POLITECNICO DI TORINO

MSc in Nuclear Energy Engineering

Master Thesis

Fire Safety Analysis of Alternative Vehicles in Confined Spaces: A Study of Road Tunnels and Underground Parking Facilities

Professor: **Candidate:**

Prof. Papurello Davide **Leone Edoardo**

Academic Year 2022/2023

Acknowledgements

Summary

This final paper analyses the fire risks associated with electrically driven cars, and the comparison with hybrid and internal combustion vehicles. The paper is structured in two parts, the first of which is a literature analysis to describe the main types of cars circulating nowadays and consequently an analysis of batteries and their applications, with all their characteristics and risks, and ends with an in-depth study of thermal runaway and the cases of fire that have occurred in the past as well as the experiments carried out in this field. In the second part, the modelling of an electric or hybrid car fire using dedicated software is examined in depth, creating particular environments such as an underground car park and a tunnel, with the relevant parameters and evaluations.

Keywords

Bevs/icevs/phevs/hevs/li-ion/thermal runaway/ underground car park/galleries/fire/shutdown /sprinklers/FDS/CFD

Index

First part

Literature Review

1. Introduction

The paper begins with an overview of the automobile market and its key features, highlighting the growing importance of electric vehicles, and then goes into the details of storage systems, focusing on lithium-ion batteries, which are widely used in electric vehicles due to their high energy density and long lifespan.

Next, the paper analyses recent fire cases related to electric cars, exploring the causes and consequences of these incidents, and various real-world experiments that have been conducted to study the development of fires in electric vehicles, and analyses the results to gain a deeper understanding of the factors that contribute to these incidents.

Overall, the paper provides a comprehensive overview of the current state of the electric vehicle market, and explores the potential risks associated with lithium-ion battery-powered vehicles.

2. The car market

The development of electrically driven cars began around 1867, when a first prototype was presented at the Paris World Fair. In the following years, however, the market gave more space to internal combustion engines as petroleum products were considered to be cheaper and easier to distribute: as a result, a distribution network was created in step with the growth of the market, making this type of fuel easily accessible. It can also be observed that in history, the periods when research and development of electric vehicles returned to the forefront coincided with oil crises, at least until around 2010. In those years, due to the awareness of climate change, policies began to be implemented that aimed to lower harmful gas emissions, including those from transport by wheel. Thus, the world went from seeing very few electric cars on the market and only for niche sectors, to a booming electric car market in more recent years.

In particular, the European Community, in order to reduce its dependence on petroleum products (which currently account for almost 84% of the energy sources used for transport) and to meet the Kyoto Protocol targets [1], has made it one of its goals to ban the registration of new thermal cars starting from 2035. This started a process of conversion of the European car fleet to electric cars and increased electrification, as the need for evenly distributed recharging points increases at the same time.

This significant development of the electricity sector today can also take place thanks to increasingly mature technologies in the field of electrical storage: the lithium-ion batteries used to date are the cheapest option between battery types, and have the highest energy density. The most important barriers to this process to date, especially as far as Italy is concerned, are consumers who are largely socially unprepared for the transition, the scarcity of recharging points which requires significant intervention on the electricity grid, the reduced autonomy of electric vehicles compared to thermal vehicles, and their high cost.

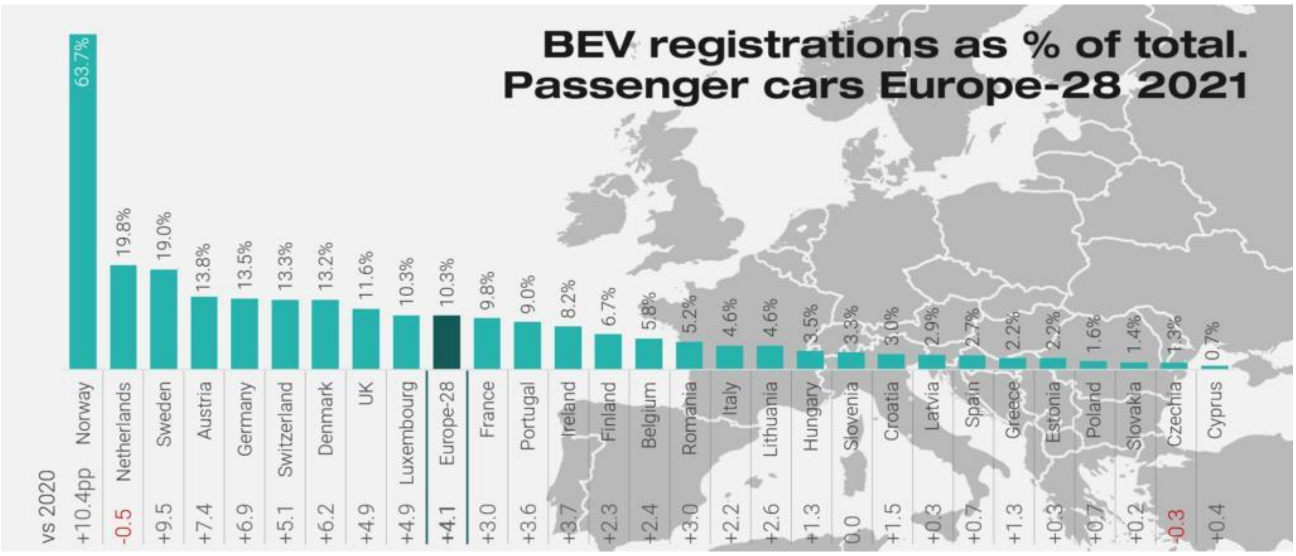

FIGURE 1 SALES OF ELECTRIC CARS IN EUROPE 2021, COMPARED TO THE PREVIOUS YEAR. [2]

A leading example for the European continent is Norway, where today electric vehicles account for more than 80% of new registrations and more than 470,000 units on the road, about 10% of the total. This is mainly due to strong government incentives to encourage zero-emission mobility; in fact, when buying an electric vehicle, Norwegians are exempt from import tax, vehicle registration tax and VAT on the purchase (25%), and also enjoy a 50% discount on motorway tolls and have access to fast lanes and other concessions in cities. [2]

This is followed in the European ranking by the Netherlands, with 19.8% of the market, and Sweden with 19%; as far as Italy is concerned, the percentage is significantly lower, at around 5%, and furthermore, there is an opposite trend to Norway with regard to the registration of plug-in hybrid vehicles, which is increasing sharply in our country. As reported by 'Bloomberg NEF', pure electric cars account for 71 per cent of sales in the electric segment in Norway, while the remaining 29 per cent are plug-in hybrids.[2]

Globally, too, there is a continuous increase in the spread of electric vehicles: according to the report compiled by Canalys in 2021, sales increased by 109% to a total of 6.5 million vehicles sold worldwide, which is particularly remarkable if one takes into account the crisis in chip production at the same time as the Covid19 pandemic. As of today, the European market leads with 19% of the total (2.3 million vehicles), followed by China in second place with 15% of the market and the United States in third place with 'only' 4%, pending more attractive cars for the American market scheduled for 2022/23. Another interesting fact concerns the vehicle manufacturer: TESLA makes about 30% of the sales, remaining the leader in all “electrified” countries. [3]

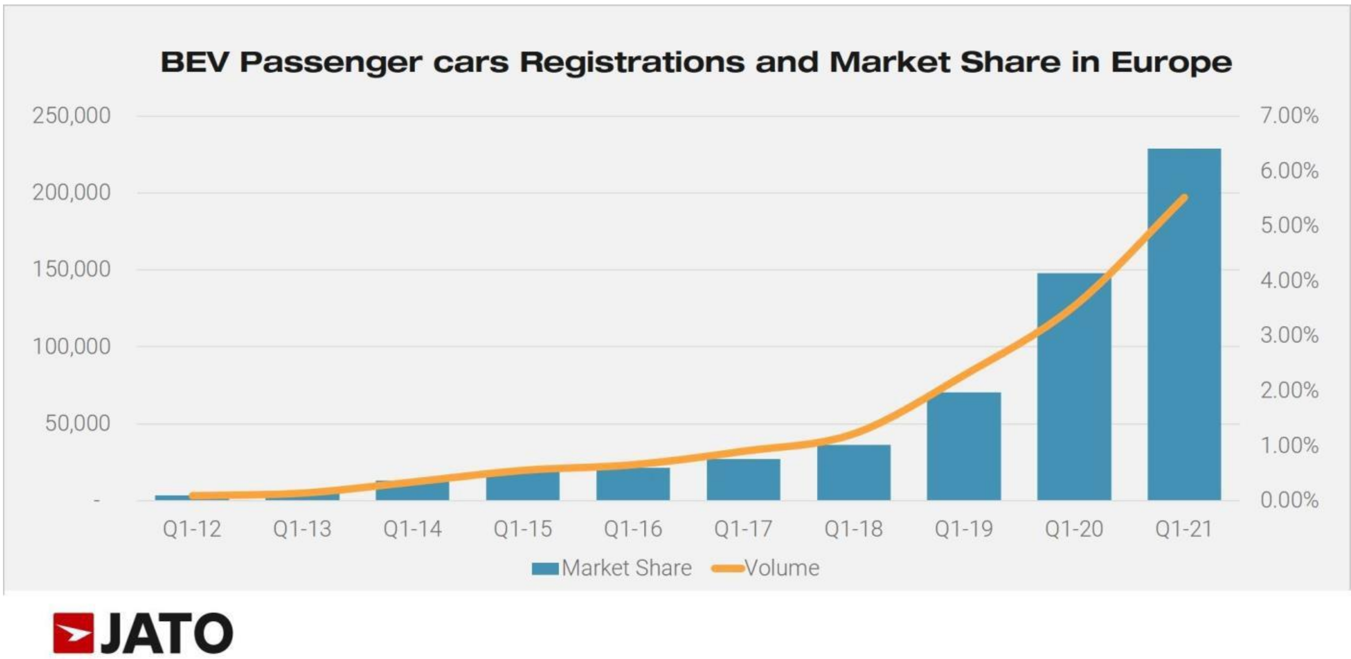

FIGURE 2 THE TREND OF FULLY ELECTRIC VEHICLE SALES IN THE FIRST QUARTER IN EUROPE, FROM 2012 TO 2021. [4]

3. Electric vehicle distinction

When it comes to vehicles, a distinction must first be made between the various types and how they operate. Today, most vehicles on the road are ICEVs (internal combustion engine vehicles), i.e., vehicles with an internal combustion engine, either an Otto cycle or a diesel cycle, depending on the type of fuel used. In general, EVs (electric vehicles) can be defined as all vehicles that use electric motors for traction, a definition that is used for all vehicles and not only for road transport.

Four main types of electric vehicles can then be identified:

- MHEVs (mild hybrid EVs)
- HEVs (hybrid EV)
- PHEVs (plug-in hybrid battery EV)
- BEVs (battery EV)

The first three listed types couple a heat engine and an electric motor in different ways: mild hybrids, literally 'light hybrids', turn out to be the first step towards electrification, as cars of this type are equipped with a small electric motor that is not directly connected to the traction, which has the function of helping the heat engine during acceleration and recovering energy during braking by acting as a generator. This saves about 10 per cent of fuel, but because of the small size of the electric components and the fact that they are connected in series with the heat engine, the vehicle can never travel in full electric mode.

The second type, full hybrid, was the first hybrid form adopted by the automotive industry: it is similar to the previous one but with more powerful motors and batteries that allow the vehicle to travel short distances with electric traction, state of charge and power requirements permitting. The third, more innovative type, combines the two systems, electric and conventional, in parallel, allowing more substantial distances to be travelled with the electric engine, and consequently, more powerful storage and motors. It also allows direct charging of the batteries, as shown in figure 3.

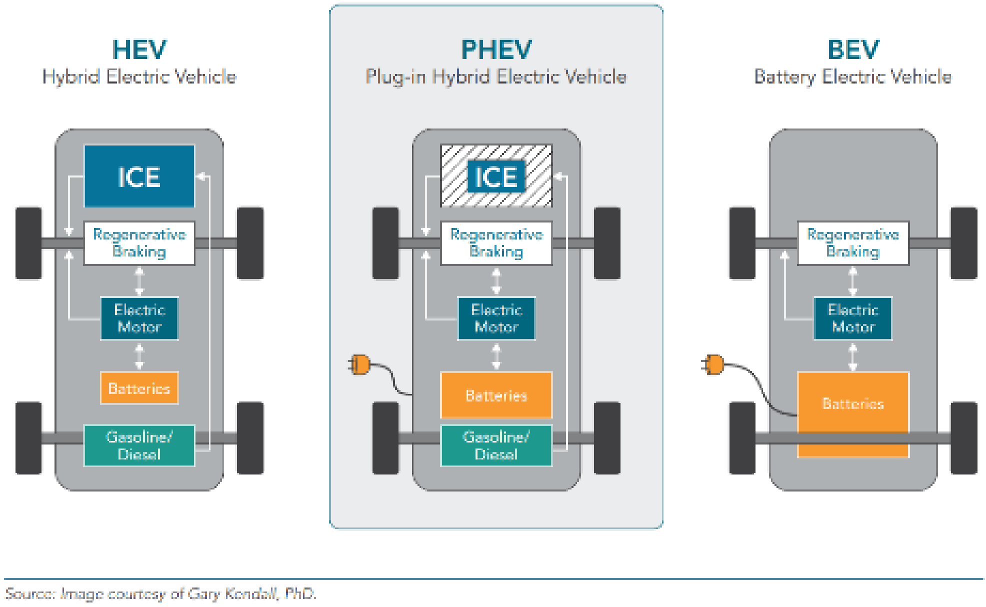

FIGURE 3 DIAGRAM OF OPERATION OF ELECTRIC VEHICLES [5]

Unlike the previous types, which still have an internal combustion engine in parallel or in series with the electric motor, BEVs are purely electrically driven vehicles with a storage system as the sole source of energy, usually consisting of lithium-ion battery packs also referred to as LIBs (Li-ion batteries), as analysed below.

3.1 Advantages BEV

Electric vehicles, compared to conventional thermal vehicles, offer considerable advantages, including:

- Higher yields: electric motors, even taking into account losses in the batteries, have a yield of 80/90% compared to the 30/40% typically achieved by internal combustion engines; the yield is evaluated by considering the power expressed (at the wheel) in relation to the potential of the fuel used, e.g., petrol or diesel.
- Possibility of expressing higher engine torque, resulting in considerable power already at low revs.
- As they have no internal combustion, these vehicles do not generate direct emissions, which is particularly relevant in areas of heavy vehicular traffic, such as the center of large cities.
- They require less maintenance as they have fewer moving parts.
- They are able to recover energy when braking and descending, thus exploiting a potential that is normally lost thermally with the brakes.

3.2 Disadvantages BEV

The disadvantages, however, cannot be ignored either. These include significantly longer charging times, charging points that are not yet present everywhere, and reduced autonomies; not to mention the disadvantages of possible overloads on the distribution line and the power available.

In addition, end-of-life (disposal, recycling or reuse) is considered a problematic point, as it is a complicated and not yet standardized process: disposal is one of the major causes of emissions over the life of an electric vehicle, so it would be desirable to make it more effective in order to further improve the ecological performance of these cars.

In fact, considering electric cars as environmentally friendly regardless is not correct, as comparing them with traditional cars, there are no big differences in total emissions, starting with those due to production, which are very similar and slightly lower for ICEVs as they do not have to obtain materials for the batteries; considering emissions during use, they are lower than for fossil fuel powered cars, but this is strongly influenced by the energy mix (how the electricity is generated) of the country in question; disposal is more complex and with more emissions for electric vehicles, not so much of greenhouse gases, but mainly of metals and toxic compounds.

As a consequence of the above, considering electric vehicles as environmentally friendly, or even 'zero emission' vehicles is formally wrong, since the specific situation of their use must be considered: it is estimated that they are more environmentally friendly if used for many kilometers and many years (battery life permitting). Moreover, at the moment replacing a latest-generation vehicle (e.g., of the 'euro 6' category) with an electric vehicle certainly leads to an increase in emissions, considering that in any case the ICEV will continue to be used or, should it even be disposed of, there would have to be a consideration of the emissions due to the production of the electric vehicle.

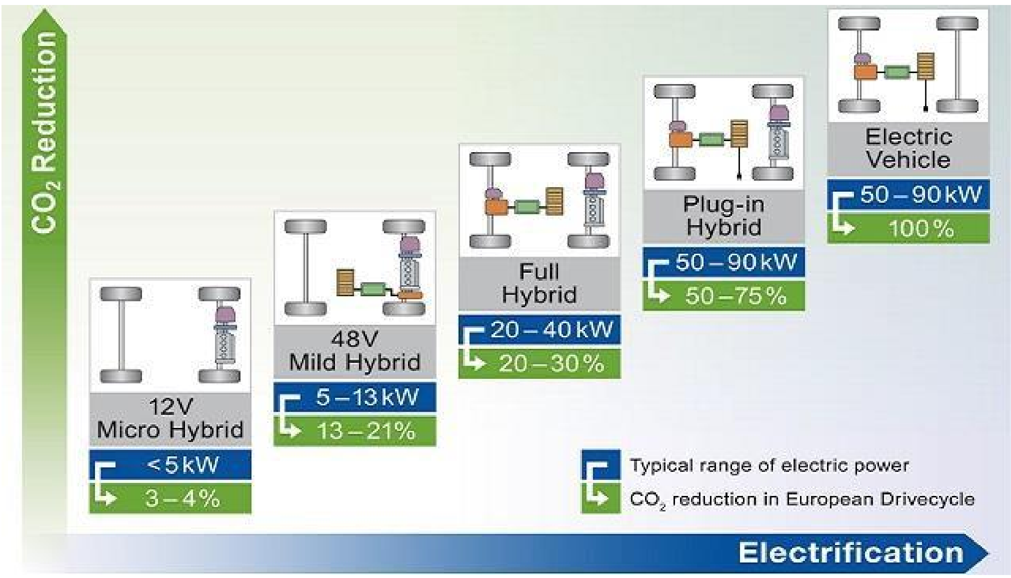

FIGURE 4 TYPES OF EV AND RELATIVE POWER AND EMISSIONS [6]

4. Batteries

The storage system can be considered the most important part for an electric car, being the only source of power, comparable to the function performed by a fuel tank for a thermal car. Storage takes place within one or more battery packs. Historically, nickel-cadmium (NiCd), nickel-metal hydride (NiMh) or lead-acid batteries have been used, but since they have low energy densities and charging and discharging times that are considered excessively long, the most commonly used solution today is the LIB (lithium-ion battery), which has a higher energy density, low price and greater reliability. This type of storage, however, has three main negative aspects: the use of rare earths, which are difficult to find and whose extraction is highly polluting; if damaged, it can release substances that are toxic to the environment, and above all it presents a greater risk of fire, as will be discussed in more detail below. This relatively young technology was invented in 1980 by J.B. Goodenough and commercialized by Sony in '91.[7]

The operation of the battery is based on oxidation-reduction reactions, which generate the movement of electrons, and thus current, and of lithium ions, which migrate to the cathode during the discharged state. In the course of the charge, due to the presence of an external source of energy, the opposite reactions take place, and the Li+ ions migrate to the anode through the electrolyte, and then find a position within the crystallographic structure of the anode material. The voltage is generated by the free energy difference between the lithium ions within the crystalline structure of the electrode materials.

4.1 Structure

Lithium-ion cells consist of four main components:

- Anode
- Cathode
- Electrolyte
- Separator

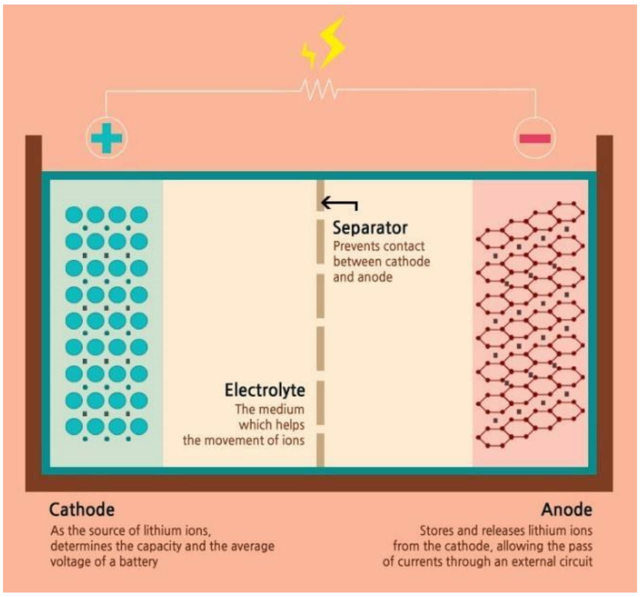

FIGURE 5 COMPONENTS OF THE LI-ION BATTERY [8]

4.1.1 Anode

The negative electrode of the cell, the anode, is the most expensive element of the system, and has direct consequences on the capacity and behavior over time of the battery. It consists of carbon-based materials, usually powdered graphite, deposited on a metal substrate, e.g. copper, and combined with a binding material. The nature of graphite can vary considerably starting from the source (natural or synthetic), as well as in the purity, size, porosity, compaction, and shape of the particles. [8]

Graphite can also be replaced by lithium-titanate, graphene, and anodes composed of silicon, germanium and titanate have also been tested, but are rarely used. The use of graphite has numerous advantages, including compatibility with a large number of cathode materials, a very low specific weight, high porosity that favours the intercalation of lithium ions, high reliability and low cost.

4.1.2 Cathode

The positive electrode is composed of metal oxide powders, which are also combined on a substrate with a binder. There are multiple compositions that characterize the chemistry of the battery, the most commonly used powders are composed of cobalt oxides (Co), but other metal oxides can also be found e.g: lithium manganese oxide ($LiMn_2O_4$), nickel cobalt aluminate ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, abbreviated NCA), nickel manganese cobalt ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ or NMC), lithium iron phosphate ($LiFePO_4$). [8] [9]

As with the anode, the characteristics may vary depending on the purity, size, porosity, compaction, shape or use of dopants in the particles.

