4-2019

Design & Evaluation of Cooling Systems for Photovoltaic Modules

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MER-497: Senior Project

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Fall 2018 & Winter 2019

Executive Summary

There is a persistent need for further development and implementation of renewable energy sources, such as wind and solar. Due to the increase in global population, the disappearance of fossil fuels, and the reality of climate change, renewable power is needed now more than ever. One such renewable power technology is solar photovoltaic, otherwise known as PV. These modules work via silicon cells which are as semiconductors, outputting electrical energy when incident with solar radiation. This is done by separating electrons and protons within the cell. One of the largest issues with PV technology is that there is a linear reduction in power production and module efficiency as the temperature increases, known as the negative temperature coefficient. Crystalline silicon solar cells are the leading standard and have a reduction in conversion efficiency of approximately 0.5% for every degree Celsius of temperature rise [1]. Additionally, the lifespan of a PV system is significantly reduced as a result of cell degradation due to excess thermal stress.

For this project, I have modeled, prototyped, and tested three cooling systems for PV modules. Two of the cooling systems are passive, non-power consuming. One simply consisting of a large aluminum heat sink centered on the backside of the module, and the other consisting of a combination of copper heat pipes and the same aluminum heat sink. The third system consisted of a water-cooling method where water was pumped over the working surface of the module from a reservoir, being evenly spread across the working surface through a perforated tube.

A successful cooling system, the module's electrical efficiency must increase significantly and have a low payback period. If the system is viable, I will seek to present my project at external conferences and look for possible publication in an appropriate journal.

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Introduction:

The use of photovoltaic (PV) modules for electric power generation has been steadily increasing, for a number of reasons: 1) Due to technological improvement, reductions in material cost 2) Government support for renewable-based electric power option 3) The declining amount of accessible fossil fuels 4) The growing acceptance of climate change as a real and present danger all life on Earth. All of these factors have caused a huge increase in the investment of renewable power options. Solar PV, photovoltaic, is just one of numerous promising renewable power generations methods. Unfortunately, PV cell technology performance is sensitive to operating temperature. Since power is generated via silicon cells which is a semiconductor material, outputting electric power when incident with solar radiation. Like all semiconductors as the operating temperature increases, the output voltage drastically decreases despite a slight increase in the output current resulting in an overall significant reduction in power production and module efficiency. Photovoltaics global potential, as a primary power source, is dependent upon designing more efficient PV systems. Creating immense interest within the scientific community in possible PV cooling over the last 40 years.

PV Technology & Temperature Versus Performance Relationship

Photovoltaics directly convert solar radiation into electricity. Each cell is comprised of layers of a semiconducting material, p and n-Type. When incident with light, the cell enacts an electric field between layers, resulting in an output voltage and current. The cells are either polycrystalline, made up of pieces from numerous silicon crystals, or monocrystalline, which are cut from a single large crystal. The monocrystalline cells have a greater conversion efficiency and cost. This presents an issue since current PV technology has relatively low conversion efficiencies, 6-20%. Meanwhile, the other 80-94% of incident solar radiation is converted to heat, greatly increasing the PV cell temperature, and lowering the efficiency [1].

The impact of the operating temperature on a PV modules performance has been well documented, where high temperatures significantly influence the power output. As displayed in Figure 1, an increase in temperature causes a slight increase in the current, but a substantial decrease in the output voltage resulting in a significant reduction in the power output for a given amount of solar radiation. This has been equated to a reduction in PV modules conversion efficiency of approximately 0.4–0.5% for every degree Celsius of temperature rise [2]. Additionally, the semiconductor effect itself produces heat, as all electronics do, so that also compounds this problem.

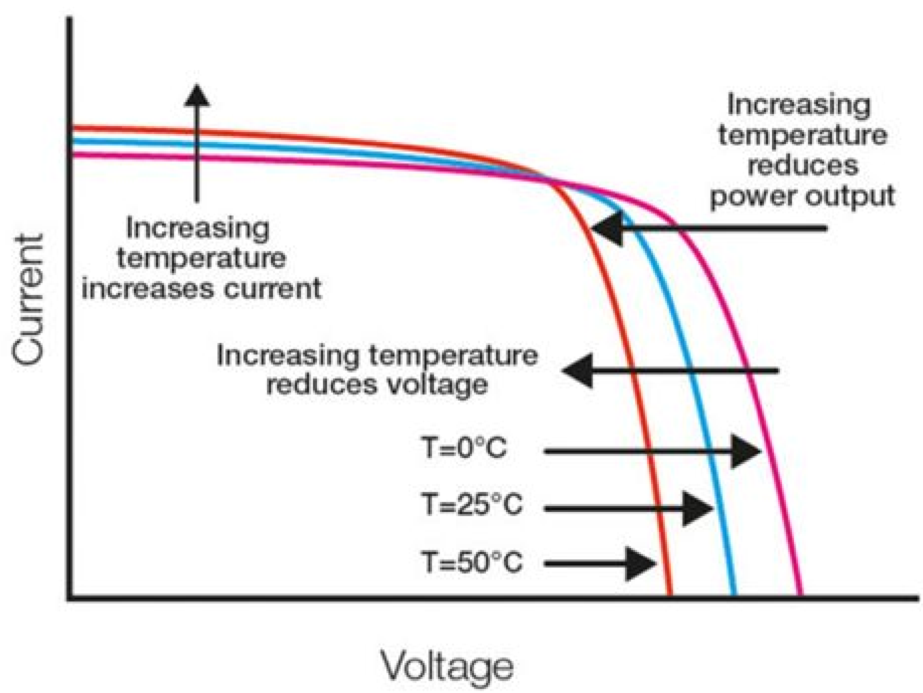

Figure 1. Temperatures influence on the output voltage and current curve for PV performance [3].

The parts of Earth with the most solar potential tend to have hot climates, showing an immense opportunity to increase Solar's global power production capabilities by cheaply and effectively lowering PV cell temperature. Dubey [1] researched temperature dependent PV efficiency and its effect on power production around the world, finding that PV performance is primarily a result of the PV material used and the climate conditions, where the difference between PV cell temperature and the ambient is greatly dependent on the wind speed, solar rather than the atmospheric temperature, showing the effectiveness of the natural from convection from the wind.

During the Fall term baseline module testing was performed outside, and a cell temperature that was 10 to 20 °C hotter than the ambient was observed. In addition, on a particularly cold Autumn day where the recorded cell temperatures were approximately 25°C below the panels specified nominal operating temperature, resulting in an observed conversion efficiency that was 6-12% higher than the one provided on the panel's specifications. Further, confirming the large influence of operating temperature on PV conversion efficiency.

High operating temperatures have also been found to greatly reduce the lifespan of the PV module. This is due to increased thermal fatigue, causing excessive stress in solar cells [4]. The quality of silicon PV material is the primary determining factor of the conversion efficiency and initial cost for a solar module, where one gets what they pay for. Additionally, a typical PV module warranty is 20 years, where 1% of degradation is expected each year. High temperatures greatly increase the stress on solar cells. It has been found, that if the same constant rate of incident solar radiation was applied "it would take four times as long at 65°C to cause the same amount of degradation as seen at 85°C" [5]. This approximately reduces the lifespan of the module to 5 years, with a 4% degradation each year. Further, revealing the opportunity for cost-effective PV cooling systems to increase global solar power production.

Challenges of Cooling PV Modules

Due to the significant influence of temperature on PV performance, much research has been dedicated to possible cost-effective ways to cool PV modules. PV cooling attempts have been researched as early as the 1980s, with a variety of methods and results. In recent years, the opportunity for refined PV cooling techniques has grown, as the cost of Silicon solar cells decreases, and the popularity of renewable energy increases.

The challenges for designing a cost-effective PV cooling system can be broken down into three different issues. The first is to understand and consider the numerous factors that influence cell temperature, and how they would affect potential cooling systems. The second challenge is the large surface area that needs to be cooled in regard to the relatively low power production per module. Additionally, a challenge in PV cooling is ensuring an even temperature distribution across the working surface, as hotspot increase degradation of the module. These challenges must be met if a cooling system is to be effective in optimizing cooling.

PV cell temperature is a function of the insolation received, wind speed and direction over the module surface, as well as the ambient temperature [6]. Despite these factors being largely out of human control, it is important to keep them in mind for designing a PV cooling system. However, the orientation of the module, as well as the location and components of the cooling system are in one's control. As a result, knowing the specifics of how these environmental factors influence cell temperature differently is vital to mitigate the retention of heat. The difficulty in cooling PV modules is that the cooling system must not significantly increase the overall initial cost, and effectively increase the efficiency to be worthwhile. If a system is designed without considering environmental influences the cost of system maintenance could outweigh the benefits of the improved electrical yield.

Additionally, one of the largest challenges with PV cooling is the large surface area with respect to the power produced. A single top-rated PV module would have an area of about $2\ m^2$ and a nominal power output around $335\ W$. As a result, approximately $6\ m^2$ need to be cooled for every kilowatt produced in the best scenario. Therefore, any large-scale solar project would require so much area to be cooled, that any effective cooling system must be extremely inexpensive, as to not noticeably drive up the system cost.

Furthermore, an even temperature distribution is important for PV performance so any cooling system must seek to disperse the heat evenly across the working surface. Hot spots in a PV system have an immense influence on the system's performance and lifespan.
Non-uniformity temperature across a PV module results in an increase in series resistance, and a decrease in conversion efficiency and the fill factor [4]. Additionally, most conventional cooling mechanisms result in a variation in temperature across the working surface.

In summary, cost-effectively cooling PV modules present a number of difficult challenges that have led to the ongoing research in this field, further opportunity for improvement. As recently, published as of October 2018 to as far back as 1981, research studies have been dedicated to PV cooling.

Project Overview

The goal for this project was to investigate the potential for cost-effective PV cooling systems, by comparing three prototypes that were constructed and tested. Two of the prototypes cooled by passive means, non-power consuming cooling. One utilized a large aluminum heat sink, centered on the back of the module. Next, copper heat pipes were added in addition to the aluminum heat sink, to further explore the possibility of passive cooling. Lastly, for comparison, a rainwater cooling system was prototyped, which consisted of a submersible pump, small reservoir and a perforated tube secured to the top of the module to evenly spread the water across the working surface. It is important to note that these prototypes were tested on only a mono-facial module, but could be easily implemented on a bifacial module as well. A bifacial PV module has cells exposed on both sides, in doing so it doubles the PV working surface without taking up any more volume, and are often used in concentrating PV systems via using of reflectors and lens. Due to the increase in power generation per unit area, bifacial PVs deal with an exacerbated amount of heat when operating as compared to mono-facial. However, due to limitations of resources and time, it was decided to focus on mon-facial cooling for this project. The decision was made to test and compare these three systems because each has a great potential to cost-effectively cool PV modules due to their relatively low cost, high heat transfer rates, and low maintenance. Completing the project in hope, that future designers can recognize the most promising cooling method so that it can be further refined and implemented.

