A DIRECT COMPARISON BETWEEN A CENTRAL INVERTER AND MICROINVERTERS IN A PHOTOVOLTAIC ARRAY

A Thesis
by
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ABSTRACT

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More than 50,000 photovoltaic systems were installed in the United States during 2010 with a grid-tied capacity of 894 MW_{DC}, a 46% growth from the prior year (IREC, 2011). Increasing demand for clean energy along with federal and state incentives have expanded the solar market, but the high initial cost of photovoltaic systems is still inhibiting increasingly widespread adoption. Existing technologies are being continually refined to reduce cost and increase efficiency, while relatively new technologies such as maximizers and microinverters seek to advance new means of affordably generating solar electricity. These two recent additions to the PV marketplace saw shipments increase by 500% in 2010. While this is still less than 1% of photovolatic inverter revenues, projections indicate a 6% industry share by 2015 (IMS Research, 2011).

Microinverters clearly have an expanding role in the solar marketplace, but lack independent verification of industry claims pertaining to increased system performance. Third-party confirmation is critical to judging the efficacy of this technology, and determining the most cost-effective solutions for residential energy production.

The purpose of this study was to conduct an independent experiment on two photovoltaic systems, one with a central inverter and the other with microinverters, to determine their comparative performance characteristics in real, outdoor conditions. An unshaded existing array was retrofit for the two systems to operate side by side, and the power output of each array measured and recorded. This data was combined with daily irradiation measurements from a calibrated pyrheliometer and analyzed. After 30 days of initial testing, controlled shading was introduced on each system, and the experiment was then repeated.

This thesis presents experimental data that supports the conclusion that microinverters can outperform central inverters in both unshaded and shaded conditions. Within a 95% confidence level of the mean and for irradiance levels greater than 650 W/m^2 and less than 1200 W/m^2, the microinverter system produced an average of over 20% additional power than the central inverters, and in partially shaded conditions the microinverters exceeded the central system by an average of 26% more power.

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CHAPTER 1: INTRODUCTION

According to the U.S. Energy Information Administration (2011), 13.2% of U.S. energy produced from January 2011 though August 2011 came from renewable sources. As limited resources such as oil, coal, and natural gas become more expensive to extract and remain fraught with political and environmental risks, renewable energy production will continue to expand. Renewable energy sources are those that are constantly replenished, and will never run out, including wind, hydropower, geothermal, biomass, and solar. Among these sources, solar power can most readily be used in small-scale, residential systems for hot water, space heating, or electricity.

Photovoltaic (PV) panels or modules are used to directly create electricity. This electricity can be stored or, more commonly, sold back to the electric grid. Besides these solar panels however, you also need the “balance of system” components, including inverters, wiring, breakers, racking, and switches, which can account for up to half of a system’s cost.

When selecting an inverter to use for a PV system, there are currently two types of technology available: traditional central inverters, which invert the electricity from an entire array, and microinverters, which invert a single panel. Current research predicts that microinverters will serve more than 6% of the global PV market by 2015, with over 1 GW of residential and commercial installations by the end of 2013 (IMS Research, 2011). Enphase Energy is currently the leading producer of microinverters, and claims electrical energy gains of 5 - 25% when compared to traditional central inverter systems (Enphase Energy, 2010).

No third-party research has been published verifying the increased system efficiency reported from microinverter manufacturers such as Enphase.

To compare these two different technologies, a side-by-side comparison was conducted using as many identical system components as possible. Using an already existing solar PV system comprised of eight identical panels, one section of four panels was retrofit with microinverters. The other four-panel section used a traditional, appropriately sized central inverter. This efficient method reduced the number of confounding variables and overall cost of the experiment. Utilizing electrical current transducers connected to a data logger, measurements were taken over the course of 30 days to establish whether or not a difference exists between the power outputs of the two setups. After that initial testing, equivalent shading was introduced to each array to test how the systems perform with one panel on each system was 3% partially shaded. This second phase was recorded for 42 days.

By comparing the AC outputs of the unshaded and shaded setups and statistically analyzing the results, it was possible to determine if using microinverters increased the total power output of the system. This research and experimentation was designed to verify or refute the microinverter industry's claims of increased electrical power efficiency when compared to conventional central inverters. The results of this study were also intended to inform the solar system design of the Appalachian State University home competing in the Department of Energy Solar Decathlon 2011 competition, the Solar Homestead.

Statement of the Problem

Currently, there are no third party published findings available that pertain to the performance of microinverters in comparison to central inverters. The microinverter industry has released its own studies and predictions on increases in efficiency that their technology should create, but these results are unverified. Furthermore, microinverters are said to outperform traditional systems when no shading occurs, although no independently published comparisons are available to back this finding up either. It is unknown how much difference microinverters will be able to make in energy production, and the differences in energy production under shading and light debris conditions are unconfirmed.

The high cost of PV is the primary factor restricting more widespread adoption; determining how much more energy harvest, if any, can be expected with this technology may prove to reduce the economic payback period. Decreased simple payback periods could foster wider adoption of PV technologies, reducing our country's need for carbon-intensive energy sources.

Purpose of the Study

The purpose of the study was to establish the relationship between central inverters and microinverters with regards to instant power at a given irradiance. This study will validate or refute the performance claims made by the manufacturer about a relatively new technology. Besides informing PV design decisions of future Appalachian State Solar Decathlon teams, these results will be relevant to the design of similarly sized PV systems in residential or commercial settings.

Research Hypotheses

This research sought to confirm the claims made by manufacturers regarding the performance of microinverters compared to central inverters. This would be accomplished by establishing a definitive relationship between a central inverter and microinverters with regards to instant power for two situations: a system with unobstructed panels and a system with partial shading on one panel.

The data provided from advertised industry claims, the Enphase research, and the critical analysis of that information has led to the following hypotheses:

H1 When comparing unobstructed microinverter systems to unobstructed central inverter systems, the difference in power output will be less than 5% in favor of the Enphase microinverter system.

H2 When comparing a partially shaded microinverter system to a similarly shaded central inverter system, the difference in power output will be greater than 10% variation in favor of the Enphase microinverter system.

Definition of Terms

DNI – Direct normal irradiance is the amount of irradiation received by a surface that is always perpendicular to the sun's rays.

I-V Curve – A graph of the basic electrical output profile of a PV device, which shows all possible current-voltage operating points. A device can operate anywhere along the I-V curve.

I_{MP} – Maximum power current in amps is the operating current where the power output is highest.

Inverter – A device used to convert direct current (DC) electricity into alternating current (AC). In this paper, the inverters referenced convert the DC power from solar panels into grid-compliant AC.

I_{SC} – Short circuit current in amps is the maximum current of a PV device under no load or short-circuit condition and no voltage output.

Microinverter – An inverter that converts the DC output of a single PV module into grid-compliant AC power.

NEC – National Electric Code is a standard for the safe installation of electrical wiring and equipment, frequently mandated by state laws.

P_{MAX} – Maximum power point is the operating point of a PV panel where the product of current and voltage is highest.

POA – Plane of the array is the total irradiation (diffuse and direct) measured at a given angle, or plane.

PV – Photovoltaic, a device that converts light into electrical current.

THD – Total Harmonic Distortion is the ratio of the sum of all harmonic components in a waveform to the fundamental frequency component, which serves as a measure of sine wave purity.

UL – Underwriter's Laboratory is an independent product safety certification organization.

V_{MP} – Maximum power voltage in volts is the operating voltage when power output is at maximum.

V_{OC} – Open circuit voltage in volts is the maximum voltage of a PV device under infinite load or open-circuit condition with no current output.

V_{RMS} – Root mean square voltage in volts is the amount of power a sinusoidal signal is capable of providing. It is calculated by dividing peak voltage by the square root of two.

Limitations of the Study

This project was limited to a specific model of microinverter (Enphase D380), a specific model of central inverter (Sunny Boy 700U), and a specific group of PV panels (Sharp NE-170U1). Switching any of these devices, especially the inverters, may yield different results. Exchanging a comparable solar panel would likely yield results similar to this study, although this would require further testing to verify. This experiment was limited to eight panels in two systems of four panels each. A four-panel system is small scale, even for residential PV, and larger systems could potentially perform differently. Even if there were small energy gains or losses on each panel, those results could magnify, depending on the number of panels in the array. Slight manufacturing differences do occur between PV modules, even from the same silicon cell batch, and every attempt was made to measure and assure the equity of the two groups prior to experimentation and measurement. All panels were affixed to the same mounting rack, but it is possible that extremely minute variations in angle existed between the panels.

It is also worth noting that this experiment took place in a specific location (Boone, North Carolina at 36.2057N, 81.6585W), at a specific altitude (970 m), during a certain time of year (August 17 to October 27), and no attempt to control the insolation, temperature, or other natural elements was made, due to the fact that each group was exposed equally to these conditions. Repeating this experiment with different climatic factors could also impact the results, as temperature affects both voltage and amperage, and plays a role in both panel and inverter efficiencies. This experiment was also performed over a limited time frame; increasing the amount of measurement time would likely further enhance the reliability of the results. Long-term reliability is one of the primary issues facing all inverter manufacturers, and harsh outdoor environmental conditions take their toll on all electronics. This study made no attempt to predict the longevity of any electronic components.

The data analyzed in this experiment came only from the peak of the day, from 9:00 AM until 3:00 PM. This timeframe was used since the majority of irradiation falls during these peak sun hours and because the pyrheliometer used to record direct and diffuse irradiance received partial shading in the late afternoon. This is also one of the reasons why the power output was used as a basis of comparison rather than daily energy output.

All of these factors serve to limit the external validity of this study, or the extent to which the results gained can be generalized to other contexts. However, every attempt was made to maintain a high level of external validity by performing these tests in real-world situations, using a representative sample of products common in the PV market, and by soliciting peer feedback in the analysis of the methods and results of this experiment.

Significance of the Study

Prior to this study, there were no published third party studies directly comparing the performance of microinverters to traditional central inverters. This study sought to verify the industry's claims about the solar energy collection efficiency of microinverters. Evidence to support the industry claim of 5 - 25% increased solar harvest should be of great interest to system designers for applications such as the Appalachian State University team, along with any installers or consumers interested in investing in PV systems. Besides reducing manufacturing costs, decreasing payback periods is the best way for PV systems to become more affordable and increase widespread adoption.

CHAPTER 2: OVERVIEW AND LITERATURE REVIEW

Solar Photovoltaic Systems

Photovoltaic (PV) devices convert light energy, usually from the sun, into electricity. This is accomplished through the use of semiconductor materials, which are most commonly crystalline silicon (Dunlop, 2010). Silicon based PV panels come as monocrystalline cells, polycrystalline cells, or thin film ribbons. Individual solar cells are arranged in groups to capture the sunlight as a solar panel, and panels (modules) are combined to form an array. Panels are rated by the power they can produce at Standard Testing Conditions (STC): 1000 W/m^2 irradiance, AM1.5 spectral conditions, and a cell temperature of 25°C (Dunlop, 2010).

Solar cells create electric current through the unique chemical makeup of two types of crystalline silicon. The top side (facing the sun), the n-type layer, is comprised of silicon doped with a Group 15 element such as phosphorus, whose unique atomic makeup leaves a weakly bound valence electron. The bottom p-type layer is made up of silicon doped with a Group 13 element such as boron, which has an electron void. When light strikes the n-type layer, the energy imparted from the photons breaks free the extra valence electrons in the phosphorus, creating an electrical current. This current of electrons moves through a lattice of conductive metal wires that have been integrated into the cell layer. As the electrons pass through this wire and are drawn to the p-type layer electron voids, they perform work (Dunlop, 2010). This flow is direct current (DC), and it always flows in one direction, in contrast to alternating current (AC), where the current flows in both directions. AC is the most common form of household electricity in the United States.

