Tesla electric vehicles batteries

Lesson plan for teachers

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STEP AHEAD II

The support of Professional development of VET teachers and trainers in following of New trends in Automotive Industry
Automotive Innovation & Teacher training Academy
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Tesla Electric Vehicles Batteries

Important: The timing for this learning unit is two sessions of 55 minutes each.

The aim of the lesson:
To gain knowledge about the constitution and function of electric vehicles batteries cells.

Activity No.1 Part of the lesson: **EVOCATION**

The aim of the activity: To get a general idea about batteries cells.

<table>
<tr><td rowspan="2">Step 1</td><td>Brief description of the activity</td><td>An image is projected on a whiteboard. Students are just required to carefully observe the image and answer a question: What has this image to do with Tesla? *</td></tr>
<tr><td>Instruction (what you need to tell the students)</td><td>There is something that links the image on the screen with a component of Tesla cars. They are just required to carefully observe the image and, in groups of three, write in their notebooks which possible relations could be the correct.</td></tr>
<tr><td>Step 2</td><td>Brief description of the activity</td><td>Write a list of those elements that in your opinion does a battery contain inside
<table><tr><th>List of elements</th><th>What is it for?</th></tr><tr><td></td><td></td></tr><tr><td></td><td></td></tr><tr><td></td><td></td></tr></table></td></tr>
</table>

	Instruction (what you need to tell the students)	In groups of three you are going to think about which type of elements a battery needs to work properly and which is the function of each of those elements. Just give some general ideas.
Tools for the activity (everything you need to take to the classroom)		An image – Projection on the classroom screen.
Estimated time (max. 40 min.)		10 minutes
Notes		Resources: free open source available image from the Internet * If you will be using the method used in the Step 1, "associative questions", the question should sound a bit unusual, drawing the interest of students, with the possibility to generate as many ideas as possible, encouraging the learning process, as the ideas that will be told will be remembered by students...In using this method, the process of generating ideas/possible answers by students is much more important than the answer as such... Example of the associative question: What has a human body, leaf of a plant and Tesla car have in common? The answer: They could not exist without a cell… (on the lesson you will be introducing the topic of electric batteries cells) You can think of using other, alternative questions in Step 1 to start this lesson.

Activity No. 2 Part of the lesson: **APPRECIATION**

The aim of the activity: To analyse the text and extract key information related to the topic, learn new facts about battery cells.

<table>
<tr><td rowspan="2">Step 1</td><td>Brief description of the activity</td><td>Students, in groups of three, using the given text:
• Students, in groups of three, will be given a text.
• Each group of Students will read and understand the text they have been given:

- Group 1. Appendix 1: Battery cells and how they work
- Group 2. Appendix 2: Battery modules. How they work and how they are assembled.
- Group 3. Appendix 3: Battery packs. How they work and how they are assembled

They should highlight in the text the main ideas and data to copy them afterwards on their classroom notebook.</td></tr>
<tr><td>Instruction (what you need to tell the students)</td><td>You should read the text given to your group carefully, highlighting what bit of information you consider to be more relevant. If you need it, you can write down some notes on your notebooks. This information will be useful in the next task to be done.</td></tr>
<tr><td rowspan="2">Step 2</td><td>Brief description of the activity</td><td>Each group chooses their spokesperson, who is going to explain the information to the rest of the students in the classroom.</td></tr>
<tr><td>Instruction (what you need to tell the students)</td><td>In each group:
- Get the main ideas about the technical piece of text in order to explain it clearly to the rest of the students in the class.

- Choose the spokesperson, the one to explain all those ideas

- Write a brief script ordering the ideas</td></tr>
</table>

		- The spokesperson will present the ideas to the class during the next step.
Tools for the activity (everything you need to take to the classroom)		One copy of the text on Appendix for each student: - Group 1. Appendix 1: - Group 2. Appendix 2: - Group 3. Appendix 3: A blackboard, paper sheets, pens- pencils- highlighters- internet connection.
Estimated time		45 minutes

Session 2

Activity No. 3 Part of the lesson: **REFLECTION**

The aim of the activity: Each group teach the rest everything they have learned during the previous activities.

Step 1	Brief description of the activity	Presentation of the group work results. Noting the unclear issues/ terminology on the blackboard. If anything unclear, there can be short discussion about it, an student can be challenged to find additional information on the internet as a homework.
	Instruction (what you need to tell the students)	After 5 minutes consulting your work during the previous session each group will explain to the rest of the class the main ideas and concepts that have learnt. The goal is to teach your fellow students about the matter. If there is anything unclear we will explain it on a next lesson. Each group has 10 minutes to explain the lesson.

Tools for the activity (everything you need to take to the classroom)	One copy of the text on Appendix for each student: - Group 1. Appendix 1: - Group 2. Appendix 2: - Group 3. Appendix 3: A blackboard, paper sheets, pens – pencils – highlighters - internet connection.
Estimated time	35 minutes
Notes	Resources: Step Ahead Project. You can ask students to prepare presentations in creative way (eg. through role play, where each student in a group acts out a different component and shows how components work together as a whole, OR creating a mind map on flip paper, explaining relations between the components, etc.)

