Photovoltaic System Performance Under Partial Shading: An Undergraduate Research Experience

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Abstract:

This paper presents the results of a study on the performance of various inverter technologies for commercial photovoltaic systems (PV) when subjected to different shading and soiling conditions. The conditions included both sunny and cloudy days as a control group, as well as four different shading setups designed to simulate realistic conditions such as cloud cover, soiling, and shadows. During the execution of the project, there was a large wildfire from Canada that resulted in significant smog cover for two weeks over the area where the solar panels are installed. This provided an additional opportunity to study the impact of smog on solar panel power production.

From the data collected over one year, it is determined that the AP Systems microinverters are the most efficient under all conditions. It is evident from the data that partially shading strings horizontally across multiple solar modules had a larger impact on power output than completely shading strings vertically across single solar modules. In addition, the effects of the smog from nearby wildfires were observed to be similar to that of cloud cover, but with a lesser impact on the dynamics of the total energy generated.

This project was conducted in collaboration with two undergraduate students in electrical engineering, two faculties in the engineering department, and engineers from local industry. The nature of this research was interdisciplinary, which proved to be challenging for the students but also offered a very rewarding experience. The students applied the theory learned in classrooms to practical hands-on field experience by working alongside engineers from the solar panel industry. Moreover, the team-oriented nature of this project enhanced students' development of essential skills in teamwork, communication, and time-management, which will serve them well in their professional careers.

1.0 Background

This project was supported in part by an NSF Advanced Technological Education grant (DUE #1400490), which provided undergraduate students from Bellingham Technical College and Western Washington University, in partnership with local industry, to work on research projects [1]. The benefits of this collaborative effort include strengthening a working relationship between a technical college, a state university, and an industry partner, and providing a meaningful research experience for the students such that the data gathered is also valuable for the industry partner.

The first phase of the research began in October of 2016 and concluded in August of 2017. A cohort of 10 students from both institutions were involved in the project design and construction. Solar panels donated by the industry partner, Itek, were set up at a shared off-campus laboratory called the Technical Development Center (TDC). The students from the technical college received elective credit for their participation while the students from the university worked on a volunteer basis during the school year and were paid a stipend during the summer, when the students typically worked 20 hours a week. There was also an understanding that parts of the project could be incorporated into their senior project [2].

This paper focuses on the results collected from the second phase of the project, which spanned from September of 2017 to October of 2018. During this time, the students observed the performance of solar panels and power electronic converters when subjected to different operating conditions. Factors such as shading, soiling, and weather on power generation were investigated.

2.0 Project Description and Results

Solar photovoltaics have been one of the fastest growing sources of renewable energy in recent years [3], [4]. A 2018 report by the Solar Energy Industries Association (SEIA) claims that 55% of all new electric generating capacity in the U.S. originated from solar [5]. Figure 1 shows the actual and forecasted U.S. PV installation from 2010 to 2023.

This growth provides opportunities to investigate and develop innovative technologies that allow for increased efficiency and reliability in the renewable energy sector. The research team evaluated the performance of solar module power electronic converters under different operating conditions with the hope that the data collected would be useful for the industry partner and spurn advancements in their PV panel technology.

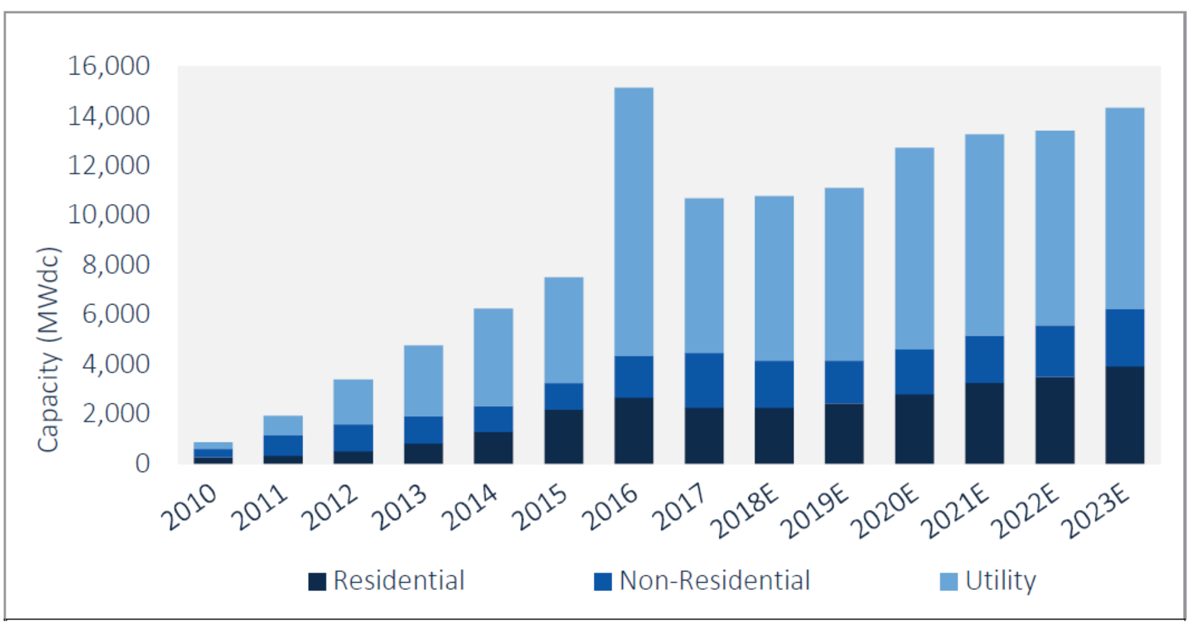

Figure 1: U.S. PV installation forecast [5]

2.1 Solar Panel and Converter Functionality

Solar panels consist of individual silicon solar cells to convert the sun's energy into electricity. When a solar cell is exposed to light, the photons from the light displaces electrons from their respective atoms and generate current [6]. Since individual solar cells do not produce significant electricity, they are grouped into larger components called solar modules, which are themselves connected into strings.

The bulk power grid uses alternating current (AC) to transmit and distribute electricity efficiently. However, PV systems produce direct current (DC) that must be converted to AC through a power electronic converter before injecting power onto the grid. In a traditional PV system, the power output of each string is connected to one central string inverter. This reduces the number of inverters required. However, the amount of power produced by the overall string is limited by the lowest power generating module of the string. Some common reasons for low power generation include shading, soiling, and damage to the module [7].

