AC 2008-2241: LARGE-SCALE PHOTOVOLTAIC SYSTEM DESIGN: LEARNING SUSTAINABILITY THROUGH ENGINEERING CLINICS

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I. Abstract

Working on cutting edge technology projects with industry is a key component of Rowan University's engineering clinics. Industrial affiliates of the College of Engineering are sponsors of the curriculum and bring exciting real world engineering design challenges to our students. The result: industry sponsors education and students provide expertise to renewable energy companies who can benefit from their scientific and thorough electrical engineering approach. This paper highlights one project and an optimization analysis that was completed by engineering students participating in the Rowan Junior/Senior Engineering Clinic sponsored by SunTechnics, a world leader in photovoltaic (PV) system installation. During this project they learned many aspects of sustainability while also applying their electrical engineering knowledge and engineering economics skills to meet an important need. The large scale PV system involved is 3 MW in size and is ground mounted spread across 12 acres in eastern Pennsylvania. At Rowan University a multidisciplinary engineering clinic team has participated in a DC wiring optimization for the electrical circuits for the 390 sub-arrays comprising the design. The system involves the locating of six 500 kW inverters and three 1MVA 480-34.5kV transformers on the site so as to minimize the wire runs and DC losses. The students used their engineering skills to optimize location, wire size selection and junction/combiner locations to assess lifecycle cost over the project's 20 year economic design life. The students were involved in many aspects of the project including the design of novel foundations for the array field, the medium voltage switchgear, and e-metering system specifications. This paper provides an overview of the student contribution to the DC optimization strategy, the use of computer aided design maps, economic analysis and NEC review for various AC wire sizes, load loss calculations for the AC systems with the final product being a well developed and detailed wiring scheme for the installers. The student project team was assisted and led by their electrical and computer engineering professor and a graduate student. The team provided this turnkey technical service to our industrial affiliate and the students learned the best methods for optimizing many components of a large scale PV system. The paper describes our approaches to this project and the impact on student learning.

II. The Clinic Project Begins - [Thursday 20 September 2007 – 2PM]

Without having known or understood what this project would entail, six undergraduate engineers from Rowan University found themselves on a field in Tulleytown, PA conversing with engineers from PECO (Philadelphia Electric Co. – the local utility) and SunTechnics. The topics of their discussion involved the interconnection, pole locations, module placement and everything related to the planned, but not yet designed, 3MW PV power plant to be located at that site. The 15 acre tract adjacent the landfill would soon be covered by more than 17,000 photovoltaic modules. Although the size and complexity of the project seemed overwhelming, this small handful of undergraduate students (and a few others) would play a significant role in the design of the largest PV system to be constructed in the U.S. east of Arizona. From the beginning, the project was designed to throw the students head first into a profoundly real-world, technologically advanced and multi-disciplinary project. The project also offered many hands on learning experiences that created an excitement about engineering and sense of ownership for the students involved. The responsibility and interdependence this brought to the junior, senior and graduate engineering student team working on the project was irreplaceable and irreproducible by any of their more formal engineering classes. None of the students had done any work of similar intricacy or scale. A key reason why the engineering clinic was developed uniquely as a hallmark for the College of Engineering at Rowan University was for these real world experiences to be brought to the classroom. Designed to be the key component of the engineering student's education, it has given many students the opportunity to be part of a project that may look initially intimidating and unapproachable. The details of the clinic are described in numerous papers[1,2,3] so they have not been discussed here. In recent years many other papers have been written to demonstrate the usefulness of the clinic and to share many opportunities that students at this university have had to apply the clinic to innovative renewable energy and sustainability activities[4-10].