Activity No. 4 Part of the lesson: **REFLECTION**

The aim of the activity: Summary and practical application of the gained knowledge

Step 1	Brief description of the activity	Check if students have clearly learnt the knowledge related to Tesla Vehicles batteries and their function within the vehicle. Students have to do a Multiple Entry Diary activity based on the following items: positive, negative and prognoses of Tesla Hybrid Vehicles batteries.
	Instruction (what you need to tell the students)	Each student will get a chart they have to complete properly:

	POSITIVE	NEGATIVE	PROGNOSES
TESLA BATTERY			

<table>
<tr><td rowspan="2">Step 2</td><td>Brief description of the activity</td><td>Lift Pitch. We divide the class in pairs, and in each pair students have to persuade each other to buy a Tesla Car.</td></tr>
<tr><td>Instruction (what you need to tell the students)</td><td>The teacher organises the class in pairs. Each student (customer) has 30 seconds to persuade his/her partner (salesman) to buy a Tesla vehicle. After 30 seconds they have to change roles and repeat the persuasive activity. Preparation time of the argumentation is 3 minutes maximum.</td></tr>
<tr><td rowspan="2">Step 3</td><td>Brief description of the activity</td><td>Additional possible activity for reflection (lesson extension):
Each student in the classroom will provide the teacher with ideas to relate different pictures contained in the text from appendix 2.</td></tr>
<tr><td>Instruction (what you need to tell the students)</td><td>Chose two of the images shown by the teacher to explain concepts you have learnt in this unit related to Tesla batteries.</td></tr>
<tr><td colspan="2">for the Tools activity (everything you need to take to the classroom)</td><td>Any programme of visual presentations/ppt, prezi etc. - computer and overhead projector.</td></tr>
<tr><td colspan="2">Estimated time (max. 40 min.)</td><td>20 minutes</td></tr>
<tr><td colspan="2">Notes</td><td>Resources: Step ahead material
Step 3 of the reflection part does not necessarily need to be taken on the lesson. It can be skipped and the lesson can end with Step 2.</td></tr>
</table>

APPENDIX 1 - 3

Tesla Electric Vehicles Batteries

(Source 2019-11-15 https://es.m.wikipedia.org/wiki/Archivo:Tesla_Model_S_(Facelift_ab_04-2016)_trimmed.jpg)

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APPENDIX 1

Tesla Batteries

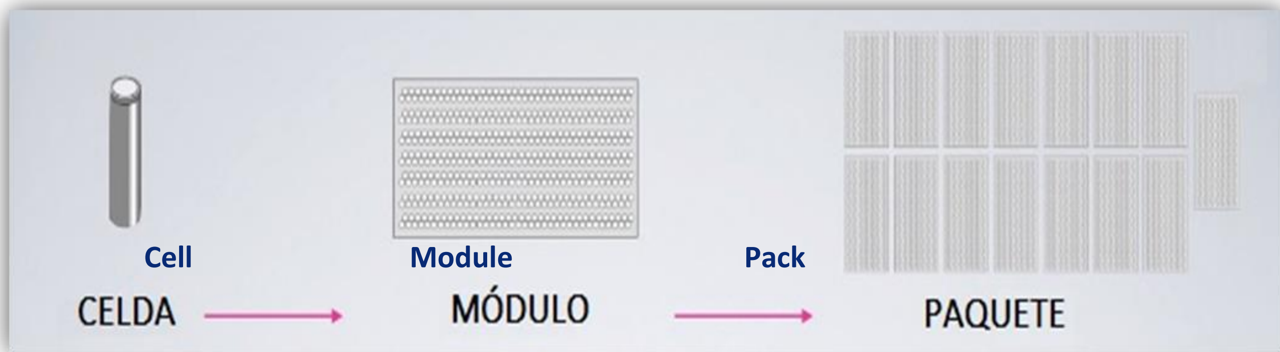
Introduction

Tesla is a North American company situated in Silicon Valley (California), under the leadership of Elon Musk who designs, manufactures and sells electric vehicles.

Tesla was founded to speed the transition towards sustainable transport with the aim to fight global warming and reduce the deaths caused by pollution.

The company core is focused on the electric vehicle propulsion system engineering, which includes: battery packs, engine, power electronics and control software.

In this teaching unit we are going to focus on the battery pack, learning about the three parts it is composed by. We will explore the chemistry and the cells format. We will also have a look at the modules pack model, as well as their design. To finish we will focus on how these battery packs are assembled.



Tesla claims they have the battery with the highest energy density in the market, but also de lowest cost per kilowatt/hour (from now on, kwh).

To test to which extent this is true, we will explain the different parts of a Tesla battery, as well as its characteristics and its functioning.

Cells

For a start we will talk about cells, which is the main component of these batteries.

Types

Cells can be found in three different formats: cylindrical, prismatic and cartridge cells.

Cylindrical cells. Tesla Model S

Cylindrical cells

These cells are made by winding up the electrodes materials and inserting them on a aluminium cylindrical capsule.

Cylindrical cells are the cheapest option, compared to those prismatic or cartridge cells, because they can be manufactured in huge quantities in standard sizes.

As there are several companies manufacturing this type of cell with a standard size from the very first moment of lithium-Ion batteries commercial application (in 1991 by Sony company) the manufacturing process and the internal design of those cells have been highly optimized. This greatly improved design reduces the non-active components, that is, those which do not directly combine energy storage with reduction of space which is not used to store it. That is why, cylindrical cells usually have the highest volumetric power density.

Nevertheless, not everything is positive, as these cells are very difficult to cool and this problem means a reduction in efficiency and a shortening in the cell life. Moreover, cylindrical cells have a further inconvenience, which is, geometrically speaking, cylindrical cells are not ideally packed in battery modules with cuboidal shapes.

Prismatic cells

They can be presented with several settings. However, automotive prismatic cells have cuboidal shapes to fit better within the module.

94Ah and 37Ah Samsung prismatic cells

Internally they have a quantity of windings similar to those of cylindrical cells which are compressed afterwards to fit the cell inner volume. Prismatic cells can present a certain design complexity for their manufacturer, but they make things easy for the car assembler as they adapt easily to modules, and they are relatively easy to cool thanks to their geometry, whether internal or external, which helps to heat transfer. Manufacturers such as BMW assemble them in highly automated batteries in models such as i3.

Although bigger size cell terminals help to reduce resistance and allow a greater heat transfer, both add moisture content, which at the same time reduces the energy density in cells. In addition, as we are compressing the cylinders around two electrodes, the compression is not the same at all points. This implies some problems with the lifespan after repeated charging and discharging cycles.