In order to ameliorate the effects of power output mismatch between modules, module-level power electronics (MLPEs) are often used. They individually connect to each solar module to increase the overall power generation of the PV system. There are two different types of MLPEs: DC-DC optimizers and microinverters. DC-DC optimizers are devices that tune the DC output voltage of each solar module so that it is operated at the maximum power point (MPP). A string inverter is still used for converting the DC power into AC. Microinverters, on the other hand, replace the string inverter with inverters directly connected to each solar module. Under this setup, the DC power generated by each module is directly converted to AC, bypassing the central string inverter. This method of energy conversion is typically the most expensive, but is also the most efficient.

2.2 Effects of Shading

The effects of shading (i.e., cloud cover, soiling, shadows) on solar panel performance was investigated. An equivalent model for a single solar cell is shown in Figure 2. The current flowing through the left branch of the circuit, I_{SC}, is directly proportional to solar irradiation. The diode in the center branch of the circuit models the semiconductor properties of the solar cell and R_P represents the losses due to the cell's parallel leakage resistance [6].

Under sunny conditions, the total current through the cell, I, is nearly equal to I_{SC}, minus some losses due to the currents flowing in the reverse direction. When the cell is shaded and no light impinges upon it, then I_{SC} is equal to zero and the left branch produces no current. Because the diode is reverse biased, the current flow through the center branch is also negligible. Therefore, if the cell is connected in series with other cells to form a string, current is forced to flow through R_P, resulting in a reduction of the output voltage across the entire string. This model explains why shading even just one cell in a module can have such a significant impact on the power output of the entire string.

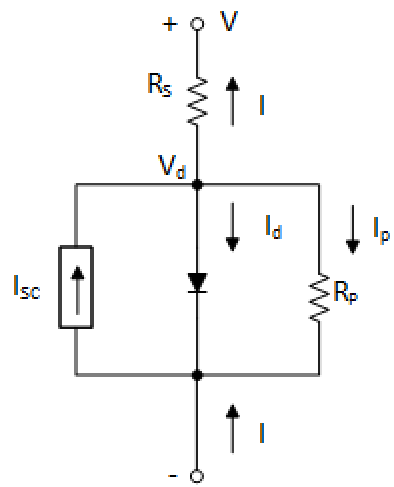

Figure 2: Solar cell equivalent circuit model with losses

2.3 Test Setup

All testing of the solar panels and converters were conducted at a pre-existing community solar site in Bellingham, WA that is managed by Itek Energy. The site has 236 Itek solar modules installed. Eight strings, each consisting of 10 solar modules, are connected to 8 PVI 6600TL Solectria string inverters with a total capacity of 60 kW [8]. Another four of the strings are connected to different converters for this project. The converters tested in this project include Tigo DC-DC optimizers [9], AP Systems microinverters [10], and Enphase microinverters [11]. The fourth string of solar modules served as the control group and is connected to a Solectria string inverter. Figure 3 shows the project setup. Table 1 summarizes the comparison between the different MLPEs used in this project. It is worth noting that the Tigo DC-DC optimizer requires the Solectria string inverter to function.

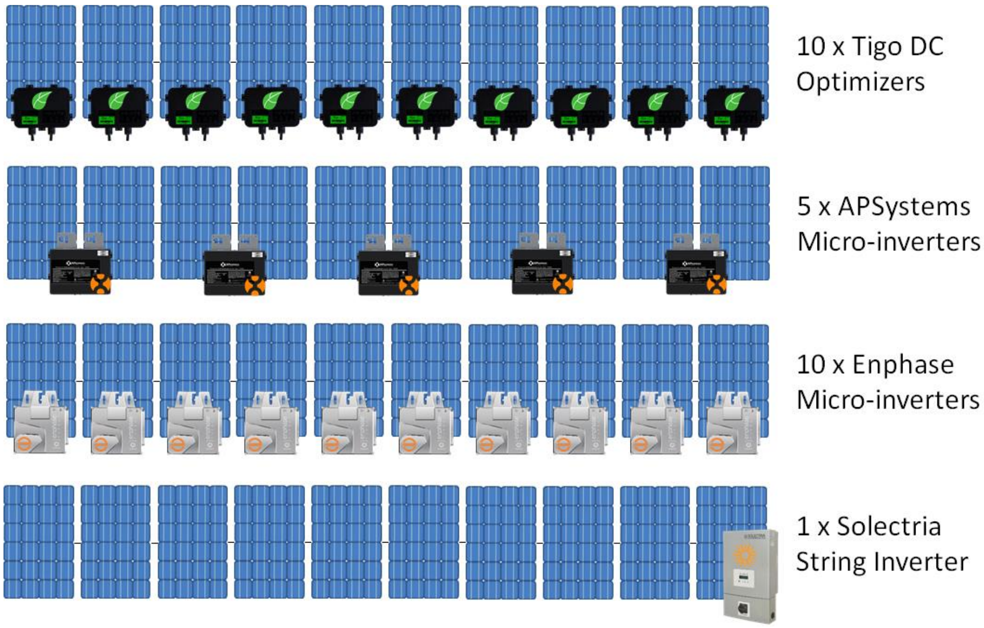

Figure 3: Project setup

Table 1: Comparison of power electronic converters.

	Tigo	**Enphase**	**AP Systems**	**Solectria**
Type of Device	DC-DC optimizer	Microinverter	Microinverter	String inverter
Model Number	MM-ES50	M250	YC500I	PVI 6600TL
Installation Type	Module-level DC-to-DC	Module-level DC-to-AC	Module-level DC-to-AC	String-level DC-to-AC
MPP Voltage Range	16 V – 48 V	27 V – 48 V	22 V – 45 V	200 V – 500 V
Cost (per unit)	$60	$216	$150	$1850
Units per String	10	10	5	1

The power generated from each string was measured and recorded using both the internal meters of the converters and external Egauge meters for redundancy [12]. Weather related data were downloaded from the National Weather Service website and compared against a local weather station set up at the community solar site. Figure 4 shows the power output on April 25, 2018 with no shading and sunny weather, which serves as the control for the project. Figure 5 shows the power output on April 29, 2018 under cloudy weather conditions. It is evident from the plots that the clouds reduced the amount of power generated by the solar panels. A more detailed analysis of the data is presented in Table 2, which shows the daily peak and average power output per string under both sunny and cloudy weather conditions. The average temperature is computed over the time in which the solar panels were generating power.

