1A. Conceptual System Design
Northern Arizona University
NAU Capstone

1 System Design Summary of Approach and Solution

The system designed for the New Mexico State University (NMSU) district consists of three different systems: the Pan American Center Solar Parking Awnings, Geothermal Substation Ground Mount system, and Hadley Hall Spanish Solar Tiles. All three subsystems were designed in both Aurora solar [1] and System Advisory model (SAM) [2] to create more accurate models. The team's approach for the NMSU district was to prioritize financial feasibility and the campus's goals stated in the District Master Plan. The team also wanted to ensure there were three components present in the final system: efficiency, practicality, and creativity. Secondly, we wanted to create innovative designs that could benefit the campus with more than just electricity. The results of the innovative designs are shown in the solar parking awnings and the Spanish solar tiles on Hadley Hall. The parking awnings will create over 570 shaded parking spots—a substantial increase from the campus's original 10 spaces. The solar Spanish tiles located on Hadley Hall will not only generate electricity, but it preserves the Spanish Renaissance style the university has throughout its campus.

The team believes Hadley Hall is the best location for the Spanish solar tiles because this building is a common area shown on campus tours, and it houses the campus administration. The panels provide a great talking point on tours and will promote innovation and renewable energy for the campus, one of its major goals in the District Master Plan. The Spanish solar tiles design is meant to be a creative design that is both functional and aesthetically pleasing to look at. The design is not meant to be the most efficient or cost-effective design, but instead an innovative solution to align with the university's needs. The lack of efficiency and financial savings are compensated for and offset in the other two systems.

Figure 1: Spanish Solar Tiles Subsystem

The second design is the Pan American Center Solar Parking Awnings. This design is located in the Pan American Center parking lot which is one of the largest parking lots on campus. The parking structure will be south facing, meaning the parking spaces will have to be re-painted running east to west. The parking awnings will be able to shade 577 parking spots, making them the majority of the covered parking spaces on campus. By converting the parking spots to covered parking, an increase in price can be charged annually on the parking permits for that lot. After comparing covered parking prices from different colleges and the current parking prices at NMSU, the team believes charging $78 extra for each spot is a conservative value when comparing to other universities. With a 2% inflation value, the parking structure itself would generate roughly 1.1 million dollars after 20 years. This extra revenue combined with the 2MW PV system makes the parking structure a very desirable design. There are two drawbacks to the system: the mounting system costs more than a ground mount system, and the panels won't be optimally tilted. To ensure full shading underneath the panels, the awnings will have a collective tilt of 10 degrees. The solar parking awnings' purpose is to provide solar energy and double as shaded parking and extra income.

Figure 2: Solar Parking Awning Subsystem

The Geothermal Substation Ground Mount system was designed with one goal: to produce the most energy possible for the lowest price. The plot of land located next to the Geothermal Substation is the largest area given in the NMSU district use case. The system is sized at 3MW in total. At 3 MW, the system has the lowest cost per watt out of all three subsystems. The Geothermal Substation system is located 3 miles east of campus. The land is flat and barren, making it ideal for a solar field.

Looking at all three system designs, each represents one of the team's primary goals: an efficient design, a practical design, and a creative design that is aesthetically pleasing.

2 Description of Equipment Selection & Specifications

The total system size of all three designs is 5.1 MW (DC). The Geothermal Substation Ground Mount system is 3 MW. The Pan American Center Solar Parking Awnings are just under 2 MW, and the Hadley Hall Spanish Solar Tiles produce 164kW. The accompanied battery system is sized to 220 kW to help flatten out the electrical peaks that come with solar power. Originally the team planned to make the system at the Geothermal Substation an 8 MW system to produce as much energy as possible. After using REopt Lite the team discovered a 5MW system across the entire campus is the largest we can create without an excess production.