There are generally three different types of PV system set-ups. The systems can be stand-alone (usually a DC system with battery backup), grid-tied (AC systems that are also called utility-interactive), or bimodal, which is a hybrid combination of both (AC power and DC backup energy storage). Over the past decade, the trend to install grid-tied systems has been growing in the United States, and in 2007 over 150 MW_{DC} of installed capacity was grid-tied; this was more than 75% of the total installed capacity that year (IREC, 2008). In 2010, over 95% of installed capacity was grid-tied, amounting to 894 MW_{DC}. Figure 1 shows how this raised the cumulative grid-tied capacity in the United States to 2.15 GW_{DC} (IREC, 2011). The growing trend of residential grid-tied installations is primarily due to the fact that most home electrical loads are designed to operate with AC power, and due to the widespread federal, state, and utility incentives for renewable energy generation (Sherwood, 2011). However, to get the DC power from photovoltaic panels into the widely utilized AC power, a critical conversion is required. To convert DC power into AC power, the use of an inverter is necessary.

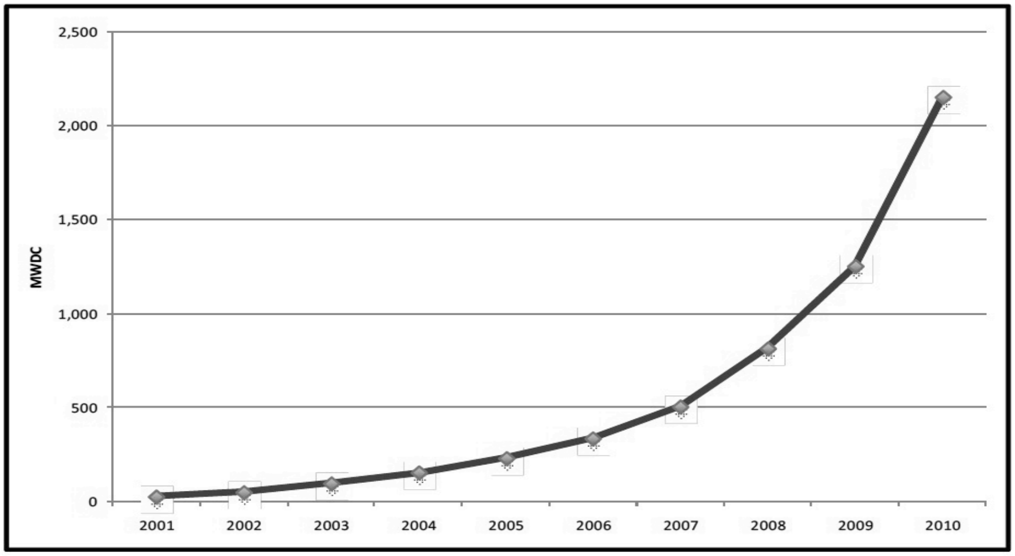

Figure 1. Cumulative U.S. grid-tied PV installations in MW_{DC} from 2001 to 2010. Reproduced from "*2011 Updates and Trends,*" by IREC, 2011, p. 18. Copyright 2011 by Interstate Renewable Energy Council. Reprinted with permission.

Types and Functions of Inverters

An inverter converts DC power drawn from PV arrays or battery banks into AC power for use on AC loads or export to the utility grid (Dunlop, 2010). The term “inverter” was initially derived from the action of inverting the constant polarity of DC into negative and positive voltages, causing the current to flow in alternating directions (Freitas, 2010b).

Different inverters produce various waveforms of AC power, including the low-quality square-wave, modified square wave, stepped sine wave, and pure sine wave. Waveforms other than pure sine wave result in poor operation of some AC loads and increased total harmonic distortion (THD), a measure of AC quality (Freitas, 2010b). The cheapest and lowest quality inverters often produce waveforms other than pure sine wave. These inverters are usually characterized by short warrantees, few safety precautions, low efficiency, lack of listings with Underwriters Laboratory (UL) standard, and lack of National Electric Code (NEC) compliance (Freitas, 2010b). This study will focus exclusively on grid-tied, pure sine wave inverters, but it is important to recognize that various qualities of inverter AC output waveforms exist.

Grid-tied systems require synching the inverter AC output with the 60 Hz sine-wave frequency of the U.S. electrical grid, and many inverters are even capable of providing lower THD than grid power. Although they are more expensive, grid-tied inverters are designed for permanent installation, provide safety systems to prevent “islanding,” and have longer warrantees, in addition to meeting NEC and UL requirements (Freitas, 2010b). “Islanding” is the dangerous, but exceedingly rare, condition in which a PV system continues to output power onto a utility grid that has gone down; this can be hazardous to line workers repairing the power outage. All grid-tied inverters manufactured in the Unites States and Europe incorporate anti-islanding systems to prevent grid feedback from occurring when the power is down.

Outside of AC waveform output, grid-tied inverters are also technologically rated by a number of other factors. These factors usually include maximum recommended PV input power, maximum power point tracker (MPPT) voltage range, efficiency, and PV start voltage (Mayfield, 2009). The maximum PV power rating tells a buyer what size system is the maximum the inverter can handle, while the MPPT voltage range indicates the area of input voltages where the inverter will perform best. A MPPT is a device, usually incorporated into an inverter's electronics, that is designed to boost the efficiency of a PV array by determining the electrical load applied to the array that will maximize the array power output (Cullen, 2009). Peak efficiency signifies the best efficiency that can be achieved in ideal conditions. Manufacturers also publish the helpful CEC (California Energy Commission) weighted efficiency, which is derived by testing the inverter at various DC voltage inputs (Mayfield, 2009).

There are many different methods to convert DC to AC power, but the most common method in the United States for grid-tied applications is through mixed-frequency sine-wave inversion. Christopher Freitas is an electrical engineer who works for *Home Power Magazine*, and he describes how mixed-frequency inverters convert from DC to AC:

> High-frequency switching transistors convert the DC source to a lower-voltage AC waveform. The transistors are switched at high frequency - hundreds of times per AC cycle or about 20,000 times a second. An inductor then smoothes the choppy, high-frequency wave form – creating a low-voltage sine wave. Then, a low-frequency

> transformer steps up the AC voltage to the required 120 or 240 VAC. (Freitas, 2010a, p. 109)

With this particular topology, or arrangement of electronic components, a pure sine wave can be created more simply and reliably than other methods (Freitas, 2010a). A typical inverter topology is shown in Figure 2. For these reasons, many popular inverters use a similar method, including the Outback FX series, the Xantrex GT and XW series, and the SMA Sunny Boy and Sunny Island series. These are some of the industry leaders in residential inverters, and their prices for grid-tied devices are around $0.72 per watt, with total prices ranging from around $1,600 to $7,000 per unit, depending on rated output (AEE Solar, 2010).

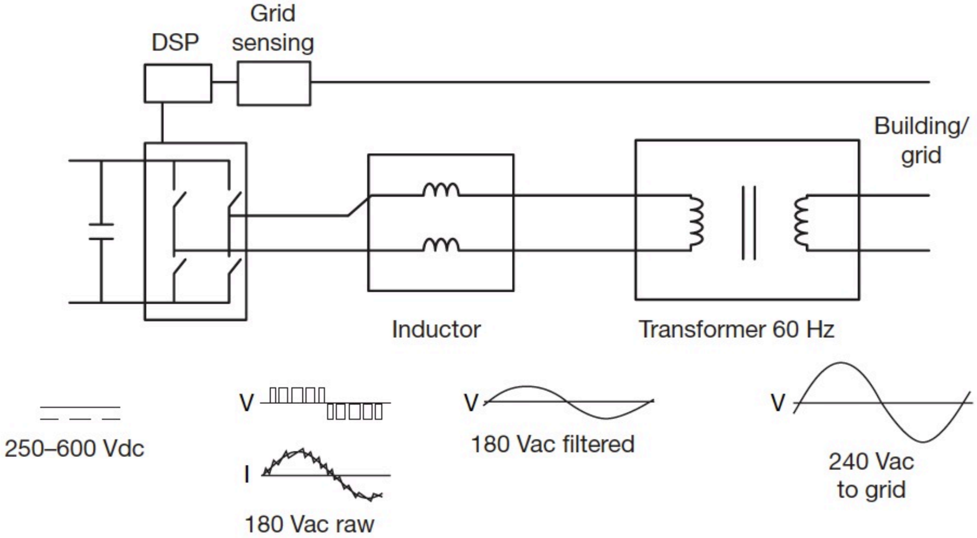

Figure 2. Topology of 60 Hz, transformer-based, single-phase inverter circuit. Reproduced from "How Inverters Work," by J. Worden and M. Zuercher-Martinson, 2009, *SolarPro*, p. 74. Copyright 2009 by Home Power Inc. Reprinted with permission.

Central Inverters

Traditionally, choosing an inverter for a residential system would begin with determining PV system size. This is frequently based on available funds, but can include examining historical electrical bills or creating a detailed listing of every electrical load in the house. By using a map depicting the sun hours in an area, one can select the appropriate power (wattage) and number of solar panels needed. Once the number of panels has been determined and the power output is known, an appropriately sized inverter can be chosen. Traditionally, a single inverter would be used to convert the entire PV array into grid-synced AC. This inverter can be placed indoors or be outside with some protection.

String sizing is an important step when designing a PV system with a central inverter. String sizing involves the creation of equal length “strings” of panels, wired together in a series. This is important in system design in order to make sure the sum of the solar panel DC voltages isn’t more than the inverter can handle or greater than the residential limit of 600 V_{DC}. For instance, ten 24-volt panels used with an inverter having a maximum input voltage of 160 V_{DC} could be organized into two equal strings of five panels. A setup like this would create two strings of panels, each operating at around 120 V_{DC}. Additionally, when sizing an inverter to an array, one must work off the worst-case scenario for highest voltage and current to ensure that the equipment is never damaged.

The leading central inverter manufacturer is Germany-based SMA Solar, with over 40% of the $6.9 billion PV inverter market share through their popular Sunny Boy, Sunny Island, and Sunny Central products (Wesoff, 2011). Other leaders include the U.S.-based Power-One with around 13% market share, Kaco New Energy (Germany), Frontius International (Germany), Satcon (U.S.), Schneider Electric (U.S. company that purchased

Xantrex), General Electric (U.S.), Sputnik Engineering (Switzerland), Advanced Energy (U.S.), and Solectria (U.S.) (Green World Investor, 2011).

Central inverters do require a dedicated space due to their larger size and because of the heat they can emit; many incorporate heat sinks and active fans. Since they are selected and sized for a specific PV array, these inverters do not readily allow for system expansion. However, the recent development of the microinverter has enabled arrays that don't require complicated string sizing calculations and can be much more flexible for the market segment that values expansion options.

Photovoltaic Microinverters

In the winter of 2008, Enphase Energy released its first microinverter, the M175, advertising the $200 device as a way to increase energy gains and reliability of an entire array (Enphase Energy, 2008). Since then, Enphase has released the M190, M210, the D380 that inverts two panels, and recently the M215; each of these is tailored for a range of panel outputs.

A microinverter is a much smaller device than a central inverter, and is mounted to the underside of an individual PV panel. These are then connected in parallel to the other microinverters in an array. When pre-mounted to a PV panel, the microinverter and panel are often referred to as an AC module (Masia, 2009a). A microinverter can accomplish the same tasks as a central inverter, including efficiently inverting DC to grid-synced AC, preventing system islanding, boosting efficiency through a MPPT, and meeting NEC and UL listing requirements.

One of the benefits of microinverters over central inverters is that they are extremely simple to install, potentially saving time and reducing installation costs. They attach to the racking behind a PV panel, the panel plugs into the microinverter, and a trunk line connects all the microinverters in parallel. The maximum number of potential connections is stated for each model, so no string sizing is required. This is safer since installers don't have to work with DC voltages that can potentially reach up to 600 volts: common 240 V_{AC} or 208 V_{AC} is used. Moreover, microinverters allow modules to be independent power producers, optimizing each panel regardless of how the rest of the array is functioning.

This modularity means that systems can be more flexible, because panels can gradually be added over time as budget allows. Panels can also be mixed and matched among different brands and models. Finally, microinverters transmit production data from each panel through the AC wiring; therefore, array analysis isn't limited only to total production (Masia, 2009b).