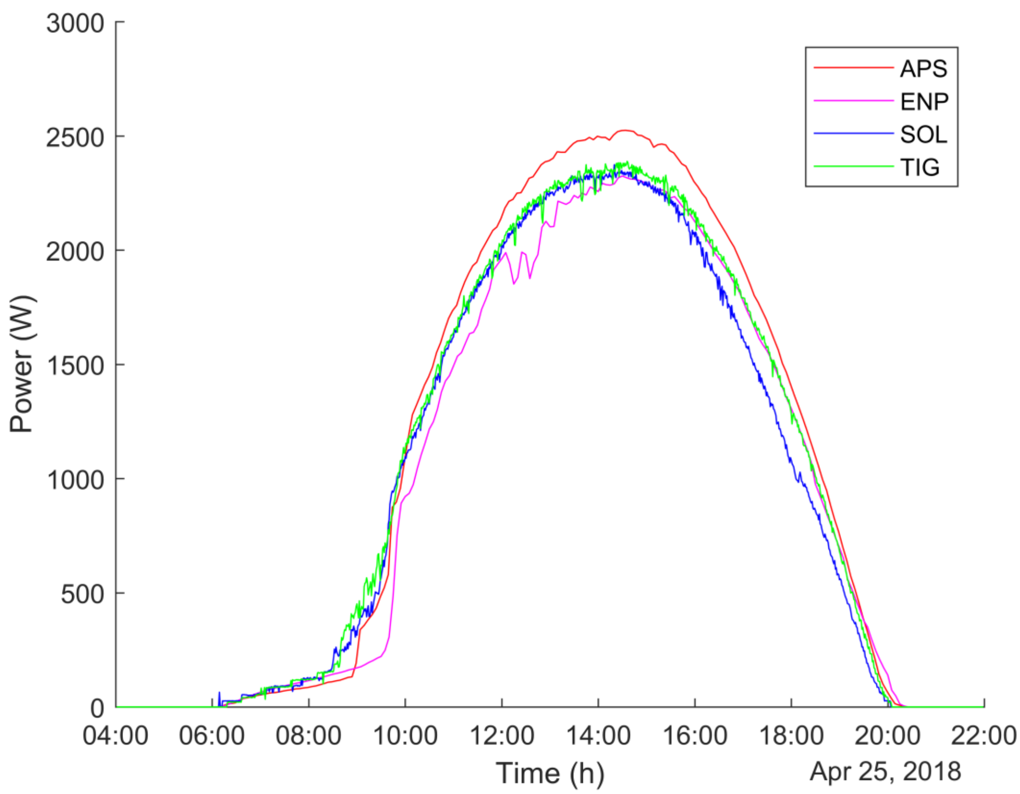

Figure 4: Power output on sunny day: 4/25/2018

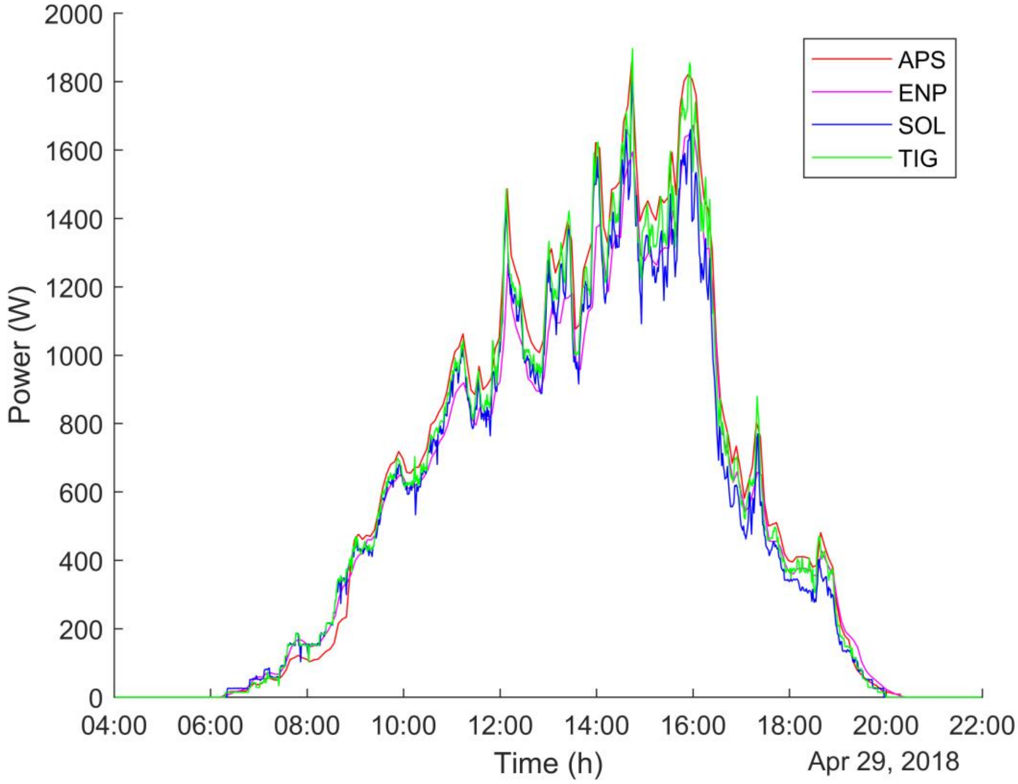

Figure 5: Power output on cloudy 4/29/2018

Table 2: Power and energy output with no shading

Converter	Weather	Avg. temp (°C)	Peak power (W)	Avg. power (W)	Total energy (J)
AP Systems	Sunny	13	2524	1352	19161
	Cloudy	11	1839	738	10337
Enphase	Sunny	13	2324	1227	17182
	Cloudy	11	1672	671	9391
Solectria	Sunny	13	2374	1245	17427
	Cloudy	11	1800	668	9355
Tigo	Sunny	13	2389	1302	18226
	Cloudy	11	1896	708	9912

Based on the data collected, it is evident that the AP Systems microinverters performed better than the other MLPEs for both sunny and cloudy conditions. This is expected since each solar module is connected to its own microinverter for optimal energy extraction. Therefore, partial shading of the string has less of an impact. The poor performance of the Enphase microinverters is rather unexpected, as one would expect them to perform better than both the Solectria string inverter and the Tigo DC-DC optimizers. One potential reason for their slightly lower peak and average power output could be the location of the Enphase meters, which could have incurred losses between the point of sensing and the point of measurement. Finally, differences in performance between the Tigo and Solectria converters were negligible, with the Tigo DC-DC optimizers performing slightly better in most cases.

