Iowa State University

Solar Power Plant and Substation Design

Final Presentation

Omer Karar, Maddy Lakomek, Madissen Lawrence, Jacob Miller, Brooke Nelson, Jenna Runge, Ashton Randolph, Zachary Zimmerman

Team Introduction

Omer Karar
Madissen Lawrence
Ashton Randolph
Brooke Nelson
Zach Zimmerman
Jenna Runge
Maddy Lakomek
Jacob Miller

Advisor: Professor Ajjarapu

Client: Black & Veatch

Project Overview

Problem Statement & Requirements

- US more aware of carbon footprint
  - Minimize emissions with more renewable energy resources
- Local utility in Roswell, New Mexico partnered with Black & Veatch
- Objective
  - Design 60 MW solar power plant
  - Design 34.5/115 kV substation that connects
- Requirements
  - Selection location, equipment, protection, layout
  - Complete multiple calculations
  - Create design using CAD and BlueBeam
  - Simulate design using ETAP

Location

Location - Roswell, New Mexico

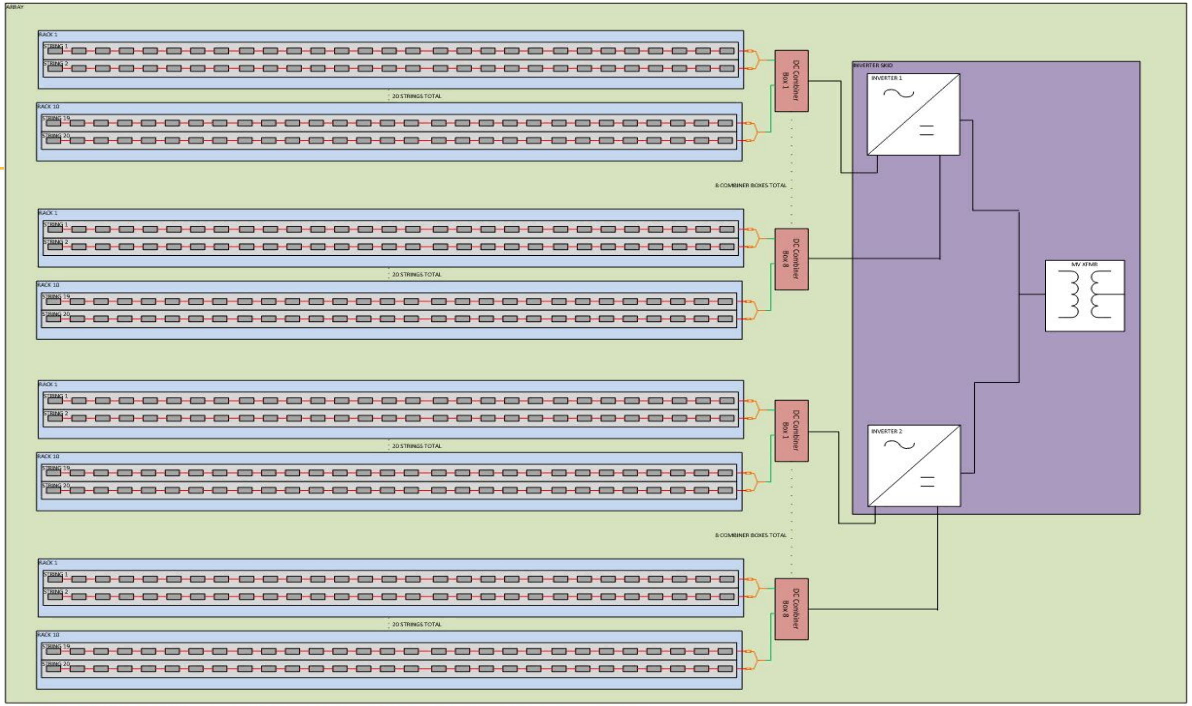
- Location Requirements
  - High irradiance
  - Low humidity
  - Flat
  - Low cost land
- Land Cost: $600/acre at time of estimate
- Land Size Used: 200 acres
- Total Estimated Land Cost: $120,000

Here is a month-by-month comparison of the average solar radiation in *Roswell* with the typical solar radiation in a city.

Month	Low	Roswell	High
Dec	1.76 k/m/d	5.45 k/m/d	4.93 k/m/d
Nov	1.87 k/m/d	6.02 k/m/d	5.87 k/m/d
Oct	3.36 k/m/d	6.63 k/m/d	6.44 k/m/d
Sep	5.01 k/m/d	6.61 k/m/d	7.46 k/m/d
Aug	5.66 k/m/d	6.56 k/m/d	7.06 k/m/d
Jul	5.92 k/m/d	6.52 k/m/d	6.72 k/m/d
Jun	5.16 k/m/d	6.6 k/m/d	7.39 k/m/d
May	5.27 k/m/d	6.78 k/m/d	7.44 k/m/d
Apr	4.94 k/m/d	7.12 k/m/d	7.38 k/m/d
Mar	3.42 k/m/d	6.94 k/m/d	6.89 k/m/d
Feb	2.83 k/m/d	6.49 k/m/d	6.18 k/m/d
Jan	2.01 k/m/d	5.91 k/m/d	5.54 k/m/d

