115kV/ 34.5kV Solar Power Plant & Substation Design Project

DESIGN DOCUMENT

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Executive Summary

Development Standards & Practices Used

This is primarily a design only project, so we will be adhering to IEEE standards for reporting and documentation, as well as design layouts. We will also adhere to standard practice when coding using AutoCAD or Bluebeam. Additionally, we will need to consider any limitations or requirements associated with construction in specific states, specifically New Mexico.

Summary of Requirements

- Design 60 MW Solar Farm (Fall 2020)
    - Select Panels
    - Select Combiner Boxes
    - Select Inverter Skids
    - Select Location
    - Design Layout of Farm
- Design Substation to handle Output from Solar Farm (Spring 2021)

Applicable Courses from Iowa State University Curriculum

- EE 201: Electric Circuits
- EE 230: Electronic Circuits and Systems
- EE 303: Energy Systems and Power Electronics
- EE 456: Power System Analysis I

New Skills/Knowledge acquired that was not taught in courses

- CAD /Bluebeam programming
- One-line diagrams
- Solar farm layout and distribution

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1 Introduction

1.1 ACKNOWLEDGEMENT

Black & Veatch will be guiding us as we work through this project.

1.2 PROBLEM AND PROJECT STATEMENT

This project sets out to develop a solar farm to increase the use of renewable energy at Black & Veatch. Additionally, a power substation must be created which will allow for the harnessing and distribution of the solar farm's energy. This project is very important because regulations pushing renewable energy on power companies are rapidly increasing and so Black & Veatch must begin to take the necessary steps towards avoiding penalties from these regulations. On the other side of this project, we can find importance through the students who are trying to learn about solar energy and power distribution. Through this project, the team of students gained real world experience of what it would be like to work for a power company using calculations that are produced from Black & Veatch's internal documents.

The final goal of this project is to design a 60MW Solar Power Plant and 115kV / 34.5kV substation. This project will be split up into two semesters with the first semester being the creation of the solar plant design and the second semester being the creation of the substation design. In order to accomplish this, the team of students must work together in unison with the mentors giving deliverables that contain the following:

- Equipment sizing Calculations
- Solar layout drawings
- Solar panel string sizing design
- Electrical layout drawings (substation equipment)
- Grounding analysis and ground-grid developed with IEEE-80
- Bus calculations for substation
- Possibility of additional calculations (DC battery bank, Lightning protection, etc.)
- Creation of solar/substation design-optimizing tool
- Voltage drop calculations
- Trench fill tool
- Economic estimates

In order to stay on track with all of these deliverables, we were required to develop a detailed engineer man-hour budget and schedule for this project; this is a very nice way to plan the overall project. Finally, the students will share their work with the Black & Veatch engineers, via Microsoft Teams, who will analyze the work we have done through the two semesters.

General Problem Statement

We as a team have been tasked with designing a 60 MW solar farm with an accompanying substation to add clean, renewable energy to the American energy grid. This project is a "from scratch" design, and while we used the resources provided to us, the overall design of the final project is of our own creation.

General Solution Approach

We will design a 60 MW solar farm and substation by selecting appropriate parts and land, and then decide the most cost-effective way to combine and set up the farm. This consists of appropriately sizing solar panels, combiner boxes, and inverters, as well as necessary parts for the substation. We will accomplish this by using excel spreadsheets to determine sizing and expected output values, as well as CAD or similar software to virtually build and assess our designs to produce a more ideal final product.

1.3 OPERATIONAL ENVIRONMENT

This solar farm will operate outside in typically hot, sunny weather and also must be able to withstand temperatures below freezing. It must also be resistant to common weather conditions of the area, such as thunderstorms or snow.

1.4 REQUIREMENTS

Functional

- Must be able to operate in environmental conditions as described in section 1.3.
- Power rating at the solar farm of 60 MW
- Adhere to IEEE standards
- Maintain reliability throughout lifespan of project

Environmental

- Parcel of land must be flat and continuous (i.e. no hills, creeks, ravines)
- High amount of average sunshine per year
- High irradiance on the land
- Must be near enough end users so energy produced is used.

Economic

- Must be able to produce enough kWh per year over the course of 10 years to recover initial investment and operational costs.

1.5 INTENDED USERS AND USES

This solar farm will service the surrounding areas as a support to current infrastructure. This may include spikes in commercial or residential power usage during the daytime.

1.6 ASSUMPTIONS AND LIMITATIONS

Assumptions

- The sun will shine a consistent number of hours per year
- A consistent amount of energy will be generated and sold each year
- Power lost to inefficiencies in equipment/transmission will be constant

Limitations

- The plant cannot operate at maximum power rating, as power is lost in wires, equipment, and to indirect sunlight.
- The solar farm must be close to enough customers so that the power generated is used.
- Land must be flat and continuous (no creeks/ravines/steep hills).

1.7 EXPECTED END PRODUCT AND DELIVERABLES

There are deliverables for this project that will be required from both the mentors with Black & Veatch alongside the mentors/professors from Iowa State. The deliverables that are required for our mentors from Iowa State include:

- Discussion posts covering various topics from the lectures.
- Bi-Weekly Project Reports
- Lighting Talks
- Final Design Document

The weekly discussion posts allowed us to learn different processes that our mentors from Iowa State think will help throughout the process of this project. The Bi-Weekly reports helped us keep track of where we were in the project. This involved us stating current problems and solutions that we were dealing with and current parts of the project that we are finishing and starting. The lightning talks forced students to practice presenting, which was helpful. This document is the last deliverable for our Iowa State mentors which will serve as an all-in-one project description.

With the information given by Black & Veatch, we can expect to report the following deliverables:

- Equipment sizing calculations
- Solar layout drawings
- Solar panel string sizing design
- Electrical layout drawings (substation equipment)
- Grounding analysis and ground-grid developed with IEEE-80
- Bus calculations for substation
- Possibility of additional calculations (DC battery bank, Lightning protection, etc.)
- Creation of solar/substation design-optimizing tool

The equipment sizing calculations are excel documents that Black & Veatch outlined for us to do. These outlines include built in formulas that were completed throughout the semester as our group put everything together. The solar layout drawings are 2D models that were created in excel to give an easier-to-understand example of our project. The solar panel string sizing is a part of the same equipment sizing calculation excel file as above and helped with knowing how to finish the 2-D model. The rest of the calculations will be discussed in further length in the second semester.

All these deliverables will help us to maintain a steady workflow resulting in a well-documented and complete project by the end of this course.

At the end of the project, our client can expect to have a completed (2-D) virtual model of the solar farm along with the power substation. This will include all the deliverables listed above along with a presentation of the overall progress we made in this project. This presentation will include both a meeting with all the students and mentors present in addition to this design document which lays out the project as a whole.

2 Project Plan

2.1 TASK DECOMPOSITION

Parts Acquisition

- Select Solar Panels based on price, company, and power rating
- Select Combiner Boxes based on price, number of inputs, Amperage rating, and company
- Select Inverter skids based on capacity, inputs, cost, and company

Design

- Design high level model in order to better visualize final product
- Design farm layout within land requirements and accessibility
- Design component attachments based on part ratings and cost and power efficiency

Analysis

- Economic efficiency analysis
- Voltage drop calculations
- Trench fill analysis

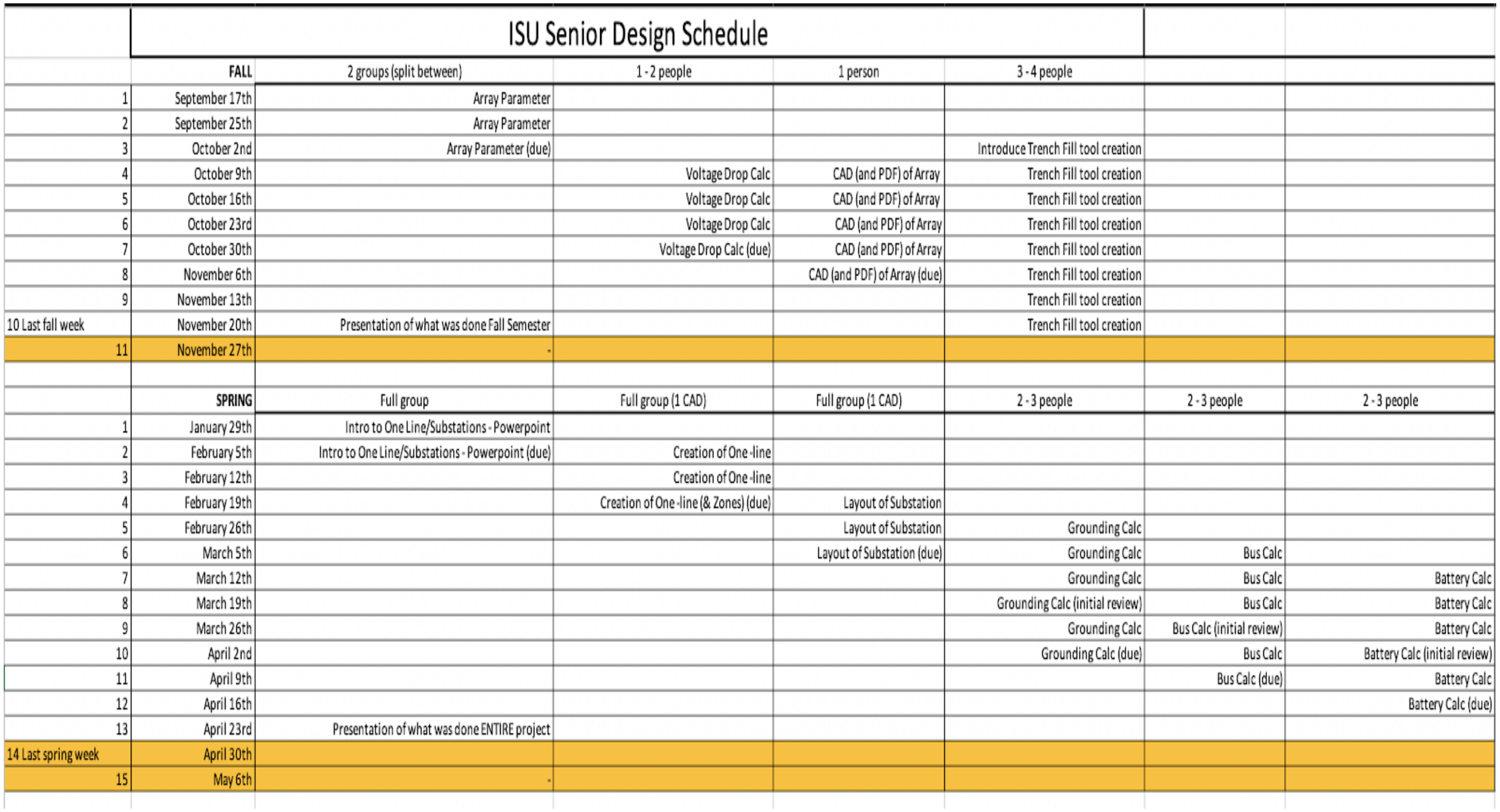
2.2 RISKS AND RISK MANAGEMENT/MITIGATION