2.4 Shading Impact

Shading cloths were used to investigate the effects of shading on solar panel power output. Black shading cloths designed to let 90% of light through covered the panels in different physical arrangements. Four different shading setups were investigated.

Shading Setup 1:

Figure 6 illustrates the first physical arrangement of the cloth that was tested. The cloth covered an entire column of four modules, each connected to a different power electronic converter. Figure 7 shows a photograph of the actual experimental setup. Data was collected from May 10, 2018 to May 23, 2018 and are presented in Table 3.

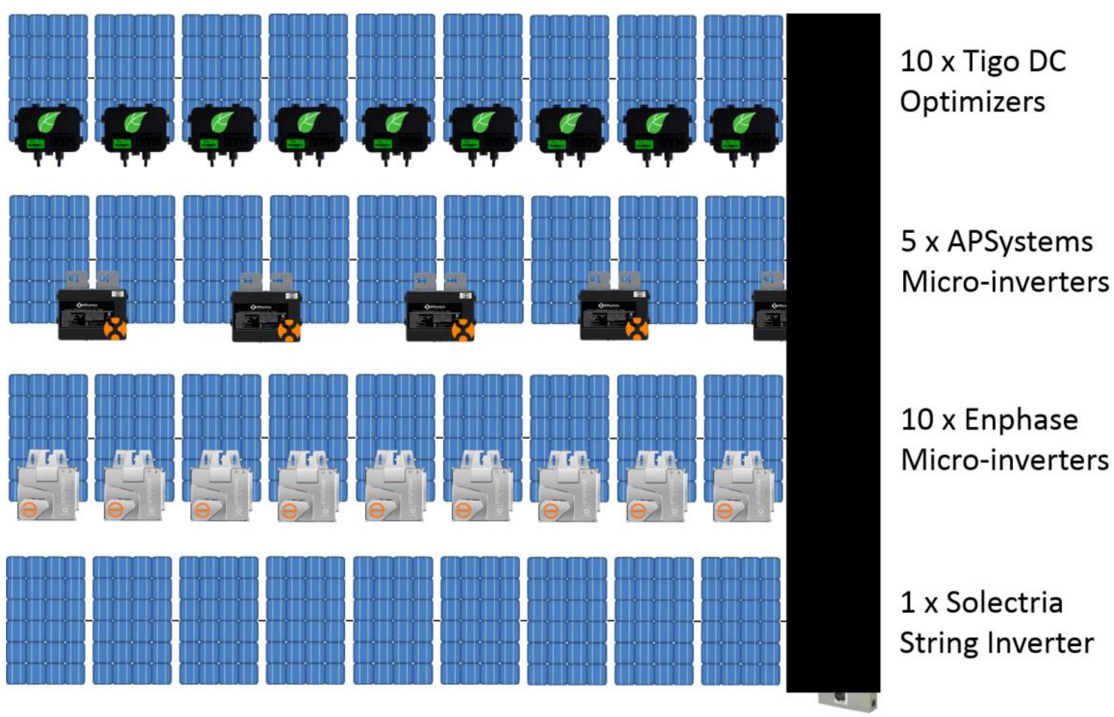

Figure 6: Shading setup 1

Figure 7: Shading setup 1 implementation

Table 3: Power and energy output with shading setup 1

Converter	Weather	Avg. temp (°C)	Peak power (W)	Avg. power (W)	Total energy (J)
AP Systems	Sunny	16	2216	1199	17981
Enphase	Sunny	16	2022	1028	15427
Solectria	Sunny	16	1771	922	13836
Tigo	Sunny	16	2092	1136	17035

Figure 8 shows the plots of power generated from the different solar strings for this shading setup on May 22, 2018. From the figure, it is clear that Solectria performed significantly worse compared to the other converter topologies. This is expected since all the other converters operated on the module level, alleviating the bottleneck of low power generation from the shaded modules.

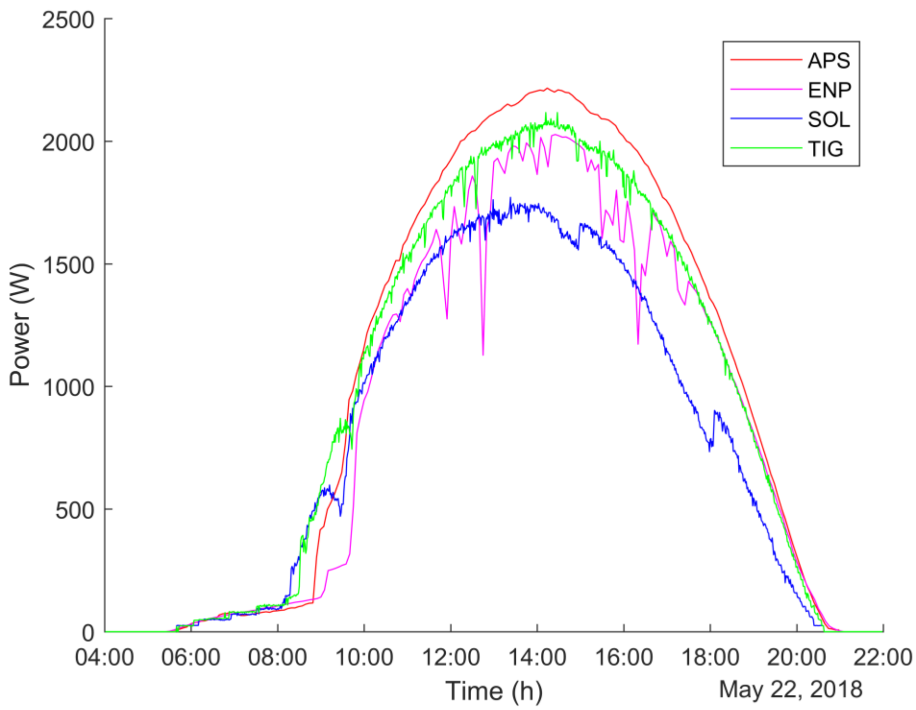

Figure 8: Power output on 5/22/2018

Shading Setup 2:

Figure 9 shows the second shading arrangement that was tested where a cloth straddled two columns of solar panel modules. Data was collected between June 13, 2018 and July 9, 2018. The data from this shading arrangement is presented in Table 4.

