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BATTERY DESIGN FOR ELECTRIC MOTORCYCLES

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ABSTRACT

In this study, the need for electric motorcycle adoption based on the greenhouse warming potential of conventional modes of transport was established. Present hurdles in e-motorcycle adoption and the importance of advanced manufacturing and clean energy technology advancement in increasing widespread usage was realized. Different cathode chemistries suitable to automotive needs were studied in detail along with a brief overview of anode, separator, electrolyte materials and cell form factor considerations. Suitable selections of the aforementioned entities were made, which were then fed into a battery performance and cost model software BatPaC by Argonne National Lab. Based on the outputs a module and pack was designed to achieve maximum possible packing density of 18650 cells. Suggestion and future improvements in design are described.

1. LITERATURE REVIEW

The need for reform in transportation is one of the most pressing sustainability challenges concerning international cities. Urban transportation systems in North America have become almost exclusively auto-dependent resulting in transportation becoming the largest and fastest growing source of greenhouse gas (GHG) emission [1]. Electric bikes and motorcycles are quickly becoming one of the fastest growing segments of the global transport market with potential for disruptive impact on existing mobility patterns [2, 3].

Across the Atlantic, motorcycles play an even more pivotal role in fulfilling daily personal and commercial needs in most Asian and many southern European cities. The small size of motorcycles, low purchase and maintenance cost has its obvious advantages. While Asia accounts for almost 85 % of new motorcycle sales, Europe is at a far second place of 8 %. A 2002 study pegged the Asian motorcycle population at 173 million with an average growth rate of 15% [4]. Therefore, even with a conservative extrapolation, today's motorcycle population can be put at around 200 million [5]. Figure 1(a) shows an image of a traditional internal combustion engine (ICE) motorcycle which relies on burning fossil fuel to produce power.

(a)

(b)

Figure 1: Traditional ICE motorcycle (left) and a modern electric motorcycle [9]

As motorcycles contribute a substantial chunk to Asia's and in turn to the world's air pollution due to sheer numbers and relatively high emission rates compared with cars as is shown in Table 1. Their environmental significance continues to rise as they displace low or non-emitting modes such as walking, cycling, and use of public transit systems. As an alternative to gasoline-powered motorcycles, electric motorcycles which rely on stored energy generated through various sources offer per se potential localized air pollution reductions, energy efficiency gains and can be an effective strategy to improve environmental performance in the transportation sector [6, 7]. Also, due to the inherent design, electric motorcycles and electric vehicles in general offer performance advantages such as superior acceleration, instant torque on demand, low center of gravity and a near equal front-rear weight distribution that improves handling.

Greenhouse Warming Potential ($g\ CO_2$ equivalent/passenger km)	Urban	Rural	Highway
Car – solo	310	180	220
Motorcycles & Scooters	260	190	330
Car – one passenger	155	90	110
Car – three passengers	78	45	55

Table 1: Greenhouse warming potential [10]

As electric vehicles in general and motorcycles specifically represent an increasingly growing share of the automotive market, replacing internal combustion engine vehicles, they impose great demands on energy storage technologies [8]. Despite tremendous progress in recent decades in battery technology, electric vehicles still face huge challenges to meet the range requirements and achieve mass market penetration at comparable costs. Let us now look at some primary factors influencing consumer adoption of electric motorcycles.

1.1 Factors Influencing Consumer Adoption of Electrified Modes of Transport

Despite the obvious advantages of electric motorcycles, the cost, availability, range, charging infrastructure, associated incentives and education on the subject has been a bottleneck in widespread adoption. Although great strides have been made in reducing battery costs, a lot of work still needs to be done to make them affordable enough to suit high-volume applications. With respect to availability, though more and more new electrified modes of transport are available to the consumers every year in comparison to traditional internal combustion variants the options seem to be rather limited in comparison to ICE variants. Consumer concern around the range, charging and maintenance infrastructure has also been a deterrent for early adoption and needs to be addressed better. Lastly, educating consumers on the similarities, differences, benefits and challenges of electrified vehicles in general has been a challenge that industry and local governments have long struggled with [11, 9].

Apart from the above, the development times for transportation related battery pack applications are far longer than those for other application such as consumer electronics due to heavy regulations and risks involved [9].

