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Developments in Composite Energy Storage

James Le Houx
Faculty of Engineering and the Environment, University of Southampton, Southampton, United Kingdom

Email: jplh1g11@soton.ac.uk

Abstract

Given the recent trend to reduce pollution at the point of use, and to improve performance characteristics of vehicles, electric vehicles provide an attractive solution and have received renewed attention in recent years. This report looks at form factors available today and summarises the battery pack designs of two popular commercial vehicles. It then goes on to propose a new form factor design in the shape of a honeycomb, filled with jelly roll battery cells. This design is described in detail before being compared to the two commercial designs. It is found to perform favourably with regards to mass and cooling but would cost more during the manufacturing stage.

Keywords: Composite Energy Storage, Honeycomb Form Factor, Electric Vehicle Battery Pack Design

1. Introduction

Worldwide concerns over climate change and security of energy supply are driving a global shift in the transport sector, from fossil fuels to alternatives; one of the most promising solutions being electric vehicle propulsion systems capable of providing long term sustainability [1]. Electric vehicles (EV) provide a way of eliminating emissions at the point of use, reducing pollution in large population centres and thus increasing quality of life. Moreover electric vehicles allow renewable generation methods to power the road transport network, significantly reducing harmful emissions and securing the energy supply.

Current electric vehicles are a promising technology, however they are still not fully competitive with conventional vehicle technology [2]. Range anxiety, cost and performance of the vehicle due to high weights associated with the required battery technology are all cited as significant challenges facing the electric vehicle market [1]. Significant research is currently being undertaken in cell chemistry, looking at higher power and energy gravimetric density cells; however, one area which has seen less active research is the design of the battery pack. The gravimetric energy density is increased by approximately 53-73% [3] during the scaling from cell-to-pack design, due to the additional materials such as active thermal management, battery management systems and physical containment of the battery. Reducing this additional mass through new design presents a method of improving the performance of electric vehicles, without the need of new cell chemistries.

Composite multi-functional materials are currently being used in a number of different applications, from integrated sensors within wind turbine blades to composite chassis/bodywork in high performance automotive vehicles. Looking at the overall design of the EV battery pack presents a possible way to integrate a number of design functions into fewer components, reducing the mass and complexity of the final pack, ultimately improving EV performance.

2. Aims and Objectives

This project will explore the usage of multi-functional composite materials within battery systems for EVs. In order to achieve this, the following objectives have been set out:

- Provide a literature review of the current EV battery systems, specifically the Nissan Leaf and the Tesla Model S, and compare their characteristics.
- Look at the different form factors available on the market today, the cylindrical, pouch and prismatic cells, and comment on the manufacturing processes used to produce them.
- Design an integrated battery pack system through the use of Solidworks and finite element analysis (FEA), and compare the thermal and structural characteristics with the EV packs on

the market today. Furthermore comment on the potential manufacturing process required in order to produce this design.

3. Method

In order to compare the battery systems currently available on the market, a number of design parameters need to be considered:

- The mass will influence the handling characteristics and the energy usage of the vehicle.
- The volume and shape of the battery pack will determine how easy the system is to package within the vehicle.
- Thermal management through active cooling provides a way of managing the cells to prevent thermal runaway, however presents a significant weight disadvantage.
- Isolating the pack against vibration will reduce the chance of any relative cell movement, helping to prevent the failure of cells [4].
- The containment of the battery pack during a crash situation is of paramount importance to the safety of the occupants.
- Use of a battery management system (BMS) and how it is integrated into the design. The BMS and its associated wiring harness makes up a large proportion of the overall mass.
- How the system is designed to cope with a failure situation, is there a failsafe gas venting mechanism during a thermal runaway situation to prevent explosions.

These parameters can then be used in a design matrix to compare each system, ranking each parameter in terms of importance and how each design satisfies them. Additionally to these there are also a number of international standards dictating the correct design of a battery pack, such as SAE J1797, that need to be satisfied. Further to this Formula E and Formula Student both provide technical regulations that specify correct design of battery packs; by providing an overview of each of these regulations the new design can be made in reference to a number of different international standards.