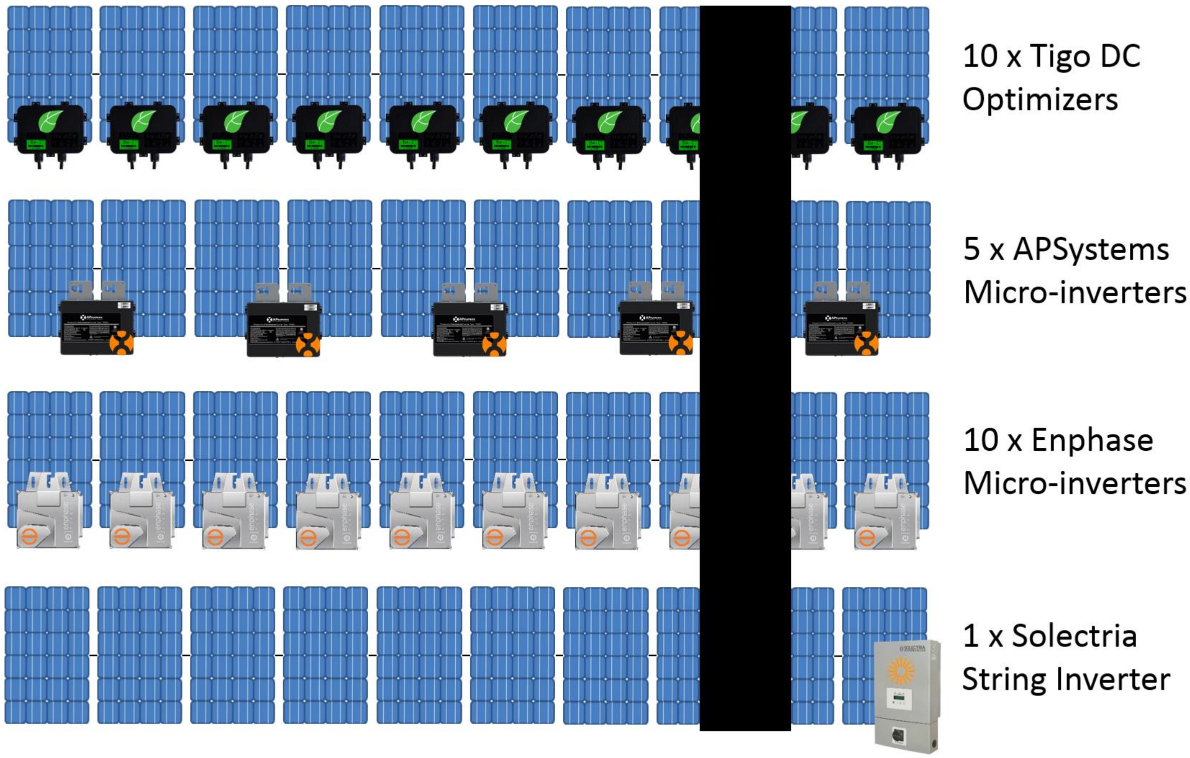

Figure 9: Shading setup 2

Table 4: Power and energy output with shading setup 2

Converter	Weather	Avg. temp (°C)	Peak power (W)	Avg. power (W)	Total energy (J)
AP Systems	Sunny	20	1984	1024	16381
Enphase	Sunny	20	1836	895	14322
Solectria	Sunny	20	1938	991	15856
Tigo	Sunny	20	1940	983	15724

Figure 10 shows the power generated from the different solar strings for this shading setup on June 18, 2018. Compared to setup 1, the average power generated for all converters except Solectria has decreased. This is due to the fact that there were two modules affected by the shading instead of one, which resulted in decreased power output from both. The solar panel string connected to the Solectria inverter experienced an increase in the power generated compared to setup 1. This is because for the string inverter, the power output was dominated by the worst performing solar module. In setup 2, since the modules were only partially shaded, their performance was not worse than the worst module of setup 1, which was completed shaded. Therefore, the overall power generated remained higher for the string inverter of setup 2 than the other MLPEs.

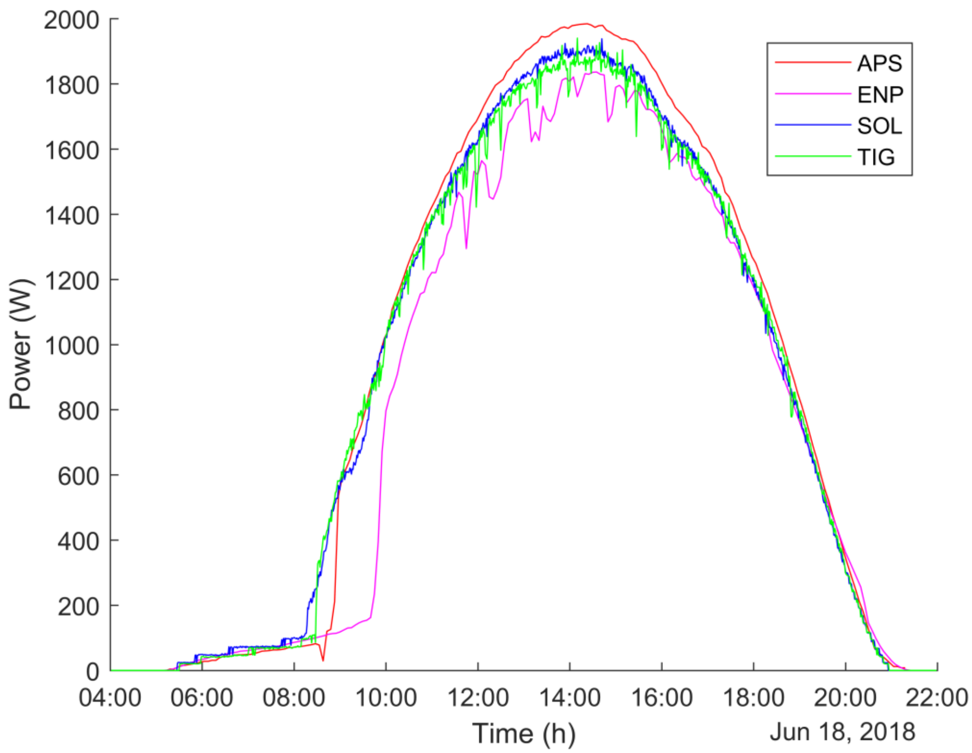

Figure 10: Power output on 6/18/2018

Shading Setup 3:

Next, an additional column of cloth was added to increase the shading. The resulting test setup is shown in Figure 11. A photograph of the test site is shown in Figure 12. Data was collected from July 10, 2018 to July 23, 2018. Figure 13 shows the power output on July 15, 2018. Table 5 tabulates the data collected for this shading arrangement.