Components

Array Parameter Tool

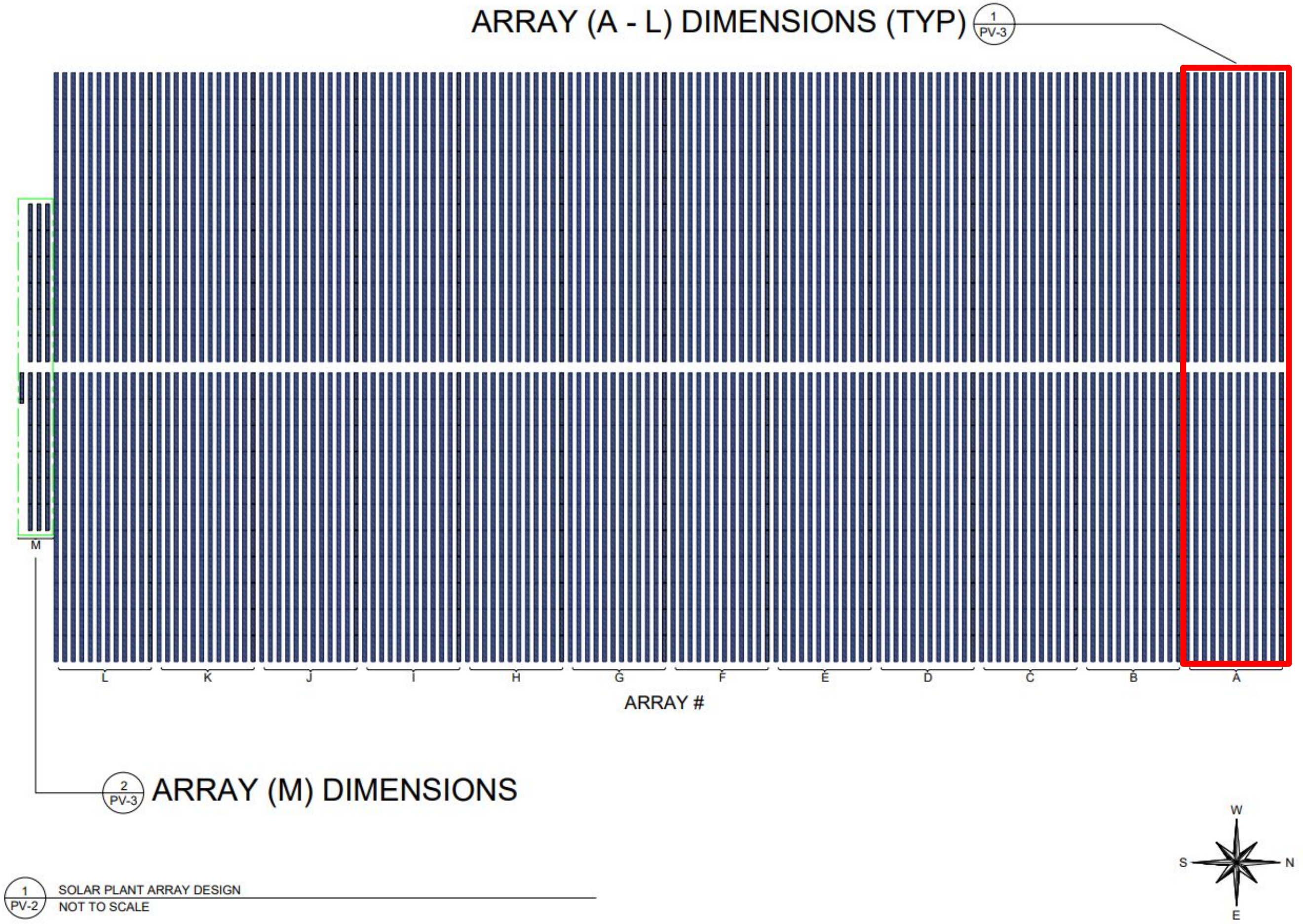


ARRAY PARAMETER TOOL OUTPUT PARAMETERS									
String Size		Electrical Rack Size		Combiner Box Capacity		Array Design		Arrary Size	
Min Temp (C)	-1.11	Orientation	Portrait	Mod/String Isc (A)	11.26	Racks per Row	22	Tilt (Degrees)	33
Voc (V)	53.61	Module Width (FT)	3.425	Max Isc (A)	17.59	Row per Array	12	Row Spacing (FT)	16.81
Referecnce Temp (C)	25	Module Height (FT)	7.267	Allowable Current (A)	400	Module Capacity (W)	480	Array Height (FT)	331.2
Temp Coeff of Voc (/C)	-0.0027	Rack Width (# Modules)	26	Racks per CB	11	Inverter Capacity (kW)	5000	Array Width (FT)	1959.1
String Voltage (V)	1500	Rack Height (# Modules)	2			ILR	1.31	Ground Coverage Ratio	0.501

CAD Layout

4 Major Decisions

- Orientation
- Tilt
- Row Spacing
  - Shading
  - Land Use
- Solar Farm Layout



Reference Section 3.2.2 1 Layout

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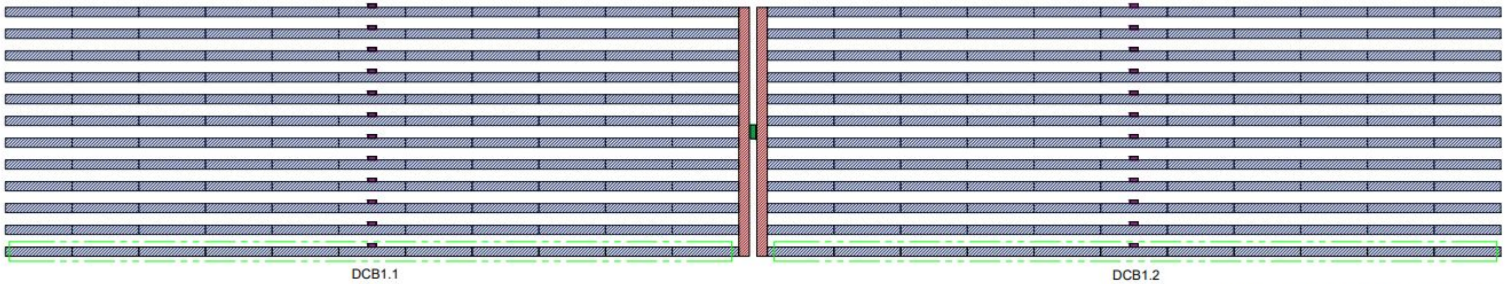


NOTE 1: ELECTRICAL DETAIL FOR ARRAY (A) IS SHOWN IN E-1 & E-2. EACH COMBINER BOX IS LABELED DCBX.X

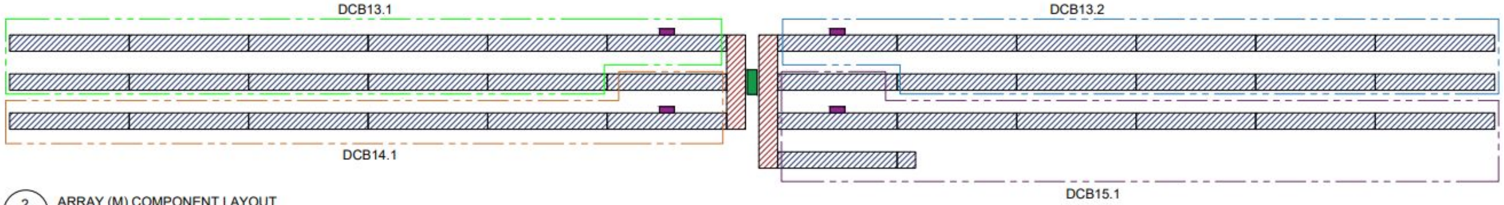
1 PV-4 ARRAY (A) COMPONENT LAYOUT (TYPICAL)
NOT TO SCALE

