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

DESIGN DOCUMENT

sdmay21-37

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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 Revit. 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/REVIT 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 will be gaining 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
- Economic estimates

In order to stay on track with all of these deliverables, we will also be required to develop a detailed engineer man-hour budget and schedule for this project; this will be a very nice way to plan the overall project. Finally, the students will find a way to share their work with the Black & Veatch engineers 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 accompanying substation to add clean, renewable energy to the American energy grid. This project is a "from scratch" design, and while we will be using resources provided to us, the overall design of the final project will be 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 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

- Plant 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

- 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 will be required for our mentors from Iowa State include:

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

The weekly discussion posts will allow us to learn different processes that our mentors from Iowa State think will help throughout the process of this project. The Bi-Weekly reports helps our own group along with the mentors to keep track of where we are in the project. This involves us stating current problems and solutions that we are dealing with and current parts of the project that we are finishing and starting. The lightning talks are ways for us students to practice talking through our project and giving verbal updates for our mentor's kind of like how we would in the real world to show our bosses our progress. 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 will be excel documents that Black & Veatch have outlined for us to do. These outlines include built in formulas that will be completed throughout the semester as our group puts everything together. The solar layout drawings are 2D models that will be 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 will help with knowing how to finish the 2-D model. The rest of the calculations will be discussed in further length in the second semester. The students have not been presented with how these calculations should be completed yet.

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

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 of 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 won't 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/Revit initial Design, AutoCAD/Revit corrections, AutoCAD/Revit final draft. These milestones can be evaluated by percentage complete, as well as projected efficiency for the AutoCAD/Revit 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

Senior Design Project: GANTT CHART

TASK NAME	START DATE	END DATE	DURATION (WORK DAYS)	TEAM MEMBER	PERCENT COMPLETE
Parts Acquisition					
Solar Panels	8/27	9/9	14	Cortland Polfliet	100%
Solar Panels	8/27	9/9	14	Christof Barrier	100%
Combiner Boxes	8/27	9/9	14	Brian Lemke	100%
Combiner Boxes	8/27	9/9	14	Nolan Rogers	100%
Combiner Boxes	8/27	9/9	14	Logan Hinkle	100%
Inverter Skid	8/27	9/9	14	Eric Schultz	100%
Inverter Skid	8/27	9/9	14	Keve Hughes	100%
Design					
High Level Model for Visualization	9/10	9/23	14	Eric Schultz	100%
High Level Model for Visualization	9/10	9/23	14	Christof Barrier	100%
Farm Layout	9/10	9/23	14	Eric Schultz	100%
Farm Layout	9/10	9/23	14	Cortland Polfliet	100%
Component Attachments	9/10	9/23	14	Logan Hinkle	100%
Component Attachments	9/10	9/23	14	Nolan Rogers	100%
Component Attachments	9/10	9/23	14	Keve Hughes	100%
Array Parameter Tool	9/10	10/1	21	Cortland Polfliet	100%
Array Parameter Tool	9/10	10/1	21	Christof Barrier	100%
Array Parameter Tool	9/10	10/1	21	Brian Lemke	100%
Array Parameter Tool	9/10	10/1	21	Nolan Rogers	100%
Array Parameter Tool	9/10	10/1	21	Logan Hinkle	100%
Array Parameter Tool	9/10	10/1	21	Eric Schultz	100%
Array Parameter Tool	9/10	10/1	21	Keve Hughes	100%
Calculations					
Economic Estimates	10/2	10/15	14	Cortland Polfliet	100%
Economic Estimates	10/2	10/15	14	Christof Barrier	100%
Economic Estimates	10/2	10/15	14	Brian Lemke	100%
Economic Estimates	10/2	10/15	14	Nolan Rogers	100%
Economic Estimates	10/2	10/15	14	Logan Hinkle	100%
Economic Estimates	10/2	10/15	14	Eric Schultz	100%
Economic Estimates	10/2	10/15	14	Keve Hughes	100%
Voltage Drop	10/2	10/22	21	Cortland Polfliet	100%
Voltage Drop	10/2	10/22	21	Christof Barrier	100%
Voltage Drop	10/2	10/22	21	Brian Lemke	100%
Voltage Drop	10/2	10/22	21	Nolan Rogers	100%
Voltage Drop	10/2	10/22	21	Logan Hinkle	100%
Voltage Drop	10/2	10/22	21	Eric Schultz	100%
Voltage Drop	10/2	10/22	21	Keve Hughes	100%

Figure 2 - Gantt Chart

2.5 Project Tracking Procedures

Our group plans to use Microsoft Teams and Google Drive to communicate and collaborate on all project materials. We will track 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 need 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 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 will be divided amongst the team members via the Gantt chart linked in section 2.4, and the person-hours task table, an example is below.