We will not be physically constructing a prototype for the 60MW solar plant, so the risks will relate only to performance targets. We have assumed that the plot of land is perfectly flat, at the standard elevation of New Mexico, and will have enough room for all components of the solar plant. One possible risk is that the minimum temperature of the solar plant's location will affect the solar string voltage. To compensate for this, we set the minimum temperature to -40 degrees Celsius. This ensures a risk factor of 0 because New Mexico simply does not get that cold at any point in the year. We have designed the system so that the combiner boxes and inverters will all be of adequate strength to handle all their inputs, even with maximum solar output. The solar plant can also store excess power to keep up production on days with less-than-optimal amounts of sunlight. This means that projected solar output will not be a risk. The main risk is that we might not complete our design in time. I would evaluate this risk at a probability of 0.25 because we are currently ahead of schedule by at least 1 week. One way of making sure that this will not happen is by asking our mentors for help whenever we feel that we are falling behind. Our mentors have been great about offering help when needed, and we are sure that they will try their best to answer any questions we might have.

2.3 PROJECT PROPOSED MILESTONES, METRICS, AND EVALUATION CRITERIA

Key Milestones in our project are part selection, high level layout design, AutoCAD/Bluebeam initial Design, AutoCAD/ Bluebeam corrections, AutoCAD/ Bluebeam final draft. These milestones can be evaluated by percentage complete, as well as projected efficiency for the AutoCAD/ Bluebeam designs.

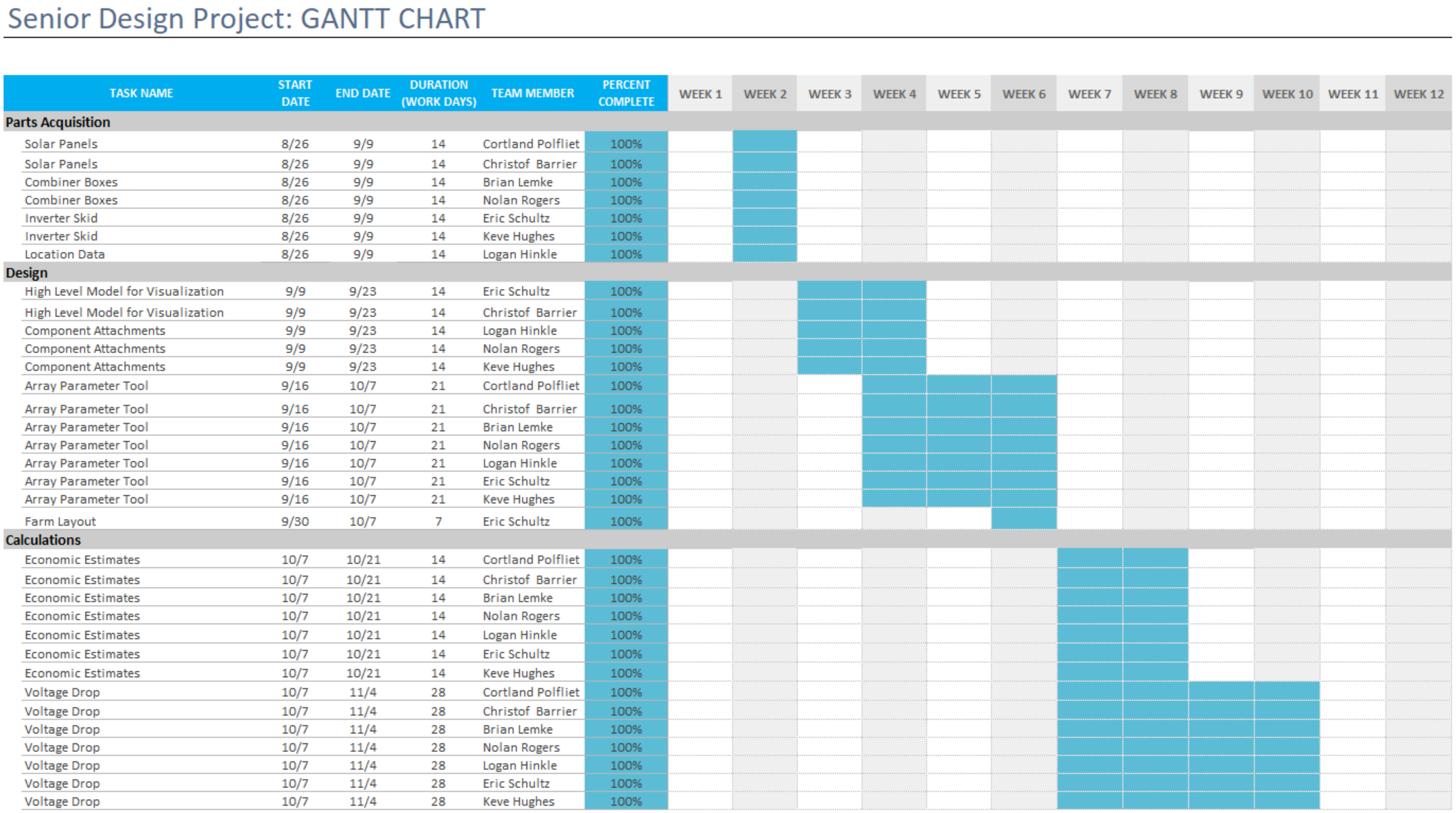
2.4 PROJECT TIMELINE/SCHEDULE



	ISU Senior Design Schedule						
	FALL	2 groups (split between)	1 - 2 people	1 person	3 - 4 people		
1	September 17th	Array Parameter					
2	September 25th	Array Parameter					
3	October 2nd	Array Parameter (due)			Introduce Trench Fill tool creation		
4	October 9th		Voltage Drop Calc	CAD (and PDF) of Array	Trench Fill tool creation		
5	October 16th		Voltage Drop Calc	CAD (and PDF) of Array	Trench Fill tool creation		
6	October 23rd		Voltage Drop Calc	CAD (and PDF) of Array	Trench Fill tool creation		
7	October 30th		Voltage Drop Calc (due)	CAD (and PDF) of Array	Trench Fill tool creation		
8	November 6th			CAD (and PDF) of Array (due)	Trench Fill tool creation		
9	November 13th				Trench Fill tool creation		
10 Last fall week	November 20th	Presentation of what was done Fall Semester			Trench Fill tool creation		
11	November 27th	-					
	SPRING	Full group	Full group (1 CAD)	Full group (1 CAD)	2 - 3 people	2 - 3 people	2 - 3 people
1	January 29th	Intro to One Line/Substations - Powerpoint					
2	February 5th	Intro to One Line/Substations - Powerpoint (due)	Creation of One -line				
3	February 12th		Creation of One -line				
4	February 19th		Creation of One -line (& Zones) (due)	Layout of Substation			
5	February 26th			Layout of Substation	Grounding Calc		
6	March 5th			Layout of Substation (due)	Grounding Calc	Bus Calc	
7	March 12th				Grounding Calc	Bus Calc	Battery Calc
8	March 19th				Grounding Calc (initial review)	Bus Calc	Battery Calc
9	March 26th				Grounding Calc	Bus Calc (initial review)	Battery Calc
10	April 2nd				Grounding Calc (due)	Bus Calc	Battery Calc (initial review)
11	April 9th					Bus Calc (due)	Battery Calc
12	April 16th						Battery Calc (due)
13	April 23rd	Presentation of what was done ENTIRE project					
14 Last spring week	April 30th						
15	May 6th	-					

Figure 1 – Proposed Project Schedule

The figure above (figure 1) outlines the proposed project schedule given to us by Black & Veatch at the beginning of the semester. However, after constant communication with our Black & Veatch mentors as our work over the semester progressed, we collectively agreed that creating a CAD for our solar array was unnecessary. We also decided to postpone the creation of the trench fill tool until after the fall semester has ended, as we felt it would be more relevant to our work with the substation. These delays were approved by our mentors, and despite this, we were still introduced to the trench fill tool and have begun asking preliminary questions to our mentors at Black & Veatch regarding these next steps. We will begin working with this tool over winter break and into the spring semester. The figure below (figure 2) shows the Gantt chart that we created, which more accurately depicts our progress and timeline of accomplishments over the course of the fall semester. Following our completion of the voltage drop calculation, we devoted the remainder of the semester to documentation and presentation creation.