The basic typology of a microinverter is similar to that of many central inverters. The Enphase M190 microinverter can invert the 22 to 40 V_{DC} produced by a module into the 208 or 240 V_{AC} used by the building circuits. Seth Masia of *Solar Today Magazine* describes the process:

> The DC filter capacitors smooth out voltage ripple caused by the power conversion process, using pulse width modulation to create a half-sine current waveform. A transformer boosts the voltage of the pulse width modulator to match the utility voltage waveform. The output bridge "unfolds" the half-sine waveform to create a full sinewave, phase-matched to the utility AC voltage waveform. The output filter section removes residual switching ripple from the AC output waveform. (Masia, 2009b, p. 52)

The process closely resembles the mixed-frequency sine wave inversion described earlier, but the components and their housing must be much more robust than the central inverters. Microinverters are designed to take the harsh outdoor environment. They can be exposed to temperatures up to 150° Fahrenheit, face high humidity, rain, and sometimes, salt spray (Masia, 2009b). Some critics have questioned the reliability of the electrolytic capacitors used by Enphase, as opposed to the more commonly used thin-film capacitors, due to their potential for the liquid-chemical to degrade under long-term high temperature exposure (Wesoff, 2011). Enphase has countered these critiques with technical papers defending the specific capacitors, as well as with a unique 25-year, 100% uptime warranty on their microinverters.

The microinverter concept has been in the solar industry for many years, but it took advances in circuitry technology to achieve the necessary efficiency, reliability, and economy to make it viable and competitive (Everyday Solar, 2011). Since this technology is still new, long-term reliability remains one of the chief concerns preventing wider adoption. However, as mentioned previously, third party research indicates that microinverters will serve over 1 GW of residential and commercial installations by 2013 and comprise more than 6% of the global PV market by 2015 (IMS Research, 2011; Osborne, 2009).

While Enphase is the undisputed leader in the microinverter market right now, many other companies have released their own competing products, including Solar Bridge, Enecsys, Direct Grid, GreenRay, and Petra Solar. The microinverter market is also competing with DC-to-DC maximizers or optimizers, which are used in conjunction with a central inverter to optimize each panel. Leading companies include SolarEdge, Tigo, eIQ, and Azuray. Seeing the expansion of distributed optimization technology over the last few years, leading central inverter companies are entering the area too, with Power-One debuting its microinverter in the summer of 2011 and SMA's Sunny Boy 240 going on sale in 2012 (Wesoff, 2011).

Shading

PV systems are particularly sensitive to shading; a small amount of shaded cell area can significantly reduce power output. While PV installers avoid shading as best as possible, there are some instances when shading is unavoidable. When constructing arrays, series string sizing with central inverters can sometimes cause problems on roofs, where features such as chimneys, vents, trees, or irregular slopes may prevent multiple equal rows of panels from being installed at the same angle and with the same amount of sunlight exposure. Severe discrepancies in solar irradiance can skew the maximum tracking point and reduce overall efficiency.

Most solar panels do incorporate technology designed to limit the effect of shading on their power output. For instance, three internal bypass diodes are each connected to a group of 24 series-connected cells in Sharp's 72-cell panels. Bypass diodes are used to allow current to pass around a group of cells that are in reverse bias due to shading. Reverse bias is a condition in which reverse voltage causes power to be dissipated as heat through the module cells. This can permanently damage panels, but internal bypass diodes help prevent this by allowing the other cell series to deliver power, although at a lower voltage (Sharp Solar, 2010).

As stated before, nearly all inverters on the market today incorporate a MPPT into the product, which maximizes power production based on the PV array's power, or I-V, curve.

This I-V curve is “the basic electrical output profile of a PV device,” and it shows all possible current (I) and voltage (V) values a device is capable of producing (Dunlop, 2010, p. 129). The main cause of static losses in PV systems is local peaks in the array’s I-V curve; this means individual panels are performing differently in comparison to the rest of the array. Dirt, panel mismatch, or shading effects cause the array’s I-V curve to exhibit more than one maximum power point, and the MPPT algorithm is unable to track multiple curves simultaneously, resulting in lost efficiency (Solar Edge Technologies Inc., 2010). This performance reduction is sometimes compared to Christmas lights, where one malfunctioning bulb affects the entire string (Williams, 2011). With this in mind, if one panel becomes inoperable or reduces output due to damage or shading, the total array I-V curve shifts, and the central inverter MPPT reacts to the new curve. This will reduce the efficiency of the entire array output.

Microinverters have the benefit of being able to track the MPP on an individual panel’s I-V curve, as opposed to tracking the I-V curve of an entire array. This individual panel focus is where microinverters have their main competitive edge. Issues that would normally paralyze a central inverter -- such as shading, dust, or panel mismatch -- a microinverter system can readily adapt to.

Department of Energy Solar Decathlon 2011

In the spring of 2010, Appalachian State University was accepted to compete in the U.S. Department of Energy Solar Decathlon 2011. The Solar Decathlon is an international, biennial competition that challenges 20 teams to design, built, test, and operate a 1,000 square-foot, net-zero energy, solar powered home on the National Mall in Washington D.C.

Once set up on the National Mall, houses compete in ten contests, including: architecture, market appeal, engineering, communications, affordability, comfort zone, hot water production, appliances, home entertainment, and energy balance (U.S. Department of Energy, 2010). Each contest is worth 100 points for a total of 1,000 possible points. The goal of the entire competition is for the homes to exemplify energy-efficient design, cost-effective construction, and appeal to consumers.

During late 2010 and early 2011, a small group of students were working to develop and advance the concepts that were submitted in the original proposal from Appalachian State. This initial proposal was formed into Appalachian's final concept, the Solar Homestead. Some of the core ideals of the house are independence and flexibility; this is evident through the seven Outbuilding Modules (OMs), which capture all of the home's energy through a large canopy of bifacial PV panels. These OMs draw their inspiration from lean-to sheds, and can be organized in any number of ways and attached to any structure. This concept became reality in September 2011, but as it was being researched, the team looked for the best ways to capture every possible unit of energy and to develop the most efficient PV system possible within the design criteria. An OM rendering and the final connected OMs are presented in Figure 3.

Due to the unique nature of the OMs, there was the initial option of incorporating microinverters or installing a central inverter into the house or closet of an OM. The decision to use a central inverter would reduce the flexibility of the project, however, by preventing the possibility of any other combination of the seven OM arrays. A central inverter based system wouldn't affect the power generating ability of the Solar Homestead at the competition, but could limit the marketability of individual OMs. Using a central inverter would also mean that more attention would need to be paid to ensure appropriate wire size across the seven OM sections. For these reasons, we also considered the option of using microinverters. Microinverters would allow for any combination of OMs, and could also potentially produce more power than a central inverter if industry claims are correct. With such a highly competitive event, this decision needed to be based off of independent research that has proven this technology's effectiveness.

Figure 3. Individual OM rendering (left) and Solar Homestead photo on National Mall (right). Seven OMs combine to form the Great Porch and bifacial PV canopy, with three Kaco central inverters located in OM closets.

Ultimately, the decision that shaped the design of the Solar Homestead PV system, more than inverter choice, ended up being panel selection. The team decided to focus on a translucent canopy made of panels using solar cells encased in two-sided glass. With a limited selection of modules that met this criterion, the team picked Sanyo HIT 195 bifacial panels, which were incompatible with any existing UL listed microinverter at the time.

With a specific panel selection decided and microinverters excluded, this research was unable to inform the PV system inverter design for the Solar Homestead. In an effort to preserve some of the system modularity, three Kaco central inverters were successfully used between the seven OM sections. Due to the team's many successes at the 2011 competition, Appalachian State University is currently exploring participation in the Solar Decathlon Europe 2014 competition. This research aims to provide valuable insights into PV system design for future endeavors.

Prior Research and Experimentation

Currently, no third-party research has been published that has directly compared central inverters and microinverters. However, leading microinverter company Enphase has conducted its own surveys and tests to establish the comparative numbers. After Enphase reached Institute of Electrical and Electronics Engineers (IEEE) standards and the UL 1741 listing required to sell its inverter on the U.S. market, the company proceeded to conduct comparison tests (Larson, 2010). During a brief interview with an Inside Sales and Technical Support Representative from Enphase, a 2009 white paper, *Enphase Energy Value Proposition*, was recommended which details the comparison tests performed on their M190 microinverter. In August 2011, David Briggs and Mark Baldassari of Enphase Energy also released the results of their field study of 143 systems, *Performance of Enphase Microinverter Systems v. PVWatts Estimates*. Each of these studies provides valuable information, but can not unequivocally address the comparative performance between central inverters and microinverters.

Enphase Energy Value Proposition

The *Enphase Energy Value Proposition* commercial white paper describes three different tests that were done to examine the capabilities of the M190 microinverter. The first test describes a 24-module array of 175-Watt modules. The modules were connected in a checkerboard pattern, with every other module connecting to a traditional central inverter rated at 94.5% efficient. Using a power meter and a data logger, the performance was recorded over 12 weeks. During that time, the modules were also cleaned weekly. At the end of the period, the Enphase system produced 14% more energy than the central inverter system (Enphase Energy, 2009).

In the second test, a home system with 54 total panels was used, and the modules were not regularly cleaned over the 12-week period. Again, a checkerboard pattern was used with 27 modules on the Enphase system and 27 modules on the 96% efficient rated central inverter. The test results showed 7% more energy gained from the Enphase system (Enphase Energy, 2009).

The third test was conducted with two different setups to discern sensitivity to debris and module mismatch and was measured over one day. Sixty modules were divided into 30 modules for an Enphase system and 30 modules in strings of 10 for a central inverter rated at 96% efficient. In setup one, a single maple leaf was placed over a corner of a single panel in each system. This resulted in a 1% greater energy harvest by the Enphase system. Setup two involved the same system configurations, but with two identical pieces of larger cardboard debris on two panels of each system. The Enphase system captured 3.5% more energy than the traditional inverter (Enphase Energy, 2009).

These tests represent a limited initial comparison of central inverters and microinverters, but they do not fully back up Enphase's claims for an additional 5 - 25% energy gain. The highest energy gain realized during these comparisons was 14%. The first two tests also suffered from shading issues, which could seem to be biased towards microinverters, based on industry claims about shaded performance. While using a checkerboard pattern of panel connections would help control for shading, it is still not a fully unobstructed test, which could yield different results.

Additionally, although the brand of central inverters used is never revealed or detailed beyond their CEC rated efficiency, more technical information should have been given to confirm that these inverters were appropriately sized. The report also leaves lingering questions about how the strings were sized for the central inverter in tests one and two. Finally, the 1% gain in part one of test three falls within the measurement accuracy range of the Dent Instruments data logger that was used, meaning this could be measurement inaccuracy. For all of the reasons above, and because this study was not performed by an unaffiliated third party, the 5 - 25% claim and the results of these tests should be independently tested and verified.

Performance of Enphase Microinverters Systems v. PVWatts Estimates

In 2009, a study was released by Gostein, et al. and published in *Photovoltaic Specialists Conference* (PVCS). This study examined 480 different PV systems in Austin, Texas, between 2005 and 2008. The majority of these installations were residential with power ratings below four kW (IEEE, 2010). Using the National Renewable Energy Laboratory's well-known PVWatts energy forecasting program, the researchers set out to compare actual performance to predicted results from PVWatts, in order to discover underperformance or over performance trends. Each month's actual energy output was compared to the monthly PVWatts site estimate. The results of this comprehensive study showed that these PV systems, with central inverters, typically underperformed estimates by an average of 8% (Briggs & Baldassari, 2011).

In August 2011, Enphase energy released a study that built off of the work of Gostein, et al. This study looked at microinverter installations across the country, both residential and commercial, with an average size around 5 kW. Using the Enphase Enlighten website, which gathers data remotely from Enphase Envoy power meters, the monthly power outputs of 143 microinverter installations were analyzed. This collected data was then compared with the PVWatts monthly estimated output of each system, using the PV array design parameters gathered from the sites, such as module type, tilt, and azimuth. A derate factor of 0.77 was used, which did not adjust for any shading or wire runs from microinverter to the grid meter. Arrays were studied over an average period of 12 months, with a minimum period of six months (Briggs & Baldassari, 2011). Approximately half the installations are reported to have greater than 5% shading.