2.7 Other Resource Requirements

We will require access to solar field modeling tools, such as the Array Design Parameter Tool we used to model our initial solar field design. These will be provided by our mentors. We will also need access to AutoCAD software for designing things later in the semester. We can get free access as students so this will not pose a problem.

2.8 Financial Requirements

Given that our project is simply designing the solar field, the only financial requirement is possible future software costs. If our project was to completely build the solar plant, the cost would be millions of dollars.

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.

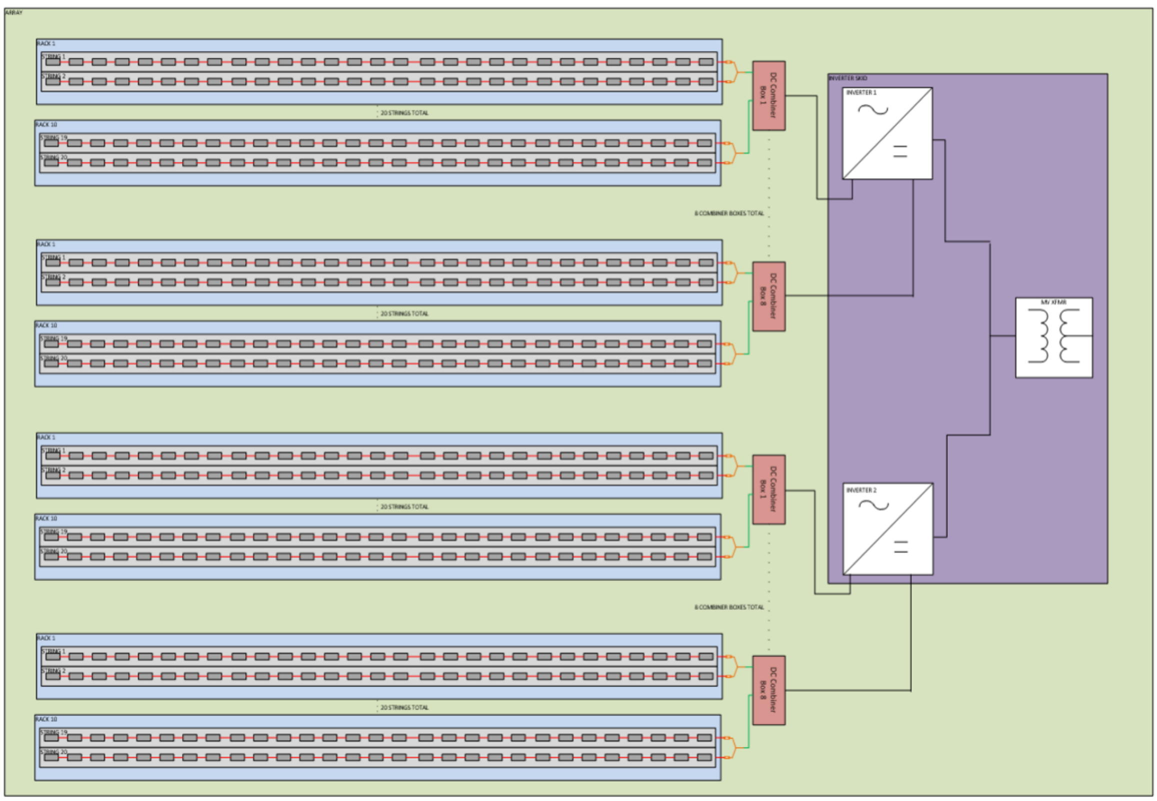

Figure 3 - Sample Solar Array Layout

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.

3.3 Proposed Design

So far, we have designated an initial layout of the panels, combiner boxes, and inverter skids. The basic idea behind our thinking was to maximize our efficiency on wiring and solar power collection. We made use of the array parameter tool with component choices to guide the layout we created. Below we can see the parameters used in our array parameter tool:

		String Size				**Electrical Rack Size**		
					Designer Choice		portrait or Landscape	
	Location Dependent	Min Temp	-40	C	Datasheet	Module width	3.36	ft
					Datasheet	module height	6.64	ft
	Datasheet (STC)	Voc	49.5	V				
	Datasheet (STC)	Ref temp	25	C	Designer Choice	Rack width	25	modules
					Designer Choice	Rack height	2	modules
	Datasheet	Temp Coeff of Voc	-0.0027	/C		Modules per rack		
		Temp delta	-65			Rack width	84	ft
		temp correction	1.18			Rack height	13.28	ft
		V0c corrected	58.18725					
Confirm possible with Panel type chosen	Designer Choice: 600, 1000, 1500, 2000V	string voltage	1500	V				
		String size	25.77884					
		string size	25					
		Actual String Voltage	1454.7					