What to Expect in the Following Sections

The remainder of this report contains a Background, Experimental Procedures, Results and Analysis, Discussion of Results, and Conclusion with recommendations. Additionally, References and Appendices are provided after the main body of the report.

The Background section provides a breakdown of previous PV cooling methods and studies. Documenting the effectiveness of each, which was utilized to select promising cooling techniques that were investigated in this study. As well as, to provide guidance for where further improvements can be made to refine different methods, and how to properly test PV modules.

The Experimental Procedure section includes the materials and methods used to test the prototypes. Reviewing the means of data collection and data analysis. Additionally, this section includes images of the test setup, and of the location of thermocouples for each prototype tested.

The Results and Analysis section consists of tables summarizing the raw data for all module testing and the cooling effectiveness of each design. Furthermore, this section provides an in-depth performance and cost analysis of each, and summarize the results for each design. Complete with payback year, life-expectancy, and increase in power production per unit area. The Results and Analysis section will be followed by the Discussion of Results section.

The Discussion of Results section explains precisely what was learned, provides a comparison of the designs and the relevance of the results. All three were compared to each other, as well as to the results of some previous PV cooling systems studied.

Lastly, the Conclusion section serves to restate the problem, further summarize the findings. Additionally, this section provides recommendations for future work and concludes the study. The Conclusion section is to be followed by References and Appendices.

Background:

This section of the report will aim to explain what has previously been attempted pertaining to PV cooling systems, as well as, provide further insight into the basis for present work. The Background consists of four subsections: Previous Research & Work on PV cooling, Effective Parameters & Test Setup Options, and The Basis for Present Work: Comparative PV Cooling System Study. Respectively, each section provides further detail about past PV cooling attempts, established module testing techniques and factors, the purpose and specifications for the current project, and functional success metrics for the heat pipe and water-cooling systems to be prototyped.

Previous Research & Work on PV Cooling

In recent years many have attempted different methods to effectively cool PV modules, resulting in a number of different findings. Effective systems should be designed to produce a uniform temperature distribution across the entire working surface, keeping cell temperature at its minimum. Previous studies to cool PV modules can be broken down into two categories. Active methods, that consume power and Passive methods which don't. Active methods utilize pumps and fans to implement forced convection across a module. Passive methods consist of non-power consuming methods such as heat sinks, and thermal photovoltaic systems (PV/T), a combination of PV and solar thermal. At large, all of these different cooling methods have downfalls but have promised to be refined for widespread use. In this section, previous PV cooling work pertaining to pump and fan-driven active cooling, passive water cooling, PV/T systems, phase change material (PCM) cooling, and heat pipe/sink passive cooling are to be presented and analyzed.

Active cooling methods consume power to apply forced convection over the PV working surface. Air or water-based cooling, respectively utilizing fans or pumps to drive the flow. Mazón-Hernández in [7] investigated forced air convection cooling, utilizing fans to cool the backside of roof-mounted PV modules, the test setup can is presented in Fig.2. An overall increase in efficiency of 2%, and a maximum decrease in cell temperature of 15°C, where the distance between the module and the roof, air mass flow rate, and the ambient temperature were found to greatly influence the performance of the system. As for water cooling, the flow can be applied to either the front or back side of the module. The authors in [8], reported on ten past PV water cooling studies concluding that front side cooling is preferred where around 20% increases in efficiency were standard. The driving factors for the cooling effect of water-cooling systems are flow depth, mass flow rate, and water temperature. Also, the power consumed by the pump has to be minimized for practical systems. Overall in these studies, water has been found to be the preferred working fluid, due to its high thermal capacity [8]. The downside of these systems is clear, as any power consumption is counter-intuitive to optimizing the amount of stored power. Questions arise if the same cooling effect could be accomplished passively. Despite this, some of these systems have been found to be cost-effective in increasing conversion efficiency.

Figure 2. Forced air cooling [7]

Passive water-cooling methods, where forced convection is implemented without power consumption or cooling through conduction with passive heat transfer devices. For convection cooling, water is the preferred working fluid, where the flow is most commonly driven by gravity. Submerging studies have had limited success, as insolation intensity drops with depth, where a depth of 4 cm in 30°C water yielded an 11% increase in efficiency [9]. There is not a large amount of published research on gravity-driven PV water-cooling since these systems are very location specific with a need for a raised rainwater reservoir on a hill or roof above the modules. Despite this, all that is stated above for the effective parameters for active water-cooling can be applied to gravity-driven flows. One intriguing, study prototyped a rainwater cooling system that utilizes a gas expansion chamber to drive the flow over the modules as the gas expands at high temperatures. A schematic of this system is shown in Fig.3. the schematic to the left. This idea of a vapor chamber driven came from scientific paper

Passive cooling technology for photovoltaic panels for domestic houses, written by Shenyi Wu and Chenguang Xiong, and published in the International Journal of Low-Carbon Technologies [10]. Currently, frontside water cooling of PV modules is one of the most promising of cooling options so one has been prototyped and analyzed for this study.

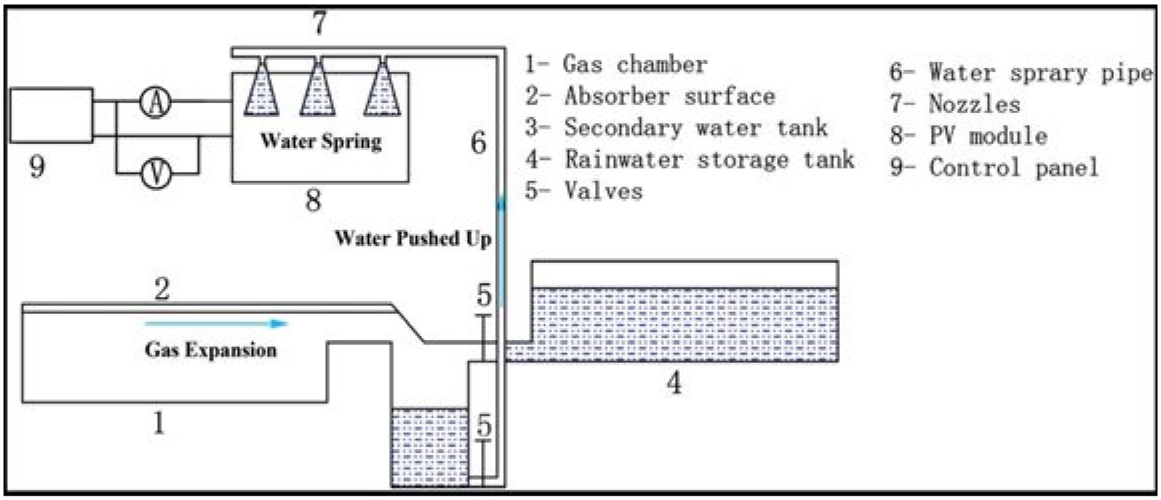

Figure 3. Passive rainwater cooling system for domestic houses [10]

PV/T systems look to improve efficiency by combining photovoltaics and solar thermal. Chandrasekar and company in [11] tried to cool down the PV cell with a thermosyphon effect, Fig.4. A PV silicon module, with a total area of 0.260 m^2 was used, with a copper sheet and tubing installed on the back of the module, and a thermosyphon water system with a water capacity of 80 liters. The increase in relative efficiency gained was 19 %. Chandrasekar et al. Proving thermosyphons, much like the gas expansion chamber aforementioned, can effectively drive the flow of water when heated by the sun. However, scaling this system would present cost issues with the number of materials needed for thermosyphon cooling. Others have tried to mitigate high PV cell temperatures while simultaneously storing solar thermal energy. However, it has been noted in [10] that these PV/T require higher operating temperature in order to supply useful heat, as a result, the gain by cooling is limited. Furthermore, a higher initial investment than other cooling options and since the overall increase in system efficiency benefit with PV/T technology is contributed to thermal energy rather than electricity [12]. This renders the PV/T is not an effective technology for the original purpose. Therefore, finding a simple and feasible way to cool the PV module without requiring further energy input is still much sought after [10]. These systems often result in a slightly more efficient system overall than other options, but the PV and solar thermal components independently are less efficient in a PV/T system. This is due to the high operating temperature of the thermal system needed to be effective. Other issues stem from the complexity of these systems, requiring regular maintenance and large initial investment.

Figure 4. PV/T with Thermosyphone[11]

Phase Change Material (PCM) cooling utilizes phase change materials like paraffin wax to lower PV cell temperature. PCMs, have high heat capacity, maintaining the same temperature as the material changes phases from solid to liquid. Figure 5, displays paraffin wax, and aluminum shavings that were used to cool the back of a PV module [13]. Additionally, vertical aluminum fins were mounted to enhance conduction. The power gain was higher by 9.7 % than that from a reference PV module [13]. In [14] authors presented a decrease of 15 °C with the right PCM material for a period of 5 hours, at insolation of 1000 W/m^2 , with 50 mm of PCM material from the back. The issue with PCMs is that they only absorb the heat, so once they heat up their cooling ability is rendered useless. The PCMs would eventually, in the afternoon, heat up to up to the point where it actually heats ups the panel rather than cool it.