Senior Design Project: GANTT CHART

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	PERCENT COMPLETE	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12
Parts Acquisition																	
Solar Panels	8/26	9/9	14	Cortland Polfliet	100%		▨										
Solar Panels	8/26	9/9	14	Christof Barrier	100%		▨										
Combiner Boxes	8/26	9/9	14	Brian Lemke	100%		▨										
Combiner Boxes	8/26	9/9	14	Nolan Rogers	100%		▨										
Inverter Skid	8/26	9/9	14	Eric Schultz	100%		▨										
Inverter Skid	8/26	9/9	14	Keve Hughes	100%		▨										
Location Data	8/26	9/9	14	Logan Hinkle	100%		▨										
Design																	
High Level Model for Visualization	9/9	9/23	14	Eric Schultz	100%			▨	▨								
High Level Model for Visualization	9/9	9/23	14	Christof Barrier	100%			▨	▨								
Component Attachments	9/9	9/23	14	Logan Hinkle	100%			▨	▨								
Component Attachments	9/9	9/23	14	Nolan Rogers	100%			▨	▨								
Component Attachments	9/9	9/23	14	Keve Hughes	100%			▨	▨								
Array Parameter Tool	9/16	10/7	21	Cortland Polfliet	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Christof Barrier	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Brian Lemke	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Nolan Rogers	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Logan Hinkle	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Eric Schultz	100%				▨	▨	▨						
Array Parameter Tool	9/16	10/7	21	Keve Hughes	100%				▨	▨	▨						
Farm Layout	9/30	10/7	7	Eric Schultz	100%						▨						
Calculations																	
Economic Estimates	10/7	10/21	14	Cortland Polfliet	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Christof Barrier	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Brian Lemke	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Nolan Rogers	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Logan Hinkle	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Eric Schultz	100%							▨	▨				
Economic Estimates	10/7	10/21	14	Keve Hughes	100%							▨	▨				
Voltage Drop	10/7	11/4	28	Cortland Polfliet	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Christof Barrier	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Brian Lemke	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Nolan Rogers	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Logan Hinkle	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Eric Schultz	100%							▨	▨	▨	▨		
Voltage Drop	10/7	11/4	28	Keve Hughes	100%							▨	▨	▨	▨		

Figure 2 - Gantt Chart

2.5 PROJECT TRACKING PROCEDURES

Our group used Microsoft Teams and Google Drive to communicate and collaborate on all project materials. We tracked progress by adhering to strict deadlines for the various tasks necessary to complete the project and holding team meetings once per week to discuss progress on tasks and to determine if additional resources needed to be reallocated to the completion of a specific task.

2.6 PERSONNEL EFFORT REQUIREMENTS

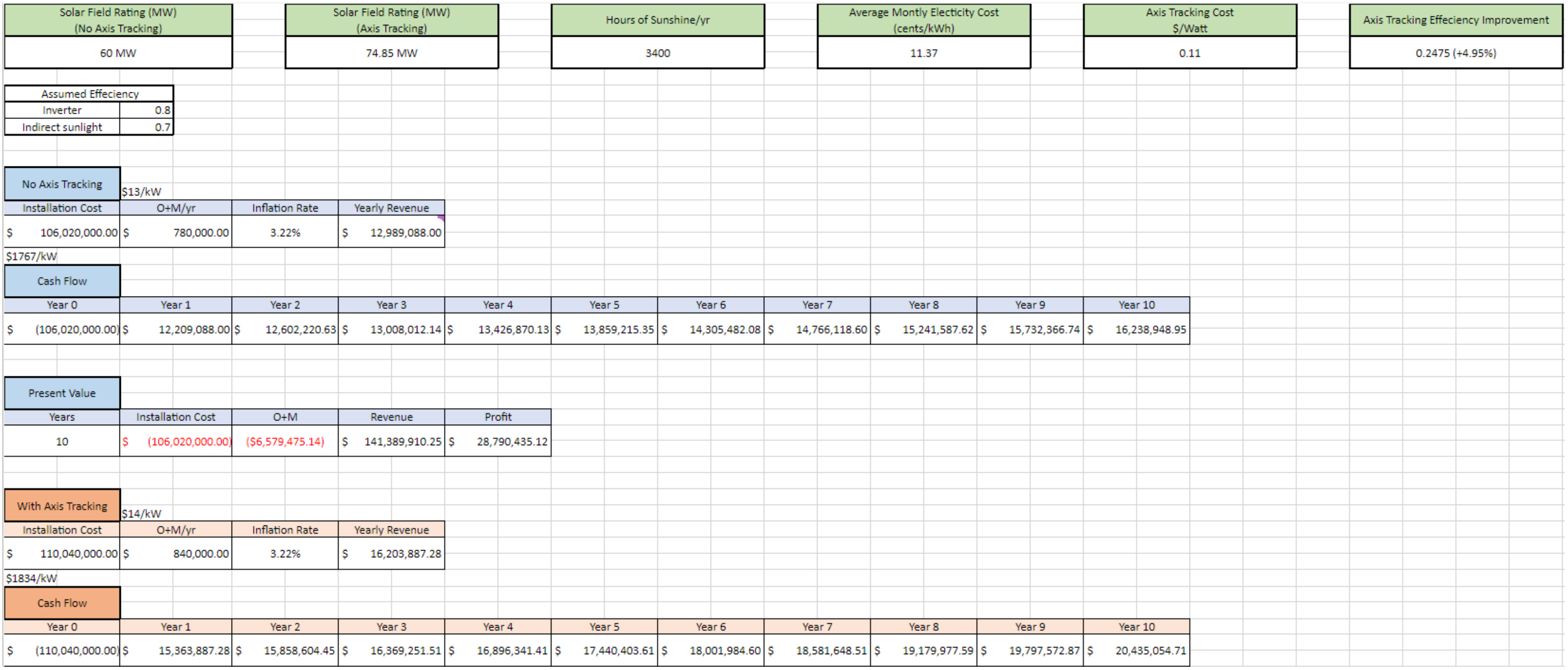
All tasks have been completed by dividing work amongst team members via our weekly group meetings. The mentors at Black & Veatch have given the team tasks from the senior design schedule and they will provide upcoming specific tasks outlined in the schedule in the coming weeks. These tasks are divided amongst the team members evenly during our team meetings.

2.7 OTHER RESOURCE REQUIREMENTS

We required access to solar field modeling tools, such as the Array Design Parameter Tool we used to model our initial solar field design. These were provided by our mentors. We will also need access to AutoCAD software for designing things in the spring semester. We can get free access as students so this will not pose a problem. We have discussed using Bluebeam with our mentors instead of AutoCAD because some of us have training in that program.

2.8 FINANCIAL REQUIREMENTS

Given that our project is simply designing the solar field, the only financial requirement is possible software costs. If our project were to completely build the solar plant, the cost would be many millions of dollars. Our economic evaluation, in the form of an array parameter tool, had sections for calculating the total cost of our required parts. Our mentors suggested that we evaluate the 10-year cash flow of the solar plant with and without axis tracking technology. They also said that we were not going to use axis tracking technology because there were many additional factors that come with axis tracking that would complicate our calculations. For starters, we would have to completely start over the design to reevaluate the number of components needed and resize the entire solar plant. The economic evaluation is shown below.



Solar Field Rating (MW) (No Axis Tracking)	Solar Field Rating (MW) (Axis Tracking)	Hours of Sunshine/yr	Average Montly Electicity Cost (cents/kWh)	Axis Tracking Cost $/Watt	Axis Tracking Effeciency Improvement
60 MW	74.85 MW	3400	11.37	0.11	0.2475 (+4.95%)

Assumed Effeciency	
Inverter	0.8
Indirect sunlight	0.7

No Axis Tracking

$13/kW

Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 106,020,000.00	$ 780,000.00	3.22%	$ 12,989,088.00

$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
$ (106,020,000.00)	$ 12,209,088.00	$ 12,602,220.63	$ 13,008,012.14	$ 13,426,870.13	$ 13,859,215.35	$ 14,305,482.08	$ 14,766,118.60	$ 15,241,587.62	$ 15,732,366.74	$ 16,238,948.95

Present Value

Years	Installation Cost	O+M	Revenue	Profit
10	$ (106,020,000.00)	($6,579,475.14)	$ 141,389,910.25	$ 28,790,435.12

With Axis Tracking

$14/kW

Installation Cost	O+M/yr	Inflation Rate	Yearly Revenue
$ 110,040,000.00	$ 840,000.00	3.22%	$ 16,203,887.28

$1834/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
$ (110,040,000.00)	$ 15,363,887.28	$ 15,858,604.45	$ 16,369,251.51	$ 16,896,341.41	$ 17,440,403.61	$ 18,001,984.60	$ 18,581,648.51	$ 19,179,977.59	$ 19,797,572.87	$ 20,435,054.71

Figure 3 - Economic Evaluation

3 Design

3.1 PREVIOUS WORK AND LITERATURE

The design of solar farms and substations has well established practices and methodologies to maximize efficiency. Our mentors at Black & Veatch guided our design process to follow these practices. The general layout of a solar array is strings of solar panels connected in parallel, forming racks, which are then linked into combiner boxes. The combiner box outputs are then fed into inverters, which connect to the transformer and into the power grid. Efficiency has been a constant problem in solar power, as power is lost in equipment, transmission, and due to uncontrollable variables, such as temperature. Some of the advantageous design choices involve strategic placement of combiner boxes and skids to minimize the amount of cable used in the farm. The graphic below shows a sample layout of a traditional solar array.