III. The Project and the Students' Many Roles

The 3-MW photovoltaic project team was first conceived in early 2007 by SunTechnics[12], a subsidiary of Conergy and the world's largest PV integrator headquartered in Germany. The local company located in Paoli, PA and their sister finance company Epuron worked out the financial model for an energy purchase agreement with Exelon[13]. Exelon Generation Company, LLC through their Wholesale Power Marketing Division located in Kennett Square, Pennsylvania, USA is one of the most active companies within PJM[14] and MISO in creating structured power marketing deals that can best optimize resources for the supply and demand portfolios (including renewable energy) of Exelon and other electric utilities. The growing market for renewable energy certificates (RECs) in the PJM market place (particularly Pennsylvania and New Jersey) has been spawned by the aggressive renewable portfolio standards that have been legislated in many states within the US and across PJM. This PV power plant will be the first to deliver multi-megawatt power to the PJM[14] grid. PJM is the largest Regional Transmission Organization (interconnection) in the world. Epuron has developed a group of investors who desire to own this project based upon the cash flow that the annual purchase of energy and RECs by Exelon creates and the value of the tax credits in the near-term. By the summer of 2007 the financial team was able to reach agreement on pricing and the technical aspects of the project were started. It was at that time that SunTechnics, a former Industrial Affiliate of Rowan University, saw a perfect role for using the College of Engineering to assist them in the medium voltage (33kV) AC aspects of the project. Table 1 provides an overall equipment list for the project; the undergraduate and graduate engineering students were involved in analysis of the design of this system for items 4-8 in the table and responsible for specification, details and plans for items 6, 7 and 8 (which is described in greater detail in another paper by the authors[11]).

Item	Component Descriptions		
	Device	#	Model
1	175 watt Photovoltaic Modules	17,160	Conergy S – 175 MU *UL 1703*
2	DC Combiner Boxes	130	SMA SCCB12 *NEMA 3R/4*
3	Lightning Arrestors	130	Delta LA602
4	DC Disconnects	79	Square D HU363RB *NEMA 3R UL98*
5	DC-AC 500 kW Inverters	6	Satcon Powergate *UL 1741 IEEE 929, 1547, 519 ANSI 62.41*
6	480V Switchgear	3	Square D
7	480V/30kV 1-MVA Transformer	3	Cooper
8	Medium Voltage Switchgear	1	G&W

Table 1 – 3MW PV System Major Components

After the successful kick-off meeting the professor met with the students to review the project's single-line diagram and describe what components the project team would be responsible for. This paper describes in greater detail the work the students performed in optimizing wire size for the DC parts of the 3MW PV system as well as the design of the 33kV system wiring and cable trenching details.

IV. Optimizing the DC and AC Wiring for the System

The approach taken by the student team to determine correct wire sizing for this system was based on the approximated percent voltage losses which were to be as small as possible while staying cost effective. We were provided with a list of available cable, their insulation as well as costs. This information was the basis for a spreadsheet that would allow quick calculations and comparisons for the many different types of cables at hand. Even though the calculations to be done were relatively basic, extracting relevant information to make the computation possible, such as the length of wiring throughout the system, was more challenging. An exceedingly large system combined with frequent changes to the plans by the other teams made this job even more complicated. Eventually once much of the information was agreed upon, estimations were made allowing for a more detailed look into price and loss differences between various wiring schemes. Combiner boxes were then located conveniently to join varying numbers of module strings. For the final plans we have 4x11 tables as well as 2x11 tables giving us 44 and 22 modules and thus four or two strings respectively per table. The proposed wiring by SunTechnics from the modules to the combiner boxes is summarized in Table 2 below.

As illustrated in Table 2 the decrease in losses for one size larger cable is insignificant, being unable to overcome the price difference of Cu $.50/ft

Wire sizing varies greatly throughout the AC side of the PV system to accommodate various needs. The AC side of the project begins at the six 500kVA SATCON inverters where the DC generated by the PV modules is converted to AC. The six inverters are separated into 3 pairs, each pair being housed on a common concrete pad. The interconnection between the inverters and the 1000kVA step-up transformers needed for the low-loss transmission of the solar generated power is done with the help of a switchboard connecting the pair of inverters into a common line, separated into 3 phases. Due to the high current of this connection it was necessary to use two 600kcmil lines per phase, giving us a resistance of ca. 0.009 Ohm/kft and losses of only .058% when

10 String combiner example

Wire	Length (ft)	R (ohm)	Imp	Vmp	Ploss
1/0	170	0.0162788	49.5	387.2	39.89W
2/0	170	0.0129096	49.5	387.2	31.63W
				Difference	8.26W
				$/yr loss diff †	$2.17