Thermal runaway is an exothermic chain reaction where the individual battery cells self-heat, this eventually leads to spontaneous combustion of the chemical components. This combustion typically causes a large quantity of gas to be formed which needs to be subsequently vented, reducing the risk to the surrounding areas and passengers. It is also important to include a failure point within the battery design in order to accommodate the associated pressure-rise, this helps to mitigate the risk of an unknown failure point causing significant damage[5].

4. Deliverables

Individual electrochemical cells are produced in a number of different shapes namely cylindrical, prismatic and pouch, each offering different advantages and disadvantages [6]. Cylindrical cells consist of an electrode assembly that has been spiralled which is then contained within a cylindrical casing, this can be seen in Figure 1. These cells are manufactured in a continuous feed process line as the full electrode assembly is a continuous strip of active materials, making them relatively cheaper to manufacture [7]. Additionally the housing is generally metallic, meaning each individual cell has inherent stiffness, providing an extra layer of safety. However due to the shape of the cylinder, packaging a module of these cells means gaps are present, reducing the overall volumetric energy density. Prismatic cells are constructed in a similar fashion however the spiral is flattened allowing the can to be shaped in a rectangular shape. They are also manufactured in a continuous feed process due to the flattened spiral. The prismatic shape allows better space utilisation and more flexible design, however they are generally more expensive to manufacture and can be less efficient in thermal management [8].

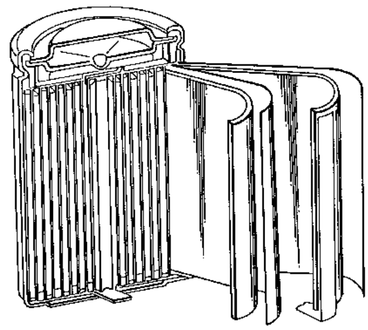

Figure 1 - Diagram of a sectioned cylindrical cell, exposing the jelly roll [9].

Pouch cells are made of a number of electrode layers stacked together, with protruding conductive tabs acting as the terminals, as seen in Figure 2. This stacked design means a stiff enclosure is not required, reducing the mass and increasing the packing efficiency however the battery still needs support. In order to manufacture the pouch cell subsequent electrode layers are stamped or cut from the feed and then stacked using robotic arms; this process is inherently slower than the continuous feed process employed for the other two designs, generally increasing cost of the pouch cells in comparison [10].

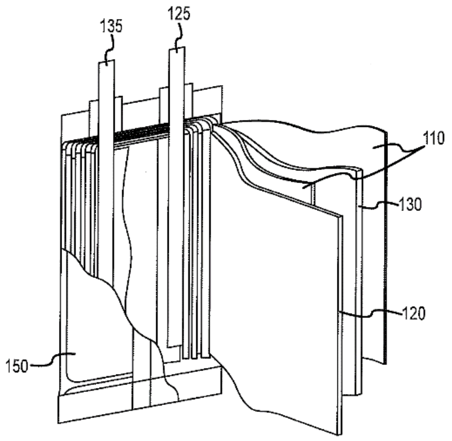

Figure 2 - Diagram of a sectioned pouch cell, exposing the individual layers [11].

Within the electric vehicle sector, a number of alternate designs are currently being used by different manufacturers. The general design methodology behind these is to manufacture individual cells in a certain form factor, or shape, and then package a series and parallel string of these into a set of modules which come together to form the overall battery pack. In this scale up from cell-to-pack it has generally been found that the overall mass increases by between 53-73% [3] due to the additional materials required to package the modules and pack, and by the inclusion of the battery management system and thermal management. This report will now consider the battery designs of two popular EVs available on the market today namely the Tesla Model S and the Nissan Leaf.