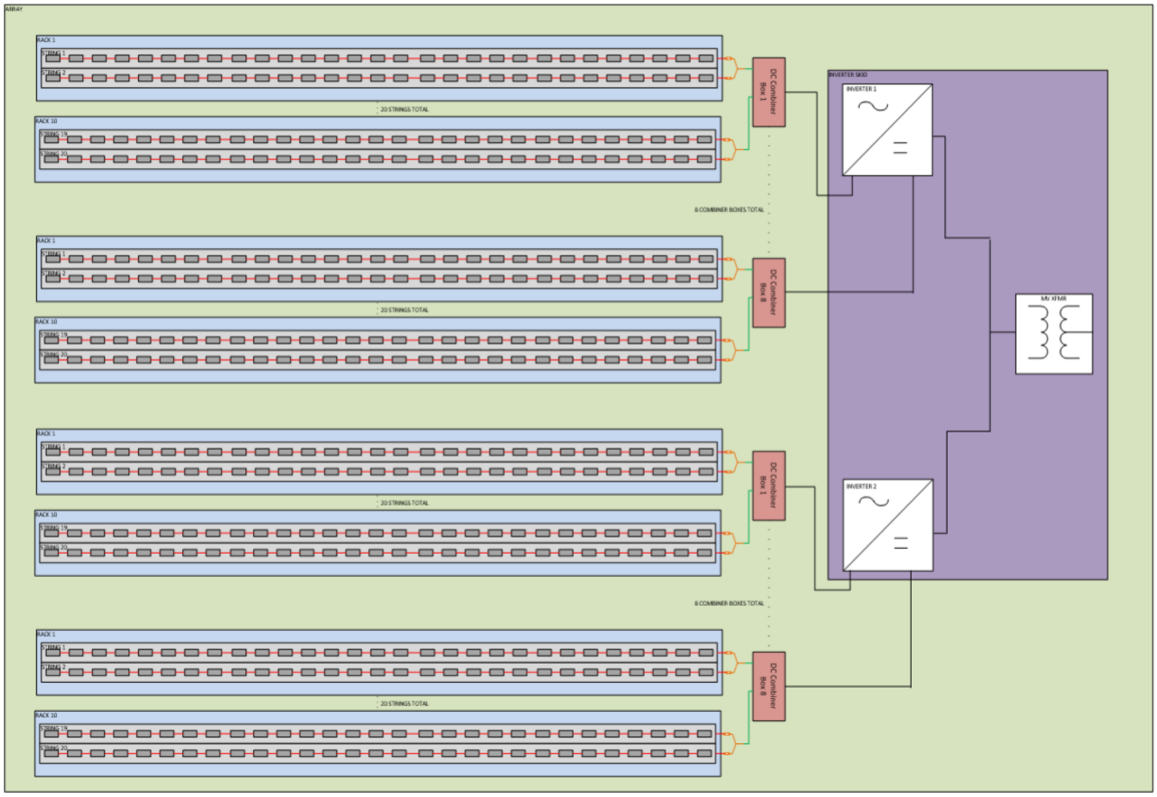


Figure 4 - Sample Solar Array Layout

We also had to calculate the size of the wires connecting our solar plant. There were many factors to consider, such as outdoor conditions, maximum current flow, distance from inverter, and temperature. Using NEC tables (shown in Chapter 6 of this document) we were able to accurately size the wires to minimize voltage drop of the wires to less than 3%, which was our target value.

Parameters for standard combiner box:

DCB	Strings per Rack	ISC 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	16.484	84	12	1.98	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-02	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-03	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-04	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-05	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-06	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-07	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-08	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-09	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-10	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-11	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-12	2	16.484	84	12	1.98	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848

Parameters for middle combiner box (near inverter):

DCB9-01	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	0.78	0.2786976	9.49016848
DCB9-02	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	0.78	0.1519289	5.181119008
DCB9-03	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	17	10	0.78	0.0251602	0.872069536
DCB9-04	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	0.78	0.1519289	5.181119008
DCB9-05	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	0.78	0.2786976	9.49016848
DCB9-06	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	0.78	0.2786976	9.49016848
DCB9-07	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	0.78	0.1519289	5.181119008
DCB9-08	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	17	10	0.78	0.0251602	0.872069536
DCB9-09	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	0.78	0.1519289	5.181119008
DCB9-10	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	0.78	0.2786976	9.49016848

Parameters for inverter:

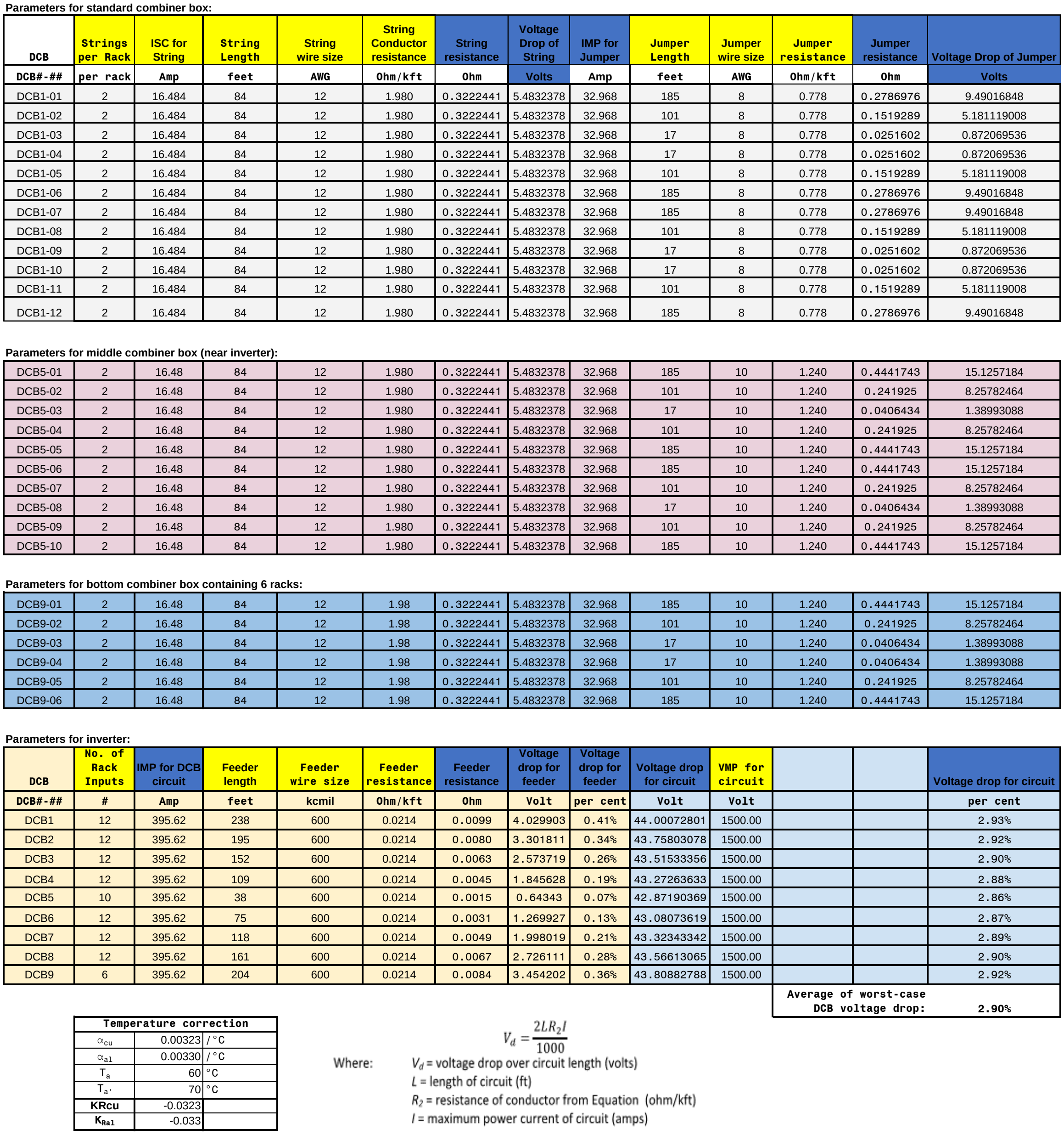
DCB	No. of Rack Inputs	IMP for DCB circuit	Feeder length	Feeder wire size	Feeder resistance	Feeder resistance	Voltage drop for feeder	Voltage drop for feeder	Voltage drop for circuit	VMP for circuit			Voltage drop for circuit
DCB#-##	#	Amp	feet	kcmil	Ohm/kft	Ohm	Volt	per cent	Volt	Volt			per cent
DCB1	12	395.62	410	600	0.0214	0.0169	6.94227	0.71%	44.97151693	1500.00			3.00%
DCB2	12	395.62	367	600	0.0214	0.0156	6.366569	0.65%	44.77961679	1500.00			2.99%
DCB3	12	395.62	324	600	0.0214	0.0135	5.486086	0.56%	44.48612247	1500.00			2.97%
DCB4	12	395.62	281	600	0.0214	0.0116	4.757995	0.49%	44.24342524	1500.00			2.95%
DCB5	12	395.62	238	600	0.0214	0.0099	4.029903	0.41%	44.00072801	1500.00			2.93%
DCB6	12	395.62	195	600	0.0214	0.0080	3.301811	0.34%	43.75803078	1500.00			2.92%
DCB7	12	395.62	152	600	0.0214	0.0063	2.573719	0.26%	43.51533356	1500.00			2.90%
DCB8	12	395.62	109	600	0.0214	0.0045	1.845628	0.19%	43.27263633	1500.00			2.88%
DCB9	10	395.62	38	600	0.0214	0.0015	0.64343	0.07%	42.87190369	1500.00			2.86%
DCB10	12	395.62	75	600	0.0214	0.0031	1.269927	0.13%	43.08073619	1500.00			2.87%
DCB11	12	395.62	118	600	0.0214	0.0049	1.998019	0.21%	43.32343342	1500.00			2.89%
DCB12	12	395.62	161	600	0.0214	0.0067	2.726111	0.28%	43.56613065	1500.00			2.90%
DCB13	12	395.62	204	600	0.0214	0.0084	3.454202	0.36%	43.80882788	1500.00			2.92%
DCB14	12	395.62	247	600	0.0214	0.0103	4.182294	0.43%	44.05152511	1500.00			2.94%
DCB15	12	395.62	290	600	0.0214	0.0120	4.910386	0.51%	44.29422234	1500.00			2.95%
DCB16	12	395.62	333	600	0.0214	0.0138	5.638477	0.58%	44.53691956	1500.00			2.97%
DCB17	12	395.62	376	600	0.0214	0.0156	6	0.65%	44.77961679	1500.00			2.99%
											Average of worst-case DCB voltage drop:		2.93%

Temperature correction		
α_{cu}	0.00323	/ °C
α_{al}	0.00330	/ °C
T_a	60	°C
$T_{a'}$	70	°C
KRcu	-0.0323	
K_{Ral}	-0.033	