In summary, the main commercial types of cathodes, compared in the following picture (Figure 6), are:

- **NMC** (NCM) – Lithium Nickel Cobalt Manganese Oxide ($LiNiCoMnO_2$)
- **LFP** – Lithium Iron Phosphate ($LiFePO_4$/C)
- **LNMO** – Lithium Nickel Manganese Spinel ($LiNi_{0.5}Mn_{1.5}O_4$)
- **NCA** – Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)
- **LMO** – Lithium Manganese Oxide ($LiMn_2O_4$)
- **LCO** – Lithium Cobalt Oxide ($LiCoO_2$).[10]

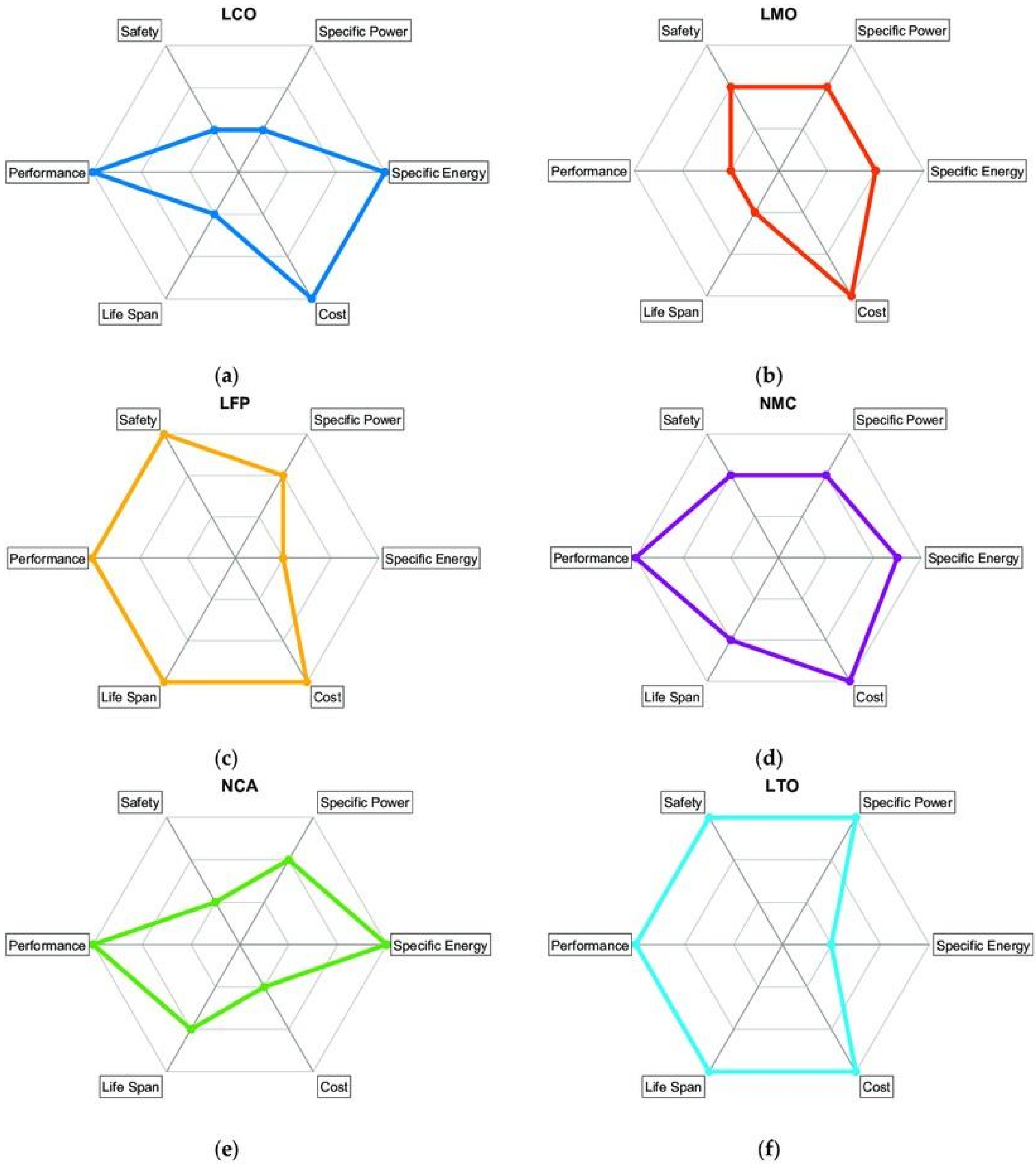

FIGURA 6 TYPES OF CATHODES AND THEIR CHARACTERISTICS: IT CAN BE SEEN THAT THE IDEAL CHARACTERISTICS ARE HARDLY EVER SATISFIED AT THE SAME TIME AND THAT AN ADEQUATE SPECIFIC ENERGY IS DIFFICULT TO ACHIEVE. IN THE CASE OF HIGH ENERGY DENSITIES THIS IS TO THE DETRIMENT OF ALL OTHER CHARACTERISTICS. THE MOST COMPREHENSIVE APPEARS TO BE THE NMC TECHNOLOGY [11].

4.1.3 Electrolyte

The electrolyte is a solid or liquid component that enables the transmission of lithium ions from the anode to the cathode and vice versa. It often consists of organic carbonates, for example a lithium salt dissolved (e.g. lithium hexafluorophosphate LiPF6) in an organic solvent or a mixture thereof. Other examples may be ethylene carbonate or diethyl carbonate. Often, the electrolyte is a moderately flammable compound and/or has toxic characteristics and could therefore cause thermal runaway if in unsafe working conditions: a serious problem that is analyzed below.[12]

The electrolyte is chosen by evaluating the working conditions of the battery pack, for example considering temperature: for low-temperature applications, a solution with a lower viscosity than a cell optimized for room-temperature applications is required; the properties of the electrolyte are adjusted with special additives to improve the characteristics in terms of capacity, service life, overcharge resistance, cycle life, cell stability and other useful aspects (such as the aforementioned viscosity by adding gelling agents).[12][13]

Electrolyte Component	CAS Registry Number	Molecular Formula	Melting Point[25]	Boiling Point[25]	Vapor pressure (torr)[26]	Flash Point[26]	Auto-Ignition Temperature[26]	Heat of Combustion[27]
Propylene Carbonate (PC)	108-32-7	$C_4H_6O_3$	-49°C -56°F	242°C 468°F	0.13 at 20°C	135°C 275°F	455°C 851°F	-20.1 kJ/ml -4.8 kcal/ml
Ethylene Carbonate (EC)	96-49-1	$C_3H_4O_3$	36°C 98°F	248°C 478°F	0.02 at 36°C	145°C 293°F	465°C 869°F	-17.2 kJ/ml -4.1 kcal/ml
Di-Methyl Carbonate (DMC)	616-38-6	$C_3H_6O_3$	2°C 36°F	91°C 195°F	18 at 21°C	18°C 64°F	458°C 856°F	-15.9 kJ/ml -3.8 kcal/ml
Diethyl Carbonate (DEC)	105-58-8	$C_5H_{10}O_3$	-43°C 45°F	126°C 259°F	10 at 24°C	25°C 77°F	445°C 833°F	-20.9 kJ/ml -5.0 kcal/ml
Ethyl methyl carbonate (EMC)	623-53-0	$C_4H_8O_3$	-14°C 6.8°F	107°C 225°F	27 at 25°C	25°C 77°F	440°C 824°F	None available

TABLE 1 MAIN TYPE OF ELECTROLYTES AND THEIR CHEMICAL PROPRIETIES [13]

4.1.4 Separator

The separator is required within a cell to physically divide the anode from the cathode to prevent an internal short circuit, but without inhibiting ionic conduction in the liquid electrolyte due to its porous structure. Separators for LIBs commonly consist of membranes of porous plastic materials (polyethylene, polypropylene, polypropylene composites or polyolefin) that are able to meet the electrical insulation and structural characteristics, with thicknesses ranging from 10 um to 40 um depending on the porosity, permeability, toughness and penetration resistance required to determine the desired cell properties. In order to maximize capacity and speed, thinner separators are preferred, thus putting more electrode material in the same volume; however, this entails greater risks of leakage and hence failure. [13]

Separators also have a safety role: they are designed to perform the electrical shutdown function (opening the circuit by breaking contact) in the event of battery overheating: as the plastic material heats up, it softens and expands, closing the pores and effectively blocking ionic diffusion into the electrolyte. This mechanism occurs at temperatures around 140° but cannot occur in the case of internal short circuits or the presence of contaminants that block the closing of pores. [13]

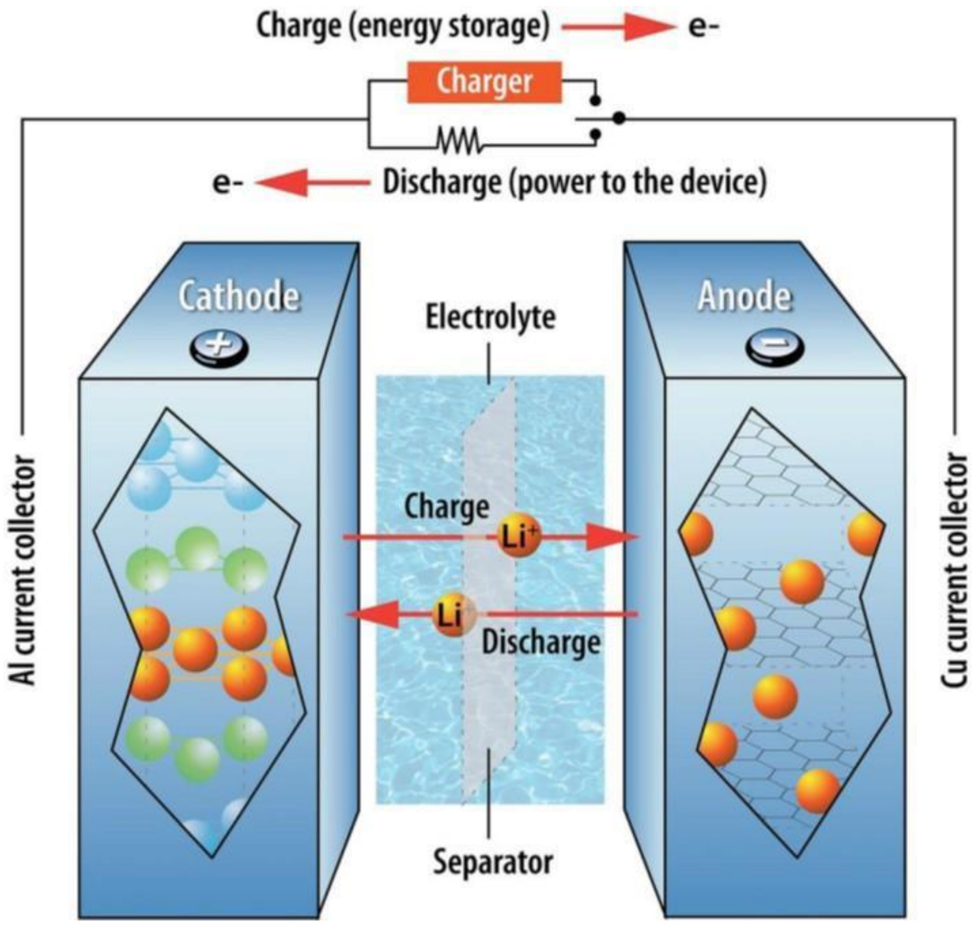

FIGURE 7 STRUCTURE OF AN ELECTROCHEMICAL CELL [14]

4.2 Operation

Lithium batteries are based on the reduction and oxidation reactions of the components, so-called redox reactions: the lithium ions contained within the electrolyte material (intercalated, because they infiltrate the crystalline structure), de-intercalate from the anode and position themselves in the cathode during the discharge phase (corresponding to utilization), oxidizing the anode and simultaneously reducing the cathode. During the charging phase, the process is the opposite.

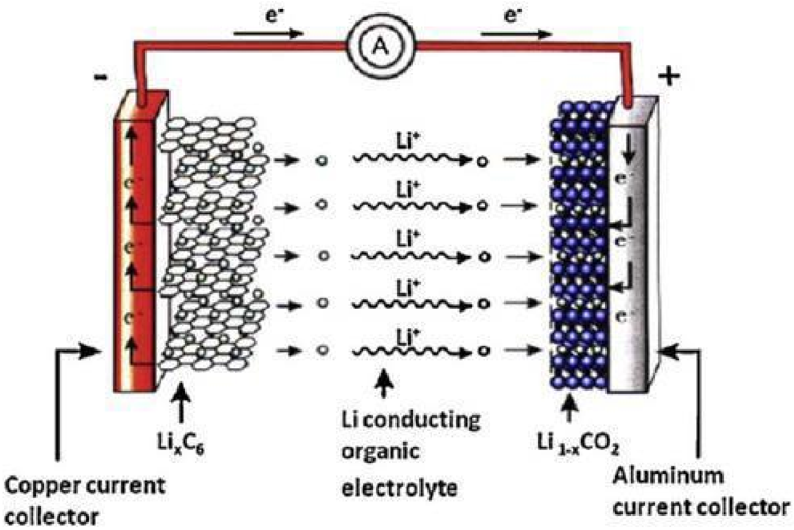

FIGURE 8 SCHEMATIC REPRESENTATION OF A CHARGING LI-ION CELL [13]

In Figure 8, it is possible to recognise the graphitic anodic material (LixC6) together with the copper current collector and the lithium cobalt oxide cathodic element (Li1-xCO2), which utilises electrons from the external electrical circuit. The chemical reactions involved in the anodic and cathodic electrode materials are given by Equations 1,2,3.

$$xLi^+ + xe^- + 6C \rightleftarrows Li_xC6$$

EQUATION 1 ANODIC REACTION IN A LI-ION CELL

$$LiCoO_2 \rightleftarrows Li_{1-x}CoO_2 + xLi^+ + xe^-$$

EQUATION 2 CATHODE REACTION IN A LI-ION CELLS

$$LiCoO_2 + 6C \rightleftarrows Li_{1-x}CoO_2 + \boldsymbol{L}\ _xC6$$

EQUATION 3 TOTAL REACTION IN ANODIC AND CATHODIC MATERIALS, IN LI-ION CELLS

4.3 Cell properties

4.3.1 Cell voltage

The cell voltage depends mainly on the electrode materials used in the manufacture of the electrochemical cell. To provide an analytical expression of the cell voltage, one can consider Equation 4, which represents the differential energy balance of a closed system involving electrochemical reactions under electrochemical equilibrium conditions.

$dG+dW_{el,rev}=0$ (eq.4)

where dG is the Gibbs free energy, dWel, rev is the electrical work provided by a reversible process, which is assumed to be positive if performed by the system.
Then, by integration, equation 5 can be obtained.

$\Delta G+W_{el,rev}=0$ (eq.5)

The term ΔG represents the change in Gibbs free energy between two thermodynamic states of the system and Wel, rev represents the total electrical work that can be obtained by a reversible process from the initial and final states considered.
From equation 5, it is possible to calculate the ideal cell voltage: in fact, the reversible electrical work Wel, rev depends on the electric potential and electric charge through equation 6.

$W_{el,rev}=-\Delta G=n_{el}*F*V_{ideal}$ (eq.6)

nel is the number of electron moles involved in the redox chemical reaction and V ideal is the ideal cell voltage measured in volts. F is the so-called Faraday constant, which represents the electrical charge associated with one mole of electrons. Its value is given by equation 7.

$F=96485{,}3 \frac{C}{mol\ el}$ (eq.7)

The product $n_{el}*F$ thus represents the total electrical charge generated by the reaction. Gibbs free energy values can be found under standard conditions (T=25°C, p=1 atm) in the chemical literature.
Thus, by rearranging Equation 6, it is possible to find a useful expression for evaluating the ideal cell voltage, Videal0, as expressed in Equation 8

$V_{ideal}^{0}=\frac{-\Delta G^{0}}{n_{el}*F}$ (eq.8)

where the superscript '0' indicates standard conditions. However, it is important to consider that the working conditions of the cell are different from standard conditions and are also influenced by the concentration of the chemical species: the Nerst equation takes these effects into account, leading to an analytical expression through which the ideal cell voltage, Videal, expressed within equation 9, can be evaluated.

$V_{ideal}=V_{ideal}^{0}-\frac{RT}{n_{el}*F}*\ln\frac{\Pi\ Concentration\ of\ products}{\Pi\ Concentration\ of\ reagents}$ (9)

The logarithmic term within equation 9 involves the ratio between the series of products and reactants (symbol Π): it indicates the gap between the voltage measured under standard conditions and that which would be obtained during actual cell operation. The concentration of the products increases while the concentration of the reactants decreases, leading to a continuous increase in the logarithmic term and thus a progressive decrease in the measured ideal voltage. The ideal voltage is also called open-circuit voltage (OCV) and can be measured at the terminals of an electrochemical cell without any utilizers connected.

4.3.2 Cell capacity

Capacitance represents the electrical charge that an electrochemical cell can store. According to the International System, capacitance is measured with the Coulomb (C), which corresponds to the charge provided by an electric current of 1 A applied for a period of 1 s ($C=A*s$). However, this is not convenient from a practical point of view and usually the preferred unit of measurement is the Ampere-hour (1 Ah=3600 C). The cell charge is usually indicated as Cx, where the 'x' refers to the discharge period (expressed in hours). For example, if one considers a capacity of C1 = 50 Ah, it means that the device provides a capacity of 50 Ah if the discharge process takes place in 1 hour with an electric current of 50 A. Usually, the data sheets of electrochemical cells state the nominal capacity. However, the actual measured capacity provided by a storage device may also depend on the electric current involved during the discharge/charge process: Equation 10 gives the definition of C-rate, i.e. the rate at which a cell is charged or discharged.

$Crate=iCn$ $[h\text{-}1]$ (eq.10)

For example, 1C states that the storage system is able to charge and discharge the nominal capacity in 1 hour. However, it can happen that the available capacity is discharged in as little as half an hour (0.5 h) with a doubled electric current (2C rate). The C-rate only weakly influences the nominal voltage of a lithium-ion cell.

4.3.3 State of charge and depth of discharge

The state of charge (SOC) indicates the percentage of charge of an electrochemical cell relative to the nominal capacity. If the cell is fully charged, then SOC = 100% applies, whereas in the case of full discharge the SOC = 0%. Similarly, Depth Of Discharge (DOD) is defined as the percentage of the available capacity that has already been supplied to the external load: if the storage device is fully charged, the condition DOD = 0% applies, whereas DOD = 100% if the electrochemical cell is fully discharged. It is not convenient to fully discharge lithium-ion cells, as the overall system lifetime would be drastically reduced. Typically, the suggested DOD is around 80%, which typically allows 3000 (and even more) life cycles.

The lifetime limit of an electrochemical cell is usually set for a loss of 20 per cent of the storage capacity compared to the nominal capacity. The lifetime of an electrochemical cell can be measured by the total number of cycles, which characterizes the number of charge/discharge cycles leading to the end of the system's life.

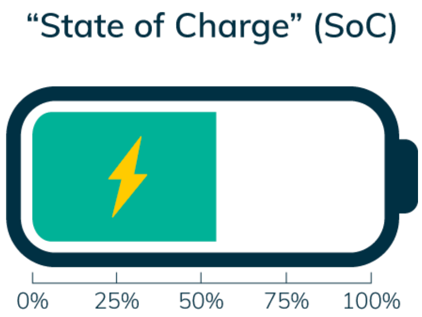

FIGURE 9 REPRESENTATION OF STATE OF CHARGE SOC [15]

4.4 Battery types

LIB batteries are structured in cells of small size and power, each with one positive and one negative pole, which through specific connections in series and in parallel achieve, respectively, specific capacities and powers required for the type of vehicle. The current flow can be incoming in the case of recharging then from the anode to the cathode, or in the opposite case when in use by the engine. The performance of the vehicles is closely linked to the characteristics of the battery, a relevant factor being the size with relative powers and technologies used as analyzed below.[13]

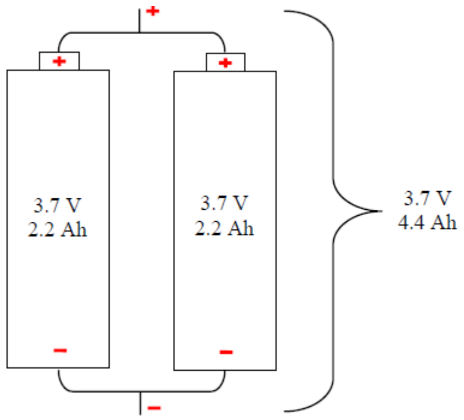

FIGURE 10 EXAMPLE PARALLEL CONNECTION [13]

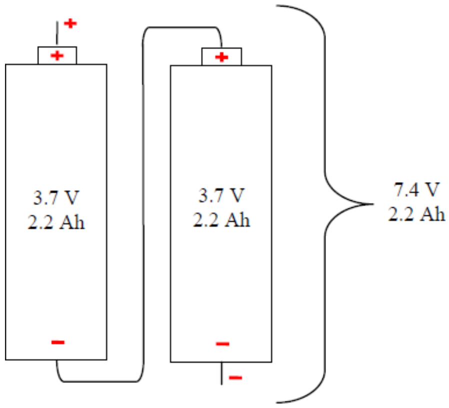

FIGURE 10 EXAMPLE SERIES CONNECTION [13]

Typically, in electric vehicles, batteries can be found organized in three main formats:

- Pouch cell (a)
- Prismatic cell (b)
- Cylindrical cell (c)

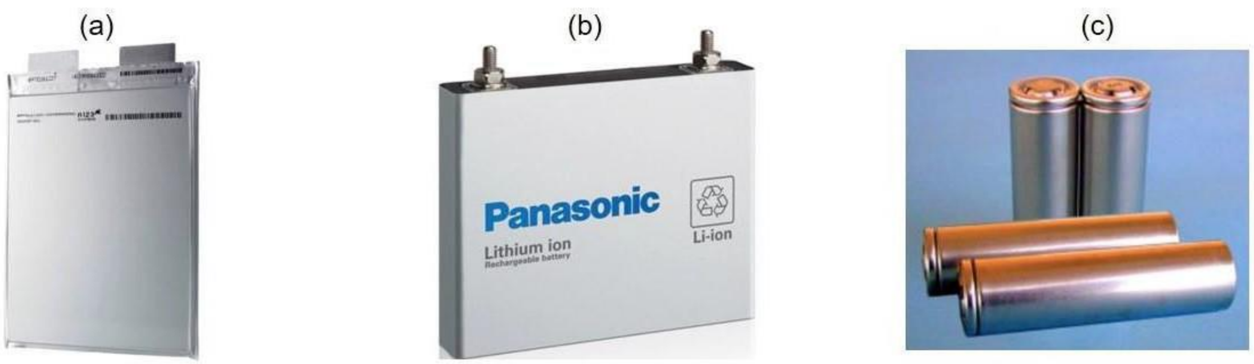

FIGURE 11 MAIN TYPE OF LI-ION BATTERY STRUCTURE [16]

The former, so-called bag-type are made up of layers of electrodes stacked one on top of the other to create a sandwich structure, which is then contained in a thin aluminum cladding that allows them to be adaptable in space and low in weight. As a result, they have a high energy density, an important advantage since space and weight are two very relevant terms in the automotive environment. This type of battery, however, has a low mechanical resistance that should not be underestimated: there can be expansions due to the formation of gases that are generated over time during use, and a production standard has not yet been reached, with the result that prices are still high. Should a standard be reached, it is expected that their use would increase as the aforementioned advantages are considered very significant in the industry. This type of battery, for example, is adopted by Renault and Hyundai.

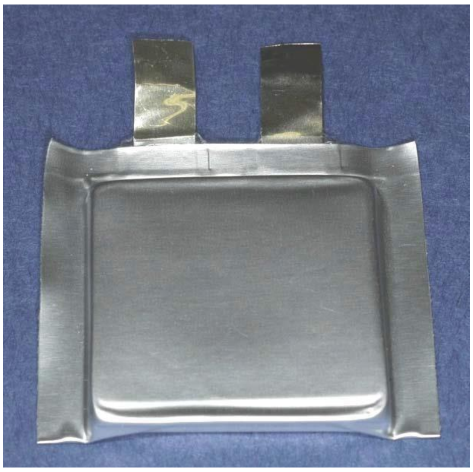

FIGURE 12 EXAMPLE OF POUCH STRUCTURE ENERGY STORAGE. [13]

The prismatic type cells instead have a rigid, non-standardized structure. Having regular shapes improves block packing, thus minimizing the space occupied. A further advantage is the possibility of fixing the layering of internal materials. This type of battery, for example, is adopted by some cars produced by BMW.

FIGURA 13 EXAMPLE OF PRISMATIC STRUCTURE CELLS.[13]

Cylindrical type cells have the typical (cylindrical) shape of AA batteries. They are advantageous in that production takes place in series and is fully automated, making them cheaper. Typically with a capacity of 25 to 100 ah, they are connected to make battery packs, but as a result of their shape, there is empty space left between the batteries, which therefore take up more space for the same capacity. It is estimated that this technology has reached its maximum potential. This type of batteries, for example, are adopted by TESLA.

