Cable Sizing Report

Utility Scale Lithium-ion Battery Energy Storage System Sddec24-18

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Client: Burns & McDonnell

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Executive Summary

A cable schedule has been created for the design of a battery energy storage system for Burns & McDonnell that will be created in Ames, Iowa. The justifications for these conductor sizes have been formulated into a report to document the process taken to determine the sizes.

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Figure 1 shows the AutoCAD drawing of the one-line diagram we created for the design of the BESS. Using this one-line diagram, we have color-coded each cable we calculated in this report and included in the cable schedule.

Figure 2 shows a screenshot of the cable schedule created based on the decisions, calculations, and measurements discussed in this report.

1.0 Overview

Many documents were referenced from the NEC 2020 version to determine how the conductors would be sized for the design of the BESS. Articles 300, 310, and 311 were primarily used to determine the sizes and used to determine the insulation, ambient temperature, and cable rating temperatures. Assumptions were made in the design process, which helped decide and calculate this schedule. The process will be detailed in this report, including calculation steps and the creation of the cable schedule using Excel spreadsheets. Additionally, the process for determining the lengths will be detailed in this report.

2.0 References

In order to determine the conductor sizes, the NEC 2020 version was referenced many times. The use of Articles 300, 310, and 311 were used extensively to determine the values concluded in the cable schedule.

2.1 NEC 2020 references

[1] National Fire Protection Association, “Article 310”, National Electric Code, NFPA, 2020, pp. 164. Table 310.16.

[2] National Fire Protection Association, “Article 311”, National Electric Code, NFPA, 2020, pp. 180. Table 311.60(C)(86).

[3] National Fire Protection Association, “Article 310”, National Electric Code, NFPA, 2020, pp. 162. Table 310.15(B)(1).

[4] National Fire Protection Association, “Article 300”, National Electric Code, NFPA, 2020, pp. 146. Table 300.5.

[5] National Fire Protection Association, “Article 300”, National Electric Code, NFPA, 2020, pp. 153. Table 300.50.

2.2 Other references

[6] Eaton. (2015, September 1). Functional Specification for Three-Phase Pad-Mounted PEAK Distribution Transformers 45 – 10,000 kVA. https://www.eaton.com/us/en-us/catalog/medium-voltage-power-distribution-control-systems /peak-three-phase-pad-mounted-transformer.html#tab-3

[7] BYD Energy. (2023, August 10). MC Cube ESS Installation Manual.

[8] O. Grudanov “Cable Schedule Report 1”, Microsoft Excel Spreadsheet, Burns & McDonnell, Ames, IA, 2023.

3.0 Assumptions

A few assumptions were made in the process of determining conductor sizes, which are listed in section 3.1

3.1 Assumptions for low and medium voltage lines

1. **Aluminum lines will be utilized for all wires, medium and low voltage.**

   Aluminum lines are much cheaper than copper lines, which was the main reason this material was selected.

2. **Power Factor of 1.0**

Assuming a power factor of 1.0 will ensure the calculations will be sized based on the "worst case" scenario.

3. Cables will be directly buried in Earth.

Upon researching the NEC 2020 version, the most suitable table to reference would be directly buried in Earth [Table 311.60(C)(86)], although conduit was the original ask. The client approved the change, so long as it will be honored throughout the rest of the design process.

4. Ambient temperature of 40 ℃

When deciding on the ambient temperature, there were two options presented: 40 ℃ or 30 ℃. None had any particular advantage over the other, and so the assumption was made to be 40 ℃. One thing is to be noted: with the use of this ambient temperature, the NEC article 310 needed to be referenced. Table 310.15(B)(1) was referenced to size the conductors by the appropriate correction factor.

5. Use of minimum voltages in the DC batteries

The use of minimum voltage requirement listed in the datasheets of the BYD battery was utilized in the calculation process to ensure the calculations of the maximum current flow through a conductor. This ensures that the size of the conductor will be rated for the maximum current in the case of low-voltage operations.

6. Changes may be necessary to conductor sizes once short-circuit analysis is run

In the case of a short-circuit fault, a spike in current could become present, making the amperage running through the line higher than what it is rated for. In this case, there is a risk of overheating, so resizing the conductors may become necessary to ensure the reliability of the system.