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

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)

Figure 5 - Full-Array Voltage Drop Calculations



Parameters for standard combiner box:

DCB	Strings per Rack	ISC 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	16.484	84	12	1.980	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-02	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-03	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-04	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-05	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-06	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-07	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848
DCB1-08	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-09	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-10	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	17	8	0.778	0.0251602	0.872069536
DCB1-11	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	101	8	0.778	0.1519289	5.181119008
DCB1-12	2	16.484	84	12	1.980	0.3222441	5.4832378	32.968	185	8	0.778	0.2786976	9.49016848

Parameters for middle combiner box (near inverter):

DCB5-01	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184
DCB5-02	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB5-03	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	17	10	1.240	0.0406434	1.38993088
DCB5-04	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB5-05	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184
DCB5-06	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184
DCB5-07	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB5-08	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	17	10	1.240	0.0406434	1.38993088
DCB5-09	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB5-10	2	16.48	84	12	1.980	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184

Parameters for bottom combiner box containing 6 racks:

DCB9-01	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184
DCB9-02	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB9-03	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	17	10	1.240	0.0406434	1.38993088
DCB9-04	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	17	10	1.240	0.0406434	1.38993088
DCB9-05	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	101	10	1.240	0.241925	8.25782464
DCB9-06	2	16.48	84	12	1.98	0.3222441	5.4832378	32.968	185	10	1.240	0.4441743	15.1257184

Parameters for inverter:

DCB	No. of Rack Inputs	IMP for DCB circuit	Feeder length	Feeder wire size	Feeder resistance	Feeder resistance	Voltage drop for feeder	Voltage drop for feeder	Voltage drop for circuit	VMP for circuit			Voltage drop for circuit
DCB#-##	#	Amp	feet	kcmil	Ohm/kft	Ohm	Volt	per cent	Volt	Volt			per cent
DCB1	12	395.62	238	600	0.0214	0.0099	4.029903	0.41%	44.00072801	1500.00			2.93%
DCB2	12	395.62	195	600	0.0214	0.0080	3.301811	0.34%	43.75803078	1500.00			2.92%
DCB3	12	395.62	152	600	0.0214	0.0063	2.573719	0.26%	43.51533356	1500.00			2.90%
DCB4	12	395.62	109	600	0.0214	0.0045	1.845628	0.19%	43.27263633	1500.00			2.88%
DCB5	10	395.62	38	600	0.0214	0.0015	0.64343	0.07%	42.87190369	1500.00			2.86%
DCB6	12	395.62	75	600	0.0214	0.0031	1.269927	0.13%	43.08073619	1500.00			2.87%
DCB7	12	395.62	118	600	0.0214	0.0049	1.998019	0.21%	43.32343342	1500.00			2.89%
DCB8	12	395.62	161	600	0.0214	0.0067	2.726111	0.28%	43.56613065	1500.00			2.90%
DCB9	6	395.62	204	600	0.0214	0.0084	3.454202	0.36%	43.80882788	1500.00			2.92%
											Average of worst-case DCB voltage drop:		2.90%

Temperature correction		
α_{cu}	0.00323	/ °C
α_{al}	0.00330	/ °C
T_a	60	°C
$T_{a'}$	70	°C
KRcu	-0.0323	
K_{Ral}	-0.033	

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

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)

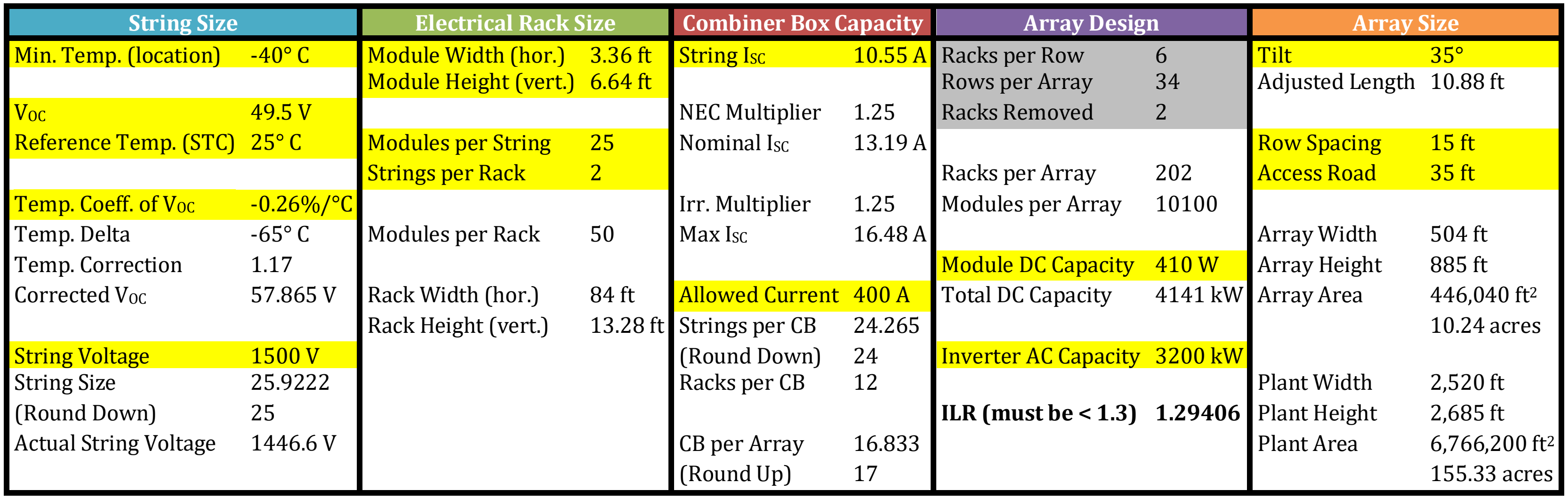
Figure 6 - Half-Array Voltage Drop Calculations

3.2 DESIGN THINKING

Much of our design process has been driven by the guidance of our client, Black & Veatch. They provided us with the specifications to meet in the array parameter tool, as well as with advice about common design principles for solar farms. Some of the important decisions we made about the design of our solar farm were the wattage of the solar panels, the location we would build the solar farm, and the location of the inverters and skids with respect to the solar panels. We compared two locations, one in Iowa and one in New Mexico. The property in New Mexico would be significantly better than the property in Iowa. The property in New Mexico has over 100 more sunny days, higher average irradiance each month, much more acreage that can be used to expand the solar farm, and it is considerably cheaper than the property in Iowa. This land costs about $750 an acre and receives approximately 310 sunny days per year.

3.3 PROPOSED DESIGN

The design of our solar layout was determined using the array parameter tool shown in Figure 7. The yellow cells depict values that we had to input based on information gathered from the datasheets of our selected components. The white cells contain equations to calculate other values of interest. The gray cells are values that alter the layout of the array and determine the number of solar panels in each array.



String Size		Electrical Rack Size		Combiner Box Capacity		Array Design		Array Size	
Min. Temp. (location)	-40° C	Module Width (hor.)	3.36 ft	String I_{SC}	10.55 A	Racks per Row	6	Tilt	35°
		Module Height (vert.)	6.64 ft			Rows per Array	34	Adjusted Length	10.88 ft
V_{OC}	49.5 V			NEC Multiplier	1.25	Racks Removed	2		
Reference Temp. (STC)	25° C	Modules per String	25	Nominal I_{SC}	13.19 A			Row Spacing	15 ft
		Strings per Rack	2			Racks per Array	202	Access Road	35 ft
Temp. Coeff. of V_{OC}	-0.26%/°C			Irr. Multiplier	1.25	Modules per Array	10100		
Temp. Delta	-65° C	Modules per Rack	50	Max I_{SC}	16.48 A			Array Width	504 ft
Temp. Correction	1.17					Module DC Capacity	410 W	Array Height	885 ft
Corrected V_{OC}	57.865 V	Rack Width (hor.)	84 ft	Allowed Current	400 A	Total DC Capacity	4141 kW	Array Area	446,040 ft^2
		Rack Height (vert.)	13.28 ft	Strings per CB	24.265				10.24 acres
String Voltage	1500 V			(Round Down)	24	Inverter AC Capacity	3200 kW		
String Size	25.9222			Racks per CB	12			Plant Width	2,520 ft
(Round Down)	25					**ILR (must be < 1.3)**	**1.29406**	Plant Height	2,685 ft
Actual String Voltage	1446.6 V			CB per Array	16.833			Plant Area	6,766,200 ft^2
				(Round Up)	17				155.33 acres

Figure 7 - Array Parameter Tool

Our first step was calculating our string size, which is the number of solar panels in a continuous string. We had to insert values for the minimum temp, and we did not know if this was referring to the minimum operating temp of the solar panels or the minimum temperature of our plot of land in New Mexico. Eventually, we determined that this was the minimum temperature of our plot of land. Our values for open circuit voltage V_{OC}, the reference temp, and the temperature voltage coefficient were found on the solar panel datasheet. These values were required to calculate a panel's actual V_{OC} in relation to temperature. We then chose the value of total string voltage as 1500 because we wanted at least 20 panels in a string. The math here is that 1500 divided by our corrected V_{OC} value of 57.865 gives 25.9 panels per string. We rounded this down to 25 to get a total string voltage of 1446.6.

The next task was calculating the physical size of our electrical rack. When it comes to solar, a rack is simply an assembly of multiple strings. We elected to orient our panels portrait because this minimizes the area of land needed. We got the values for module width and height from the solar panel datasheets. The height of our selected 410W solar panel is 6.64 feet and the width is 3.36 feet. We already calculated the rack width to be 25 modules, which is also our string length. The value we decided on for the height of the rack was 2 modules because any more would cause too much of a shadow. This gives the total rack height to be calculated as 6.64*2 or 13.28 feet and the total rack width to be calculated as 3.36*25 or 84 feet. These values will be used in calculations for array size and total solar plant size later.

