Battery Pack Design Guide

Xamier Ferran Jan 25
@Daniel Siegel

S Add a comment...

Written by @Saurabh Pal

1 Pack Specifications

In a race, we are allowed a few hours in the morning and evening to charge our batteries. If we have larger capacity batteries than other teams, and we assume that the efficiency of all cars are the same, we will be able to run faster as we can finish the day with a more depleted battery. In other words, the battery acts as a source of an additional 5-7 kWh of energy on top of what we get from the sun. Thus, we want as high of a capacity as possible in our batteries.

2024 Regulations dictate the following maximum weight for the batteries as follows:

8.2.A Battery Weight Limits

8.2.A.1 Single-Occupant solar cars are limited to the following amounts of commercially available battery technologies:

Li-S	15.00 kg
Li-Ion	20.00 kg
Li-Polymer	20.00 kg
$LiFePo_4$	36.00 kg

8.2.A.2 Multi-Occupant class solar cars do not have a battery weight limit.

2026 Regulations dictate the following:

8.2.A Battery Capacity Limits

8.2.A.1 Single-Occupant solar cars are limited to 5.25 kWh of storage capacity.
8.2.A.2 Multi-Occupant class solar cars are limited to 15.5 kWh of storage capacity.

As Li-ion is more accessible than Li-S, we decided to go the Li-ion route for high capacities while retaining low weight.

Side-note: lithium iron phosphate batteries are a great technology. They're very safe, and have incredibly long lifetimes in comparison to other technologies. The energy density issue is improving, but it's not there yet.

2 Electrical Fundamentals

2.1 Electrical Fundamentals: DC Current

Throughout the electrical system, you will need to know the following concepts well.

First and most critically:

$$P = IV$$

Where P is power, I is current, and V is DC voltage

The average power draw of solar cars during a race is about 1000W at nominal speeds. As aerodynamic losses increases as a square of speed, the faster you go, the power used by the car increases exponentially. The power use is also high when accelerating.

2.1.1 DC Electrical losses

$$P = I^2 R$$

Power lost through a conductor is proportional to the current squared, and the resistance directly.

For a wire, resistance is:

$$R = \frac{\rho L}{A}$$

Where ρ is the resistivity (related to material), L is the length of the conductor, and A is the cross-sectional area.

2.1.2 Wire loss example

Q: Suppose we have a battery pack operating at 100V. The car is cruising along the highway at 50 mph and using 1000W to sustain the speed. The battery pack is 1m from the inverter (motor controller). What size of wire should I use to minimize electrical losses? Ensure the wire is not too heavy.

A: Combine the two equations such that:

$$P_{loss} = I^2 \rho L / A$$

Important: if you are using I^2 R, the resistance is referring to the wire resistance, thus the power is referring to the power lost in the wire because of resistance. Do not confuse this with the power draw of the whole vehicle.

Instead, use the vehicle power draw and the voltage it is operating at to find the current in the wire.

$$P = VI, I = P/V = 1000W/100V = 10A$$

Next, I can find the cross-sectional area of different cable sizes. These charts are readily available online.

Wire Gauge Conversion Chart

AWG	Diameter in.	Diameter mm	Area CMA	Area mm^2	AWG	Diameter in.	Diameter mm	Area CMA	Area mm^2
4/0 (0000)	0.46	11.68	212000	107	14	0.062	1.57	4110	2.08
3/0 (000)	0.41	10.41	168000	85	15	0.057	1.45	3260	1.65
2/0 (00)	0.365	9.27	133000	67.4	16	0.051	1.30	2580	1.31
1/0 (0)	0.325	8.26	106000	53.5	17	0.045	1.14	2050	1.04
1	0.289	7.34	83700	42.4	18	0.040	1.02	1620	0.823
2	0.258	6.55	66400	33.6	19	0.036	0.91	1290	0.653
3	0.229	5.82	52600	26.7	20	0.032	0.81	1020	0.518
4	0.204	5.18	41700	21.2	21	0.0285	0.72	810	0.41
5	0.182	4.62	33100	16.8	22	0.0253	0.643	642	0.326
6	0.162	4.11	26300	13.3	23	0.0226	0.574	509	0.258
7	0.144	3.66	20800	10.5	24	0.0201	0.511	404	0.205
8	0.128	3.25	16500	8.37	25	0.0179	0.45	320	0.162
9	0.114	2.90	13100	6.63	26	0.0159	0.404	254	0.129
10	0.102	2.59	10400	5.26	27	0.0142	0.361	202	0.102
11	0.091	2.31	8230	4.17	28	0.0126	0.320	160	0.081
12	0.081	2.06	6530	3.31	29	0.0113	0.29	127	0.0642
13	0.072	1.83	5180	2.62	30	0.01	0.254	101	0.0509

AWG: American wire gauge
CMA: Circular Mils Area

If I use a 4 AWG cable, A = 21.2mm^2. ρ of copper is $1.77 \times 10^-8\Omega/m$. So, power loss is:

$$P_{loss} = 10^2 * 1.77 \times 10^-8 * 1/21.2 \times 10^-6 = 0.0835W$$

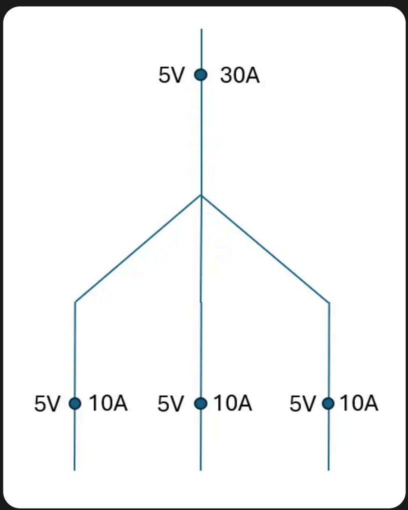
This is pretty low, but say you are accelerating up a hill, the motor is at peak power of 5000W and thus you are drawing 50A. Then, power lost is 2.09W. This is fairly significant.

Next steps: what is the weight of the wire? Hint: Use density of copper.

The best way to solve this and what you should do on the vehicle is create a spreadsheet or code that can input wire gauge, then output weight, power lost, and ampacity.

2.2 Series and Parallel

This section is just a quick reminder on how current splits when you put something in parallel. More on this later.



3 Architecture

Architecture refers to the physical design and configuration of the battery pack. Determining architecture is the first step of a battery pack design.

3.1 Battery choices

Common lithium ion battery cells are found in various types:

- Pouch (like phone batteries)
- Prismatic (pouches in a box)
- Cylindrical

We want to use cylindrical cells as they are often the most durable, cool well, very modular, and affordable. The most common size of cylindrical cell is 18650, then the 21700. The **first two numbers** refer to the battery diameter, while the next two refers to the battery height. An 18650 cell is 18mm wide and 65mm tall.