The PV modules used for both the parking structure and geothermal substation are SunPower T5-SPR 310 mono crystalline (Silicone) panels. This PV module was picked because the high irradiance in New Mexico makes monocrystalline panels more cost effective and helps produce more energy in a smaller area. The panels have a nominal efficiency of 19%, and a max power of 310 Wdc. The Solar Spanish Tiles are Hantiles which are thin-film modules. To model them in SAM we used Avancis PowerMax STRONG 115 thin-film, which had almost identical W/m^2. The Solar Tiles design in SAM was altered to produce the same energy the Hantiles would over that area.

The inverters for the solar tiles are the ABB: PVI-3.6-OUTD-S-US-Z-A [208V] which have an efficiency of 95.77% and a maximum AC power of 3600 Wac. The subsystem will have 34 inverters giving it a DC to AC ratio of 1.35 and a total AC capacity of 122.4 kWdc. The inverters for the system at the Geothermal Substation are SMA America: SC850CP-US inverters which have an efficiency of 97.594% and a maximum AC power of 888000 Wac. Because the inverters are so powerful, this design will only use 3 of them and the DC to AC ratio is 1.13. The Solar Parking Awnings use the same inverter as the Geothermal Substation Ground Mount system, but only uses 2 of them giving it a DC to AC ratio of 1.10.

Battery storage will be implemented near the Geothermal Substation building. If needed, a small storage unit can be installed to house the batteries. The battery the team chose to use is the Greenrock salt water battery module [5]. The optimal size of the storage system is found to be 585 kWh of capacity and 222 kW battery power and was determined through REopt lite [6]. This is the most economically feasible design while still providing resilience for the campus. Greenrock offers battery container packages at a maximum size of 270 kWh, so the team hopes to purchase two of these and one 30 kWh system for a total of 580 kWh, which is only 5 kWh off from the optimal size [7]. The battery systems should last more than 15 years with 70% usable capacity which makes them attractive because there is little maintenance needed—only needing to be replaced once every 15 years [5]. The batteries will be set up using the energy management system and the connection box, off grid-inverters that come with the container package. There will be 2 Connection Box Grandes, and one Connection Box Compact to accommodate the 19 battery modules needed for the system. This battery storage system will be connected as an on-grid system but is still able to function when the grid power goes out, providing back-up power for essential applications. The battery sub-system is sized according to its respective photovoltaic array and is capable of producing up to 14 A at 480 V to be delivered downline to our distribution system.

The total system is 5.1 MWs and contains 1,434 Hantiles, 15,948 SunPower modules, 34 microinverters and 5 high capacity industrial inverters. For the Geothermal Substation Ground Mount system and Pan American Center Solar Parking Awnings there are 12 modules per string, giving a maximum DC voltage of 820 Vdc and minimum MPPT voltage of 620 Vdc. These analyses were all done in SAM and the battery analysis was done in both REopt lite and OpenDSS. SAM is a powerful tool for financial analysis and REopt lite was essential for creating the battery system. The salt water batteries are a perfect match with PV generation because batteries are typically very harmful to the environment, but saltwater batteries are completely recyclable. The battery storage system will be utilized to help find equilibrium between the production and consumption lines. The team would like to note that as batteries continue to decrease in price, a large storage system might be implemented in the future.

Optimizing the system for this competition is dependent on one value: $/kW. This value determines how much we can charge for electricity. The Geothermal Substation Ground Mount system and the Pan American Center Solar Parking Awnings were designed to minimize our PPA price and hopefully net the university some profits. The Hadley Hall Spanish Solar Tiles were created to give the university good public relations which can increase student enrollment and help meet their goal towards being carbon neutral by 2050.

3 Site Plan for the Entire District

The final design consists of one system in each area provided by the university. The Hadley Hall Solar Spanish Tiles are in the Horseshoe Quad. The Geothermal Substation Ground Mount system is in the vacant dirt lot away from campus, and the Pan American Center Solar Parking Awnings are in the main part of campus.

The Hadley Hall Spanish Solar Tiles design has 6 modules per string and 47 strings in parallel on the north and south side. There are 72 strings in parallel on the east and west sides. Ideally, the inverters would be stored inside of the building but if this isn't available, the new Mexico heat won't affect the efficiency of the inverters significantly. The birds-eye view of the Hadley Hall building is shown in Figure 3.