Our third design challenge was calculating the capacity of combiner boxes in terms of our rack sizes. We took the string current from the 410W solar panel datasheet to be 10.55 Amps. We then adjusted this number to overcompensate for possible high energy solar output days. The adjusted string current was 16.48. The allowed current of the combiner boxes was chosen to be 400 Amps because that will be able to handle more racks. We then took 400/16.48 to get 24.265 strings per combiner box. Rounding down to 24 gives us the number of total strings we can put into each combiner box, which translates to 12 total racks per combiner box.

As for the array design, we needed to find optimal values of racks per row and rows per array to meet a few specifications. The industry standard for the maximum inverter load ratio (ILR) is 1.3. The ILR is the ratio of the power capacities between the DC solar array and the AC inverter. With an inverter capacity of 3200 kW, we used 1.3*3200 to determine that the capacity of the solar array should be about 4160 kW. We tested many variations but ended up choosing 6 racks per row and 34 rows per array with 2 racks removed for inverter space. This was where we spent most of our time with the array parameter tool.

Each row of racks will have 15 feet of space between them and there will be a 35 feet wide access road running through the middle for inverter maintenance. Based on these calculations, each full array will produce 4.141 MW of power. Since our target power for the entire solar field is 60 MW, we will need approximately 14 full arrays and 1 half-array. The layout of a full array as well as the half-array is shown below.

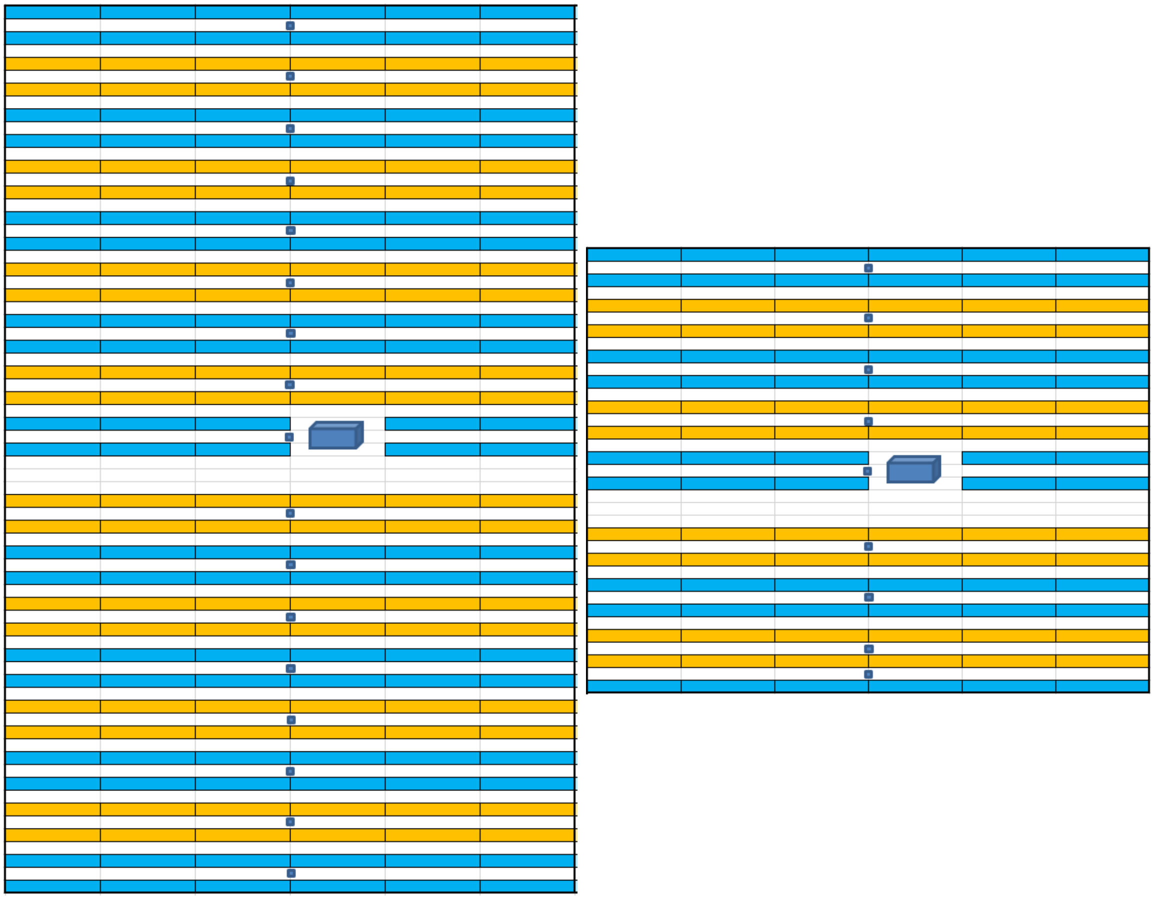


Figure 8 - Full Array and Half-Array Layouts

Each blue/orange rectangle represents a single rack of 50 solar panels. The large box in the middle of the array represents the inverter skid, while the smaller dark blue squares represent combiner boxes. Each full array contains 10,100 solar panels, 17 combiner boxes, and one inverter skid. The half-array consists of 5,000 solar panels, 9 combiner boxes, and one inverter skid. The proposed full-sized layout is shown below.

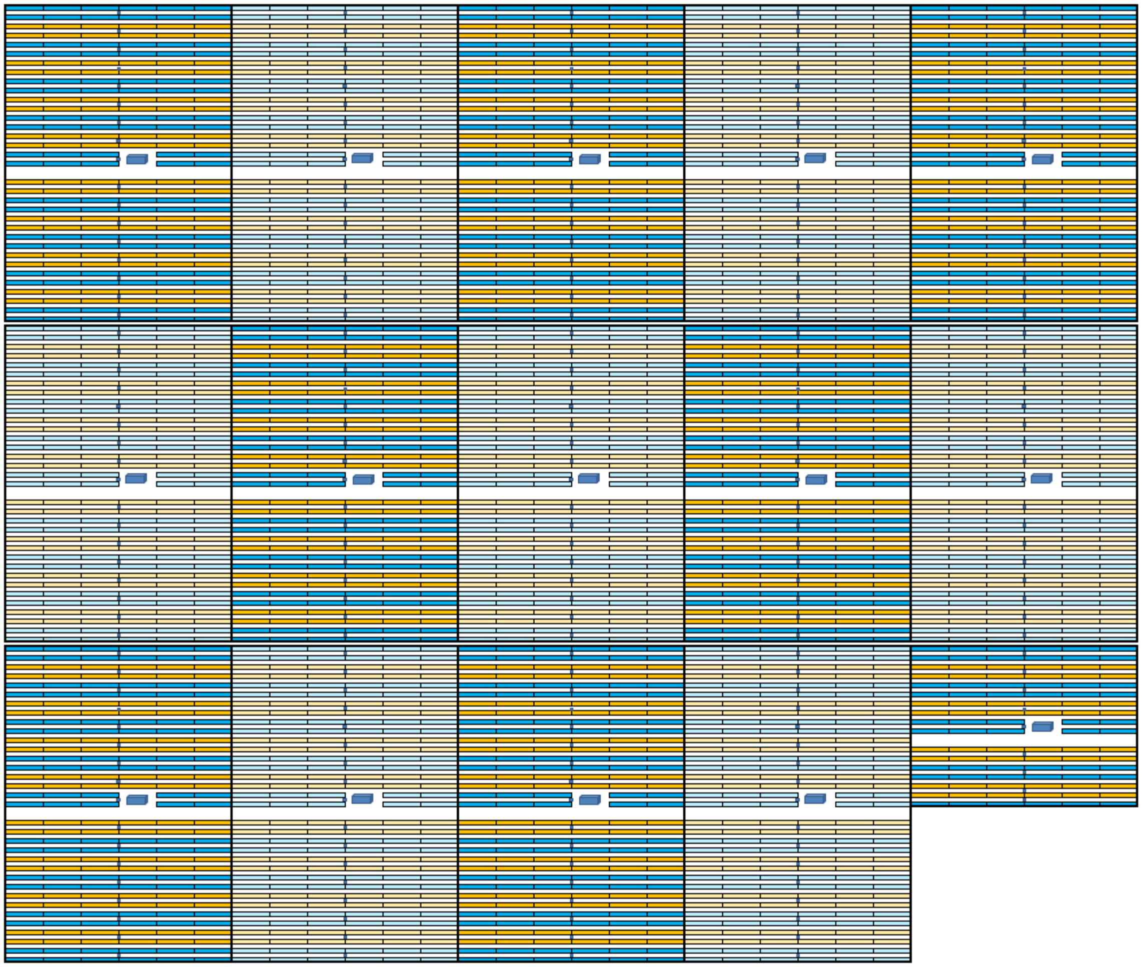


Figure 9 - Multiple Array Layout

The full combined layout of the ~14.5 arrays will have a total length of 2,684.59 ft and a total width of 2,520 ft, resulting in a total area of 6,765,168.3 ft, approximately 155.3 acres.

3.4 TECHNOLOGY CONSIDERATIONS

Solar panel technology is evolving, and as a result, large amounts of equipment with vastly different specifications is available. Higher wattage solar panels produce more energy in less space but are more expensive and require equipment that can handle the larger load. Copper cables are more efficient than aluminum cables, however they are significantly more expensive at the gauge required to transfer utility scale power. Sun tracking technology increases efficiency of the solar panels and generates more power but involves more maintenance and higher installation costs. The trade-off in equipment is usually power/efficiency for cost. After much research, economic evaluation, and asking our mentors, we concluded that using axis-tracking technology was unneeded. The benefit of producing more power is outweighed by the installation and maintenance costs, because we already are producing enough power due to the sheer number of solar panels. As for the specific tilt angle of our panels, multiple sources claimed that an angle between 30 and 40 degrees is optimal for an area like New Mexico. Given that we will not be adjusting the angle of our panels throughout the year, it makes more sense to go with the angle that provides the best year-round results. Winter has a lower sunshine output, so optimizing our tilt angle to maximize power in winter is the way to go. This gives us an angle of 35 degrees, which will compensate for the lower sunlight levels in the New Mexico winter. This careful design is the only way to minimize the impact of the tradeoffs.