One Array
528 || string combinations
1500 (V) - 5650 (A)

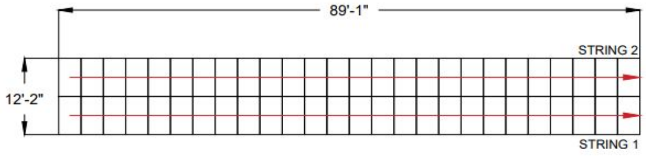
One Combiner Box
22 || string combinations
1500 (V) - 235.4 (A)

One String (26 Modules)
1500 (V) - 10.7 (A)

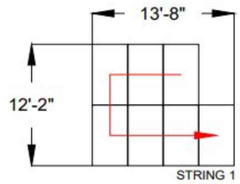
NOTE 2: ELECTRICAL DETAIL FOR ARRAY (M) IS SHOWN IN E-3. EACH COMBINER BOX IS LABELED DCBX.X



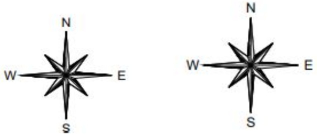
2 PV-4 ARRAY (M) COMPONENT LAYOUT
NOT TO SCALE



3 PV-3 RACK/STRINGING DETAIL (TYPICAL)
NOT TO SCALE



4 PV-3 RACK/STRINGING DETAIL
NOT TO SCALE



Voltage Drop Calculations

Voltage Drop

- Requirement Threshold: 5%
  - Original Design: 11.84%
  - Calculated along the strings, jumper, and feeder for normal array and small array
  - Final Drop - Normal Array: 4.11%
  - Final Drop - Small Array: 2.94%
  - Hand Calculations
  - Final Voltage: 1165V
    - Reference Design Document 3.2.2.4

$$V_d = \frac{2LR_2I}{1000}$$

Where: V_d = voltage drop over circuit length (volts)

L = length of circuit (ft)

R_2 = resistance of conductor from Equation (ohm/kft)

I = maximum power current of circuit (amps)

JUMPER VOLTAGE DROP CALCULATIONS: ARRAY A - L (TYP)

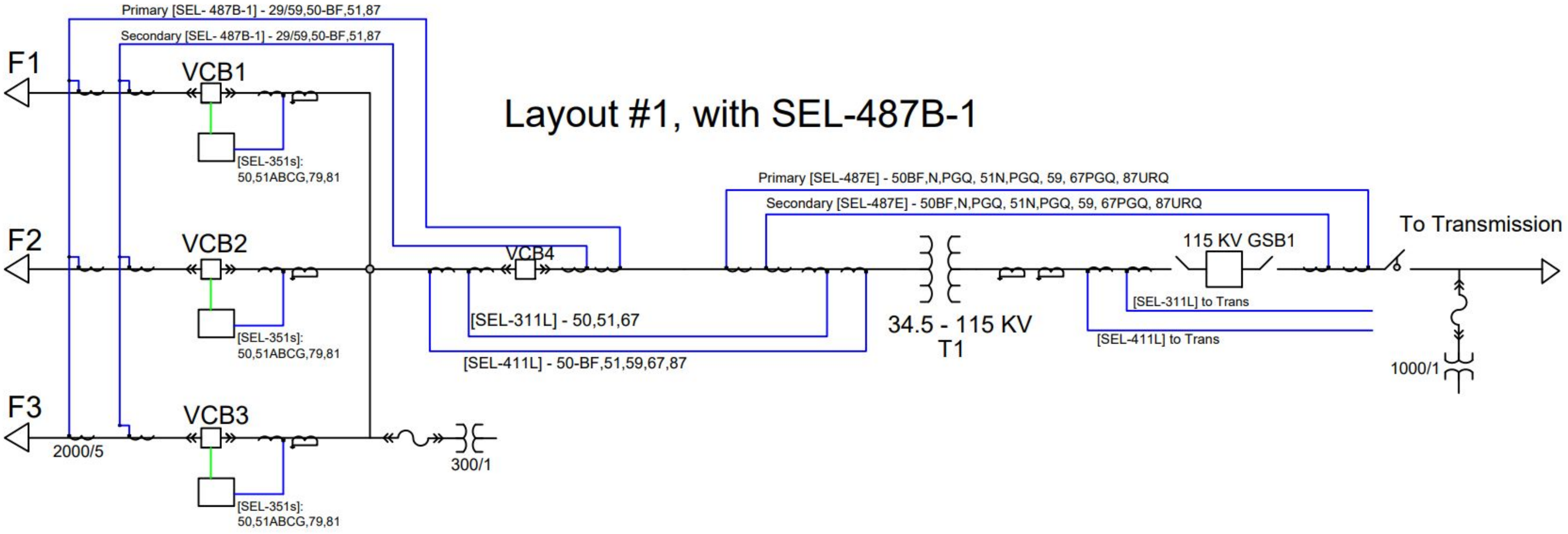
DCB	Strings per Rack	IMP for String	String Length	String wire size	String Conductor resistance	String resistance	Voltage Drop of String	IMP for Jumper	Jumper Length	Jumper wire size	Jumper resistance	Jumper resistance	Voltage Drop of Jumper
DCB#-##	per rack	Amp	feet	AWG	Ohm/kft	Ohm	Volts	Amp	feet	AWG	Ohm/kft	Ohm	Volts
DCB1-01	2	10.7	85.7	10	2.000	0.332	3.668	21.4	490.00	6	0.808	0.766	16.945
DCB1-02	2	10.7	85.7	10	2.000	0.332	3.668	21.4	400.95	6	0.808	0.627	13.866
DCB1-03	2	10.7	85.7	10	2.000	0.332	3.668	21.4	311.90	6	0.808	0.488	10.786
DCB1-04	2	10.7	85.7	10	2.000	0.332	3.668	21.4	222.85	6	0.808	0.348	7.707
DCB1-05	2	10.7	85.7	10	2.000	0.332	3.668	21.4	133.80	6	0.808	0.209	4.627
DCB1-06	2	10.7	85.7	10	2.000	0.332	3.668	21.4	44.75	6	0.808	0.070	1.548
DCB1-07	2	10.7	85.7	10	2.000	0.332	3.668	21.4	44.75	6	0.808	0.070	1.548
DCB1-08	2	10.7	85.7	10	2.000	0.332	3.668	21.4	133.80	6	0.808	0.209	4.627
DCB1-09	2	10.7	85.7	10	2.000	0.332	3.668	21.4	222.85	6	0.808	0.348	7.707
DCB1-10	2	10.7	85.7	10	2.000	0.332	3.668	21.4	311.90	6	0.808	0.488	10.786
DCB1-11	2	10.7	85.7	10	2.000	0.332	3.668	21.4	400.95	6	0.808	0.627	13.866