Figure 5. PCM and Aluminum shaving used for PV cooling [13]

Heat pipes are a promising passive cooling technique for PV modules and frequently used to cool a number of electronics, such as computers. Heat pipes are a heat transfer device, consisting of a metal envelope, a wick structure, and a working fluid. The envelope and wick are usually copper or aluminum, and the working fluid could be refrigerant or most commonly just water. Majority of applications, and for the purpose of this project, the heat pipes utilized consisted of a copper envelope and wick, with water as the working fluid. A two-phase heat transfer device, the hot end of the heat pipe evaporates the working fluid, while the cold end condenses the fluid. The flow back to the evaporating end is driven via capillary action. This results in a combination of phase change cooling together with convection of cooling medium releasing the heat into the surrounding. Heat pipes have been found to have a 100 to 1000 times greater heat flux transport capability than a solid copper rod of same diameter [15]. Similarly, aluminum heat sinks are often used in heat pipe assemblies to disperse heat to the ambient through fins. Some attempts to cool PV modules with heat pipes and heat sinks have been previously. Notably, Henandez and company in [16] used heat sinks consisting of aluminum fins with thermal grease applied and recorded a 9 % increase in electrical efficiency. Hear the depth of the flow channel, i.e. the height of the fins and space between the back of the module and roof [16]. This increase in electrical efficiency eludes to further cooling potential with the use of heat pipes. In [17], a heat pipe assembly was used to cool a concentrating photovoltaic (CPV) system, which utilizes lenses and mirrors to greatly increase solar intensity sometimes on the magnitude of 100s of suns. In this case, solar radiation is focused on a single cell that was cooled by the heat pipe assembly. Similarly, in [18] a micro heat pipe array was used to cool approximately four PV cells with a total area of approximately 0.09 m^2 , finding a 4.7 °C decrease in cell temperature, a 2.6 % increase in absolute efficiency. An issue, presented with [17] and [18] is that the area that was being cooled was very small when compared to a standard PV module, so the ability to cost-effectively use heat pipe PV cooling on a large scale hasn't been analyzed until this study. One of the largest attractants for investigating this cooling method with copper heat pipes and aluminum heat sinks on a full-size module, is due to their outstanding reliability, as these systems should last the entire lifespan of a PV module, with zero additional maintenance. Furthermore, in recent years the cost of heat pipes has decreased, as their performance has increased.

Effective Parameters, and Test Setup Options

For proper module testing there are many parameters and variables, however, standards do not exist. This leads to a variety of testing methods, and means of reporting the performance of PV cooling systems effectiveness. For this reason, this report makes a point to include gained power per unit area, relative and total efficiency, cost per unit area, reduction in payback period, temperature coefficients, as well as a decrease in temperature and a few other essential measurements like incident irradiance, and ambient temperature.

Testing conditions must be controlled to meaningful and repeatable results [19]. The temperature distribution for an operating PV module is influenced by wind, intermittent sunshine, a module frames, and mounting brackets [19]. This claim was validated during outdoor testing completed in Fall 2018, where the results were inconsistent and scattered. For this reason, as well as due to the lack of hot sunny days during the winter in Schenectady, all cooling prototypes in this study were tested in a controlled indoor environment. Some indoor testing standards have been conveyed in previous studies. Often a module that illuminated using a solar simulator and then also heated from the back, with a standard solar distribution at an irradiance of 1000 W/m^2 .   Also, it is standard to place thermocouples on the back of the modules working surface [19].

The solar simulator that was constructed for this study is shown in Figure 6. This DIY solar simulator consisted of high-quality LED hydroponics grow lamp, reflective mylar sheets, and cardboard to construct the walls. The LED grow lamp used was hung from a suspended ceiling frame in Professor Richard Wilks Energy Lab. A light tunnel for the collector helped direct the light and consisted of reflective mylar and cardboard. This system certainly is not perfect, commercially available solar simulators can cost hundreds of thousands of dollars. However, this is a solid DIY set-up that provided adequate irradiance and heat for the purposes of this study.

Figure 6. DIY Solar Simulator Example [20]

The Basis for Present Work: Comparative PV Cooling System Study

A wide array of studies have been completed in the attempt to effectively cool PV modules, leading to a large variety in the details provided, and data collection techniques used. This makes much of the previous work on PV cooling difficult to objectively compare. Few previous studies made complete calculations of gained power, the relative and total increase in efficiency [8].

The goal of this project was to prototype three different PV cooling systems, exploring each one's effectiveness and feasibility in the hope of furthering the development and implementation of PV cooling methods. First, to be built was the controlled testing area previously mentioned it, utilized an artificial LED sun within a box made out of reflective mylar wrap stapled to cardboard. This allowed for a consistent environment for testing PV cooling systems, where the ambient state hovered around 35°C. Temperature measurements near the corners and center were taken, as well as power output readings. It was important to note the ambient temperature and the amount of incident solar radiation. Following this, baseline testing was performed on the 60-Watt altE mon-facial module. When doing so the module was tested with a peak power resistor of 5.3 Ohms connected, as well as with no resistor connected. As suspected the module observed a 20°C increase in surface temperature when hooked up to its peak power resistor. Specifically, in the constructed solar simulator the back surface temperature reached 66°C with the resistor attached. Then the cooling systems of interest were modeled, prototyped, and constructed. Here all further testing was completed with the peak power resistor connected, mimicking re-world usage. The first cooling method that was analyzed utilized a large aluminum heat sink centered on the back of a mono-facial module.

The following cooling method tested was a combination of the large aluminum heat sink in combination with flat copper heat pipes. For the purposes of this study, heat pipes were secured to the back of the PV module using packing tape, where the condensing end of the heat pipes was secured in the aluminum frame of the module and to the aluminum heat sink centered on the module.

Lastly, a water cooling system was prototyped which consisted of a small submersible pump, a few feet of hose, and a section of a plastic pipe with a number of small holes drilled across its length as to spread the flow of water evenly across the modules working surface. The pump was placed in a lower reservoir and the module located in a large plastic bin that drained into said reservoir.

Experimental Procedures:

Test Setup

Module testing was completed within a solar simulator built in Professor Richard Wilk's Energy Lab. Shown in Figure 7 this solar simulator consisted of a Full Spectrum LED Grow Lights at 1600W from MarsHydro, which was suspended from a metal grid that was secured to the labs ceiling. Walls were built around the module and grow light to contain and reflect light onto the module. These walls consisted of reflective mylar sheets stapled to cardboard with duct tape and twine holding the structure together. As stated earlier, commercially available solar simulators can cost hundreds of thousands of dollars, so for the purposes of this study compromises had to be made. The LED light is preferable in this study when compared to other lighting options since the LED gives off a fraction of the heat that fluorescent bulbs. As a result, the buildup of heat in the module was due to the semiconductors transferring light into electrical energy. Instead of heat simply building as the product of an intensely hot ambient environment. A solar incidence of $200\ W/m^2$ was measured under the grow light at the distance from which the modules were located during testing. This is a fraction of the industry standard for module testing, $1000\ W/m^2$.

Figure 7. Solar Simulator in use

The module used throughout testing was an AltE polycrystalline PV module, with a maximum power output of $60W$ and a nominal voltage output of $12V$. The module's dimensions were 670x650x25mm, with an operating temperature range of -40°C to 85°C and a temperature coefficient of P_{max} equal to $-(0.410 \pm 0.05)\%/K$, further module specifications can be found in Appendices III where a copy of the modules full specification sheet is located. The relatively low insolation produced by grow light, resulted in extremely small output voltages. Rendering them useless in gauging the modules performance. As a result, the given temperature coefficient was utilized to demonstrate the impact on power output for the different cooling methods.

DAQ Information & Thermocouple Location

For data collection, a Measurement Computing USB-2408 DAQ was used. Through trial and error, a runtime of 2 hours 30 minutes with a scan rate of 0.05Hz was chosen to adequately test the different cooling systems. This ensured steady state was reached for each method. For the majority of cooling apparatuses analyzed, the module in the solar simulator reached steady state in approximately 1 hour.

Four Type-K thermocouples were utilized during the majority of module testing. In each case, a Type-K probe was secured to the corner of the module, extending out to measure the ambient testing conditions. The three other, bare wire, Type-K thermocouples were secured to the back of the module using Kapton tape. One was secured to the center of the module, one approximately 8 inches from a corner, and another 4 inches from the same corner. This setup was chosen to see the temperature gradient from the center of the module to its edges. Since, the aluminum frame naturally acts as a heat sink. For heat pipe cooling, various thermocouple locations were tested around the heat pipes to investigate their effectiveness in transferring heat. Furthermore, five Type-K thermocouples were used to properly analyze the water cooling method, as an additional Type-K probe was placed in the reservoir with the submersible pump to measure the water temperature. The thermocouples and DAQ utilized during testing have high levels of precision, ensuring proper results.

Aluminum Heat Sink Passive Cooling

The first and simplest cooling method that was analyzed consisted of a large aluminum heat sink located at the center of the modules surface back. Specifically, the heat sink used was made out of natural aluminum, spanned 400x200x50mm, and had grooved fins increasing the rate of heat transfer. This heat sink came at a cost of $60.00. Initially, this heat sink was chosen for a large heat pipe to be embedded in it, however, this wasn't pursued due to the technical machining required, at risk of ruining the heat sink. Additionally, due to the large size of the heat sink, the module rested on the heat sink in a horizontal position. Rather than securing the heat sink so the module could be set at a realistic tilt, increasing exposure the ambient. In the end, the large heat sink proved adequate to analyze the possibilities of heat sink PV cooling.

Copper Heat Pipe & Aluminum Heat Sink Combined Passive Cooling

The following cooling system that was studied, consisted of copper heat pipes and the same aluminum heat sink previously mentioned. The copper heat pipes used in this setup were 50W 3x8x250mm flat heat pipes, where the internal wick was copper with water as the working fluid. Twelve of these heat pipes were purchased totaling at a cost of $30.50. Flat heat pipes were chosen to increase the contact area with the back of the module and the heat sink. Shown in Figure 8 are the two different heat pipe and heat sink orientations analyzed. The first, shown on the right side of the page, had the heat sink centered on the modules back with one heat pipe utilized the heat sink to draw the excess by placing the heat pipes condensing end between fins., two more Additionally, two heat pipes were placed to use the aluminum frame to draw heat from the condensing end of these heat pipes. The other setup that is shown, involved simply placing the heat sink under the three heat pipes. This setup of stacking them proved to be less effective than the first by a few degrees Celsius and greatly reduced the cooling surface area. Therefore, only the data from the setup where the condensing end of the heat pipes were secured to the heat sink and frame are included in the results for combined heat pipe and heat sink cooling.

Figure 8. Heat Pipe and Heat Sink Testing Setups

Embedded Copper Heat Pipe Cooling

Next embedded heat pipe cooling was investigated. In this case, holes were drilled into the aluminum frame of the module for the heat pipes to securely fit into. This allowed for the condensing ends of the heat pipes to be exposed to the ambient conditions testing, as shown in Figure 9. This setup is the most logical and was only pursued late in this study. Initially, no permanent changes to the modules were desired, because the module is to be used in future academic studies.