Prismatic cells also tend to offer high capacity to keep non-active material at a minimum. That is why BMW i3 from 2016 uses 94Ah prismatic cells or Volkswagen e-Golf from 2017 assembles 37Ah prismatic cells. These data stand out if we compare them with the 3.4 Ah prismatic cells used by Tesla. All this situation limits the final capacity of manufacturers to offer battery packs in different sizes.

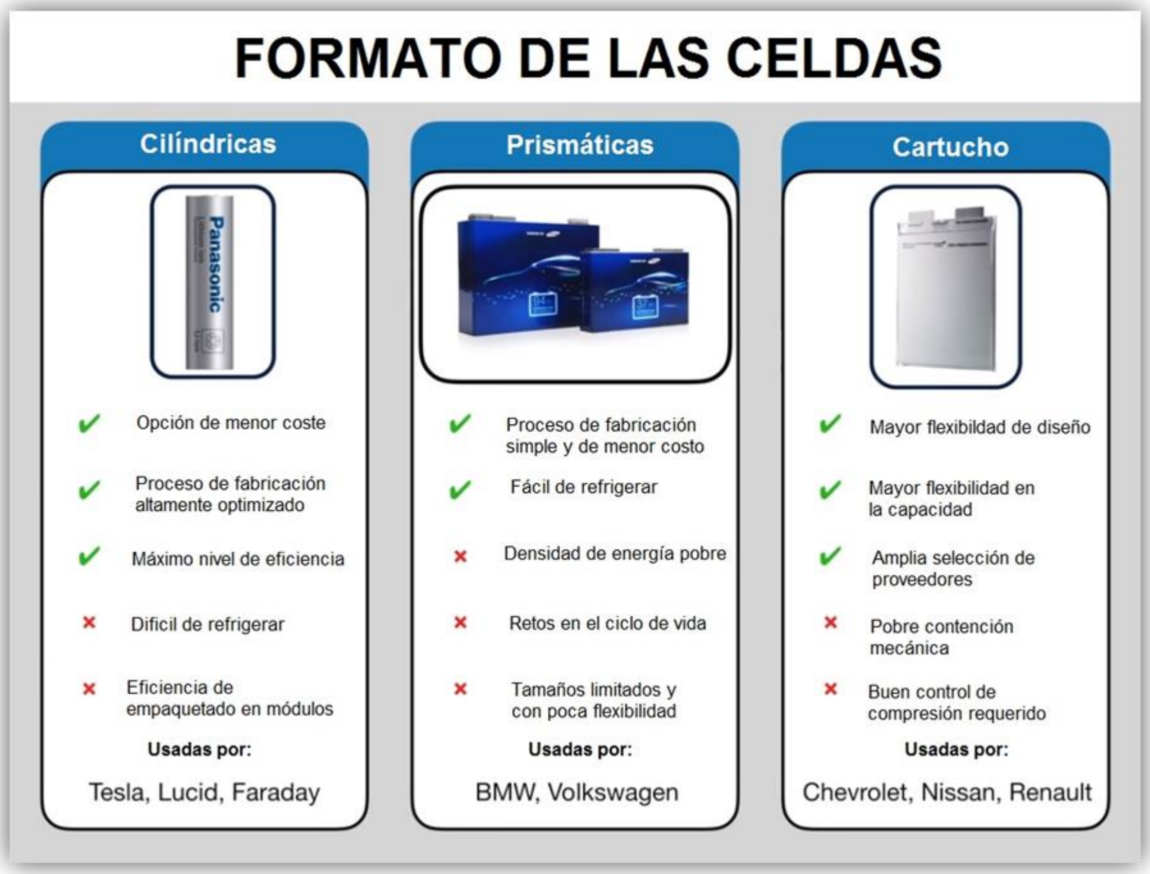
Cartridge cells

These cells use stacked electrodes and separators which are afterwards inserted in a polymer sheeting.

Cartridge Cell

Cartridge cells offer a maximum flexibility in their design, as they can usually be scaled to different sizes and the manufacturer can easily modify their capacity, by adding or removing layers.

An important number of battery manufacturers offer this type of cells because their gravimetric energy density is very competitive if compared to cylindrical cells. Gravimetric energy is the quantity of energy stored in a battery per kilo. This means, the higher this value, the higher capacity, autonomy and power we get. It can also be said that in a battery with the same capacity we get a lower weight and that is very important as well.



The main disadvantage of this type of cells is that they are much more complex to get them integrated in modules. Their cooling process also needs a very careful control.

Which type of cells does Tesla use?

Tesla Model S.

Tesla uses **cylindrical cells**, and the question is, why did they decide to assemble them in the battery pack of Model S? The answer is easy.

Cylindrical cells offered the greater energy density per cell. It should also be highlighted that at that time cylindrical cells were manufactured in huge quantities for the portable electronics. This meant that those cells had a lower price per kwh, which implied a reduction of the initial capital investment, something essential for a new company with a limited capital available.

Since the cost of these cells is still the lowest of the three formats, these are still used in Tesla new models such as Model 3 or even today at the mega-factory.

Before Model S was released big battery packs were used to produce an enormous quantity of energy. However, they were very expensive and they needed electric cars to be more reachable for most customers.

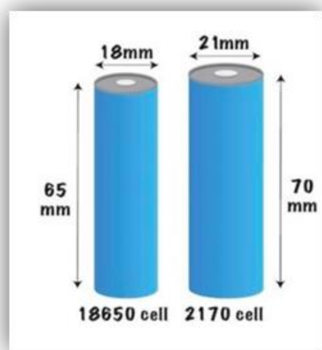
To produce a battery pack extendable to multiple capacities, it is necessary to have small capacity cells, and connect a great number of those cells connected in parallel.