7. No communication or grounding cables will be accounted for currently

There will not be any sizes calculated for the communication cables to the batteries or inverters, and there will be no grounding cables. There is not enough time to determine these sizes, as it will need to reference different articles in the NEC and new types of wire. This may be looked at further next semester.

8. Medium voltage cables will be of MV105

The medium voltage cables used between the inverters, fuses, and aux power will be of MV105. This means medium voltage (MV) and 105℃ for the temperature rating.

9. There will be two circuits of triplexed cables for the medium voltage lines

This is because we have two home runs. Because of that, we will have two circuits, and they will be triplexed. Triplexed cables are commonly used in overhead systems and consist of three cables twisted together. As our system for the medium voltage will be three-phase, we will have one conductor per phase.

10. The low voltage cables will be rated for 90 ℃

This assumption was made primarily because Iowa's weather fluctuates between hot and cold, so rating the cables at the highest temperature allowed per the NEC 2020 version table 310.16 was at 90 ℃. The ambient temperature correction factor was based on this rated temperature.

11. The low-voltage cables will be parallel conductors

Parallel conductors are cables that run parallel with one another, dividing up the current among them. The number of parallel conductors will be determined by the calculation process and approved by Burns & McDonnell.

4.0 Calculation Process

This section will explain the process for determining the conductor sizes. Low voltage and medium voltage size calculations will be detailed in separate sections.

4.1 Medium Voltage Cable Calculation

Calculating the medium voltage cables consists of using a three-phase power equation to determine ampacity. Since the system is three-phase, the equation P = $\sqrt{3} * V * I * PF$ was used. The power to the system and inverters can be supplied by the batteries, so a nominal power of 1236 kW was used. Since there will be four batteries per inverter, we will calculate at four times the nominal power. Additionally, in the assumptions, we are assuming a power factor of 1.0 to size based on the "worst case" scenario. Finally, since the voltage comes from the distribution transformer's low-voltage side, the voltage in these equations will be 34.5kV.

We started off by calculating the current from the sides of the system and towards the middle. Starting at PCS6, we calculated the current to be 82.74 A using the above values and equation.

$$I_{PCS6} = \frac{4*1236*10^3}{\sqrt{3} * 34.5*10^3*1} = 82.74$$

We simply added the currents to calculate the PCS on one side of the home run, PCS6, PCS5, and PCS4, since each PCS will produce the same amount of current.

$$I_{PCS5} = 82.74 * 2 = 165.47\,A$$

$$I_{PCS4} = 82.74 * 3 = 248.21\,A$$

After calculating the currents for the right side of the home runs, we moved on to calculating the currents on the left side. We began by calculating the current running through the cable at the surge arrest. To calculate this value, we used a voltage of 34.5 kV, a power factor of 1.0, and a power of 1250 kVA coming from the auxiliary transformer. The values were put into the three-phase power equation, and the current was derived.

$$I_{surge} = \frac{1250*10^3}{\sqrt{3} * 34.5*10^3*1} = 20.92\,A$$

Moving on to the PCS next to it, PCS1, we used the value we calculated above of 82.74 A and added the 20.92 A to obtain the current running from the surge arrest to the PCS1.

$$I_{PCS1} = 20.92 + 82.74 = 103.66\,A$$

Additionally, we began to add the current for one PCS to the total above and obtained the medium voltage cable ampacities.

$$I_{PCS2} = 103.66 + 82.74 = 186.39\,A$$

$$I_{PCS3} = 186.39 + 82.74 = 269.13\,A$$

When calculating the home run cable sizes, we used the same values from PCS3 and PCS4 and got a value of 258.67 A in each home run cable. When all of these calculations were completed, Table 311.60(C)(86) from the NEC 2020 version was used to determine the conductor sizes.