Substation Design

Drawings and Calculations

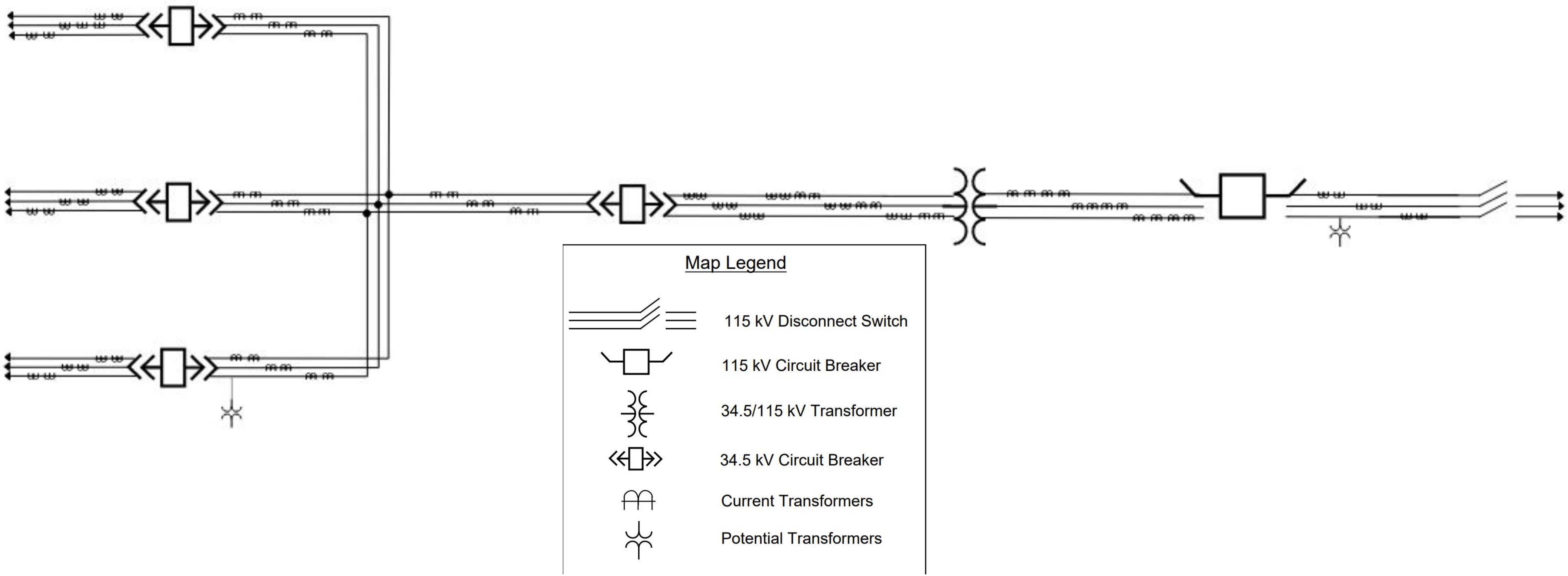
One Line Drawing

Reference Section 3.3.1.1 One Line



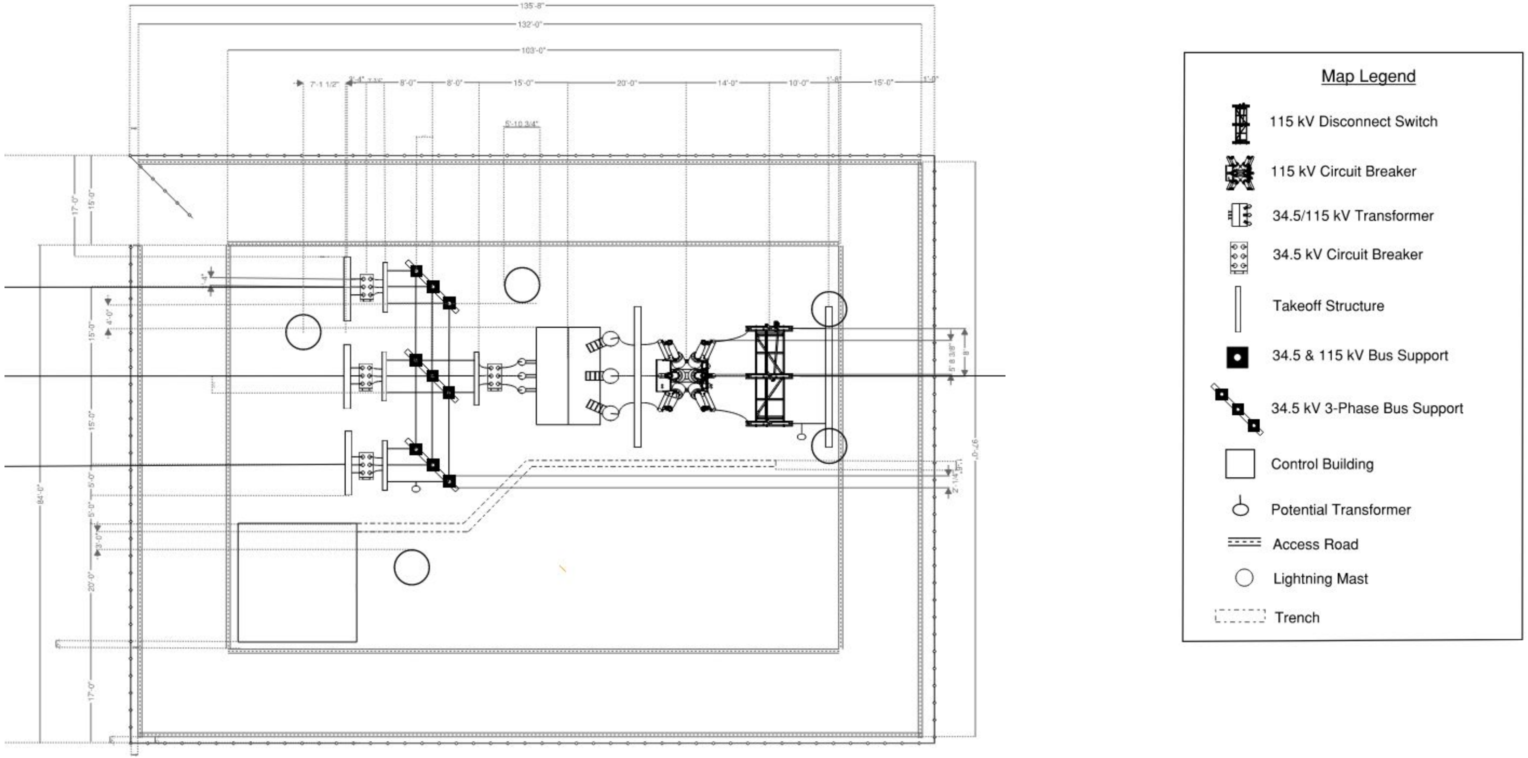
Three Line Diagram

Reference Section 3.3.1.2 Three Line



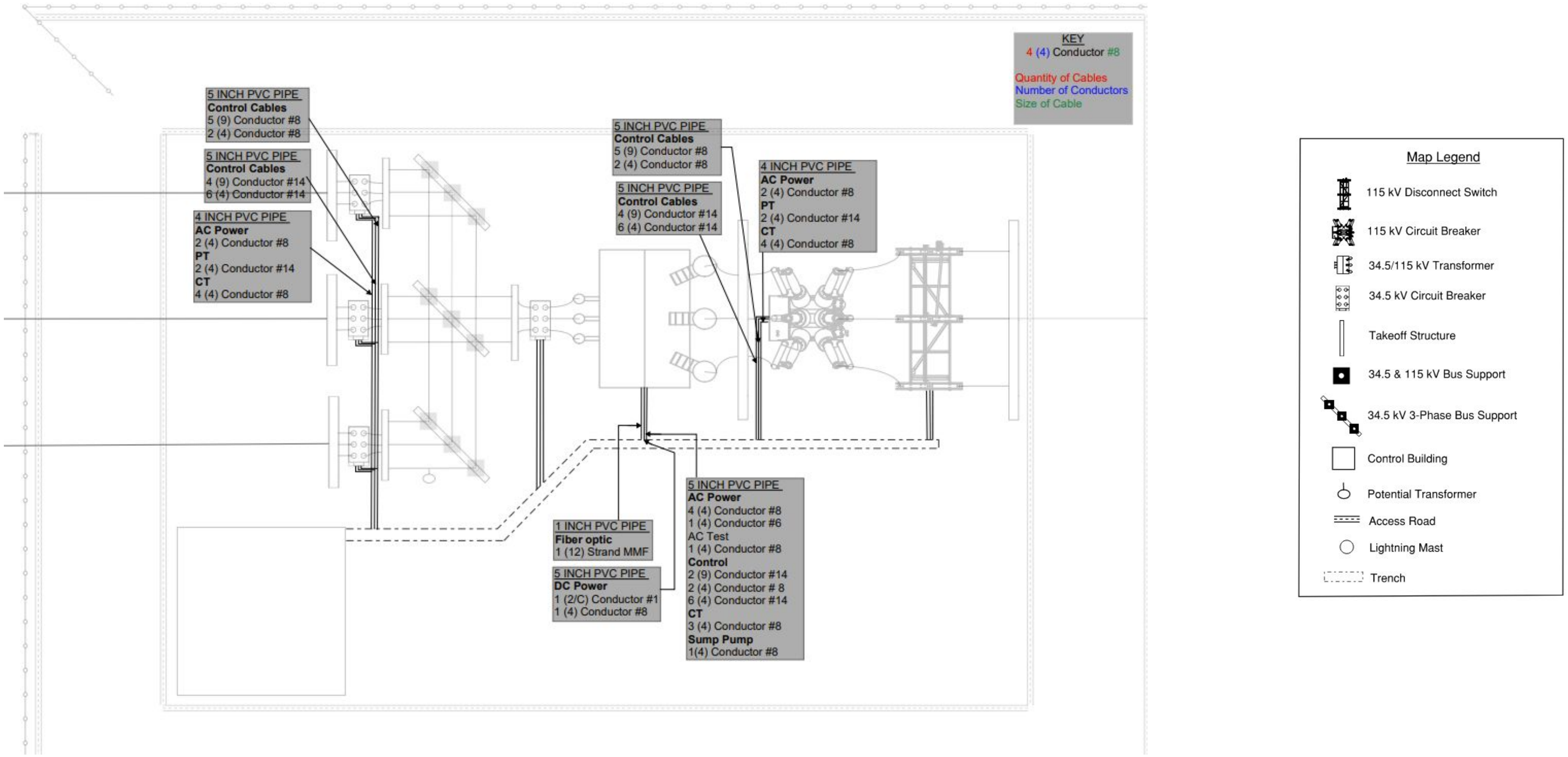
Key Plan

Reference Section 3.3.1.3 Key Plan



Conduit Layout

Reference Section 3.3.1.4 Conduit and Trench Plan



Grounding Calculations

Ref. 3.3.1.5

- Standard Formulas used - IEEE 80, ch. 16

Tolerable Step Voltage (EStep, V)

2526.351108

$$E_{step50} = (1000 + 6C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}}$$

Tolerable Touch Voltage (ETouch, V)

754.6243569

$$E_{touch50} = (1000 + 1.5C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}}$$

Step Voltage

Ks	1.264879093

$$K_s = \frac{1}{\pi}\left[\frac{1}{2\times h} + \frac{1}{D+h} + \frac{1}{D}(1-0.5^{n-2})\right]$$

Ki	2.382870017

$$K_i = 0.644 + 0.148\times n$$

Ls	3541.776

$$L_S = 0.75 \times L_C + 0.85 \times L_R$$

Es (V)	1532.76804

$$E_s = \frac{\rho \times K_s \times K_i \times I_G}{L_s}$$

Touch Voltage

Kii	1

$$K_{ii} = \frac{1}{(2\times n)^{\frac{2}{n}}}$$

Kh	1.072380529

$$K_h = \sqrt{1 + \frac{h}{h_o}}$$

Km	0.6167069683

$$K_m = \frac{1}{2\times\pi}\times\left[\ln\left[\frac{D^2}{16\times h\times d} + \frac{(D+2\times h)^2}{8\times D\times d} - \frac{h}{4\times d}\right] + \frac{K_{ii}}{K_h}\times\ln\left[\frac{8}{\pi(2\times n-1)}\right]\right]$$