BMW i3 with 94 Ah prismatic cells

Let's consider BMW i3 for example. This car uses very big prismatic cells by Samsung, all of them connected in series to build a 33kwh battery pack. To offer a 45kwh it is not possible to simply add cells in series because the voltage would change. So, the Battery Management System (BMS) and the inverter should be changed as well. However, if we add a chain of cells connected in parallel, we are doubling the number of cells, which will result in an increase capacity of the pack to reach 66 kwh, although this will be impossible to fit within the car chassis.

When we use small capacity cells and change the number of cells connected in parallel, Tesla gets greater flexibility: the 100kwh battery pack includes 96 cells connected in series and 86 in parallel, the 75kwh battery has 86 cells connected in series and 63 in parallel.

Among cylindrical cells used by Tesla there are two types: 18 650 type, used in models like *Model S and Model X*; and the 21 700 model, used in *Model 3*. Both types are manufactured by Panasonic.



Cells size 18 650 and 21 700.

18 650 cells have this name because their diameter is 18 mm and are 65mm long. The same way, 21 700 cells have a diameter of 21mm and are 70mm long. This additional length, apart from the bigger diameter, offers an increase of 33% of active material to store energy within the cell.

A 18 650 cell has a capacity of 3,4Ah or 12,4Wh and a nominal voltage of 3,66V. The resistance changes with the battery's state of charge and with its temperature, although in general it is over 30mΩ.

Giving a cell a volume of 16mL and a mass of 49gr, the cell reaches the impressive energy density of 254Wh per Kg or 755Wh por L.

NCA cell composition

If we have a look inside a 18 6500 cell, we can observe the different layers of the battery, which has a cathode composed by 80% nickel (Ni), 15% cobalt (Co), approximately 4% aluminium (Al) and less than 1% lithium (Li). On the other hand, the anode composition includes graphite although there is a tendency to replace it with silicon. The electrolyte is a solution of Li and the rest of components are made of Al and copper (from now on Cu).

Both, the anode and the cathode are two rolled sheets meant to occupy the shortest possible volume. Tesla calls it *Jelly Roll*.

On the positive terminal side, there is a compound made of carbon fibre which keeps the Jelly Roll placed. The fact that it is made of carbon fibre is to reduce the cell weight in a small proportion. When considering a huge number of cells, as we find in a complete battery pack, the weight loss is important helping to improve the battery energy density.

The positive terminal also has three ventilation openings, which help to free pression when there is a change in altitude or when there is an inner error in the cell. It also has an O ring to ensure sealing.

If we would unwind the *Jelly Roll*, we would be able to observe the anode and cathode sheets previously mentioned, separated by another plastic sheet which used as insulator between them. Their measures are approximately 1 m long and 60 mm wide.

We should underline that the Li sheet is the one containing the potential of the batteries, but it also arises a problem, as it is highly inflammable. To solve this issue, some manufacturers use a flame retardant between the layers. This causes another inconvenience, as it increases the non-active material within the cell, just the opposite effect Tesla is looking for, together with Panasonic, as they focus their research in manufacturing these sheets as thin as possible keeping their capacity to store energy with materials such as graphene.

Keeping up with the chemistry within the cell, we should mention that main manufacturers are nowadays using cobalt oxide cathodes and nickel- manganese or NMC

Tesla, however, uses LiNixCoxAlxO2 cells, as we have previously said, also called NCA. These are similar to NMC cells but they use Al instead of manganese to stabilize the crystalline structure of the Li oxide.

NCA cells have a greater energy capacity, however, these will cause thermal exhaust at a lower temperature. That is why they are considered appropriate for small 6A cells as maximum power. This explains why vehicles such as Nissan Leaf, Renault Zoe or BMW i3 use NMC.

As we have previously mentioned, the anode in almost of Li-ion batteries is made of graphite, but they are willing to change it to Si, because of their greater storage capacity.

In each new cell generation, Tesla has increased the quantity of Si in the anode, which ensures that 21 700 cells for Model 3 will have a bigger quantity of Si than the current 18 650.

APPENDIX 2

Tesla Electric Vehicles Batteries

Modules

Tesla 18 650 cells of Lithium-Ion are inserted in the battery pack. Modules themselves are from different sizes, as their configuration in parallel changes for different capacity battery packs which are available.

Tesla first generation battery packs, as those we find in 85 and 90 kwh batteries had 15 modules. Second generation packs introduced with Model S facelift have 16 modules.

Then, what is a battery module and what it is used for? Why are not cells directly placed in a battery pack?

One of the main reasons is the manufacturability. In a Tesla 100kwh battery pack, there are more than 8.000 cells, which means there are approximately 16.000 electric cells connections, which are divided in approximately 1.000 per module, which is finally a more manageable task.

Another key reason to use modules is safety while manufacturing them. The 85kwh module of Tesla pack has a configuration of 6s 74P, which means it has 6 groups connected in series and 74 cells connected in parallel per module. On the whole, that would be 444 cells per module. This produces a voltage of approximately 23,4V.

According to IEC 60038 rule, any device under 120 volts continuous stream (from now on DC) will be considered to cause a low risk electric shock through the dry skin of a person.

An additional reason for the use of modules is that they work as firewalls. In case one of the cells have a fault or in case of a car crash, if only one cell gets on fire, the number of cells exposed to the fire is lower and as a consequence, the seriousness of fire is reduced.

Moreover, from a service capability perspective, if there is an error for any reason in one cell, it is better to replace a module instead of a complete battery pack.

Nowadays there are three Tesla battery modules in the market.

1- The most extended and known model which is assembled in *Model S* and *Model X.* This has been updated and developed along the years.

2- The module Tesla assembles in its Power Packs (Batteries for industrial energy supply) which was the beginning of the transition between 18 650 cells and 21 700 cells. In addition, this uses a cooling system in the base of each module instead of cooling using pipes between cells, which reduces cost and complexity.