3.5 DESIGN ANALYSIS

Our design from section 3.3 successfully meets all the requirements outlined for us by Black & Veatch. The 410 W panels generate the 60 MW required using the least amount of space, while not overloading the equipment and keeping the costs as low as we can. Our design iterations have involved tweaking the number of panels in the arrays as well as trying out different types of cable in our design.

3.6 DEVELOPMENT PROCESS

We have adopted a Waterfall development process for this project. This method makes sense for us as our requirements have been laid out specifically for us by our clients and Black & Veatch and following with a high-level design to detailed design is the most straightforward way to getting to a final product.

3.7 DESIGN PLAN

Our design did take into consideration intended users and use cases from section 1.5, however, they were not as important as other technical aspects of our design. For example, we researched potential locations and completed an economic evaluation of the project; factors are usually very important considerations for a project like this. However, because our design will not be implemented, they just gave us a better conceptual understanding of our design; they did not significantly affect technical aspects of our design. The vast majority of our design plan focused on meeting the technical requirements for the solar plant such as component choice, physical array layout, and generating capacity because they were most pertinent to the overall design. These requirements were laid out by our Black & Veatch mentors who pushed us to design our solar plant layout to specifically meet the constraints as closely as we could.

The figure below shows a high-level overview of how Black & Veatch and our intended users went into our design requirements. Our design process and which is centered around the requirements. The component choices module includes the panels, inverters, combiner boxes, and cables for the solar plant. The physical layout module encompasses string/rack sizes, array size and layout, panel tilt, and row spacing.

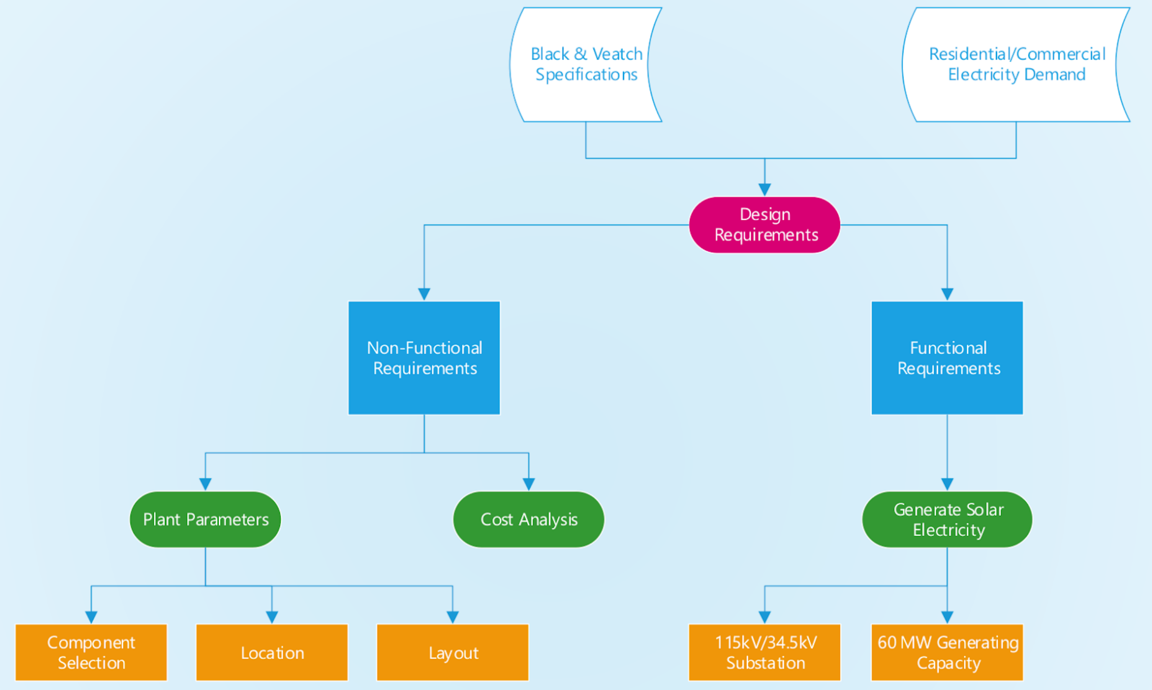


Figure 10 - Plant Design Flowchart

4 Testing

Within our project, individual unit testing is not directly related to the desired outcome. The kind of testing we did is based more on iterative calculations that met predetermined constraints such as in the array parameter tool and the voltage drop calculation and cost analysis tools. Furthermore, because we are not actually physically building this project, no real-world tests were run, we merely gained an understanding of what kind of challenges arise when building and testing a utility scale solar farm in real life.

One of the design challenges we encountered while testing within the array parameter tool was misunderstanding of the terminology used because it is proprietary to Black & Veatch. We were able to clear this up by asking our mentors questions and researching other plant designs.

4.1 UNIT TESTING

Under the category of unit testing, we are working with the solar farm and substation design as sort of separate entities. Within the solar farm design, we have a few different parts that we have spent multiple weeks on each (array parameter tool, voltage drop calculator, and trench fill tool). For our project, these can be treated as individual units and will be continually tested and improved as they are not physical but rather conceptual units.

4.2 INTERFACE TESTING

Interface testing has not been utilized, but as we transition into next semester it will be important to synthesize our solar farm with the substation to ensure the designs work together to squeeze the most efficiency possible out of the panels.

4.3 ACCEPTANCE TESTING

To show that we have met the design requirements, we presented our findings, testing, and designs with our peer mentors in our weekly meetings. There, we received feedback and criticisms to ensure that we were moving forward in the right direction, implementing what was wanted from them (the customer).

4.4 RESULTS

In our iterative testing of the array parameter tool to determine the farm's physical layout we encountered two main obstacles. First, we needed to get familiar with all the terminology and background information and second, we needed an understanding of how the array parameter tool works. We were successful in this endeavor and were able to design a 60MW solar farm consisting of modules split into 14.5 arrays of panels. This requires 1 inverter per array, for a total of 18 inverters, and 247 combiner boxes.

Our cost analysis shows that we will turn a ten-year profit of $28.8 million. Government subsidies and bonuses for solar applications may mean it's possible that the solar plant could make even more of a profit. This is very promising as the life of these solar panels is 25 years, meaning there will be 15 more years of high profitability. The voltage-drop calculations helped us determine how to efficiently wire our solar farm to minimize losses across wires.

5 Implementation

We will not be directly involved with the implementation of this project. Our two semesters will be two different design projects, and as such, we will not have time to see a fully built solar farm of our design. Any implementation will be handled by Black & Veatch after Spring semester.

6 Closing Material

6.1 CONCLUSION

We have completed selection and sizing of solar farm components, and analyzed voltage drop and layout options. We have also done cost analysis for return on investment over the course of 10 years and it looks promising. Moving forward we will look at a trench tool for optimizing cable management, and then begin work on the substation design in the spring semester.

6.2 REFERENCES

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6.3 APPENDICES

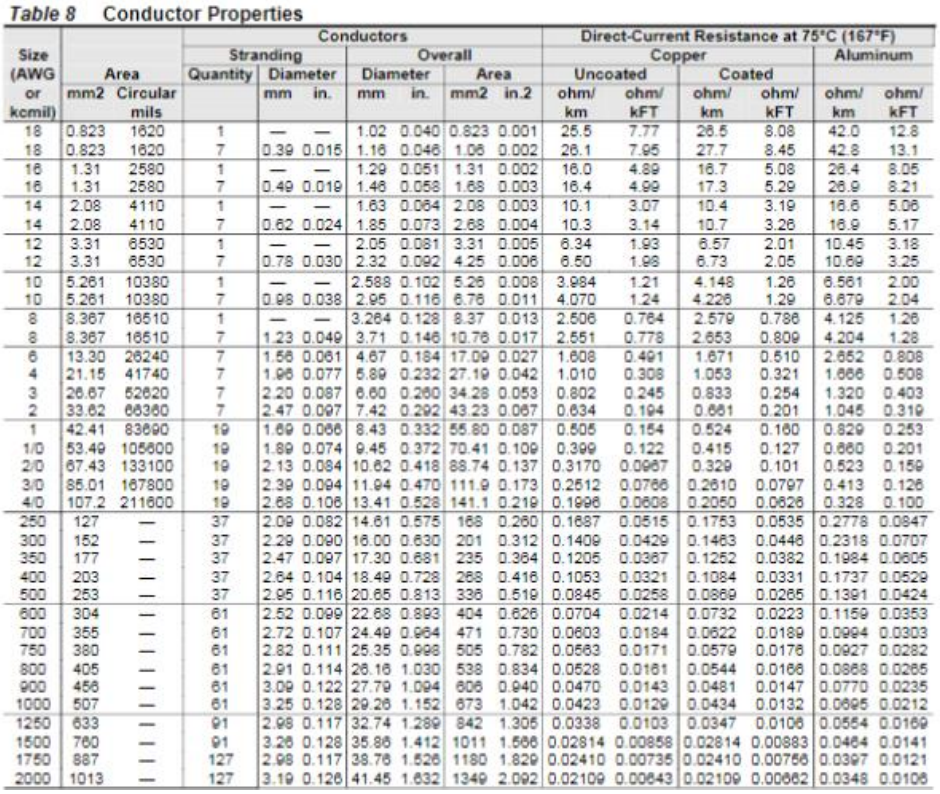
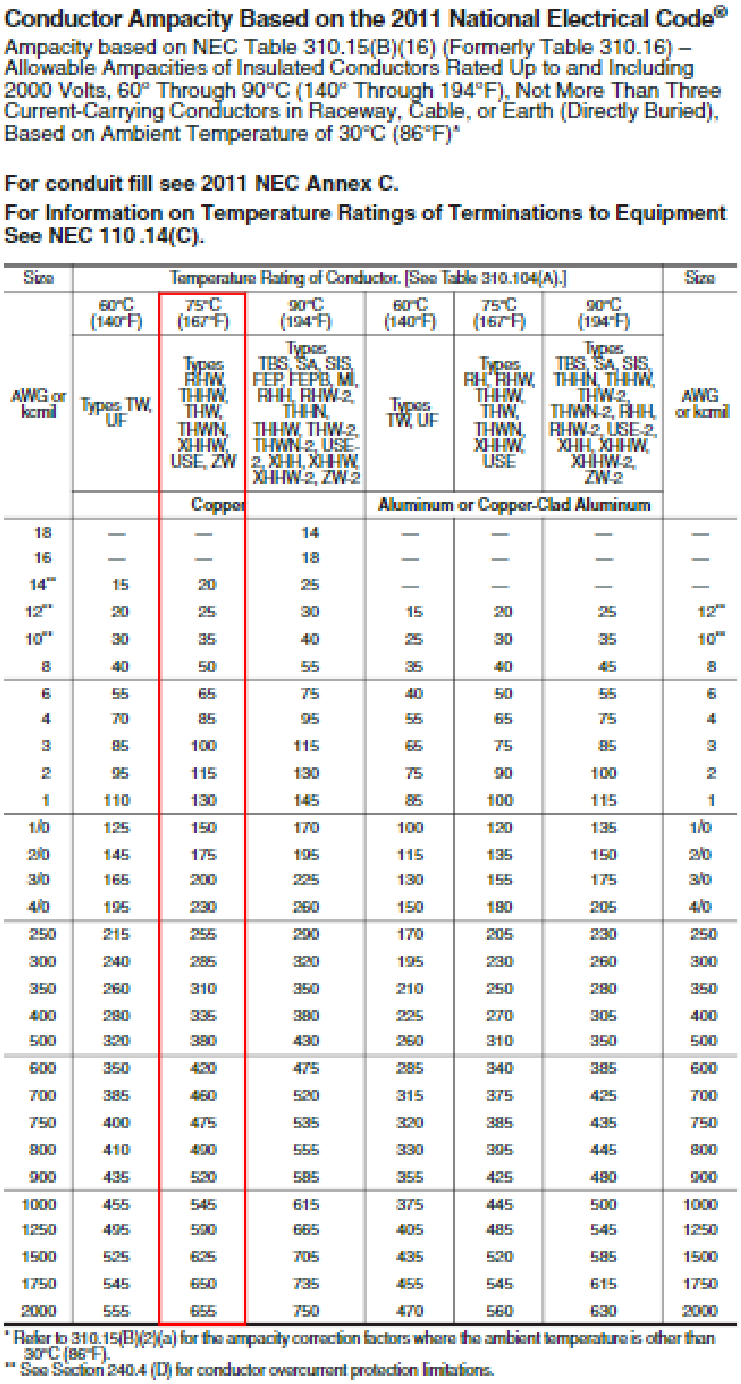