The Tesla Model S comes with a variety of battery size options including 70 kWh, 85 kWh, 90 kWh and 100 kWh; the most popular sizing being the 85 kWh which will be considered here [12]. The 85 kWh battery pack consists of 16 modules of 444 cells for a total of 7,104, the individual cells are 3400 mAh Panasonic 18650s. The 18650 code refers to the sizing of the cell meaning it is a cylindrical form factor with a diameter of 18mm and a length of 65mm. The overall mass of the pack is 540 kg which gives an energy density of 157 Wh/kg. It can be seen in US patent 8481191 [13], as shown in **Figure 3**, that these cells are arranged vertically and separated by rigid spacers. These spacers are included in order to ensure that each battery cell remains in its predetermined location, preventing relative cell movement during a thermal runaway event. The large module size employed by Tesla means it is relatively hard to package and in practice this is achieved by having a flat package acting as the floor of the vehicle with the cylindrical cells vertically mounted.

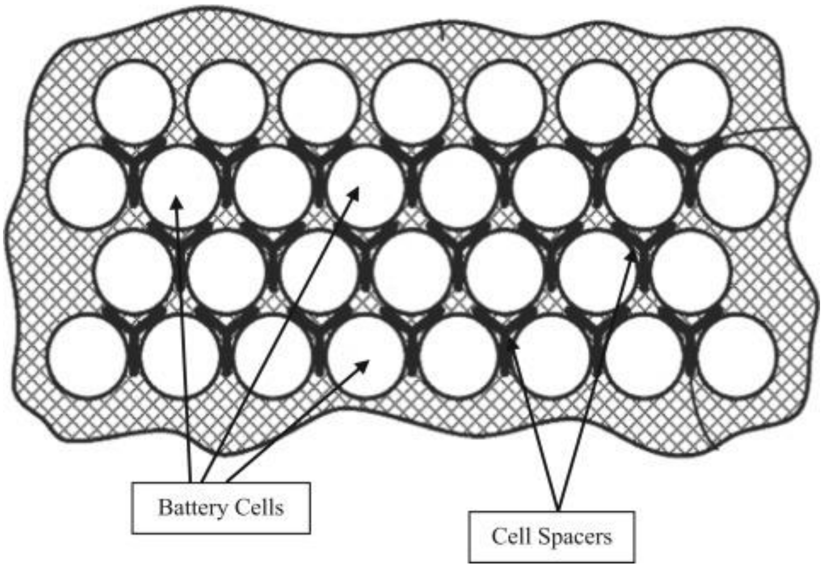

Figure 3 - A cylindrical battery cell assembly for the Model S [13].

These cells are then arranged into 16 modules of 444 cells which are then packaged within a protective casing, providing protection during a failure event. The arrangement of these modules can be seen in US Patent 8663824 [14], as shown in Figure 4. It can be seen that the battery pack has been divided into compartments through the use of cross members. These modules are then connected to the battery management system which monitors each module of cells. The battery pack also features a liquid Glycol thermal management system that is distributed using a cooling tube that snakes around each row of cells, as seen in US Patent 20110212356 [15].