These results showed that Enphase microinverter installations outperform PVWatts estimates by 8% on average (108% performance ratio), with 76% of the sites outperforming estimates. The study by Gostein, et al. showed that the average performance ratio of central inverters was 92%, with only 36% of sites outperforming estimates (Briggs & Baldassari, 2011).

These combined studies are the most significant comparison central inverters have had to microinverters. This comparison is limited in some ways: all the central inverter systems were in Texas, all were installed prior to 2009, and all microinverter data was collected through Enphase equipment. However, together they show that on average, microinverters have the potential to outperform some central inverter installations by 16%, and oftentimes more. These results are displayed in Figure 4.

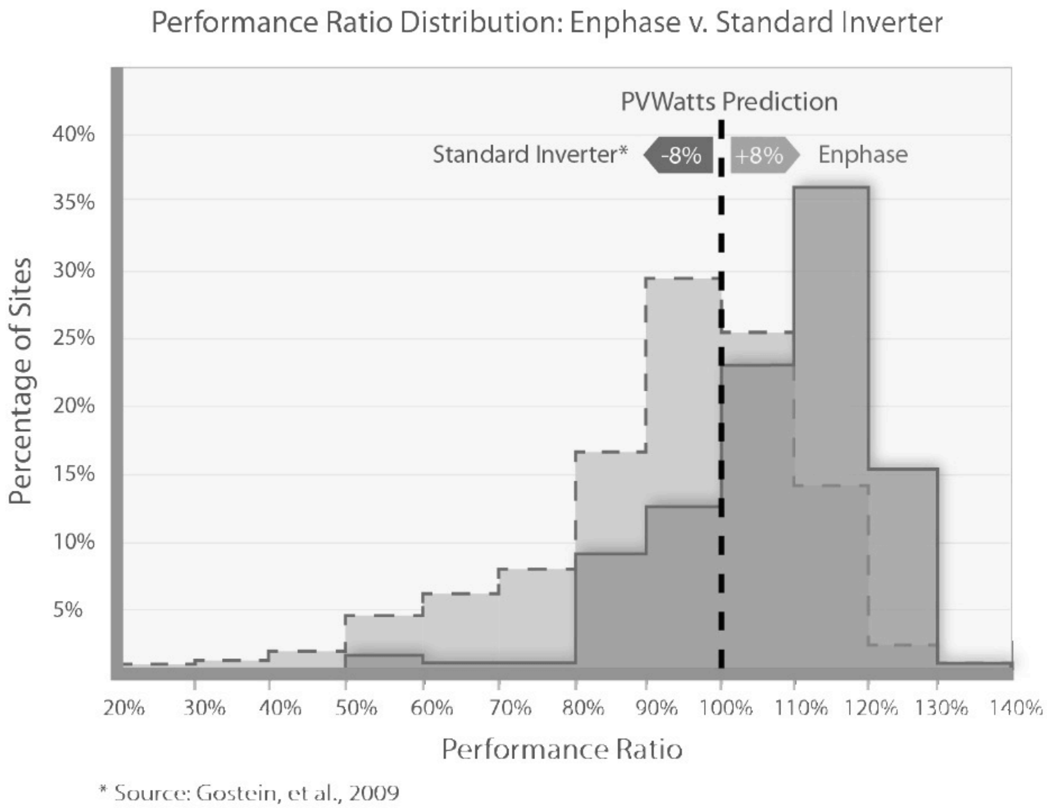

Figure 4. Comparative performance results between two separate studies. Reproduced from *Performance of Enphase Microinverter Systems v. PVWatts Estimates*, by D. Briggs and M. Baldassari, 2011, p. 3. Copyright 2011 by Enphase Energy Inc. Reprinted with permission.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

Research Methods

In order to maintain high external validity and reduce the overall cost of testing, this experiment utilized an existing installation as the foundation of the study. The location used was located at the Appalachian State University biodiesel plant and features an array of ten panels on a single, pole-mounted array. The rewiring of the PV system was done by the experimenter, and required the work of licensed electricians to complete the grid-tie.

This research used a nonrandomized control group pretest-posttest design. The original system consisted of ten Sharp NE-170 PV panels on site that were connected to a SMA Sunny Boy 2500 inverter. A detailed datasheet about the Sharp panel is available in Appendix A.

The first actions in this experimental design were to disconnect, clean, and pretest the Sharp panels individually to assess the equivalence of the panels and to determine that each one was functioning within normal parameters. This was accomplished by twice testing the V_{OC} and I_{SC} of each panel with a Tenma 72-770 digital multimeter. These tests confirmed the PV panels' average variation was 2.81% I_{SC} (0.15 A) and 2.07% V_{OC} (0.85 V), as shown in Table 1. This is well within the industry standard guarantee for modules of ±10% power output (Dunlop, 2010). A LI-COR 200SL pyranometer was used in conjunction with a second Tenma multimeter to record irradiance in the afternoon of a clear and sunny day.

Table 1. *PV Panel Comparison Test Results and Analysis of Eight Panels*

PV Panels Test 1

I_{SC}			**V_{OC}**		
Average	5.33	A	Average	40.8	V
Min	5.23	A	Min	40.4	V
Max	5.40	A	Max	41.0	V
Total Variation	0.17	A	Total Variation	0.6	V
Variation %	3.19%		Variation %	1.5%	
Standard Deviation	0.07	A	Standard Deviation	0.19	V

PV Panels Test 2

I_{SC}			**V_{OC}**		
Average	5.35	A	Average	41.1	V
Min	5.28	A	Min	40.6	V
Max	5.41	A	Max	41.7	V
Total Variation	0.13	A	Total Variation	1.1	V
Variation %	2.43%		Variation %	2.7%	
Standard Deviation	0.04	A	Standard Deviation	0.33	V

Total Average Panel Variations

I_{SC}	0.15	A	**V_{OC}**	0.85	V
	2.81%			2.07%	

After testing, the panels were divided into two linear groups of four, and randomly assigned to be either the central inverter group or the microinverter group by a coin toss. The panels comprising each of the two sets are compared in Table 2. While the microinverter array had higher variation among the panels' I_{SC}, it also had slightly lower average irradiance. As evidenced by these measurements, the four-panel arrays are nearly identical in performance, with their average I_{SC} varying by only 0.04 A and average V_{OC} by only 0.1 V.

Table 2. *Analysis of Each System's Eight PV Panels*

Central Inverter Panels

	Isc		**Voc**		**Irradiation**
Average	5.36 A		41.0 V		920 W/m^2
Min	5.33 A		40.6 V		910 W/m^2
Max	5.39 A		41.7 V		930 W/m^2
Total Variation	0.06 A		1.1 V		20 W/m^2
Variation %	1.12%		2.7%		2.17%
Standard Deviation	0.02 A		0.36 V		8.02 W/m^2

Microinverter Panels

	Isc		**Voc**		**Irradiation**
Average	5.32 A		40.9 V		904 W/m^2
Min	5.23 A		40.4 V		890 W/m^2
Max	5.41 A		41.3 V		910 W/m^2
Total Variation	0.18 A		0.9 V		20 W/m^2
Variation %	3.39%		2.2%		2.21%
Standard Deviation	0.07 A		0.29 V		9.16 W/m^2

The Sunny Boy 700U, with a maximum efficiency of 93.6%, was the central inverter to four panels in a series. This model is adjustable to different levels of DC input, and was configured to the middle 200 V_{DC} setting to ensure the system would MPPT most efficiently. Details about this operating range are available in Appendix B. The Sunny Boy was grid connected on a 120 V_{AC} line. It was located outside, facing north under a small awning, with an electrical line running approximately 45 feet from the PV array. Both DC and AC disconnects were used, and the entire system was appropriately grounded. The inverter and disconnects are show in Figure 5.

The unique location of the array required either 120 V_{AC} or single-phase 208 V_{AC}, whereas the majority of U.S. installations require 240 V_{AC} or three-phase 208 V_{AC}. Two Enphase D380 microinverters were selected in lieu of using four of the most widely used M190s, because each D380 can operate on a 208 V_{AC} single-phase connection. The 208 V_{AC}

three-phase microinverters were grid-tied with a single-phase 240 V trunk line, as recommended by Enphase. As the equivalent of two 190 W microinverters contained in a single enclosure, each D380 unit is able to invert two solar panels. The operating characteristics are detailed in Appendix C. Adaptors were used to change each solar panel's two MC connectors into TYCO locking connectors, which the D380s employed. These microinverters were mounted directly behind the PV array, and about 45 feet of electrical line connected them to the grid through an AC disconnect, close to the Sunny Boy. The panels and microinverters were grounded per manufacturer specifications. The installation is compared to the central inverter setup in Table 3, and Figure 6 shows the location of the D380s behind the solar panels.

Table 3. *Summary of Inverter Setups and Configuration*

Inverter	SMA Sunny Boy 700U on 200 V_{DC} input setting	Two Enphase D380 208 V
PV Panels	Four Sharp NE-170 Panels	Four Sharp NE-170 Panels
Grid Connection	120 V_{AC}	208 V_{AC} single-phase

All eight of the panels were on the same monopole structure facing due south with an approximate 36° tilt angle. There were no noticeable differences between panel mounting angles. This mounting structure appeared to expose each panel to the same ambient temperatures, because there was plenty of ground clearance. This initial testing and the random group selection were done to ensure the groups were equal and to help maintain the internal validity of the experiment. Figure 7 shows all of the panels on their monopole mount, as well as the shading strip across the panels of each system.

As stated in the limitations of the study, this sample included a specific type of microinverters, inverter, and PV panels. This means that the data may not necessarily apply to different brands of device or system setups, although the inverter brands chosen were selected because of their company's leadership in the market, their wide availability, and their ability to be replaced with mostly similar items.



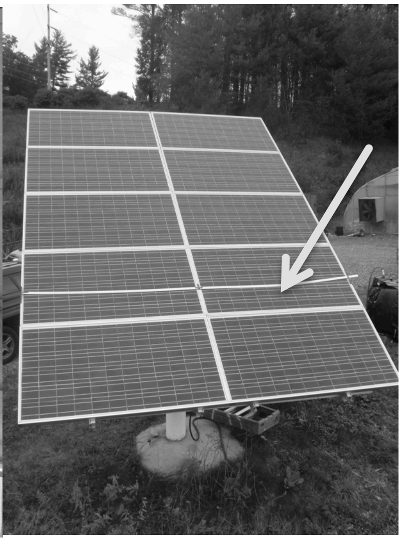

Figure 5. Photo of covered equipment mount area, with the SB700U central inverter, CR-800 data logger (white), and array disconnects.

Figure 6. Photo of the installation of D380 microinverters on the back right side of the array.

Figure 7. Photo of the south face of the PV array. The arrow indicates the 1" shading strip across the third line of cells in the lowest of the four panels used in each setup. The right side is the central inverter setup and the left side is the microinverters.

The central inverter and microinverters were compared in two different experimental variations. In phase one of the experiment, each array operated as normal, with no obstructions to the PV array. During phase two, however, a 1-inch wide, 3/16-inch thick, and 10-foot long strip of wood was introduced to establish 3.2% shading on the lowest panel of each array, but everything else remained constant. The shading strip was placed over the third row of 12 cells, which is the middle string and bypass diode. This shaded setup served to simulate conditions that may be experienced in real-world situations, such as shading from a roof exhaust vent, chimney, or tree branches, and is visible in Figure 7.

The first phase of the test, with an unobstructed array, began August 17, 2011 and ran until September 12. Starting September 13, phase two began with 3% shading on one panel of each array, and this ran until October 20. Conditions during the week of October 21 - 27 were sunny and clear, so the setup was switched twice to provide a few extra days to each configuration. There were a total of 30 recorded days for the unobstructed setup, and 42 recorded days for the shaded setup.

Data Collection Procedures

After random assignment to a microinverter or central inverter system, each set of four panels was connected to their inverters. Utilizing the Sunny Boy 700U set at $200V_{DC}$ and the Enphase D380s, each array had appropriately sized inverters connected.