Lm	6628.914678

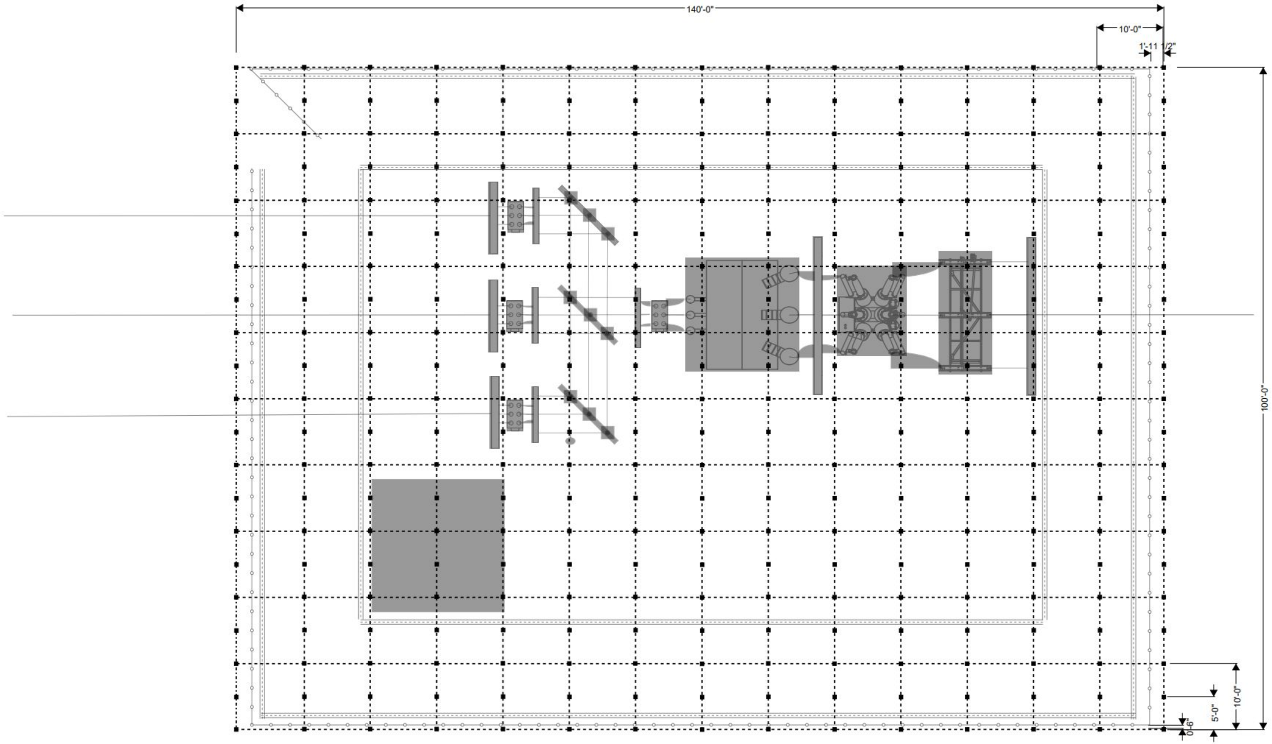
$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}}\right)\right]L_R$$

Em (V)	399.2867873

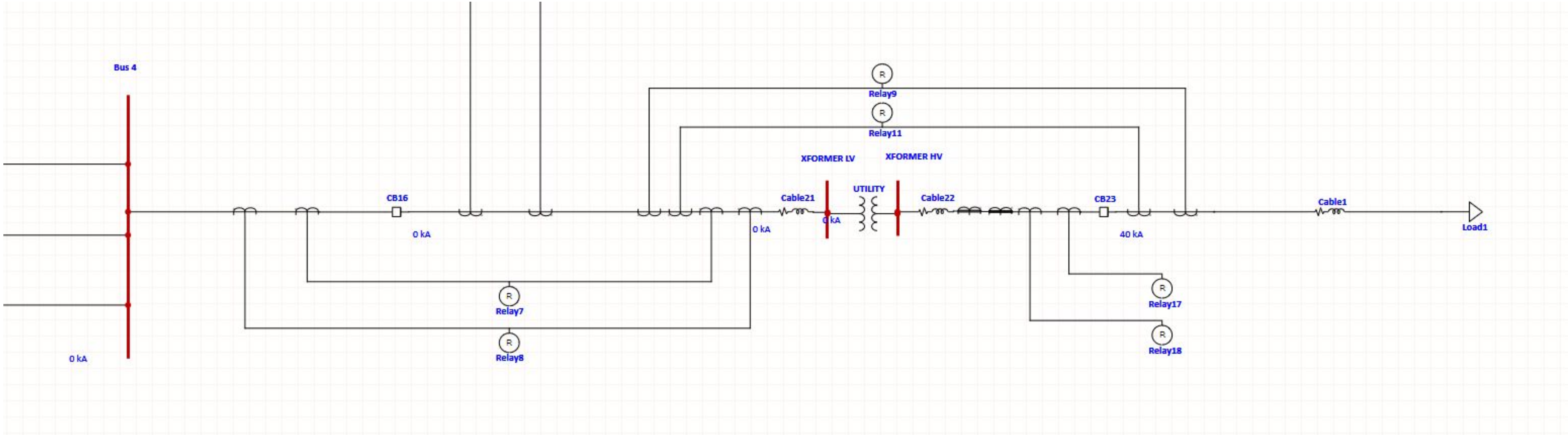
$$E_m = \frac{\rho \times K_m \times K_i \times I_G}{L_M}$$

Grounding Layout

Ref. 3.3.1.5



Simulation



Bus 4
0 kA
CB16
0 kA
Relay7
Relay8
Relay9
Relay11
XFORMER LV
XFORMER HV
UTILITY
Cable21
0 kA
Cable22
CB23
40 kA
Relay17
Relay18
Cable1
Load1