† w/ 6hr insolation 365d/yr @ $.12/kWh

Table 2 – DC Wire Size Optimization

generating the maximum 1MVA of power, at 600A per inverter. For the portion of the wiring design between the 480V switchboard into the transformer, six 1000kcmil cables were chosen to carry the ca. 1200A in a 480/277V three-phase arrangement, using two cables per phase and a 3/0 copper ground. In Table 3 we can see a typical spreadsheet calculation developed by the student team to help hone in on the best wiring for the given application. This particular example shows the difference between using two 600kcmil or one 1000kcmil cable per phase. Both meet the ampacity requirements, but have very different installation and size specifications. As illustrated in Table 3 these were the types of calculations that the team performed for every connection within the AC system to determine if there was an economic means to avert any significant power losses. Choosing a small sacrifice in losses ($4-$11/year) would make for significantly simpler installations, and thus cheaper wiring and installation costs.

The transformers stepped up the voltage to a one compatible with PECO's local distribution system, namely 33000Y/19052V. At this higher voltage a low current (17.5) was generated and losses and wire size could be reduced. In this case the team chose three aluminum 1/0 TRXLPE insulated cables with concentric neutrals, similar to standard underground distribution lines used by the utility company. These wires are to be direct-buried following NEC rules and regulations. The length of the cables, illustrated in Table 4, was also taken into consideration while sizing the cable. The difference in losses for a move from the 1/0 to a 2/0 Al TRXLPE was not significant enough at $26/year to warrant the increase in cable cost (approaching $1,000). The resulting losses for this decision may be seen in Table 4 as well.

Losses per Inverter house - 1000kcmil

	Amps/phase	Vloss	% Loss	Vtotal loss	VA Loss
1MVA	601.41	0.19	0.0703	0.42	253.5184
800kVA	481.13	0.16	0.0562	0.34	162.2518
600kVA	360.84	0.12	0.0422	0.25	91.26664

Resistance of 1000kcmil is **1.07865×10^{-2} Ω/1000ft** or **3.23595×10^{-4} Ω/30ft**

Losses per Inverter house – 2 x 600kcmil

	Amps/phase	Vloss	% Loss	Vtotal loss	VA Loss
1MVA	601.41	0.16	0.0585	0.35	211.2654
800kVA	481.13	0.13	0.0468	0.28	135.2098
600kVA	360.84	0.10	0.0351	0.21	76.05553

Resistance of 2-600 kcmil is **8.98875×10^{-3} Ω/1000ft** or **2.69663×10^{-4} Ω/30ft**

Efficiency/Cost Comparison

	Diff. (V)	Diff (VA)	kWh/yr	$/yr
1MVA	0.0703	42.25	92.53	11.10411
800kVA	0.0562	27.04	59.22	7.106629
600kVA	0.0422	15.21	33.31	3.997479

Table 3 – AC Wire Cost vs. Efficiency Calculations

Transformer	Dist	8ft ends/bends		Total cable	Power Loss Al 1/0	Power Loss Al 2/0
1	377ft	385ft	x3	1155ft	53.40W	42.35W
2	877ft	885ft	x3	2655ft	154.80W	122.76W
3	1247ft	1255ft	x3	3765ft	276.80W	219.51W
				Total Loss	485.00W	384.62W
				Difference		100.38W
				$/yr loss diff †		$ 26.38

† w/ 6hr insolation 365d/yr @ $.12/kWh

Table 4 – Medium Voltage AC Wire Cost vs. Efficiency Analysis

All information regarding cable sizing, grounds, conduits and bending radii that the students determined from the NEC were provided in the details and specifications they developed for the project's CAD drawings. One sample of this work is shown in the Cable & Conduit Specification illustrated as Table 5.

CABLE & CONDUIT SPECS INVERTERS - SWGR - TRANSFORMER					
	CABLE	CONDUIT	GROUND CONDUCTOR	DIAMETER	MIN. BENDING RADIUS
INVERTERS TO SWGR	6-600MCM Cu HHW OR EQUIV	4" PVC SCHED. 80 2 CONDUCTORS PER CONDUIT	2/0 egc	1.029"	12.4"
SWGR TO TRANSFORMER	6-1000MCM Cu RHH OR EQUIV	3" PVC SCHED. 80 1 CONDUCTOR PER CONDUIT	3/0 egc	1.34"	16.1"
TRANSFORMER TO 34.5kV SWGR	3-1/0 Al TRXPLE	-	-	1.228"	14.8"

Table 5 – Cable and Conduit Specifications

V. Other Major Contributions from the Engineering Clinic Team

Other major parts of this project included the details for the designs of the actual concrete pads and houses that will contain the switchgear, transformers and inverters. The students' development of the designs assured all components fit and had appropriate clearances. They then developed the detailed CAD drawings used by our clinic affiliate SunTechnics in their final design. Elevation views of the switchgear and inverter pad/structures can be seen in Figures 1 and 2 respectively.

As seen in those figures, the pads consist of reinforced concrete walls, with appropriate conduit runs in between, which is then sealed with a 6" slab of concrete. This is designed to be 9" higher than surrounding grades and a gradual slope is created with crushed stone to keep water from settling around equipment. Fencing is placed around the perimeter for security and safety reasons. The transformers are placed on a second concrete pad which will not be connected with the inverter pad and is surrounded by a grounding system. Lastly, a roof was designed to be placed over the inverter houses to shield the equipment from the effects of the sun and weather. To give a better overview of all the equipment, connections, and wiring schemes a Single-Line diagram was created and can be seen in Figures 3 and 4 below. The Single-Line drawings provide summaries of all the key data necessary for the interconnections of the equipment, as well as conduit sizing, voltage and current specifications.

In order to safely and properly connect the whole system to the utility grid, the main switchgear is utilized. Its pad holds three main pieces of equipment: a four-way triad gas switch, dual metering cabinet, and a final gas switch connecting the entire power plant to the grid. Figure 3 includes information on the 33kV switchgear side of this project. As shown in the single line diagram, a four-way gas switch is used to combine the three incoming 1/0 AL TRXLPE lines per phase to a single 1/0 XHHW-2 Cu line. As the separate aluminum lines are connected in parallel, the current is increased, and a larger wire size is necessary on the secondary side of the switch. However, due to the minimal distance required to run between the switch and the metering cabinet, more conductive