On the AC connection side of each system, a 5-amp Magnelab SCT-0400-005 split-core current transformer was installed. These were used to monitor each array's current flowing onto the grid. On the Sunny Boy, this was installed on Line 1 inside of the inverter casing. For the D380s, the snap-on current transformer was installed inside the AC disconnect box, on Line 1 of the grid side of the switch. These sensors output 0.0666 V_{AC} per amp in a linear form, and have an accuracy of ±1%. Voltage was assumed to be a nominal 120 V for the central inverter and 208 V for the microinverters.

A Campbell Scientific CR-800 data logger was used to record the current measurements from both arrays. The logger box was mounted in close proximity to the Sunny Boy and AC disconnect for the microinverters, to provide short runs for the current transformers. The current transformer outputs an AC voltage proportional to the amperage measured. This differential voltage was measured across the current transformer for both the central inverter and microinverters, and the CR-800 program sampled data every 30 milliseconds, or 2000 times per minute. Every minute the program logged the maximum and minimum values over that timeframe. This type of sampling was done because the sampling rate of the data logger was not fast enough to capture the 60 Hz waveform output in one cycle (1.8 cycles/ 30 ms measurement). Measuring the current transformer voltage samples over a full minute allowed the peak voltage (V_{PEAK}), or sine wave amplitude, to be recorded in millivolts either as the maximum or absolute value of the minimum. The root mean square voltage (V_{RMS}), or the amount of power the AC current can provide, was then calculated by dividing the greater of the two measurements by the square root of two. The V_{RMS} was then divided by the current transformer's conversion ratio, 0.0666 V/A, or 66.6 mV/A. This calculation is shown in Equation 1 and yielded the AC current (I) from both PV systems. The main sections of the CR-800 data logger program are available in Appendix D.

$$I = (\frac{Vpeak}{\sqrt{2}})(\frac{1}{66.6})$$

Equation 1. Converting the CT AC output voltage in mV to current in amps.

In order to calculate power output during each one-minute interval, the current of each system was multiplied by its respective voltage. The central inverter current was multiplied by 120 V to transmute the value into the maximum power per minute. Since the 208 V single-phase connection had two lines that measure a 120 V difference between the line and neutral (L1 and L2), the microinverter current was doubled and multiplied by 120 V.

To collect superior irradiation, temperature, and humidity data, a Campbell Scientific CR-1000 logged information from a Hukseflux pyrheliometer. The pyrheliometer collected plane of the array (POA) and fixed direct normal irradiance (DNI) at 36°, the same angle as the array. The station also collected global DNI, global diffuse irradiation, ambient temperature, and humidity. The CR-1000 clock was synchronized to less than two seconds difference of the CR-800 power monitoring clock. This data was recorded in one-minute intervals and combined with the CR-800's power data. The pyrheliometer was located approximately 1000 ft. away at the Appalachian State University Solar Lab.

Data Analysis

Analysis began as each of the experimental tests was completed and the irradiation data was matched to the power production results. First, the data had to be combed through to remove any obvious problems. This included times when one set of values was missing, such as missing irradiance, or a skipped minute on power monitoring. The data was also initially trimmed back to only include 9:00 AM until 3:00 PM every day. This was done because the majority of irradiation occurs during this timeframe, as well as to remove the effects of the late afternoon shading issues the pyrheliometer experienced.

Following this initial data validation, the next task was recognizing and cleaning individual irregular moments. These included large positive or negative spikes in either of the three main data sets: irradiation, central inverter power, and microinverter power. If one of these changed drastically without any perceivable change in the other variables, it was removed. Figure 8 shows some examples of data points that were removed.

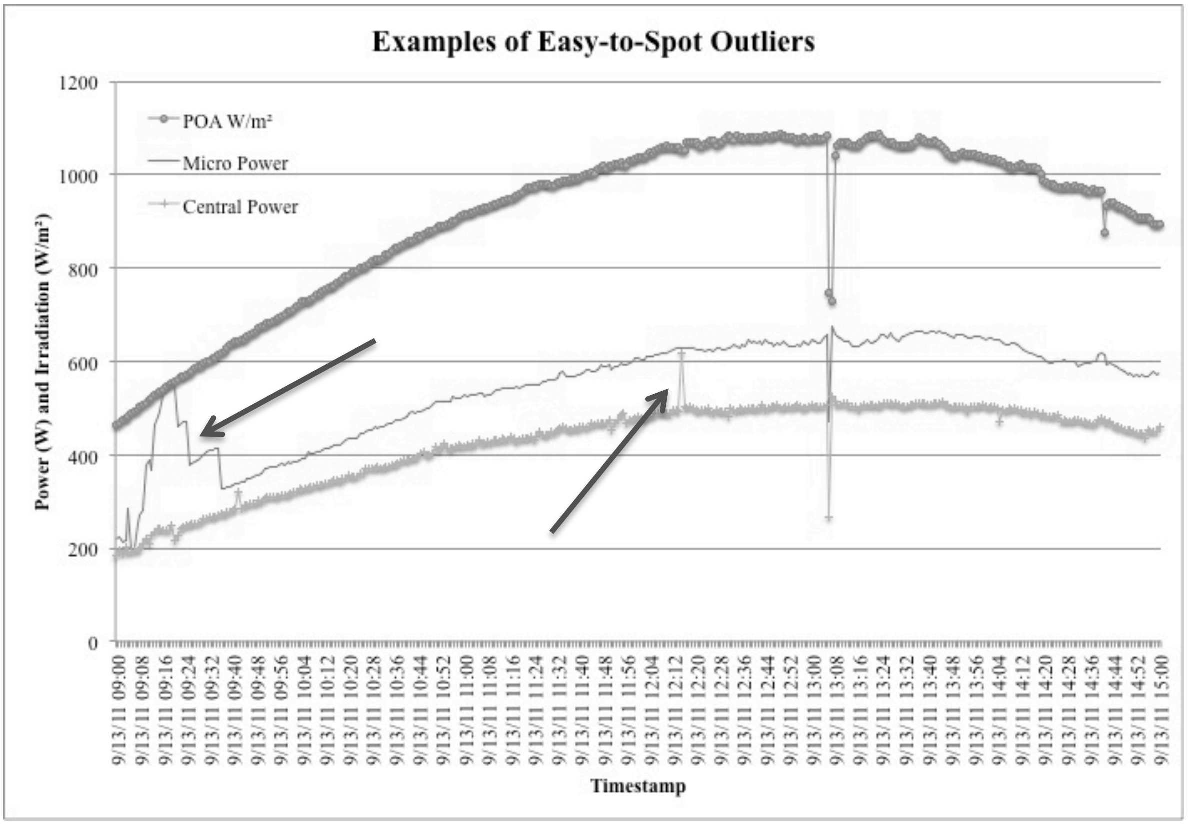

Figure 8. Chart of 9/13 irradiation, power output, and arrows indicating removed data points.

Figure 8 also shows the frequent phenomenon of the microinverter system power spiking around 9:00 AM. These instances were removed as they could indicate factors such as low-light microinverter "Burst Mode," or perhaps or grid voltage fluctuations, which are not indicative of the real power performance during that one-minute interval.

Most of the data points analyzed were much more complicated than Figure 8, and required a more in-depth review. It was critical that the irradiance and power didn't fluctuate too quickly, because swift changes often wouldn't register until the subsequent minute of measurements. If a given day of measurements had only a few quick changes in irradiance or power, the unmatched minutes were removed. Days rife with fluctuations frequently had to be removed entirely, such as October 20 shown in Figure 9.

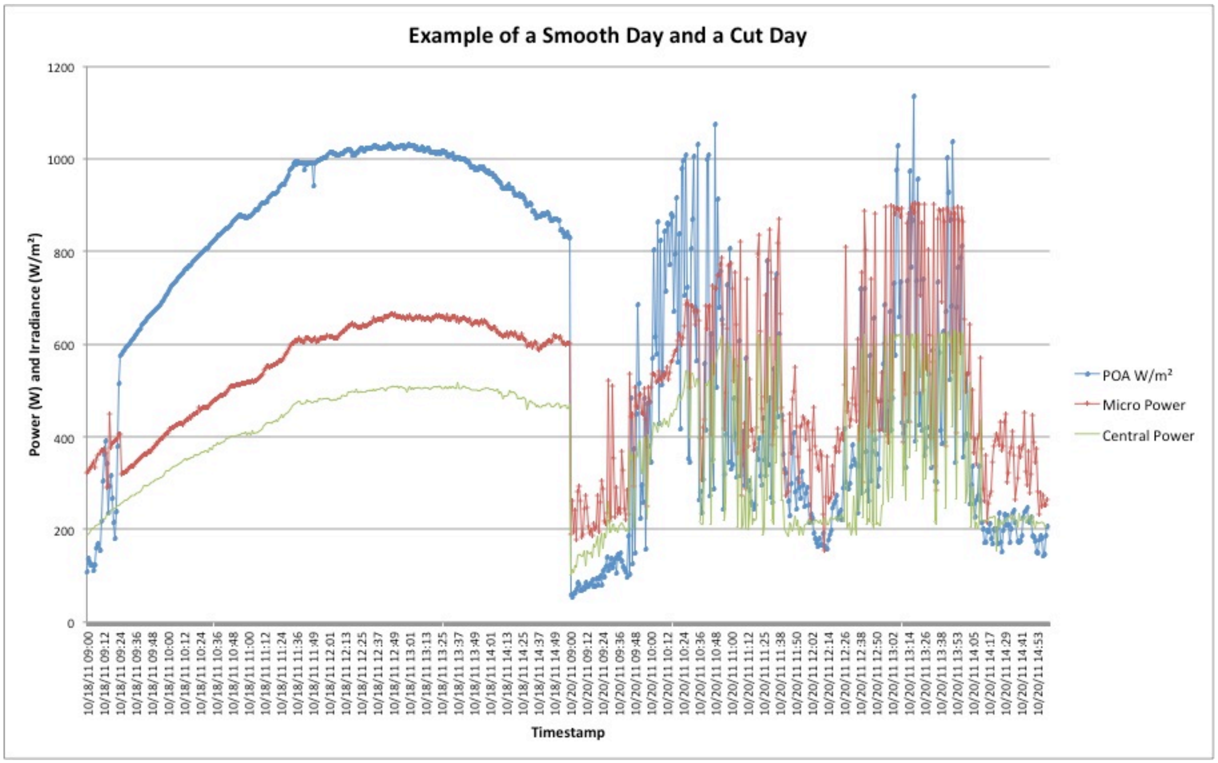

Figure 9. A day with slow changes in irradiance and a day with erratic fluctuations. October 20 was removed due to the amount of mismatch between the one-minute data points.

Table 4 is an example of a few minutes that were removed from the 8/18/11 data. These lines seem to indicate that at 12:59 the systems were producing 712 W and 578 W under less than half the irradiance from the preceding minute. These instances seem to be artifacts from fast-changing conditions in the prior minute, overlapping into the next measurement. In a process that was repeated hundreds of times, mismatched and overlapping data points were carefully analyzed and removed from the dataset. For this reason, days with slowly changing irradiance provided the most reliable information about comparative system performance.

Table 4. *Example of Removed Data Due to Mismatch*

Timestamp	POA (W/m²)	Microinverter Power (W)	Central Inverter Power (W)
8/18/11 12:58	1139	701.93	570.02
8/18/11 12:59	448.9	712.46	578.68
8/18/11 13:00	333.3	281.99	237.74

Removing the explainable issues from the collection left a cleaner dataset from which to perform some basic statistical analysis. After removing the most volatile timeframes, the unobstructed setup was left with 6,221 measurements, or 103.7 hours of data. The shaded setup contained 11,314 measurements, equaling 188.6 hours of data. To begin analyzing this data, POA irradiance was rounded into 10 W/m^2 bins, and a pivot table created the mean power of each system for each bin. The standard deviation for each bin and each system was derived from the distribution, and this was divided by the square root of the bin's number of data points (N) to determine the standard error of the mean.