Figure 3: Hadley Hall

The Pan American Center S parking structure will consist of 12 modules per string with 523 strings in parallel. This is broken into 5 separate structures with one smaller structure on the side. Four of the structures contain 1260 PV modules and the fifth one has 1236 modules. Each awning should produce around 390 kWdc. The two inverters will either need to be located inside the Pan American Center or outside the parking lot. A birds-eye view of the highlighted lot is shown in Figure 4.

Figure 4: Pan American Center Location

The Geothermal Substation Ground Mount System is located three miles east of campus and just southeast of the NMSU golf course. This system has 12 modules per string and 806 strings in parallel. All the panels are south facing with a 30 degree tilt. The optimal tilt for New Mexico is 32.7 degrees tilt, but the tilt was changed to 30 degrees for manufacturing purposes. The ground coverage ratio of the dirt lot is 0.5 when the panels are horizontal. This value should give little to no shading at all on the panels. A birds-eye view of the lot used in the Geothermal Ground Mount system is shown in Figure 5.

Figure 5: Half of the Geothermal Substation Subsystem

The solar altitude of New Mexico is 44 degrees and the team used right triangle rules to determine the optimal spacing.

4 Individual System Plans & One Line Diagrams

The line diagram for the saltwater batteries system for AC and DC coupling is given in the informative PDF shown in Figure 6 [7]. This diagram shows how the wires connect the modules to the inverter then the battery system and then the electricity can be sent to the grid or buildings.

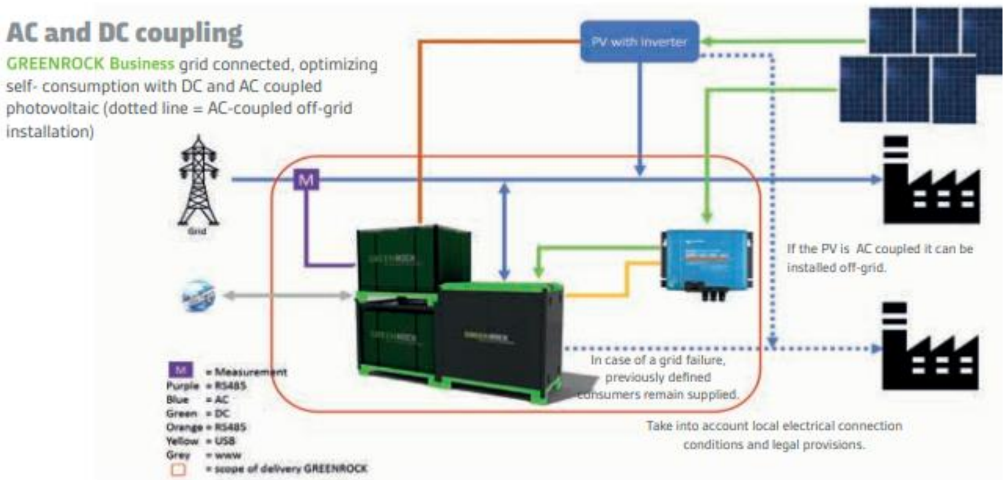


Figure 6: Batteries line diagram

The one-line system designs for our three photovoltaic arrays along with their peripheral circuitry can be found below in figures 7 and 8. Each block is labeled with the name of the circuit element and shows the line phases and power signal being transmitted. The Geothermal Substation Ground Mount sub-system is the largest of the three and as such is divided into three sections. The one-line system for this design is shown in Figure 7.