Let's compare specs from some battery cells. High current batteries and high capacity batteries

Manufacturer	Samsung SDI
Model	50E (2)
Size	21700
Positive Terminal	Flat Top
Nominal Capacity	5000mAh
Continuous Discharge Rating (max)	9.8A
Nominal Voltage	3.6V
Maximum Voltage	4.2V
Discharge cut-off Voltage	2.5V
Protected	No
Rechargeable	Yes
Approx. Dimensions	20.25mm x 70.80mm
Approx. Weight	68.67g
Country of Origin	Republic of Korea, China or
Associated Names	INR18650-50E
Data Specification Sheet	Samsung 50E Datasheet

Manufacturer	Samsung SDI
Model	30T
Size	21700
Positive Terminal	Flat Top
Nominal Capacity	3000mAh
Continuous Discharge Rating (max)	35A
Nominal Voltage	3.6V
Maximum Voltage	4.2V
Discharge cut-off Voltage	2.5V
Protected	No
Rechargeable	Yes
Approx. Dimensions	21.10mm x 70.20mm
Approx. Weight	68.2g
Country of Origin	Republic of Korea, Chin
Associated Names	INR21700-30T
Data Specification Sheet	

Manufacturer	Molicel
Model	P45B
Size	21700
Positive Terminal	Flat Top
Nominal Capacity	4500mAh
Continuous Discharge Rating (max	45A (80C Temp cut-off)
Nominal Voltage	3.6V
Maximum Voltage	4.2V
Discharge cut-off Voltage	2.5V
Protected	No
Rechargeable	Yes
Approx. Dimensions	21.55mm x 70.15mm (Max)
Approx. Weight	70g (Max)
Country of Origin	Canada or Taiwan
Associated Names	INR-21700-P45B
Data Specification Sheet	Molicel P45B Datasheet

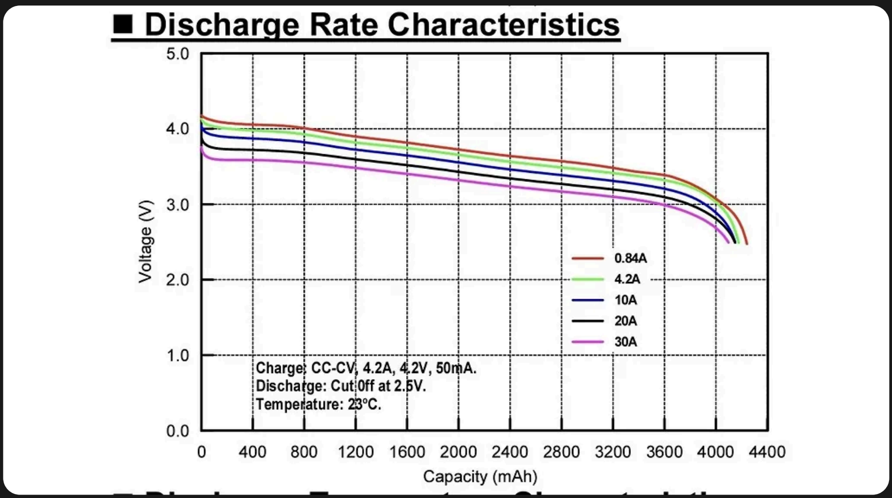
Generally, there is a trade-off between maximum discharge rate and capacity. **For a solar car race, we want capacity.** This is because starting with a large battery gives you more energy that you can utilize throughout the race, and thus let you run faster or longer with the same solar input. As proof, the top 4 finishing teams in WSC 2023 all used the same ultra-high density pouch batteries from Amprius.

⚠️ New 2025/2026 regulations mean, however, that our goal is now is to:

- Get as close to the capacity limit dictated by regulations
- Keep the weight as low as possible
- Ensure the batteries operate within current limits
- Ensure the batteries operate within temperature limits
- Minimize electrical losses.

Xamier Ferran Jan 12
added years for clarifica

Some notes: Battery voltage reduces as the battery discharges. The full charge of the battery is the maximum voltage (4.2V), and the minimum voltage is the voltage in which the battery is considered depleted (2.5V). The nominal voltage (3.6V) is that in which the battery spends most of its time.



This relationship can be mapped with a battery discharge test. These differ by battery make and how fast you are pulling energy out of the battery.

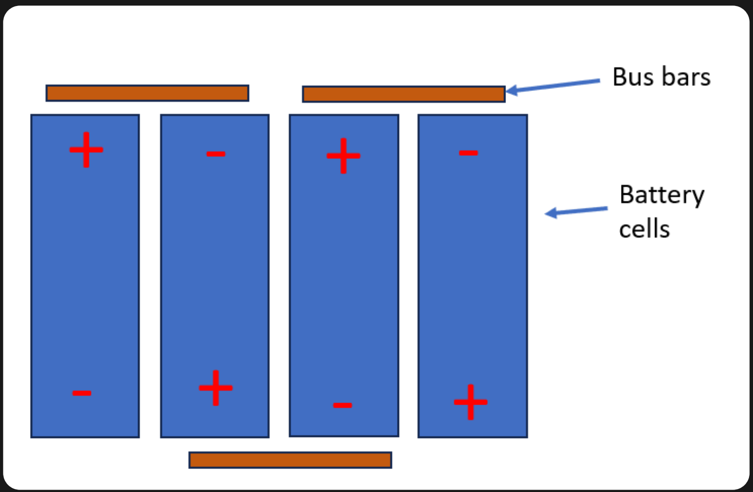
> 🔋 When selecting batteries, take a look at the independent discharge and internal impedance measurements. Mooch is a great resource, but just look up the battery on google if you find a good one. Also ensure that the batteries come from a reputable brand with a datasheet and certifications. Get the batteries approved by ASC staff before purchasing them.

3.2 Series-Parallel Configuration

3.2.1 Battery Modules

A module is made by stringing battery cells in series and parallel. Every module will have a sensor that continuously gauges the voltage, ensuring that charge doesn't go over or under what it needs to be. For our configuration, we will be splitting our battery pack into four modules so that we can assign a cell management unit to each module.

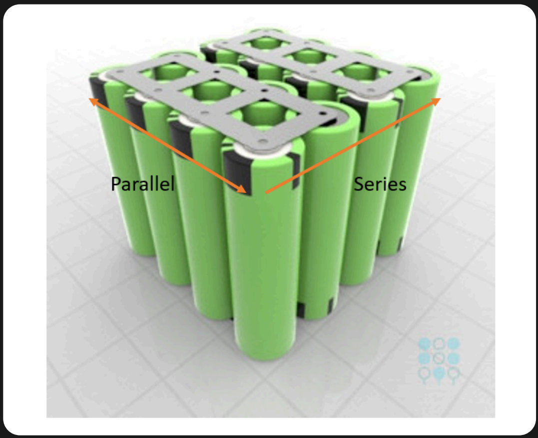
3.2.2 Cells in Series



This is a module in its simplest form. This one is a 4S module.

Batteries in **series** will **increase the voltage of the pack**, where the pack voltage is the sum of voltage of every individual cell. Current out of every battery and its Ah capacity does not change.

3.2.3 Cells in Parallel

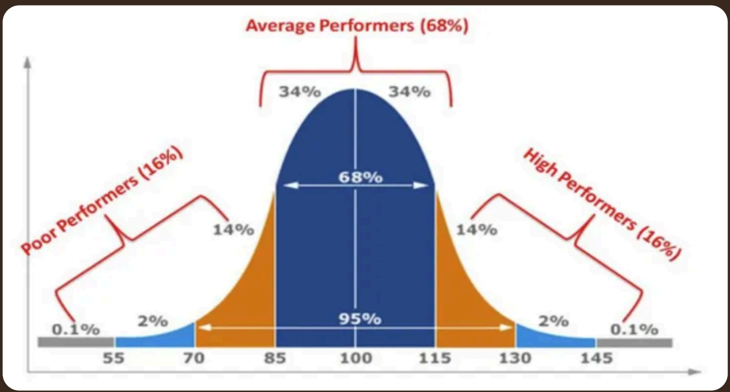


Cells in parallel are those connected with the same terminal (positive/negative). The above module is a 4P4S module, where there are 4 cells in series and 4 in parallel.

Cells in parallel divide current and increase Ah capacity without increasing voltage.

However, take note that if you connect two cells in parallel with different voltages, the cell with a higher voltage will discharge into the cell with a lower voltage. This is a potential fire risk. Thus, **ensure that cells in parallel have the same charge before connecting them together.**

This phenomenon also is the reason why we need to ensure all cells in parallel discharge the same way. Cells have natural variation in internal impedance and capacity. So, we need to ensure that the cells come from the same manufacturer lot, and we order double the number of cells we need, test every cell, and determine the internal impedance of each cell.