Respectively, the cable sizes based on the ampacities calculated using Table 311.60(C)(86) from the NEC 2020 version are as follows:

Surge Arrestor: 20.92 A – 6AWG

PCS1: 103.66A – 4AWG

PCS2: 186.39A – 1/0 Kcmil

PCS3: 269.13A – 4/0 Kcmil

Home run 1: 258.67A – 4/0 Kcmil

Home run 2: 258.67A – 4/0 Kcmil

PCS4: 248.21A – 4/0 Kcmil

PCS5: 165.47A – 1 AWG

PCS6: 82.74A – 6 AWG

4.2 Low Voltage Cable Calculations

To begin the low voltage cable calculations, we began by calculating the DC cables of the battery. Since these are DC cables, we will be using Ohm's law to calculate the current. The equation used is $P = V * I; \rightarrow I = \frac{P}{V}$. Since there will be one cable per battery container to inverter, we will use the nominal power of 1236 kW, from the datasheets provided. For the voltage, we decided to use the minimum voltage produced by the system in order to calculate the highest current flow, which is 1075 V (from the datasheet). The value calculated for the current in each battery cable is:

$$I_{DC} = \frac{1236*10^3}{1075} = 1149.767.$$

Using article 310, table 310.16, this current is higher than any rated cable for low voltage. For this, we needed to add more conductors per phase in order to lower the current per line. Additionally, the use of the datasheet was needed to determine that the battery cable window for the BYD battery did not permit larger than 500-750 Kcmil, as the wires would be too thick to fit. We select a conductor size of 500 Kcmil from table 310.16 and determine that the current rated for that line is 350 A. Next, by trial and error, we determined that four conductors per phase would achieve the closest rating of current for the value we calculated of 1146.767A.

350A * 4 conductors/phase = 1400 A

Furthermore, since the ambient temperature we chose was 40℃ and Table 310.16 uses an ambient temperature of 30℃, Table 310.15(B)(1) was used to determine the ampacity correction factor. This correct factor is used to correct the ampacity value we calculated based on a 40℃ ambient temperature. Using this table, the correction factor 'T' is equal to 0.91.

1400 A * 0.91 = 1274 A

1274 A is close to the ampacity current calculated at 1149.767 A. This decision to do four conductors per phase was O.K. by Burns & McDonnell. Since all the DC cables are the same, the values for each of the 24 DC battery cables were calculated at an ampacity of 1274 A with four conductors per phase.

Next, we calculated the equipment pad cable running from the auxiliary transformer to the switchboard. For this cable, we used the auxiliary transformer power rating of 1250 kVA for the power (PF = 1.0, so S = Re{P} = P) and the current from the secondary side of the transformer of 480 V. Since this system is in three-phase, the three-phase power equation will be utilized to calculate the ampacity in that line. The calculation processes developed a current of:

$$I_{Equip} = \frac{1250*10^3}{\sqrt{3} * 480 * 1} = 1503\ A$$

Once again, this current is much higher than the rated lines in Table 310.16. The same process was conducted to determine how many conductors per phase would be necessary for this line. Receiving input from the team at Burns & McDonnell, we were advised not to go over

1000 Kcmil for any of our lines. We decided to choose the conductor size of 1000 Kcmil, which is rated for 500 A. Trial and error were used to determine that 4 conductors per phase would help us achieve the necessary current ratings for the line we chose. Additionally, we needed to use the ampacity correction factor of 0.91 to size our cables correctly. With this process, we determined the calculated ampacity for this line was:

$$I_{Equip} = 500\,A * 4\,cond/phase * 0.91 = 1820\,A$$

Finally, the last cables that needed to be calculated included the auxiliary power cabinet cables. There will be 30 of these cables, one for each battery and inverter in the system. Each of these cables will have the same ampacity and, therefore, will be sized the same. Using the datasheet, we determined the power for this section will be 38 kVA and a rated voltage of 480 V from the secondary side of the auxiliary transformer. A power factor of 1.0 will again be used to calculate this three-phase system. As instructed by the team at Burns & McDonnell, we will use 120% rated current for this line. We will multiply 1.2 by the current we calculate to determine the final ampacity.

$$I_{Aux\ Cabinet} = \frac{38 * 10^3}{\sqrt{3} * 480 * 1} = 45.71 * 1.2 = 54.84\,A$$

Respectively, the cable sizes based on the ampacities calculated using Table 310.15 from the NEC 2020 version are as follows:

DC cables (Batteries): 500 Kcmil

Aux equipment pad cable: 1000 Kcmil

Aux power cabinet: 4 AWG.

5.0 Cable Length Decisions

To determine the lengths of each of these cables, we needed to size them based on our site layout. To do this, we measured lengths in AutoCAD to determine the lengths and referenced the NEC article 300 to determine raceway lengths.