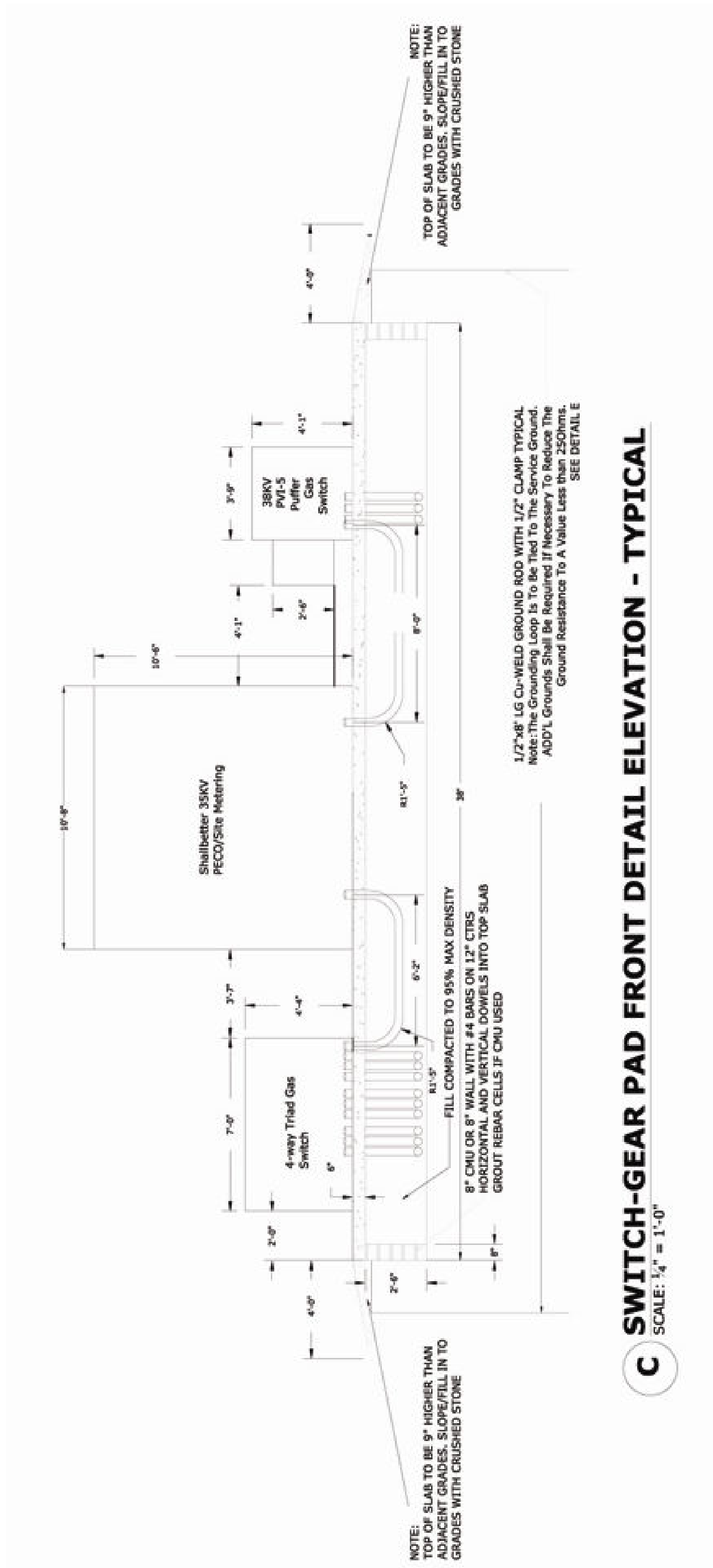

Figure 1 – CAD Drawing of Medium Voltage Switchgear Elevation View

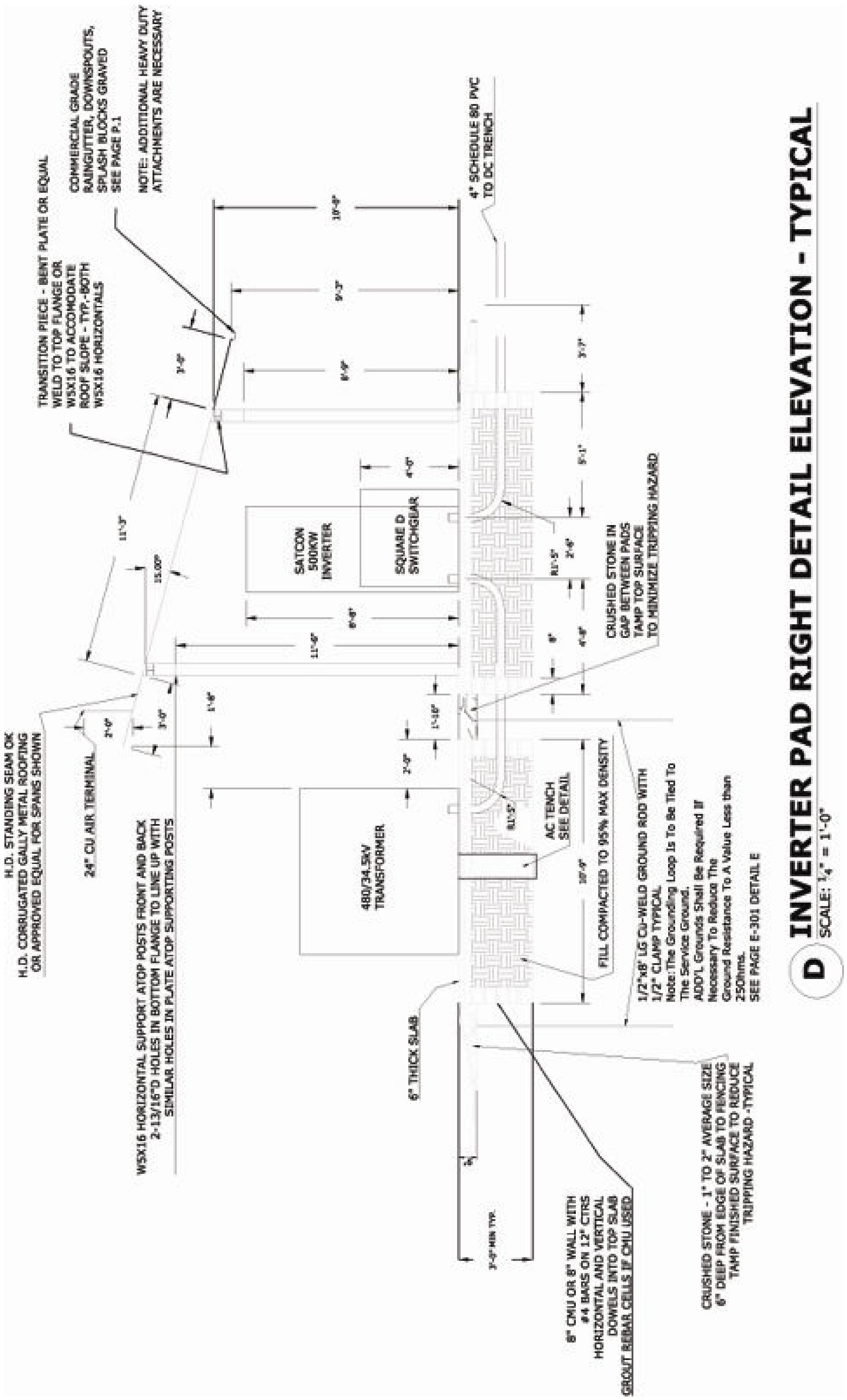

Figure 2 – CAD Drawing of Inverter Pad/Structure Elevation View

but expensive copper cables were proposed. The actual breaker being used for each phase is a SF_6 gas switch with an inrush current rating of 12.5kA. It is expected that each phase will carry a maximum of 21A. Therefore, 30A fuses are used for fault protection.

The metering cabinet holds two meters, a utility meter, and a PJM meter. Current and voltage transformers are used for metering as specified in the single line drawing. The transformers used by the utility will be supplied by them and are therefore not specified. Placed closest to the switch are the utility's meters so as to decrease unnecessary losses in the system, and ensure maximum profits.

Finally, a 38kV gas switch is placed after the metering cabinet, isolating the entire PV system from the grid. This switch is also properly fused with 100A fuses to allow for a 63A maximum current draw on each phase. The underground lines (1/0 AL TRXPLE) then run to a three phase riser pole with a load-breaking 100A fused disconnect. Both the pole and disconnect are utility supplied.

The switchgear is supported by a similar pad used for each inverter station. There is no need for a roof over the switchgear since all equipment is outdoor-rated. The pad will be surrounded by a barbed wire fence and high voltage signs will be posted for the public's safety. The equipment is spaced on the pad such that the size of the pad is kept to a minimum and all wire losses are reduced. At the same time, the equipment must be placed far enough apart to allow for the cabinet doors to open properly and for maintenance crews to access the equipment easily, as well as to allow for the minimum bending radius of the cables as listed in Table 5. A ground grid is also placed around the switchgear pad.

VI. Conclusions

The 3MW PV power plant described in this paper will reduce the amount of greenhouse gases entering the atmosphere by at least 3.8 million pounds, annually nearly 2,000 tons of CO_2. Over its life this amounts to over 50,000 tons of carbon being kept out of the atmosphere. The project will generate over 3,500 MWh per year (on-average) over its 25-year life. The PV electricity provides significant utility and environmental benefits. The project contributes to the lessening of summer peak demand on the electric grid. In this part of the US the electric grid is extremely strained during the summer due to air conditioning loads which are very coincident with solar energy availability. The project also provides an excellent learning environment for young engineers to get excited about their chosen profession. We close this paper with some quotations from participants on the project.