With a standard error calculated for the mean power production of the central inverter and microinverters for each bin, a 95% confidence interval for the mean was calculated. By using t-values based off of each bin's degrees of freedom, or (N), the 95% interval was created for the central inverter system and the microinverters system at irradiance bins from 20 W/m^2 to 1200 W/m^2. The t-value, anywhere from 1.96 to 3, depending on N, was multiplied by the standard error of the mean to create the interval. Figure 10 shows the number of measurements, or N, and displays the four data sets with error bars representing the 95% confidence intervals. When there was a lower degree of freedom, or smaller N, broad confidence intervals resulted. Broad confidence intervals were also created when there were wide distributions of power production within each POA irradiance bin, which produced larger standard deviations.

CHAPTER 4: FINDINGS AND CONCLUSIONS

Results

By taking the means of all power production by the PV systems at a given POA irradiation bin, an accurate model for output can be constructed. This model has a 95% confidence interval (CI) without error bar overlap from 660 W/m^2 to 1200 W/m^2, and it is even more significant between 950 W/m^2 to 1050 W/m^2. The higher levels of confidence are derived from the larger amount of data at these irradiation bins; data point counts run from 123 to 370 per bin in this selection, as displayed in Figure 10. Below 660 W/m^2, larger and overlapping confidence intervals suggest more data is required to establish the relationship between the systems.

For these reasons, analysis of the data was done in different sections, with extra emphasis on the higher irradiance bins, since greater error bar separation is more significant. The higher irradiance values are also where most of the potential power is located. The evaluated irradiance bins are as follows: 20-300 W/m^2, 300-650 W/m^2, 660-1200 W/m^2, 900-1100 W/m^2, 950-1050 W/m^2. The data ranges from 650 W/m^2 and above are shown in Figure 11, and they can be evaluated with confidence to determine the comparative performance of each setup.

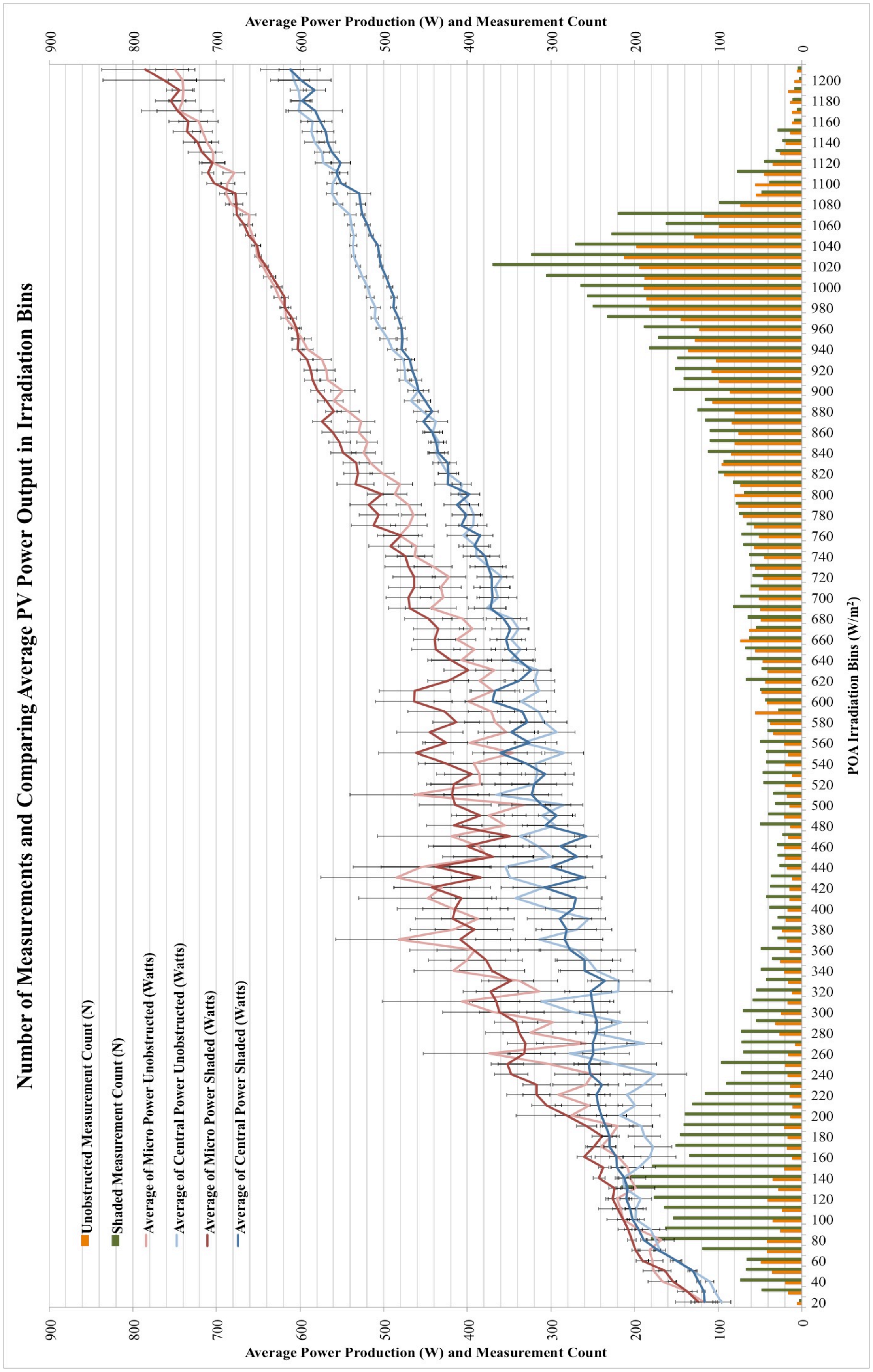

Figure 10. Average power produced at given POA irradiance and number of data points per POA bin. Average power error bars show 95% confidence intervals.

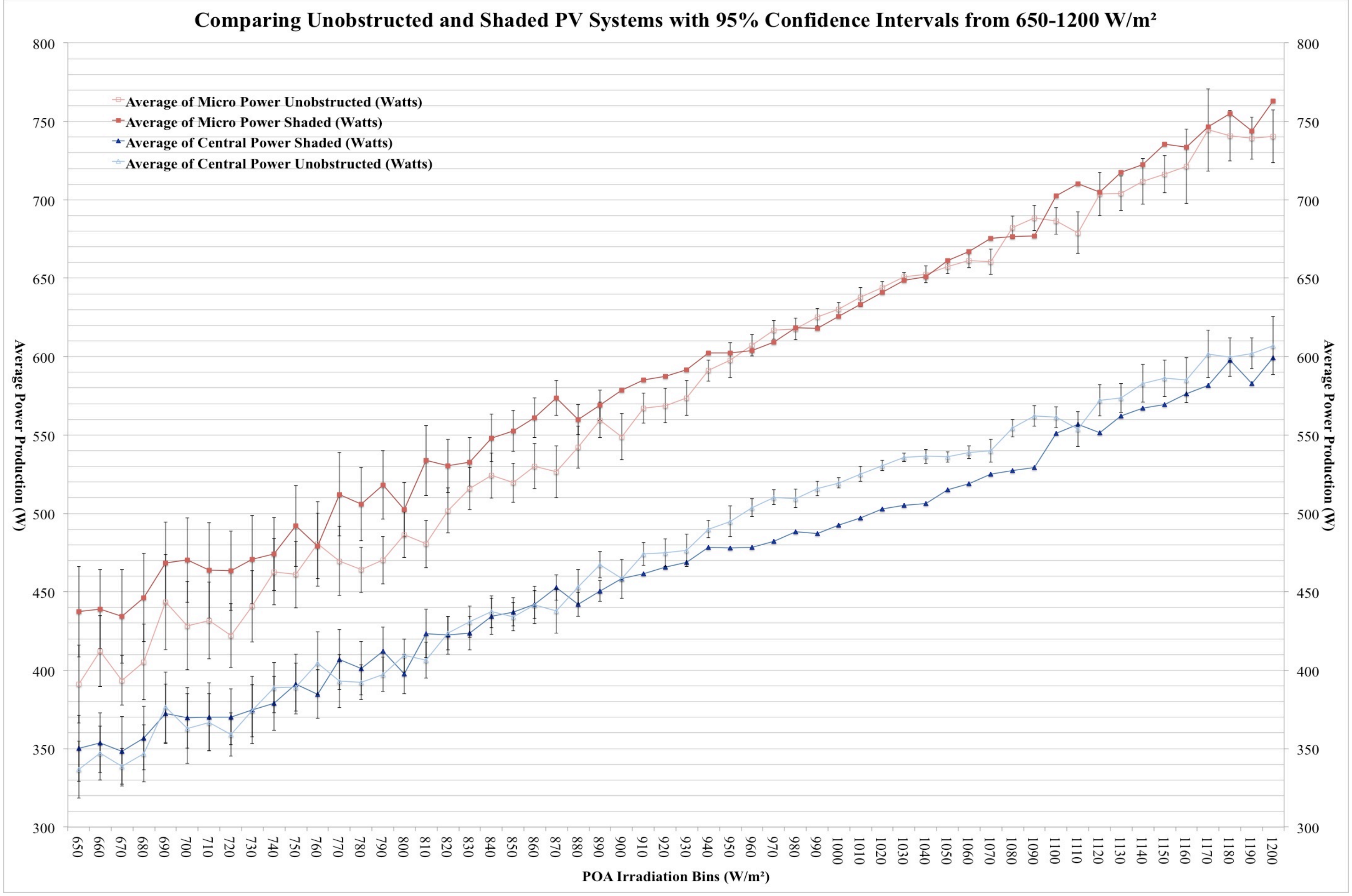

Figure 11. Chart comparing the power outputs of microinverters and central inverters. Error bars indicate 95% confidence intervals. Notice the bar overlap at 650 W/m^2, were comparative results become statistically insignificant.

Table 5 shows the unobstructed system's POA irradiation bins, the average microinverter power output for each of the irradiance levels, the average central inverter power output for each of the irradiance levels, the average difference between microinverter power and central inverter power from each one minute measurement, the uncertainty of that difference, and the average percentage of power difference. The average percentage power difference was calculated by dividing the micro/central power difference by the average central power output. The uncertainty of the power difference is the square root of the sum between the squares of the respective confidence intervals.

Table 5. *Unobstructed Average Power and Average Difference from 950-1050 W/m^2*

POA Irradiation Bins (W/m²)	Average of Micro Power Unobstructed (Watts)	Average of Central Power Unobstructed (Watts)	Average of Unobstructed Power Difference (Watts)	Uncertainty of Unobstructed Power Difference (±Watts)	Average of Unobstructed Power Difference
950	597.69	495.02	102.67	14.87	21.05%
960	607.36	503.62	103.74	8.92	20.61%
970	617.05	510.32	106.73	7.54	20.92%
980	617.58	509.53	108.05	8.95	21.28%
990	625.13	515.92	109.21	7.30	21.22%
1000	630.47	519.41	111.06	5.14	21.39%
1010	637.97	525.23	112.75	7.67	21.42%
1020	644.20	530.51	113.69	4.95	21.45%
1030	650.77	535.81	114.96	4.04	21.48%
1040	652.40	536.39	116.01	7.05	21.61%
1050	657.27	536.01	121.27	5.44	22.62%
Weighted Averages	**632.54**	**521.23**	**111.31**	**7.44**	**21.38%**

Table 5 shows that the average output of the unobstructed microinverter system from 950 W/m^2 to 1050 W/m^2 was 632.5 W, and on average it performed 21.4% better than the central inverter, with a 95% confidence interval between 19% and 23% increase in average power. The central inverter system in the unobstructed setup output an average of 521.2 W.

When the systems were shaded, the microinverter average power remained nearly the same as the unobstructed microinverter system for that irradiance range, providing 630.9 W, a 1.6 W difference. However, when the central inverter was shaded, power dropped to an average 495.5 W from the unobstructed 521 W, giving the microinverter system a 27.4% average power advantage. This relationship is shown in Table 6. In terms of power, the microinverters are creating an average of 111 W more power than the central system in unobstructed conditions and 135 W more during light shading. With only 3.2% of the panel's area shaded, or less than 1% of the total array area shaded, the entire central inverter array lost an average of 25.8 W, or a nearly 5% drop from average power output while operating between 950 and 1050 W/m^2.

