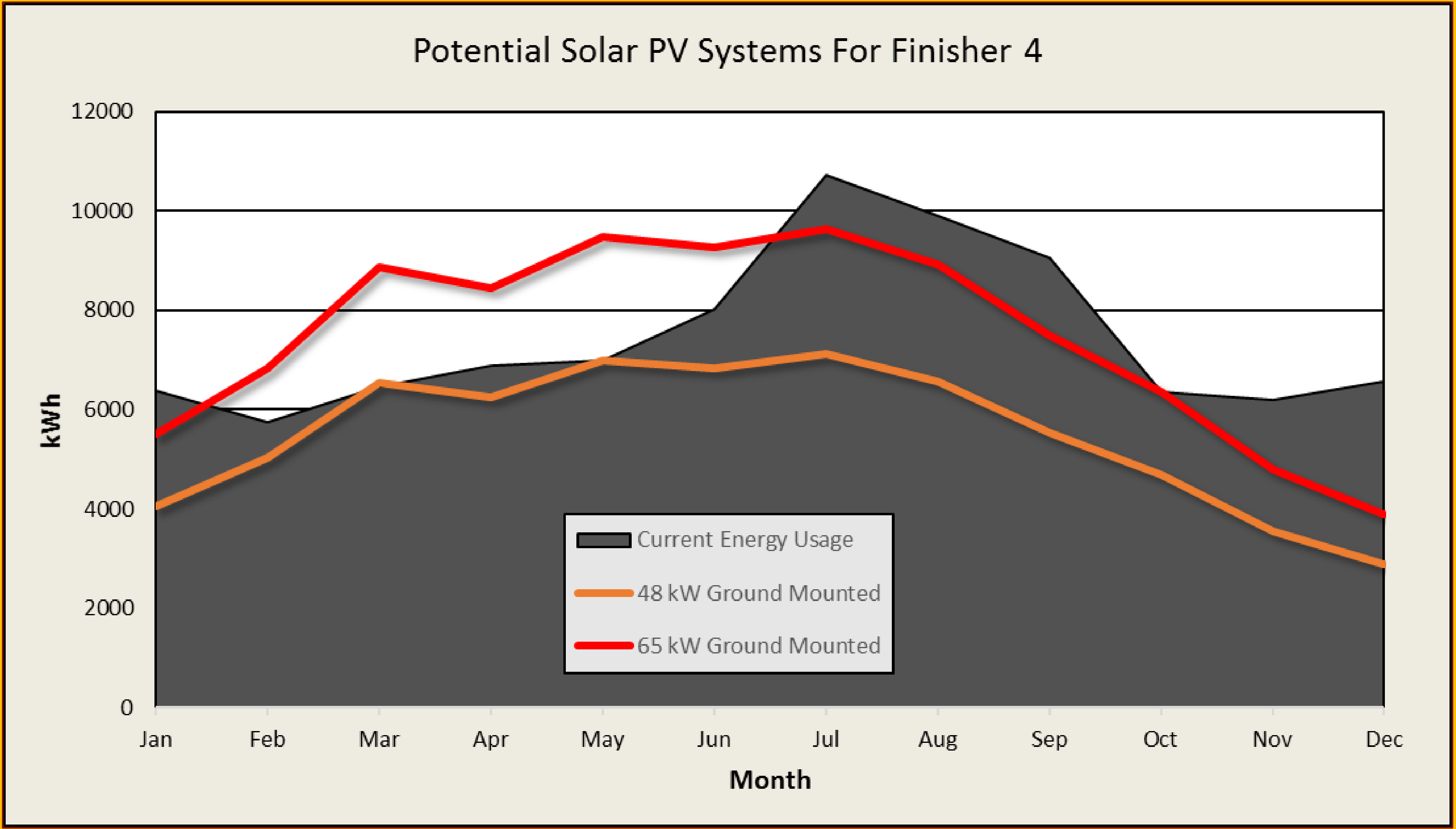
Comparison with PVWatts



Case Study: Finisher 4

- Tunnel-vented, two room barn with a 2,400 pig capacity
- Roof faces east and west, making roof-mounted solar panels much less feasible than ground-mounted