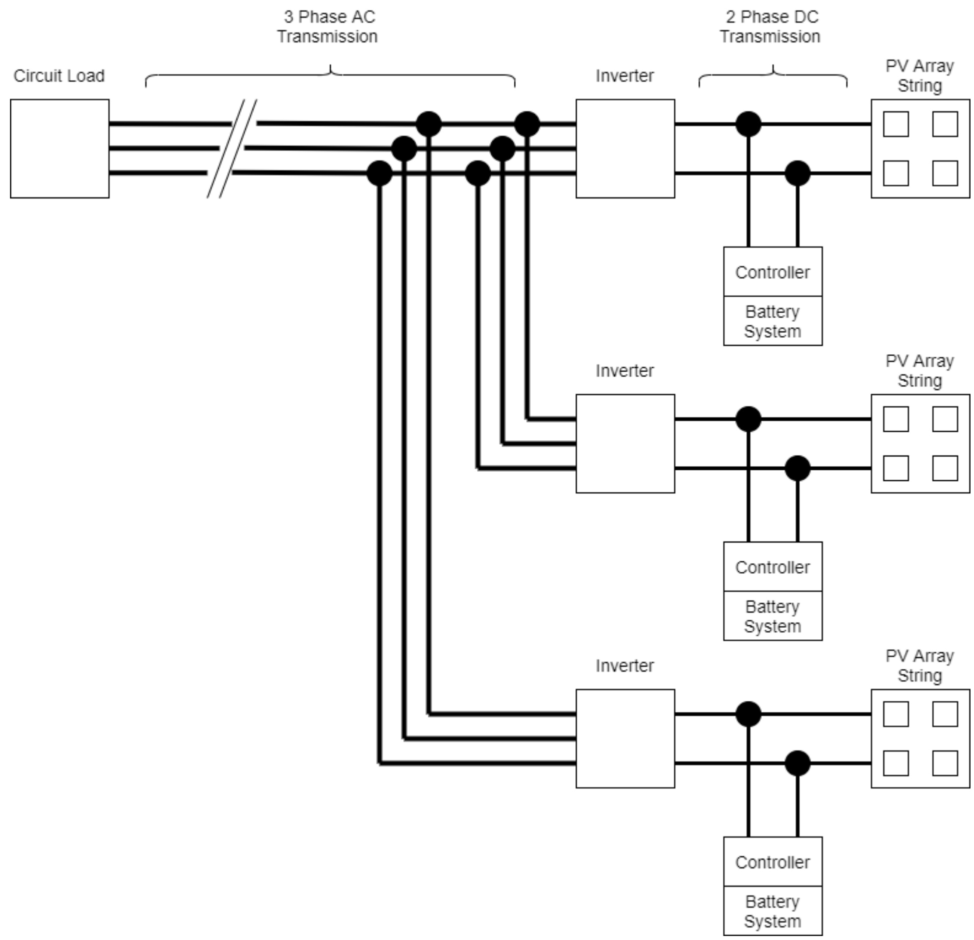


Figure 7: One-line diagram for the dirt lot sub-system

Neither the Hadley Hall Solar Spanish Tiles nor the Pan American Center Solar Parking Awnings have integrated battery sub-systems, so their one-line diagrams are not significantly distinct. The one-line diagram for the two designs is shown in Figure 8.