1.2 The Storage Battery

Having looked at the hurdles in implementation, one can see that technological advancement, particularly in the battery technology is at the heart of reducing electric motorcycle cost and increasing adoption. Let us now take a brief look about their origin and history before we deep dive on various battery chemistries and their design aspects.

Batteries are often thought as modern inventions; however, their first forms can be traced back to several thousand years. In 1930s, a configuration resembling that of a battery was unearthed at an archaeological site in Baghdad. It came to be known as the Baghdad battery and was believed to be developed around 2000 years ago. Around the mid-1700s two inventors in separate work discovered what was known as the 'Leyden' jar. It was a device used to store static electricity [12]. In the late-1700s Alessandro Volta discovered what he called a "Voltaic Pile", the results of Volta's discovery were however only published in 1800. His invention proved to be the first electrochemical energy storage cell [13]. Next major step was in 1859 when Gaston Plante, a French physicist, invented the first rechargeable lead-acid storage battery. The capabilities of this battery were enhanced by Camille Faure in 1881. These works were the basis for the modern lead-acid (PbA) battery used in most automobiles today. However, lead acid batteries suffer from low cycle life only achieving 300-500 cycles. Other issues like flaking and gassing further reduce its suitability for modern electric motorcycles [9].

Another battery chemistry that has received a lot of attention in the 1990s and early 2000s is the nickel-based chemistries, including Nickle Metal Hydride (NiMh) and Nickle Cadmium (NiCd). As these chemistries offered higher voltage and capacities than traditional lead acid batteries, they saw widespread adoption in hybrid electric vehicles (HEVs) and a few electric motorcycles. Some challenges of nickel-based chemistries however are the lower voltage and lower energy density as compared to lithium-ion chemistries which are discussed in detail in section 1.3. Also, NiMh suffers from "memory effect" that reduces the availability of energy over time [9].

It was is the year 1991 that Sony Corporation came up with a new product called lithium-ion battery as we know it today based on the work of Dr. John Goodenough of the University of Texas [14]. Considering the scope of the project, here we focus only on different Li-ion cell chemistries in greater detail. Also, it is also worthwhile at this point of time to look at some important battery terminologies.

1.3 Battery Terminology

The following battery terminology will be handy in better understanding the contents of the further sections.

Anode – It represents the negative terminal inside the battery. It is normally a thin and conductive copper or aluminum piece with coated carbon or graphite.
C-rate – It describes the rate at which a battery can charge or discharge. 1C-rate is the rate at which a 1 Ah battery is fully charger or discharged in 1 hour.
Capacity or Nominal Capacity – Capacity is the measure of the amount of energy in a system. It is measured in Ampere hour (Ah).
Cathode – It is the positive terminal inside the battery. It is typically a thin piece of aluminum or copper that is coated with lithium-ion materials such as lithium cobalt oxide (LCO), lithium-

iron phosphate (LFP), lithium-nickel-manganese-cobalt (NMC), lithium-manganese oxide (LMO) or other lithium-based chemistries as described in Table 2 and 3.

Depth of Discharge (DOD) – The DOD is a measurement of how much of the cell or pack energy will be used for an application. Typically, a lithium-ion battery only uses somewhere between 20% and 90% of the total amount of energy in order to prevent overcharge at the top and manage low end voltage.

Electrolyte – The electrolyte is responsible for transfer of lithium-ions between the anode and cathode. It mostly has the consistency of a gel or liquid.

Energy or Nominal Energy – Energy which is measured in kilowatt hours (kWh), refers to the amount of energy that a battery will store. It is analogous to the size of a gas tank in an internal combustion engine car.

Energy Density – It is a measure of the amount of energy a cell or pack can store in relation to its mass or volume. Energy density is measured in watt hour per kilogram (Wh/kg) or watt hour per liter (Wh/L).

Jelly Roll – It is the combined assembly of anode, separator, and cathode that can be arranged in any favorable configuration in a suitable form factor.

Power Density – Measured in kilowatt per kilogram (kW/kg) or kilowatt per liter (kW/L), it is the measure of the power of a battery in relation to its weight or volume.

Separator – The separator consists of a thin sheet of material that separates the anode form the cathode in order to prevent them from touching each other or creating a short circuit. It is usually made of a single or multilayer plastic (e.g. polypropylene) or ceramic based material. The separator also allows the lithium-ions to pass between anode and cathode.

State of Charge (SOC) – While DOD measures how much of the battery is being used, SOC measures how much is left at a specific point in time.