Results for Finisher 4



Based on the TenKSolar model XT-A PV system on the UMM campus

Financial Analysis for Finisher 4

Completed by Justin Miller

		Before Incentives	
	Total Savings	Payback Period (yrs)	Return-on-Investment
48 kW	$186,492.85	19.5	28%
65 kW	$234,831.98	20.8	20%

		Tax Credit		REAP Grant & Tax Credit	
	Total Savings	Payback Period (yrs)	Return-on-Investment	Payback Period (yrs)	Return-on-Investment
48 kW	$186,492.85	13.6	84%	8.8	186%
65 kW	$234,831.98	14.6	72%	9.4	167%

Assumptions: installation at $3/W and system life is 25 years

Conclusion

- A solar PV system appears to be a good option for supplementing swine barn energy usage.
- Knowing where and how much energy is being used is the first step to choosing a solar system that fits the farm.
- More electricity is used and produced in the middle of the day. However, a grid connection or solar battery is required during times of no production (e.g. night).
- Making a barn net-zero may not be as economically beneficial as a smaller system due to net metering.
- PVWatts is a simple and free program that provides a reasonable estimate of how much energy can be produced from a particularly sized system.

Special Thanks to….

- Michael Reese
- Eric Buchanan
- Kirsten Sharpe
- Lee Johnston
- Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR)
- University of Minnesota WCROC

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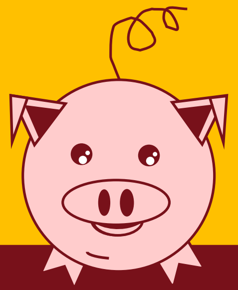
- WCROC
- YouGen
- Renu News
- Kirsten Sharpe
- PVWatts
- Google Earth



Funding Acknowledgment This project was supported by The Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative - Citizen Commission on Minnesota Resources (LCCMR)

The three systems modeled in electricity production (by Rachael) were solar PV systems of 40, 48, and 65 kW. The 40 kW system was modeled because the maximum size system in Minnesota that allows for net metering compensation at retail is 40 kW. A 48 kW system was modeled as a system that would generally not net meter at any month over the course of a year. The 65 kW system was modeled as the smallest size system in order to have close to net zero electricity usage in the first year.

Each system was modeled to project the amount of electricity it would produce (in kWh). This production was calculated monthly and then yearly. All the systems were then put into a 25-year projection table. The categories used in the projection table were *installation cost, electricity production, baseline load, net electricity/electricity used from solar, electricity price, money saved from solar, maintenance cost, net savings,* and *discounted savings*. The 65 kW system also had some projected months where it produced more electricity than the baseline load. This system was put through a net metering return analysis in order to determine the net metered kWh produced and the kWh purchased from the grid during times where the load demand exceeded system production. Since the system is greater than 40 kW, it receives compensation through net metering as payment from grid electric companies at the avoided cost price. The data from the net metering return analysis was used in the corresponding 25-year projection table. The 25-year projection tables were then used to calculate the return on investment of each system, along with other measurements such as net present value of investment, internal rate of return, and payback period. The return on investment and other measurements were done three different times for each system. These were before incentives, with a federal tax credit, and with the maximum REAP grant and a federal tax credit.

Assumptions/Calculation Methods

- Type of Modules:
  - The module types used for this analysis were TenK solar modules, model XT-A at 410 Watts. These modules are reported by the manufacturer to decline in production by 3% after the first year and then by 0.2% each year afterwards. The warranty for these modules is 25 years and they are not supposed to produce less than 92.2% of their initial energy production at the end of the warranty life.
    - For more information: http://tenksolar.com/wp-content/uploads/2015/12/410W-Nested-Module.pdf
- Actual kW used for each system:
  - Using the 410 Watt modules, the number of modules had to be approximated since a number such as 0.9 or 0.3 of a module cannot be used. This will result in the actual size of each system being 40.2, 48.4, and 65.2 kW if the systems are implemented. The original respective sizes were still used in calculations and assumed to not affect the calculations in a significant way.
- *Installation Cost:*
  - Installation costs for each system were assumed to be 3 dollars per Watt. This equates to $1,230 per module and $3,000 per kW. $3,000 per kW was used in order to find the installation cost for each system.