3- The Tesla Model 3 module. There is not much information about this module, we just know that it is longer than those modules used in *Model S* and *Model X*. It uses 21 700 cells the same as Power Packs. It has a refined thermal management system and they join the positive terminal and the negative terminal on the same side of the cell instead of using opposite sides.

Hereafter we will focus on the Model S and Model X modules.

Image Source (15 November 2019):
http://skie.net/skynet/projects/tesla/view_post/20_Pics+and+Info%3A+Inside+the+Tesla+100kWh+Battery+Pack

This image represents the top view and bottom view of a 100kwh battery pack module belonging to a Model S 100D.

In the top view, we can appreciate that it is divided in four segments. Meanwhile in the bottom view we can only observe the division into three segments.

Each segment of the module connects 86 terminals from positive cells in parallel with 86 terminals of negative cells also in parallel. It included a connection in series between both of them, with the exception of the segments connecting orange terminals that can be observed at the top of the image.

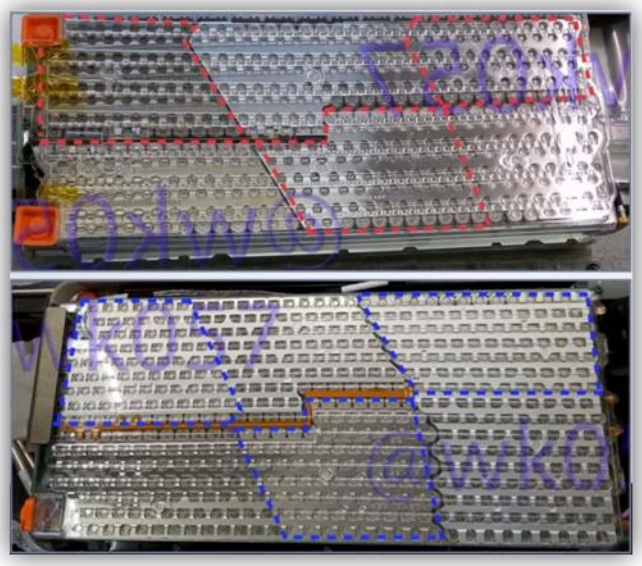


Image Source (15 November 2019):
http://skie.net/skynet/projects/tesla/view_post/20_Pics+and+Info%3A+Inside+the+Tesla+100kWh+Battery+Pack

In the top view, the red segments show where the connections with the positive terminal are made. We can see the placement of the negative terminals in blue in the bottom view. The adjacent segments have opposite polarity.

Cells Electrical connection to Bus Bar.

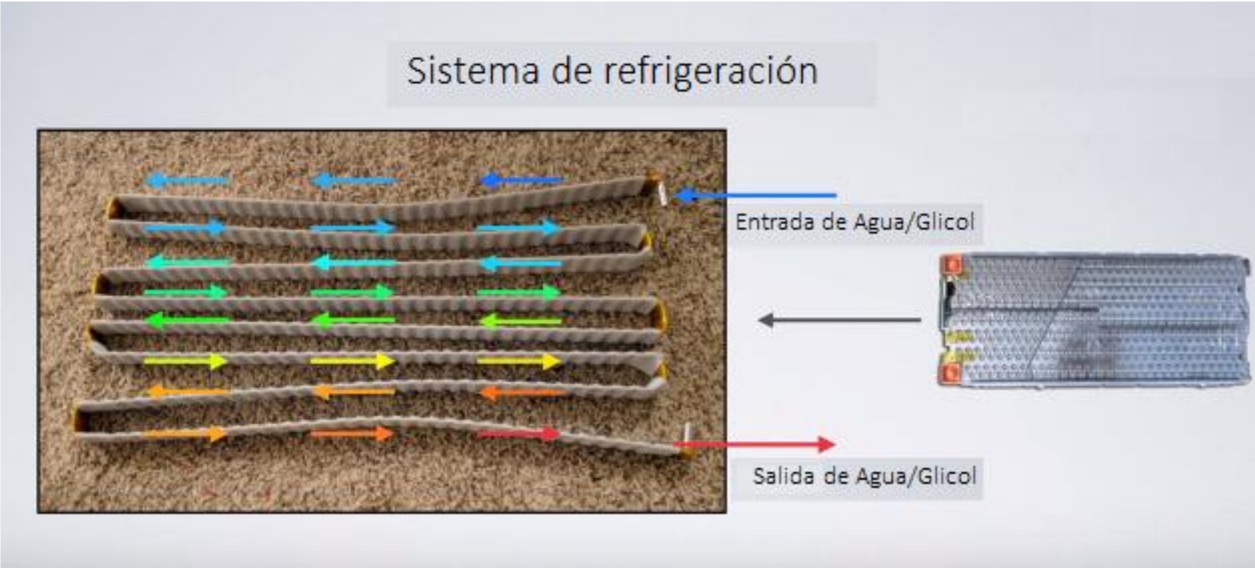
Tesla used wire connections to connect electrically cells to the Bus Bar. Although this method increases resistance, which reduces the operative efficiency and increases heat, it has a number of advantages. During the connection process no significant heat is generated in the cell, the connection using a wire also works as a fuse, and if the connection has a fault for any reason, it is not very likely that the cell is damaged, which reduces the number of cells wasted while being manufactured.

A 100 kWh module has 516 cells so it requires 1.032 wire connections. If this process was 99,9% effective, an error per module would be possible, which means the manufacturing capacity is the key.

The voltage can be calculated multiplying the minimum voltage, each cell nominal and maximum by the number of cells connected in series. This module, of a 100kwh pack is 6s 86P with a minimum voltage of 2,5 V, nominal voltage 3,6 V and maximum voltage 4,2 V. Acknowledging this we know that this module has a nominal voltage of 21,6 V.