ETAP- Load Flow & Short Circuit Analysis

Reference Section 5.1 ETAP

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
Bus 1	34.500	99.927	-0.1	0.000	0.000	0.000	0.000	Bus 4	59.118	4.216	992.6	99.7	
								Node 1	-59.118	-4.216	992.6	99.7	
Bus 2	34.500	99.914	-0.1	0.000	0.000	0.000	0.000	Bus 4	0.000	0.000	0.0	0.0	
								Node 2	0.000	0.000	0.0	0.0	
Bus 3	34.500	99.914	-0.1	0.000	0.000	0.000	0.000	Bus 4	0.000	0.000	0.0	0.0	
								Node 3	0.000	0.000	0.0	0.0	
Bus 4	34.500	99.914	-0.1	0.000	0.000	0.000	0.000	Bus 1	-59.110	-4.213	992.6	99.7	
								Bus 2	0.000	0.000	0.0	0.0	
								Bus 3	0.000	0.000	0.0	0.0	
								XFORMER LV	59.110	4.213	992.6	99.7	
*Node 1	34.500	100.000	0.0	59.157	4.274	0.000	0.000	Bus 1	59.157	4.274	992.6	99.7	
Node 2	34.500	99.914	-0.1	0.000	0.000	0.000	0.000	Bus 2	0.000	0.000	0.0	0.0	
Node 3	34.500	99.914	-0.1	0.000	0.000	0.000	0.000	Bus 3	0.000	0.000	0.0	0.0	
Node 4	115.000	99.496	-3.3	0.000	0.000	0.000	0.000	Node 5	59.006	0.888	297.8	100.0	
								XFORMER HV	-59.006	-0.888	297.8	100.0	
Node 5	115.000	98.852	-4.1	0.000	0.000	58.631	0.000	Node 4	-58.631	0.000	297.8	100.0	
XFORMER HV	115.000	99.496	-3.3	0.000	0.000	0.000	0.000	Node 4	59.006	0.888	297.8	100.0	
								XFORMER LV	-59.006	-0.888	297.8	100.0	
XFORMER LV	34.500	99.902	-0.1	0.000	0.000	0.000	0.000	Bus 4	-59.103	-4.209	992.6	99.7	
								XFORMER HV	59.103	4.209	992.6	99.7	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)

# Indicates a bus with a load mismatch of more than 0.1 MVA

Short-Circuit Summary Report

& LLG Fault Currents

the Bus Nominal Voltage

	3-Phase Fault			Line-to-Ground Fault			Line-to-Line Fault			*Line-to-Line-to-Ground		
kV	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.	Real	Imag.	Mag.
34.500	0.306	-5.697	5.706	0.716	-7.305	7.340	5.048	0.415	5.065	-5.444	4.453	7.033
115.000	0.063	-1.293	1.294	0.114	-1.757	1.760	1.140	0.079	1.142	1.081	1.360	1.737
34.500	0.310	-5.695	5.703	0.726	-7.293	7.329	5.045	0.418	5.063	-5.455	4.434	7.030

1/2 Cycle network) values in rms kA.
the two faulted line currents.

Bill of Materials

Cost Analysis - Solar Array

No Axis Tracking	$13/kWh		
Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 103,689,637.13	$ 585,000.00	3.22%	$ 11,510,246.23

$1767/kW

Cash Flow

Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
$ (103,689,637.13)	$ 10,925,246.23	$ 11,277,039.16	$ 11,640,159.82	$ 12,014,972.96	$ 12,401,855.09	$ 12,801,194.83	$ 13,213,393.30	$ 13,638,864.56	$ 14,078,036.00	$ 14,531,348.76

Present Value

Years	Installation Cost	O+M	Revenue	Profit
10	$ (103,689,637.13)	($4,934,606.35)	$ 126,522,110.71	$ 17,897,867.22

Reference 3.2.2.3 Racking Components, 3.4 Technology Considerations, Figure 32: Solar Cost Analysis

Cost Analysis - Substation

Ref: 3.3.2.6

Component Type	Price (per unit)	Lead Time	Notes	Number of Units Used	Total Cost	Link to Source
Power Transformer	$1,500,000	1 year regarldess of size	Cost estimate for PT from 50 MVA to 100 MVA	1	$1,500,000.00	PE Guru - Power Transformer
Circuit Breaker	$35,000 / $80,000	6 months	$35k is estimated for 35kV gas tank CB. $80k is estimated for 138kV dead tank	5	$140,080.00	PEGuru - Circuit Breaker
Disconnect Switch	$20,000	22 weeks	Estimate for 138kV 2000A with motor operator	1	$20,000.00	PEGuru - Disconnect Switch
Circuit Switcher	$40,000	18 weeks	Estimate for 138kV 2000A circuit switcher. Alt option - capacitor switcher	0	$0.00	PEGuru - Circuit Switcher
Voltage Transformer	$2,000 per phase	4 weeks	34.5 kV wound transformer	1	$6,000.00	PEGuru - Voltage Transformer
Capacitor Voltage Transformer	$7,000 per phase	16 weeks	138kV to 67/115V CVT	1	$7,000.00	PEGuru - Capcitor Voltage Transformer
Current Transformer	$15,000 per phase	1 year	138 kV wound stand-alone	78	$1,170,000.00	PEGuru - Current Transformer
Capacitor Bank	$75,000+ based on model and sizing	25 weeks	Pricing based on 69kV+	0	$0.00	PEGuru - Capacitor Bank
Inductor	$60,000+ depending on model and specs	20 weeks for MV, 30 weeks for HV and EHV	Pricing based on 34kV and 138 kV inductors	0	$0.00	PEGuru - Inductor
Surge Arrestor	$600 - $17,000 per phase	20 weeks	Pricing based on 69kV - 500kV range, price of 138kV+ includes cost of structual steel	0	$0.00	PEGuru - Surge Arrestor
Wave Trap	$12,000 - $30,000	20 weeks	Pricing based on 69kV - 345 kV	0	$0.00	PEGuru - Wave Trap
Insulator	$500 each	8 weeks	Price for 138 kV	0	$0.00	PEGuru - Insulator
Gas Insulated Switchgear	$500,000 - Single leg/bay of 138kV breaker & half sub $2,600 per ft - 345kV gas-insulated	1 year	$500,000 equipment does not include protective relays	0	$0.00	PEGuru - Gas Insulated Switchgear
				Estimated Total Cost of Equipment	$2,843,080.00	