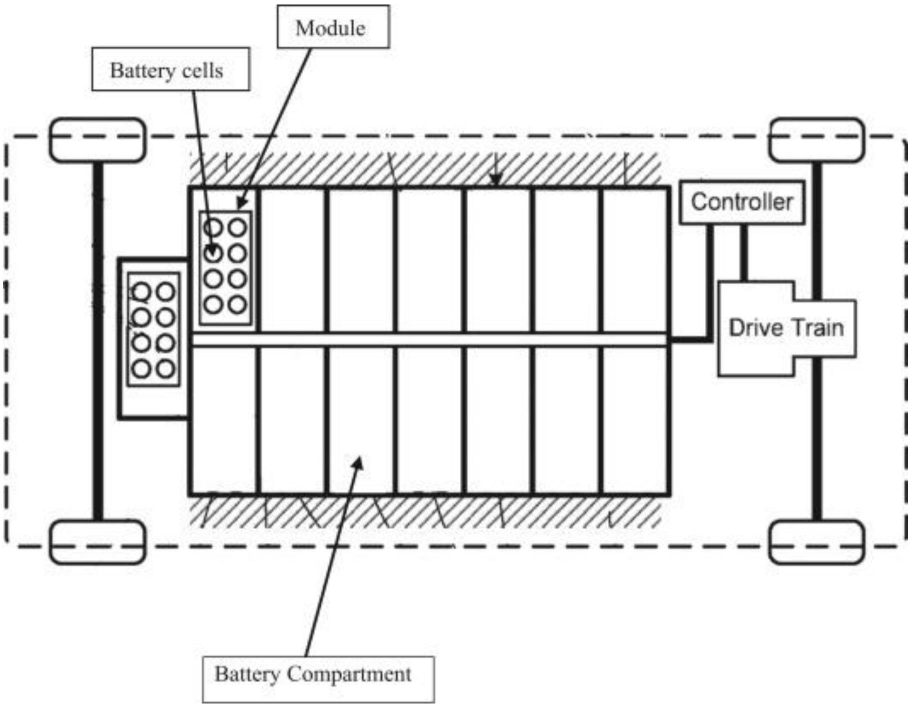

Figure 4 - An overall battery pack design for the Model S [14].

Looking at the mass composition of the 18650, which can be seen in Figure 5, the physical housing of each individual cell comprises approximately 20% of the overall mass. Spread over all 7,104 cells this makes up a significant portion of the overall battery pack mass.

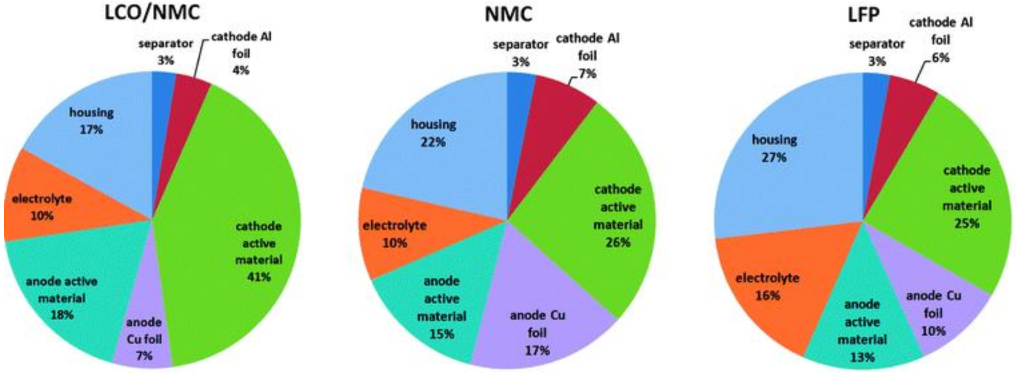

Figure 5 - Mass split of the main components of three different 18650 Lithium cell chemistries [16].

The Nissan Leaf uses a 24 kWh battery, made up of pouch type lithium ion cells. Four of these pouch cells make up a module, of which 48 make up the overall battery pack [17]. The overall pack weighs 294 kg giving an energy density of 81.6 Wh/kg [18]. It can be seen in Figure 6 that the individual modules are housed within steel cases which are then rigidly stacked both horizontally and vertically in order to fit within the specified packaging constraints, the small module size employed allows a more tailored battery pack to be designed to fit within the vehicle [19]. These modules are then electrically connected via copper bus bars. Most electric vehicles utilise liquid cooling mechanisms however the Nissan Leaf relies on air cooling in order to manage the temperature of the cells [20].

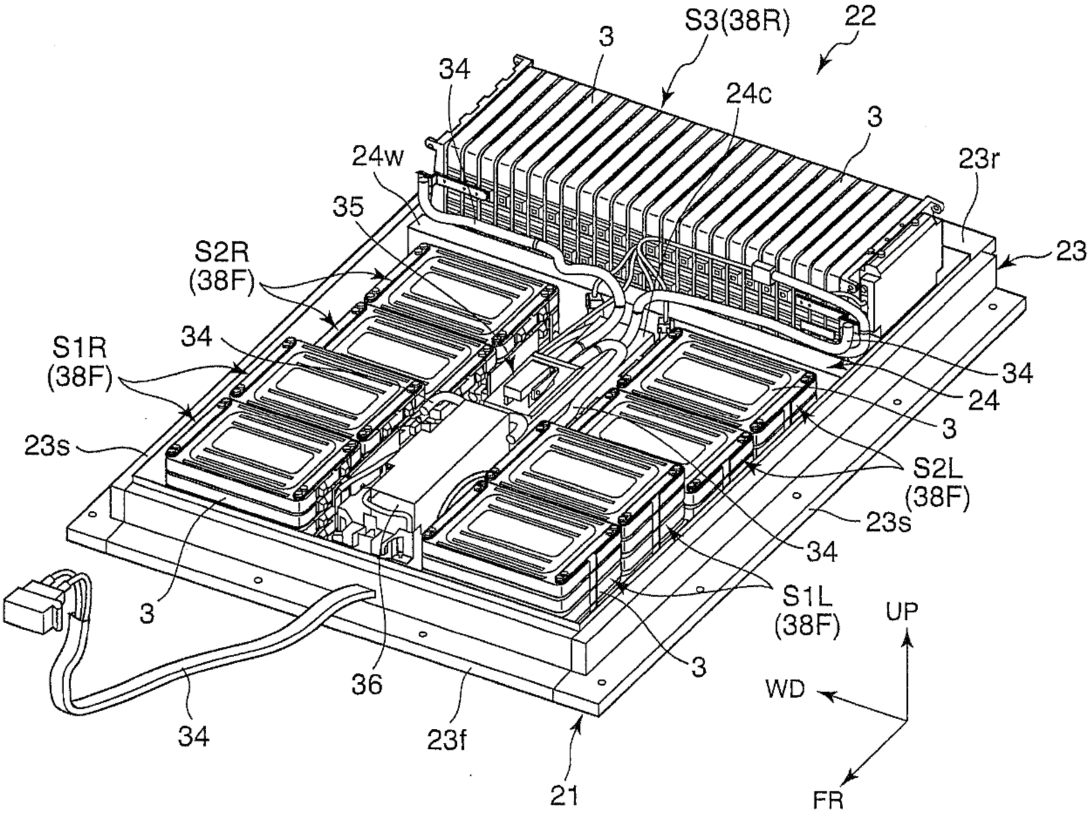

Figure 6 - Overview of the Nissan Leaf battery assembly [19].

5. Challenges

Having considered both designs it can be seen that in the scale up from cell-to-module-to-pack, a significant amount of mass is added to the overall pack. Through the use of a new form factor in the form of a honeycomb structure the structural mass can be better utilised by directly manufacturing the module. Most cells of the honeycomb are filled with an 18650 jelly roll, utilising the continuous feed manufacturing process in order to reduce cost, additionally the wall of each cell is also used as the wall of the adjacent cell reducing the casing mass. Every central cell in a petal pattern is left free in order to allow its use as a cooling channel, using a glycol liquid based coolant, this pattern means every cell has an adjacent wall to the cooling channel. The structural stiffness of the design is high in x, y and z directions, when compared to the Tesla and Nissan, meaning in the case of a thermal runaway event each cell is supported by the adjacent without the need for additional spacers as seen in the Tesla pack. Expansion of the electrodes due to intercalation of the Lithium ions is allowed through tolerances of the jelly roll compared to the honeycomb cell size.

The cells are connected through the use of a 3d printed circuit top and bottom panel that uses button shaped terminals to interface with the electrodes in a similar manner to that of an 18650 cell. This consists of two insulation plates adjacent to the electrode, with both negative and positive terminal leads used to connect the cell, a compressible gasket is also included in allow for a compression load to be applied during the sealing of the cell. This design also incorporates an anti-explosion valve in the top button connection, which is broken when sufficient pressure is reached within the cell, venting exhaust gases, the internal structure can be seen in Figure 7 whilst the materials used for each component is shown in Table 1. A vacuum is then applied to the cells and they are filled with electrolyte, finally the top circuit panel is then adhesively bonded to the honeycomb structure, in a similar method to the construction of a composite sandwich panel [21], sealing the overall module as seen in Figure 8.

Component	Material
Insulation Plate	Plastic sheet
Electrode Roll	Compound of electrochemical materials coated onto aluminium and copper foils.
Gasket	Compressible neoprene
Honeycomb	Extruded stainless steel, 0.064mm wall thickness
Top and Bottom Panel	Glass fibre composite

Table 1 - Table detailing the materials used within the assembly.