- *Electricity Production:*
  - An online calculator called "PV Watts" was used to calculate expected production from the solar PV system at each size. These values were used for the first year and the degradation percentages from the TenK manufacturer information were used to calculate each year after.
- *Baseline Load*:
  - Baseline energy usage, both monthly and yearly, was taken from load data from Halls farms. Available data usage was used to project what an "average" electricity load year at Halls would look like. Not all months were available for each actual year of data that was used to make the average year. It was assumed that over the 25-year span that each year would not unreasonably deviate from the average projected year, so the same average projected year load data was used for each year in the 25-year projection.
- *Net Electricity/Electricity Used from Solar:*
  - For systems that had months that produced more than the baseline load, the amount net metered and amount of electricity purchased from the grid were used to find the electricity used from solar. Monthly production values were found each year using the same degradation percentages from the manufacturer. With the other systems the yearly net electricity was used in the same way. For the 48 kW system there was one month in the first year that went over by 90.5 kWh which was subtracted from the net electricity. The returns from avoided cost for 90.5 kWh over production in the system's first year were determined to be insignificant.
- *Electricity Price:*
  - Commercial electricity prices were analyzed from 2001 to present. The linear trend of these prices was an average increase of 3.35% per year. It was assumed that this trend would continue in the future, so an increase of 3.35% in the price per kWh was used for the 25-year projection. 9.5 cents per kWh was used for year 0 which was the average price in 2015.
- *Money Saved from Solar:*
  - Electricity used from solar or electricity production multiplied by the electricity price
- *Money from Net Metering:*
  - Typical avoided cost for electricity production companies is around $0.04 per kWh. This was assumed to be what the electric company would pay each year for any electricity provided to the grid for the 65 kW system. This value was multiplied by the net metered kWh found from the net metering return analysis.
- *Maintenance Cost:*
  - It was assumed that around $1 per Watt would need to be spent over the life of the system in order to fix things such as replacing inverters. This cost was divided evenly among the 25-year life of the system.

- *Discounted Savings:*
  - Discounted savings is the value of net savings in present dollars and takes into account the time value of money. Using the time value of money is the idea with the question of whether having a certain value of money in the future is better than having a lesser amount of money now in order to be able to invest it. Most analyses use discount rates of around 3-5%. For this analysis a discount rate of 3% was used to convert each year's net savings into the value they would have today. For example, this means that discounted savings for the 25th year is the value of the net savings that would equal the net savings if invested at 3% interest for 25 years.
- Return on Investment:
  - Percent of original investment that is gained as revenue. Calculated by taking the difference between net cash flow and investment cost divided by the investment costs. This percentage can be looked at as the percentage of each dollar invested that is collected as a return.
- Net Present Value:
  - This is the sum of the discounted savings with the investment costs subtracted. This value represents the present value of the investment.
- Internal Rate of Return:
  - Discount rate in order to make the net present value equal zero. If this is greater than the ideal discount rate (3%) then the net present value will be positive. It also would mean that the initial investment will internally generate a greater return than if the net present value of the investment was invested at the ideal interest rate over the same period of time.
- Payback Period:
  - Amount of time to generate enough returns to cover the initial investment cost. Found by dividing the investment cost by the average yearly cash flow.
- REAP Grant:
  - REAP stands for the Rural Energy for America Program. This is a federal grant from the U.S. Department of Agriculture that can be applied to Solar PV systems. The maximum amount of the investment cost that can be covered is 25%. The full 25% was used in calculations but the grant could be less than that.
    - For more information: http://programs.dsireusa.org/system/program/detail/917
- Federal Tax Credit:
  - This is the federal Business Energy Investment Tax Credit (ITC) which can be applied to Agricultural industry and solar PV systems. The tax credit is for 30% of the investment cost. Savings from the tax credit were directly applied to lower the investment cost.
    - For more information: http://programs.dsireusa.org/system/program/detail/658