To calculate the stored energy in a module, we multiply the cell capacity by the nominal voltage of that module and by the number of cells connected in parallel. Tesla cells have a capacity of 3,4A, the nominal voltage for this module is 21,6 V and as it is 6s 86P we have 86 cells connected in parallel, so we can say that this module stores 6,3 kWh of energy.

In the image we can observe the cooling pipes inside the module. This thermal management system consists of a metal pipe, flat on the most of its surface and straight, it crosses the module following zig-zag patterns. This pipe is covered by grey colour heat insulating material which provides electrical insulation between the cooling system and the battery cells. At the same time it causes a certain level of heat transfer



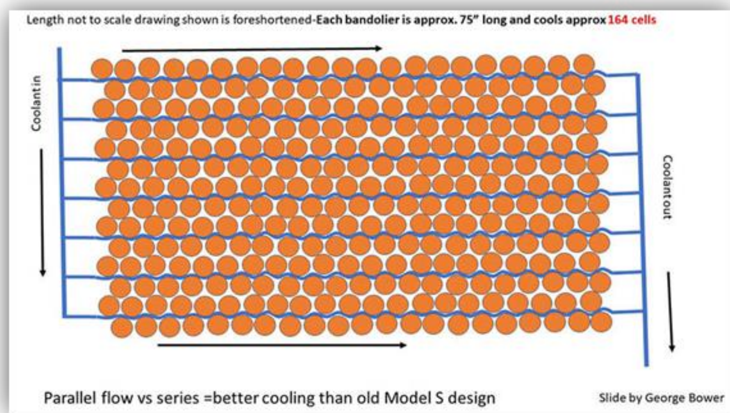
As we can see in the bending of the pipe, it is there where the connection between the cells and itself happens.

The orange tape we can observe in the image is the so-called Captain Tape in the US and provides additional electrical insulation.

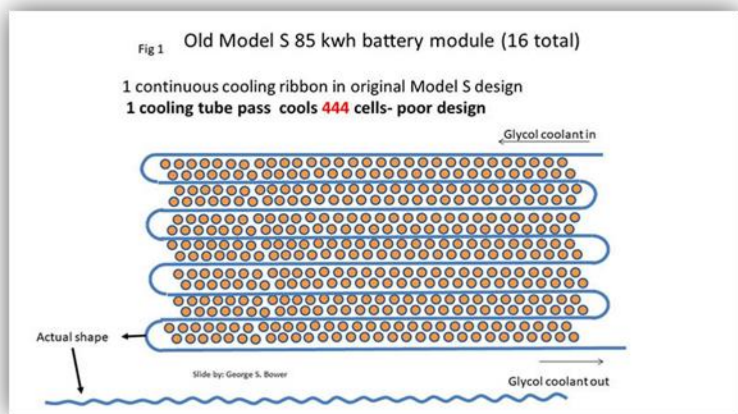
A water and glycol solution is introduced through the opening which goes across the cooling pipe to be discharged at the end of the module.

This is the cooling system used in Model S and in Model X, although Tesla made a major progress for Model 3.

Tesla managed to almost double the cooling capacity of the Thermal Management System (TMS) with a new pipe design which reduces the number of cells per each cooling pipe, adding more of these in parallel, and doubling the cooling fluid volume.



Tesla Model S and Model X TMS

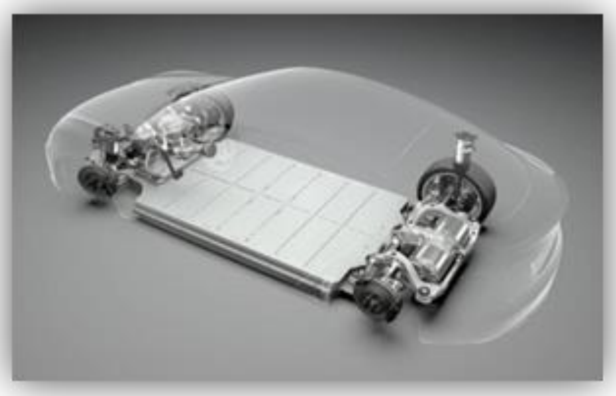


Tesla Model 3.TMS

APPENDIX 3

Tesla Electric Vehicles Batteries

Packs



Paquete de baterías Model 3.

Distinct from the cell and the module, the battery pack is an intelligent device which can be controlled by the Battery Management System (BMS) to maximize the performance, to guarantee a safe functioning and to adapt the output to avoid excessive degradation of its performance capacity in the long run.

Cells became modules by adding mechanical frames, Bus Bars, the cooling interface and a sensor harness. Each of these elements has an additional support to transform modules into intelligent and safe battery packs.

Modules mechanical frames are interconnected with the mechanical structure of the battery. This structure must hold a battery pack of more of 600 kg. This provides enough rigidity and resistance for the rest of the car, improving the driving dynamics and its safety in case of a car crash.

Modules are electrically connected by high voltage Bus Bars, in addition to a thermal connection by means of the cooling system with the combination of rigid and flexible pipes.

The sensors harness is in charge of powering BMS, which works as a controller for the battery system to maximise its performance and safety.

Moreover, the battery includes fuses to avoid an excessive power surge, a contact to turn on and off the battery from the rest of the vehicle, and an input-Output I/O connector to connect electrically and thermally the battery to the car.

Model S and X 100kwh battery pack has an absolute energy capacity of 102,4kWh. Its type 18 650 8.256 cells are arranged in a 96s 86P configuration with a nominal voltage of approximately 400V.

The weight of the battery is 641kg, which offers a gravimetric energy density of 182,5W*kg. This means 63% of the battery is the mass corresponding to the cells.