Figure 7 - Figure detailing the internal structure of an individual cell, similar to that of an 18650.

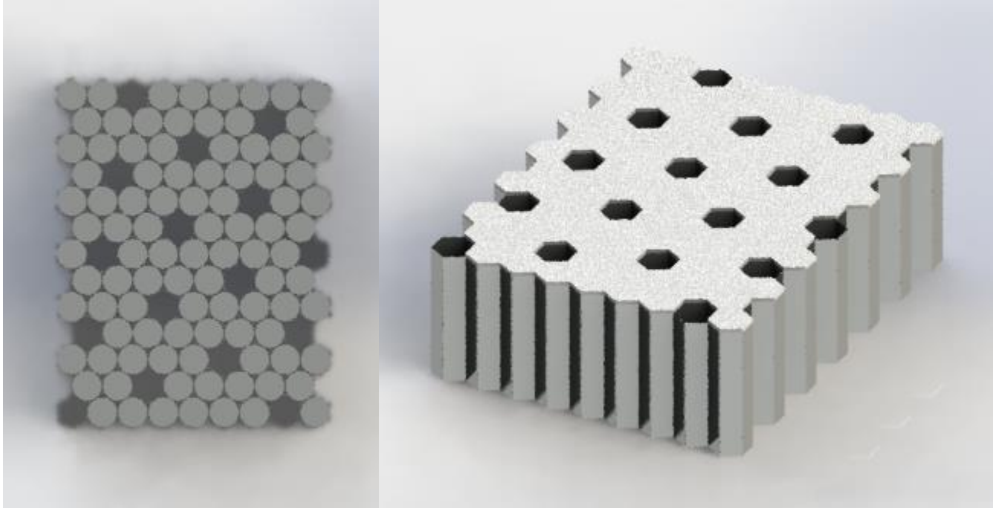

Figure 8 - Top and Isometric views of the proposed design.

With the design now proposed a design analysis can be performed, comparing it to commercial solutions. This is performed through the use of a design matrix as shown in Table 2. From this table it can be seen that the honeycomb solution provides the most favourable energy density characteristics, however is anticipated to cost more in comparison to both designs. Additionally the adhesive bond used to secure the top and bottom panel will be harder to achieve than the crimped solution seen in 18650 cells, however the design still incorporates a gas venting mechanism.

		Tesla Model S		Nissan Leaf		Honeycomb	
Criteria	Weighting	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Energy Density	5	3	15	1	5	5	25
Ease of Packaging	2	2	4	4	8	2	4
Thermal Management	3	4	12	1	3	4	12
Containment/ Safety	5	5	25	5	25	4	20
Cost	3	4	12	5	15	3	9
		Total	**68**	**Total**	**56**	**Total**	**70**

Table 2 - Design matrix comparing the two commercial battery pack designs with the proposed honeycomb form factor.

6. Conclusions

This report has looked at the battery pack design for two popular electric vehicles available on the market today, finding that the Tesla Model S far exceeds the energy density of the Nissan Leaf. A comparison is also made of the form factors of cells available, finding that a continuous feed manufacturing process allows for quicker mass manufacturing of cells. These characteristics are then taken through to aid the design of a new honeycomb form factor, utilising the continuous feed manufacture process seen in cylindrical and prismatic cells. It also incorporates a thermal management and battery management system, and is found to compare favourably with the mass of the two commercial systems. This provides a direct way of significantly improving the energy density of battery packs without having to modify the battery chemistry within the cell.

7. Future Work

- Validate the FEA of a cylindrical cell through physical compression testing in the TSRL.
- Perform detailed analysis of the thermal management system in order to optimise the cooling system.
- Produce a 3D printed model of the proposed design which can then be used as a demonstrator.
- Analyse the predicted manufacturing costs associated with design in order to provide a better comparison.
- Perform a strip down of a 3400 mAh Panasonic 18650 in order to obtain more detailed mass characteristics of the mechanical components.

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