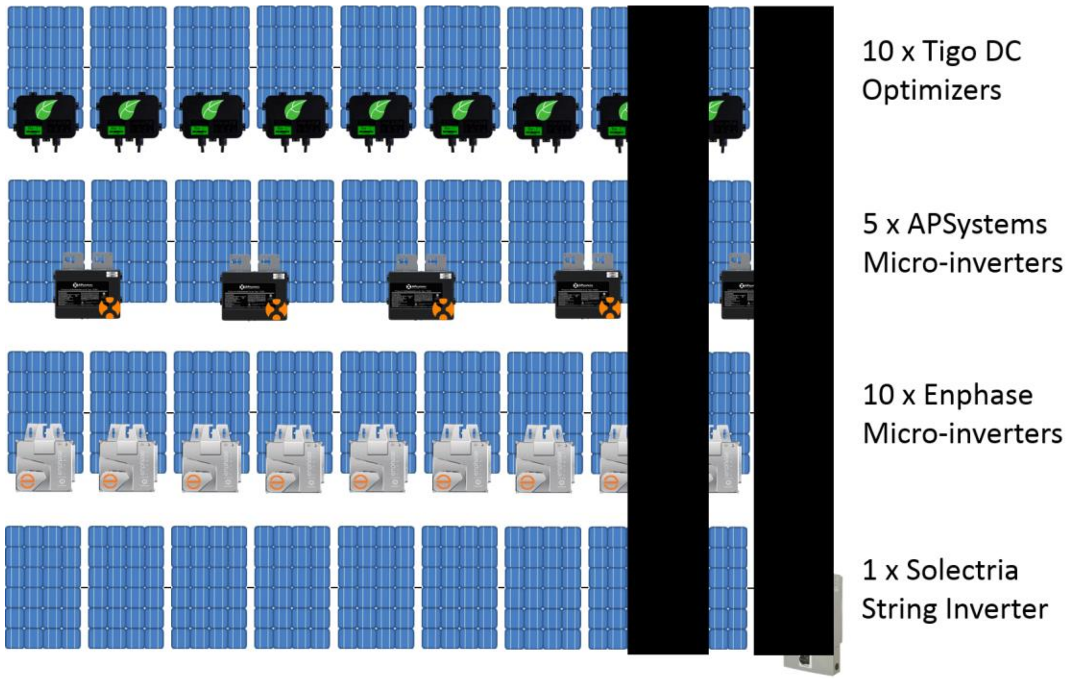

Figure 11: Shading setup 3

Figure 12: Shading setup 3 implementation

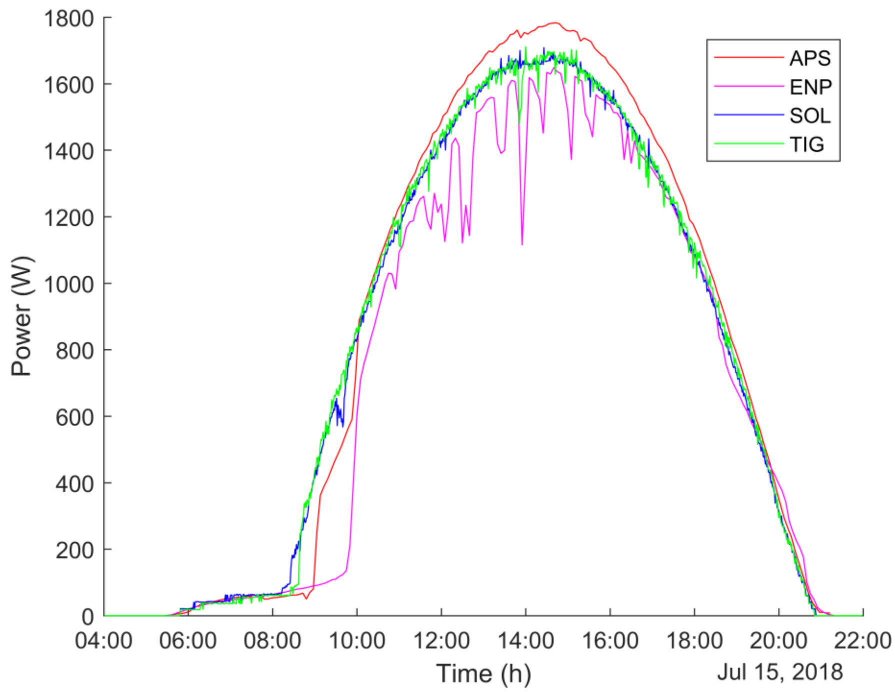

Figure 13: Power output on 7/15/2018

Table 5: Power and energy output with shading setup 3

Converter	**Weather**	**Avg. temp (°C)**	**Peak power (W)**	**Avg. power (W)**	**Total energy (J)**
AP Systems	Sunny	21	1783	933	14457
Enphase	Sunny	21	1648	814	12616
Solectria	Sunny	21	1709	900	13952
Tigo	Sunny	21	1711	905	14027

Compared to setups 1 and 2, setup 3 generated even less power, which is expected due to the increased shading. However, it is also evident that the decrease in the generated power was nonlinear. That is, the percentage decrease in the generated power for setup 3 was not simply the sum of the percentage decrease in generated power for setups 1 and 2.

Shading Setup 4:

The final shading arrangement is shown in Figure 14, where four modules from each string experienced partial shading. A photograph of this test setup is shown in Figure 15.