"Having gone through the entire process and worked together with SunTechnics and Bohler Engineering in Germany, it will be an exciting and pleasurable event seeing all of it come together and manifest itself into what it was designed to be." – Graduate student

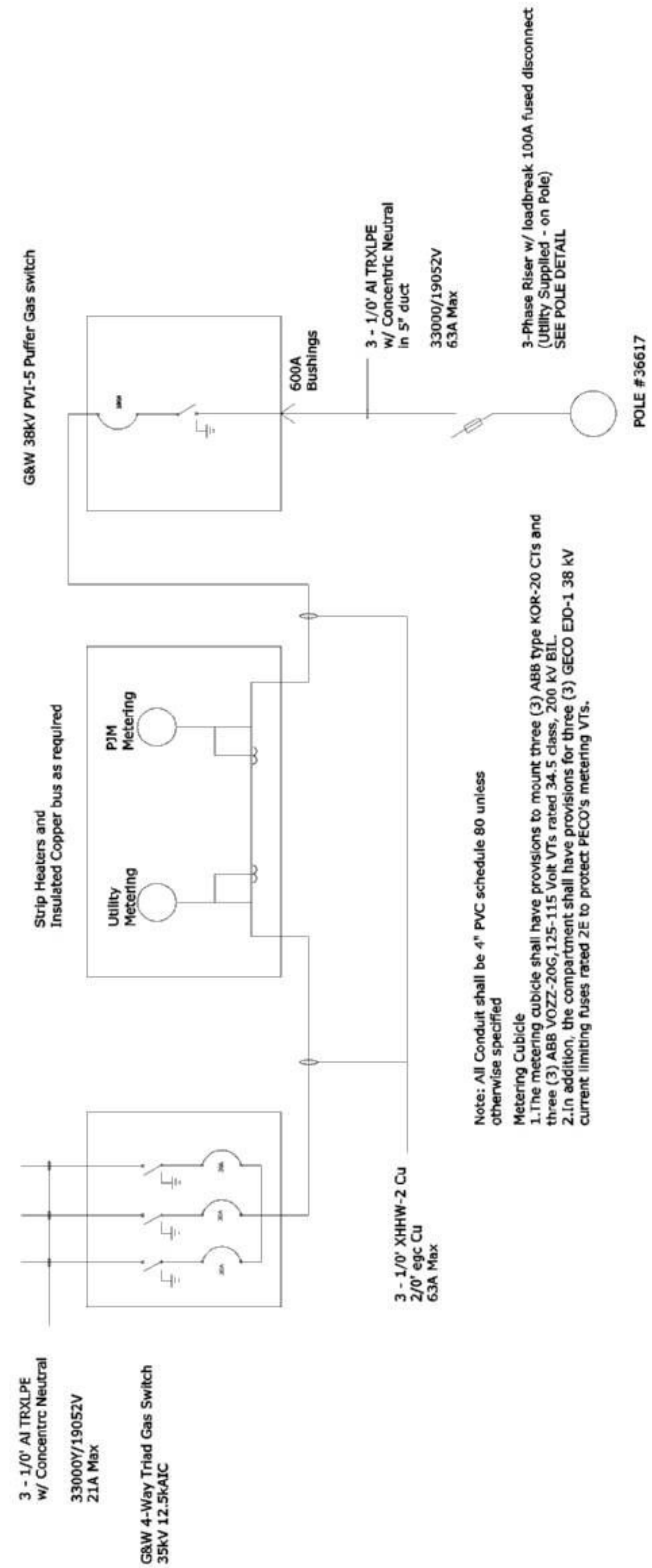

Figure 3 – 3 MW PV System Single Line (33 kV Switchgear)