Within the cells we order, we only use cells that are in the middle 68% of the normal distribution. Within the cells we select, we group the cells with the closest internal impedances in parallel. Having different impedances in series will lead to different discharge rates, but the BMS system will balance the discharge rate such that they deplete at the same time. BMS's can't balance in parallel.

This is called **characterization** and it is mandatory to ensure good pack performance and prevent fires.

3.3 Selecting the Ideal Voltage

During the battery selection process, you will also need to determine what configuration you can put a specific cell in. Remember that we want to get as close to the 5.25 kWh limit dictated by regulations.

However, the overall pack voltage determines a few things.

- Peak motor RPM & efficiency
- DC bus current

We must also be aware of the current limit of the Wavesculptor 22 motor controller (160V), the MPPTs (170V).

Our current maximum voltage target is 150V.

3.4 Determining configuration

Based on this, the number of series cells needs to be 150V/4.2V = 35.7 ~36. Going slightly over is fine as it's still under the voltage limit of the Wavesculptor.

From this, we can determine the number of parallel cells to bring us near the limit. The calculation for pack capacity is:

$$E_p = N_p N_s I_h V_n$$

Where N is the number of cells in parallel and series, Ih is the individual cell capacity, Vn is the nominal cell voltage.

We can rearrange this equation to get Np. The variable here would be the cell capacity in Ah. Assume we are using the Samsung 50E2 batteries we got that have a capacity of 5 Ah.

$$Np = E_p/N_s I_h V_n = 5250Wh/(36 \times 3.6V \times 5Ah) = 8.1$$

Therefore, for the Samsung 50E2s in this car, our configuration is **8P36S**.

4 Supplemental Electronics

4.1 Battery Protection Systems (BPS)

The battery box must include a BPS. Below are the regulations that spell this out.

8.3 Protection Circuitry

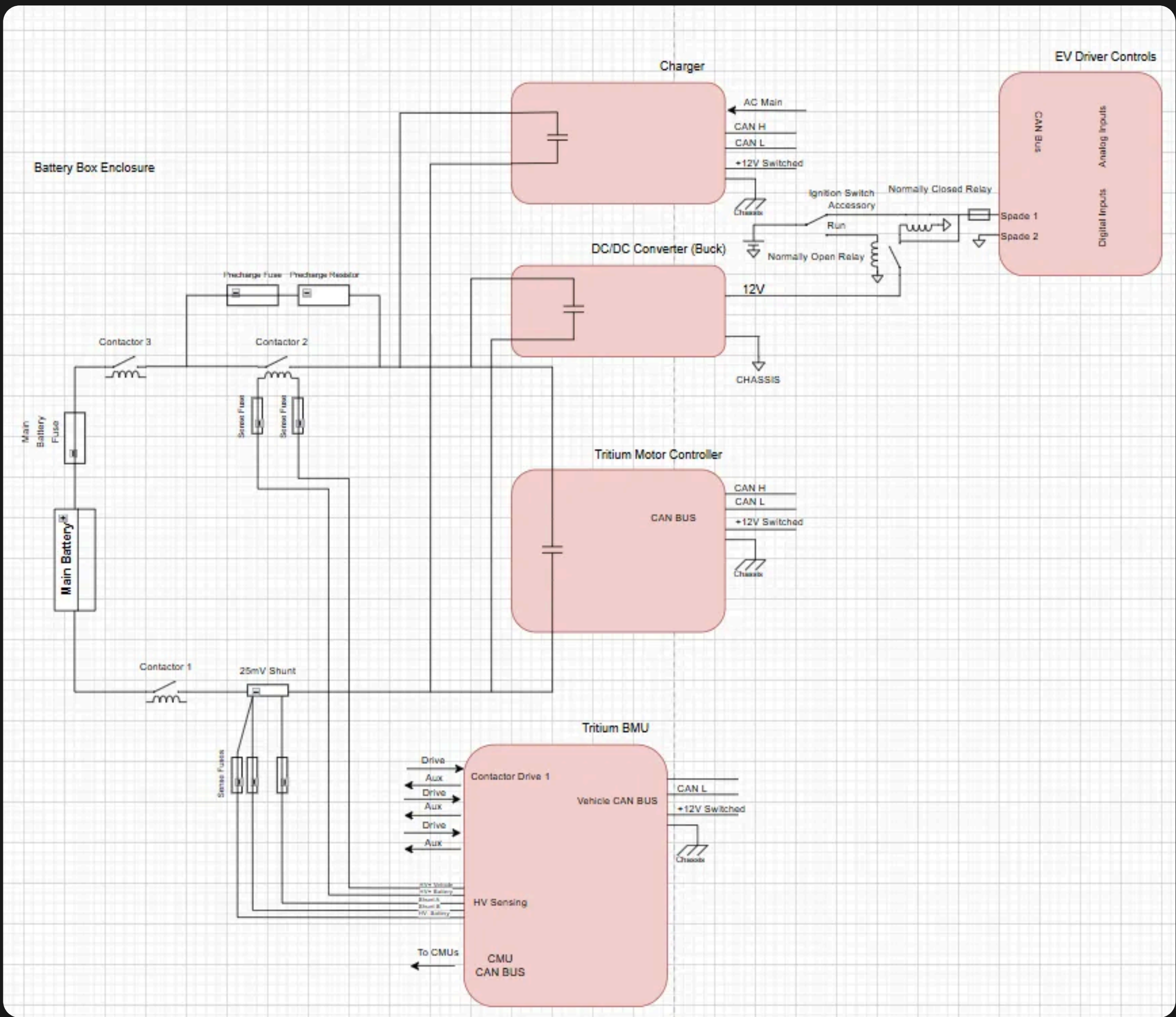
All batteries must have protection circuitry appropriate for the battery technology used. Proof is required at Scrutineering that the protection system is functional and meets manufacturer's specifications. Testing procedures will be provided, and the protection system design should allow for such testing. All protection circuitry should be contained in the battery enclosures per Reg 8.4.

8.3.B.1 **Li-Based:** All lithium based battery packs must have **active** protection such that over-voltage, over-temperature (for charge and discharge rating), over-current and under-voltage cause the Main Power Contactors per Reg 8.7.A to open and to electrically isolate the source and sink for the vehicle. The level of protection measurement is required down to the module level at a minimum and may be required at a cell level depending on the cell manufacturer. The fuses required in Reg 8.6 are not sufficient for battery over-current protection.

Some teams make their own BPS systems. However, as these power electronics components are quite complex, we decided to outsource ours. We use the Prohelion BMS system.

This guide won't explain the in-depth functionality of this system, but we will take the wiring diagram from the manual and use it do design the interior of the battery box. For an in-depth explanation please refer to Prohelion's official documentation page.

4.2 Wiring Diagram



4.2.1 Definitions

Contactor: A high-voltage switch or relay. It is normally open. When we supply a 12V input through the contactor control wires, the switch will close.

Shunt: A device that provides a low resistance pathway for current. In this case, it it used to measure the current in the system.

4.3 Pre-charge Circuit

The motor controller (inverter) has a high capacitance. When the high voltage battery is connected to the motor controller, there will be a large inrush of current that may damage the motor controller. To dampen the effect of this, we create a branch off contactor 2 that has a resistor. The sequence of events upon startup is:

1. Contactor 1 energizes pack negative to the DC Bus. This means all electronics are energized and closing contactor 2 and 3 will complete the circuit.
2. Contactor 3 energizes pack positive. Now, there is a complete circuit passing through the precharge resistor.
3. The HV Sense lines measures the voltage across the contactor 2. When the pack and DC-BUS voltages are close, contactor 2 is closed. Now, the precharge circuit will be bypassed as contactor 2 offers a path of least resistance.
4. The BMU is now in “Run” mode.

The precharge resistor chosen is the Vishay RH-50 series with a 160 ohm resistance. This was chosen following calculations on this page of the BMS manual.

4.4 Fuses

The regulations provide the following information about fusing the main battery pack:

8.5 Fusing

8.5.A Main

A DC-rated fuse (not a circuit breaker) must be placed first in series with the battery starting at the positive connection within each battery enclosure. Both leads to the fuse must be mechanically constrained to battery enclosure using a fuse block and cover. The fuse rating must not exceed 200% of the maximum expected current draw or 75% of the rated wire current capacity. It must be rated to break the Fault Current due to a shorted pack and protect the relay or switch. (High Speed or Fast Acting Semiconductor Type Fuse)

8.5.B Branch

All other wiring branching off the main bus circuit must have properly sized fuses. Fuses must be located near the branch point, either within the same enclosure or before a reduction in rated conductor ampacity.

8.5.C Voltage Taps

8.5.C.1 When in the Safe State, residual current draw on any battery measurement tap shall be less than 10 mA.[4]

8.5.C.2 When in the Safe State, any voltage tap leaving the battery box must be current limited to less than 10 mA.

The peak current on the vehicle is anticipated to be 60A. This can be derived by considering the minimum battery voltage and number of series cells $V = 2.5V * 36 = 90V$, and the maximum power output of a Mitsuba motor, 5000W. Using $P = VI, I_{max} = 56A$

Thus, the selected main battery fuse is rated for 100A. All wires from the battery to the motor controller must have a minimum ampacity of 133A.

As all branches need to be fused appropriately, the solar collector holds a 50A fuse, and the motor controller holds the same 100A fuse as the main bus. Additionally, the branch to the DC-DC converter branch and the precharge circuit have 5A, snap-in fuses.

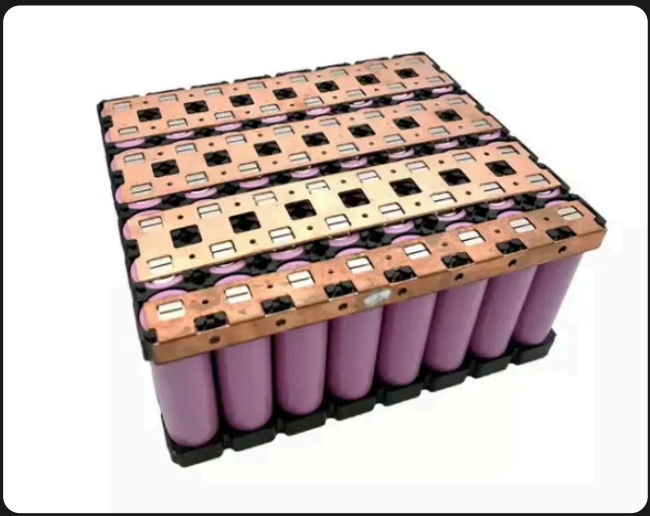
4.5 BMS & CMU system and wiring

5 Battery Pack Design

5.1 Module Design

5.1.1 Possible Layouts

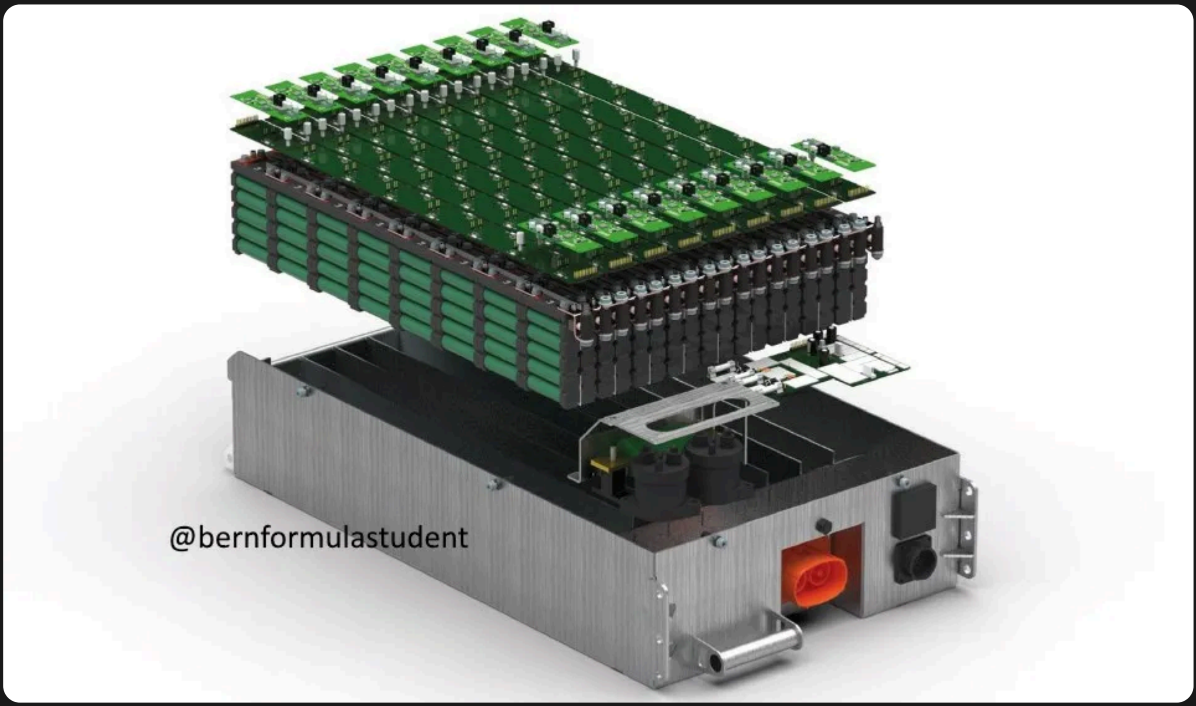
There are two commonly used layouts used in the design of cylindrical battery packs. The first is the vertical orientation, in which the batteries are places vertically with opposing polarities.



This layout is easy to visualize and is commonly used in e-bikes and production electric vehicles. Above is an example of what an e-bike battery would look like, and below is a 21700 battery pack from a Tesla Model S. Lucid and Rivian also use this configuration.

The reason these packs are laid out this way is likely for water cooling. Production EV's are mostly water-cooled such that batteries can be placed very close to each other. If you are interested in this topic, watch this video.

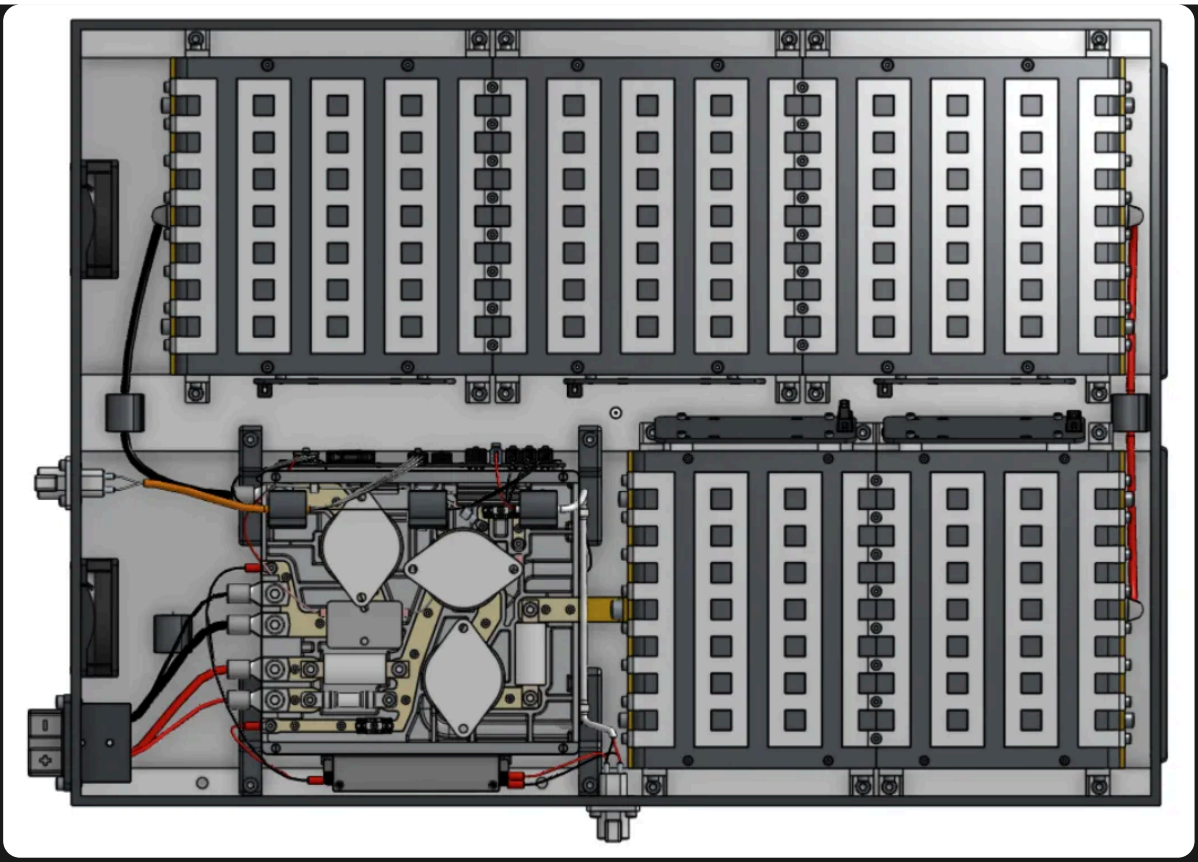
The other layout is used commonly in FSAE and some solar cars. This layout has some advantages in ease of manufacturing and flexibility in sizing the battery pack. Parallel cells are grouped, then large plates tying parallel strings together are spot welded on. By placing the batteries horizontally, you could bolt positive and negative cells to create serial strings.



As we are not too space constrained, we elected to use a vertical configuration which will allow us to space cells further apart from each other and enhance airflow. It is also the simpler and more repairable option.

5.2 Our Pack Layout

Below shows our general pack layout. Mod 1 consists of three 8P8S modules, and Mod 2 consists of two 6S8P modules. Each module has a CMU mounted to its side. The BMS and all branching will happen through a specially developed distribution module.

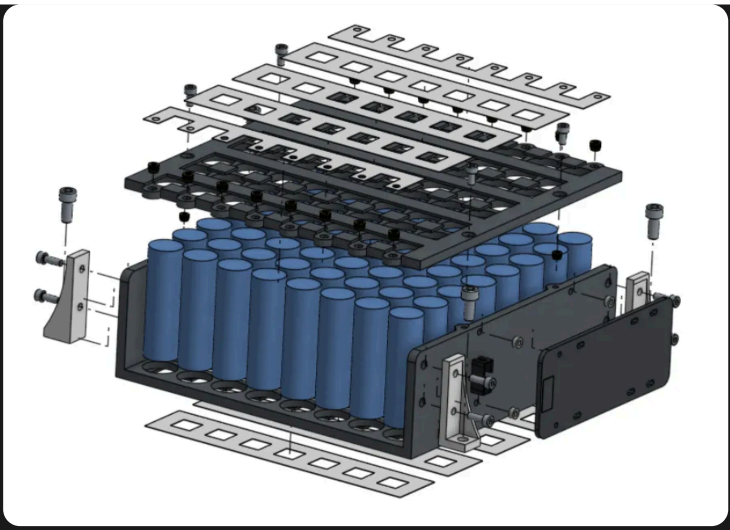


5.3 Module Design

Our modules are designed to be made with a 3D printer and with minimal supports. Each module has two sections that are connected via M3 screws into heat set inserts. There is a recess in the module to accommodate flat bus bars that will be spot welded to the batteries.

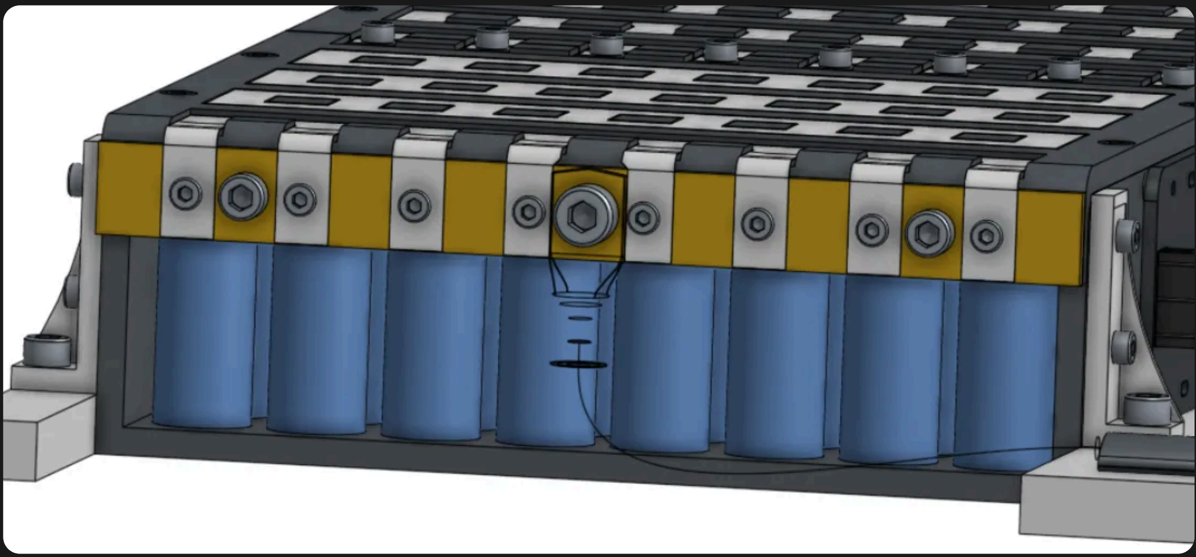
5.3.1 Sub-Modules

In Module 1, there are three sub-modules with 8 series strings each. Below shows the central sub-module and its corresponding exploded view.



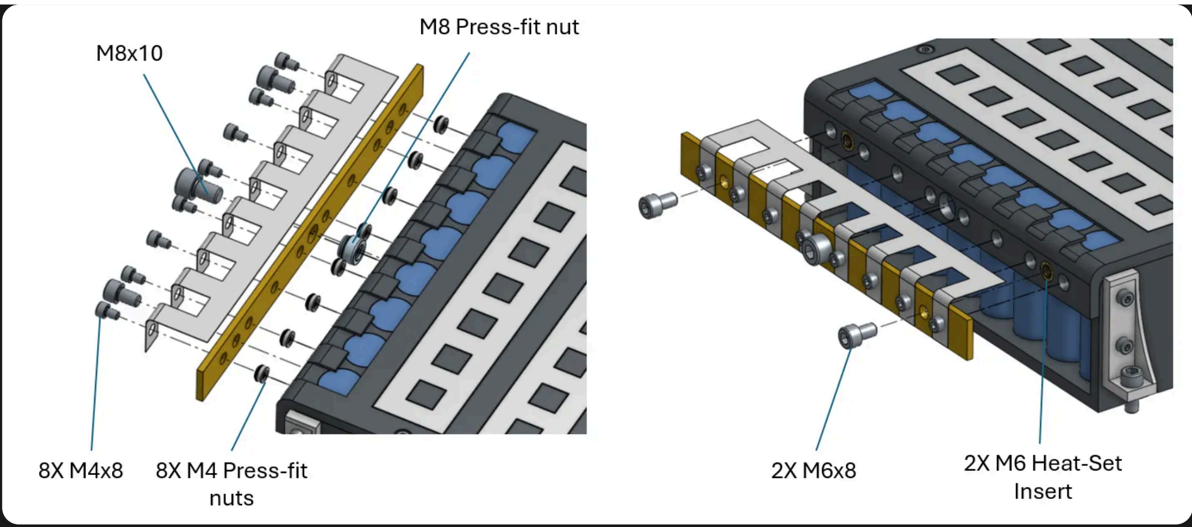
5.3.2 Terminal Modules

All other modules in the pack are terminal modules. This means that a single wire collects all of the parallel strings so it can connect to something else. Terminal modules have 1/8″ pure copper bus bars to handle the higher currents when all parallel strings are combined.



The copper bus bar is oriented vertically to decrease the amount of space consumed and increase the rigidity of the upper battery holders. The bus bars are screwed into the battery holders with M4x8 screws into heat-set inserts.

Xamier Ferran Feb 24
what does safety wired



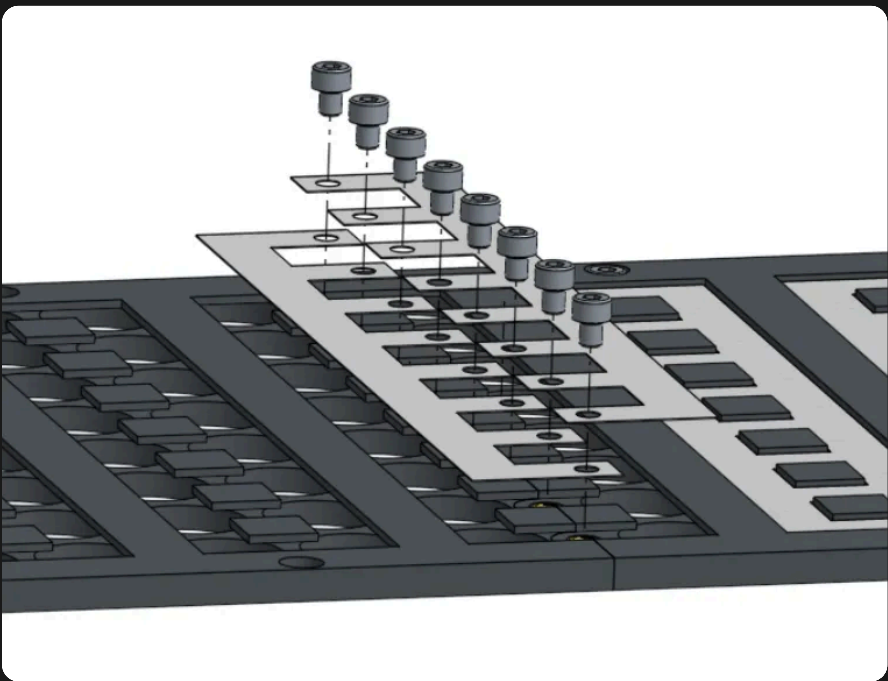
M6 HEAT-SET CHANGED TO M4, M4x8 SCREWS TO BE USED

The Clad 60 bus bars spot welded to the battery fold over and screw to the copper bus bars with M4x8 screws. I advise that these connections are soldered and bolted to ensure there is good electrical contact. The copper bus bars must be backed by press-fit nuts, for which we can assemble with the hydraulic press in Bray. Additionally, an M8 nut must also be pressed in to allow an M8 ring terminal to be attached.

5.3.3 Module-Module Connections

Between adjacent sub-modules, there are specific bus bars designed to attach via M4x5 screws such that sub-modules can be replaced or removed easily. These modules screw into heat-set inserts in the upper battery holders.

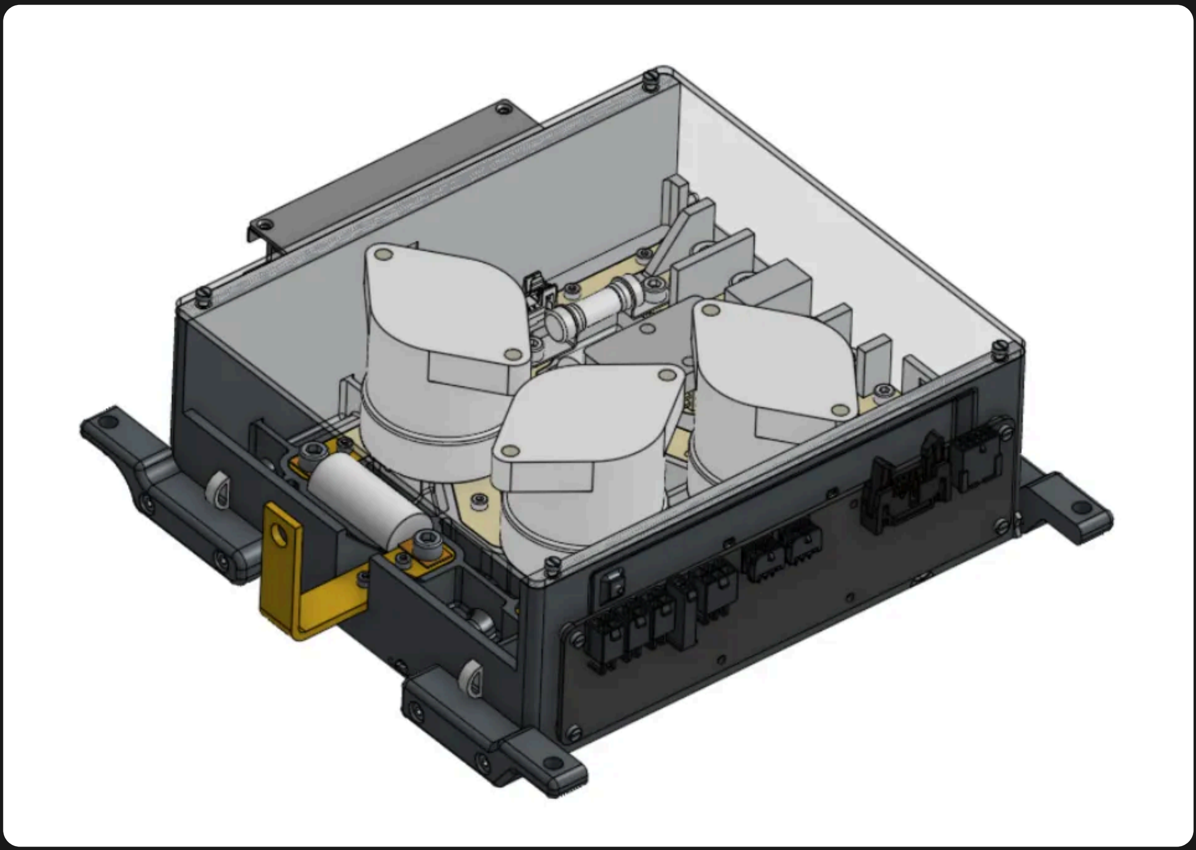
IMPORTANT: These screws need to have their heads drilled such that they can be safety wired. This can be done in Bray.



🔋 We split the modules this way as we have 5 CMUs that can each monitor a maximum of 8 series strings. As we have 36 cells in series, we can configure modules in different ways.

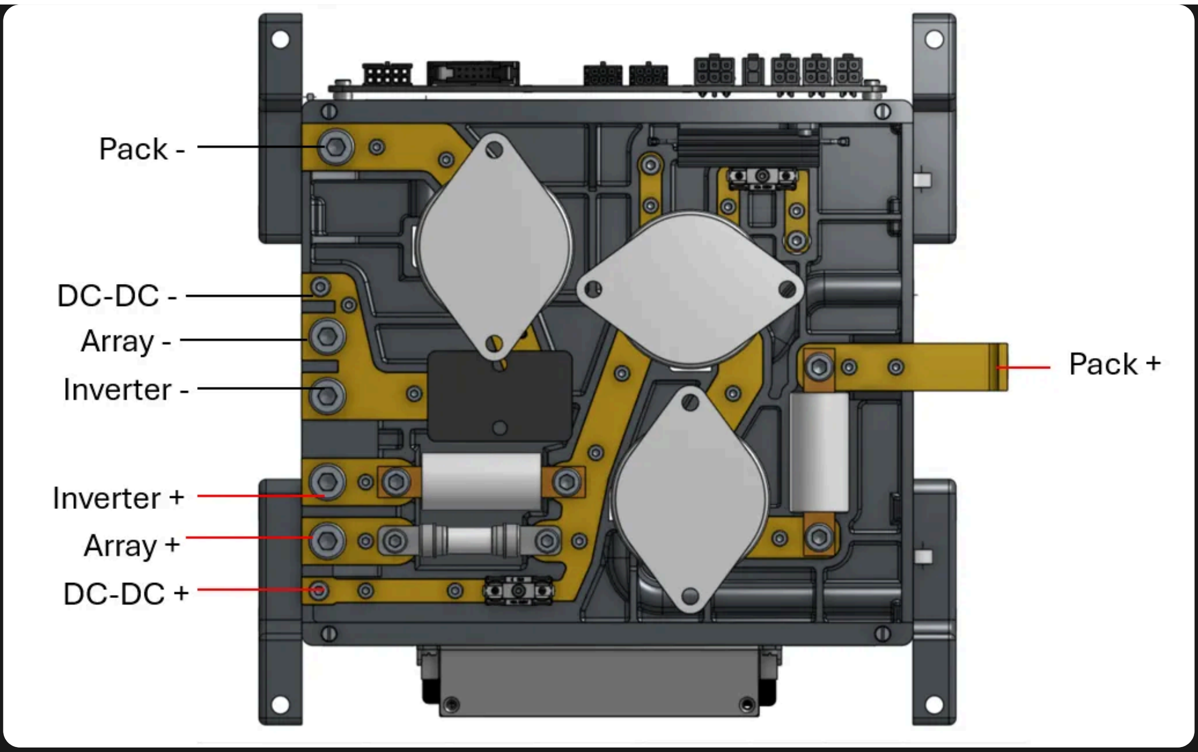
The configuration we chose was (3x8S + 2x6S). The important part to note is the even numbers of cells in series (8/6). This ensures that the module-module connections always originate from the top of each module, whereas an odd number would alternate between the top and bottom, complicating repair and manufacturing.

5.4 Distribution Module

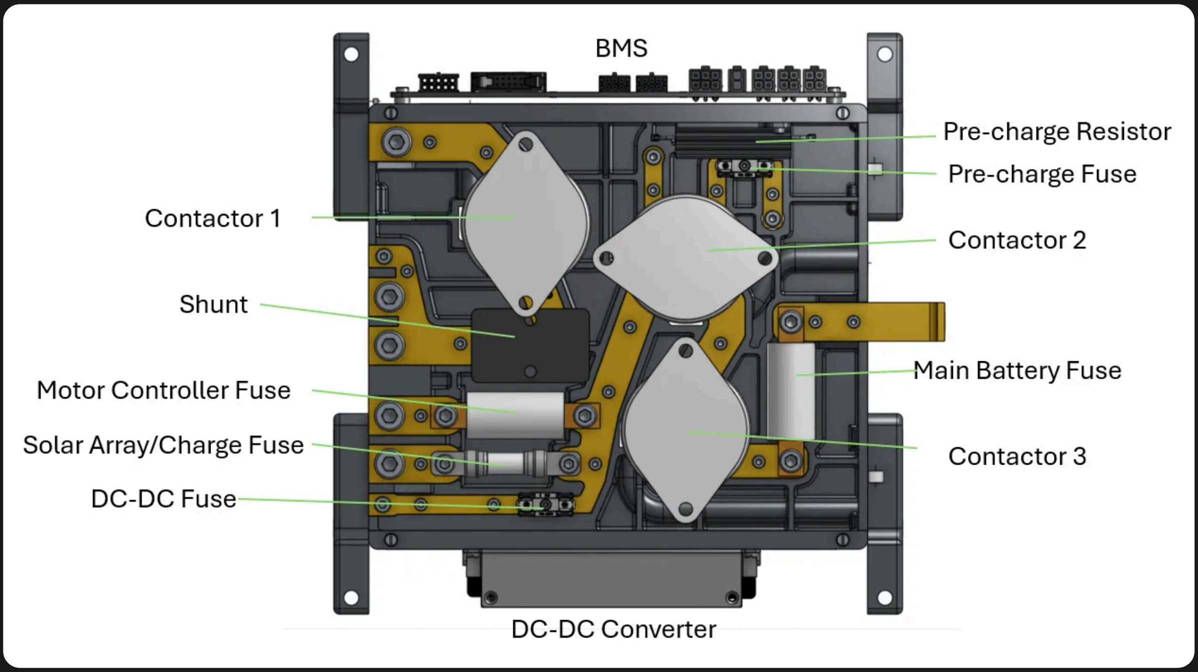


The distribution module is a clean way to reduce the amount and complexity of wiring needed within the battery box. This module houses the contactors, fuses, precharge circuit, BMS and DC-DC converter into one module. This module plugs into the positive and negative terminals of the battery and has dedicated outputs for the motor controller, solar array, CAN bus, and DC-DC converted 12V outputs for the car lights.

5.4.1 Inputs and Outputs



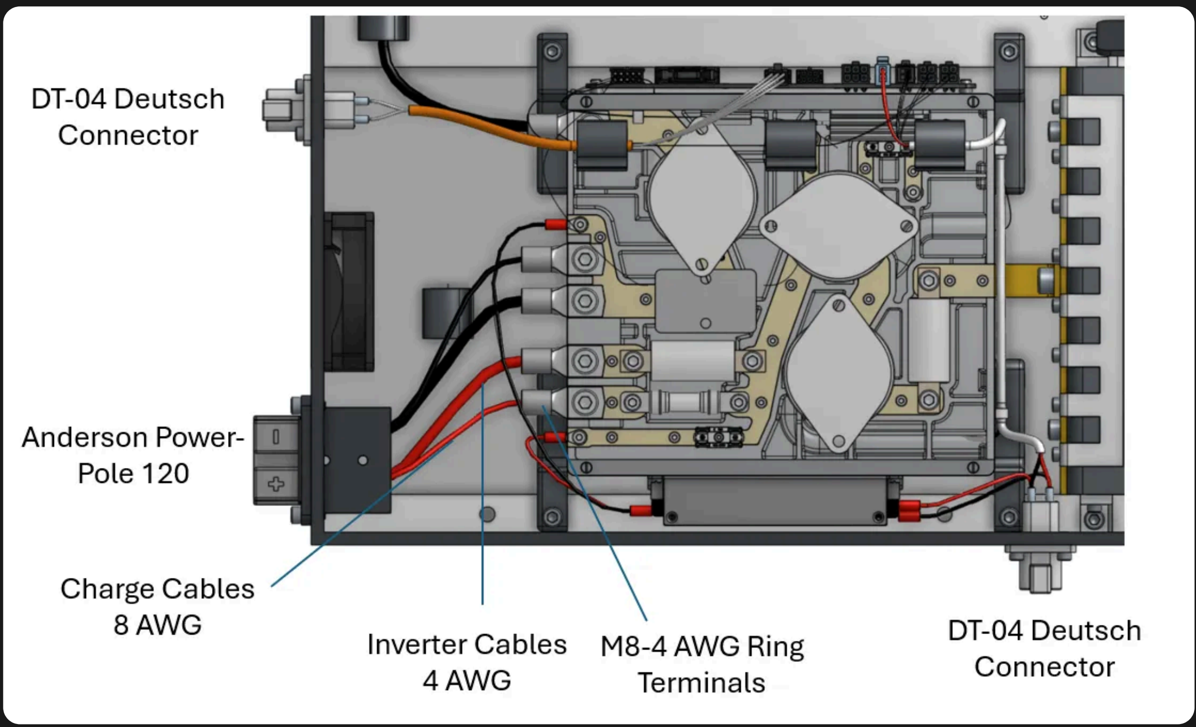
5.4.2 Parts and Fuses



▼ Distribution Box BOM

Part	Part No.	Details
Contactors	EV200A1NA	No aux output. Refer to BMS manual to match contactor number to connector on BMS.
Shunt	Blue Sea 9230	100A/50mV
Main Battery Fuse	Littelfuse 20EV100	100A
Motor Controller Fuse	Littelfuse 20EV100	100A
DC-DC Fuse		5A
Precharge Resistor	Vishay 71-RH50-160	160 Ohm, 50W
DC-DC Converter	RSD-60-H12	40-160V in, 12V 5A out
Small Fuse Holder	Littelfuse 05200101Z	Must be soldered and permanently fixed to bus bars

5.4.3 Wiring



Any cable mounted to the distribution box attaches via a ring terminal. These must be crimped with a hydraulic crimper and protected via heat shrink tape. Primarily, we are using

▼ Wiring BOM

Part	Part No.	Qty	Details
M8 Ring Terminals	5580825		4 AWG
M3 Ring Terminals	3240021		14-16 AWG
4 AWG Wires			
8 AWG Wire			
Anderson Connectors			
Deutsch Connectors	DT04-6P-L012		Need crimping tool for Deutsch, useful video for parts needed
4 AWG Anderson Pins	1319G4	8	
Small Fuse Holder			

References for creating wiring in CAD:

Tutorial video

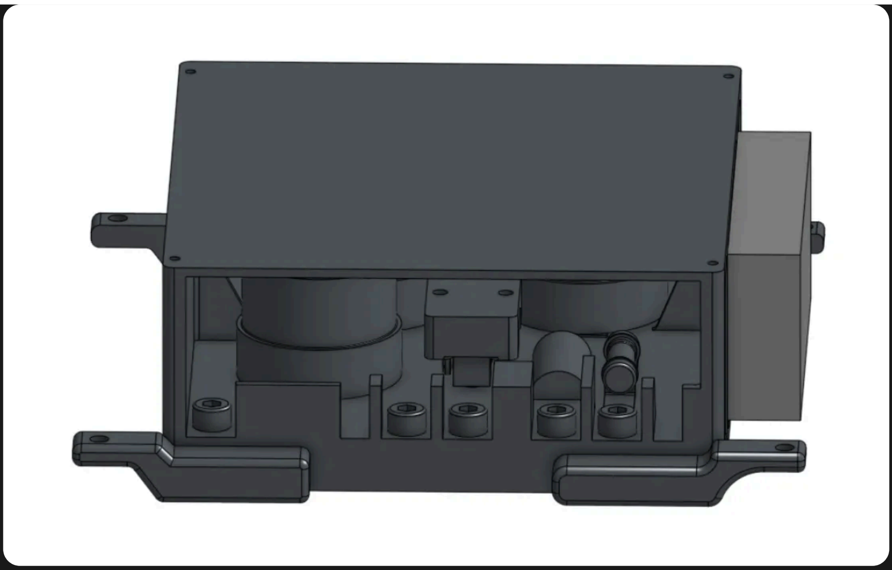
Wiring references

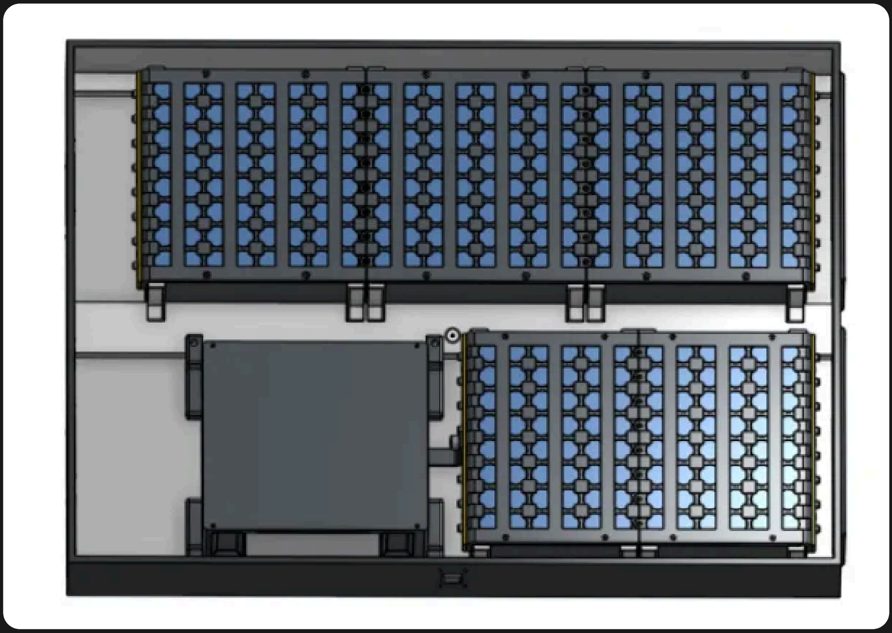
5 Steering

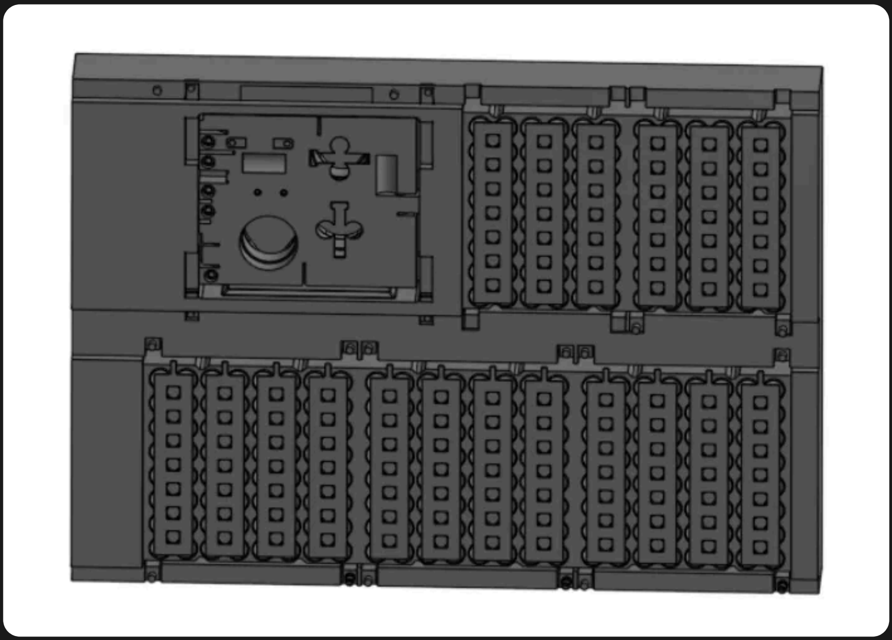
5.1 Steering rack

6 Thermal Modeling

6.1 CFD Preparation







Archive