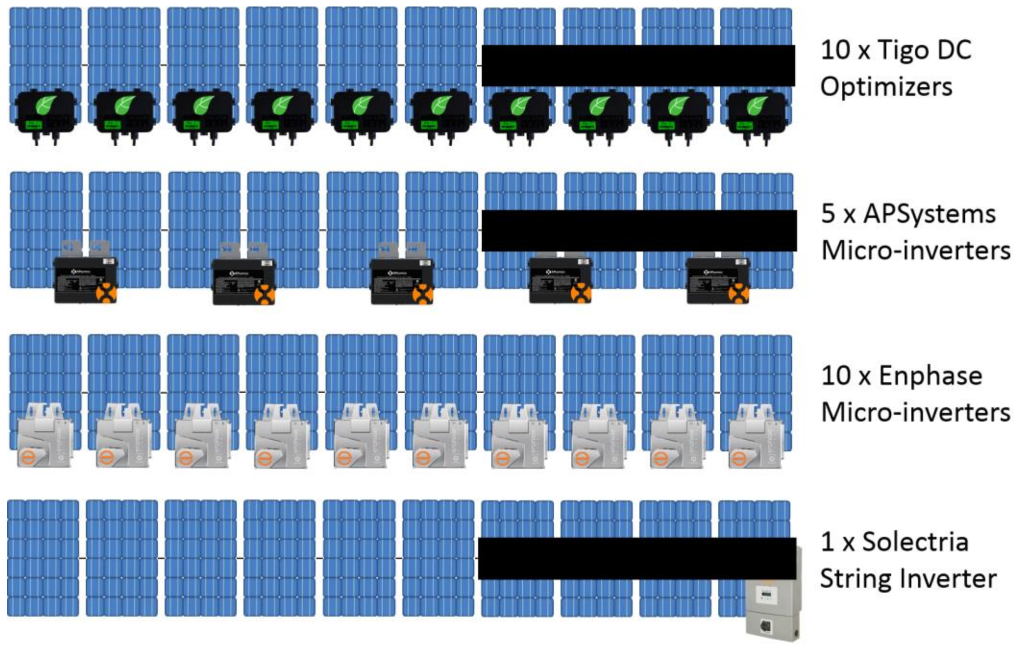

Figure 14: Shading setup 4

Figure 15: Shading setup 4 implementation

Data was collected from July 25, 2018 to July 30, 2018. Figure 16 shows the power output on July 25, 2018. Table 6 tabulates the data collected for this shading arrangement.

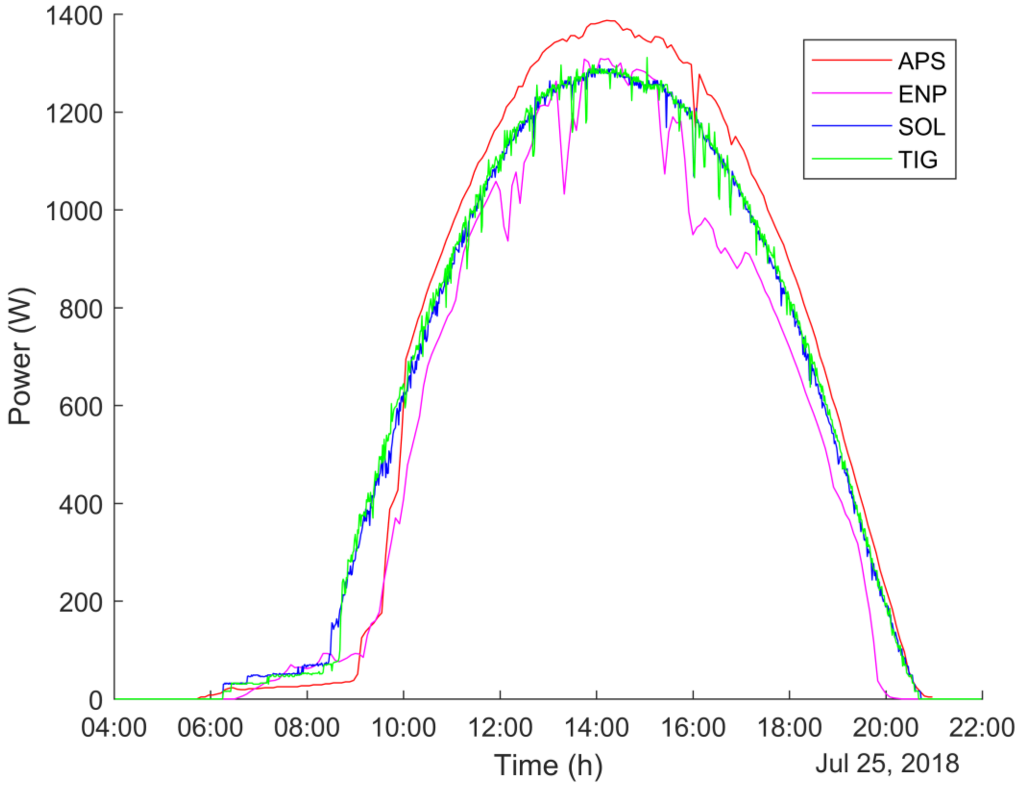

Figure 16: Power output on 7/25/2018

Table 6: Power and energy output with shading setup 4

Converter	**Weather**	**Avg. temp (°C)**	**Peak power (W)**	**Avg. power (W)**	**Total energy (J)**
AP Systems	Sunny	22	1387	732	10986
Enphase	Sunny	22	1309	620	9298
Solectria	Sunny	22	1296	698	10469
Tigo	Sunny	22	1311	701	10522

This shading arrangement resulted in the lowest power output from all solar strings across all setups.

2.5 Smoke from Wildfires

During summer months, wildfires in the Pacific Northwest are a frequent phenomenon. The smoke produced by these fires often result in smoggy conditions, which affect the performance of the solar panels. In 2017, there were a total of 1,346 wildfires reported in Washington, which burned through 404,223 acres of forest [13]. Wildfires are also a major concern in states neighboring Washington as the smoke has the potential to propagate over long distances. This project examined the effects of smog on solar panel power output as there was a large fire that occurred in the week of August 13, 2018.