Energy capacity is calculated by multiplying the cell capacity by the pack nominal voltage and the number of cells connected in parallel.

$$E = Capacidad\ de\ la\ celda\ \times Vnominal\ paquete\ \times Celdas\ en\ Paralelo$$
$$E = 3{,}4Ah \times 400V \times 86P = 116.9kWh$$

The gravimetric energy density of the battery is calculated by dividing the energy capacity by the battery mass.

$$DEG = \frac{E}{masa\ de\ la\ batería} = \frac{116.9kWh}{641kg} = 182{,}5W*kg$$

As we know the definite mass for each cell, we can also conclude that the battery has an approximate weight of 404 kg, therefore, 237 kg of the battery are components which are not cells

$$Masa\ total\ de\ las\ celdas = (96s * 86P) * 49g = 404{,}5kg$$

$$\frac{404{,}5kg}{641kg} = 0{,}63 = 63\%$$

The maximum power Tesla can get from its battery is 567kwh. The power output of our battery is affected by our voltage, which is defined by the voltage in a cell by the number of these cells connected in series, the maximum electric current of the cell and by the battery resistance.

The alfa power ($P\alpha$) is simply the battery voltage multiplied by the intensity of its electric current

$P\alpha = V * I$

The voltage of the battery (V) when it is producing energy will be lower than when the circuit is open (Vca). That difference is also known as delta voltage ($V\delta$).

$V = Vca - V\delta$

$V\delta$ is calculated by multiplying the maximum intensity of the combined cells by the resistance of the battery.

$V\delta = I * R$

Therefore, to calculate the maximum power of a battery first we have to know its resistance.

Cells resistance is very much affected by factors such a change in its state, the temperature of the discharging speed. To simplify it we will use a number for a discharge of 10 seconds of 1 C to 25ºC. The resistance of an individual cell would be approximately 30mΩ.

The resistance of the wire link (Rec) which connects cells with Bus Bar is approximately 1mΩ per union. Each Bus Bar has an approximate resistance of 0,1mΩ to room temperature.

The resistance of a series (R-series) is, therefore, the cell resistance (R-cell) plus the double of the wire link resistance, since there would be a union in the positive terminal as well as in the negative terminal. All this has to be divided by the number of cells connected in parallel.

R-series = R-cell+ (2*Rec) / number of cells in parallel

R-series = 30mΩ + (2*1mΩ) / 86 = 0,372mΩ

The resistance of the module (R-module) is the resistance of the series plus half resistance of the Bus Bar, all of it multiplied by the number of cells in series within the module, we previously mentioned modules were 6.

R-module = (R-serie + (R del Bus bar/2)) * number of cells in series

R-module = (0,372mΩ + (0,1mΩ / 2)) * 6 = 2,53mΩ

in addition to the resistance of the module, we can also observe the resistance of the high voltage Bus Bar which is connecting modules.

It would be approximately 0,02mΩ.

The resistance of the high voltage connection is 0,20mΩ.

The fuse resistance is 0,23mΩ.

The shunt resistance allows BMS to measure the pack current intensity which is 0,05mΩ and the high voltage connector resistance which is 0,2mΩ.

Therefore, the total resistance of the pack is calculated as the module resistance (R-module) multiplied by the number of modules in series (Ms), plus the resistance of the high voltage Bus Bar by the number of modules in series minus the intensity of these, plus the resistance of the connector (R-ct), plus the fuse resistance (R-fus), plus the shunt resistance (R-sh) and plus the HV connector resistance (RCHV)

RT = (R-module * Ms) + (R de HV Bus Bar *(Ms - I)) + Rct + Rfus + Rsh + RCHV

This gives us as a result the resistance of the pack, 41,8mΩ.

The cells resistance represents approximately 80% of the total resistance of the battery.

With this information we can deduce that with a maximum output power of 567kW, the intensity of our battery pack will be from 1.800A to 2.000A depending on the charging state and the cell temperature.

The result of this is a cell current intensity of about 21A to 23A, which is equivalent to 6,2C to 6,7C per cell like a short term power peak

Hereafter we will have a look at the structure of a battery pack:

Mechanical structure of a battery pack

The mechanical structure of a pack holds more than 600 kg of the battery plus the fact of being the base to support the rest of the vehicle structure. It has been designed to provide enough rigidity, to allow the car to have a nice, driving dynamics and to pass the Crash Tests.

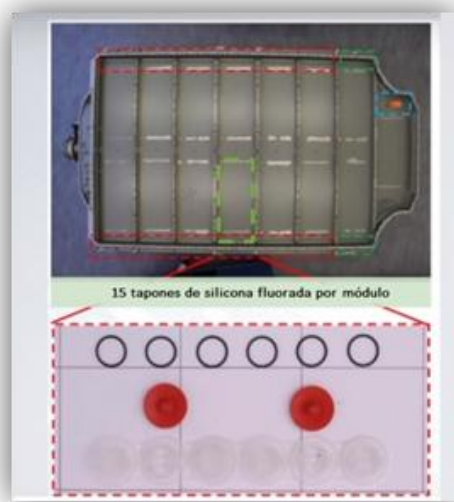
Thicker longitudinal crossbars increase resistance to lateral impacts and the longitudinal bending. Meanwhile the other crossbars provide additional torsion rigidity and also resistance of lateral impact. Tesla also used internal sections to physically separate each module, which is useful to prevent the spread of fire in case of fault.

The results in a test done in 2015 showed what happens to a cell when it is pierced by nails and when it is kept at high temperatures for long periods of time. Considering US requirements, the results shown that fire is possible, so it is important to design a strategy to extinguish battery fires.