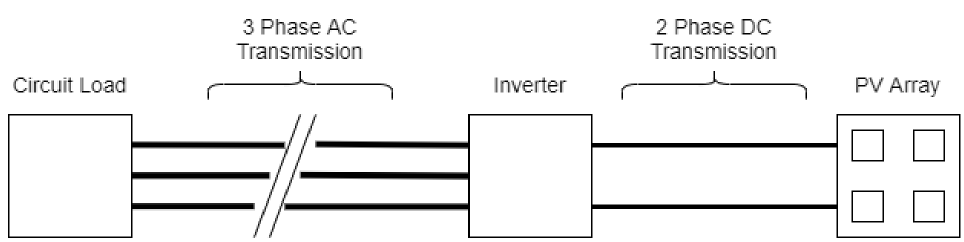
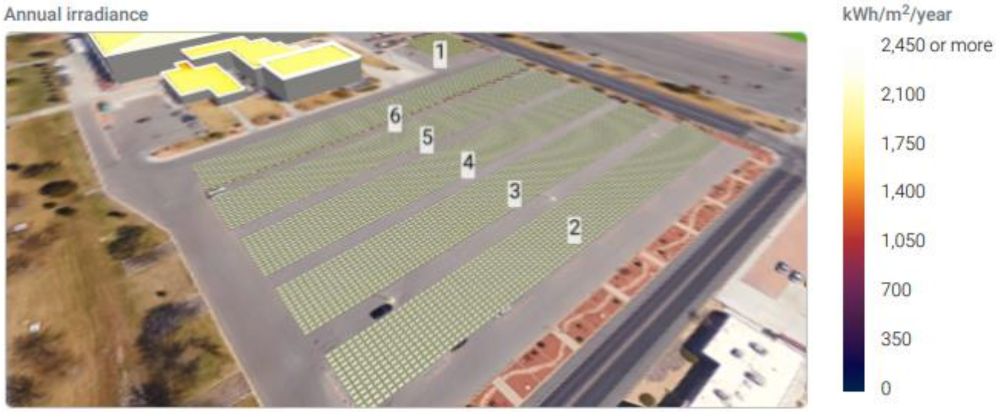


Figure 8: One-line diagram for the Hadley Hall and parking structure sub-systems

5 Shading Models for Each Installation

The shading models for each installation were generated using Aurora Solar [1]. The models show the annual irradiance of each design along with further details of the number of panels, the azimuth angle, the pitch, annual tilt and orientation factor (TOF), annual solar access, and annual total solar resource fraction (TSRF).

The Solar Parking Awning shading report shows that TOF and TSRF are the same which implies that there is no shading on the panels. They are not at 100% because the angle the panels are tilted at is not optimal.



Summary

Array	Panel Count	Azimuth (deg.)	Pitch (deg.)	Annual TOF (%)	Annual Solar Access (%)	Annual TSRF (%)
1	432	168	3	90	100	90
2	1235	169	9	94	100	94
3	1235	169	9	94	100	94
4	1235	169	9	94	100	94
5	1235	169	9	94	100	94
6	1235	169	9	94	100	94
Weighted average by panel count	-	-	-	-	99.9	93.6

Figure 9: Parking structure Irradiance

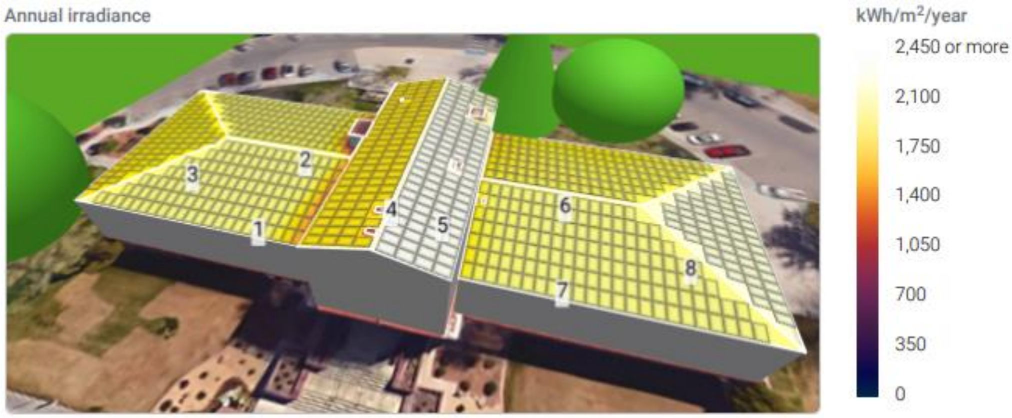
Monthly solar access (%) across arrays

Array	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	100	100	100	100	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100	100	100	100	100
3	99	100	100	100	100	100	100	100	100	100	100	100
4	99	100	100	100	100	100	100	100	100	100	100	100
5	99	100	100	100	100	100	100	100	100	100	100	100
6	99	100	100	100	100	100	100	100	100	100	100	99

Figure 10: Parking structure Monthly solar access

The Spanish Solar Tile shading model is not as ideal as the parking solar awning due to shading. Because the panels will cover the entire roof the team designed a system of solar panels that covers the entire roof to model the shading that would affect the solar tiles (figure 11). The TOF and TSRF are different for most of the sections of the building because either the building or the surrounding trees shade the roof which increases the losses. The design still gets a decent amount of irradiance because of the high irradiance in New Mexico which is one of the reasons why the design is viable.