	CB capacity				**Array Design**			**Array Size**		
Datasheet (STC)	mod/string Isc	10.55	A	Designer Choice	Racks per row	6	Designer Choice	tilt	35	
NEC sectio	multiplier	1.25								
	nom Isc	13.1875		Designer Choice	rows per Array	34		table height proj	10.87834	ft
Irr.	multiplier	1.25								
	max Isc	16.48438	A	Designer Choice	Racks removed	2	Designer Choice	row spac	15	ft
Designer Choice: 200, 400A etc.	allowed current	400	A		Total Racks/Array	202		pitch	25.87834	ft
	is this disconnect A?							Space for Inverter Maintenance	35	ft
	strings per CB	24.2654			Total modules	10100		Array height	914.8635	ft
	Round down:	24								
	racks per CB	12		Datasheet (STC)	module capacity	410	W	Array width	504	ft
								Ground Coverage Ratio	0.51317	
	Total CB/Array	16.83333			dc capacity	4141	kW			
	Round up:	17								
				Designer Choice	inverter capacity	3200	kW			
							MVA			
				Provided: Industry standard 1.3	ILR	1.294063				

Figure 4 - Array Parameter Tool

Using this parameter tool, we determined that there would be 25 solar panels in each string, resulting in 50 solar panels per rack. For the layout of the racks, we settled on 6 racks per row, with 34 rows per array. In each array, there will be 2 racks removed to provide space for the inverter skid, and there will be a 35 ft wide access road running through the middle for 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.