5.1 Determining raceway lengths of cables

To determine the base lengths of the cables in our cable schedule, we utilized the AutoCAD measuring tool to draw and measure lengths for where we will be connecting our cables. We started off by drawing the lines in AutoCAD, ensuring we chose to take the shortest path, and then measuring. We were able ti determine lengths for all cables associated with this design, apart from the communication cables and grounding cables. The specific lengths will be detailed in the cable schedule as raceway lengths. These lengths will consist of the wires that will be buried underground.

5.2 Total lengths of cables

To determine the total lengths of the cable, including the raceway length and the lengths of the wires that will be vertical from the ground, article 300 of the NEC version 2020 was used to determine the minimum coverage of the wire. Table 300.5 was used to determine the minimum coverage of the low voltage lines, including an additional length of 14 ft added to the raceway length measured. Table 300.50 was used for the medium voltage minimum coverage. An additional 16 feet will be added to the raceway length measured for the medium voltage.

6.0 Cable report columns

To determine the column used in the cable report, we referenced an example document given to us by Burns & McDonnell. We numbered each of the 64 cables in our system (excluding ground and communication cables), starting from the left side of the medium voltage cables and moving down to the DC battery cables and the rest of the low voltage cables. We determined that we will include a Cable ID column to list the numbered cables for easy identification, the current flowing in the cables so we can have it in a documented form, a from and to column to explain where the cables will be connected, as well as a description column so anyone reading this report can understand what these cables are for. Additionally, we included the conductor sizes calculated for the system, how many conductors per phase and how many wires are included in this conductor. Lastly, we included the raceway length of the cable running underground and the total length, including the vertical lengths of the wires. Finally, we added a column indicating whether a cable is low- or medium-voltage. All these columns will make up the cable schedule depicted in **Figure 2**.

7.0 Conclusion

To summarize, we looked at all the aspects that were considered when creating the cable schedule for the design of the BESS. We looked at the assumptions made to determine how we will size the cables, referenced several articles in the NEC 2020, and discussed the process taken to calculate the sizes in detail. Furthermore, we discussed the process used to determine the cable lengths and how we utilized the NEC 2020 article 300 to decide this. All the steps included in this report will make up the process of creating the cable schedule.