Table 6. *Shaded Average Power and Average Difference from 950-1050 W/m^2*

POA Irradiation Bins (W/m²)	Average of Micro Power Shaded (Watts)	Average of Central Power Shaded (Watts)	Average of Shaded Power Difference (Watts)	Uncertainty of Shaded Power Difference (±Watts)	Average of Shaded Power Difference
950	602.38	477.96	124.42	9.73	26.18%
960	603.99	478.55	125.44	7.55	26.25%
970	609.43	482.26	127.17	6.77	26.40%
980	618.37	488.30	130.08	5.87	26.66%
990	618.13	487.22	130.90	5.61	26.99%
1000	625.82	492.58	133.24	5.71	27.09%
1010	633.25	497.20	136.05	5.34	27.38%
1020	640.85	502.88	137.97	3.96	27.46%
1030	648.81	505.35	143.46	3.78	28.40%
1040	651.07	506.48	144.58	4.94	28.61%
1050	661.44	515.07	146.37	4.62	28.43%
Weighted Averages	**630.86**	**495.46**	**135.40**	**5.81**	**27.36%**

These results are taken from a slice of irradiance bins, and the results of this range do not apply to the entire distribution. For instance, under 930 W/m^2 it becomes impossible to say with confidence that the shaded central inverter system is performing significantly better or worse than the unobstructed central system. The same goes for the microinverter system, which alternated between shaded and unobstructed, as the top average power producer at lower irradiation bins. This variation is due to broadening standard deviations of the mean and resulting confidence intervals. With more data, it would likely be possible to establish narrower CIs.

Although the systems had higher variability at lower irradiance levels, the 660 to 1200 W/m^2 samples exhibited many of the same characteristics of the 950-1050 W/m^2 irradiance bins. As shown in Table 7, unobstructed microinverters (579 W) outperformed unobstructed central inverters (490 W) by over 20%. The shaded microinverters in this range average slightly more power (597 W), and were 26.8% more effective than the shaded central inverters (471 W), similar to the other irradiation ranges. While average power was lower due to the range of lower irradiance bins included in the set, the average difference percentage between the two setups remained similar.

Table 7. *Average Power Production and Average Difference at Selected Irradiance Levels*

	Unobstructed		
POA Irradiance W/m^2	Micro Avg. Power (W)	Central Avg. Power (W)	Avg. Difference
20-1210	514.2	424.4	21.90%*
20-300	226.6	189.5	23.18%*
300-650	390.3	308.8	28.97%*
660-1200	579.2	490.0	20.46%
900-1100	626.7	516.6	21.33%
950-1050	632.5	521.2	21.38%

	Shaded		
POA Irradiance W/m^2	Micro Avg. Power (W)	Central Avg. Power (W)	Avg. Difference
20-1210	469.2	372.2	26.25%*
20-300	251.6	214.5	20.66%*
300-650	407.2	302.6	36.90%*
660-1200	597.3	470.5	26.83%
900-1100	629.2	494.3	27.29%
950-1050	630.9	495.5	27.36%

Note. * denotes a field where comparative performance conclusions can not be drawn. These irradiance groups contain data with overlapping 95% confidence intervals.

One factor that is important to mention is that the Sunny Boy 700U, the smallest grid-tied inverter SMA offers, has a lower rated maximum efficiency than the majority of central inverters on the market: 93.6% versus 96%. Since the majority of PV systems installed are larger than four panels, it is important to consider that a higher efficiency may be a more realistic estimate of performance. While inverters don't operate at maximum efficiency all the time, an increase of 2.4% power output by the unobstructed and shaded central inverter would create slightly different results within irradiance bins of 950 to 1050 W/m^2.

The unobstructed central system would hypothetically provide an average additional 11 W to produce an average 532.3 W. The microinverter system would only have 18.8% more power as compared to the measured 21.4%. On the shaded systems, the central inverter would, on average, produce an additional 10 W of power (505.8 W) and be 24.7% lower than the average microinverter power production. The original measurement was 27.4%.

This hypothetical scenario has decreased the percentage difference between the average power outputs of the two systems, but the microinverter system still produces more power than both the shaded and unobstructed central inverter systems by large margins for this irradiance range.

Conclusions and Discussion

The results of these experiments establish means and 95% confidence intervals that confirm increased array performance of the microinverters over a central inverter in both unobstructed and partially shaded setups of PV systems while irradiance levels were between 660 and 1200 W/m^2. By comparing the average power produced at each irradiation bin, as well as the average difference between the systems, it was possible to infer a definitive relationship between the PV systems. On average, the microinverter system was able to produce over 21% more power than the central inverter system at any given minute when POA irradiation was above 650 W/m^2. Within the same irradiance bins and with 3.2% shading on one panel of each array (0.8% total array shading), the microinverters produced an additional 97 W or 26.3% of power greater than the shaded central array. During this time, the shaded central inverter lost an average 52 W or 12.3% in comparison to the unshaded central inverter array.

By controlling for as many factors as possible and drawing from large sample sizes, this study has been able to maintain high levels of external and internal validity. While confidence intervals that allowed conclusions at every irradiance bin would have been ideal, these results apply to the range of irradiance that PV systems are primarily designed for. The compiled results were also able to achieve the goals set out from the beginning of the research.

Hypothesis one was rejected: the unobstructed microinverter and central inverter systems saw a difference in average power output greater than 5%. The results indicated that the microinverter power output averages were over 20% higher than from the central inverter at irradiance levels above 650 W/m^2. As explored in the hypothetical calculations, this number would likely be reduced if the efficiency of the central inverter were closer to the current industry standards.

Hypothesis two was accepted: the shaded microinverter system generated over 26% more power than the central inverter system, when irradiance was between 660 W/m^2 and 1200 W/m^2.

The results of the research seem to correlate both with industry claims about increased power from microinverters and with prior research, specifically the Enphase study relating their systems to the ones studied by Gostein, et al. in Austin, TX.

This independent research signifies that microinverters have the potential to produce more power under certain conditions. This additional power can decrease the payback periods for PV systems, and hopefully foster more widespread adoption and implementation of the technology. Increases in solar installations can potentially further reduce costs through economies of scale, in addition to reducing greenhouse gas emissions through offsetting traditional power sources.

Suggestions for Further Study

This experiment revealed important information about the comparative performance of two technologies, but there is still more research that could be done to provide more comprehensive knowledge of this emerging technology. This research didn’t examine the power variations caused by different ratios of diffuse and direct radiation. This would be valuable not only for a comparative study, but for the entire PV industry. Additionally, a long-term study examining the effect of temperature variations on a microinverter array output could provide insights.

Within this experiment there are a number of items that have been left unexamined, most notably power spikes from the microinverter system in the mornings, around 9:00 to 9:30. While these events took place below the irradiance levels examined in this study, determining if they are due to grid voltage fluctuations or due to the microinverters in “Burst-

Mode” at times with reduced irradiance could change the total daily energy production available from the system.

Finally, conducting the same experiment on a larger system could prove to be extremely valuable. In selecting an average-sized residential PV array, between three and five kilowatts, the latest central and microinverters can be used on a scale that could reveal further trends. Additionally, an experiment like this could include DC maximizers or optimizers to establish their value in MPPT individual panels and reducing the effects of shading.

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APPENDICES

Appendix A: Sharp NE 170-U1 Datasheet

SHARP®

solar electricity

170 WATT

MULTI-PURPOSE MODULE

NEC 2008 Compliant

NE-170UC1

MULTI-PURPOSE 170 WATT MODULE FROM THE WORLD'S TRUSTED SOURCE FOR SOLAR.

Using breakthrough technology, made possible by nearly 50 years of proprietary research and development, Sharp's NE-170UC1 solar module incorporates an advanced surface texturing process to increase light absorption and improve efficiency. Common applications include commercial and residential grid-tied roof systems as well as ground mounted arrays. Designed to withstand rigorous operating conditions, this module offers high power output per square foot of solar array.

Multi-purpose module ideal for ground mounted solar systems and the preferred solution for landowners.

ENGINEERING EXCELLENCE
High module efficiency for an outstanding balance of size and weight to power and performance.

DURABLE
Tempered glass, EVA lamination and weatherproof backskin provide long-life and enhanced cell performance.

RELIABLE
25-year limited warranty on power output.

HIGH PERFORMANCE
This module uses an advanced surface texturing process to increase light absorption and improve efficiency.

Sharp multi-purpose modules offer industry-leading performance for a variety of applications.

Improved Frame Technology

SHARP: THE NAME TO TRUST
When you choose Sharp, you get more than well-engineered products. You also get Sharp's proven reliability, outstanding customer service and the assurance of our 25-year limited warranty on power output. A global leader in solar electricity, Sharp powers more homes and businesses than any other solar manufacturer worldwide.

BECOME POWERFUL

170 WATT

NE-170UC1

NEC 2008 Compliant
Module output cables now 12 AWG with locking connectors

ELECTRICAL CHARACTERISTICS

Maximum Power (Pmax)*	170 W
Tolerance of Pmax	+10%/-5%
Type of Cell	Polycrystalline silicon
Cell Configuration	72 in series
Open Circuit Voltage (Voc)	43.2 V
Maximum Power Voltage (Vpm)	34.8 V
Short Circuit Current (Isc)	5.47 A
Maximum Power Current (Ipm)	4.90 A
Module Efficiency (%)	13.10%
Maximum System (DC) Voltage	600 V
Series Fuse Rating	10 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.36%/°C
Temperature Coefficient (Isc)	0.053%/°C

*Measured at (STC) Standard Test Conditions: 25°C, 1 kW/m^2 insolation, AM 1.5

MECHANICAL CHARACTERISTICS

Dimensions (A x B x C below)	32.5" x 62.0" x 1.8"/826 x 1575 x 46 mm
Cable Length (G)	43.3"/1100 mm
Output Interconnect Cable**	12 AWG with MC4 Locking Connector
Weight	35.3 lbs / 16.0 kg
Max Load	50 psf (2400 Pascals)

**A safety lock clip (Multi Contact part number PV-SSH4) may be required in readily accessible locations per NEC 2008 690.33 (C)

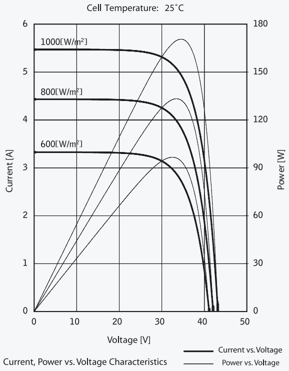
QUALIFICATIONS

UL Listed	UL 1703
Fire Rating	Class C

WARRANTY

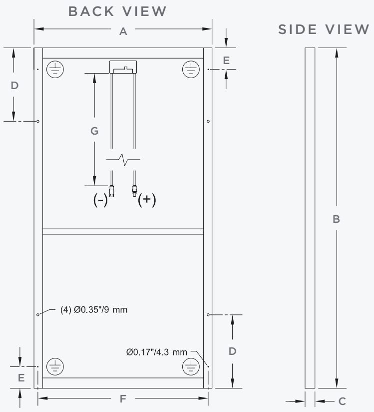
25-year limited warranty on power output
Contact Sharp for complete warranty information