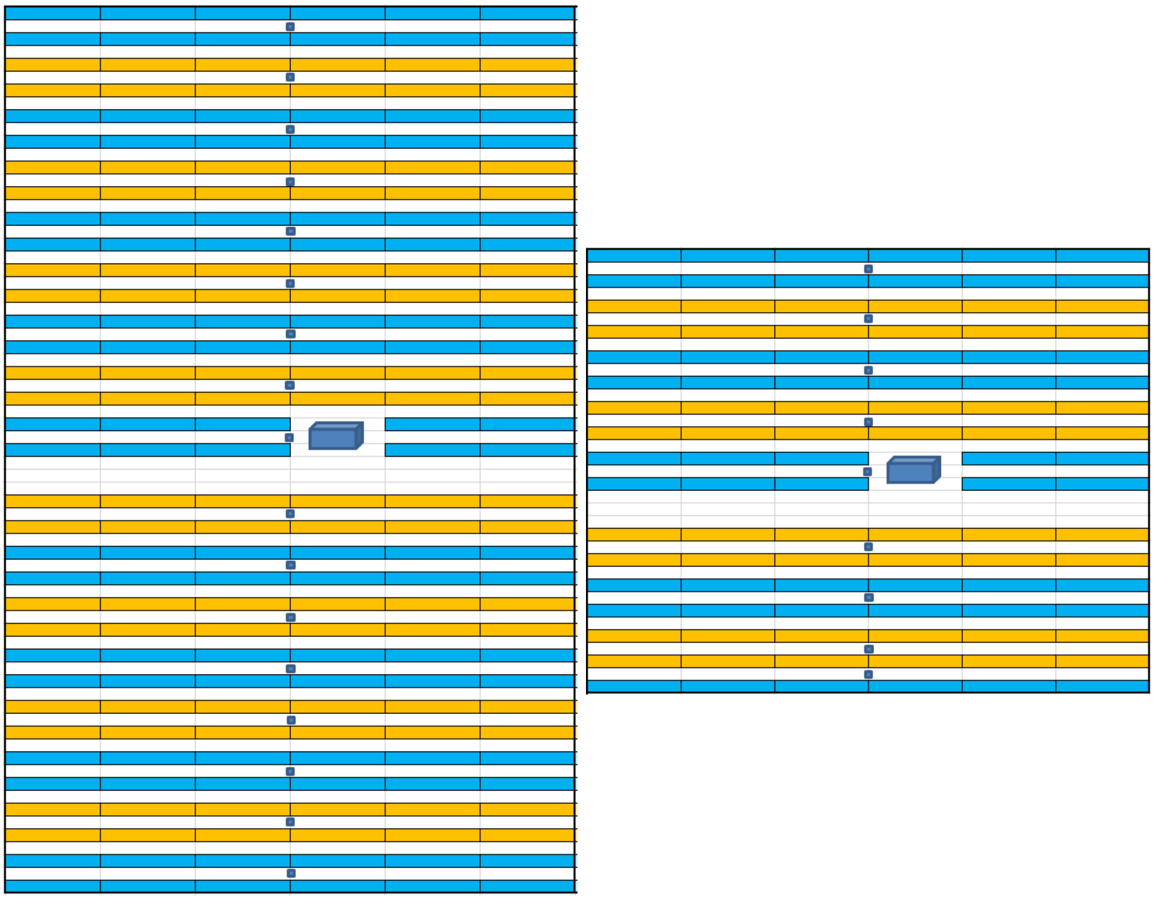

Figure 5 - Full Array and Half-Array Layouts

Each blue/orange rectangle represents a single rack. The large box in the middle of the array represents the inverter skid, while the smaller dark blue squares represents combiner boxes. Each full array contains 10,100 solar panels, 17 combiner boxes, and one inverter skid.

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. The proposed full-sized layout is shown below.

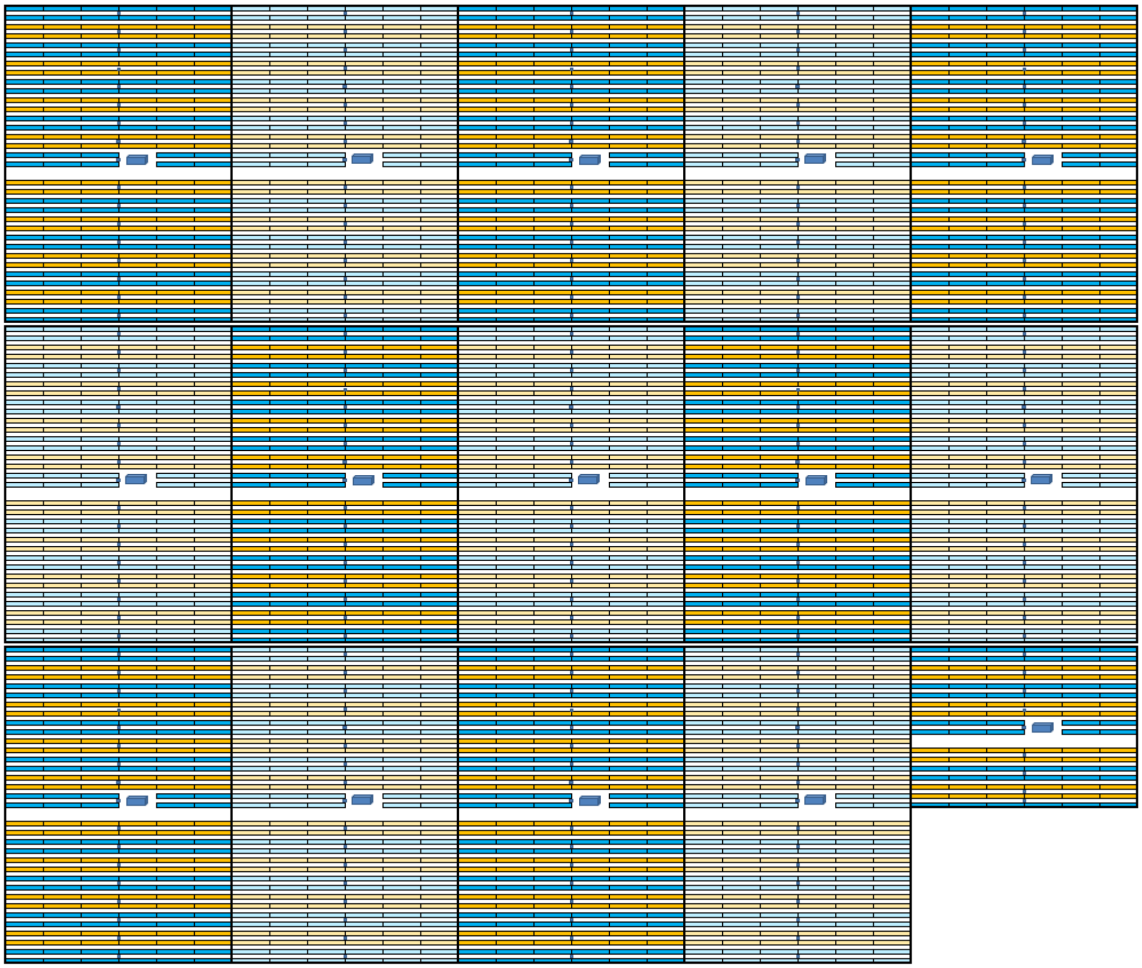

Figure 6 - Multiple Array Layout

Having well-defined information on how to design a solar farm and substation has been very helpful for us. It allows us to focus more on getting this piece of infrastructure built in a timely manner - something important in a renewable energy industry that is continuously innovating and creating more efficient products. However, one downside to having such rigid constraints is removal of creativity in a way - we cannot go out and create something completely original the way an artist might. Efficiency and conformity are rewarded in an industry like this; the most effective plant designs are ones that amalgamate all the best parts of other plans.