Spanish Solar Tiles



Summary

Array	Panel Count	Azimuth (deg.)	Pitch (deg.)	Annual TOF (%)	Annual Solar Access (%)	Annual TSRF (%)
1	128	258	10	89	96	85
2	128	78	10	86	94	81
3	71	348	10	81	97	79
4	100	349	15	76	100	76
5	96	169	15	97	99	96
6	131	78	10	86	94	81
7	130	259	10	89	99	88
8	63	168	10	94	100	94
Weighted average by panel count	-	-	-	-	97.1	84.6

Figure 11: Spanish Solar Tiles Irradiance

Monthly solar access (%) across arrays

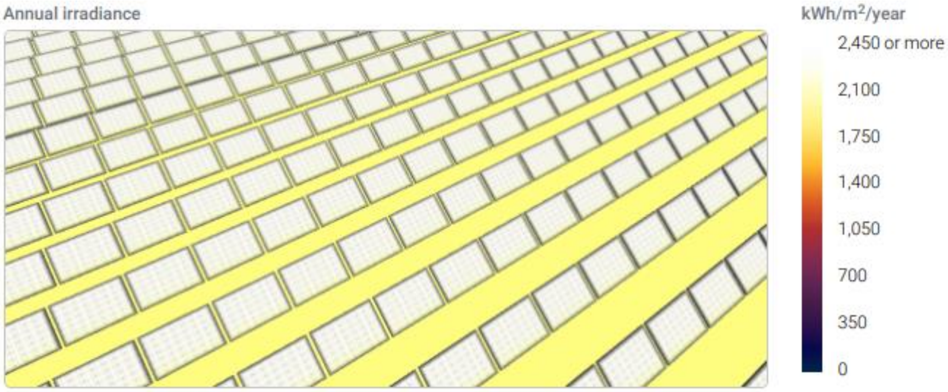
Array	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	88	92	95	98	99	99	99	98	96	92	89	86
2	87	90	93	96	98	99	98	97	95	91	86	83
3	97	98	98	97	96	96	96	97	98	98	98	98
4	99	99	100	100	100	100	100	100	100	99	99	99
5	99	99	99	99	100	100	100	99	98	99	100	100
6	94	94	94	94	94	94	94	94	94	94	95	96
7	99	99	99	99	99	99	99	99	99	99	99	99
8	100	100	100	100	100	100	100	100	100	100	100	100

Figure 12: Spanish Solar Tiles Monthly Access

The Geothermal substation ground-mount system performs similarly to the parking awning because there is very little to no shading. The panels shade each other a very small amount which is why the TOF and TSRF are different. The TOF is 100% because the panels are south facing and tilted at 30 degrees which is the optimal set up for the location. The Lidar (figure 14) shows that the design is in a location with elevation that is north of the design so shading from the mountain should not affect the panels, and the ground is flat where the design is so minimal landscaping is required.

Geothermal Substation

Annual irradiance



Summary

Array	Panel Count	Azimuth (deg.)	Pitch (deg.)	Annual TOF (%)	Annual Solar Access (%)	Annual TSRF (%)
1	4712	167	30	100	97	97
Weighted average by panel count	-	-	-	-	96.6	96.6

Monthly solar access (%) across arrays

Array	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	94	97	98	98	98	97	98	98	98	97	95	93