Figure 9. Heat Pipe Improved Testing Setup

Active Water Cooling with Submersible Pump

Lastly, active water cooling was investigated in this study. The setup, shown in Figure 10, consisted of a small submersible pump located in a reservoir, trash can. Water was pumped up through clear Tygon tubing. The tubing was secured to a flowmeter with copper fittings attached, which from there fed into a half-inch diameter PVC pipe secured to the top of the module. Water was spread across the working surface using a PVC pipe that had 1/16th-inch diameter holes milled out in a straight line separated by approximately a 1/4-inch each. The module was placed in a bin that drained water into the reservoir so that the system could run continuously run without the need for more water.

Figure 10. Water Cooling Testing Setup

The submersible pump utilized was a Homasy 400GPH Submersible Pump 25W Ultra Quiet Fountain Water Pump, coming in at a cost of $24.00. This pump provided more than enough to pumping power for a single module, it is certainly strong enough to cool an entire array of modules five times as wide as the module tested. Additionally, this inexpensive pump controls the flow rate by a simple plastic valve that limits the intake. A flow of 0.8 gpm was used during testing, and was the lowest the pump could operate at. Furthermore, the pump constantly consumes 25W, which is extremely excessive to cool a single 60W module and not at all effective in lowering the payback period. Despite the unrealistic nature of this particular test setup, it was still important to analyze since water cooling is currently the most popular option in real-world PV cooling systems. The other components of this water cooling system, besides the pump, were supplied by Prof. Richard Wilk's Energy Lab. Overall, this system was successful in significantly lowering the operating cell temperature. Despite the difficulty in evenly distributing the water across the entire module, which will be further expanded on in the Discussion of Results section.

Presentation of Results & Analysis:

The results, revealed in Figure 11, show the steady state temperature in degree Celsius at the center or area where cooling was applied. It also displays the corresponding power output for that particular cooling method. The histogram is arranged with the most effective cooling at the top where the baseline, with no cooling is at the bottom. As one can see, the active water cooling method was the most effective. Additionally, the various passive conduction cooling methods which utilized heat pipes and heat sinks all yield similar results. These results were only slightly less effective at lowering the module temperature as the water cooling. In the end, all setups greatly reduced the modules operating cell temperature from the baseline testing with no cooling applied.

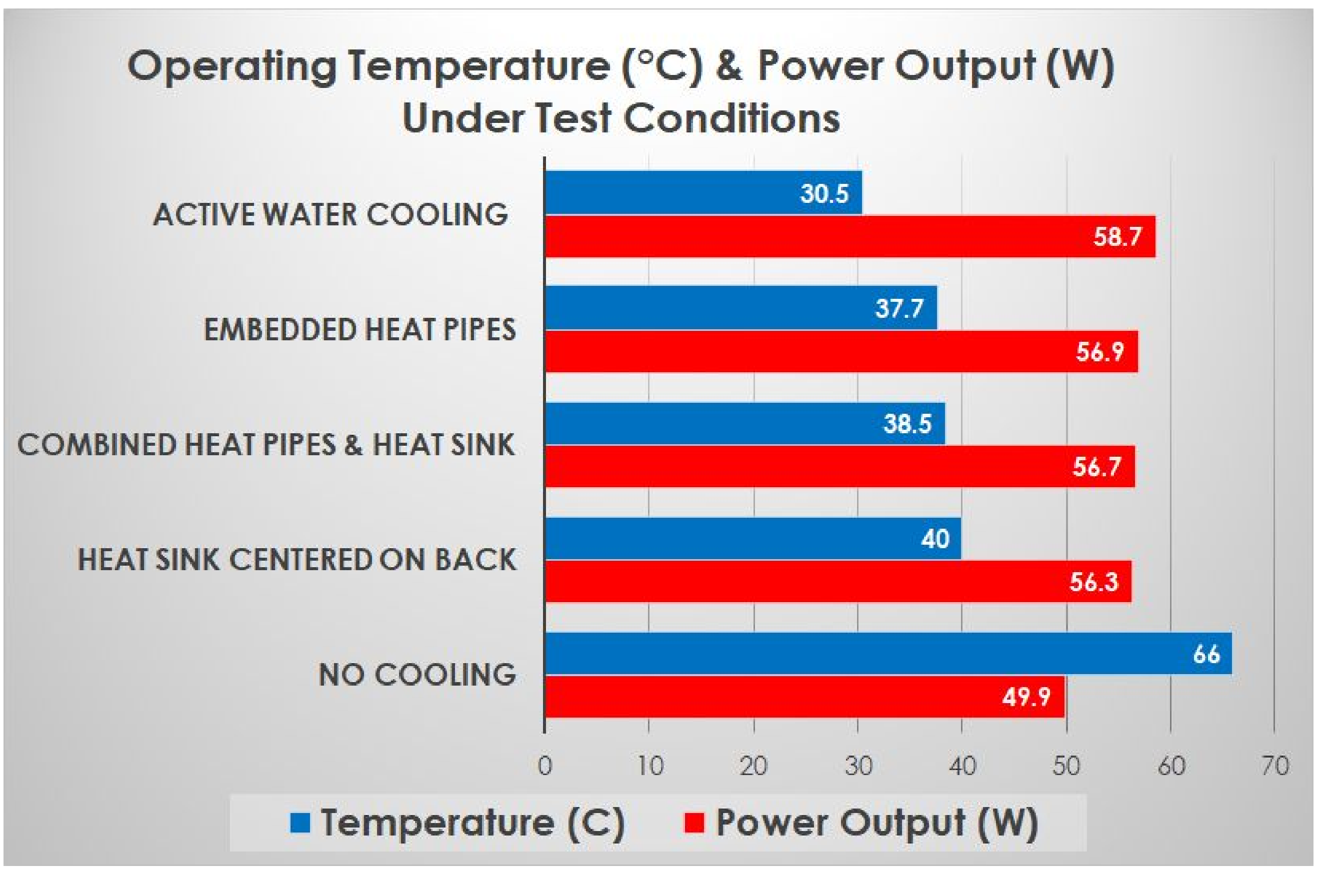

Figure 11. Temperature & Power Output for each cooling method tested

Discussion of Results:

The results do reveal that these methods of PV cooling have a number of promising attributes. Despite this, there are undoubtedly a number of ways this study could be improved to provide more precise and useful information.

This study has demonstrated the opportunity for cost-effective cooling utilizing heat pipes, heat sinks and active water cooling. Water cooling proves to be the most effective at lowering operating cell temperature and should be pursued under the following circumstances, in a hot environment where water is easily accessible and stored. Also, water cooling is especially useful to cool large arrays with massive surface areas. Ideally, a gravity fed cooling from a raised reservoir on a hill or roof so that there is no pump power consume. Despite this other studies have shown that giving up some power output to power pumps for active water cooling is worthwhile, as demonstrated by Grubišić-Čabo and company in [8]. In tropical, moist environments water cooling is certainly the PV cooling method of choice.

On the other hand, many areas where PV cooling is of interest the environment lacks excess water for cooling. Such as arid deserts and plains. Additionally, places like California come to mind which have strict water rights and frequent droughts. In these areas, the results from this study reveal that passive conduction cooling with embedded heat pipes are the logical choice. It is important to note, that a medium-sized aluminum heat sink should be centered on the back of the module with flat heat pipes embedded in the heat sink and the modules aluminum frame to best lower the operating cell temperature. This conclusion was reached for a few reasons. First, in this study heat pipe cooling only consisted of three to four heat pipes, cooling only a single quadrant of the module instead of the entirety of it. Additionally, larger heat pipes than the 250mm long 50W ones used are quite a bit more expensive and fragile, so to keep the initial cost down an inexpensive aluminum heat would increase the cooling surface area exposed to cooling ambient air. Helping to evenly spread heat dissipation across the back of the working surface. The embedded heat pipes in the frame, are very effective at transferring heat, but when they are not projecting out of the frames module, they actually tend to contain and build up the heat near the condensing end. The results of this study revealed that properly placed heat pipes are only slightly less effective than active water cooling. Therefore in many scenarios, combined embedded heat pipes and heat sinks should be the preferred choice in a cooling method. Especially, as heat pipe technology continues to decrease in price as manufacturing techniques improve.

As stated earlier, there are a number of ways the precision of this project could be improved, as will now be disclosed.

An improved solar simulator would have also increased the validity of this study. The low insolation provided by the grow light resulted in an extremely small output voltage across the peak power resistor, rendering them next to useless to be analyzed. The LED 1600W MARS Hydro grow light only produced an insolation $200\ W/m^2$ meanwhile standard testing conditions are done under $1000\ W/m^2$. Furthermore, the enclosed setup, had stagnant air when in real life the modules will be exposed to at least a slight breeze, increasing the rate of cooling. Additionally, the test setup was unable to reach the same steady state temperature in the flat and tilted orientation. When testing was completed in the flat position, a steady state temperature approximately $10°C$ hotter was observed than when set at a 45 ° angle as required for water cooling.

Next, the Corners and edges of a module are naturally at a lower temperature than the center of the module. As a result, this study would be improved if all cooling methods were analyzed at the exact center of the module. Instead of applied cooling to a single quadrant of the modules back, as was done with the heat pipe cooling methods.

Additionally, more secure and real world means of attaching cooling methods to the module would yield better results. The heat pipes were secured with packing tape, the module was simply placed on the large heat sink and the water cooling method was attached to the top with duct tape. The tape almost certainly insulated the cooling apparatuses to some degree.

A smaller pump, which utilized less power, would allow for the cost-effectiveness and payback period of each cooling system to be better analyzed and compared. The 25W pump used during testing could easily cool an area five times as large as the single module tested.

Similarly, when testing active water cooling it was difficult to evenly spread the flow across the entire working surface. Most of the water flowed out of the holes close the pump and furthest away from the pump, leaving the middle relatively dry. After troubleshooting, this issue was largely mitigated by drilling holes below the previously milled holes at locations of poor flow.

In addition, more consistent and precise thermocouple locations, would have improved this study. It was attempted as best as one could to secure the thermocouples at the same locations for the different methods, but when changing to a different cooling method the thermocouples would often fall off. Additionally, the solar simulator with the module in it is very tight, making it tough to ensure proper thermocouple placement with some of the cooling methods, such as the active water cooling. In hindsight, thermocouple locations should have been marked with a marker from the start of testing

Moreover, the ability to embed heat pipes into the heat sink or to be able to build a heat sink around a heat pipe was not possible in this study. The machining processes involved are quite difficult and it is especially challenging to work with thin aluminum sheets, which are preferably in the construction of a heat sink.