Table 8 **Conductor Properties**

Size (AWG or kcmil)	Area		Conductors							Direct-Current Resistance at 75°C (167°F)					
			Stranding			Overall				Copper				Aluminum	
			Quantity	Diameter		Diameter		Area		Uncoated		Coated			
	mm2	Circular mils		mm	in.	mm	in.	mm2	in.2	ohm/ km	ohm/ kFT	ohm/ km	ohm/ kFT	ohm/ km	ohm/ kFT
18	0.823	1620	1	—	—	1.02	0.040	0.823	0.001	25.5	7.77	26.5	8.08	42.0	12.8
18	0.823	1620	7	0.39	0.015	1.16	0.046	1.06	0.002	26.1	7.95	27.7	8.45	42.8	13.1
16	1.31	2580	1	—	—	1.29	0.051	1.31	0.002	16.0	4.89	16.7	5.08	26.4	8.05
16	1.31	2580	7	0.49	0.019	1.46	0.058	1.68	0.003	16.4	4.99	17.3	5.29	26.9	8.21
14	2.08	4110	1	—	—	1.63	0.064	2.08	0.003	10.1	3.07	10.4	3.19	16.6	5.06
14	2.08	4110	7	0.62	0.024	1.85	0.073	2.68	0.004	10.3	3.14	10.7	3.26	16.9	5.17
12	3.31	6530	1	—	—	2.05	0.081	3.31	0.005	6.34	1.93	6.57	2.01	10.45	3.18
12	3.31	6530	7	0.78	0.030	2.32	0.092	4.25	0.006	6.50	1.98	6.73	2.05	10.69	3.25
10	5.261	10380	1	—	—	2.588	0.102	5.26	0.008	3.984	1.21	4.148	1.26	6.561	2.00
10	5.261	10380	7	0.98	0.038	2.95	0.116	6.76	0.011	4.070	1.24	4.226	1.29	6.679	2.04
8	8.367	16510	1	—	—	3.264	0.128	8.37	0.013	2.506	0.764	2.579	0.786	4.125	1.26
8	8.367	16510	7	1.23	0.049	3.71	0.146	10.76	0.017	2.551	0.778	2.653	0.809	4.204	1.28
6	13.30	26240	7	1.56	0.061	4.67	0.184	17.09	0.027	1.608	0.491	1.671	0.510	2.652	0.808
4	21.15	41740	7	1.96	0.077	5.89	0.232	27.19	0.042	1.010	0.308	1.053	0.321	1.666	0.508
3	26.67	52620	7	2.20	0.087	6.60	0.260	34.28	0.053	0.802	0.245	0.833	0.254	1.320	0.403
2	33.62	66360	7	2.47	0.097	7.42	0.292	43.23	0.067	0.634	0.194	0.661	0.201	1.045	0.319
1	42.41	83690	19	1.69	0.066	8.43	0.332	55.80	0.087	0.505	0.154	0.524	0.160	0.829	0.253
1/0	53.49	105600	19	1.89	0.074	9.45	0.372	70.41	0.109	0.399	0.122	0.415	0.127	0.660	0.201
2/0	67.43	133100	19	2.13	0.084	10.62	0.418	88.74	0.137	0.3170	0.0967	0.329	0.101	0.523	0.159
3/0	85.01	167800	19	2.39	0.094	11.94	0.470	111.9	0.173	0.2512	0.0766	0.2610	0.0797	0.413	0.126
4/0	107.2	211600	19	2.68	0.106	13.41	0.528	141.1	0.219	0.1996	0.0608	0.2050	0.0626	0.328	0.100
250	127	—	37	2.09	0.082	14.61	0.575	168	0.260	0.1687	0.0515	0.1753	0.0535	0.2778	0.0847
300	152	—	37	2.29	0.090	16.00	0.630	201	0.312	0.1409	0.0429	0.1463	0.0446	0.2318	0.0707
350	177	—	37	2.47	0.097	17.30	0.681	235	0.364	0.1205	0.0367	0.1252	0.0382	0.1984	0.0605
400	203	—	37	2.64	0.104	18.49	0.728	268	0.416	0.1053	0.0321	0.1084	0.0331	0.1737	0.0529
500	253	—	37	2.95	0.116	20.65	0.813	336	0.519	0.0845	0.0258	0.0869	0.0265	0.1391	0.0424
600	304	—	61	2.52	0.099	22.68	0.893	404	0.626	0.0704	0.0214	0.0732	0.0223	0.1159	0.0353
700	355	—	61	2.72	0.107	24.49	0.964	471	0.730	0.0603	0.0184	0.0622	0.0189	0.0994	0.0303
750	380	—	61	2.82	0.111	25.35	0.998	505	0.782	0.0563	0.0171	0.0579	0.0176	0.0927	0.0282
800	405	—	61	2.91	0.114	26.16	1.030	538	0.834	0.0528	0.0161	0.0544	0.0166	0.0868	0.0265
900	456	—	61	3.09	0.122	27.79	1.094	606	0.940	0.0470	0.0143	0.0481	0.0147	0.0770	0.0235
1000	507	—	61	3.25	0.128	29.26	1.152	673	1.042	0.0423	0.0129	0.0434	0.0132	0.0695	0.0212
1250	633	—	91	2.98	0.117	32.74	1.289	842	1.306	0.0338	0.0103	0.0347	0.0106	0.0554	0.0169
1500	760	—	91	3.26	0.128	35.86	1.412	1011	1.566	0.02814	0.00858	0.02814	0.00883	0.0464	0.0141
1750	887	—	127	2.98	0.117	38.76	1.526	1180	1.829	0.02410	0.00735	0.02410	0.00756	0.0397	0.0121
2000	1013	—	127	3.19	0.126	41.45	1.632	1349	2.092	0.02109	0.00643	0.02109	0.00662	0.0348	0.0106

Figure 11 - NEC Table 8: Conductor Properties



Conductor Ampacity Based on the 2011 National Electrical Code®

Ampacity based on NEC Table 310.15(B)(16) (Formerly Table 310.16) – Allowable Ampacities of Insulated Conductors Rated Up to and Including 2000 Volts, 60° Through 90°C (140° Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)*

For conduit fill see 2011 NEC Annex C.

For Information on Temperature Ratings of Terminations to Equipment See NEC 110.14(C).

Size	Temperature Rating of Conductor. [See Table 310.104(A).]						Size
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RH, RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	AWG or kcmil
	Copper			Aluminum or Copper-Clad Aluminum			
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14**	15	20	25	—	—	—	—
12**	20	25	30	15	20	25	12**
10**	30	35	40	25	30	35	10**
8	40	50	55	35	40	45	8
6	55	65	75	40	50	55	6
4	70	85	95	55	65	75	4
3	85	100	115	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	145	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	195	230	260	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	350	420	475	285	340	385	600
700	385	460	520	315	375	425	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	445	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	525	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	555	655	750	470	560	630	2000

* Refer to 310.15(B)(2)(a) for the ampacity correction factors where the ambient temperature is other than 30°C (86°F).

** See Section 240.4 (D) for conductor overcurrent protection limitations.

Figure 12 - NEC AWG Chart