Summary Tables

Before Incentives

	Initial Investment	Savings per year	Payback Period (years)	Total Savings	Return on Investment	Net Present Value	Internal Rate of Return
40 kW	$ 120,540.00	$ 6,216.38	19.4	$ 155,409.52	29%	$ (18,540.54)	1.8%
48 kW	$ 145,140.00	$ 7,459.71	19.5	$ 186,492.85	28%	$ (22,739.71)	1.7%
65 kW	$ 195,570.00	$ 9,393.28	20.8	$ 234,831.98	20%	$ (41,565.15)	1.3%

With Tax Credit

	Initial Investment	Savings per year	Payback Period (years)	Total Savings	Return on Investment	Net Present Value	Internal Rate of Return
40 kW	$ 84,378.00	$ 6,216.38	13.6	$ 155,409.52	84%	$ 17,621.46	4.5%
48 kW	$ 101,598.00	$ 7,459.71	13.6	$ 186,492.85	84%	$ 20,802.29	4.5%
65 kW	$ 136,899.00	$ 9,393.28	14.6	$ 234,831.98	72%	$ 17,105.85	3.9%

With REAP Grant and Tax Credit

	Initial Investment	Savings per year	Payback Period (years)	Total Savings	Return on Investment	Net Present Value	Internal Rate of Return
40 kW	$ 54,243.00	$ 6,216.38	8.7	$ 155,409.52	187%	$ 47,756.46	8.5%
48 kW	$ 65,313.00	$ 7,459.71	8.8	$ 186,492.85	186%	$ 57,087.29	8.5%
65 kW	$ 88,006.50	$ 9,393.28	9.4	$ 234,831.98	167%	$ 65,998.35	7.8%

In order to determine whether installing a solar PV system is worthwhile to Halls, there are factors to initially consider. One of the main factors is payback time. If this project is something that needs to be paid back in under 10 years, then it may be best to not invest in a solar PV system at this time. Even with all possible grants and tax credits, the ideal systems take close to 10 years to pay for themselves. Otherwise all the systems project to say a payback period that is less than the warranty life of the system even without incentives. Another thing to remember is that the returns from this investment are found in the form of savings. This puts even more emphasis on whether or not there is available money because the investment will not generate new monetary returns on its own.

Something else to consider are that these numbers could be the best case scenario. If all the incentives are received, then all systems are good options. The payback periods are just under 10 years, the net present values of the investments are positive, and the investment will be more than doubled after the 25-year period. However, this data is just projections that could be better or worse in reality. The panels will likely produce less than expected and there are also chances of not receiving both incentives or receiving less grant money than 25%. Electricity prices could also drop which would lead to less dollar savings from using the solar PV system. This means that there definitely is some risk involved. A positive outlook though is that there is a chance that electricity prices could spike at any time, leading to greater savings during years that see a spike.

The other question to ask is what the most important outcome of this investment is; generating a substantial return or making the farm more energy efficient and environmentally friendly? If the investment potential of generating a substantial return is most important, then there could be a little too much risk involved with this investment. The net present value is only positive when all incentives are realized. If the net present value of the investment is negative, the investment still could generate a positive return. However, this means that the present value of the returns is less than the initial investment, so an equivalent amount of money to the present value of returns could be invested somewhere else in a better way.

A 25-year projection is a long period of time, so there is definitely some risk involved with this investment, but if there is more emphasis on energy efficiency and being more environmentally friendly then this investment could be made to work. All systems should be able to pay for themselves at some point in the 25-year system life. As far as which system to choose, it would depend on how much the electric bill is desired to be cut down. The 65 kW system will reduce the electric bill the most, but also has a higher starting cost and with less value for every dollar invested. Looking at the return on investment percentages, the 40 kW and 48 kW systems seem to have a better return for each dollar invested than the larger 65 kW system. Since the payback period and other metrics are very similar for the 40 and 48 kW systems, the 48 kW system is probably a better choice. It costs a little more but will cut down the electricity bill more while still seeing the same return for every dollar invested. The farm would be producing electricity at close to net zero and reducing its carbon footprint by using less energy produced from fossil fuels. If most of the incentives are realized, the investment should be able to pay for itself, through savings, in at least around 10 years.