Figure 13: Geothermal Substation Irradiance

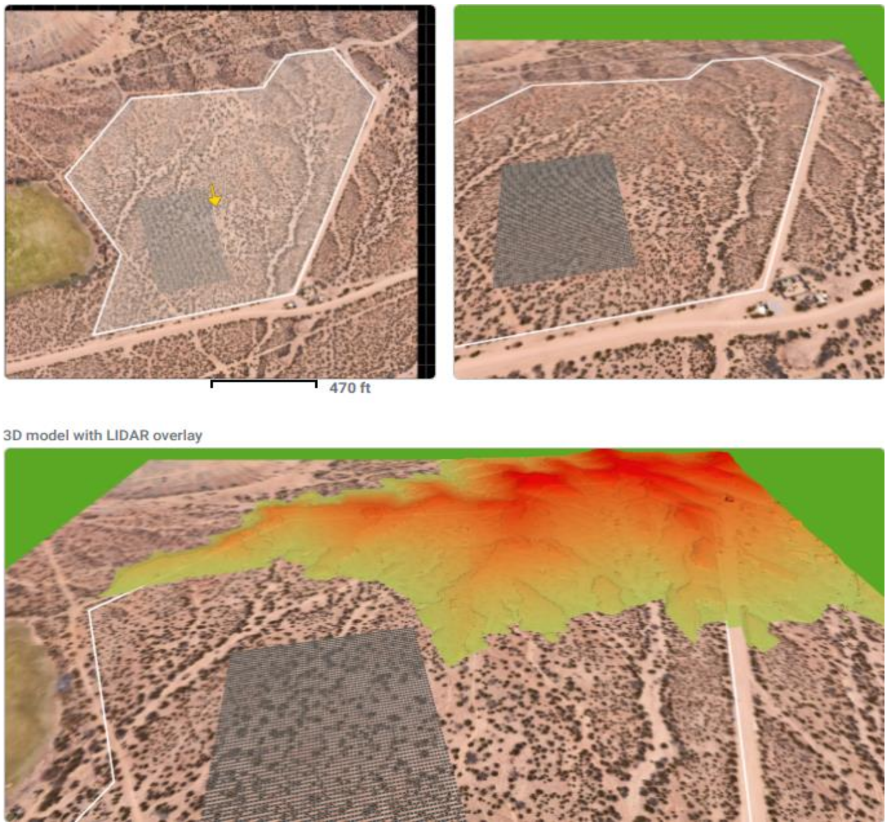


Figure 14: Geothermal Substation Lidar

Before the system can be optimized the team must determine the most important characteristics that define Optimal. In the Solar District Cup the optimal design would follow all of the rules of the competition and district use case while minimizing cost. To determine the real cost of a subsystem the team broke it down into $/ kW or the PPA price. Minimizing the cost of production while also producing enough energy to partially offset the given usage data is important. Another important component for optimizing the system was ensuring minimal losses from shading. The wanted to make sure shading losses were minimal so all 3 designs have little to no shading at all. Lastly was to make sure the system wasn't producing too much energy for the campus too consume at any point during the day. Initially the Geothermal substation was an 8 MW system, after REopt lite and OpenDSS Analysis the team determined the system should be 5MW in total. The dirt lot was reduced by a factor of $3/8^{th}$ to maintain a 5MW system which ensured no energy produced would be wasted at any given time.

Work Cited

[1] 2020. Aurora Solar Inc. SunShot U.S Department of Energy.

[2] 2020. *System Advisory Model*. National Renewable Energy Laboratories.

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[5]"GREENROCK Home," *BlueSky Energy I Stromspeicher Batterien*, 03-Dec-2019. [Online]. Available: https://www.bluesky-energy.eu/en/greenrock-home-2/. [Accessed: 12-Apr-2020]

[6] 2020. *Reopt Lite*. National Renewable Energy Laboratories.

[7] 2020.*Https://Bluesky-Energy.Eu/Wp-Content/Uploads/2019/04/Bluesky-Business-Broschuere_Engl_29042019_Klein.Pdf.* 1st ed. [ebook] BlueSky Energy, pp.1-8.[Accessed 12 April 2020].