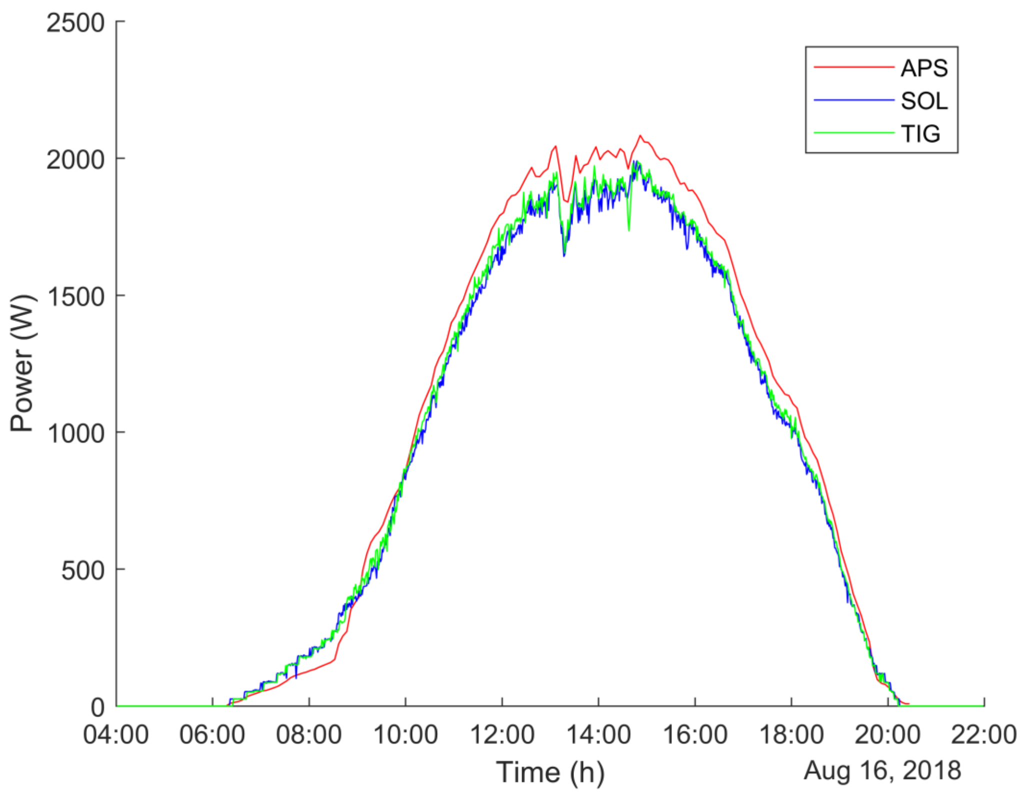

Figure 17: Power output on 8/16/2018

Figure 17 shows the power output of the solar panels on August 16, 2018, with no shading cloths but under smoggy conditions. There was no cloud cover. Compared to Figures 4 and 5 of sunny and cloudy days, respectively, it can be concluded that while the smog did decrease the power generated by the solar panels, it did not affect them as much as the cloud cover did. When a cloud covered the sun, the power output of the solar panels dropped immediately, resulting in the "jagged" power generation curves. Since the smog was more persistent, lasting over several days, the power generation curve from the solar panels under smoggy conditions remained "smooth".

Table 7 lists the peak and average power output for each converter type, as well as the total daily energy generated under smoggy conditions. From the data, it is evident that the smog did decrease the power generated from the solar panels but not to the same extent as that of shading the panels. This is because even with the smog, diffuse and reflected irradiance were able to reach the solar panels.

Table 7: Power and energy output with smoggy conditions

Converter	Weather	Avg. temp (°C)	Peak power (W)	Avg. power (W)	Total energy (J)
AP Systems	Smog	17	2083	1127	15774
Solectria	Smog	17	1990	1051	14714
Tigo	Smog	17	1988	1067	14932

3.0 Student and Faculty Experience

Every collaborative project brings about benefits as well as challenges. Cross-institutional projects such as this not only institutes long-term partner relationships but also allows each institution to leverage their strengths, creating a stronger team and allowing for cross-institutional training and educational opportunities. Table 8 highlights the key benefits of this collaboration.

Table 8: Key benefits to each stakeholder

Technical College Students	University Students	Faculty Members	Industry Partner
Participate in applied industry-based research projects	Gain access to state-of-the-art technical labs and equipment	Develop working relationships to advance academic and technical knowledge	Collaborate with local academic institutions
Apply theory to practice	Gain hands-on technical skills	Share lab facilities and expertise	Opportunity for cost effective research
Work with university students and industry experts	Collaborate with BTC faculty and industry experts	Work with industry to identify research opportunities	Develop relationships with students - early recruitment opportunities

The participants were surveyed about their experience with this project and encouraged to provide feedback. Overall, the diverse nature of the team involved in this project was instrumental to its success. No one member held all of the knowledge needed to answer the research questions posed. Each member of the team was aware of his or her responsibility within the execution plan of the project.

Participating in projects such as these has been shown to build student self-efficacy as well as a sense of belonging [14] [15]. These attributes contributed to the overall success of the project related to both technical aptitude and interpersonal relationships and helped students to develop confidence in their ability to work through challenges.

"This project helped me find my voice in project development. This is something I struggled with in the beginning of the project. I learned that I need to voice when I have ideas and being wrong is not a bad thing. There are many parts in a project where ideas shift and something you try to do may not work. It is okay, it is part of the process. This has given me the courage to try some things that might be more of a pipe dream. I know that just engaging in the process is progress." – BTC student

"Before coming to the university, I have spent some time at a community college and a technical school, which made working with the students from BTC particularly rewarding. In my experience, educational institutions benefit when their students can share learning opportunities like this as it leads to a more diverse and holistic experience." – WWU student

"Working with these technologies outside of the lab on a larger scale gave me a greater appreciation for the scope of the engineering challenge associated with a solar installation. The difficulties we ran into during our research and the problems we needed to solve helped us develop technical understanding of a real-world solar installation. These problems also helped us build teamwork and communication skills by requiring collaboration with the other students, faculty, and industry partners." – WWU student

"One of the benefits of working on this project was establishing a relationship with faculty at the university. Working with the faculty from WWU has been rewarding as it has allowed me to extend my professional network beyond the technical college in a meaningful way. I imagine this relationship will continue beyond this project as we have already started thinking of ways we can collaborate on projects in the future." – BTC faculty

"This project provided me with project management experience in addition to the technical expertise. It will allow me to give more enlightening lectures to my students. I found the experience of working on a larger project like this very rewarding. We were able to learn from each other and lean on the strengths of each person." – WWU faculty

"I think was a really great project for these students to be able experience a few important aspects of how solar is integrated into the real world. It was not only a good educational research study, but also a hands-on opportunity for the students to experience a skilled trade. Itek believes strongly in education and outreach to the community. We are happy to be involved in this project and any in the future. We also got an upgrade on our solar array." – Itek employee

This real-world experiential learning for the students was essential for their growth and understanding as an engineer. The students were exposed to systems engineering, where they managed this project from its inception to termination. The relationships developed extended beyond the project timeline and allowed for future collaboration opportunities.

4.0 Conclusion

With the rapid proliferation of solar generation onto the distribution system, it is important to provide engineering students the hands-on experience of working with these renewable devices. Students from a university and a technical college worked together alongside faculty and professional engineers from industry to design, install, and test different solar panel converter topologies. The effects of shading and weather conditions were carefully documented. The data collected were useful for the industrial partner in their development of better solar panels. The students also gained invaluable field experience, developed communication skills, learned about project management, and built relationships with industry.

Analysis of the data gathered from this project showed that AP Systems microinverters were the most efficient under all weather and shading conditions. Tigo DC-DC optimizers were the second most efficient converters under most cases. Surprisingly, Enphase microinverters performed only better than the Solectria string converter. Future work includes investigating the sources of inefficiencies within the different types of converters and observing the long-term reliability of the MLPEs.

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