Appendix A: Figures

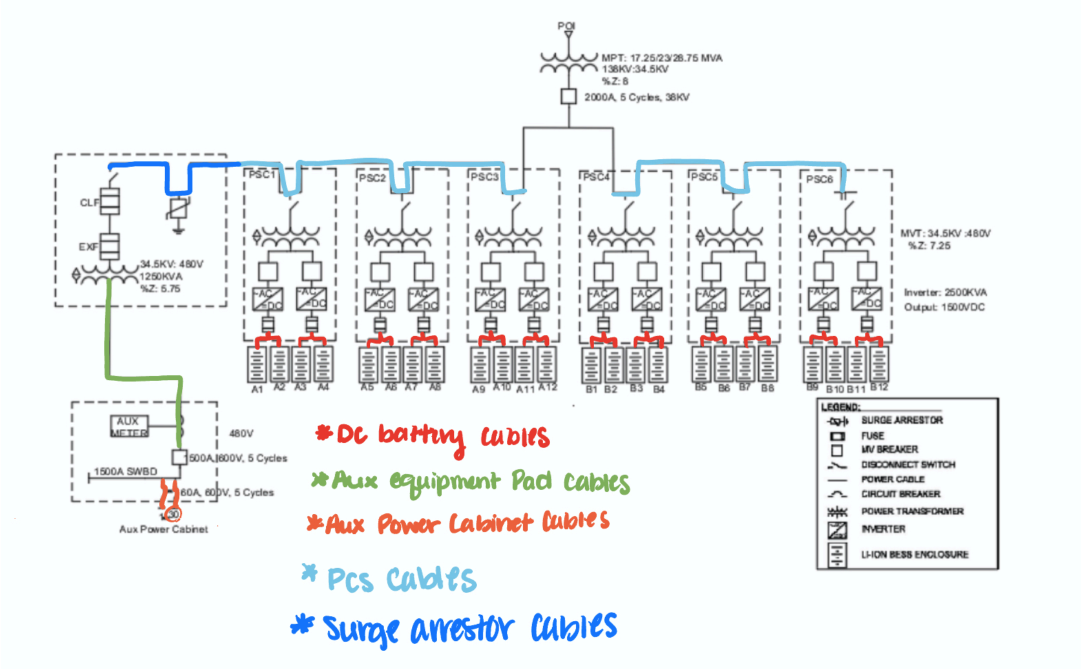

Figure 1: one-line diagram depicting where each cable calculated is located

Cable ID	Current flow	From	To	Description	Voltage Type	Conductor Size	Length		Conductors per phase	Qty	Raceway Length
1	20.92 A	Surge Arrestor	PCS A1	Fuse/ Surge Arrestor	Medium AC	6 AWG	45.57	ft	1	3	29.57 ft
2	103.66A	PCS A1	PCS A2	PCS1	Medium AC	4 AWG	53.02	ft	1	3	37.02 ft
3	186.39A	PCS A2	PCS A3	PCS2	Medium AC	1/0 Kcmil	53.02	ft	1	3	37.02 ft
4	269.13A	PCS A3	Substation Breaker	PCS3	Medium AC	4/0 Kcmil	53.02	ft	1	3	37.02 ft
5	258.67A	Substaion Breaker	Substation Breaker	Home run 1	Medium AC	4/0 Kcmil	572.05	ft	1	3	556.05 ft
6	258.67A	Substation Breaker	PCS B4	Home run 2	Medium AC	4/0 Kcmil	563.99	ft	1	3	547.99 ft
7	248.21A	PCS B4	PCS B5	PCS4	Medium AC	4/0 Kcmil	53.02	ft	1	3	37.02 ft
8	165.47A	PCS B5	PCS B6	PCS5	Medium AC	1 AWG	53.02	ft	1	3	37.02 ft
9	82.74A	PCS B6	PCS B6	PCS6	Medium AC	6 AWG	53.02	ft	1	3	37.02 ft
10	1274A	Inverter	Battery B12	DC Battery B12	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
11	1274A	Inverter	Battery B11	DC Battery B11	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
12	1274A	Inverter	Battery B10	DC Battery B10	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
13	1274A	Inverter	Battery B09	DC Battery B09	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
14	1274A	Inverter	Battery B08	DC Battery B08	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
15	1274A	Inverter	Battery B07	DC Battery B07	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
16	1274A	Inverter	Battery B06	DC Battery B06	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
17	1274A	Inverter	Battery B05	DC Battery B05	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
18	1274A	Inverter	Battery B04	DC Battery B04	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
19	1274A	Inverter	Battery B03	DC battery B03	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
20	1274A	Inverter	Battery B02	DC Battery B02	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
21	1274A	Inverter	Battery B01	DC Battery B01	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
22	1274A	Inverter	Battery A12	DC Battery A12	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
23	1274A	Inverter	Battery A11	DC Battery A11	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
24	1274A	Inverter	Battery A10	DC Battery A10	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
25	1274A	Inverter	Battery A09	DC Battery A09	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
26	1274A	Inverter	Battery A08	DC Battery A08	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
27	1274A	Inverter	Battery A07	DC Battery A07	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
28	1274A	Inverter	Battery A06	DC Battery A06	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
29	1274A	Inverter	Battery A05	DC Battery A05	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
30	1274A	Inverter	Battery A04	DC Battery A04	Low DC	500 Kcmil	30.86	ft	4	4	16.86 ft
31	1274A	Inverter	Battery A03	DC Battery A03	Low DC	500 Kcmil	74.19	ft	4	4	60.19 ft