Other Work Completed

- Solar Wiring Diagram
  - Reference: 3.2.2.2
- Solar Racking Components
  - Reference: 3.2.2.3
- Voltage Drop Hand Calculation Check
  - Reference: 3.2.2.4
- DC Battery Calculations
  - Reference: 3.3.2.1
- Lightning Protection
  - Reference: 3.3.2.2
- Bus Calculations
  - Reference: 3.3.2.3
- AC Load Calculations
  - Reference: 3.3.2.4
- Trench Calculations
  - Reference: 3.3.1.4

Major Individual Contributions

Madissen Lawrence
- Voltage Drop Calculations
- DC Battery Calculations
- Website
- AC Load Calculations
- Grounding Grid
- Substation Part Estimate

Jenna Runge
- Voltage Drop Calculations
- DC Battery Calculations
- AC Load Calculations
- Grounding Grid
- Substation Part Estimate

Madison Lakomek
- Solar field cost analysis
- Bus calculations
- Key Plan
- Conduit Plan
- Three Line Diagram

Ashton Randolph
- Solar Farm Cost Analysis
- Cable Trench Calculations
- ETAP

Jacob Miller
- Substation One-line Diagram (AutoCAD)
- Lightning Protection
- Relaying Protection

Zachary Zimmerman
- Solar Plant Configuration (APT)
- Solar Plant Design (AutoCAD)
- Voltage Drop Calculations
- Bus Calculations
- ETAP

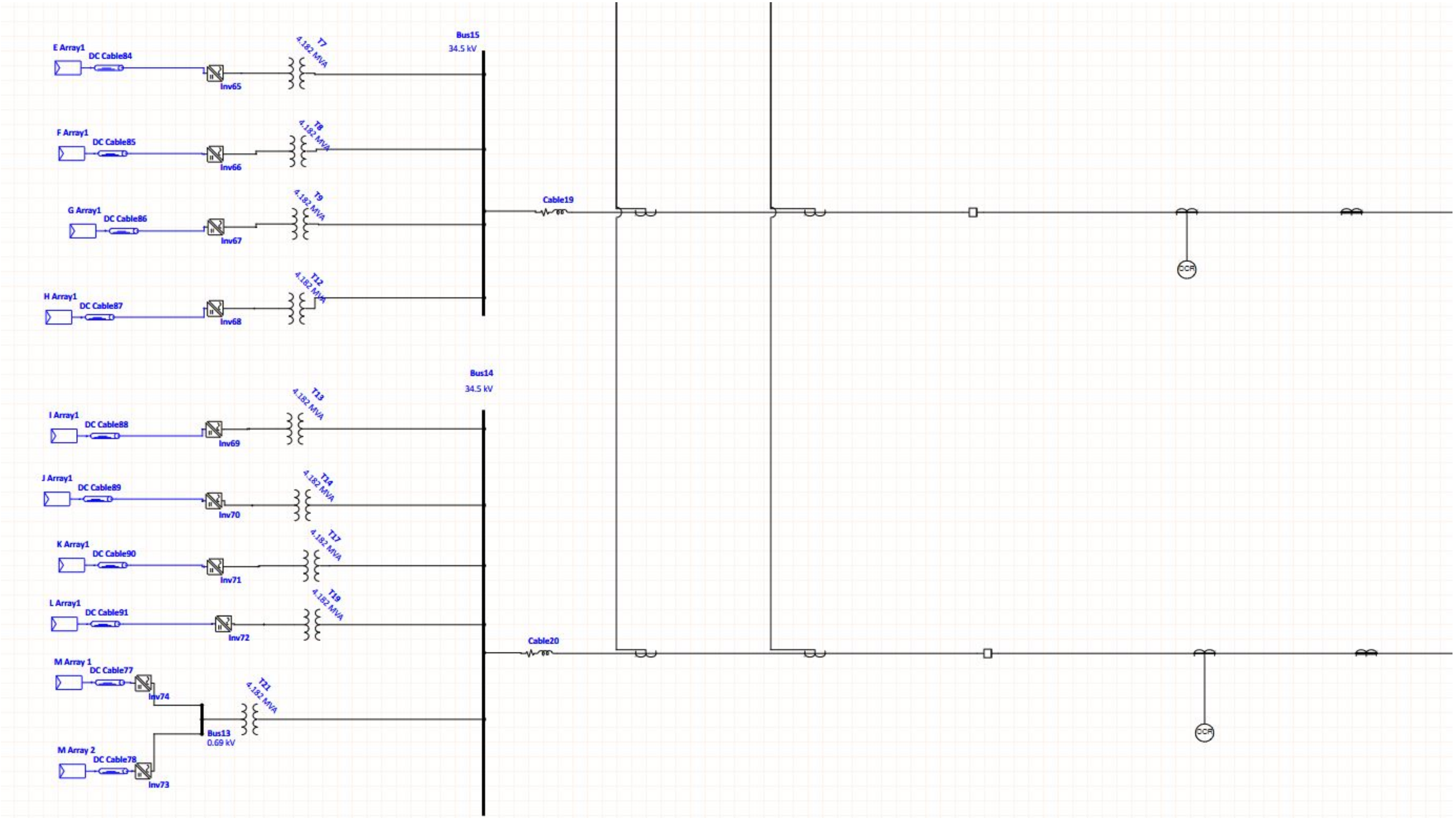
Omer Karar
- Relaying Protection
- Substation One-line diagram (AutoCAD)
- Lightning Protection

Brooke Nelson
- Voltage Drop Hand Calculations
- Cable Trench Calculations
- AC Load Calculations
- Conduit Plan

Possible Future Work

- Control House Design
- Bill of Materials - Full Project
- Breakdown of 3 Line Diagrams

Questions?


E Array1
DC Cable84
Inv65
T7
4.182 MVA
Bus15
34.5 kV
F Array1
DC Cable85
Inv66
T8
4.182 MVA
G Array1
DC Cable86
Inv67
T9
4.182 MVA
Cable19
H Array1
DC Cable87
Inv68
T12
4.182 MVA
Bus14
34.5 kV
I Array1
DC Cable88
Inv69
T13
4.182 MVA
J Array1
DC Cable89
Inv70
T14
4.182 MVA
K Array1
DC Cable90
Inv71
T17
4.182 MVA
L Array1
DC Cable91
Inv72
T19
4.182 MVA
Cable20
M Array 1
DC Cable77
Inv74
T21
4.182 MVA
Bus13
0.69 kV
M Array 2
DC Cable78
Inv73
OCR
OCR