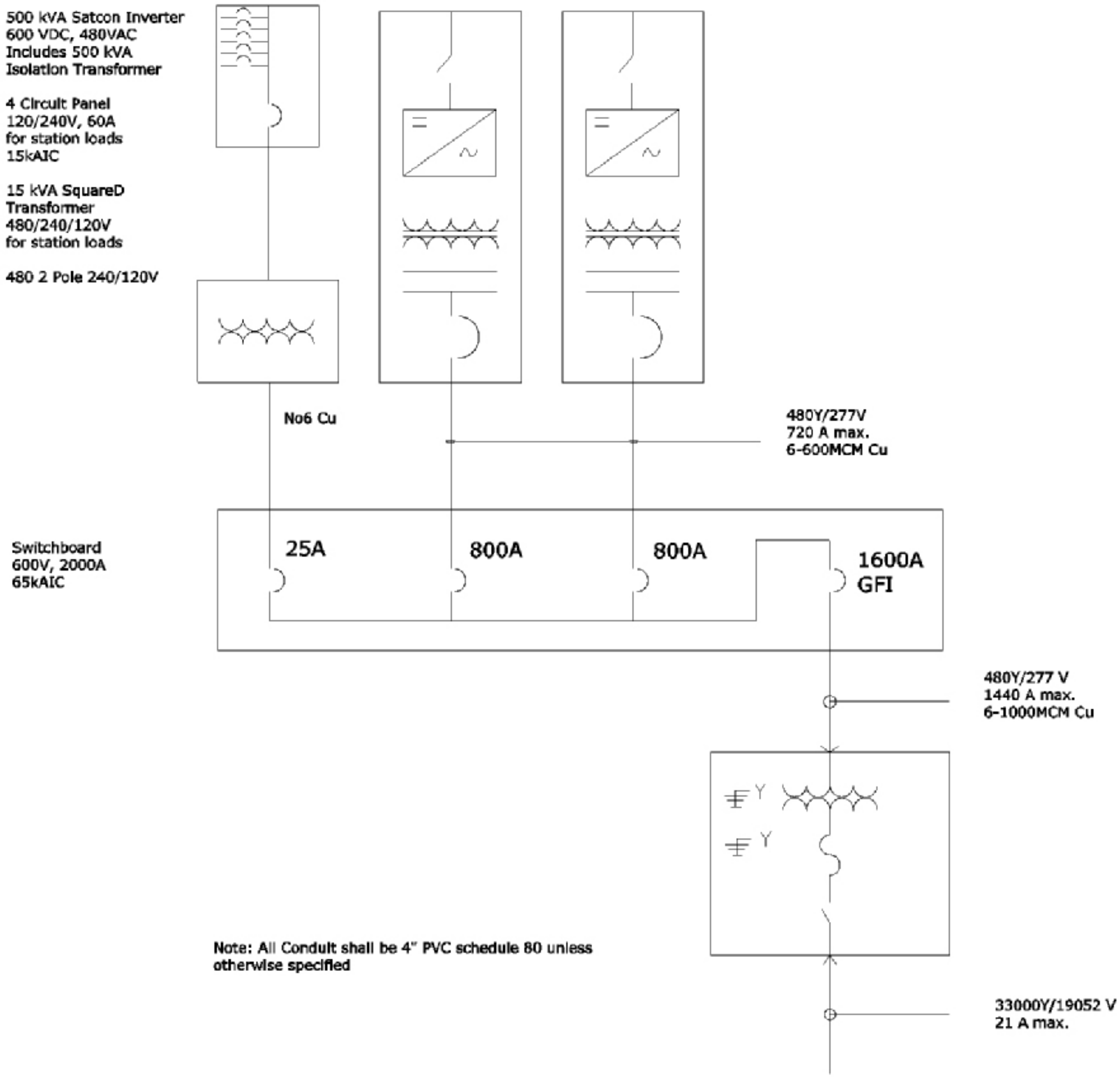

Figure 4 – 3 MW PV System Single Line (Inverter to Transformer)

"This clinic project offered a great overview of power engineering and PV system design. Having no previous experience in PV design, I learned how solar modules are interconnected to produce power while keeping DC current and system losses low. This project also enhanced my knowledge of how both DC and AC power is transmitted using proper system protection and grounding. Once the system design was understood, optimization techniques were used to transmit power both efficiently and cost effectively. These optimization techniques were vital to the success of the overall system, and will prove to be useful in all future engineering designs." – Senior engineering student

"The start of this project was by far the hardest. As students without any prior knowledge of utility grade designing, NEC codes, medium/high voltage lines and their design it was a frightening experience having immediate deadlines for the completion of specs, outlines and diagrams for a project of this size. It was a learning experience that challenged our resilience and capacity for new knowledge all the while forcing us to immediately make use of newly learned material and guidelines. Not only was it interesting to learn about such an intricate system, but designing it at the same time created a whole new understanding of things we see everyday and take for granted. Transformers, inverters and cables never looked to be such a result of delicate calculations as they do now. A grasp of these assemblies gave us a great look into the field of power systems, sustainable design and a taste of group work that may span the entire globe with the sole purpose of completing a single project." – Graduate student

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