32	1274A	Inverter	Battery A02	DC Battery A02	Low DC	500 Kcmil	72.62	ft	4	4	58.62 ft
33	1274A	Inverter	Battery A01	DC Battery A01	Low DC	500 Kcmil	24.03	ft	4	4	10.03 ft
34	1820A	Aux Transformer	Aux Equipment pad		Low AC	1000 Kcmil	40	ft	4	4	24 ft
35	54.84A	Aux Cable C1	Battery A01	Aux Power Cabinet C1	Low AC	4 AWG	58.7	ft	1	1	44.7 ft
36	54.84A	Aux Cable C2	Battery A02	Aux Power Cabinet C2	Low AC	4 AWG	80.24	ft	1	1	66.24 ft
37	54.84A	Aux Cable C3	Battery A03	Aux Power Cabinet C3	Low AC	4 AWG	88.23	ft	1	1	74.23 ft
38	54.84A	Aux Cable C4	Battery A04	Aux Power Cabinet C4	Low AC	4 AWG	67.86	ft	1	1	53.86 ft
39	54.84A	Aux Cable C5	PCS A1	Aux Power Cabinet C5	Low AC	4 AWG	44.36	ft	1	1	30.36 ft
40	54.84A	Aux Cable C6	Battery A05	Aux Power Cabinet C6	Low AC	4 AWG	88.07	ft	1	1	74.07 ft
41	54.84A	Aux Cable C7	Battery A06	Aux Power Cabinet C7	Low AC	4 AWG	109.62	ft	1	1	95.62 ft
42	54.84A	Aux Cable C8	Battery A07	Aux Power Cabinet C8	Low AC	4 AWG	117.6	ft	1	1	103.6 ft
43	54.84A	Aux Cable C9	Battery A08	Aux Power Cabinet C9	Low AC	4 AWG	97.23	ft	1	1	83.23 ft
44	54.84A	Aux Cable C10	PCS A2	Aux Power Cabinet C10	Low AC	4 AWG	73.48	ft	1	1	59.48 ft
45	54.84A	Aux Cable C11	Battery A09	Aux Power Cabinet C11	Low AC	4 AWG	117.44	ft	1	1	103.44 ft
65	54.84A	Aux Cable C12	Battery A10	Aux Power Cabinet C12	Low AC	4 AWG	138.99	ft	1	1	124.99 ft
47	54.84A	Aux Cable C13	Battery A11	Aux Power Cabinet C13	Low AC	4 AWG	146.96	ft	1	1	132.96 ft
48	54.84A	Aux Cable C14	Battery A12	Aux Power Cabinet C14	Low AC	4 AWG	126.6	ft	1	1	112.6 ft
49	54.84A	Aux Cable C15	PCS A3	Aux Power Cabinet C15	Low AC	4 AWG	102.6	ft	1	1	88.6 ft
50	54.84A	Aux Cable C16	Battery B01	Aux Power Cabinet C15	Low AC	4 AWG	123.4	ft	1	1	109.4 ft
51	54.84A	Aux Cable C17	Battery B02	Aux Power Cabinet C17	Low AC	4 AWG	143.76	ft	1	1	129.76 ft
52	54.84A	Aux Cable C18	Battery B03	Aux Power Cabinet C18	Low AC	4 AWG	147.67	ft	1	1	133.67 ft
53	54.84A	Aux Cable C19	Battery B04	Aux Power Cabinet C19	Low AC	4 AWG	126.08	ft	1	1	112.08 ft
54	54.84A	Aux Cable C20	PCS B4	Aux Power Cabinet C20	Low AC	4 AWG	90.49	ft	1	1	76.49 ft
55	54.84A	Aux Cable C21	Battery B05	Aux Power Cabinet C21	Low AC	4 AWG	152.77	ft	1	1	138.77 ft
56	54.84A	Aux Cable C22	Battery B06	Aux Power Cabinet C22	Low AC	4 AWG	173.13	ft	1	1	159.13 ft
57	54.84A	Aux Cable C23	Battery B07	Aux Power Cabinet C23	Low AC	4 AWG	177.05	ft	1	1	163.05 ft
58	54.84A	Aux Cable C24	Battery B08	Aux Power Cabinet C24	Low AC	4 AWG	155.45	ft	1	1	141.45 ft
59	54.84A	Aux Cable C25	PCS B5	Aux Power Cabinet C25	Low AC	4 AWG	119.61	ft	1	1	105.61 ft
60	54.84A	Aux Cable C26	Battery B09	Aux Power Cabinet C26	Low AC	4 AWG	181.89	ft	1	1	167.89 ft
61	54.84A	Aux Cable C27	Battery B10	Aux Power Cabinet C27	Low AC	4 AWG	202.5	ft	1	1	188.5 ft
62	54.84A	Aux Cable C28	Battery B11	Aux Power Cabinet C28	Low AC	4 AWG	206.42	ft	1	1	192.42 ft
63	54.84A	Aux Cable C29	Battery B12	Aux Power Cabinet C29	Low AC	4 AWG	184.82	ft	1	1	170.82 ft
64	54.84A	Aux Cable C30	PCS B6	Aux Power Cabinet C30	Low AC	4 AWG	148.73	ft	1	1	134.73 ft

Figure 2 shows the cable schedule created for the BESS.