Likewise, the large scale of this projects scope limited the complexity of the cooling methods analyzed. For a senior project, one or two cooling methods should be modeled really well instead of attempting to test and compare four simple cooling systems. More funding and time was required to more precisely validate the real-world effectiveness of these PV cooling techniques.

In the end, this project still successfully compared different cooling methods for photovoltaics in a controlled environment. Providing valuable insight for further cooling research, as well as many lessons gained for the individuals involved.

Conclusion:

One of the largest issue with photovoltaics is the significant reduction in output voltage as operating cell temperature increases. Resulting in an overall large reduction in a modules power output for a given amount of incident solar insolation. This has been equated to an approximately 0.4–0.5% decrease in a PV modules conversion efficiency for every degree Celsius of temperature rise [2]. Consequently, many have investigated a number of possible cooling methods for PV technology.

The aim of this study was to compare the most promising PV cooling methods, in hope to gain better insight and aid in the further development of PV cooling effectiveness. The probability of widespread application of photovoltaic cooling has increased in recent years. Continuing to grow as renewable energy forms gain in popularity, cost of PV modules decrease with better manufacturing techniques, improved cooling technology, and as temperatures around the world are hotter and more extreme.

Specifically, this study investigated PV cooling utilizing: 1) Aluminum heat sinks 2) Embedded heat pipes 3) Combined heat pipe and heat sink cooling 4) Active water cooling. The findings revealed that active water cooling is the most effective cooling technique and should continue to be pursued. However, active water cooling is often not practical. For worthwhile active water cooling the environment must have a steady supply of cool water and the array to be cooled must be large to offset the small power consumption of a pump. In many scenarios cooling with embedded heat pipes and a medium sized aluminum heat sink would prove to be the most practical. In arid environments, with water scarcity and high winds, this method is the logical choice. As with many things in engineering, the proper PV cooling choice relies on a number of environmental implications.

Unfortunately, there are a few important points lacking in this study due to time and funding. Mainly the inability to truly get a precise understanding of the different payback periods and cost-effectiveness for the cooling methods investigated. This is due to the ineptitude to lower the power consumption of the pump with respect to flow rate. The pump utilized could easily cool a large area, at least five times the size of the module that testing was completed on. Additionally, the insolation provided by the LED grow light is a fraction of what a module would be exposed to outside on a sunny day. In reality, commercially available solar simulators can cost hundred of thousands of dollars so for module testing during winter in Schenectady this was the best that could be done.

Future research should aim to focus on one of the two promising cooling techniques, active water cooling and combined embedded heat pipe and sink cooling Refining and optimizing each method, so that large scale worldwide use can be implemented as needed. The reality is that the world's future is in question as we continue to carelessly burn fossil fuels and pollute our environment on countless levels. It is up to us as the engineers, being educated citizens, to lessen the burden of humanity on our environment and extend our existence here. The way we produce our power needs to change, solar PV and other renewables need to be further refined to cost effectively meet the demand.

I would like to thank Professor Richard Wilk for helping guide me with this project, as well as for the materials he graciously provided for this study.

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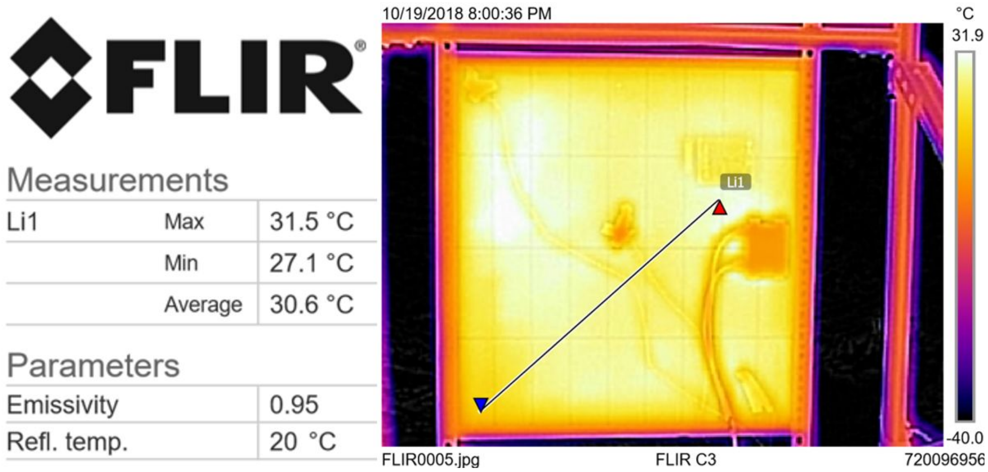
Appendixes:

I. Fall Outdoor Module Testing
II. Heat Pipe Capabilities Testing
III. Specification Sheets for Module, LED light, Heat Sink, Heat Pipes & Pump
IV. Project Presentation Slides

I. Fall Outdoor Module Testing



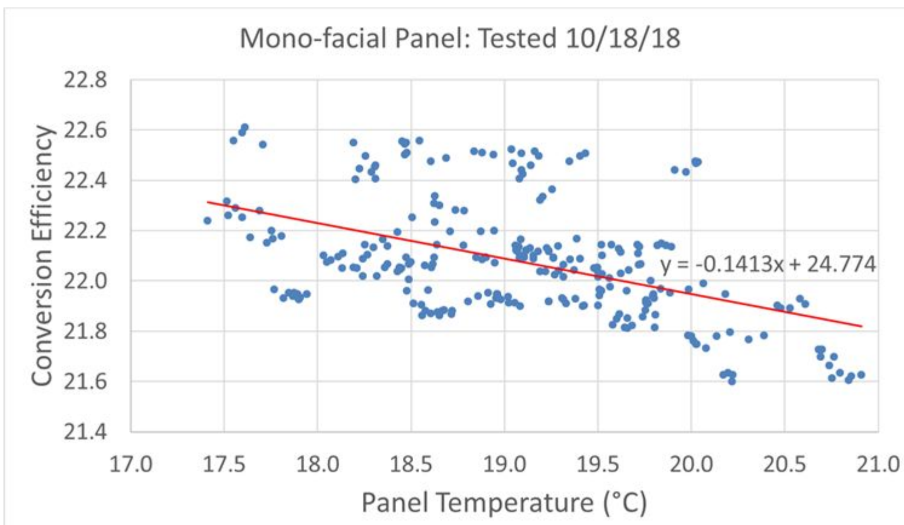


Figure 12. Shows a fitted linear trendline, revealing a decrease in conversion Efficiency with rise in panel temperature.

Circumstances	Module S.S. Temperature	Power Output
Module Specifications	25°C	60W
Fall Outdoor Testing	18.5°C	63.5W

Figure 13. Comparison between Module Specifications and Fall Outdoor Testing, showing temperatures effect on power output.

Incident insolation on the day of testing for which the data shown was under $682\ W/m^2$ while the panel specifications were under a constant $1000\ W/m^2$. Despite this difference in insolation the outdoor testing the outdoor testing yielded a higher output power due to the lower temperature.