IV CURVES



Current, Power vs. Voltage Characteristics

DIMENSIONS



A	B	C	D	E
32.5"/826 mm	62.0"/1575 mm	1.8"/46 mm	13.4"/340 mm	3.9"/100 mm

F	G
31.1"/790 mm	43.3"/1100 mm

Contact Sharp for tolerance specifications

SHARP ELECTRONICS CORPORATION
5901 Bolsa Avenue, Huntington Beach, CA 92647
1-800-SOLAR-06 • Email: sharpsolar@sharpusa.com
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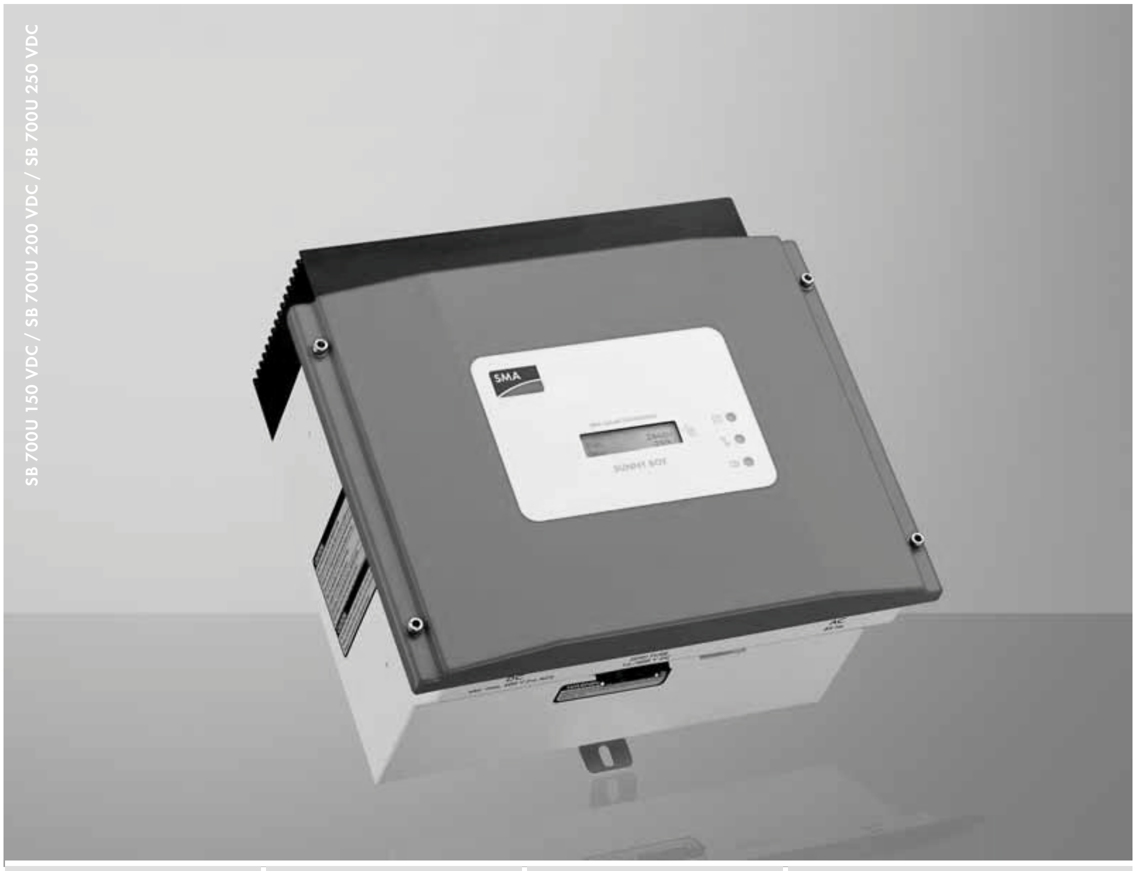
Appendix B: Sunny Boy 700U Datasheet

SUNNY BOY 700U



SB 700U 150 VDC / SB 700U 200 VDC / SB 700U 250 VDC

- 10 year standard warranty
- Rugged stainless steel enclosure
- Exceptional reliability and energy capture ratio
- Easy-to-install three-point mounting system
- Comprehensive communications and data collection options
- Modular string inverter design is easily expandable
- Certified to UL 1741/IEEE-1547

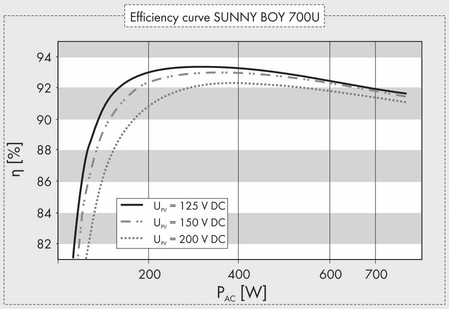
SUNNY BOY 700U

The versatile choice for any system configuration

The SMA Sunny Boy 700U was SMA's first mass-produced string inverter and it continues to enjoy immense popularity in today's solar market. Its compact size and economical price make it ideal for starter or demonstration systems. It is also perfectly suited for adding a bit more power to an existing solar system. Its modular design makes expansion to almost any size system easy. Three different configurable input voltage ranges make the Sunny Boy 700U a versatile choice, whatever your system configuration.

Technical Data

	Sunny Boy 700U (150 V_{DC})	Sunny Boy 700U (200 V_{DC})	Sunny Boy 700U (250 V_{DC})
Input Values			
Recommended max. PV power (modules at STC)	575 W	750 W	875 W
Max. DC voltage	150 V	200 V	250 V
MPP voltage range	77 V – 120 V	100 V – 160 V	125 V – 200 V
Max. DC input current	7 A	7 A	7 A
Max. number of fused string inputs	2	2	2
Output Values (AC)			
Nominal AC ouput	460 W	600 W	700 W
Max. AC output power	460 W	600 W	700 W
Max. AC output current	4.4 A	5.7 A	6.6 A
Nominal AC voltage / range	106 V – 132 V	106 V – 132 V	106 V – 132 V
AC frequency / range	60 Hz / 59.3 – 60.5 Hz	60 Hz / 59.3 – 60.5 Hz	60 Hz / 59.3 – 60.5 Hz
Phase shift	0.99 at nominal power	0.99 at nominal power	0.99 at nominal power
Efficiency			
Max. efficiency	93.6%	93.6%	93.6%
CEC Weighted Efficiency	91.5%	91.5%	91.5%
General information			
Dimensions (W / H / D) in inches	12.7 / 12.6 / 7.1	12.7 / 12.6 / 7.1	12.7 / 12.6 / 7.1
Weight / Shipping weight	51 lbs / 57 lbs	51 lbs / 57 lbs	51 lbs / 57 lbs
Ambient temperature	–13 °F to 113 °F	–13 °F to 113 °F	–13 °F to 113 °F
Power consumption at night	0.1 W	0.1 W	0.1 W
Topology	LF transformer	LF transformer	LF transformer
Cooling concept	convection	convection	convection
Mounting Location In-/Outdoor (NEMA 3X)	●/●	●/●	●/●
Features			
LCD	●	●	●
Communication: RS485	❍	❍	❍
Warranty: 10 years /15 years / 20 years	●/❍/❍	●/❍/❍	●/❍/❍
Compliance: IEEE-929, IEEE-1547,UL 1741, UL 1998, FCC Part 15 A & B	●	●	●
● Standard ❍ Optional			
Data at nominal conditions – Last update: March 2009			
Type Designation	SB 700U 150 VDC	SB 700U 200 VDC	SB 700U 250 VDC



Accessories

RS485 interface of type 485USPB-NR

Tel. +1 916 625 0870
Toll Free +1 888 4 SMA USA
www.SMA-America.com

SMA America, LLC

Appendix C: Enphase D380 Datasheet

ENPHASE MICROINVERTER D380

The Enphase Energy Microinverter System improves energy harvest, increases reliability, and dramatically simplifies design, installation and management of solar power systems. The Enphase System includes the microinverter, the Envoy Communications Gateway, and the web-based Enlighten monitoring and analysis website.

PRODUCTIVE

- Maximum energy production
- Resilient to dust, debris and shading
- Performance monitoring per module

RELIABLE

- System availability greater than 99.8%
- No single point of system failure

SMART

- Quick & simple design, installation and management
- 24/7 monitoring and analysis

SAFE

- Low voltage DC
- Reduced fire risk

MICROINVERTER TECHNICAL DATA

60 and 72 Cell Modules

The D380 “TwinPack” microinverters contain 2 independent DC inputs. The Input Data (DC) values below apply to both DC Inputs A and B individually

Input Data (DC)

	D380-72-2LL-S12/3 and D380-72-2LL-S12/3-NA
Recommended input power (STC)	230W
Maximum input DC voltage	56V
Peak power tracking voltage	22V – 40V
Min./Max. start voltage	28V/54V
Max. DC short circuit current	12A
Max. input current	10A

Output Data (AC)

	@208 Vac	@240 Vac
Maximum output power	380W	380W
Nominal output current	1.8A	1.6A
Nominal voltage/range	208V/183V-229V	240V/211V-264V
Extended voltage/range	208V/179V-232V	240V/206V-269V
Nominal frequency/range	60.0/59.3-60.5	60.0/59.3-60.5
Extended frequency/range	60.0/59.2-60.6	60.0/59.2-60.6
Power factor	>0.95	>0.95
Maximum units per 20A branch	15	10

Efficiency

Peak inverter efficiency	95.5%
CEC weighted efficiency	95.0%
Nominal MPP tracking	99.6%

Mechanical Data

Operating temperature range	-40°C to +65°C
Night time power consumption	50mW
Dimensions (WxHxD)	12.25” x 6.00” x 1.33”
Weight	6.25 lbs
Cooling	Natural Convection – No Fans
Enclosure environmental rating	Outdoor – NEMA 6

Features

Communication	Powerline
Warranty	15 Years
Compliance	UL1741/IEEE1547, FCC Part 15 Class B

Enphase Energy, Inc.
201 1st Street, Suite 300, Petaluma, CA 94952
877 797 4743 enphaseenergy.com

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Appendix D: Relevant Sections of CR-800 Data Logger Program

```
'CR800 Series
'Created by David M. Lee at Appalachian State University with assistance from Dr. Brian Raichle.

…

'DEFINE DATA TABLES $$$$$$$$$$$$$$$$$$$$$$$
DataTable(Minute2,True,-1)
        DataInterval(0,1,Min,10)
        Average(1,HalfBR,FP2,False)
        Average(1,Temp,FP2,False)
        Average(1,Irrad,FP2,False)
        Maximum(1,DiffVoltM,FP2,False,False)
        Minimum(1,DiffVoltM,FP2,False,False)
        Maximum(1,DiffVoltC,FP2,False,False)
        Minimum(1,DiffVoltC,FP2,False,False)
        Maximum(1,ABS(DiffVoltM),FP2,False,False)
        Maximum(1,ABS(DiffVoltC),FP2,False,False)
        Maximum(1,AmpM,FP2,False,False)
        Maximum(1,AmpC,FP2,False,False)
        Maximum(1,WattM,FP2,False,False)
        Maximum(1,WattC,FP2,False,False)
EndTable

…

'MAIN PROGRAM $$$$$$$$$$$$$$$$$$$$$$$
BeginProg
        Scan(30,mSec,1,0)
                VoltSe(DiffVoltM,1,mV250,5,False,0,250,1,0)
                VoltSe(DiffVoltC,1,mV2500,6,False,0,2500,1,0)
                'RUN CALCULATIONS
                AmpM=DiffVoltM*0.7071067812/66.6
                AmpC=DiffVoltC*0.7071067812/66.6
                WattM=120*2*AmpM
                WattC=120*AmpC

                CallTable(Minute2)
                CallTable(FiveMin2)
                CallTable(HalfHour2)
                CallTable(Hour2)
 NextScan
…
EndProg
```

VITA

David Meriwether Lee was born during the summer of 1984 in Shreveport, Louisiana to Charles R. Lee of Kilmarnock, Virginia and Anita C. Lee of Paramus, New Jersey. He is a lifetime member of the Society of the Lees of Virginia. After completing his work at Peninsula Catholic High School in Newport News, Virginia, David attended the University of Virginia. After graduating in 2006 with a Bachelor of Arts in Anthropology, he sought employment as a hang gliding instructor and spent time travelling. In the fall of 2009, David was accepted into the Department of Technology and Environmental Design graduate program at Appalachian State University. He became heavily involved in the Solar Decathlon 2011 project, and was Communications Manager for the Solar Homestead until its successful completion in October 2011. David is slated to graduate in December of 2011, earning a Master of Science in Technology, with concentrations in both Appropriate Technology and Building Science.

David Lee is a LEED G.A. and has passed the NABCEP Entry Level PV exam. He has been hired to work in a renewable energy and sustainability management position at Lowe's Home Improvement Corporate Headquarters in Mooresville, North Carolina beginning January 2012.