When we get to the design aspect of the substation, there are even more rigid constraints and pre-established norms to guide us in bus design configuration. It will be up to us to determine the correct configuration for our needs when we reach that point.

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. Careful design is the only way to minimize the impact of the tradeoffs.

3.5 Design Analysis

Our design from section 3.3 works well. It 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 not take into consideration intended users from section 1.5 because they do not directly affect the parts of the design we have control over. Our intended users would affect factors which were simply given to us like plant location and generating capacity. Factors we do have control over (component choice, plant layout, and Revit model) do not change based on who the intended users will be. Meeting our requirements is the central focus of our designs. The technical nature of our project pushed us to design our solar plant layout to meet the constraints laid out by Black & Veatch as closely as we could. This includes component selection (panels, inverters, combiner boxes, and cables) as well as physical layout in the solar plant.

The figure below shows an abstract version of our design process which is centered around the requirements we were given by our Black & Veatch mentors. 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.

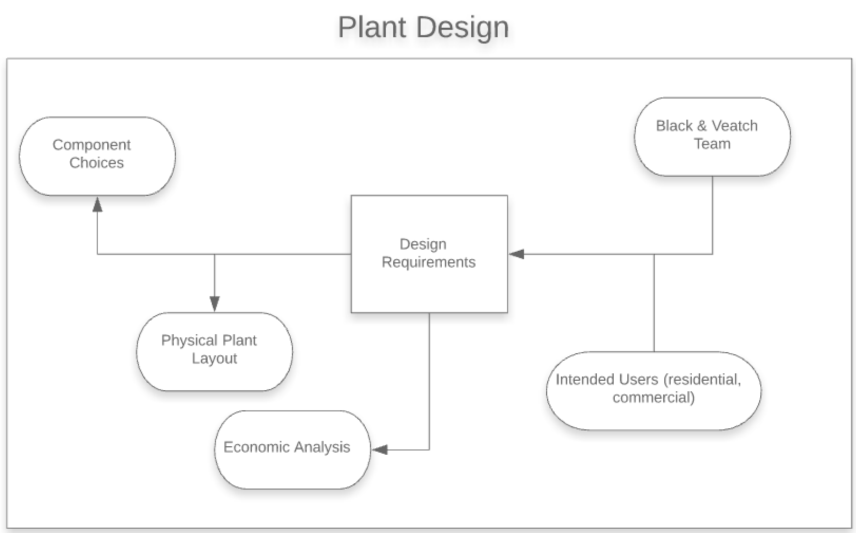

Figure 7 - Plant Design Flowchart

4 Testing

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

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

4.1 Unit Testing

Under the category of unit testing, we will be 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 will spend multiple weeks on each (array parameter tool, voltage drop calculator, and trench fill tool). For the purpose of 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 will be presenting our findings, testing, and designs with our peer mentors in our weekly meetings. There, we will receive feedback and criticisms to ensure that we are moving forward in the right direction, implementing what is wanted from them (the customer).

4.4 Results

Thus far, we have completed our iterative testing of the array parameter tool which determines the farm’s physical layout.

- Two main obstacles we had to overcome at first were getting familiar with all the terminology and background information as well as getting an understanding of how the array parameter tool works.

We have also completed the voltage drop calculations and cost analysis tool.

- Our cost analysis shows that we will lose money, but because of government subsidies and bonuses for solar applications, our mentors say that everything will work out. The voltage-drop calculations helped us determine how to efficiently wire our solar farm to minimize losses.

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

Summarize the work you have done so far. Briefly re-iterate your goals. Then, re-iterate the best plan of action (or solution) to achieving your goals and indicate why this surpasses all other possible solutions tested.

6.2 References

List technical references and related work / market survey references. Do professional citation style (ex. IEEE).

6.3 Appendices

Any additional information that would be helpful to the evaluation of your design document.

If you have any large graphs, tables, or similar data that does not directly pertain to the problem but helps support it, include it here. This would also be a good area to include hardware/software manuals used. May include CAD files, circuit schematics, layout etc,. PCB testing issues etc., Software bugs etc.