II. Heat Pipe Capabilities Testing

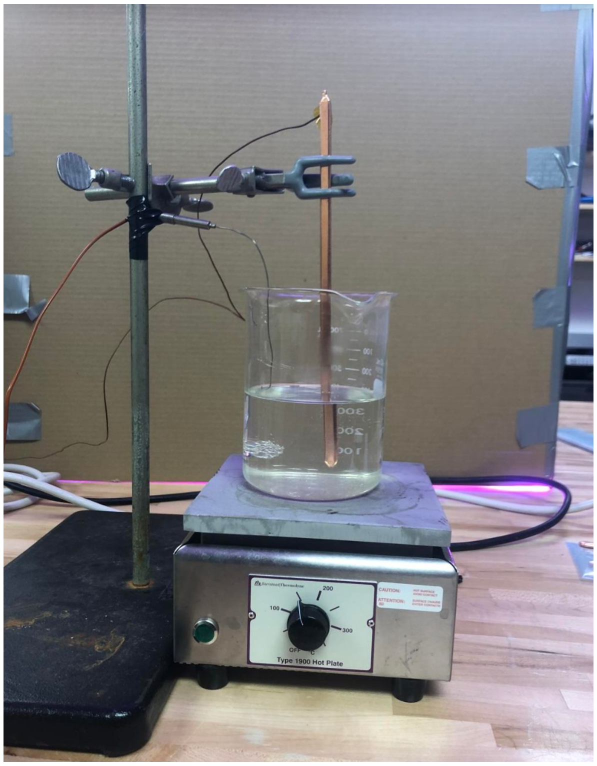


Figure 14. Heat Pipe Effectiveness Testing Setup

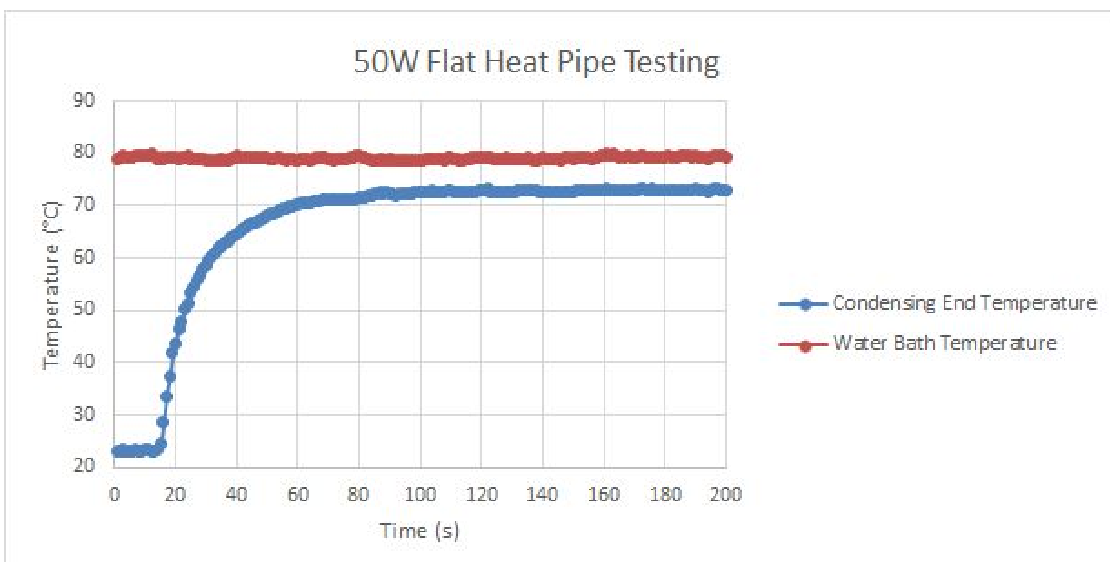


Figure 15. Heat Pipe Effectiveness Testing Results

III. Specification Sheets for Module, LED light, Heat Sink, Heat Pipes & Pump

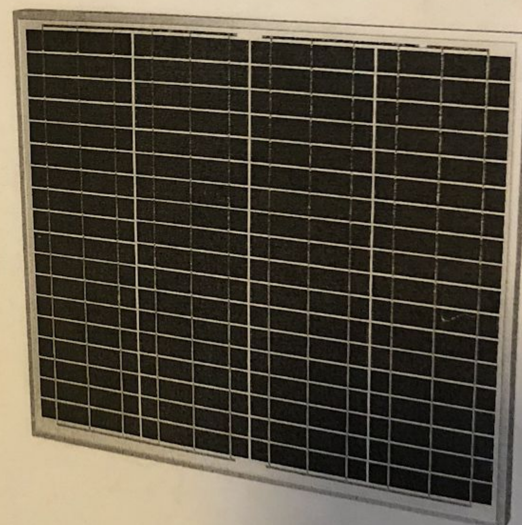
Module: ALT60-12P

Polycrystalline Photovoltaic Module

altE

ALT60-12P

60 WATTS, 12 VOLTS



DESIGNED FOR OFF-GRID APPLICATIONS

altE solar modules are designed specifically for use in off grid applications. Manufactured in accordance to ISO9001 standards and certified by IEC61215 and CSA/US to assure electrical safety compliance.

APPLICATIONS

- Off-grid Power for Cabins and Vacation Homes
- Solar Water Pumping
- Solar Powered Refrigerators
- Remote WiFi and Wireless Repeaters
- Power for RVs and Campers
- Electrification of Remote Villages
- Hobbyist Projects Needing Remote or Mobile Power
- Power for Remote Monitoring Systems

CERTIFICATIONS

WARRANTY INFO

altE modules offer 3 year workmanship / 25 year performance warranty.

877-878-4060 | www.altEstore.com

Polycrystalline Photovoltaic Module

altE

ELECTRICAL SPECIFICATIONS

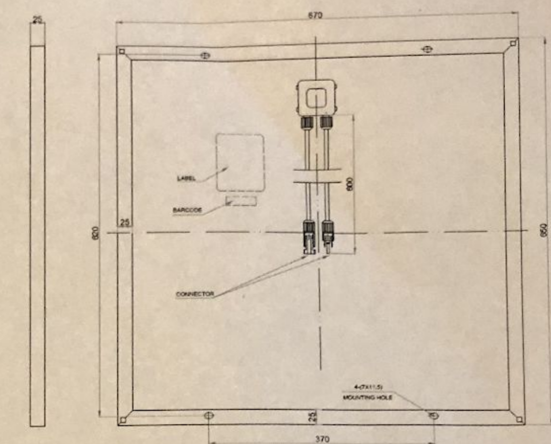
Open-Circuit Voltage (Voc)	20.87V
Optimum Operating Voltage (Vmp)	17.90V
Short-Circuit Current (Isc)	3.58A
Optimum Operating Current (Imp)	3.35A
Maximum Power at STC* (Pmax)	60W
Module Efficiency	11.5%
Operating Temperature	-40°C to 85°C
Maximum System Voltage	600V DC
Power Tolerance	±2W
Nominal Voltage	12V

TEMPERATURE CHARACTERISTICS

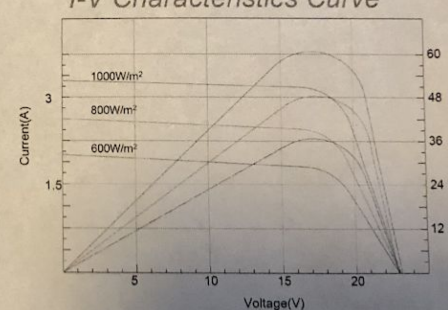
Nominal Operating Cell Temperature (NOCT)	45 ± 2°C
Temperature Coefficient of Pmax	-(0.410 ± 0.05)%/K
Temperature Coefficient of Voc	-(0.320 ± 0.01)%/K
Temperature Coefficient of Isc	+(0.050 ± 0.05)%/K
Maximum Series Fuse/Current Rating	10A

MODULE CHARACTERISTICS

Module Dimensions	670 x 650 x 25mm 26.4" x 25.6" x 1"
Weight	5Kg 11lbs
Cells Array & Numbers	4 x 9 (36 Cells)



I-V Characteristics Curve



SOLAR CELLS: Poly crystalline (156 x 65mm)
LAMINATE: Glass/EVA/TPT (tedlar/pet/tedlar) or TPE
FRONT SIDE: High-transmission 3.2mm tempered glass
BACK SIDE: TPT /TPE
FRAME: Clear anodized aluminum frame
RELATIVE HUMIDITY: 0 to 100%
RESISTANCE: 227g steel ball dropped from 1m high an[d] 60 m/s wind
SNOW LOAD PARAMETERS: 2400Pa
OUTPUT: MC4 Compatible Connector Cables (+/red terminal on right and -/black terminal on left)
STC: Irradiance 1000W/m², Module temperature 25°C, AM = 1.5

[A]ll the data on this sheet are subject to change without notice.

877-878-4060 | www.altEstore.com

LED Grow Light: Mars II 1600 LED Full Spectrum Hydroponic LED Grow Light-Mars Hydro

Item NO.	Mars II1600
Coverage	Core Coverage: 4.5ft*4.5ft | Max Coverage: 6.5ft*6.5ft
Max Yield	1.8g/w
Compare to HPS/MH/HID	800 watt
Draw power	110V:Growth:632W@110v; 630W@220v
Hanging Distance	Seedling stage: 24~30'' Veg Stage: 16~24'' Flowering Stage: 12~16''
Certificate	ETL,CE,Rosh
Spectrum	440nm, 460nm, 630nm， 660nm,730nm(IR), 2700k-3000k
Chip Brand	Epistar
Voltage	85v-265v
Amps	5.92 @ 120v | 3.148 @ 240v
BTU	2555
Decibel Value	61.4
Plug Type	EU,UK,AU,USA,Japan
View Angle of LED	90°-120°
Humidity	≤90%
Lifespan	50000 hours
Dimension	20 x 20 x 3.5 inches
Work Temperature	-4°F ~105°F (-20°C ~ 40°C)
N.W/G.W	31lb. 15Kg.
Warehouse	UK,USA,Canada, Australia, Germany,China
UPC Number	600740984648

Heat Sink: 15-3/4" X 7-13/16" X 2" Large Aluminum Heat Sink

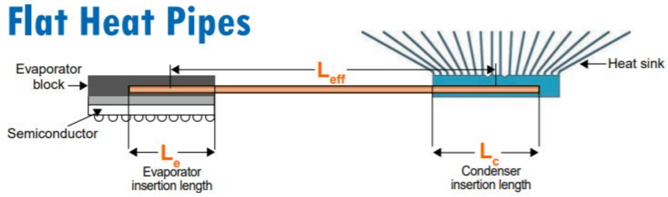
No data sheet

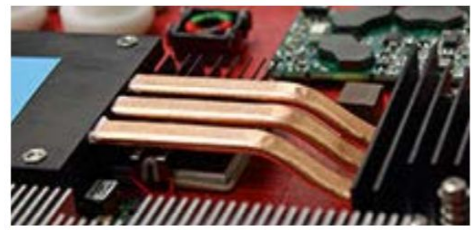
Link:

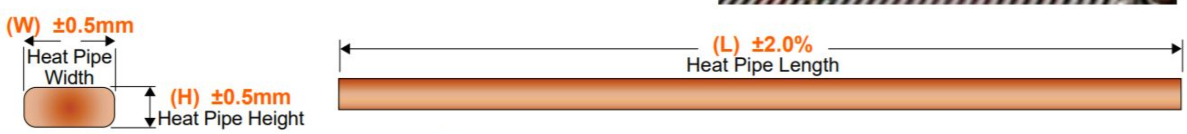
https://www.mpja.com/15-3_4-X-7-13_16-X-2-Large-Aluminum-Heat-Sink/productinfo/33306+HK

Heat Pipe: FLAT HEATPIPE 50W 3X8X250MM

Flat Heat Pipes







$$Q_{max} = \frac{Q_t}{L_{eff}} \times 1000 \qquad L_{eff} = L-(L_e+L_c)/2$$

PRODUCT SPECIFICATIONS

L=Length (mm); W=Width (mm); H=Height (mm); WT=Wick Type (S=Sintered, G=Grooved); WF=Working Fluid; TR= Temperature Range (°C)

Part Number	L	W	H	WT	WF	TR	QT (W•m)	L_{eff} (mm)	Q_{max} (W)	L_{eff} (mm)	Q_{max} (W)	L_{eff} (mm)	Q_{max} (W)
ATS-HP-F6L250S50W-023	250	8	3	S	Distilled H_2O	30-120	9.35	125	75	150	62	200	47

Pump: Homasy 400GPH Submersible Pump 25W Ultra Quiet Fountain Water Pump with 5.9ft Power Cord, 2 Nozzles for Aquarium, Fish Tank, Pond, Hydroponics, Statuary

Disassemble & Cleanable

The device doesn't need any tools to disassemble it and is very easy to be cleaned. Please clean it regularly in case of debris blockage, the pump would make noises if blocked.

Note:

1. Please use socket with stable voltage and keep the motor running within rated power to ensure long lifespan.
2. Put the pump into water first before connecting power supply. When changing water, please disconnect power supply.
3. It is advisable to use a lubricant when the motor makes loud noises. The lubricant oil of electric hair clippers is a good choice.

Specifications:

Max Flow Rate: 400GPH

H-Max: 6.9ft

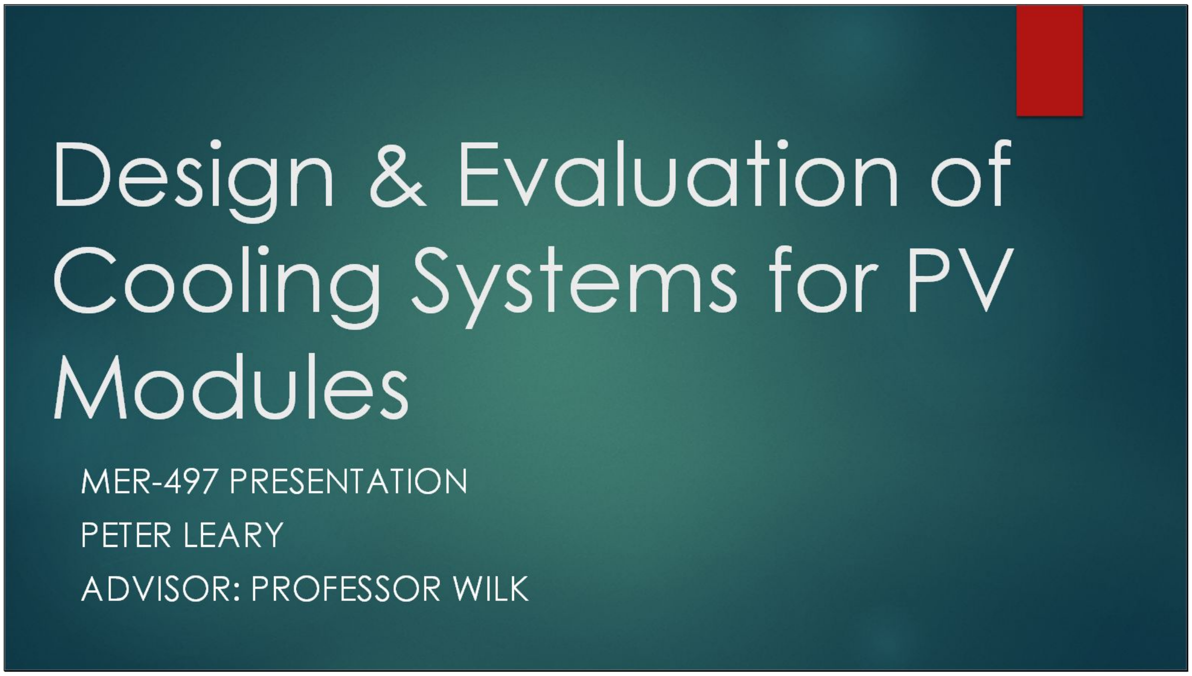
Power: 25w

Length of power cord: 5.9ft

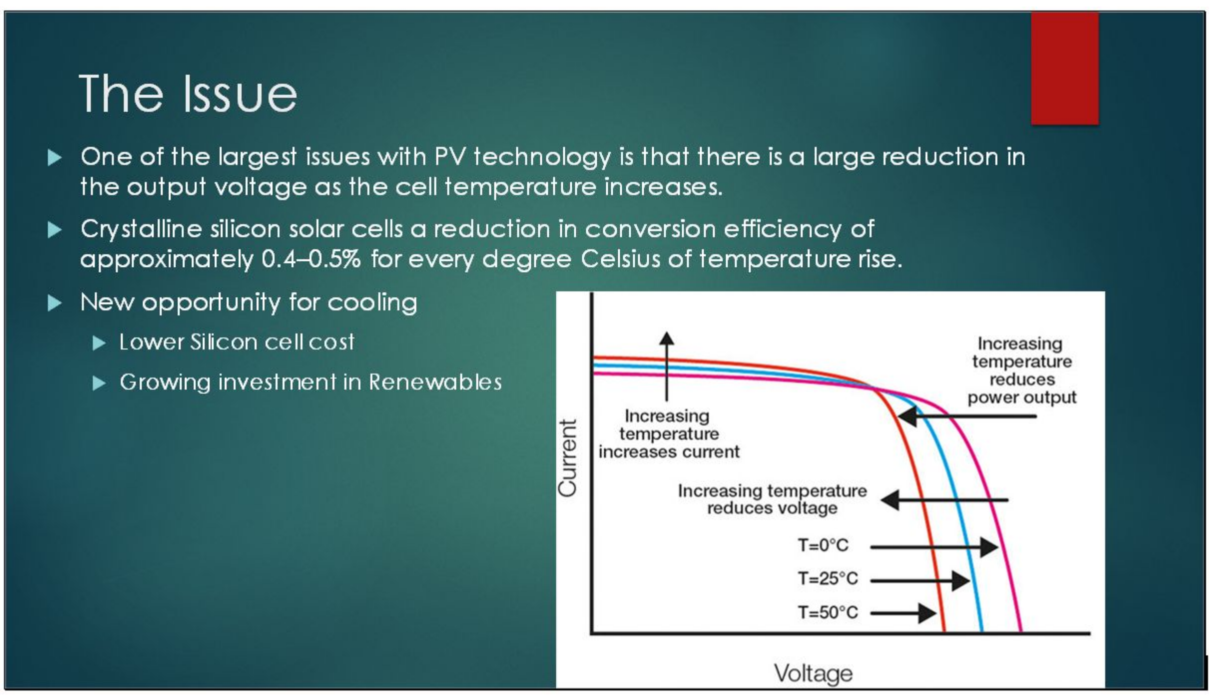
Color:Black.

IV. Project Presentation Slides

Slide 1



Slide 2



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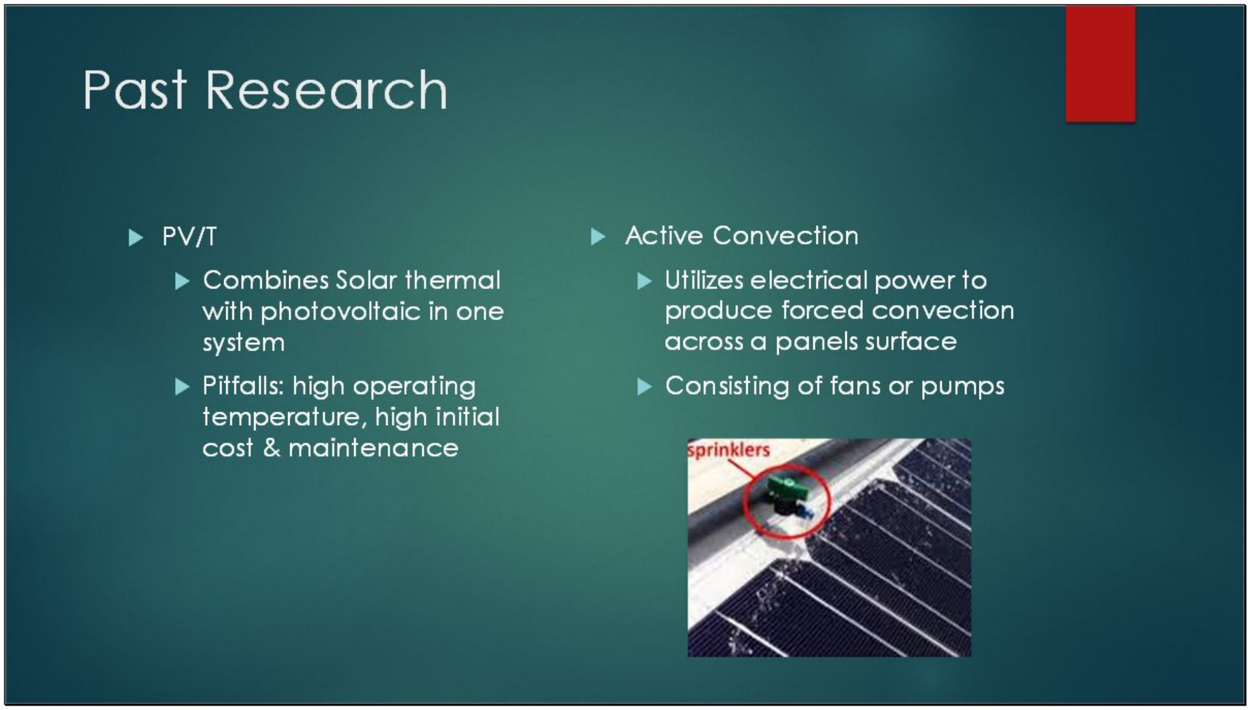

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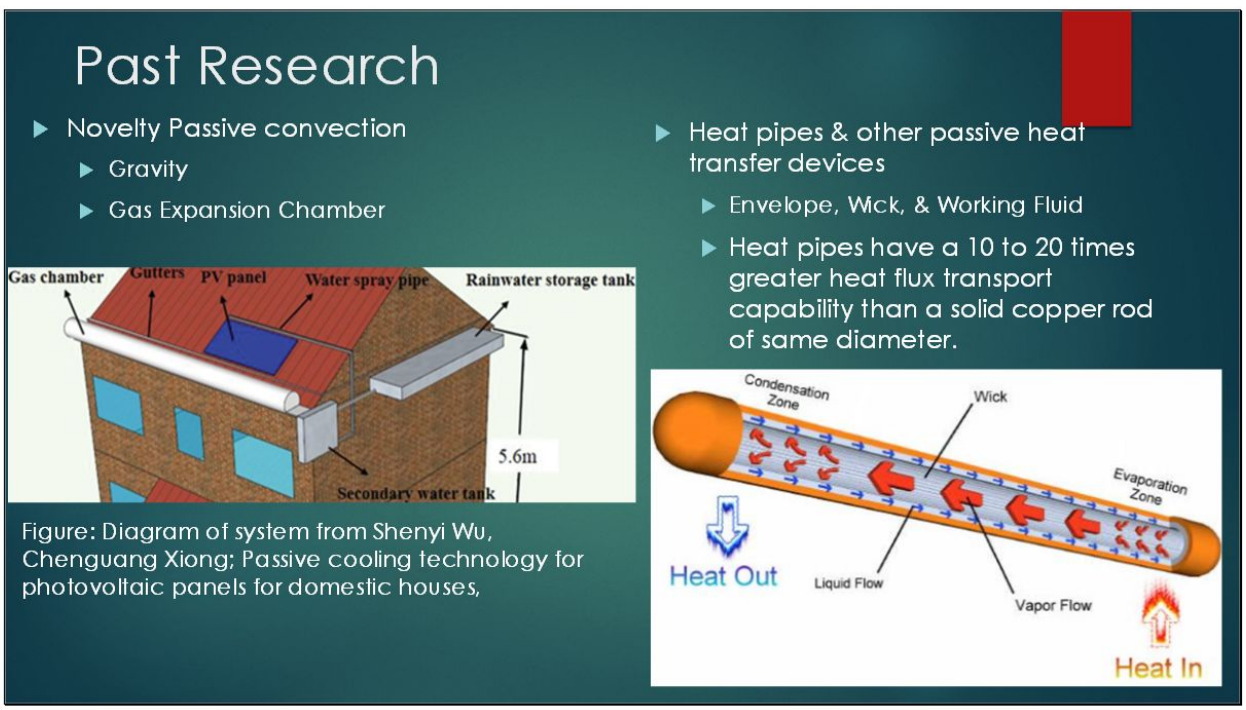


Slide 5

Project Description & Goal

Comparative Analysis of Promising PV cooling solutions

- Model, prototype, and test promising cooling systems for bifacial and mono-facial PV modules.
- Three different systems to be prototyped and tested
  - Utilize heat pipes and sinks to cool bifacial PV modules in a concentrating PV system
  - Utilize heat pipes and sinks to cool mono-facial (standard) PV panels
  - Pump stored rainwater to cool mono-facial/ bifacial PV modules
- Bifacial modules, have cells exposed on both sides.

Slide 6

Plan of Action & Expectations

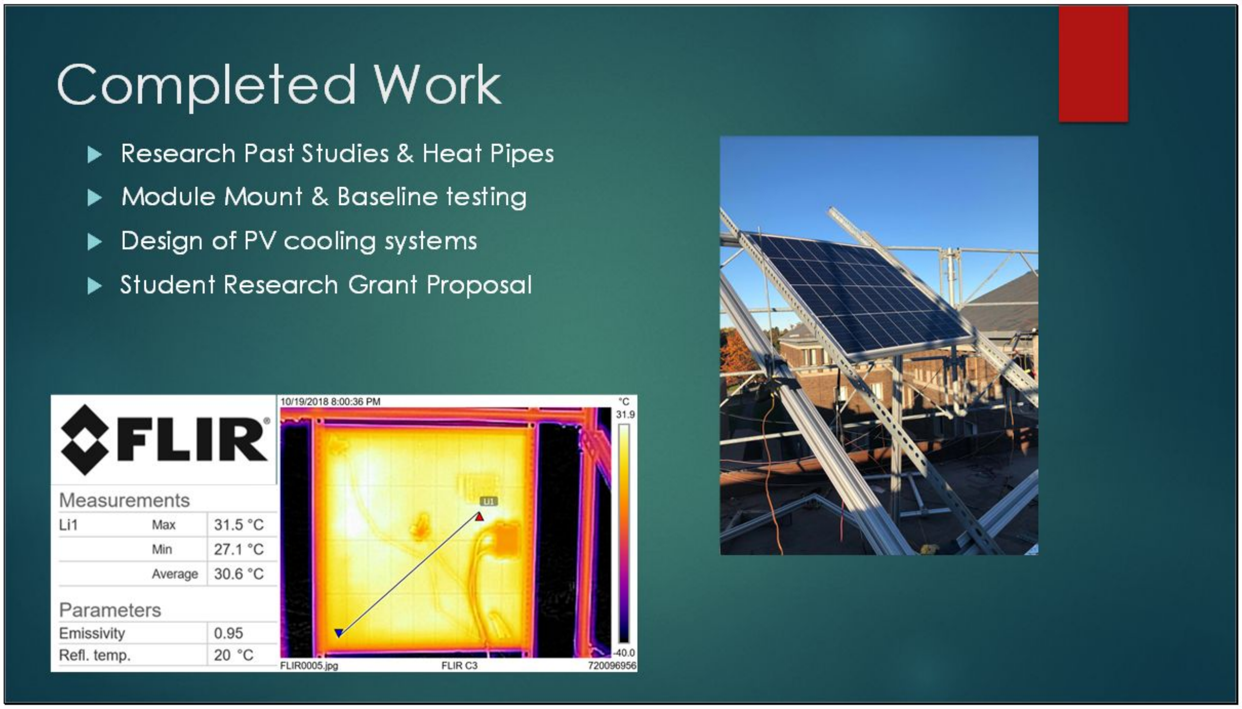
Fall Term

- Study past research papers
- Collect baseline data
- Conceptualize and design different possible cooling systems
- Order necessary components

Winter Term

- Construct and Test prototypes
- Analyze data & determine effectiveness
- Report & present findings
- Set-up in door Solar Simulator

Slide 7



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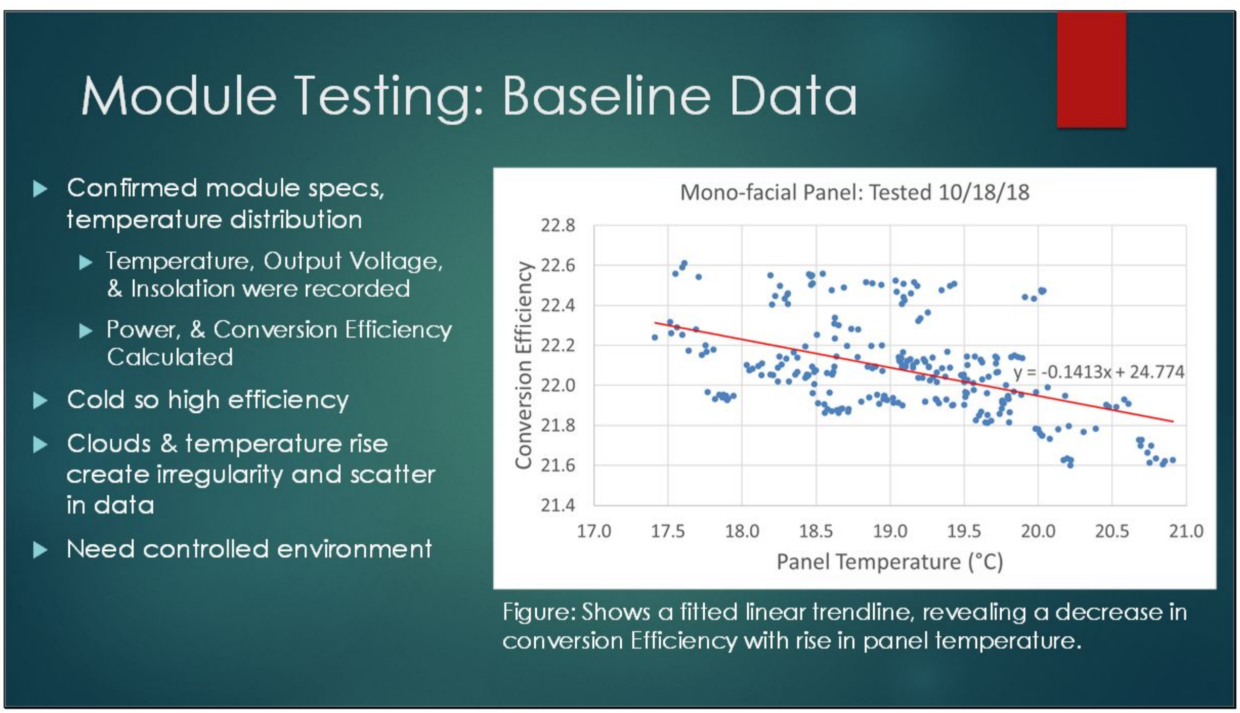

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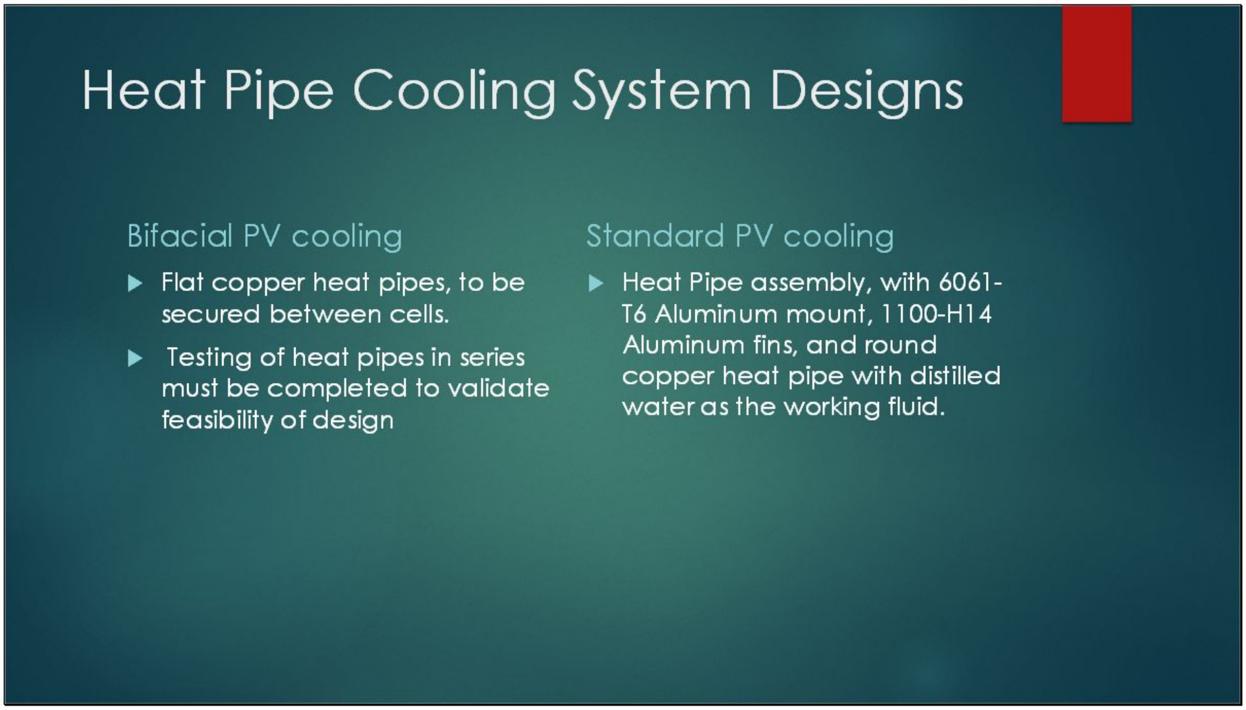

Slide 10