FIGURA 14 EXAMPLE OF A CYLINDRICAL STRUCTURE [13]

FIGURA 15 EXAMPLE OF A BATTERY PACK (TESLA) WITH CYLINDRICAL BATTERIES [13]

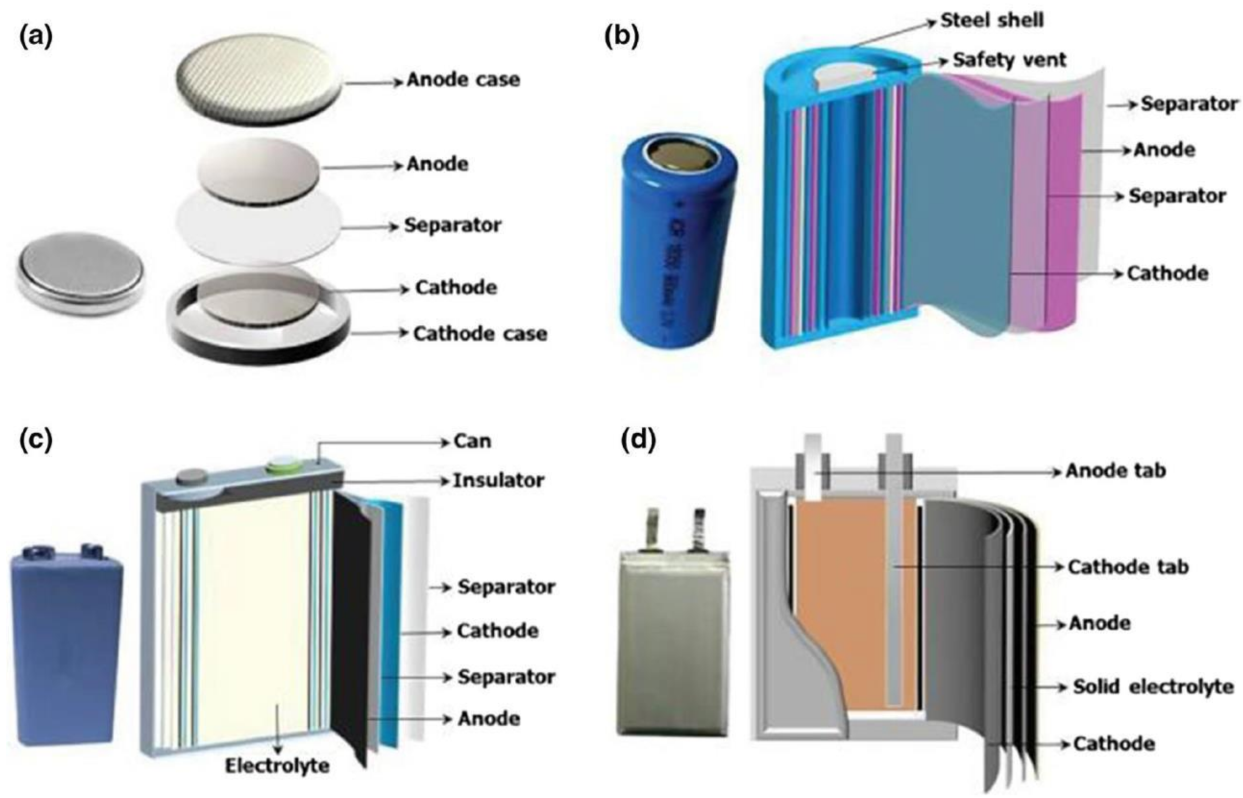

FIGURE 16 TYPICAL EV BATTERY FORMATS: (A) BUTTON CELL; (B) CYLINDRICAL; (C) PRISMATIC; (D) POUCH [17]

Table 2: Comparison between capacity, energy density and battery type and related cars in BEVs. [16]

Brand	Capacity [kWh]	Cell density [Wh/kg]	Cell type
Nissan Leaf S (2017) [55]	40	229	Pouch
Renault Zoe 40 (2017) [56]	41	228	Pouch
BMW i3(2016) [57]	42.2	230	Prismatic
Tesla Model S (2017) [58]	90	~250	Cylindrical 18650

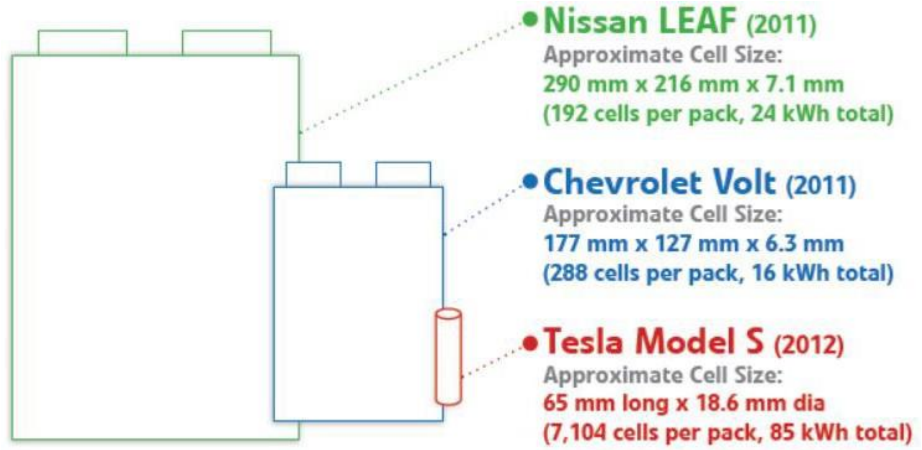

FIGURE 17 COMPARISON OF THE SIZE AND CAPACITY OF BATTERIES WITH THEIR USERS [13]

4.5 BMS

Lithium-ion systems require a control device (BMS - battery management system) that manages the balance of the state of charge, balancing it between the cells and the different battery packs, both during charging and discharging. This ensures that the vehicle can always obtain the best performance and prevent damage to the storage system; in fact, it has the fundamental function of guaranteeing operating conditions that prevent thermal runaway by keeping the battery within safe voltage and temperature ranges. The device, in fact, is equipped with sensors to determine the instantaneous values of the parameters and consequently the state of charge (SOC), recognizing the conditions that could induce electrical or thermal failures and consequently going to operate with the activation of the refrigeration or by indicating the active danger. In the event of a safety failure, the system intervenes, for example by switching off the power supply in the event of an overcharge, over temperature or short circuit, acting as an interface between the user and the electromechanical components.[18]

It is also functional in the event of a thermal runaway as it is structured to section off the battery packs, preventing the rapid propagation of thermal runaway, which allows a longer vehicle evacuation time and additional protection.

Further protection in the event of a BMS failure is provided by the fuses that are always present as a double safety in the event of shocks or over temperatures.

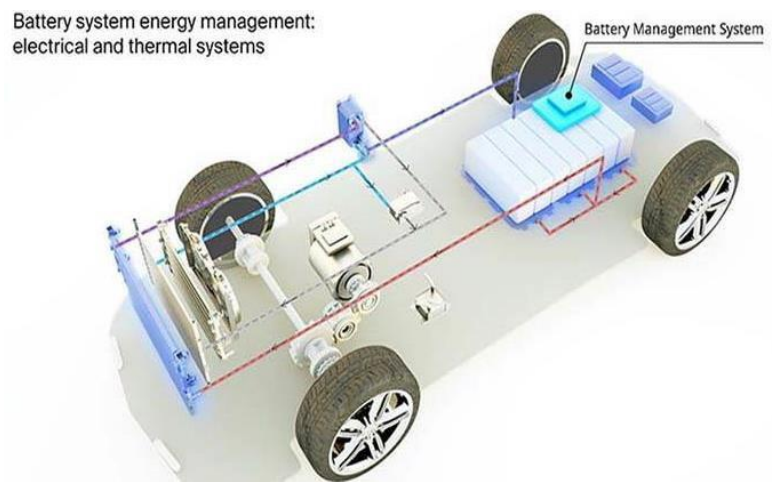

FIGURE 18 BMS PLACING REPRESENTED IN THE SCHEME. [22]

4.6 Recycling batteries

A recurring theme with regard to electric vehicles is the question of battery pack recovery, because when the accumulators no longer meet the necessary parameters for automotive use, they have to be replaced. Today, as lithium batteries are in common use, a recycling chain is being created, similar to the one that has been in place for some time for the material recovery of classic stylus batteries. LIBs are sent to special centres that, depending on their condition, can either reuse them for other purposes or recover their materials: the evaluation of batteries depends on the condition of the individual cells, because the weakest individual cell will determine the parameters of the entire battery pack. Storage systems that can be recovered for second use are applied in cases that do not require the release of high power in very short periods of time (as is the case with cars), such as power storage for photovoltaics or with storage on the electricity distribution line. This type of reuse is not yet common but is becoming increasingly popular, as demonstrated by the recent creation of the joint "Second Life batteries" project by Bosch and BMW (figure 19). [19]

A problematic factor in recycling is transportation: as LIBs have an electrical and/or chemical potential within them, they are considered a fire and explosion hazard, and consequently must be transported according to hazardous materials regulations. This entails high costs and transport difficulties: above a certain capacity threshold, neither ships nor planes allow the transport of used batteries, because while for new batteries there are no major problems as they are guaranteed by the manufacturer, on recycled batteries there is no guarantee as to their condition, which increases the risks.

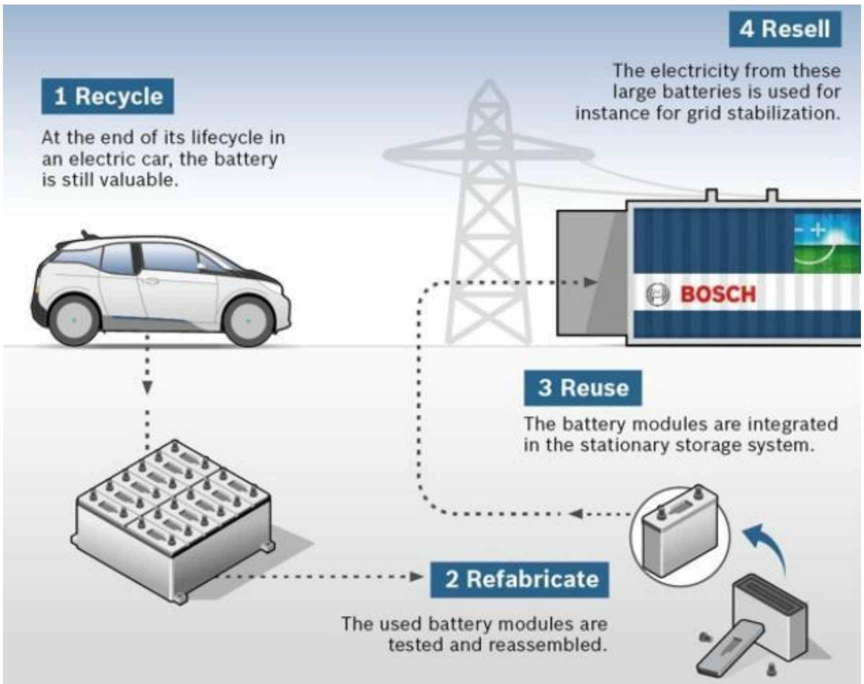

FIGURE 19 BOSCH "RECYCLING" PROCESS FOR AUTOMOTIVE BATTERY PACKS: ONE OF THE MAIN USES OF THESE STORAGES IS TO GUARANTEE STABLE SUPPLY OF ENERGY THROUGH THE ELECTRICAL GRID BY MITIGATING THE EFFECT OF PEAKS AND DEFICIENCIES, WHICH ARE BECOMING A MORE PROMINENT ISSUE AS THE USE OF RENEWABLE ENERGY SOURCES INCREASES. [19]

5. Vehicle structure

Battery packs need to be strategically positioned inside cars, both for weight distribution and safety reasons; they are usually placed on the car floor so that their weight is distributed downwards and centrally, in order to improve road holding and stability while driving. In addition, the central body of the car is designed not to be deformed in the event of an accident as shown in Figure 20, the front and rear of the car in the event of impact absorb the energy of the impact, thus avoiding damage to the passenger compartment and consequently to the passengers and the battery pack. Depending on the size required, the batteries can be distributed across the axles, either centrally or in a 'T' shape (figure 21).[20]

FIGURE 20 ARRANGEMENT OF CAR BATTERY PACKS [16]

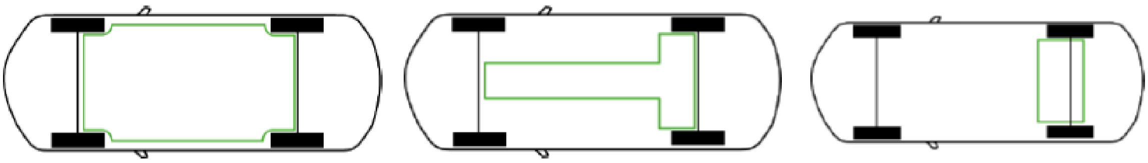

FIGURE 21 EXAMPLES OF BATTERY ARRAYS; FLOOR; “T” AND REAR AXLE [16]

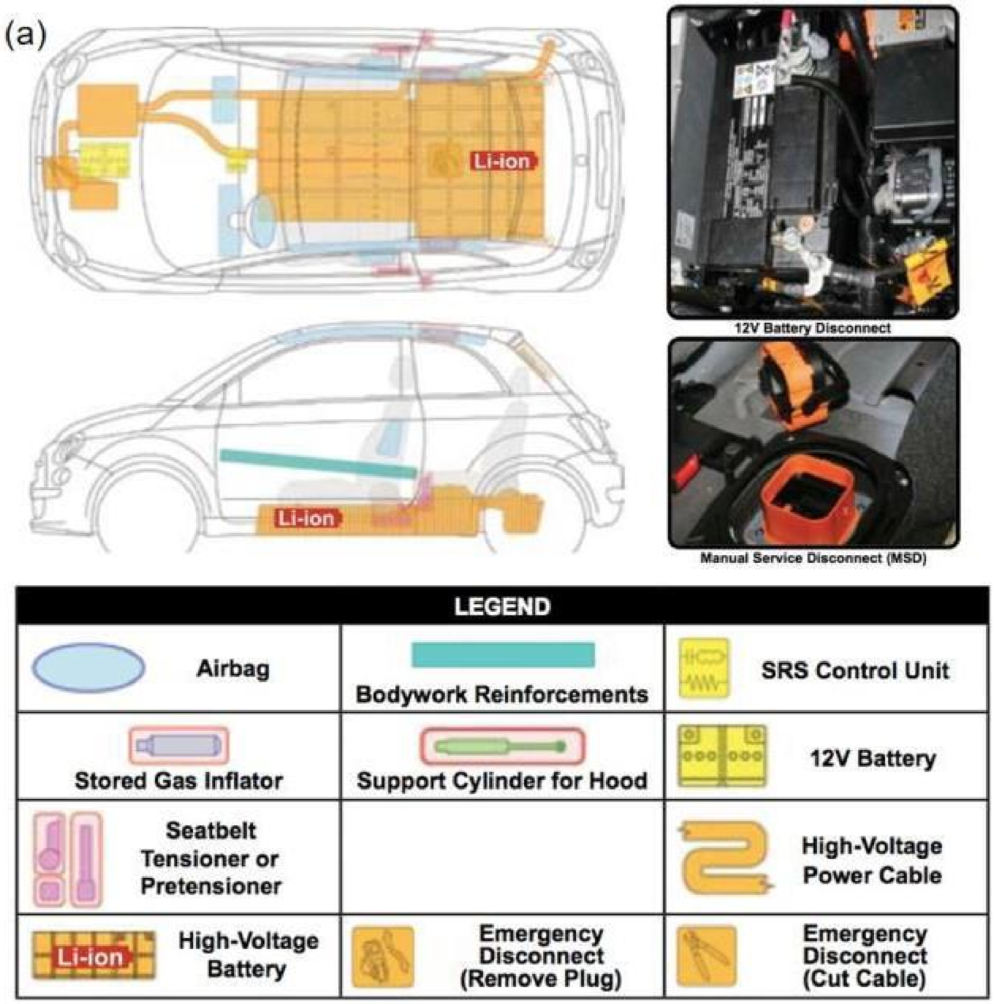

FIGURE 23 DISPOSITION PACKAGES BATTERY AND ELECTRIC SCHEME ON A FIAT 500 ELECTRIC [21]

FIGURE 22 THE VOLKSWAGEN "E-GOLF" MODEL USES A T-SHAPED BATTERY PACK, IN ACCORDANCE WITH THE INTERIOR SPACES OF THE CAR (SEATS, FLOOR). 24.2 KWH [26] [27]

FIGURE 22 CHEVROLET VOLT (CALLED OPEL AMPERE IN EU) USES A T-SHAPE ARRANGEMENT WITH POUCH BATTERIES [26] [28]

FIGURE 23 VOLVO XC60 MODEL, A PLUG-IN HYBRID EV, HAS A PARTIAL T-SHAPE LAYOUT AS ONE "BRANCH" IS THE BATTERY WHILE THE OTHER HAS THE FUEL TANK [26] [29]

Veuicle	[kWh]	Tipe		Chatode
Nissan Leaf (2015)	30	Floor	Pouch	C/LMO-NCA
Renault Zoe (2017)	41	Floor	Pouch	C/NMC
Volkswagen e-Golf (2016)	36	Floor / T-shape	Prismatic	C/LMO-NCA-NMC
BMW i3 (2017)	33	Floor	Prismatic	C/LMO-NCA-NMC
Tesla Model S (2012)	60-100	Skateboard	Cylindrical	C/NCA
Mitsubishi Outlander (2015)	12	Floor	Prismatic	C/LFP
Volkswagen Passat GTE (2015)	9.9	Rear	Prismatic	-/-
Volvo XC60 (2017)	10.4	Linear	Pouch	NMC
Volkswagen Golf GTE (2015)	8.7	Rear	Prismatic	C/LMO-NCA-NMC
Kia Niro (2017)	1.56	Rear	Pouch	-/-
Chevrolet Volt (2016)	18.4	T-shape	Pouch	C/LMO-NMC

Table 3 types of cars and their battery packs [26]

6.Risks

With the growth of electric mobility, safety concerns are also on the rise, because although it is common to be in contact with electronic devices with LIB accumulations such as PCs and smartphones, there is no perception of danger with the latter, which are now more than common devices with very few accidents in their history; when it comes to EVs, however, we are dealing with a power that is of orders of magnitude greater and with more relevant stresses on the electrical components. Above all, one wonders what happens in the event of an accident, with regard to the high electrical voltages to which the vehicle is subjected or in the event of a fire: the main source of concern is the lithium contained in the cells, which is very reactive when in contact with water, the most commonly used fire extinguishing method at present. With regard to high voltages, inertial switches have been implemented so that in the event of an impact, deceleration causes the power supply to be disconnected, separating the battery pack from the rest of the car. In the event of fire, the problem is more complex, both in terms of the choice of extinguishing methods and of the toxic gases and residues released.

Thermal accidents in electric vehicles can be divided into two main categories:

-thermal runaway, a chain reaction following the overheating of one of the cells (discussed in more detail in the next chapter) and considered highly dangerous.

- fires caused by external factors, i.e., open flames inside or outside the vehicle and short circuits in contact with flammable materials leading to the ignition of a flame.

Electric vehicle batteries are designed to withstand high charging and discharging cycles, shocks from the vehicles they are intended for, and extreme working conditions from -20°C to 50°C, but in the event of significant shocks, working conditions beyond the overheating limit or charging and discharging cycles beyond the set limits, they can be damaged or rupture, emitting flammable gases, sparks, toxic gases and/or smoke that can cause a fire or explosion in extreme cases. Figure 23 shows the working window within which it is safe to work: beyond the imposed limits, internal chemical reactions are no longer controlled, thus creating the risks listed above. [23]

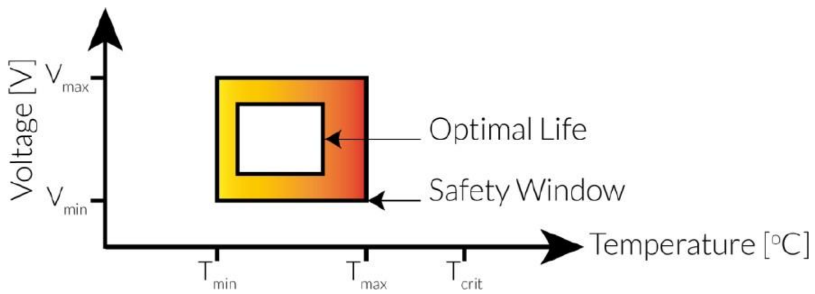

FIGURE 24 OPERATING RANGE OF A BATTERY PACK IN TERMS OF VOLTAGE (V) AND TEMPERATURE (°C) [16]

FIGURE 25 EXAMPLE OF A BATTERY INFLATED AS A RESULT OF GAS RELEASE [9]

7. Thermal runaway

Thermal runaway is a potentially hazardous situation that occurs in electric vehicle battery packs, and it can have severe consequences if not properly managed. The cause of thermal runaway is the overheating of a battery cell, which in turn can be caused by several factors such as manufacturing defects, mechanical stress, electrical stress, or thermal stress. When a cell overheats, the internal temperature rises, which can trigger a chemical reaction within the cell that releases heat, causing the temperature to rise even further. This reaction can quickly spread to other cells within the battery pack, creating a self-sustaining chain reaction that can raise the internal temperature of the battery pack by a rate of 10°C/minute or more.

Once the thermal runaway has started, it is difficult to control the temperature and it can quickly exceed the safety limits for operation. This can result in smoke, gases, and sparks being released from the battery pack, creating a high fire risk. The safety valves that are designed to prevent the battery from exploding are not enough to stop the thermal runaway, and the gases released can also be flammable, further increasing the risk of fire. To avoid the onset of thermal runaway, it is important to use high-quality materials and to take proper care of the battery pack, avoiding mechanical and electrical stresses, and monitoring the temperature regularly. If the temperature starts to rise, it is important to take action to cool the battery pack as soon as possible.

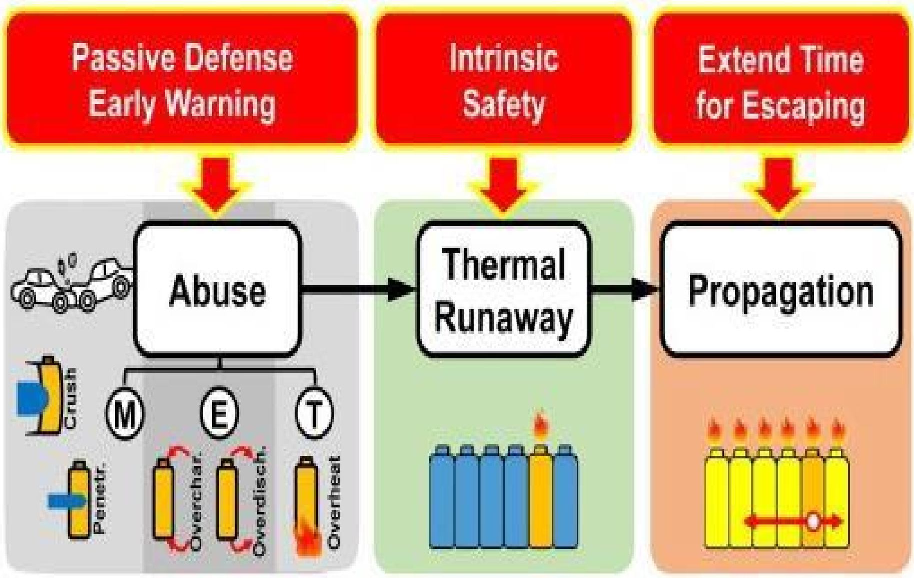

FIGURE 26 CAUSE-EFFECT SEQUENCE WITH RELATED SAFETY SYSTEMS: THE FIRST PREVENTION STEP IS TO AVOID POSSIBLE CAUSES SUCH AS OVERHEATING, OVERLOAD OR COLLISION. IT IS FOLLOWED BY INTERNAL INTRINSIC SAFETY TO AVOID INTERNAL PROPAGATION TO THE BATTERY PACK, WHICH GUARANTEES MORE TIME TO EVENTUALLY EVACUATE [23]

During normal operation of a battery, the temperature tends to rise both during charging and discharging. This occurs due to the movement of lithium ions from the cathode to the anode during charging, and vice versa during discharging. To regulate the temperature and prevent overheating, cooling devices are usually employed. However, if these cooling devices fail or are not sufficient, the battery can overheat and cause the electrolyte to react with other elements present, resulting in the production of fumes and gases.

These fumes and gases increase the internal pressure of the battery, which can exceed 6 bar and further raise the temperature. The gases are usually expelled through special valves to prevent the battery pack from exploding. It is important to note that the emitted gases may contain flammable substances, such as oxygen, which can pose a fire or explosion hazard under certain conditions.

There are several factors that can contribute to thermal leaks in batteries, including manufacturing defects, mechanical stress, electrical stress, and thermal stress. In the case of thermal stress, it is believed that a thermal runaway event can be initiated if the cells are kept at 80°C for more than 24 hours, exposed to temperatures of 150°C for a few minutes, or exposed to an open flame for a few seconds. At high temperatures, the positive electrode may rupture and release oxygen, which can result in a reaction proportional to the state of charge.

Electrical stress can be mitigated to a great extent by using high-quality materials. However, the most dangerous type of damage is mechanical damage due to shocks, which can occur hours or even days after the initial impact and is therefore difficult to predict.

FIGURE 27 CONDITION OF A CYLINDRICAL CELL (18650) AFTER THERMAL RUNAWAY, THE RESULIDIFICATION OF ALUMINIUM IS EVIDENT IN THE CROSS-SECTION [24]

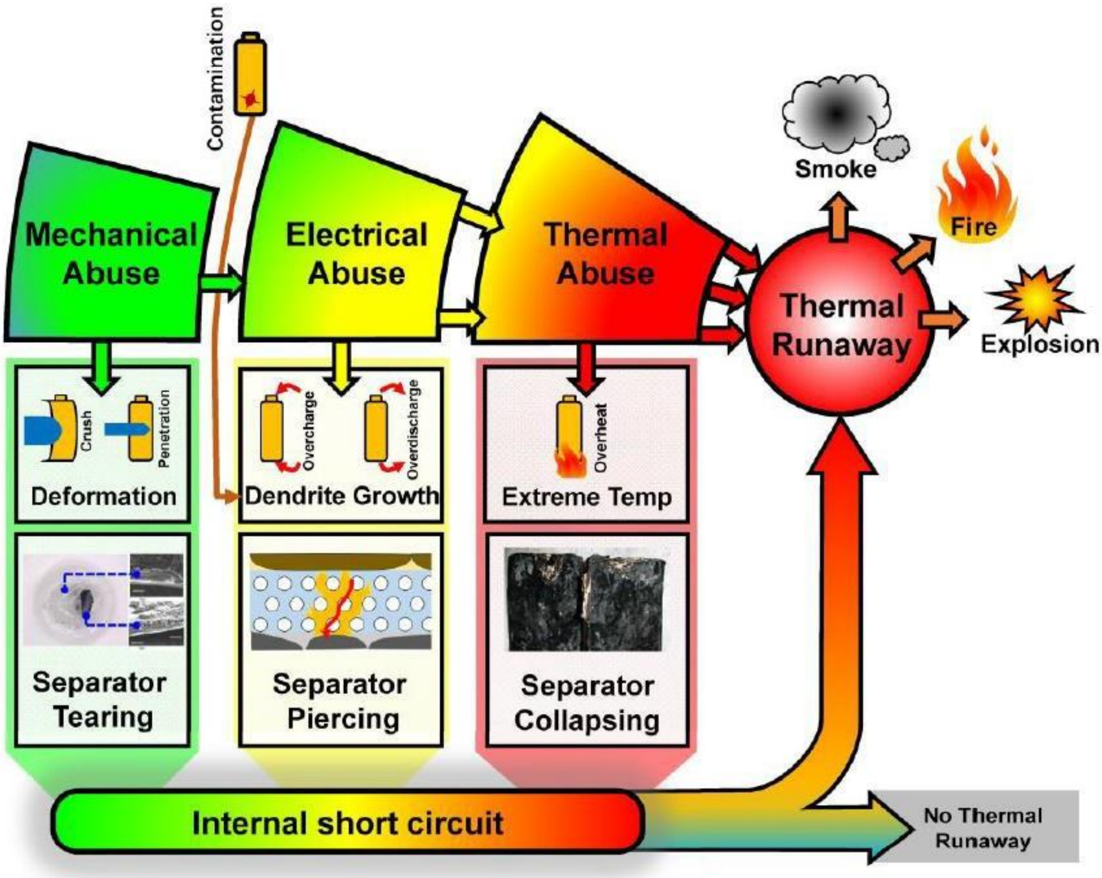

FIGURE 28 PROCESS OF THERMAL RUNAWAY [23]

8. Flammable Components

When it comes to the safety of electric vehicles, it's important to consider all aspects, such as the potential for fire given by the presence of flammable materials. All types of cars have plastic components both in the interior and exterior, making up an estimated 25% and 35% of the weight of the car. The calorific value of these elements is comparable to that of fossil fuels, for example 38.4 MJ/ kg for polyethylene against 47 MJ/ kg of gasoline and considering the greater amount of polymers compared to fuels these give the greatest energy contribution in case of fire. As for batteries, their energy density is on average of an order of magnitude lower than fuels, meaning that to emit an equivalent amount of heat it would require an amount about an order of magnitude greater than traditional tanks. This is often the case (the mass of LiB storages in an EV is much higher than that of a full fuel tank in an ICEV), meaning that the overall heat potential of an electric car and an internal combustion car with a fully fueled tank is very similar.

In addition, it has to be considered that the tank of a car is hardly completely full and instead the batteries roughly maintain their heat potential regardless of the state of charge, so electric vehicles retain their thermal potential while for traditional vehicles it decreases with the reduction of fuel. In conclusion, it is possible to estimate a heat release around 7MW for a BEV electric vehicle and 6 MW for a traditional ICEV vehicle, with a lot of variability mainly due to the layout and dimensions of the vehicle: considering comparable size and arrangement there is a difference of 1/1.5MW between BEV and ICEV. [25]

To mitigate the risk of thermal runaway and fires, electric vehicle manufacturers have implemented a number of safety features. These can include overcharge protection, cooling systems, and multi-layered protection in the battery design.

In the event of a fire, the way in which the energy is released is different in an electric vehicle compared to a traditional vehicle. In a traditional vehicle, the fuel is stored in a tank that can ignite easily in the event of a fire. In an electric vehicle, the batteries are distributed throughout the car, often in different compartments, which can make it more difficult for a fire to spread and give first responders more time to respond.

In addition to the potential for fires, there are also other safety considerations when it comes to electric vehicles. For example, electric vehicles don't have a fuel tank, which can be a source of danger in the event of a collision. They also tend to have a lower center of gravity and a more rigid frame, which can improve stability and reduce the risk of rollover accidents.

9.Toxicity

In the event of a fire, in addition to the notoriously toxic and carcinogenic fumes generated by the combustion of the plastic components in all cars, there are also the fumes generated by thermal runaway in the cells as a result of high temperatures, among which the most harmful are phosphoryl trifluoride (POF3), hydrofluoric acid (HF), hydrogen cyanide (HCN) and carbon monoxide (CO), as well as HCL, CO2, H2, C2H4, CH4, C2H6, C3H6...

Inhalation of such gases can lead to severe health effects, up to and including death:

depending on the type of gas produced, different types of health damage can occur, e.g. H2, N2, CO2 and methane are called simple asphyxiate, and they mainly cause dizziness and nausea. Other asphyxiate such as carbon monoxide (CO) and hydrogen cyanide (HCN), on the other hand, act more significantly on the human body by replacing oxygen in the blood and also lead to more severe symptoms, even leading to death: it is estimated that carbon monoxide poisoning causes half of all fire-related deaths.

In EV fires, certainly the most toxic component is hydrofluoric acid, which is a strong irritant and can cause severe respiratory injury if inhaled. The main difference between HF and other irritant gases is that the fluoride ion is able to penetrate the skin and other tissues causing systemic poisoning and altering calcium, potassium and magnesium levels in the blood [30].

It can also be seen that the release of heavy metals is different between EVs and conventional vehicles. The latter release metals such as zinc (Zn), lead (Pb) and copper (Cu), while EVs, as a result of battery components, release high levels of cobalt (Co), lithium (Li), nickel (Ni) and manganese (Mn). These hazardous substances are therefore different from what firefighters are used to, and for this reason they need to be further trained and enabled to operate with appropriate protective equipment and guidelines to follow.[30]

$$LiPF6 \rightarrow LiF + PF$$
$$PF_5 + H_2O = POF_3 + 2HF$$
$$LiPF6 + H_2O \rightarrow LiF + POF_3 + 2HF$$

Equation 11 Reaction during a thermal runaway event.

Reporting the results obtained and published in the paper 'Scenario-based prediction of Li-ion batteries fire-induced toxicity' by: A. Lecocq, G. Gebrselassie, S. Grugeon, N. Martin, S. Laruelle, G. Marlair, the relationship between the state of charge (SOC) and the heat release in the event of combustion (Heat Release Rate, HRR) can be shown: in particular, the evolution of the HRR as a function of time for LiPF6 cells at different states of charge of 100, 50 and 0% SOC respectively, Figure 31. It can be seen that the state of charge influences the heat release in a fairly linear manner, and furthermore in the case of a fully charged battery the release is concentrated, thus showing a high temperature peak but ending in about half the time [31].

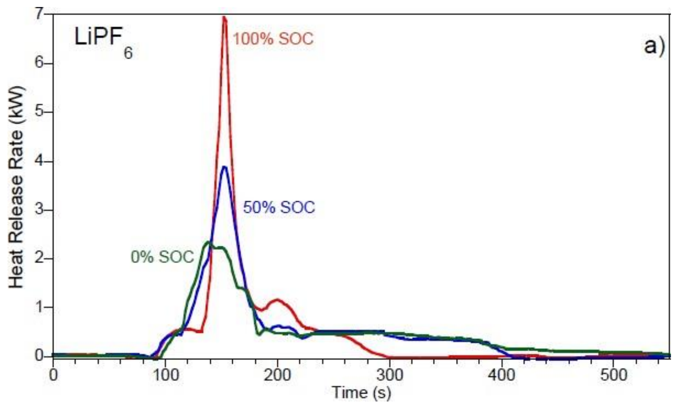

FIGURE 29 HRR IN RELATION TO TIME FOR LIPF6 BATTERIES [31]

The same conclusion can be drawn regarding the degrees of release in grams/second of carbon monoxide and hydrofluoric acid, the main toxic elements generated during a thermal fugue, as the charge increases: the releases are more intense, concentrated and anticipated. In particular, for the release of CO, this is due to the fact that a higher SOC favors a so-called incomplete combustion (i.e. in O2 deficiency), as it leads to a more rapid transition from an oxygen-rich to an oxygen-poor environment. The same behavior is observed in the reaction patterns that apply to the formation of COx (oxidation processes of organic substances dominate) and HF (decomposition processes from inorganic salts).[31]

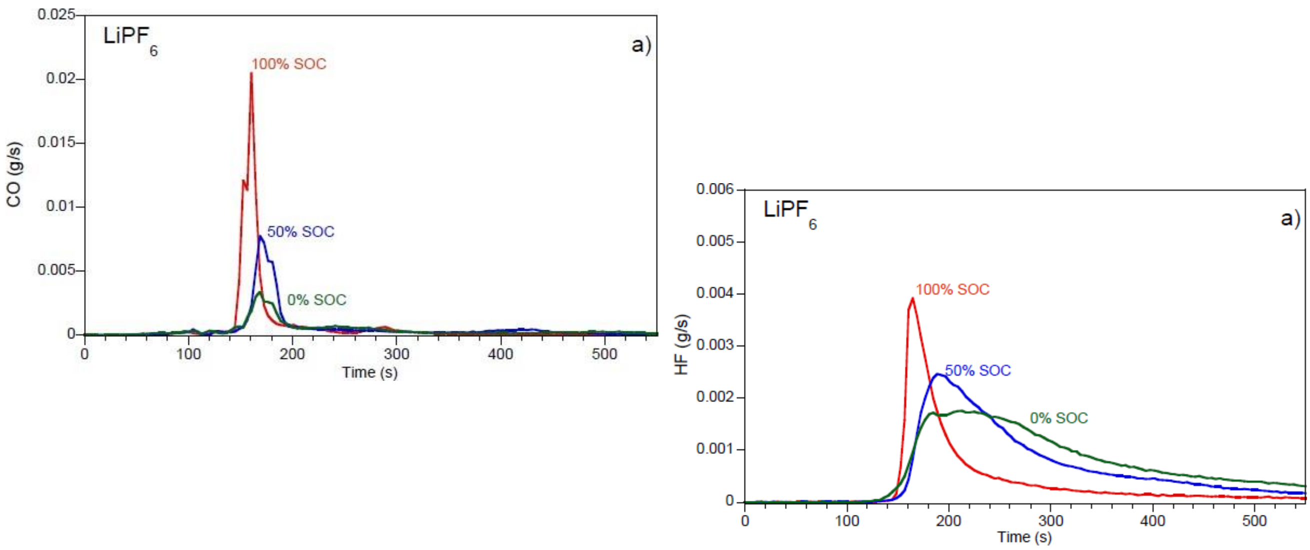

FIGURE 30 RELEASE OF TOXIC ELEMENTS RELATED TO THE TIME IN LIPF6 BATTERIES [31]

9.1 Toxicity testing

To assess the toxicity produced by the combustion of electric vehicles, reference can be made to the study carried out by Ola Willstrand, Roeland Bisschop, Per Blomqvist, Alastair Temple and Johan Anderson for the RISE (Research Institutes of Sweden) [32]; the fire of three different vehicles, one ICEV and two BEVs, was tested in a special room with instrumentation capable of determining the gases produced. Table 4 shows the characteristics of the three vehicles taken into the experiment.

Test	Type	Energy	SOC	Cell type	Model	Year	Manufacturer
1	ICEV	Diesel, 44 l	-	-	Full-size van	2011	A
2	BEV	40 kWh	80 %	Pouch, NMC	Full-size van	2019	A
3	BEV	24 kWh	80 %	Prismatic, NMC	Small family car	2016	B

Table 4 Characteristics of tested vehicles [32]

Table 5 shows the values found in the gas analyses, the total quantities and the quantities in relation to mass loss in brackets. It can be seen that the BEVs have far higher values for toxic substances than vehicle A (ICEV), and in particular HF is the gas with the greatest percentage difference between the vehicles. This is mainly due to battery pack components such as phosphorus pentafluoride and lithium hexafluorophosphate as analyzed above.

Gas measurements	ICEV A	BEV A	BEV B
CO_2, [kg] / [g/lost g]	344 / (1.4)	335 / (1.4)	438 / (1.1)
CO, [g] / [mg/lost g]	6 420 / (25.5)	7 790 / (31.5)	9 510 / (23.8)
THC, [g] / [mg/lost g]	2 370 / (9.4)	3 130 / (12.7)	2750 / (6.9)
HF, [g] / [mg/lost g]	11 / (0.04)	573 / (2.3)	859 / (2.1)
HCl, [g] / [mg/lost g]	1100 / (4.4)	1590 / (6.4)	1800 / (4.5)
HBr, [g] / [mg/lost g]	18 / (0.1)	115 / (0.5)	88 / (0.2)
HCN, [g] / [mg/lost g]	-	-	155 / (0.4)
SO_2, [g] / [mg/lost g]	479 / (1.9)	575 / (2.3)	645 / (1.6)
NO, [g] / [mg/lost g]	452 / (1.8)	371 / (1.5)	617 / (1.5)
NO_2, [g] / [mg/lost g]	44 / (0.2)	25 / (0.1)	76 / (0.2)
PAH, [g] / [mg/lost g]	112 / (0.4)	29 / (0.1)	334 / (0.8)

Table 5 Gas values collected during testing [32]

The total quantities of metals and anions due to combustion are shown in Figure 33. Here too, the values found in vehicles B and C are higher than in vehicle A, particularly for metals found inside lithium-ion batteries such as nickel, cobalt, manganese, lithium, aluminums and copper.

FIGURE 31 QUANTITIES OF METALS DETECTED DURING THE TRIAL [32]

10. Fire cases

As electric vehicles are currently more expensive and less widespread, in continuous development and with relatively few cases of fire, there is no large sample to refer to, as there is for internal combustion cars. Manufacturers, probably precisely because this is a developing sector, are not willing to release information obtained during in-house studies, and as a result only a few more relevant cases that have occurred in recent years can be analyzed: below are reported fires from 2011 to 2019 of PHEV (plug-in hybrid), HEV (hybrid) and BEV (battery). [16][33]

Year	Location	Vehicle	Type of accident	Cause	Comments
2011	Hangzhou, China	Zotye M300 EV	Fire while driving		All electric taxis (30) in the city were temporary pulled off
2011	Wisconsin, USA	Chevrolet Volt	Fire 3 weeks after crash test	Leaking coolant in battery	
2012	Michigan, USA	GM testing facility	Battery explosion during testing	Old operating cycle not compatible with new battery prototype	
2012	Shenzhen, China	BYD e6	Hit from behind and collision with tree	High collision impact, the tree penetrated 1 m	
2012	Sweden	Rebuilt Fiat 500	Fire during charging (after 25 hours)	Fire started in engine compartment, probably heater	
2012	Texas/ California, USA	2 Fisker Karma	Fires in parked vehicles	Second fire: the damage was confined away from the battery	Two fires among 1000 Fisker Karma hybrid electric sedans
2012	New Jersey, USA	3 Toyota Prius & 16 Fisker Karma	Fire in vehicles immersed in sea water due to hurricane Sandy	Saltwater	More than 2000 Toyotas (hybrid) not having a fire
2013	Paris, France	2 Bolloré Bluecar	Fire in parked vehicle and spread to second vehicle	Maybe vandalism, but not for sure	
2013	USA, Mexico	3 Tesla Model S	3 different fires within 6 weeks	Hitting road debris and concrete wall (and tree)	After the incidents, Tesla reinforced the construction
2013	Japan	Mitsubishi Outlander PHEV	A few battery overheating incidents	Production was shut down for 5 months	
2014	Toronto, Canada	Tesla Model S	Fire in garage	Four months old not plugged in	
2015	Østfold, Norway	EV	Fire 2 hours after hit by train	Fire service report long extinguishing time	
2016	Oslo, Norway	Tesla Model S	Fire when plugged to Tesla supercharger station	Short circuit in electrical system of the car	
2016	Ånge, Sweden	Tesla Model S	Fire during charging	Battery was not involved	
2016	France	Tesla Model S	Fire during test drive event	Improperly tightened electrical connection	
2017	Essex, UK	Smart ForTwo ED	Fire during charging	Electrical fault	
2017	Guangzhou, China	Tesla Model X	Post-crash fire	High-speed crash	evacuated through front doors from backseat
2017	austria	Tesla Model S	Post-crash fire	High-speed crash	
2017	California, USA	Tesla Model X	Post-crash fire which also spread to home	Re-ignited on tow truck and at tow yard	
2018	Bangkok, Thailand	Porsche Panamera	Fire while being charged, spread to home	Car's charging cable plugged to socket in living room	
2018	California, USA	Tesla Model X	Post-crash fire (vehicle on "auto-pilot")	Re-ignited twice at tow yard, days later	
2018	Florida, USA	Tesla Model S	Struck wall and pole, immediate fire	Battery case ruptured	Re-ignited during loading on tow truck and again at tow yard
2018	Rumpt, Netherlands	Jaguar I-Pace	Fire in parked vehicle	Maybe arsonist, battery not involved	One of the first I-Pace delivered
2018	California, USA	Tesla Model S	Fire while driving	Battery start venting	
2018	California, USA	Tesla Model S		Towed due to flat tyre, fire started at workshop parking lot	Re-ignited at tow yard three months old
2019	Tilburg, Netherlands	BMW I8	Smoke from the front, parked in showroom at dealership	Fire service dropped the car into a container filled with water	

2019	China	3 BJEV minivans	Fire while charging	Three companies have stopped using the model	
2019	Shanghai, China	Tesla Model S	Fire in parking garage, half an hour after arrival	Battery start venting	Video shows fast fire development

TABLE 6 FIRE CASES 2011-2019 [16][33]

On a case-by-case basis, it can be observed that it is possible to see a re-ignition of the fire some time, even months, after the first case of fire or accident, probably due to the reactivation of the exothermic reactions resulting from the rupture of the separator. Other cases to be highlighted are, for example, the 2012 saltwater flooding in New Jersey, USA following a hurricane, which led to 3 Toyota Priuses and 16 Fisker Karmas catching fire: contact with the saltwater probably led to corrosion of the electrical components resulting in short circuits. However, it was observed that in the same event more than 2,000 Toyota hybrids were immersed in the same water without causing a fire, thus highlighting how effective targeted design is in preventing adverse events. There are also cases of manufacturing defects, leading to parent company recalls or system upgrades: a relevant example is related to vehicles produced by Tesla, with 3 cases of fire over the course of 6 weeks in 2012, all involving 'Model S' cars. After these events, due to impacts with the road surface or debris, resulting from too low trim and poor protection, the company took action by reinforcing the protective structure surrounding the battery pack with a recall of the cars, preventing further possible accidents.

Basing the safety assessment solely on the percentage of fires per number of vehicles sold it appears, despite the considerations in the previous chapters, that electric vehicles are safer than conventional internal combustion vehicles. According to manufacturer statements, Tesla reports one case of fire per 280 million kilometers travelled by its vehicles, 9 times less than the US average for conventional vehicles, while Karma, another parent company with its production in Finland, reports 2 cases of fire per thousand vehicles, which corresponds to the 0.2%. Comparing the different types of fuel, a study carried out by AutoInsuranceEZ [34], a US portal that provides an insurance brokerage service, shows that out of every 100,000 vehicles there are 1529 cases of fire for petrol cars, 3474 for hybrid vehicles and 25 cases for battery vehicles: hybrid vehicles record the highest number of fires because they are subject to the risks of both types, both the classic ones of thermal engines and those linked to large battery packs.

FIGURA 32 CAR FIRES CASES [35]

An example of a fire resulting from a collision could be the one that occurred in October 2017 in Austria, involving a Tesla Model S on the Arlberg Expressway, which collided with a concrete barrier at high speed. The passengers abandoned the vehicle before it caught fire, but the battery fire proved extremely dangerous as it was sudden. Tesla's protection systems (firewalls) inside the battery worked properly, isolating the different cells, and the firefighters managed to stop the fire before it spread to the entire battery pack by using large amounts of water as per the manufacturer's guidelines, but despite this, the fire destroyed most of the car. [16]

FIGURE 33 EXAMPLE OF A FIRE DUE TO A COLLISION [16]

To analyses another example, but in the case of charging, one can cite a Tesla Model S at a Supercharger station in Brokelandsheia, Norway in 2016. The fire originated in the electrical distribution box contained in the vehicle, probably due to a short circuit or under sizing of the cables that led to overheating. The Tesla owner had enough time to disconnect the power supply and remove all personal belongings from inside the cabin, but the vehicle was completely destroyed. The flames that consumed the vehicle were largely fueled by the plastic and other materials used in the interior, while the battery pack, while partially involved, did not exhibit explosive behavior.[33]

11. Firefighting

As analyzed in the previous points, once a fire starts in an electric vehicle, it is difficult to extinguish it: one can therefore approach the fire passively, letting it burn if there is no risk in the vicinity, or an offensive approach by trying to suppress the fire.

In the event of a fire, the guidelines call for the use of water as a means of heat removal, and this procedure can extinguish the flames in the cabin and cool the battery packs in a thermal runaway, but this type of fire requires large quantities of water for a long time in order to remove the heat that continues to be generated in the accumulations, unlike a 'classic' fire: this process is not easy since the batteries are compact and difficult to access, and furthermore they are IP67 certified, i.e. not directly accessible by liquids. This extinguishment can be facilitated by firewalls, physical barriers that limit interactions between neighboring batteries, which are therefore important components in terms of safety, but since their inclusion involves an increase in weight and reduction of space in the battery packs, they are inserted in modest quantities.

Some manufacturers (e.g. Renault), in order to facilitate the cooling process, have inserted thermal fuse covers (fireman access), which by yielding allow water to be inserted directly into the battery packs.[33]

FIGURE 34 EXAMPLE OF RENAULT WITH FIREMAN ACCESS [36]

Moreover, considering that thermal runaway and subsequent fire may develop or restart even after a significant amount of time has passed after the first case or impact, in many cases the solution is to completely submerge the vehicle in water for transport or to keep it in storage before proper disposal.

FIGURE 35 EXAMPLE OF COMPLETE IMMERSION IN WATER [37]

For extinguishing it would be optimal to use a substance that is a heat conductor to remove heat but not an electrical conductor, to avoid short circuits and electrocution risks; water meets the first condition but not the second. Deionized water could be used but coming into contact with ash and other substances present in the fire it would almost immediately lose its electrical insulation characteristic. Since short-circuit prevention is not the priority, water is still the preferred solution. There is also the possibility of using other extinguishing methods for electrical components in general, e.g. the mineral oil typical of transformers, MIDEL oil (known to be safer from a fire-fighting point of view) or dry chemical extinguishers.

An important aid in prevention could come from BMS control systems, which through voltage, temperature, pressure and capacitance sensors in general could determine system anomalies attributable to the start-up of fires or thermal leaks. Negative aspects are the toxic component of the electrolyte, which is an alkaline, caustic and tissue-damaging liquid. Normally its leakage from the casing is extremely unlikely, but in the event of a battery pack rupture it can bind with water making it extremely harmful to the environment, and furthermore in the event of a failure to cool, the thermal leakage will generate gases that could lead to an explosion in the battery pack with the associated risks, a rapid release of mechanical chemical and thermal energy.[16][33]

12. Tunnel testing

An interesting analysis, on which the fire modelling reported in the following chapters was based, is the experimental test performed at the 'Zentrum am Berg' tunnel research facility in Austria [25]. This facility consists of a test tunnel, two motorway tunnels and two railway tunnels, each approximately 400 m long, with regular cross-sections: Figure 32 shows the layout of the test site.

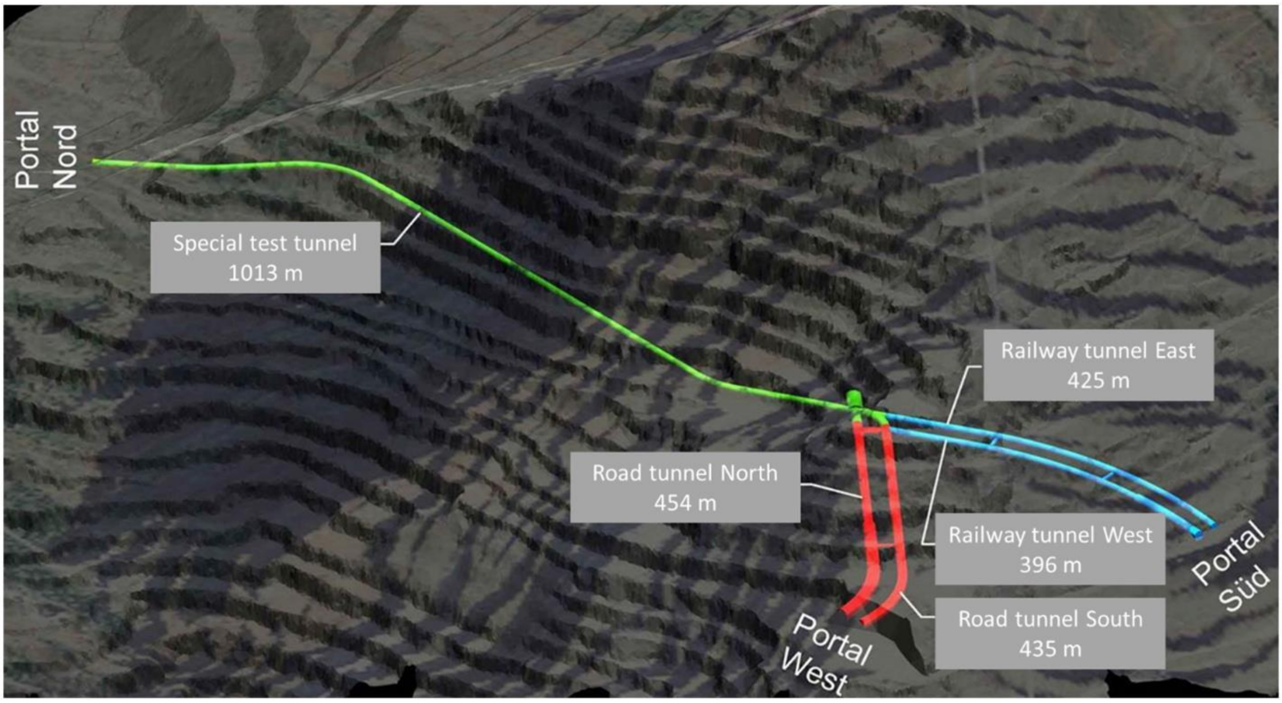

FIGURE 36 TUNNEL LAYOUT OF THE INSTALLATION IN ZENTRUM AM BERG [25]

TABLE 7 VEHICLE CHARACTERISTICS TESTED [25]

Test	Vehicle (model year)	Battery type/fuel	Capacity
BV01	BEV, compact car (2020)	NMC	80 kWh
BV02	BEV, utility van (2016)	LMO	24 kWh
BV03	ICEV, SUV (2020)	Diesel	unknown
BV04	ICEV, utility van (2010)	Diesel	50 l
BV05	BEV, SUV (2020)	NMC	80 kWh

The full-scale fire tests involved five different vehicles (listed in Table 7), where the fire was caused by different methods: for the first electric vehicle, for example, the ignition source was a saline solution (NaCl(aq)), which injected directly into the battery pack caused a short circuit and quickly the resulting fire due to thermal runaway. For the other vehicles a propane burner was used, starting combustion from the seats inside the car.

During the tests, the developments of temperature in time and space, the accumulation of toxic substances and the effectiveness of different extinguishing methods were analyzed.

The most interesting conclusions found during the tests are the following:

- The state of charge (SOC) of the batteries affects the development of combustion because it is found that to start the thermal escape a minimum charge level is necessary. Fully discharged cells, in fact, do not react even if heated to 250 °C, while with a charge of 100% at 140 °C there was a significant increase in temperature: it was concluded that at higher charge levels correspond to higher and faster release rates. [25][31]

- The use of fire blankets has been tested without success, as once the battery is involved in the fire, the high release of heat and the release of oxygen in the battery self-powers the flames; the most efficient method of extinguishing turned out to be the use of a fire lance directly in the battery pack: using this method you can block the thermal escape and tame the flames in no time with a small amount of water. The negative factor is that to implement this practice a direct intervention of specialized firefighters is required, exposing them to a high risk. Instead, using traditional methods to tame the flames and remove the heat took more than 10,000 litres of water.

- There has been an improvement in the latest generation of battery packs with regard to cooling systems: the system with improved efficiency delays the involvement of the battery in the fire, provided that the battery itself is not the cause of the fire.

- The levels of toxicity detected in electric vehicle fires are covered by the law, with the exception of hydrofluoric acid (HF), detected in much more significant quantities than ICEV fires with limit values. Additional pollutants have also been found in the drainage water used for quenching, in particular metals such as nickel and cobalt in concentrations that require special treatment.

- The study carried out showed no factors that increase the risk compared to the fires of ICEV vehicles, therefore, despite the increasing number of BEV circulating, it was established that the motorway tunnels (Austrian, in this case) do not require changes in safety standards.

- It should be noted that the heat release rate of a BEV is higher than that of the ICEV in proportion to the battery involvement. The maximum HRR (heat release rate) was in fact 8 MW for BEV, or a difference between 1.0 and 1.5 MW compared to a traditional car; while the combustion heat in MJ/kg does not differ greatly in that the greater contribution is made, as provided for in Chapter 8, by the interior of the vehicle, which is similar regardless of the type of engine.

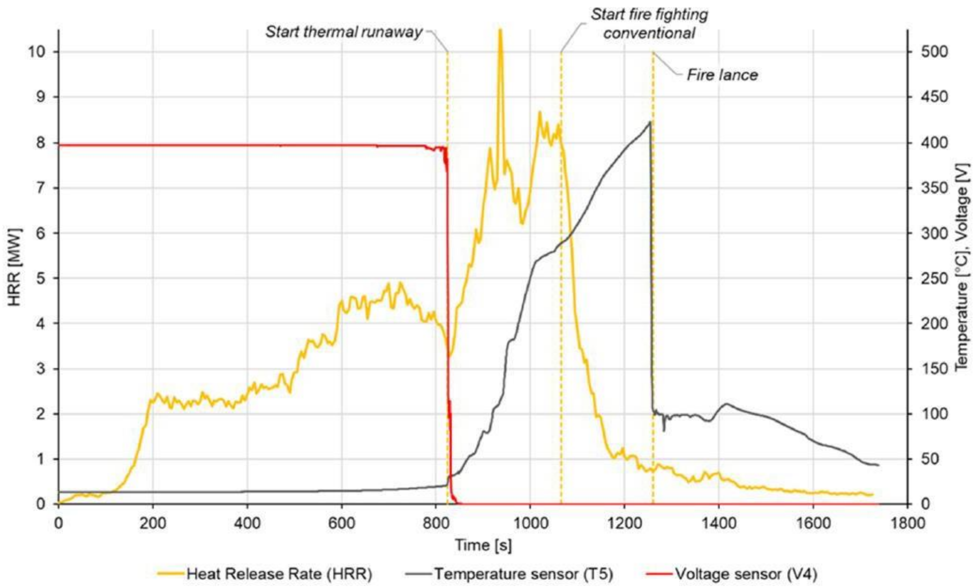

FIGURE 37 BEV TEST: HRR, TENSION AND TEMPERATURE [25]

This can be observed in Figure 39, relative to the measurements made, as at 820 seconds from the beginning of the test the battery voltage dropped in a few seconds from 400 V to zero, consequently at the beginning of the thermal runaway and its short circuit, while at the same time the temperature began to rise suddenly.

Second part

Modelling

13. Introduction

The FDS program, Fire Dynamics Simulator [38], an open-source computational fluid dynamics modelling (CFD) software developed by the National Institute of Standard and Technology (NIST) of the United States, was used to simulate the types of fire mentioned in the literature. It is a program for the study and resolution of Navier-Stokes equations for low-speed flows, with iteration between heat and fumes developed during combustion.
SMW, Smokeview [39], a visualization program developed by the same institute, was used to display the obtained data.
Two distinct environments have been modelled: a first model of an underground car park on floor -1, in which there are 10 vehicles with the same characteristics, a cavity, a large entrance and four side openings closed with windows, while the second environment studied consists of a tunnel with only one vehicle inside and an opening for ventilation on the ceiling. The models were developed by varying the heat release according to the type of vehicle considered.

14. Targets

The objective of the modelling is to create a simulation as close to reality as possible to visualize the development of fires and determine the differences in heat release of different types of vehicles, mainly BEVs and ICEVs, in varying ventilation conditions and in different environments. Finally, switching off is simulated with the intervention of automatic sprinklers.

15. Parameters

In the assessment of the fire, the parameters regarding the heat release rate per unit area (HRRPUA) for the two types of vehicles taken into account were changed between ICEV and BEV; the values were estimated on the basis of the data obtained from the combustion of vehicles in the experimental test carried out at the Zentrum am Berg tunnel research facility [25], previously considered.

The heat release of an electric vehicle is approximate around a value of 7 thermal MWs; consequently, if this value is compared with the size of the stylised cars in the modelling, a HRRPUA value of 219 kW/m 2 can be estimated with a good approximation for the BEV, whereas for an internal combustion vehicle having a 5 MW release, approximated downwards considering the high fuel variability present in the vehicle, and consequently an HRRPUA of 156 kW/m 2.

The test of hybrid vehicles is not performed because the values obtained for the two extreme cases BEV and ICEV are similar, and since the values of the Hybrids vary between these extremes it would make the representations less clear. Moreover, there would be very variable reference values depending on the type of hybrid and the consequent capacity of the storage system.

16. Parking model simulation

For the modelling of the underground parking on FDS a code has been elaborated starting from the creation of a mesh with dimensions 16x15x2.4 with the origin of the central points to the system. The program processes the development for a time of 1200 seconds, or 20 minutes, which is the average time of the development of a fire before the intervention for extinguishing; the program performs the analysis at 3000 frames per second.

```
&MESH IJK=32,30,10, XB= 0.0, 8.5, 0.5, 8.5, 0.0,2.4 /
&MESH IJK=32,30,10, XB=-8.5, 0.0, 0.5, 8.5, 0.0,2.4 /
&MESH IJK=32,30,10, XB= 0.0, 8.5, -7.5, 0.5, 0.0,2.4 /
&MESH IJK=32,30,10, XB=-8.5, 0.0, -7.5, 0.5, 0.0,2.4 / MULT_ID='mesh' /
&MULT ID='mesh', DX=2.5, DY=2.5, I_UPPER=1, J_UPPER=1 /

&TIME T_END=1200. /

&DUMP NFRAMES=3000, DT_HRR=5., DT_DEVC=5. /
```

[38]

FIGURE 38 STRUCTURE OF THE UNDERGROUND PARKING [39]

Two different materials were defined, the "BRICK" with characteristics similar to concrete for the definition of the walls defined as 'WALL' surfaces, and the 'car_mat' to define the characteristics of the vehicles, then divided into two different surfaces to distinguish the vehicle that will undergo combustion and adjacent vehicles.

```
&MATL ID = 'MATTONE'
     CONDUCTIVITY = 0.48
     SPECIFIC_HEAT = 0.84
     DENSITY       = 1440. /

&MATL ID='car_mat'
    CONDUCTIVITY=54.0
    SPECIFIC_HEAT=0.465
    DENSITY=7850.0 /

&SURF ID='first_car'
     HRRPUA=211.86
     TAU_Q=-600
     COLOR='FLESH' /

&SURF ID='car'
     MATL_ID='car_mat'
     HRRPUA=211.86
     TAU_Q=-600,
     IGNITION_TEMPERATURE=250.
     THICKNESS=0.005,
     BACKING='EXPOSED'
     COLOR='DARK OLIVE GREEN 1' /


&SURF ID            = 'WALL'
      COLOR         = 'BRICK'
      DEFAULT       =. TRUE.
     RGB           = 200,200,200
     MATL_ID       = 'MATTONE'
     THICKNESS      = 0.03 /
```

[38]

Then the walls, the entrance, the windows and the open surfaces were created, and finally the position of the vehicles with the appropriate parameters and conditions (visible in Figure 41, the vehicle from which the fire starts is indicated in orange).

```
&OBST XB= 7.5, 7.75, -7.5, 7.5 ,0.0, 2.4, SURF_ID='WALL' / E wall
&OBST XB= -7.5, -7.75, -7.5, 7.5 ,0.0, 2.4, SURF_ID='WALL' / W wall
&OBST XB= -7.75, 7.75, 7.5, 7.75,0.0, 2.4, SURF_ID='WALL' / N wall
```

```
&HOLE XB= -1.5, 1.5, 7.0, 8.0 ,0.0, 2.0 / N entrance

&HOLE XB= 7.0, 8.0, 2.0, 7.0 ,2.0, 2.2, COLOR='PALE GREEN', DEVC_ID='N_ broke', TRANSPARENCY=.6 / NE window
&HOLE XB= -7.0, -8.0, 2.0, 7.0 ,2.0, 2.2, COLOR='PALE GREEN', DEVC_ID='NW_broke', TRANSPARENCY=.6 / NWwindow
&HOLE XB= 7.0, 8.0, -2.0, -7.0 ,2.0, 2.2, COLOR='PALE GREEN', DEVC_ID='SE_broke', TRANSPARENCY=.6 / SE window
&HOLE XB= -7.0, -8.0, -2.0, -7.0 ,2.0, 2.2, COLOR='PALE GREEN', DEVC_ID='SW_broke', TRANSPARENCY=.6 / SW window

&VENT XB= -7.5, 7.5, -7.5, 7.5 ,2.4, 2.4, SURF_ID='WALL' / soffit
&VENT PBX= 8.5, SURF_ID='OPEN' / E opening
&VENT PBX=-8.5, SURF_ID='OPEN' / W opening
&VENT PBY= 8.5, SURF_ID='OPEN' / N opening

&OBST XB= 3.0, 7.0, 5.0, 7.0 ,0.2, 1.5, SURF_ID='car' / +E2 car
&OBST XB= 3.0, 7.0, 2.0, 4.0 ,0.2, 1.5, SURF_ID='car' / +E1 car
&OBST XB= 3.0, 7.0, -1.6, 0.4 ,0.2, 1.5, SURF_ID='car' / E0 car,
&OBST XB= 3.0, 7.0, -2.0, -4.0 ,0.2, 1.5, SURF_IDS='first_car','first_car','car' / -E1 car
&OBST XB= 3.0, 7.0, -5.0, -7.0 ,0.2, 1.5, SURF_ID='car' / -E2 car
&OBST XB=-3.0, -7.0, 5.0, 7.0 ,0.2, 1.5, SURF_ID='car' / +W2 car
&OBST XB=-3.0, -7.0, 2.0, 4.0 ,0.2, 1.5, SURF_ID='car' / +W1 car
&OBST XB=-3.0, -7.0, -1.0, 1.0 ,0.2, 1.5, SURF_ID='car' / W0 car
&OBST XB=-3.0, -7.0, -2.0, -4.0 ,0.2, 1.5, SURF_ID='car' / -W1 car
&OBST XB=-3.0, -7.0, -5.0, -7.0 ,0.2, 1.5, SURF_ID='car' / -W2 car
```

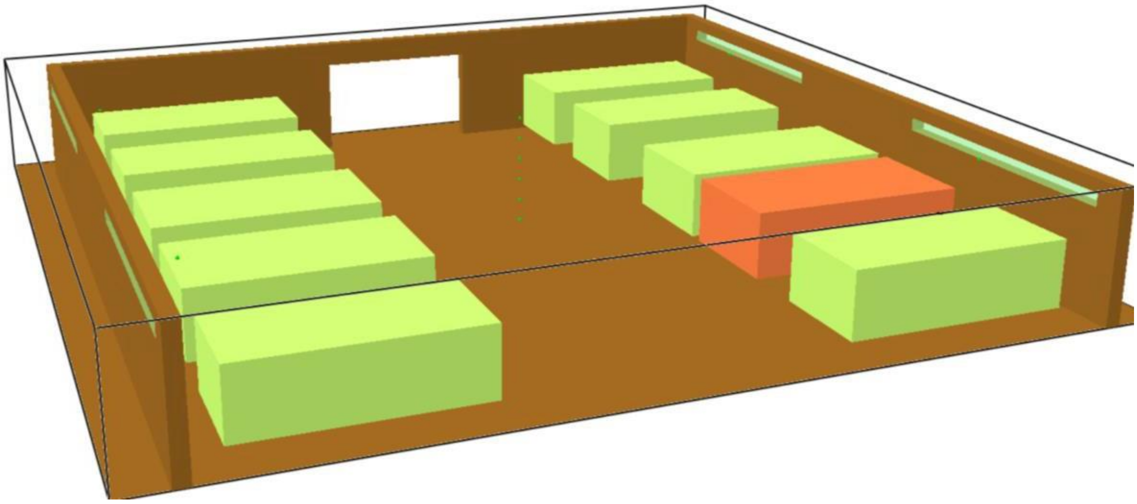

FIGURE 39 STRUCTURE OF THE UNDERGROUND PARKING WITH THE VEHICLES POSITIONED AND SIDE WINDOWS [39]

With "ignition particle" the ignition point has been defined, positioned inside the vehicle defined as first vehicle.

```
&PART ID='ignitor particle', SURF_ID='ignitor', STATIC=.TRUE. /
&SURF ID='ignitor', TMP_FRONT=1000., EMISSIVITY=1., GEOMETRY='CYLINDRICAL', LENGTH=0.15, RADIUS=0.01 /
&INIT XB=2.4,2.7,4.1,4.4,0.60,0.70, PART_ID='ignitor particle', N_PARTICLES_PER_CELL=1, CELL_CENTERED=T /
```

The side openings are defined as closed, but open when the temperature reaches 300 ºC, which occurs at different times depending on the ventilation and will affect the spread of fire and smoke circulation. This ideally represents the cracking of the glass in the side openings that would occur in real conditions around that temperature.

```
&DEVC ID='NE_broke', XYZ= 7.0, 4.5, 2.1, QUANTITY='TEMPERATURE', SETPOINT=300. /
&DEVC ID='NW_broke', XYZ=-7.0, 4.5, 2.1, QUANTITY='TEMPERATURE', SETPOINT=300. /
&DEVC ID='SE_broke', XYZ= 7.0, -4.5, 2.1, QUANTITY='TEMPERATURE', SETPOINT=300. /
&DEVC ID='SW_broke', XYZ=-7.0, -4.5, 2.1, QUANTITY='TEMPERATURE', SETPOINT=300. /
```

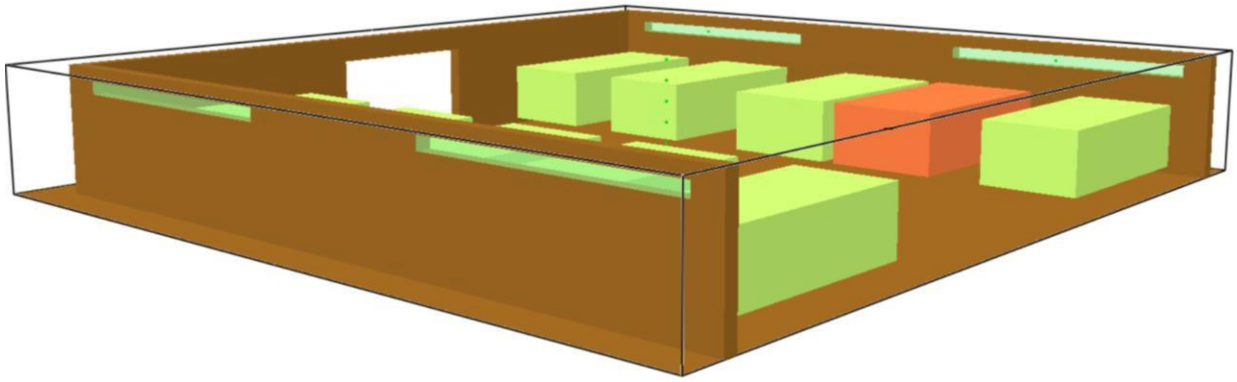

FIGURE 40 LATERAL VISION, DETAIL OF SIDE WINDOWS AND CAVITIES [39]

In the final section the positions of the thermocouples were defined to evaluate the temperatures, in particular along the central axis of the system, then the requests for the evaluation of the flows, convective conductive and radiated, the temperature on the walls, the development of the heat release and the parameters for analysing the direction and velocity of the incoming air and the hot fumes coming out.

```
&DEVC XYZ=0.1,0,2.39, QUANTITY='THERMOCOUPLE', ID='2.4' /
&DEVC XYZ=0.1,0,2.0, QUANTITY='THERMOCOUPLE', ID='2.0' /
&DEVC XYZ=0.1,0,1.6, QUANTITY='THERMOCOUPLE', ID='1.6' /
&DEVC XYZ=0.1,0,1.2, QUANTITY='THERMOCOUPLE', ID='1.2' /
&DEVC XYZ=0.1,0, .8, QUANTITY='THERMOCOUPLE', ID='0.8' /
&DEVC XYZ=0.1,0, .4, QUANTITY='THERMOCOUPLE', ID='0.4' /
&DEVC XYZ=0.1,0,2.0, QUANTITY='FED', ID='FED' /
&DEVC XB=0.1,0.1,0,0,0.0,2.4, QUANTITY='LAYER HEIGHT', ID='layer_h' /

&ISOF QUANTITY='TEMPERATURE', VALUE (1) =60.0 /
&ISOF QUANTITY='VISIBILITY', VALUE (1) =10.0 /

&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /
&BNDF QUANTITY='NET HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /
&BNDF QUANTITY='ADIABATIC SURFACE TEMPERATURE' /

&SLCF PBX= 0.1, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY= -3., QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBX= 0.1, QUANTITY='VISIBILITY' /
&SLCF PBZ= 2.0, QUANTITY='VISIBILITY' /

&TAIL /
```

16.1 Graphic elaboration

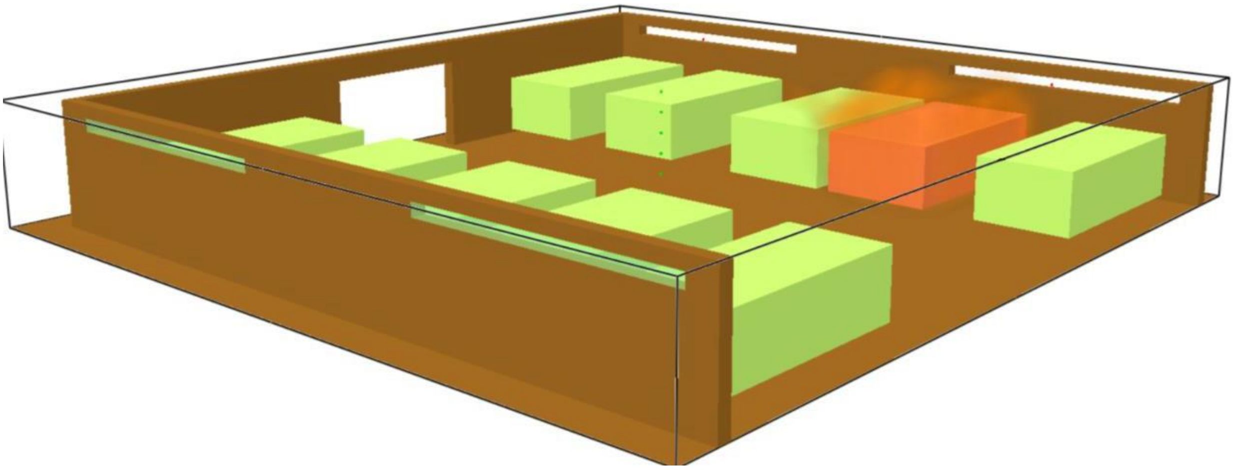

FIGURE 41 DETAIL OF THE DEVELOPMENT OF FLAMES (75S) **[39]**

The graphical visualization program SMW [39] is used to graphically analyse the complete development of the fire starting from the ignition, increase of the flames, development of the smoke and air recirculation as shown in figures 43-53, useful for the analysis of the flame behaviour and related parameters:

- Figure 43 Initial development of flames from the "pilot" car highlighted in orange
- Figure 44 Development of fumes at initial combustion, side openings still intact
- Figure 45 Development of smoke at developed fire, escape from the main entrance and from the lateral openings following the explosion of the glass at the target temperature
- Figure 46, equal to Figure 45 but with lateral vision highlighting the side openings
- Figure 47 section of the temperatures along the central axis of the model and perpendicular to the same at the height of the burning vehicle, shows how the heated air flows along the ceiling towards the entrance, the only point of exit for the fumes at the initial moments
- Figure 48 Fire temperature detail developed with evidence on ignition of adjacent vehicle
- Figure 49 Detail of the burning rate in kg/m 2/s with evidence of the fire of the adjacent vehicle with initial values around 5*10 -3 for the second vehicle and around 9.9*10 -3 for the first vehicle
- Figure 50 Detail of flows exchanged (total flow) in kW/m 2
- Figure 51 Detail of the direction and velocity of the circulating air at fire with directional vectors, evidence of cold air entering at high speed at the lower part of the central opening
- Figure 52 Temperature detail and direction of flame propagation with directional vectors, evidence of convective motion above the burning vehicle
- Figure 53 Detail of smoke propagation and relative temperature at start of fire (50s)

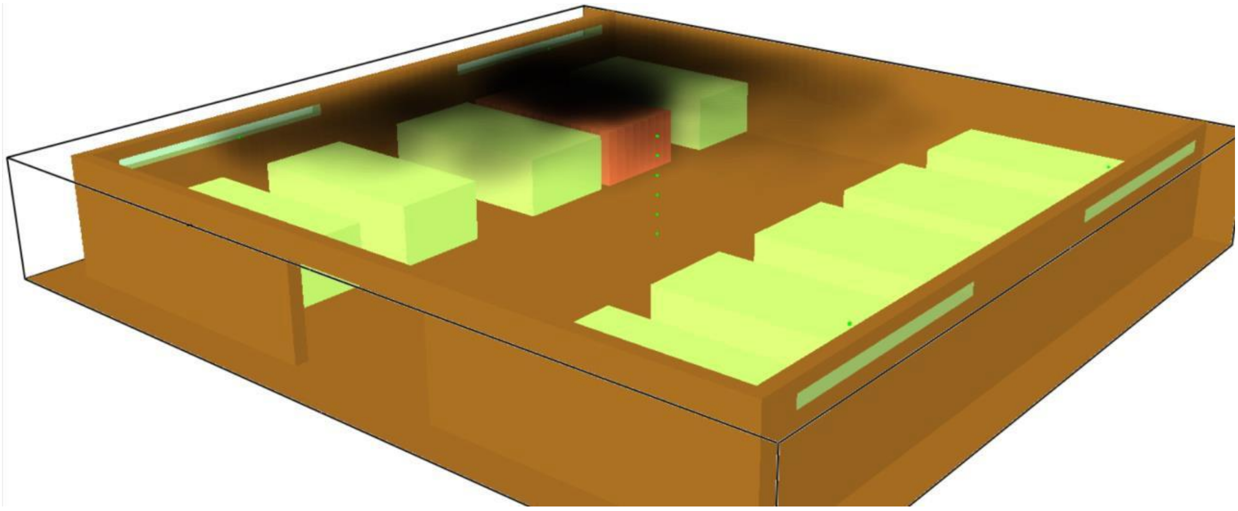

FIGURE 42 DEVELOPMENT OF SMOKE IN THE ENVIRONMENT AT THE BEGINNING OF COMBUSTION (50S)[39]

FIGURE 43 DEVELOPMENT OF SMOKE IN THE MODEL AS THE FIRE HAS SPREAD (400S) [39]

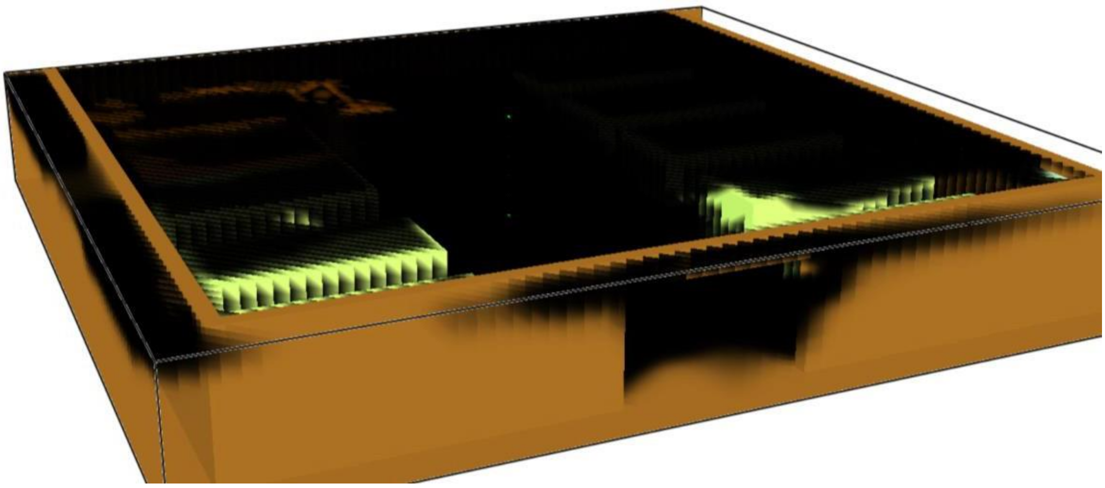

FIGURE 44 DETAIL OF THE DEVELOPMENT OF SMOKE AS THE FIRE HAS SPREAD, WITH EXPLODED LATERAL WINDOWS (LEFT SIDE) (600S)[39]

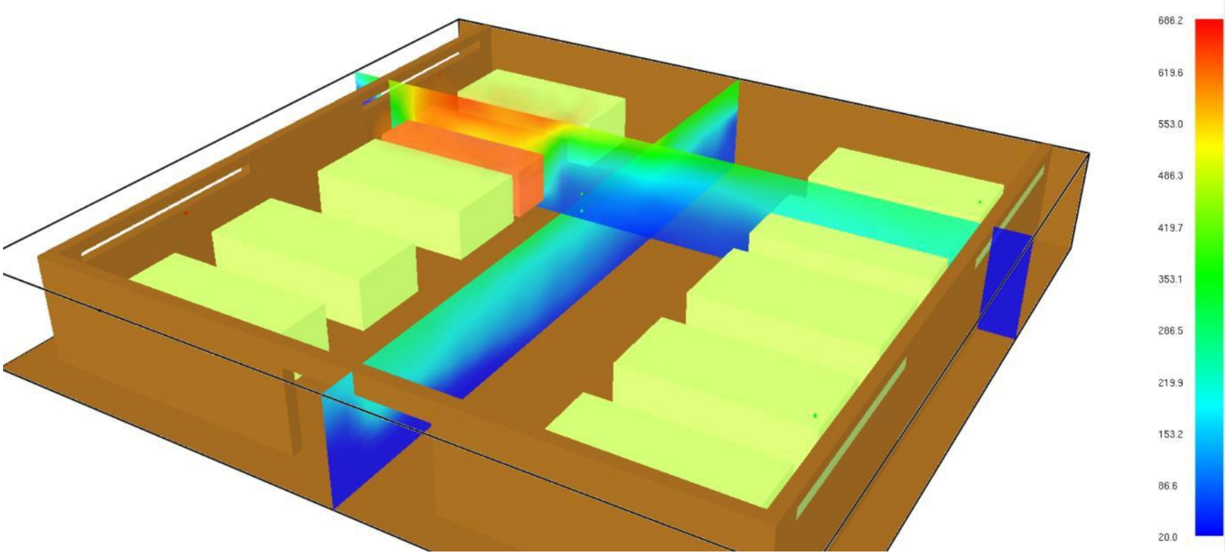

FIGURE 45 FRAME THAT SHOWS THE DEVELOPMENT OF TEMPERATURES °C IN THE ENVIRONMENT AT (1135S) [39]

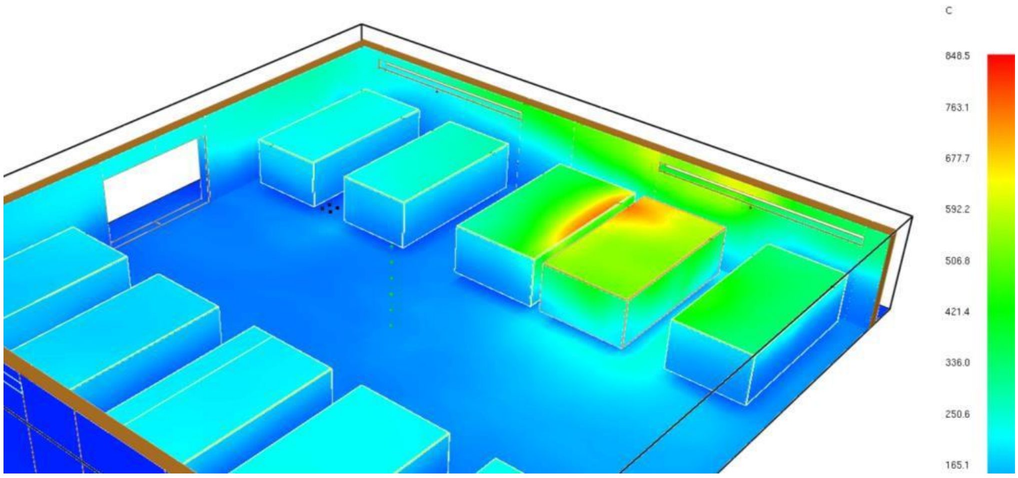

FIGURE 46 DISPLAY OF ADIABATIC SURFACES WHICH SHOWS PRESENCE OF FIRE IN THE ADJACENT VEHICLE AS WELL (1125S) [39]

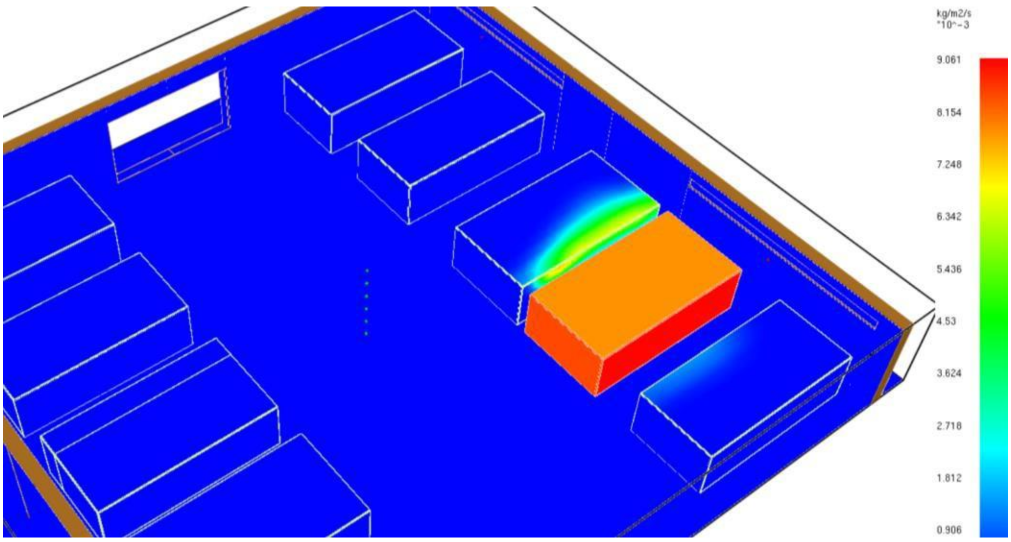

FIGURE 47 DISPLAY OF THE BURNING RATE IN THE PARKING LOT (EXPRESSED IN KG/M^2/S), WITH EVIDENCE OF FIRE IN THE ADJACENT VEHICLE (1125S) [39]

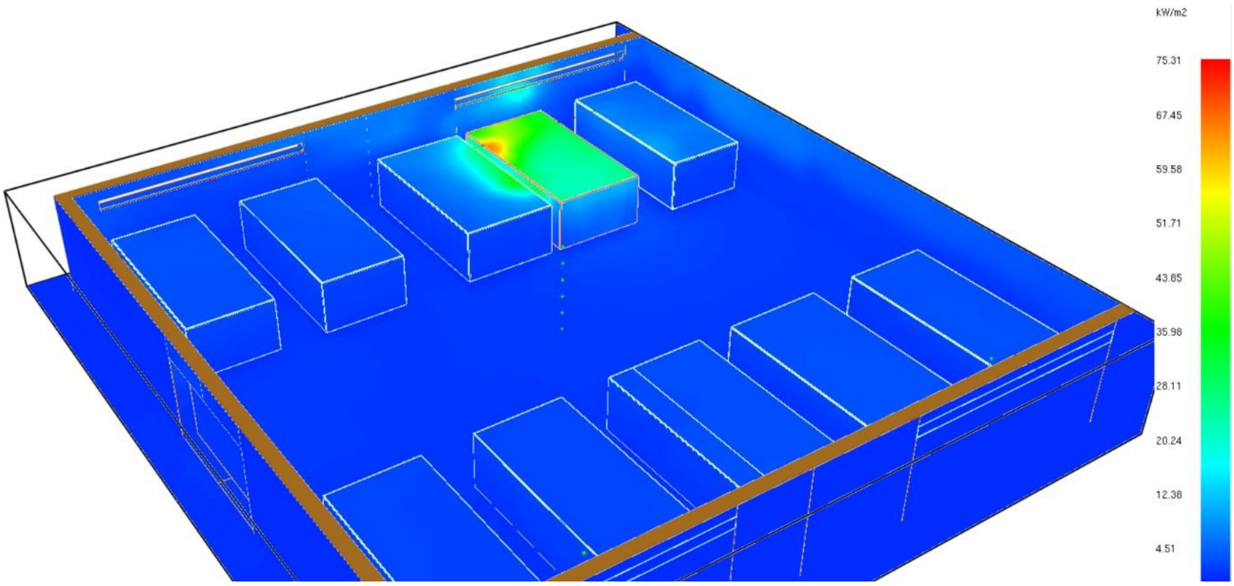

FIGURE 48 DETAIL OF THE EXCHANGED, CONVECTIVE AND RADIATIVE FLUXES WHEN THE FIRE HAS STARTED (30S) [39]

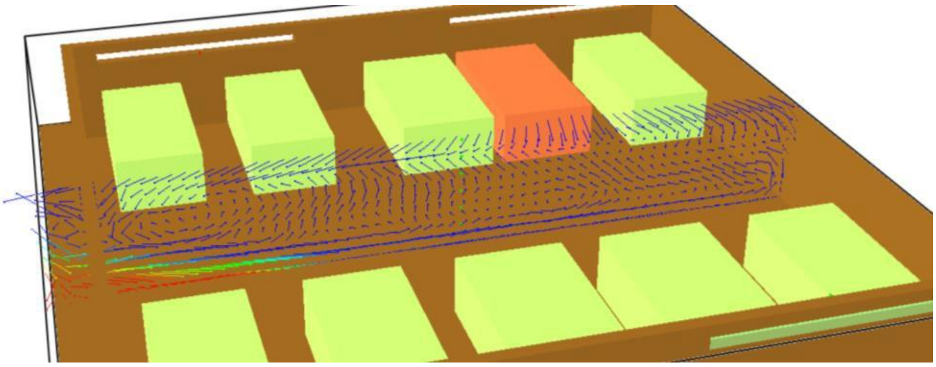

FIGURE 49 DETAIL OF DIRECTION AND VELOCITY OF CIRCULATING AIR AT DEVELOPED FIRE (50S) [39]

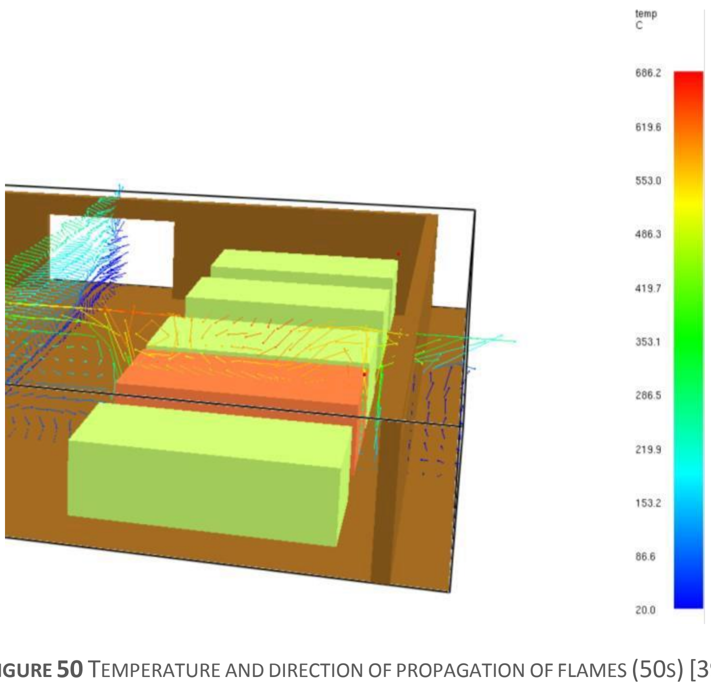

FIGURE 50 TEMPERATURE AND DIRECTION OF PROPAGATION OF FLAMES (50S) [39]

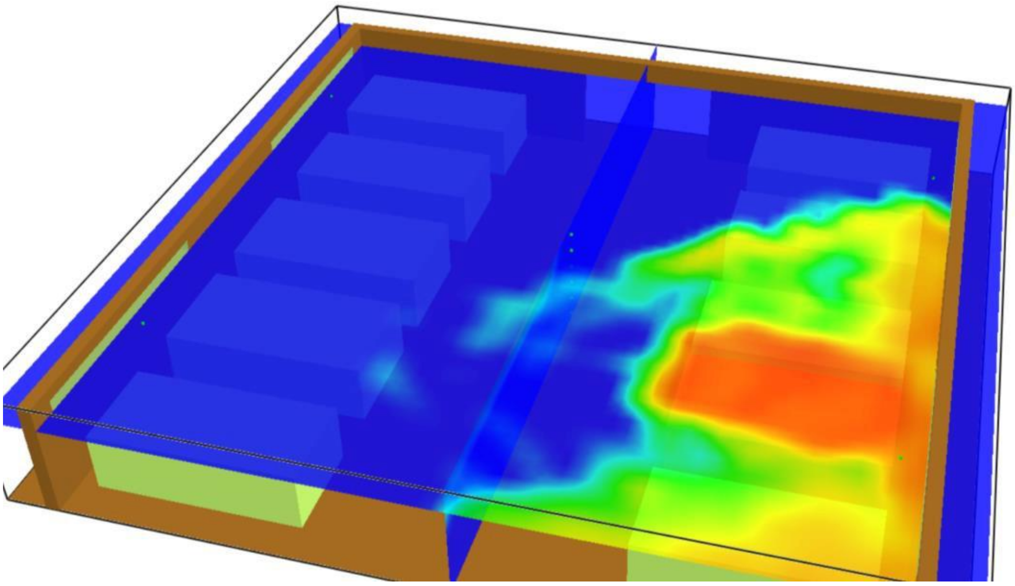

FIGURE 51 PROPAGATION OF SMOKE AT BEGINNING OF THE FIRE (50S) [39]

16.2 Ventilation variation

The values obtained were compared by limiting the ventilation and increasing it, in particular by opening all four side openings and keeping them closed. The study was carried out with the parameters described above relating to a BEV, the key vehicle of the study, and subsequently with an ICEV.

The variation was made on the side openings, going to vary the temperature at which they open, starting from the standard case with glass explosion at 300 ºC and then processing a case with reduced ventilation without opening the windows and reduced ventilation from the main entrance, and finally a case with increased ventilation keeping the side windows open immediately; the entrance has a surface of 6 m^2 and the variation in ventilation is given by the natural convective flow of air over the four side windows of 5 m^2 each.

There is less variation in temperature and heat release for reduced ventilation because the flames have less oxygen available and about the same time the saturated smoke chamber compresses the heat release values, while for the case of increased ventilation (red) the highest release values are achieved, as might be expected, particularly in the BEV case. The difference between normal and increased ventilation is about 1MW while for reduced ventilation and hardly comparable as it is saturated in about half the time. The processed data, however, deviate from the Real behavior because the thermal runaway does not require external oxygen because it is self-powered, this parameter could not be included in the modelling, so the BEV case is more imprecise in case of reduced ventilation.

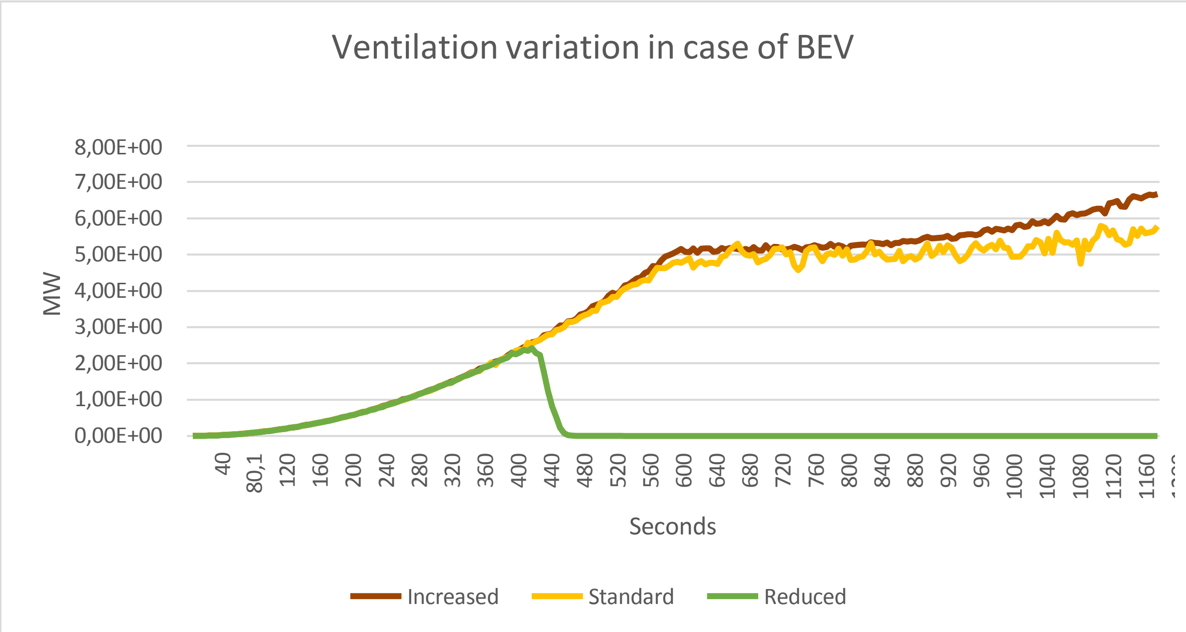

FIGURE 52 HRR IN RELATION TO TIME IN THE BEV CASE [38]

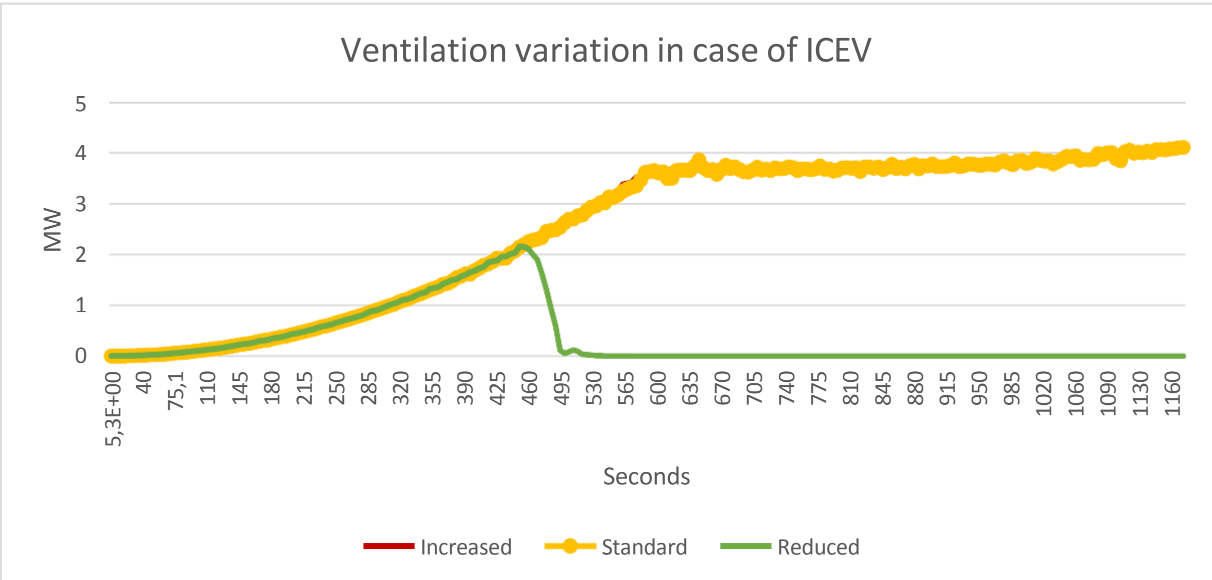

FIGURE 53 HRR IN RELATION TO TIME IN THE ICEV CASE [38]

16.3 Analysis results

Considering the overall model of the underground car park, the heat release values obtained are higher for battery-powered vehicles, as per the parameters set, the maximum was estimated at 7MW for BEV and 5MW for ICEV, and up to 1200 seconds of computation you get comparable values, respectively of 5.8 MW and 4.3 MW. Considering the case of normal ventilation reported in Figure 56, it can be said that a modelling with an acceptable approximation has been obtained, referring to the actual experiments previously analysed, Even more precise values could have been obtained with longer computational times. It is noted that the development of the fire develops regularly with the release of heat with a similar trend until reaching a plateau close to its maximum HRR values, the small successive variations are consequent to the convective motions and the air flows in input and output, moreover it is evident in particular in the case of the BEV that towards the end of the computation there is a slight increase due to the ignition of the adjacent vehicle, with a longer development one might expect to see values increase as a result of the development of flames on all vehicles.

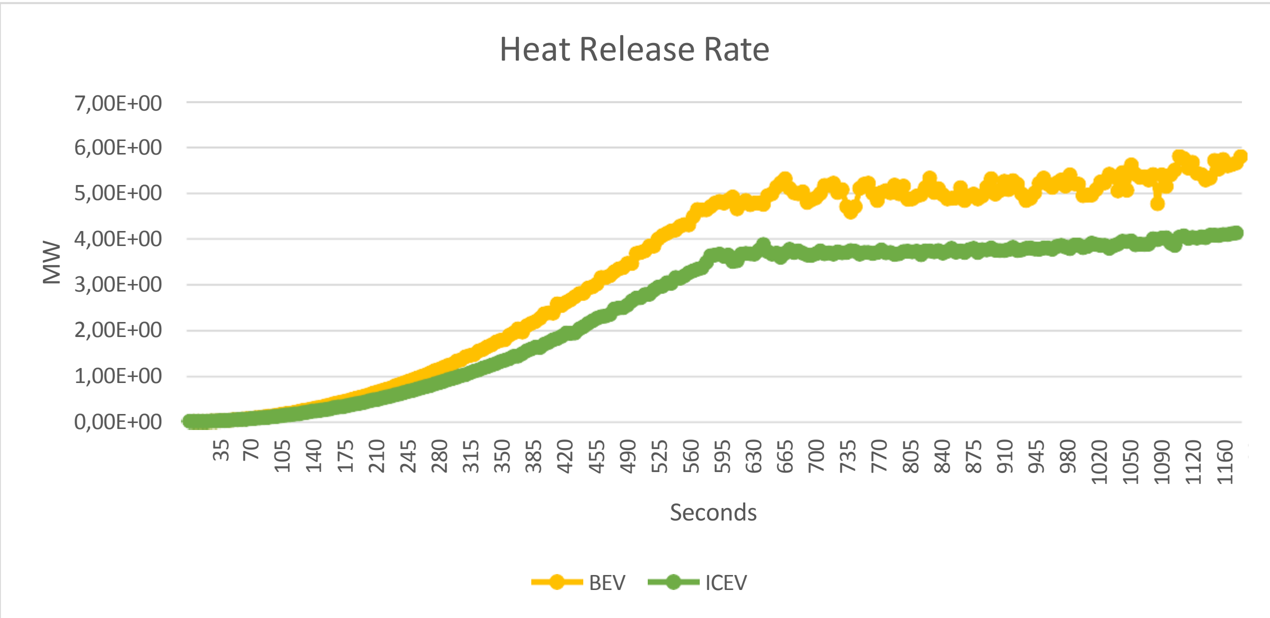

FIGURE 54 COMPARISON OF HRRS OF A BEV AND AN ICEV IN CASE OF STANDARD VENTILATION.[38]

16.4 Firefighting

An automated extinguishing system was modelled by activating 3 water jets positioned centrally at the parking lot, which through sprinklers (figure 57) vaporize water in the entire room. The set parameters are a flow rate of 80 liters per minute and 10 m/s as the output speed of the jet, values comparable to the standard of fire protection systems. The ignition of the jets takes place 500 seconds after the start of the modelling, since for fires in particular places such as tunnels or parking at risk a first intervention is estimated within 10 minutes: in the case modelled then 8.20 minutes from the start of the fire were considered.

FIGURE 55 EXAMPLE OF SPRINKLER FOR EXTINGUISHING WITH HIGH PRESSURE WATER [40]

In figure 58 the start of the jets can be observed, and in figure 59 after about a minute as the entire floor of the parking lot is filled with water vapor (in blue in the image).

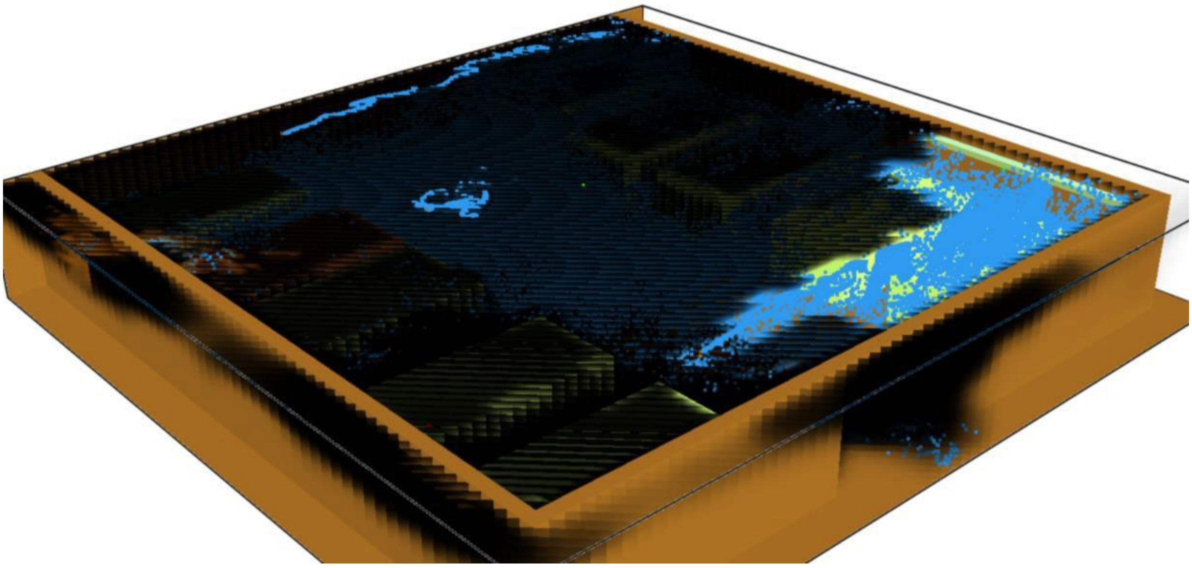

FIGURE 56 START OF SPRINKLER ACTION (520S) [39]

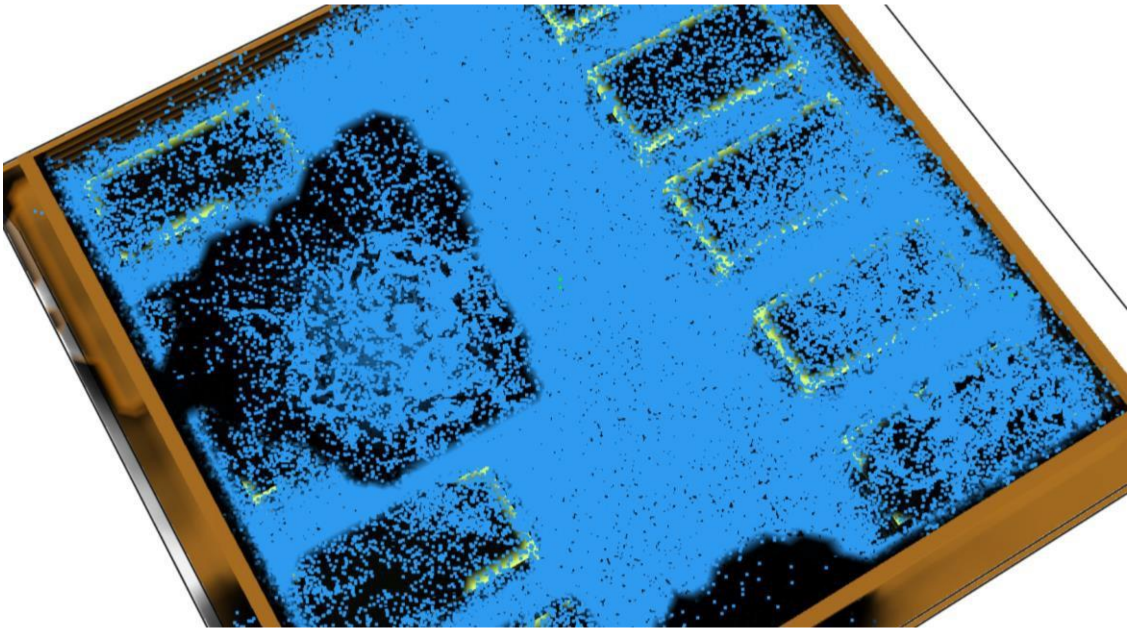

FIGURE 57 EFFECT OF SPRINKLER ACTION ON THE PARKING.[39]

The graph below shows the values of heat release of a BEV in standard ventilation conditions, comparing the computation without extinguishing and that with suppression of fire; it shows how at the start of the water jets the release of heat collapses, as well as the temperature, and within 100 seconds the fire turns out to be practically inactive. At about 620 seconds the values of the version with extinguishing reset.

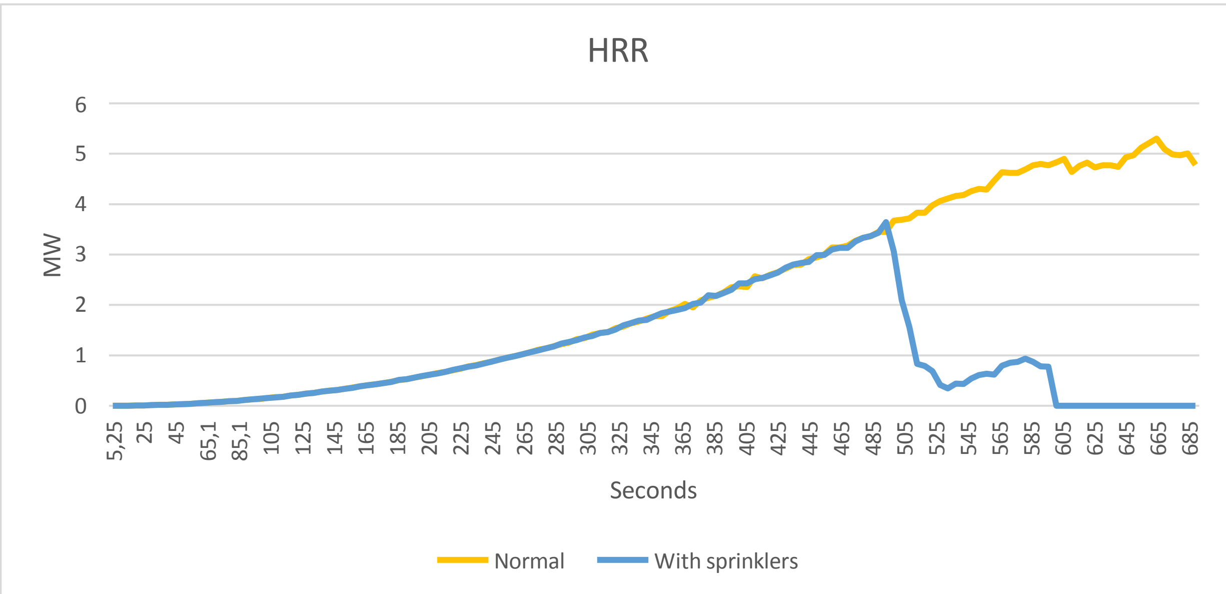

FIGURE 58 COMPARISON OF HRR OF A BEV IN THE STANDARD CASE AND IN THE CASE OF EXTINGUISHING WITH SPRINKLERS.[38]

17. Tunnel model simulation

For the modelling of the Tunnel on FDS, a code has been elaborated starting from the creation of a mesh with dimensions 6.5x20.5x5.5 with the origin of the points in an extreme. The program processes the development for a time of 655 seconds, that is 11 minutes, the average time of the development of a fire before the intervention for extinguishing, because in environments such as tunnels with significant traffic staff specialized in extinguishing is always on alert; the program analyses at 3000 frames per second.

Since the length of the tunnel is assumed as less than 500 meters, it is not necessary to insert a forced ventilation system, therefore only a ventilation chimney was modelled.

Subsequently, as with the previous modelling, two different materials were defined, the "BRICK" with characteristics similar to concrete for the definition of the walls defined as 'WALL' surfaces, and the 'car_mat' to define the characteristics of the vehicle.

```
&MESH IJK=65,205,55, XB= 0,6.5,0,20.5,0,5.5/

&TIME T_END=1200. /
&DUMP NFRAMES=3000, DT_HRR=5., DT_DEVC=5. /

&MATL ID = 'MATTONE'
     CONDUCTIVITY = 0.48
     SPECIFIC_HEAT = 0.84
     DENSITY = 1440. /

&MATL ID='car_mat'
    CONDUCTIVITY=54.0
    SPECIFIC_HEAT=0.465
    DENSITY=7850.0 /

&SURF ID='first_car'
     HRRPUA=156
     TAU_Q=-600
     COLOR='FLESH' /

&SURF ID = 'WALL'
     COLOR = 'BRICK'
     DEFAULT =. TRUE.
     RGB = 200,200,200
     MATL_ID = 'MATTONE'
     THICKNESS = 0.03 /
```

[38]

After that, the walls, the entrance, the exit and an opening for the upper ventilation, as well as the position of the vehicle with the appropriate parameters and conditions were created.

```
&OBST XB= 6.5, 6.,0, 20.5 ,0.0, 5.5, SURF_ID='WALL' / sx
&OBST XB= 0.5, 0,0, 20.5 ,0.0, 5.5, SURF_ID='WALL' / dx
&OBST XB= 0, 6.5,0, 20.5 ,5., 5.5, SURF_ID='WALL' / tetto

&HOLE XB= 0.5,6,0,0.5,0,5 / N entrance
&HOLE XB= 0.5,6,20,20.5,0,5 / N entrance
&HOLE XB= 2,4,9,10,5,5.5, COLOR='PALE GREEN', DEVC_ID='SW_broke', TRANSPARENCY=.6 / vent
```

&DEVC ID='SW_broke', XYZ=3,9.5,5, QUANTITY='TEMPERATURE', SETPOINT=300. /

&VENT PBX= 0, SURF_ID='OPEN' / E opening
&VENT PBY= 0, SURF_ID='OPEN' / N opening

&OBST XB= 3,5,8,12,0.2, 1.5, SURF_ID='first_car' /

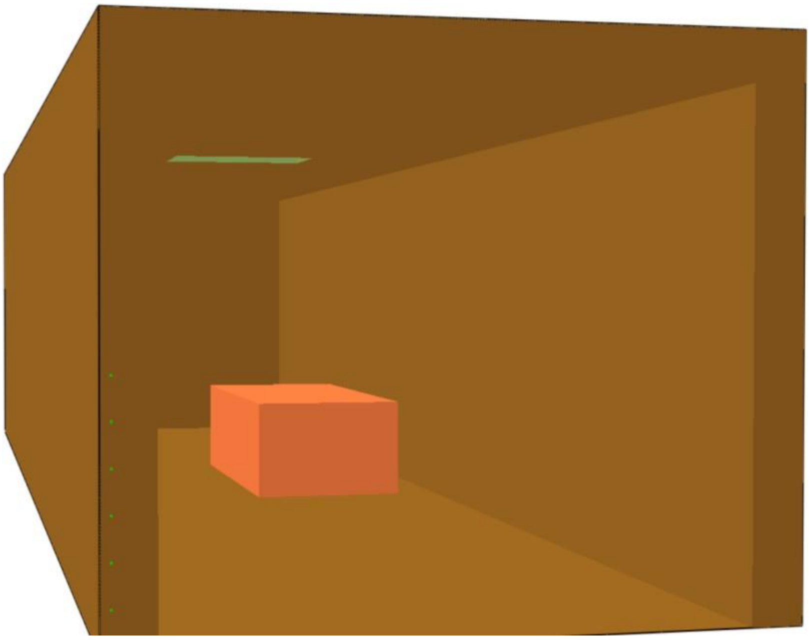

FIGURE 59 STRUCTURE OF THE TUNNEL WITH VEHICLE POSITIONED INSIDE.[39]

With ignition particle as previously defined, the ignition point was located inside the vehicle defined as first vehicles.

The upper opening is defined as closed, but it will open when the temperature reaches 300 ºC, which occurs at different times depending on the ventilation and will affect the spread of fire, the release of heat and the circulation of fumes.

&DEVC XYZ=0.1,0,2.39, QUANTITY='THERMOCOUPLE', ID='2.4' /
&DEVC XYZ=0.1,0,2.0, QUANTITY='THERMOCOUPLE', ID='2.0' /
&DEVC XYZ=0.1,0,1.6, QUANTITY='THERMOCOUPLE', ID='1.6' /
&DEVC XYZ=0.1,0,1.2, QUANTITY='THERMOCOUPLE', ID='1.2' /
&DEVC XYZ=0.1,0, .8, QUANTITY='THERMOCOUPLE', ID='0.8' /
&DEVC XYZ=0.1,0, .4, QUANTITY='THERMOCOUPLE', ID='0.4' /
&DEVC XYZ=0.1,0,2.0, QUANTITY='FED', ID='FED' /

&ISOF QUANTITY='TEMPERATURE', VALUE (1) =60.0 /
&ISOF QUANTITY='VISIBILITY', VALUE (1) =10.0 /

&PART ID='ignitor particle', SURF_ID='ignitor', STATIC=.TRUE. /
&SURF ID='ignitor', TMP_FRONT=1000., EMISSIVITY=1., GEOMETRY='CYLINDRICAL', LENGTH=0.15, RADIUS=0.01 /
&INIT XB=3.5,3.8,8,8.3,0.5,0.6, PART_ID='ignitor particle', N_PARTICLES_PER_CELL=1, CELL_CENTERED=T /

&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /
&BNDF QUANTITY='NET HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE' /
&BNDF QUANTITY='BURNING RATE' /
&BNDF QUANTITY='ADIABATIC SURFACE TEMPERATURE' /

&SLCF PBX= 0.1, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY= -3., QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBX= 0.1, QUANTITY='VISIBILITY' /
&SLCF PBZ= 2.0, QUANTITY='VISIBILITY' /

&TAIL /
[38]

In the final section the parameters to be analysed, such as air velocity/fume direction, etc., are defined. In particular, thermocouples have been placed virtually to obtain temperatures in certain positions.

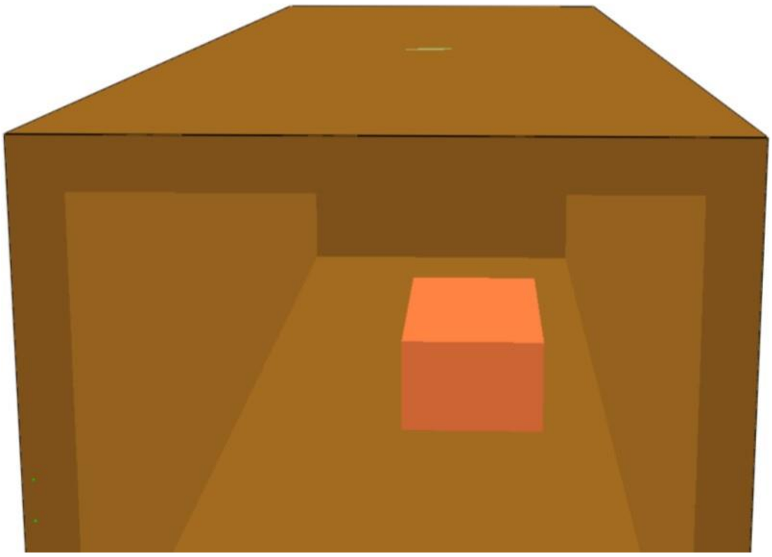

FIGURE 60 VIEW OF THE TUNNEL FROM ABOVE.[39]

17.1 Graphic elaboration

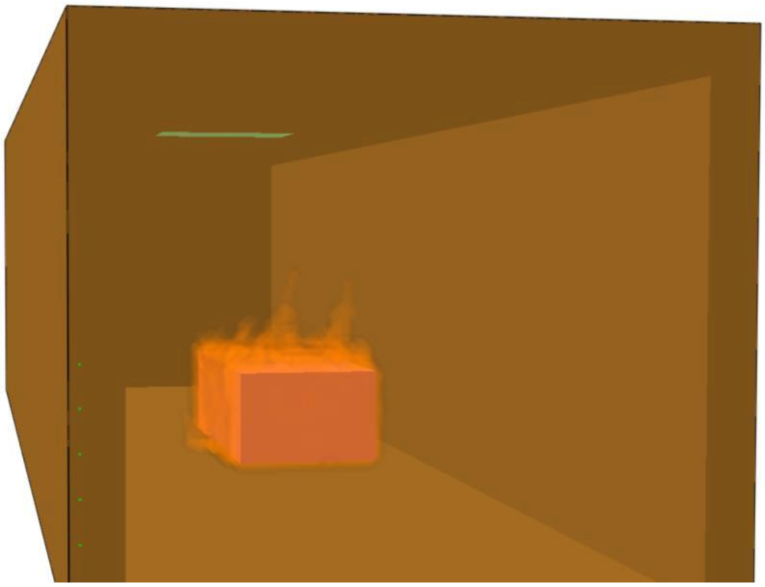

FIGURE 61 DEVELOPMENT OF FLAMES (30S) [39]

Through the SMW [39] graphical visualization program it is possible to graphically analyze the complete development of the fire starting from the ignition, increase of the flames, development of the smoke, and finally recirculation of air as shown in the figures 63- 68 used to analyse the behaviour of flames and their parameters.

- Figure 63 initial development of flames
- Figure 64 initial smoke development (28s)
- Figure 65 Development of smoke at fire initiation (450s), view from below
- Figure 66/67 Detail of temperature development along the wall at vehicle height and evidence of adjacent surfaces
- Figure 68 Detail of the total flux exchanged, convective, conductive, and irradiated at fire.

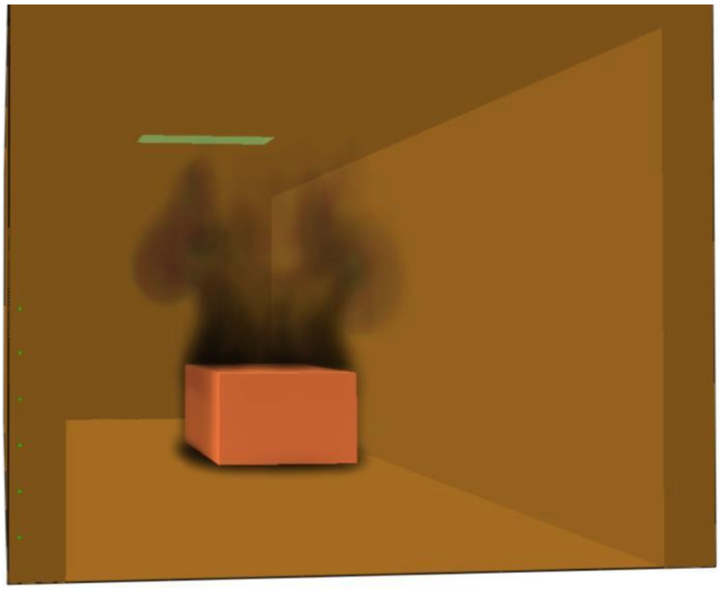

FIGURE 62 DETAIL OF SMOKE DEVELOPMENT AT BEGINNING OF COMBUSTION. (28S) [39]

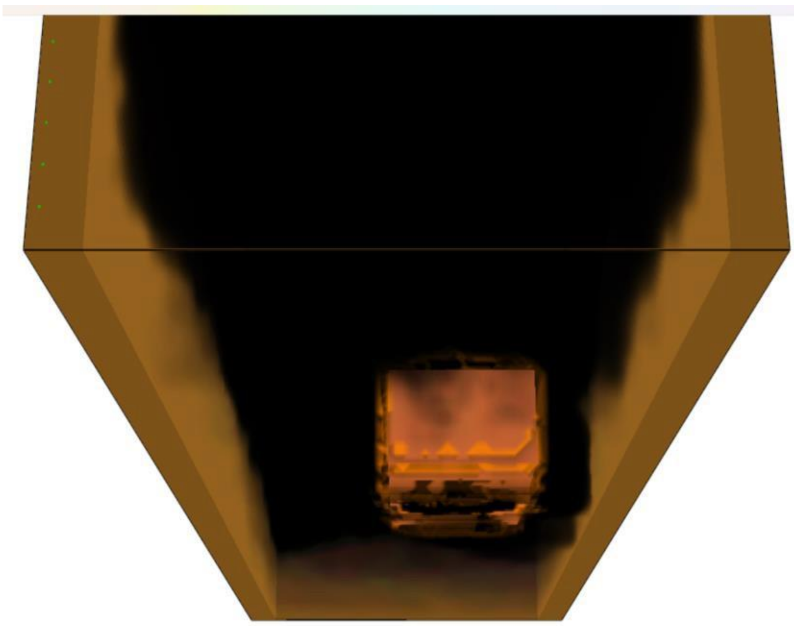

FIGURE 63 DETAIL OF SMOKE DEVELOPMENT AS FIRE IS SPREAD, VIEW FROM BELOW (450S) [39]

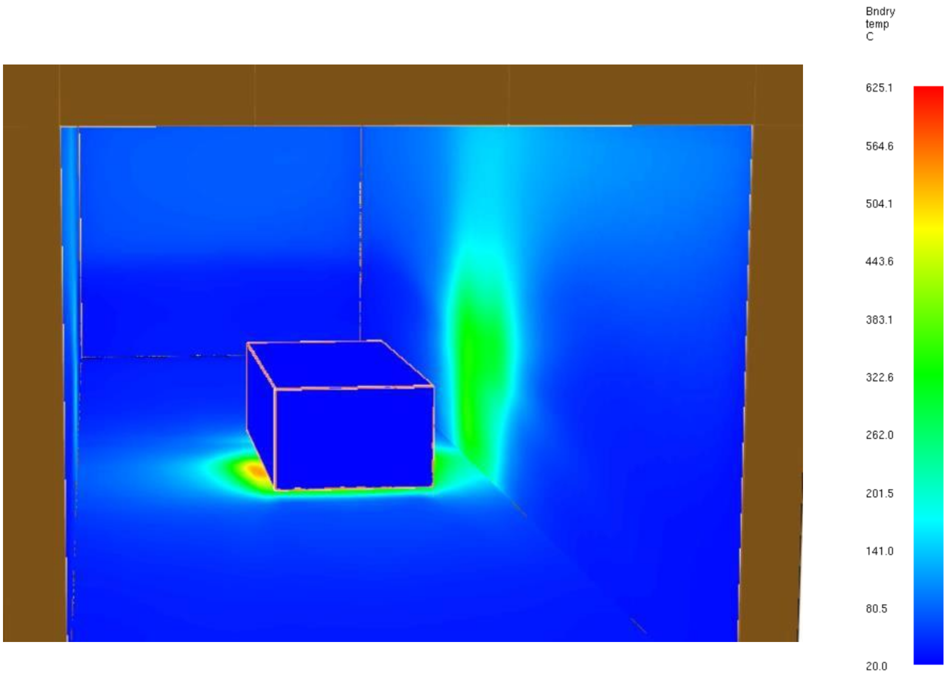

FIGURE 64 DETAIL OF WALL TEMPERATURE DEVELOPMENT (490S) [39]

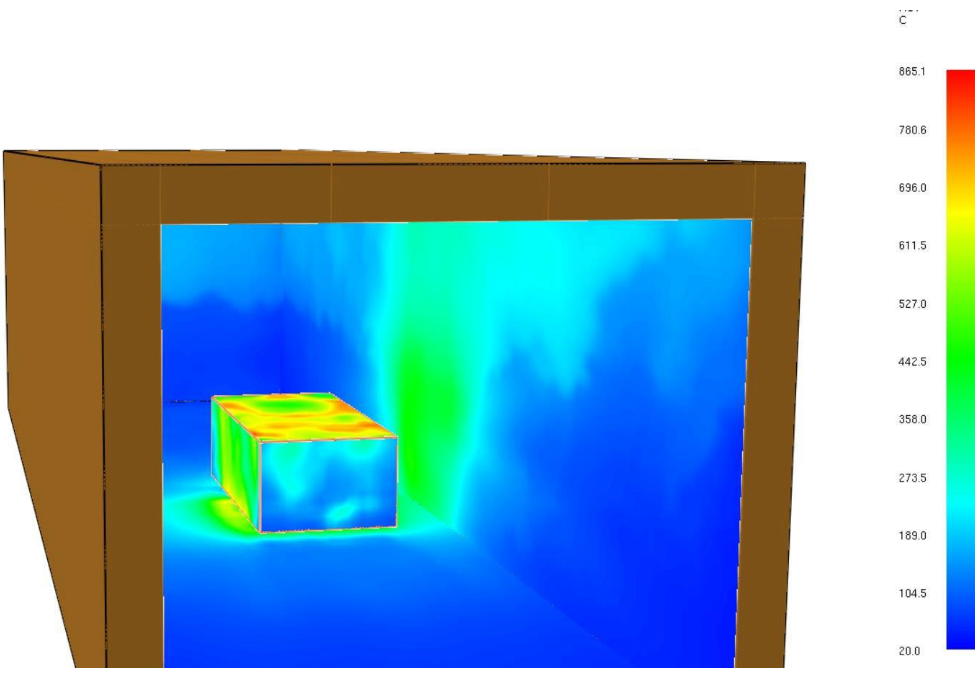

FIGURE 65 DISPLAY OF ADIABATIC SURFACES (580S) [39]

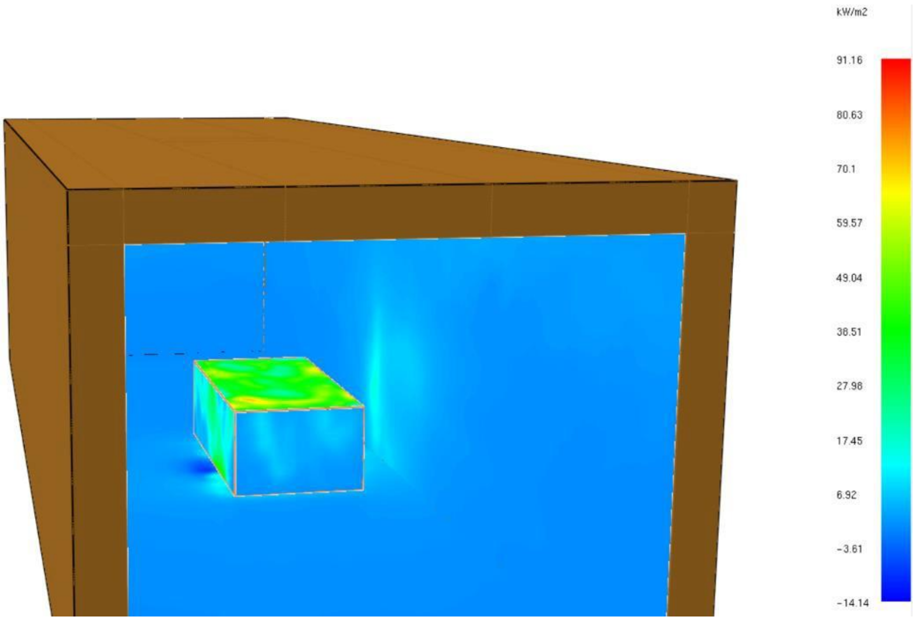

FIGURE 66 DETAIL OF EXCHANGED, CONVECTIVE AND RADIATIVE FLUXES WHEN FIRE IS DEVELOPED (82S) [39]

17.2 Analysis results

Considering the overall tunnel modelling, the heat release values obtained are higher for battery-powered vehicles, as per set parameters: the maximum was estimated at 7MW for BEV and 5 for ICEV and reaching 655 seconds of computation is approaching, respectively 7.2 MW and 4.9 MW. Considering the case shown in Figure 69, it can be said that a modelling with an acceptable approximation has been obtained by referring to the experiments previously analysed, with longer computational times it would have been possible to obtain more precise values; consider that the calculation time in the case of the tunnel is around 3 days, 72 hours, with the means available, and having noticed the achievement of a plateau after 600 seconds for the final version, the evaluation was limited to the first 655 seconds.

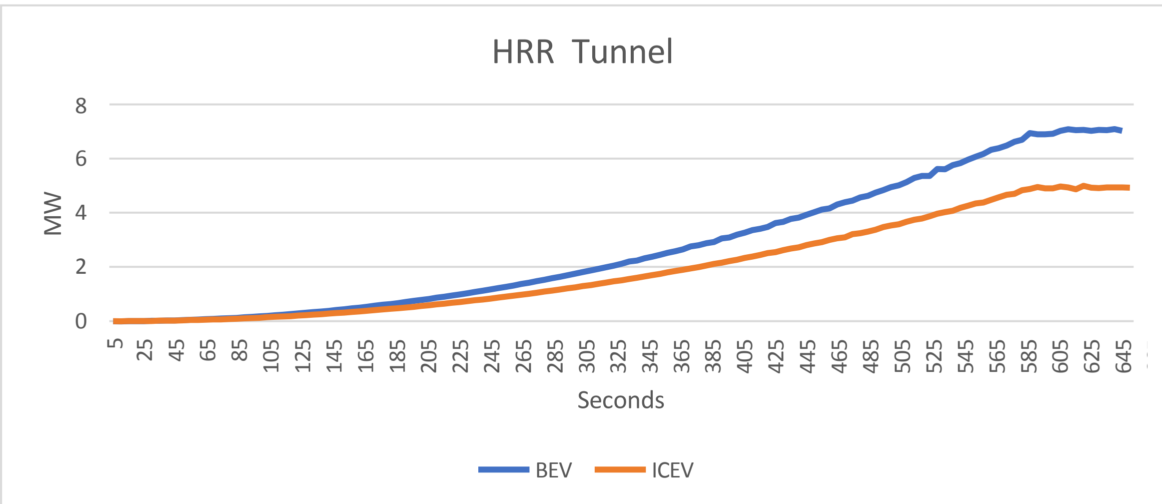

FIGURE 67 COMPARISON BETWEEN THE HEAT RELEASE RATES OF A BEV AND AN ICEV IN THE TUNNEL MODEL CASE. [38]

18. Comparison results

We can say that we have obtained a modelling with an acceptable approximation by referring to the experiments previously analysed: with the available means the computational times have been very long, about 72 hours for each model and each variation made, but with longer times or greater computing power more precise values could have been obtained and different models studied. In Figure 70 the results obtained are compared with an evaluation of 1200 seconds for parking and 660 for the tunnel, and there is a greater release of heat in the case of the tunnel at the same parameters set: this is due to the greater ventilation typical of the tunnels due to their shape and structure.

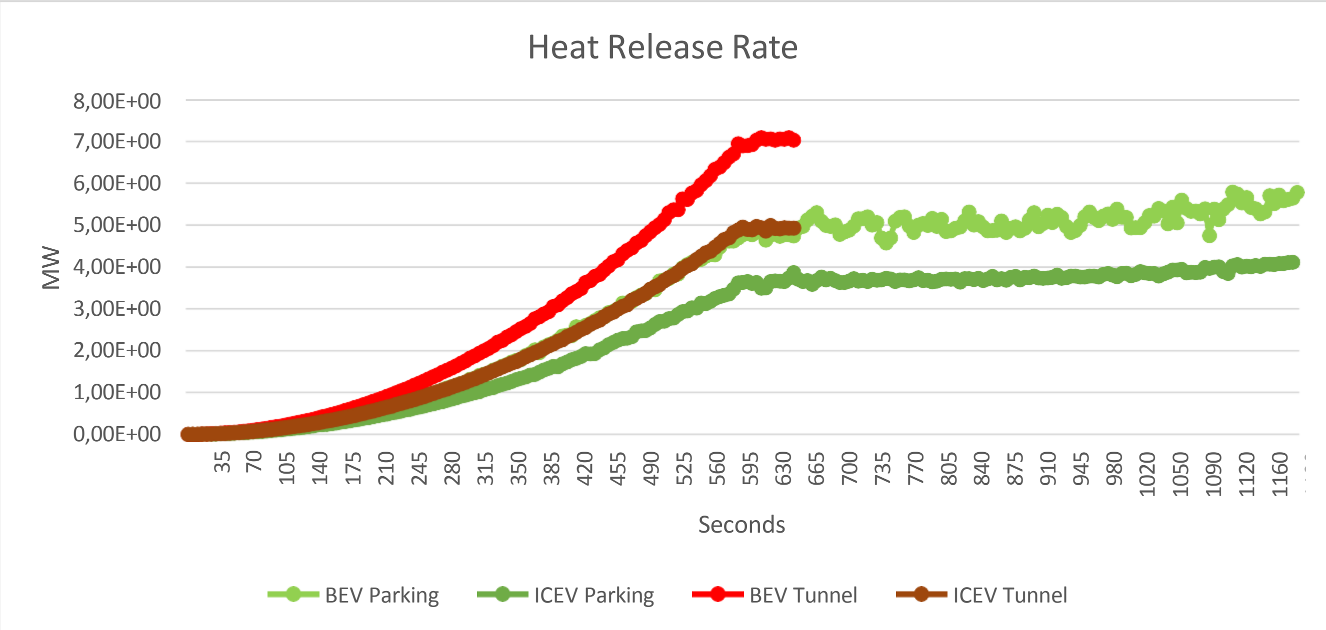

FIGURE 68 HRR COMPARISON BETWEEN THE TWO MODELS [39]

19. Conclusions

This master's thesis addresses the issue of fire risk in electric vehicles, which is a major issue for consumer safety, the environment, and the global economy. This research aimed to identify the primary sources of risk and to analyse the comparison with conventional vehicles.

The work was developed through a systematic review of the scientific literature, which allowed an in-depth analysis of the leading causes of fire in electric vehicles, as well as the chemical and physical properties of the materials used in these vehicles. In particular, this thesis analyses the characteristics of lithium-ion batteries, their components and their safety systems. The environmental implications and the principal cases and characteristics of fires that have occurred in recent years were then reported.

Regarding the knowledge acquired, it can be stated that electric vehicles do not present a greater fire risk than conventional vehicles. In fact, they occur less frequently in relation to the number of vehicles registered.

Not counting fires caused by undersized recharging systems or those used beyond their limits, which cause overheating with related consequences on the vehicle or the recharging stations, the main risk is a thermal runaway, caused in turn by shocks or short circuits. This risk is closely linked to the storage system, and the solution to the problem can be found in efficient safety systems, cooling systems, and constant research to develop new technologies for the battery components, particularly separators, to avoid mixing of different compounds, electrodes, and electrolytes.

Of the extinguishing methods analysed, all those that aim to remove heat are efficient, but it should be noted that there is a high risk of subsequent re-ignition even days later. To overcome this problem, the best solution is to completely immerse the entire vehicle in water or completely flood the battery pack, thus preventing the fire from being reactivated.

The final part of the paper concentrates on modelling cases of fire in underground car parks and tunnels, using dedicated software. The results of the simulation showed that electric vehicle fires generate a more sudden and higher heat development than conventional vehicles and are also less affected by variations in airflow: even though heat emission remains proportional to it, the dependence is less marked, as electric fires don’t necessarily require contact with the atmosphere to ignite.

In conclusion, this work provides a complete picture of the fire risk in electric vehicles, the environmental implications, and the solutions adopted. In particular, it can be deduced that the type of vehicles that are most subjected to fire hazards are hybrid vehicles, as they inherently have both the risks associated with electric cars and those related to traditional engines. However, electric mobility appears to be safe and ready to be developed in the territory without requiring additional concerns about fire risk.

List of Figures

List of tables

List of Acronyms

- ICEVs (Internal Combustion Engine Vehicles)
- EV (Electric Vehicle)
- MHEVs (Mild Hybrid EV)
- HEVs (Hybrid EV)
- PHEVs (Plug-in Hybrid EV)
- BEVs (Battery EV)
- LIB (Li-Ion Battery)
- NMC o NCM (Lithium Nickel Cobalt Manganese Oxide ($LiNiCoMnO_2$))
- LFP (Lithium Iron Phosphate ($LiFePO_4/C$))
- LNMO (Lithium Nickel Manganese Spinel ($LiNi_{0.5}Mn_{1.5}O_4$))
- NCA (Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$))
- LMO (Lithium Manganese Oxide ($LiMn_2O_4$))
- LCO (Lithium Cobalt Oxide ($LiCoO_2$))
- SOC (State of Charge)
- DOD (Depth of Discharge)
- BMS (Battery Management System)
- HRR (Heat Release Rate)
- FDS (Fire Dynamics Simulator)
- SMW (Smokeview)
- CFD (Computational Fluid Dynamics)
- HRRPUA (Heat Release Rate Per Unit Area)

Bibliography

[1] "   https://www.isprambiente.gov.it/it/servizi/registro-italiano-emission-trading/contesto/protocollo-di-kyoto"

[2] ''https://www.sicurauto.it/news/auto-elettriche-ibride/in-norvegia-l80-delle-auto-nuove-sono-elettriche/''

[3] ''https://www.smartworld.it/mobilita/in-cina-meta-delle-auto-elettriche-immatricolate-durante-il-2021.html''

[4] ''https://www.jato.com/q1-2021-ev-global-sales-at-the-same-level-as-2017-full-year-figures/''

[5] ''https://www.sporthome19.com/?category_id=793774''

[6] "https://greenmotorsport.it/auto-elettriche-il-glossario-sulla-mobilita-facciamo-chiarezza-tra-hev-bev-phev-e-mhev"

[7] ''https://it.wikipedia.org/wiki/Accumulatore_agli_ioni_di_litio''

[8] "http://www.bestgopower.com''

[9] A. Nyman; "An Experimental and Theoretical Study of the Mass Transport in Lithium-Ion Battery Electrolytes''; 2011

[10] ''https://www.targray.com/li-ion-battery/cathode-materials/cathode-active-materials''

[11] Euskal Herriko, Unibert sitatea. José Ignacio, San Martín Inmaculada, Zamora Francisco, Javier Asensio, Gaizka Saldaña; ''Analysis of the Current Electric Battery Models for Electric Vehicle Simulation''; Universidad del País Vasco; July 2019

[12] M. S. Whittingham and W. M. S.; "Lithium batteries and cathode materials"; Chem. Rev., vol. 104, no. 607; 2004

[13] Celina Mikolajczak, PE, Michael Kahn, PhD, Kevin White, PhD, Richard Thomas Long, PE Exponent Failure Analysis Associates; ''Inc. Lithium-Ion Batteries Hazard and Use Assessment Final Report''; Fire Protection Research Foundation; July 2011

[14] Illustrazione della Argonne National Laboratory " https://www.anl.gov/"

[15] ''https://www.evgo.com/blog/5-things-that-affect-your-charging-speed/''

[16] P. Sun, R. Bisschop, H. Niu, X. Huang; "A Review of Battery Fires in Electric Vehicles"; ResearchGate; january 2020

[17] ''https://www.batterypowertips.com/li-ion-batteries-part-1-building-massless-batteries-faq/''

[18] D. Doughty and E. P. Roth; "A General Discussion of Li Ion Battery Safety"; 2018

[19] ''https://www.ilfattoquotidiano.it/2015/02/02/seconda-vita-delle-batterie-delle-auto-elettriche-idee-bosch-vattevall-bmw/1384395/''

[20] ‘’https://www-esv.nhtsa.dot.gov/Proceedings/22/files/22ESV-000199.pdf’’

[21] NFPA’s; Emergency *Field Guide; NFPA; 2015*

[22] " https://www.autocarpro.in/news-international/marelli-develops-gamechanging-wireless-bms-for-evs-92294"

[23] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He; “ Thermal Runaway Mechanism of Lithium Ion Battery for Electric Vehicles: A Review”; Tsinghua University – Beijing; December 2016

[24] C. Mikolajczak, M Kahn, K. White, R. Long; " Lithium-Ion Batteries Hazard and Use Assessment"; Fire Protection Research Foundation; July 2011

[25] P. Sturm, P. F¨oßleitner, D. Fruhwirt, R. Galler, R. Wenighofer, S. Heindl, S. Krausbar, O. Heger; "Fire tests with lithium-ion battery electric vehicles in road tunnels"; Fire Safety Journal 134; 2022

[26] R. Bisschop, O. Willstrand, F. Amon, M. Rosengren; "Fire Safety of Lithium-Ion Batteries in Road Vehicles"; RISE Research Institutes of Sweden; 50-2019

[27] ’’ http://www.electric-vehiclenews.com/2014/08/lg-chem-signs-battery-deal-with.html’’

[28] R. Russel; “GM's Voltec comes up a winner”; The Globe and Mail; 24 February 2012 - ‘’https://www.theglobeandmail.com/globe-drive/news/gms-voltec-comes-up-a-winner/article548874/’’

[29] ‘’https://tinyurl.com/yawulhqj’’

[30] S. Koch, A. Fill, and K. P. Birke; “Comprehensive gas analysis on large scale automotive lithium-ion cells in thermal runaway”; J. Power Sources, vol. 398; no. July 2018

[31] A. Lecocq, G.G. Eshetu, S. Grugeon, N. Martin, S. Laruelle, G. Marlair; " Scenario-based prediction of Li-ion batteries fire-induced toxicity"; Journal of Power Sources 316; 2016

[32] O. Willstrand, R. Bisschop, P. Blomqvist, A. Temple, J. Anderson; " Toxic Gases from Fire in Electric Vehicles"; RISE Research Institutes of Sweden; 90-2020

[33] ‘’https://www.vigilfuoco.it/allegati/biblioteca/RischiConnessiConLoStoccaggioDiSistemiDiAccumuloLitio-Ione.pdf’’

[34] ’’ https://www.autoinsuranceez.com/’’

[35] ‘’https://insideevs.it/news/560514/auto-elettriche-rischio-incendio-studio/’’

[36] ‘’https://www.vigilfuoco.it/aspx/download_file.aspx?id=27522’’

[37] ‘’https://www.vaielettrico.it/auto-elettrica-e-incidenti-come-si-interviene/’’

[38] "https://pages.nist.gov/fds-smv/"

[39] "https://pages.nist.gov/fds-smv/"

[40] ” https://vanguard-fire.com/quick-response-vs-standard-response-sprinkler-heads/”