Now that we have a base understanding of the lingo and jargon that is used in battery design, we will look deeper into our chemistries of interest in the li-ion domain.

1.4 Lithium-Ion Cell Chemistries

Lithium-ion gained popularity as the battery of choice because of its higher energy density than other cells in the market. To illustrates this with an example, one can create a battery with the same energy as NiMh at about half its size.

Other advantage of a lithium-ion battery as compared to typical NiMh and NiCd rechargeable cells is that it operates at a higher nominal voltage of 3.2 to 3.8 V. Having higher voltage implies that fewer cells are needed to achieve desired pack voltage. Additionally, lithium-ion cells have a lower rate of self-discharge and much better cycle life. Table 2 and 3 below summarizes general performance characteristics of some commonly used lithium-ion chemistries [9].

	Lithium Iron Phosphate	Lithium Manganese Oxide	Lithium Titanate
Cathode chemistry descriptor	LFP	LMO	LTO
Specific energy (Wh/kg)	80 – 130	105 – 120	70
Energy density (Wh/L)	220 – 250	250 – 265	130
Specific power (W/kg)	1400 – 2400	1000	750
Power density (W/L)	4500	2000	1400
Volts (per cell)	3.2 – 3.3	3.8	2.2-2.3
Cycle life	1000 – 2000	>500	>4000
Self-discharge (% per month)	< 1%	5%	2-10%
Cost (per kWh)	$400 - 1200	$400 - 900	$600-2000
Operating temperature range (C)	-20 to +60	-20 to +60	-40 to +55

Table 2: Lithium-ion chemistries

	Lithium Cobalt Oxide	Lithium Nickle Cobalt Aluminum	Lithium Nickle Manganese Cobalt
Cathode chemistry descriptor	LCO	NCA	NMC
Specific energy (Wh/kg)	120 -150	80 - 220	140 - 180
Energy density (Wh/L)	250 - 450	210 - 600	325
Specific power (W/kg)	600	1500 -1900	500 - 3000
Power density (W/L)	1200 - 3000	4000 - 5000	6500
Volts (per cell)	3.6 - 3.8	3.6	3.6 - 3.7
Cycle life	>700	>1000	1000 - 4000
Self-discharge (% per month)	1-5%	2-10%	1%
Cost (per kWh)	$250 - 450	$600 - 1000	$500 - 900
Operating temperature (C)	-20 to +60	-20 to +60	-20 to +55

Table 3: Lithium-ion chemistries

Looking at the data in Table 2 and 3 and the fact that NMC currently accounts for 71% of the electric transportation market share with NCA at a far second of 16% [15-17]. In this design project our cathode will be taken to be NMC details of which are elaborated in section 2.8.

1.5 Anode, Separator and Electrolyte

The negative electrode in the cell is know as the anode. Today, most anodes are made of a mixture of one of two materials – graphite or soft/hard carbons. Out of many different grades of graphite, graphene is primarily used; although final selection is dependent on the performance requirement of the cell. Other anode materials such as lithium-ion titanate are also used for low temperature operation and increased power density. A large amount of research is being done into several new anodes including silicon, tin, germanium, carbon nanotubes, and other nanocomposite materials of which figure 2 provides a brief overview.

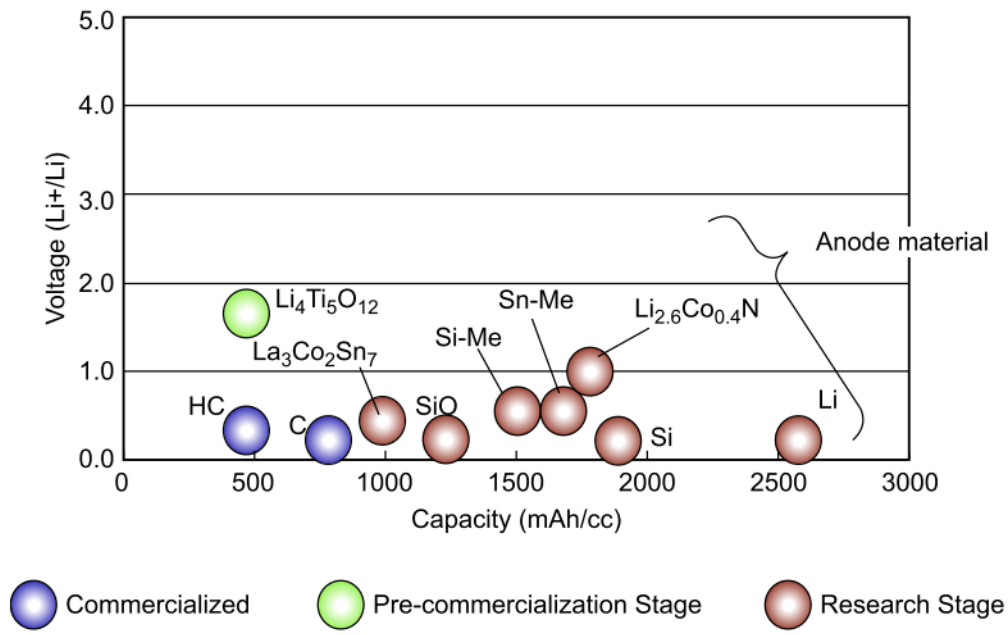

Figure 2: Anode materials performance comparison [6]

A separator is often a thin piece of plastic or ceramic that is used to separate the anode from the cathode. It must be able to withstand the corrosive hydrocarbon-based electrolytes for the lifetime of the cell while still maintaining isolation. Choice of separators ranges from use of polymers like polypropylene (PP) or polyethylene (PE) to glass-fiber mats.

The electrolyte is usually a liquid or gel-based solution in which the anode and cathode are immersed. It allows the conduction of lithium-ions between the two electrodes. The electrolyte is typically a hydrocarbon (HC) based mixture with several additives. Typical electrolytes may include alkyl carbonates such as ethylene carbonate, dimethyl, diethyl, and ethylmethyl carbonates and lithium salts (LiPF6) [18]

1.6 Cell Form Factor

There are primarily three types of li-ion cell form factors namely small cylindrical, large prismatic, and large pouch (or polymer) cells. The highest volume of lithium-ion cell format in production today is the 18650 cylindrical cells with nearly 660 million produced in 2013 [19]. The nomenclature implies that the cell diameter is 18 mm and 65 mm in length. This is indicative of a well-established manufacturing procedure for these types of cells and hence is the choice of form factor for this project.

2. METHODOLODY AND APPROACH

The specification for the battery pack design are enlisted in section 2.1. Sections 2.2 to 2.6 explains and enlist equations that can be used for manual calculations. Section 2.7 describes a tool (BatPack Version 3) that was used to obtain and/or calculate parameter presented in section 3. A high-level overview of the approach used is presented in figure 3.

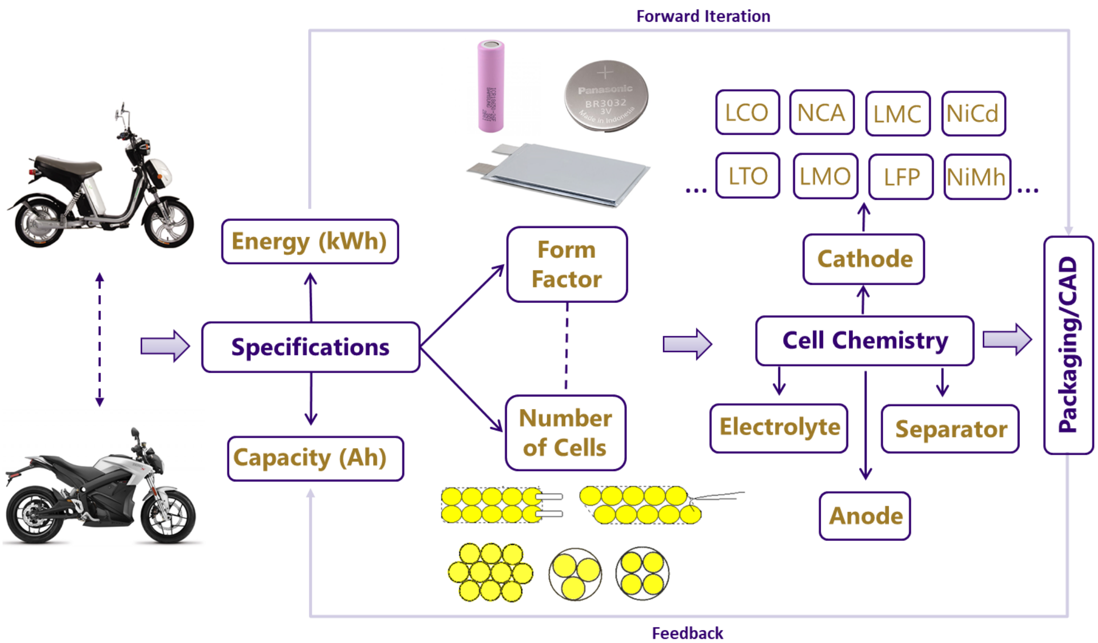

Figure 3: Design methodology and approach

2.1 Defining Battery Pack Specification

The battery pack specifications are a function of several parameters like range, desired top speed, end of life requirements, system operating voltage, cost, etc. In this project the specifications are defined based on the Zero S™ by Zero Motorcycles®. The desired range for a curb weight of 140 kg is 80 miles (~130 km) with a maximum achievable speed of 80 mph. These requirements for a motor that delivers 25kW of maximum power at 4300 rpm translate to an energy requirement of 6.5 kWh and a capacity of 90 Ah to 90% depth of discharge. The desired pack voltage (V_p) is pinned at 72 V.

2.2 Ohm's Law

Ohm's Law is the most basic, yet highly useful relation used in battery pack design calculations. It can be stated as:

$$V = I \times R \tag{1}$$

where V is the cell voltage in Volts (V), I is the cell current in Ampere (A) and R is the cell resistance in ohm (Ω).

2.3 Basic Battery Calculations

One of the first things that comes to our mind when we think of a battery pack design is the number of cells that will be needed to meet the basic voltage and current requirements. With the starting point of the desired pack voltage (V_p) and choice of cell chemistry which gives the cell voltage (V_p) one can find the number of cells needed as:

$$\frac{V_p}{V_c} = N_s \tag{2}$$

where N_S is the number of cells in series.

2.4 Pack Energy and Capacity

To calculate the pack energy (E_p) if we know the needed capacity, or current of the pack, we can multiply the pack voltage (V_p) by the current capacity (I_p) as shown below:

$$E_p = V_p \times I_p \tag{3}$$

The required pack energy can also be determined by considering the electric motor the pack intends to drive (based on the application), leading to an overall system efficiency (S_e) in kWh/miles, and the intended vehicle range (V_{Range}) in miles:

$$E_p = V_{Range} \times S_e \tag{4}$$

The pack capacity (C_p) can be calculated if the capacity of individual cells in Ah is known. Cell capacity (C_c) is determined primarily by the electrode chemistry i.e. percentage of active material in the electrodes.

$$C_p = C_c \times N_p \tag{5}$$

where N_p is the number of cells in parallel.

2.5 Calculating System Power

In order to calculate how much power per cell (P) the system can provide, in addition to Ohm's Law we can use the Joule's Law as below.

$$P = I_p^2 \times R \tag{6}$$

The resistance (R) of the cell can be measured by running a hybrid power pulse characterization (HPPC) and measuring the change in voltage and current and dividing the two [6].

2.6 Calculating Charge Voltages

The maximum charging voltage ($V_{c\,max}$) can be calculated by multiplying the total number of cells in series (N_{cs}) by the cell's maximum voltage (V_{max}) as is defined by cell chemistry and/or manufacturer.

$$V_{c\,max} = N_{cs} \times V_{max} \tag{7}$$

Similarly, minimum charging voltage can be calculated by using $V_{c\,min} = N_{cs} \times V_{min}$.

2.7 BatPaC Software

The Battery Performance and Cost model or BatPaC is an open source software prepared by Argonne National Laboratory to design li-ion batteries for electric-drive vehicles based on modeling with Microsoft® Office Excel spreadsheets. Figure 4 gives a brief overview of model used by BatPaC version 3.

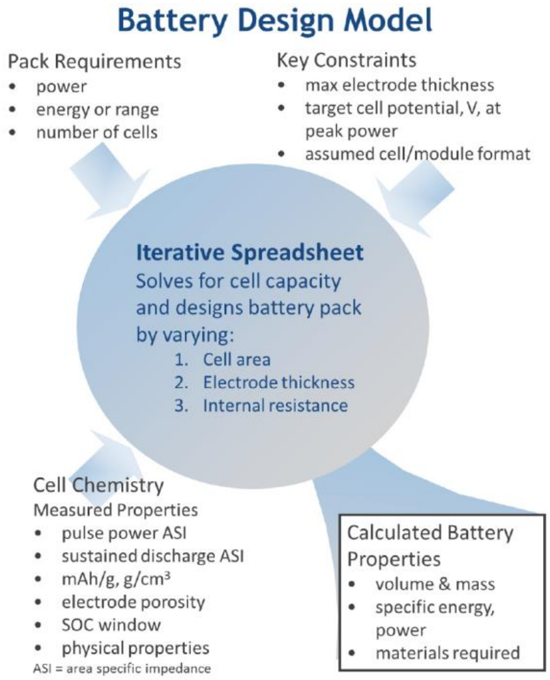

Figure 4: Summary flow of the design model

2.8 Manufacturing Considerations

In greater detail than mentioned earlier, the choice of cathode is 90 % NMC, 5% Carbon and 5% Polyvinylidene fluoride (PVDF). This shall be deposited on an Aluminum foil of 15 µm. While that of anode, the negative side of the electrode is 92% Graphite, 2% Carbon and 6% PVDF binder which shall be deposited on 10 µm Copper foil. The selection of separator is a glass-fiber mat of 15 µm thickness with 50% void percentage and a density of 0.46 g/cm^3. And electrolyte is $LiPF_6$ in 3:7 solution of ethylene carbonate (EC): ethyl methyl carbonate (EMC).

Cylindrical cells are generally manufactured and assembled as follows. The electrolytes are formed from pastes of active material powders, binders, solvents, and additives and are fed to coating machines to be spread on current collector foils. A process such as doctor blading can be incorporated in this step. Calendaring is done for homogeneous thickness and particle size is followed by a slitting operation to the correct width. The components so formed are then stacked to separator-anode-separator-cathode stacks followed by winding to the cylindrical form factor, insertion in cases, and welding of a conducting tab. The cells are then filled with electrolyte. The electrolyte has to wet the separator, soak in, and wet the electrodes and therefore is the slowest step and determining factor in the speed of the line. All other needed insulators, seals, and safety devices are then attached and connected. Then, the cells are then charged the first time and tested. Often cells must be vented during the first charge. First charging cycles follow sophisticated protocols to enhance the performance, cycling behavior, and service life of the cells [20].

3. FINDINGS AND DISCUSSION

The following parameters were outputted by the BatPaC software based on the inputs described in section 2.1 and 2.8.

Parameter	Description	Value
V	Cell voltage	3.565 Volts
C_c	Cell capacity	5000 mAh
N_s	Number of cells in series per module	20
N_p	Number of cells in parallel per module	16
E_p	Pack energy	5.99 kWh
C_p	Pack capacity	80 Ah
V_p	Pack voltage	75 Volts
$V_{c\ max}$	Open circuit voltage at 50% SOC	3.755 Volts

Table 4: BatPaC output

Based on the above obtained parameters a CAD model of the module consisting of 20 cells in series was designed which is shown in figure 5. This module has a capacity of 5 Ah and voltage of 75 V. Connecting 16 such modules in parallel gives the required pack capacity.

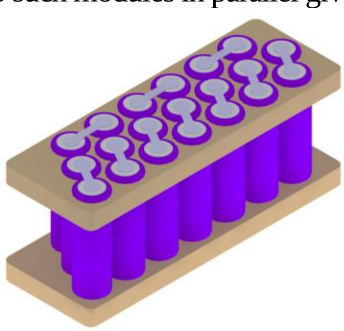

Figure 5: 20S battery module (14×6×7 cm)

The parameters obtained in table 4 were verified by hand calculations described in sections 2.2 to 2.6. Further calculations made based on CAD model indicate that the pack occupies a total volume of 9408 cm^3, which is less than the space occupied by the average ICE gas tank and radiator assembly. This design however does not consider in detail the battery management system (BMS), mechanical packaging, thermal management system and system control electronics which may be considered in case of a more detailed study.

4. CONCLUSIONS

A Lithium-ion battery pack with 20S16P module configuration was designed considering suitable cathode, anode, separator and electrolyte chemistries. A high-level overview on cylindrical cell manufacturing procedure was presented. The use of an open source battery performance and cost model to make meaningful design calculations was demonstrated. A CAD study on closest possible packing of 18650 cells was conducted. Potential additions to the existing design in other design domains were identified to represent a holistic understanding of the subject.

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