Celda perforada

Celda sometida a alta temperatura

Let’s see how this strategy goes:



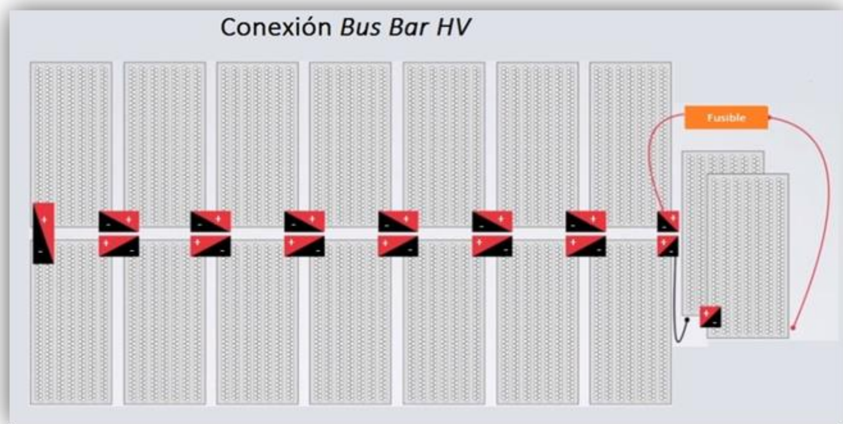
Physical separation between modules (upper part) and the fluoridated silicon plugs (lower part).

Starting with the modules, they are separated by mica layers which are placed around the module to provide electric insulation among these. These sheets are also very stable till they reach temperatures of about 900ºC, therefore, in case of an error within a cell it won’t immediately decomposed and it will keep an ideal electric insulation from module to module.

Modules are also separated on its upper side and lower side by metal sheets which keep the battery assembled. Moreover, it has an insulation layer 9,3mm thick which avoids the heat getting into the compartment.

If there is any error in a cell gas pressure will be generated, that is why it is important to have good ventilation within the pack. Since each module is physically separated, each of them should have their own ventilation openings. Except those two modules on the front part which are stacked one over another and share their ventilation ports.

For these openings, fluorated silicon plugs are used, because they allow a good sealing of the battery as they do not degrade as they get older. When there is a presence of hot gases, these decomposed easily allowing the flow through the openings.



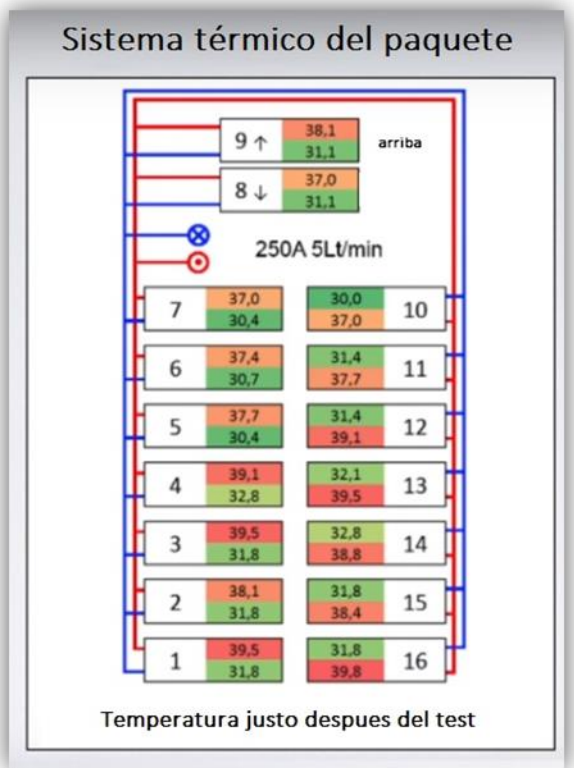
High Voltage Bus Bars connect 16 modules in series as we can observe in the image, the red part is the positive terminal and the black one the negative.

These Bus Bars are made of tin, they have a transversal section of 75mm2, longer than the ones used to match together the stacked front modules, which are connected through the main fuse.
To finish with the packs, we will deal with its cooling system.

Results of different tests made by AVL show that the 100kwh battery pack provides good information about the cooling system.

The test consisted of repeated cycles of charging and discharging of 250A till the moment a stable temperature was reached. The test started at 20ºC with a coolant flow of 5L/m.

In the following diagram the cold side of the coolant flow is shown in blue and the hot one in red.



The coolant is divided from the very beginning to provide service to the 16 modules in parallel. The hot side in each module is connected in parallel to the hot output of the battery. Each module has two NTC sensors, which allow to measure the temperature of the coolant when going into the circuit and when getting out of it.

It is important to minimize the temperature changes in each cell, as the hotter they get, the sooner they degrade.

We can see in the image that under the conditions previously mentioned there are important temperature differences, reaching 8 degrees of difference between the entry and exit points as we can see in module 16. Moreover, there are almost 10 degrees temperature difference on the whole pack.

This temperature difference in modules arises because of the way in which the coolant circulates between cells. As it is an “s” shape movement it gets hotter and hotter till it goes out. As we have previously seen the cooling process in modules, Tesla has already started to replace this cooling system used in Model S and X, with a new one they are using in Model 3.

Conclusion

21 700 cells are the future in the short run for Tesla cells. The company will stop manufacturing 18 650 cells. They are already working on it for next Model 3 and Power Wall. According to Elon Musk, from Tesla, they will be cheaper and with a greater energy density, the greatest all over the world.

Tesla has relied on these battery formats, just the contrary as other traditional manufacturers have done. The intention of the Californian brand is to reduce costs with this type of cell. No doubt, they have already got the honour to be leading the sector of 100% electric vehicles.

The technology of Tesla batteries will be remembered as a key technological development in history, completely transforming automotive industry and that in just 5 years since it was released with the initial researches of Model S has proved that the lifespan and performance of the battery in real world is very efficient. And for sure, they will continue overcoming expectations.

The prospective for this technology is based in getting a battery ready to store a huge quantity of energy in a smaller space. The aim is to solve the main inconvenience of electric vehicles according to customers, that is, the autonomy and the charging time of these vehicles.

With current progresses in cells research, which show they are able to store more energy for longer periods of time, and with the possibilities opened by capacitors, it won't be long the moment in which we could see cars with an equal or superior autonomy to that of a combustion engine vehicles, and with faster charging times.

NOTES: