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Filed: Electrotechnical

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Subject:

Study of techniques to increase the autonomy of electric cars

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2025/2026

بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

: وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلاً {الإسراء:85} ؛

In the Name of Allah, the Entirely Merciful, the Especially Merciful.

And you have been given only a little knowledge.

{Al-Isra: 85}

ملخص:

في هذا العمل، قمنا بدراسة السيارة الكهربائية من عدة جوانب، مع التركيز على التجديد والابتكار في هذا المجال. تناولنا من خلال مجموعة من الأفكار الحديثة التي ساهمت، وما زالت تساهم، في تطوير أداء السيارات الكهربائية، سواء من ناحية سعة البطارية، أو راحة المستخدم، أو الاستجابة للتحديات البيئية. تطرقنا للمفاهيم العامة المتعلقة بالسيارات الكهربائية، من حيث مكوناتها الأساسية وآلية عملها، كما ركزنا على تقنيات زيادة مدى السيارة الكهربائية والعوامل المؤثرة على مدى كفائتها من خلال تأثيراتها.، كما قمنا بمحاكاة استراتيجية إدارة البطارية باستخدام نظام الأردوينو ، حيث تم التركيز على مراقبة حالة الشحن، وتوزيع الطاقة بكفاءة، وضمان سلامة البطارية من خلال نظام إدارة ذكي يساهم في تحسين الأداء العام للسيارة..

الكلمات المفتاحية: محرك سيارة كهربائية مركبة كهربائية ; مركبة كهربائية تعمل بالبطارية ; تقنية البطارية ;نظام الاردوينو ; العوامل البيئية ، نظام إدارة البطاريات ; محطات الشحن الذكية .البياماس

Résumé

Dans ce travail, nous avons étudié les véhicules électriques sous plusieurs angles, en nous concentrant sur l'innovation et la rénovation dans ce domaine. Nous avons abordé plusieurs idées modernes qui ont contribué, et continuent de contribuer, au développement des performances des véhicules électriques, que ce soit en termes de capacité de batterie, de confort d'utilisateur ou de réponse aux défis environnementaux. Nous avons abordé les concepts généraux liés aux véhicules électriques, notamment leurs composants de base et leur mécanisme de fonctionnement. Nous nous sommes concentrés sur les technologies permettant d'augmenter l'autonomie des véhicules électriques et les facteurs affectant leur efficacité. Nous avons également simulé une stratégie de gestion de batterie à l'aide du système Arduino, tout cela en concentrant sur la surveillance de l'état de charge, la distribution efficace de l'énergie et la garantie de la sécurité de la batterie grâce à un système de gestion intelligent contribuant à l'amélioration des performances globales du véhicule.

Mots-clés: Moteur de véhicule électrique; Véhicule électrique; Véhicule électrique à batterie ; Technologie de batterie; Système Arduino; Facteurs environnementaux; Système de gestion de batterie; Stations de recharge intelligentes ;BMS.

Abstract

. In this work, we studied electric vehicles from several perspectives, focusing on innovation and renewal in this field. We addressed a set of modern ideas that have contributed, and continue to contribute, to the development of electric vehicle performance, whether in terms of battery capacity, user comfort, or response to environmental challenges. We addressed the general concepts related to electric vehicles, in terms of their basic components and operating mechanism. We also focused on technologies for increasing electric vehicle range and the factors affecting their efficiency by presenting these factors. We also simulated a battery management strategy using the Arduino system, focusing on monitoring the state of charge, distributing energy efficiently, and ensuring battery safety through an intelligent management system that contributes to improving the vehicle's overall performance.

Keywords: Electric vehicle motor ;Electric vehicle; Battery-powered electric vehicle; Battery technology; Arduino system; Environmental factors; Battery management system; Smart charging stations ; BMS.

Thanks, and appreciation

All Praise be to God, Lord of the heavens and the earth, who has enabled me to complete this modest project. To Him belong all thanks, first and last.

I thank myself for my patience and perseverance, which, after God, have helped me reach this moment. I also extend my sincere gratitude to my colleagues at **2M ELTI** for five years of memories and experiences that will remain etched in my heart.

I cannot fail to thank my dear supervisor, **Dr. Mahjoubi Abdelhalim**, for his generous support and guidance, and all my professors who have accompanied me on this academic journey.

I conclude with the words of the Prophet ﷺ: "He who does not thank people does not thank God."

Thank you to everyone who has been a part of this journey.

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BIRANE MOHAMMED ELSADEK

Dedication

I dedicate this work to my dear parents, who raised me, worked, struggled, and strived for more than twenty years to achieve these moments, and especially to my beloved mother, who battled cancer and continues to fight it every day for us.

To my late aunt Sarah, who always stood by me and supported me, encouraging me to become a doctor. I wish she could have been present today.

To my beloved brother, the keeper of my secrets and future doctor.

To my Sheikh and Quran teacher, Imam Muhammad Chouarana.

To my friends, all family, loved ones, and everyone who has done us a favor.

To my brothers and family in the Al-Haniya Association for Cancer Patient Aid.

To our loyal resistance fighters and our righteous martyrs in Gaza and Palestine.

To our righteous martyrs. I hope this work is sincerely for the sake of God and contributes to the advancement of our civilization. May blessings and peace be upon the Messenger of God, our Prophet Muhammad, and upon his family, companions, wives, followers, and those who follow him in righteousness until the Day of Judgment.

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BIRANE MOHAMMED ELSADEK

SUMMARY

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AC	Alternative Current
BEV	Battery Electric Vehicle
DC	Direct Current
EV	Electric Vehicle
GM	General Motors
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
kW	kiloWatt
kWh	kiloWatt-Hour
HV	High Voltage battery pack. voltage is > 60 V and ≤ 1500 V DC or > 30 V and ≤ 1000 V AC root mean square (rms)
LFP	Lithium Iron Phosphate
LIB	Dual-Ion Battery
mAh	milli Ampere-Hour is one thousandth of an Ampere-hour Ah
Na+	Sodium ion cell
NiMH	Nickel Metal Hydride
NMC	lithium-ion cell that uses a cathode made of lithium Nickel Manganese Cobalt Oxide
SOC	State Of Charge is defined as the amount of charge in the cell as a percentage compared to the nominal capacity of the cell in Ah.
IP	(Indicator of Protection)
BMS	Battery Management System
ML	Machine Learning
RL	Reinforcement Learning
CATL	Contemporary Amperex Technology
BYD	Build Your Dreams: Chinese automobile manufacturer

General introduction

Electric vehicles (EVs) are revolutionizing the era of technology. With climate change and growing concerns about air pollution, electric vehicles offer a sustainable alternative to traditional fossil-fuel-powered vehicles around the world.

These vehicles are powered by rechargeable batteries and produce energy with no emissions, making them a friendly choice for the environment and drivers. Reducing fossil fuel consumption and reducing pollutant emissions in the automotive sector, is a significant challenge. This has led to a growing interest in the clean vehicle market. The need for greener vehicles, coupled with the emergence of a new type of technologies, is driving manufacturers to develop more energy-efficient vehicles.

A promising solution, this one still eludes many manufacturers, given that these vehicles are exposed to factors that affect their operation and efficiency, such as climate and land type. This has allowed us to develop mechanisms that help control these factors to ensure safe driving and comfort for vehicle users.

In the coming years, this sector is expected to generate significant research and development activity, as many emerging solutions still need to prove their effectiveness. Today, a variety of energy management systems have been developed for electric vehicles. However, there are still significant opportunities to enhance this activity and transition to this technology.

this development is of great importance to the transportation sector, as it contributes to improving the efficiency of energy systems and reflects our vision of the need to employ modern technologies in the service of sustainability.

. The work was structured as follows:

- **Chapter I,** which is a bibliographic study state of the Art of Electric Vehicles.
- **Chapter II** A technical investigation into enhancing the range and efficiency of electric vehicles, with a focus on key influencing factors and ideal battery types.
- **Chapter III** Develop a model using Arduino and BMS to achieve greater range.

. Finally, we close with a general conclusion.

Chapter I

Generalities about electric vehicle EVs

I.1. Introduction

At a time when human activity and economic potential continue to evolve, the 20th century witnessed an unprecedented climate change. The causes are not so much found in nature but in the concentration of pollutants, particularly CO2, in the atmosphere due to human activities. The transportation sector is now the leading contributor to greenhouse gas emissions, which is why the automotive industry is focusing on the issue of pollution to reduce greenhouse gas emissions and promote a healthier life. As a solution, electric vehicles.

Electric and hybrid vehicles are currently seen as a potential alternative to conventional vehicles powered by fossil fuels, allowing vehicle manufacturers to focus on meeting the performance and consumption requirements of users while aligning with air protection laws (reducing pollutant emissions) . [1]. In this chapter, we will present the state of the art of electric vehicles, highlighting the main components of the powertrain and discussing various configurations. We will also emphases their advantages and disadvantages.

I.2. Electric Car

The electric car is characterized by being driven by one or more electric motors that transmit the driving force to the wheels through an appropriate transmission system. Given the scientific and technological advances made in the field of power electronics, many ideas and new designs are being explored to develop this mode of propulsion. All these explorations are related to common issues: the production, storage, and use of electricity. The drive system is the main component of the electric vehicle, powered by one or more electric motors and includes a transmission system designed to drive either two or four wheels . [1]

The architecture is very simple. It consists of an electric actuator, a transmission device, and the wheels **(see figure I.1).**

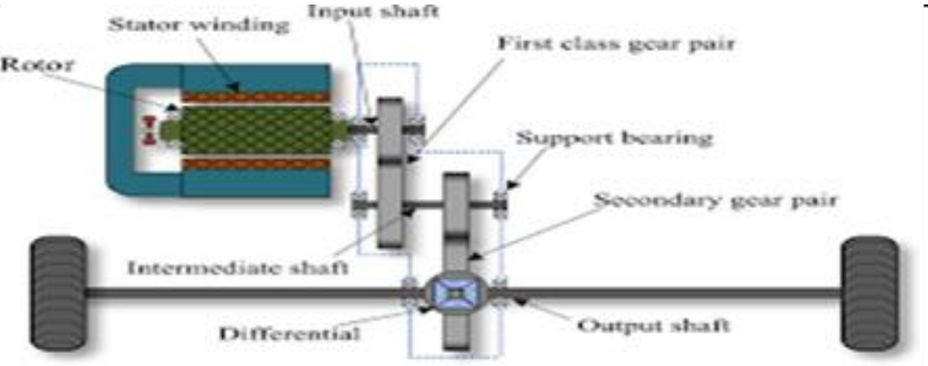

FIG I.1 –Drive system of an EV **[1]**

I.3. History of electric cars in detail

The electric car, often promoted as “the solution” to the problem of exhaust gas pollution,

At the end of the 19th century, during the early days of the automobile, several propulsion systems were competing with each other electric motors, steam engines, and internal

Below is a timeline of key electric vehicles that have made history

- Between 1832 and 1839, the first electric vehicle made its appearance. Scottish businessman Robert Anderson was the first person to invent an electric car more accurately, it was an electric carriage.
- Around 1835, American inventor Thomas Davenport built a small electric locomotive.
- Around 1838, Scotsman Robert Davidson developed a similar model that could reach speeds of up to 6 km/h.
- In 1859, Frenchman Gaston Plante invented the lead-acid rechargeable battery, which was later improved by Camille Faure in 1881.

- In 1884, Thomas Parker sat in the world’s first electric car. **(See Figure I.2).**

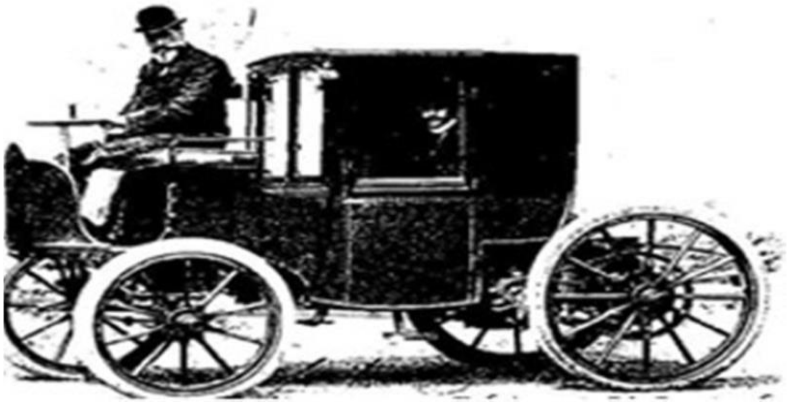

***FIG I.2 –First car in the world* [1].**

In1899 in the United Kingdom, La Jamais Contente became the first electric car to exceed 100 km/h.[1] The vehicle, shaped like a torpedo, was driven by Belgian engineer Camille Jenatzy (see Figure I.3).

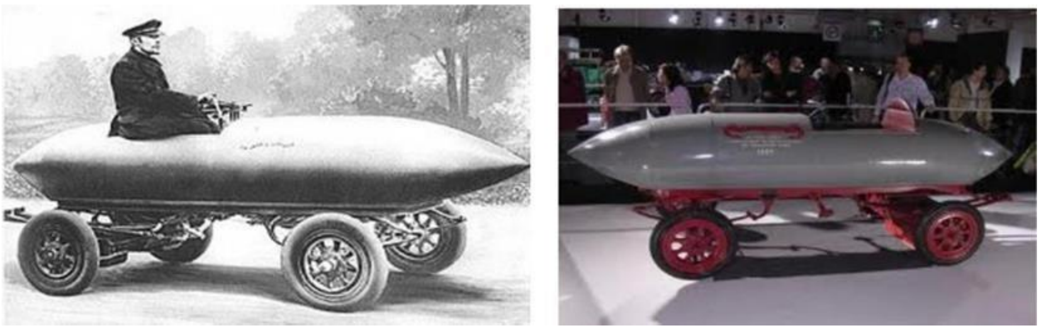

***FIG I.3 –First cars in development* [1].**

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By 1900, the electric car had its heyday. More than a third of the cars on the roads were electric, while the rest were powered by gasoline or steam engines.

- In the 1920s, several factors led to the decline of the electric car. These included limited range, low speed, lack of power, the availability of oil, and the fact that electric cars were priced twice as high as their gasoline counterparts.
- In 1972, Victor Wouk, the pioneer of the hybrid vehicle, built the first hybrid car, the Buick Skylark

***FIG I.4 –First hybrid car.*[1]**

- In 1976, the U.S. Congress passed the Electric and Hybrid Vehicle Research, Development and Demonstration Act, which helped promote the advancement of new technologies for batteries, motors, and hybrid components.
- By 1988, General Motors launched a research project aimed at developing a new electric vehicle, which would later become the EV1. This car was produced Be tween 1996 and 1998.
- In 1997, Toyota introduced the Prius **(see Figure I.5),** the first mass-produced hybrid car. In its first year, 18,000 units were sold in Japan, and by 2006, Toyota had surpassed 500,000 units sold worldwide of this iconic hybrid model .[2]

FIG I.5 –Prius

- From 1997 to 2000, many hybrid and electric vehicle models were introduced, including the Honda EV Plus, GM EV1, Ford Ranger Pickup EV, Nissan Altra EV, Chevy S-10 EV, and Toyota RAV4 EV.
- However, starting in 2000, electric cars began to decline once again. In 2004, the EV1 program officially ended—General Motors recalled all EV1 vehicles and proceeded to destroy them, despite widespread protests. The company was accused of yielding to pressure from oil industry lobbyists.

- In July 2009, the Mitsubishi i-MiEV was launched in Japan for commercial use, and in April 2010, it became available to individual consumers. Sales to the public in Hong Kong began in May 2010.
- In December 2010, the Nissan LEAF (Leading, Environmentally Friendly, Affordable, Family car), a five-seater electric vehicle first announced in 2009, was officially released in Japan and the United States. It later entered the European market at the end of 2011 **(see Figure I.6).**

***FIG I.6 –Nissan LEAF* [2]**

Today, electric vehicles have become a reality. Major car manufacturers, such as Renault with its fully electric ZOE model launched in 2013 **(see Figure I.7),** have developed 100% electric vehicles rather than simply electrified versions of existing models. Charging station infrastructure is also expanding rapidly [2].

FIG I.7 –Renault ZOE **[2]**

I.4. Latest Developments in Electric Vehicles

Currently, the driving range of most electric vehicles (EVs) offered by manufacturers is based on battery systems that allow speeds ranging between 70 km and 200 km. However, the introduction of fuel cell technology has significantly extended this range reaching between 400 and 450 km bringing EVs closer in performance to conventional internal combustion vehicles and opening up new possibilities.

Power output among EVs varies widely, from approximately 15 kW up to around 100 kW. The intended use of the vehicle typically determines the required power level: 20 to 30 kW is generally sufficient for city driving, while 40 to 50 kW is more suitable for highway travel.

As for pricing, it remains difficult to determine accurately, given that current production volumes are still quite limited often involving only a few units. However, if energy supply technologies such as batteries and fuel cells were produced on a larger scale, their costs could become comparable to those of traditional vehicles. Indeed, the power source accounts for the largest portion of an electric vehicle's total cost. [3]

I.5. How an Electric Vehicle Works

Electric vehicles are equipped with a battery that stores energy and is recharged using electricity from the power grid. They also include one or more electric motors, a control system, and a battery charger.

The battery is connected to the electric motor through a controller and a converter. The controller regulates the amount of current delivered to the motor. The process is relatively straightforward: when the driver presses the accelerator pedal, the battery releases electrical current. This current, initially in direct current (DC) form, is then converted into alternating current (AC) by the converter to power the motor.

The converter is integrated into the motor system. One of the main advantages of electric vehicles lies in their electromechanical powertrain. This system is well-suited to driving needs, as vehicles require high torque at low speeds for acceleration and less torque at cruising speeds—characteristics that align naturally with electric motors. [3]

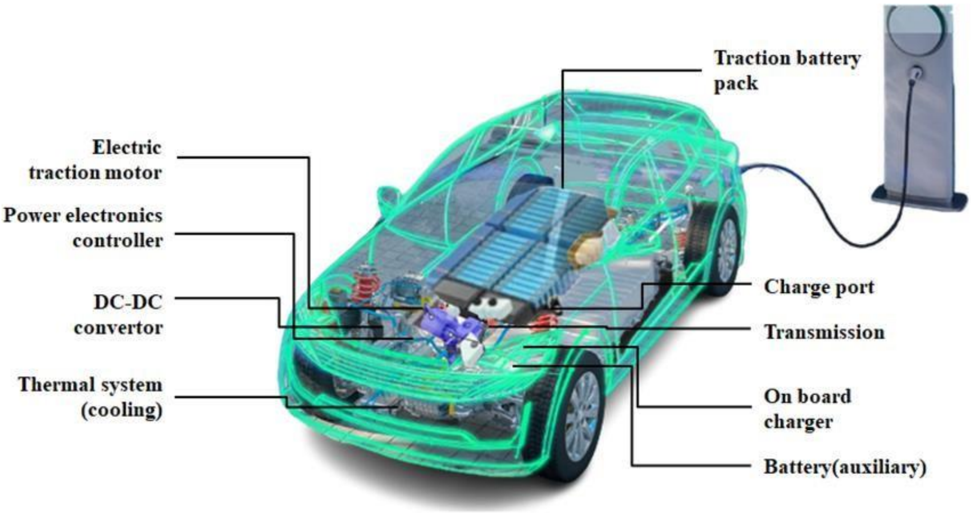


FIG I.8 –Components and Operation of an Electric Vehicle **[3]**

I.6. Classification of Electric Vehicles

Given the scientific and technological advancements in the field of power electronics, many ideas and new designs for electric vehicles (EVs) are being explored to further develop this mode of propulsion. All these efforts are focused on a common challenge: the production, storage, and use of electricity. [4] Electric vehicles (EVs) are part of the broader category of electrified vehicles, which includes hybrids, plug-in hybrids, and fully electric vehicles. Within these families, several subcategories can exist.

I.6.1 - Fully Electric Vehicles (FEVs)

Fully Electric Vehicle (FEV) is one that uses only a battery as its energy source. As such, FEVs are well-suited for small urban vehicles. In urban environments, these vehicles are not significantly impacted by limitations in power and range, as they offer a solution to the issues of gas and noise pollution typically associated with large cities [4][5]. The development of electric vehicles (EVs) is closely linked to advancements in their energy supply systems.

I.6.2 - Battery Electric Vehicles (BEVs) with Rechargeable Batteries via Power Outlet

Battery Electric Vehicles (BEVs) are currently the majority of the global electric vehicle fleet. A battery is an embedded system capable of storing electrical energy and later releasing it as needed. To date, it is the most suitable system for powering electric vehicles. The invention of the battery dates back to the 19th century, making it the most technically

I.6.3 - Fuel Cell Electric Vehicles (FCEVs)

Fuel cell electric vehicles (FCEVs) are similar to other electric vehicles, except that they generate their own electricity on board. This electricity is produced by a fuel cell — an electrochemical device that shares many similarities with a battery. However, unlike batteries that store and release electrical energy, a fuel cell generates electricity continuously through a chemical reaction, as long as it is supplied with fuel.

There are various types of fuel cells that operate using different fuels, but the most promising for automotive applications is the proton exchange membrane (PEM) fuel cell. This type uses hydrogen (H_2) and oxygen from the surrounding air as its primary fuels.

The use of this technology in the automotive sector is relatively recent and is still largely at the experimental stage. However, the fuel cell itself has been around for nearly two centuries. It was invented in England in the early 19th century by two Englishmen, Sir Humphry Davy and Sir William Grove. Its operating principle (Figure I.9) is based on generating energy through a reaction between hydrogen and oxygen. This reaction produces electricity, water, and heat, as described by the following equation. [6]

$$2H_2 + O_2 \rightarrow H_2O + \text{Electricity} + \text{Heat} \qquad \text{(I.1)}$$

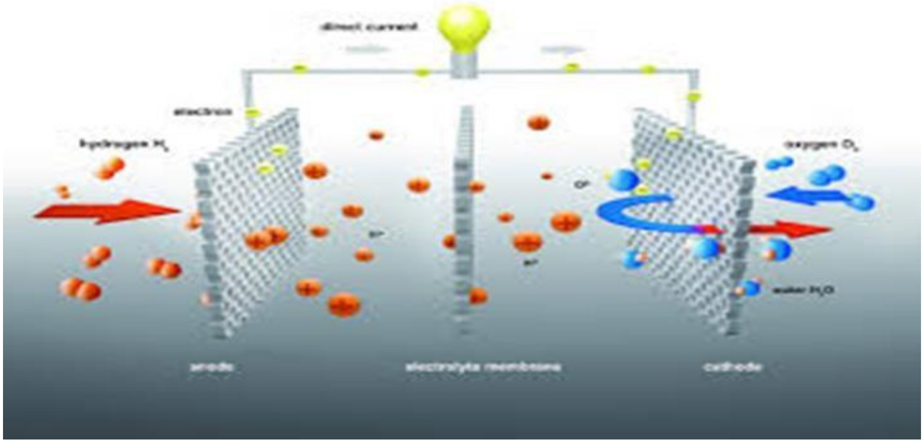


FIG I.9 – Operating Principle of a Fuel Cell (Rephrased English Version) **[6]**

Ballard Power Systems announced that it is the first fuel cell company to have enabled buses **(Figure I.10)** in service to collectively travel over 10 million kilometers [7] .

FIG I.10 –Fuel Cell Bus (Rephrased English Explanation **[7]**

La The company achieved this milestone over seven generations of its **Velocity** fuel cell engine, which has been deployed in buses across 15 countries on 5 continents over the past 10 years. During this time, Ballard has collaborated with 13 bus manufacturers to develop a variety of fuel cell bus configurations, while also evaluating a wide range of climate conditions and funding models . [8]

I.6.4 - Hybrid Vehicles (Rephrased English Explanation)

Hybrid vehicles use at least two types of energy production and storage—typically a conventional internal combustion engine (gasoline or diesel) along with at least one electric motor and a battery to store electricity. These systems can operate either simultaneously or independently from one another. Hybrid vehicles (HVs) are equipped with both a traditional engine and an electric motor that work together depending on the vehicle's speed and acceleration. The electric motor helps enhance the performance of the combustion engine and increases the vehicle's overall range. There are two main types of hybrid drive systems: parallel and series. These systems differ in how they integrate and manage the operation of the two energy sources.

I.6.5 - Series Hybrid Vehicles (Rephrased English Explanation)

In this case, the principle is based on the fact that the electric energy used by the motor can be generated by an alternator driven by an internal combustion engine operating at a constant rotational speed. The two motors (thermal and electric) are thus arranged in series, which is where the name "series hybrid" comes from. This setup allows the combustion engine to run at its optimal speed to achieve maximum efficiency, thereby increasing the proportion of fuel burned per engine cycle and reducing gas
missions as a result. Additionally, the constant engine speed improves the acoustic profile of the combustion engine, making it quieter and more consistent. A schematic

representation of this type of vehicle is shown in **Figure I.11.**

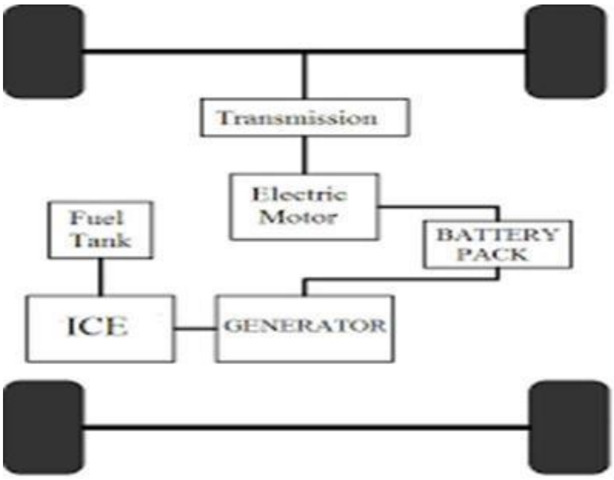


FIG I.11 –Series Hybrid Vehicle Rephrased English Explanation **[9]**

In a series hybrid vehicle, most of the electrical energy required to power the electric motor is supplied by the generator. The battery mainly serves as a buffer, providing extra power during peak demand or enabling short-distance all-electric driving . [9]

One major drawback of this architecture is its relatively low overall efficiency. This is because the mechanical power produced by the internal combustion engine is first converted into electrical energy by the generator, potentially stored in the battery, and then converted back into mechanical power by the electric motor. However, from a control standpoint, this architecture provides two degrees of freedom: the engine’s speed and torque can be adjusted almost independently of the vehicle’s driving conditions [10].

I.6.6 - Parallel Hybrid Vehicle (Rephrased English Explanation

The main idea behind a parallel hybrid vehicle (PHV) is to combine the advantages of both types of powertrains. The PHV has two motors that operate in parallel: one electric and one internal combustion. The two motors are used independently, which addresses the environmental concerns of the combustion engine in urban areas by operating in electric mode, while also solving the issue of range for electric vehicles on longer trips by switching to the combustion engine mode outside of urban areas [10]. A schematic of this type of vehicle is shown in **Figure I.12**.

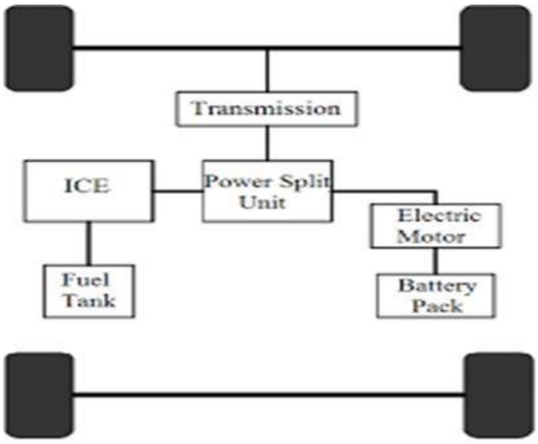


FIG I.12 – Parallel hybrid vehicle **[10]**

The electric motor usually also functions as a generator driven by the internal combustion engine to recharge the batteries when electric power is not needed to propel the vehicle

I.7. The different configurations of electric vehicles

Our objective is to provide a non-exhaustive list of preliminary solutions to the challenges related to electric vehicle propulsion. These solutions are proposed in the form of either a single-motor or multi-motor configuration [11]

I.7.1. Single-motor electric vehicles

The single-motor architecture **(Figure I.14)** employs a direct current (DC) motor, a battery, and a reversible chopper (as a power converter) connected in series, along with a differential reducer that decreases speed while increasing torque [12].

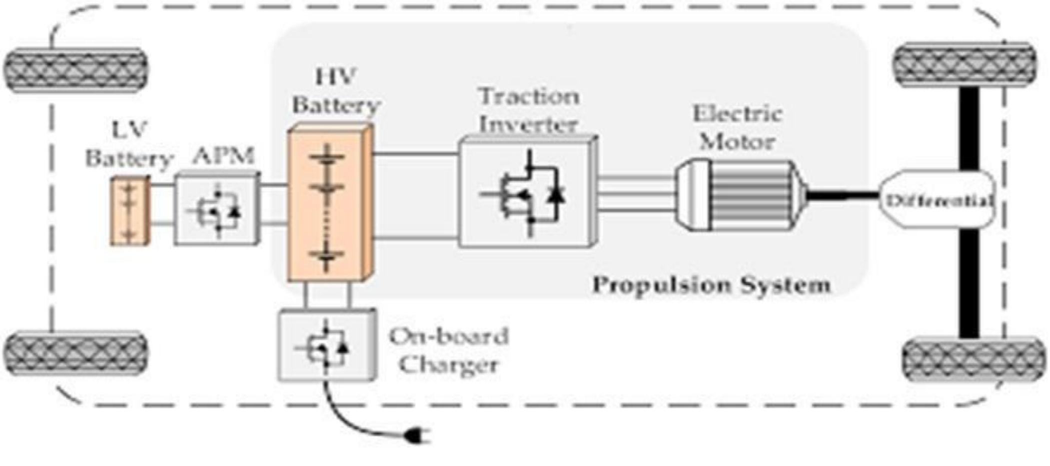


FIG I.13 – Single-motor solutions **[12].**

I.7.2. Multi-motor electric vehicles

On multi-motor EVs there are two main architectures, one uses a double traction chain using two direct current motors which allows for greater reliability on the motor side **(Figure I.15),** the other uses an asynchronous motor and two wheel motors to increase the mechanical differential of the vehicle [13].

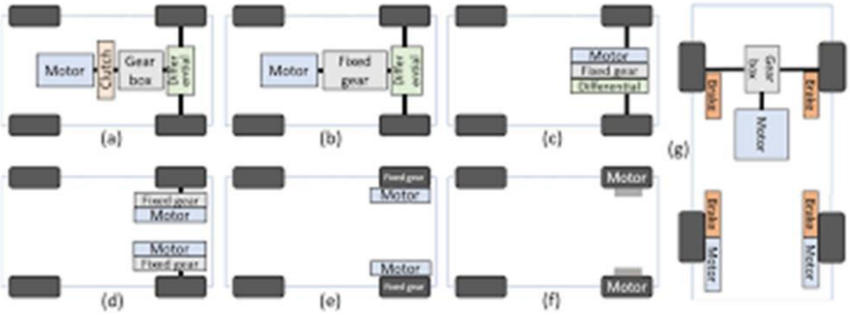


***FIG I.14 – Solutions based on multi-motor electric* [13].**

The electric wheel motor (Figure I.16) is very similar to a conventional motor; the main difference lies in its configuration. Instead of having a single motor located under the hood, two (or even four) smaller motors are integrated directly into the vehicle's wheels. It is worth noting that the batteries remain positioned inside the vehicle [13].This system allows for highly precise and independent control of the torque applied to each wheel, while also maximizing regenerative braking efficiency. When these motors are used on steering wheels, they eliminate the need for traditional mechanical transmission components, enable independent wheel control, and free up space within the vehicle [14]. This high degree of flexibility allows for individual torque control, which can significantly enhance transport safety. However, the drawbacks of this type of motor include an increase in unsprang mass and the difficulty of integrating a gear reducer. As a result, placing a high-torque motor directly in the wheel can potentially destabilize the vehicle.

***FIG I.15 –Wheel hub motor* [14].**

I.8 General description of the powertrain system

The powertrain system of an electric vehicle (EV) is simpler than that of a conventional internal combustion vehicle. The selection and arrangement of the components that make up the powertrain are illustrated in **Figure I.16**.

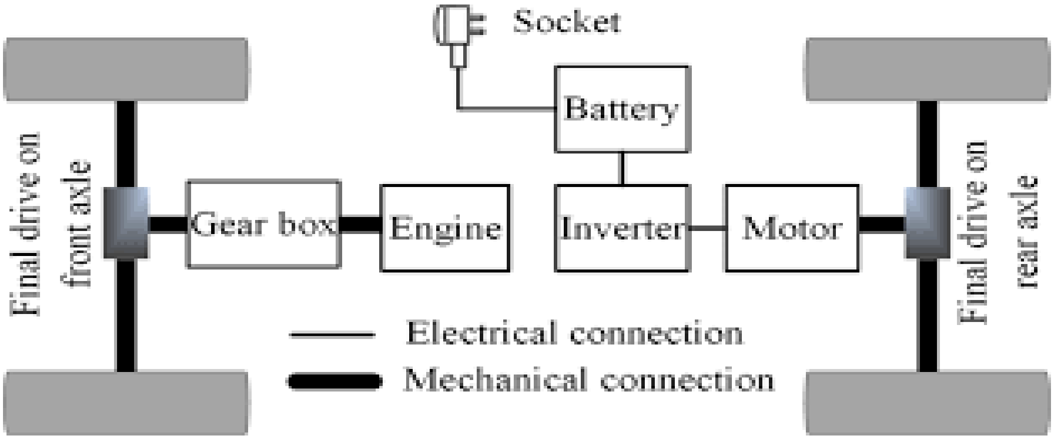


FIG I.16 – Drivetrain in an electric vehicle **[15]**

Starting from the alternating supply network, the system includes the battery charger, the electrochemical battery, the onboard electric energy source, the static converter assembly for the electric motor, and the control system. Finally, there is the mechanical transmission, which adapts the mechanical characteristics of the load to those of the motor.

For total consumption analysis, it is also necessary to consider auxiliaries such as the motor and converter cooling system (air or water), as well as the management of energy flows between them, which are still at the research stage.

In this section, we will aim to present the components of the electric traction system, justifying the choice of each component [15].

The electric traction system begins with the AC supply network and includes the battery charger, electrochemical battery, onboard power source, static converter for the electric motor, and the control system. It ends with the mechanical transmission that matches the load to the motor. Total energy consumption analysis also considers auxiliary systems like motor and converter cooling (air or water) and energy flow management, which remain under research. This section presents and justifies the selection of each system component.

I.9 - Power electronics in electric vehicles

I.9.1 - Rectifiers (AC/DC)

In an electric vehicle, rectifiers are used to convert the alternating current (AC) electrical energy supplied either by the general power grid or by an alternator placed on board the vehicle and coupled to an internal combustion engine, into direct current (DC) electrical energy. This DC energy can then be stored in an electrochemical battery or a high-capacity storage battery.

FIG I.17–Rectifiers (AC/DC) **[16]**

I.9.2 - Inverters (DC-AC)

In electric vehicles equipped with an alternating current (AC) motor, it is necessary to place a conversion device—called an inverter—between the energy source and the traction motors. The inverter converts direct current (DC) electrical energy into alternating current (AC), enabling both torque control of the motors and regulation of the vehicle’s speed in both driving and braking modes [16].

FIG I.18–Inverters (DC-AC) **[16]**

I.9.3 - DC-DC converters (choppers)

A chopper is a current converter that allows the transformation of a constant DC voltage source into controlled and adjustable voltages and currents, tailored to meet the needs of various devices (such as sensors, regulators, etc.).

In an electric vehicle, choppers serve two essential purposes:

- They are crucial for powering the propulsion motors when these are DC motors.
- They are needed to adapt the main battery voltage to the lower voltage requirements of electronic auxiliaries (such as sensors, regulators, etc.).

FIG I.19–DC-DC converters (choppers) **[17]**

I.9.4 The charger

battery chargers are specific to the type of electrical supply available at their location (whether onboard or external to the vehicle) and the mode of energy transfer. During the charging process, the battery behaves as a current receiver [16][17]. Two main types of chargers have been defined for this function

FIG I.20– Charger **[17]**

- **a - Slow chargers :**

Slow chargers are medium-power devices, typically rated at around 3 kW. A full battery pack recharge using this type of charger generally takes between 5 to 8 hours. This charging process is therefore well-suited for off-peak hours

- **b - Fast chargers :**

Charging systems with power levels exceeding 10 kW are classified as fast chargers. Today, maximum charging power can reach up to 150 kW. The purpose of this setup is to allow a partial recharge (up to 80%) of the battery in a short time, typically under 30 minutes [17].

***Table I.* 1 :** *provides an estimate of charging times based on different power sources*

Charging Time	Power Supply	Voltage	Max Current	Charging Type
6 to 8 hours	Single-phase, 3.3 kW	230 VAC	16 A	Slow
2 to 3 hours	Three-phase, 10 kW	400 VAC	16 A	Slow
3 to 4 hours	Single-phase, 7 kW	230 VAC	32 A	Slow
1 to 2 hours	Three-phase, 22 kW	400 VAC	32 A	Fast
20 to 30 minutes	Three-phase, 43 kW	400 VAC	63 A	Fast

I.10 - Various sources of electrical energy

I.10.1 - The battery

The battery serves as the main storage point for electrical energy. It is connected to the electric motor through a regulator and a converter. The battery is recharged from an external source during idle periods. Its major drawbacks are its relatively limited lifespan and the significant amount of time required for recharging. Battery types may include lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), or lithium-based technologies

- Lithium batteries:

Lithium-based batteries offer the best mass-to-power and mass-to-energy ratios. Furthermore, they do not suffer from the "memory effect" (a loss of capacity when recharged before full discharge). The most common type is the Lithium-ion battery. Researchers believe this technology could significantly extend vehicle range.

In fact, next-generation lithium batteries could allow electric vehicles to travel over 200 km on a single charge. Moreover, lithium batteries help reduce energy consumption costs and are therefore gaining strong appeal among consumers.

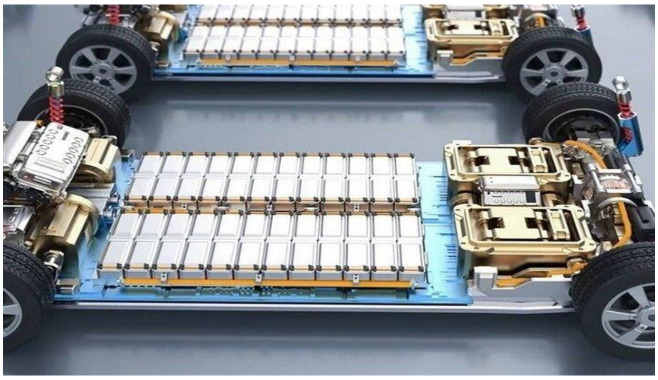


FIG I.21–Designs lithium-ion battery for electric cars [18]

Table I.* 2 :** *Here is a simplified table showing the key characteristics of* ***Lithium-ion batteries*, widely used in electric traction systems and other applications*

Battery Type	**Li-ion**
Energy Density (Wh/kg)	160–200
Number of Cycles (charge/discharge)	400–1200
Charging Time	2–4 h
Operating Temperature Range	-20°C to 60°C

I.10.2 - Supercapacitors

Supercapacitors (Figure I.19) store energy in the form of electrostatic charge. They are energy storage systems with low energy density but high power density. As a result, they are used during transient phases to supply the power peaks required, helping to reduce current demand, decrease the size, and extend the lifespan of the primary energy source (batteries or fuel cells) [19]

FIG I.22 –Example of a Supercapacitor

The supercapacitor consists of two metal collectors (Figure I.20), each coupled with two porous carbon electrodes impregnated with an electrolyte

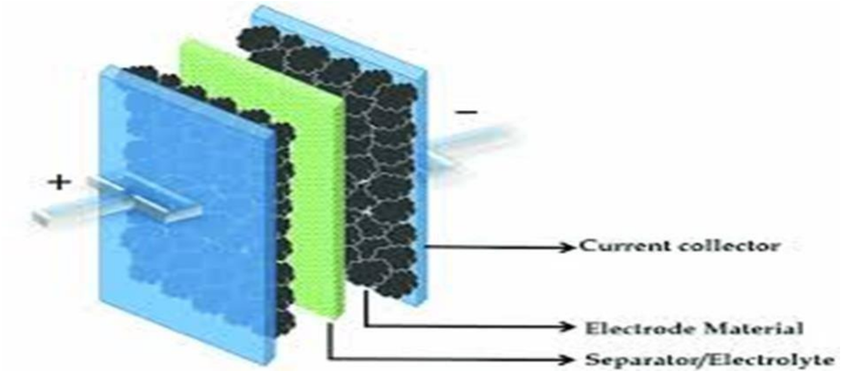
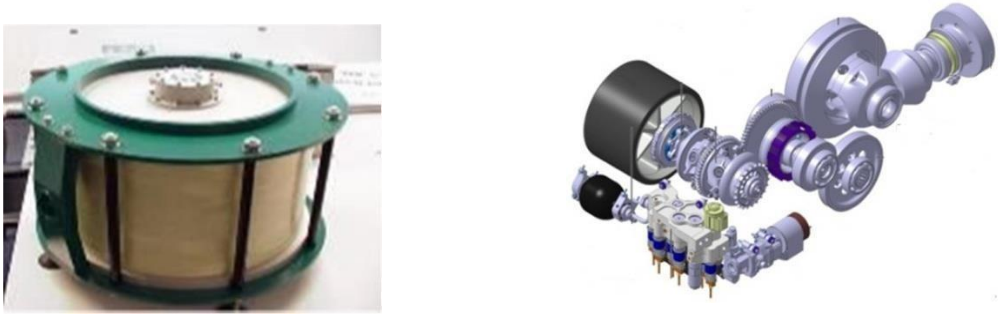


FIG I.23 – Composition of a Supercapacitor **[20]**

To address the issues of over-dimensioning of batteries in electric vehicle applications, supercapacitors offer very interesting properties. The charge transfer kinetics are faster than in batteries. Their lifespan is in the order of several hundred thousand charge/discharge cycles [20].

I.10.3- Flywheels

Flywheels store electrical energy in the form of kinetic energy. They can either be entirely mechanical, with a clutch system and a speed multiplier (Figure I.21b), or the system may consist of a flywheel driven by an electric machine (Figure I.21a). The advantages include the long lifespan of the vacuum-sealed components and the high specific power. The major challenge of this technology is safety, as the rotor operates at very high speeds (up to 80,000 rpm) [21].



(a) Tramway Flywhee ***(b) Mechanical Flywheel***

FIG I.24 – Flywheels **[21]**

The coupling of this flywheel with a motor-generator allows for the conversion of kinetic energy into electrical energy. To increase energy density and minimize the system's volume, it is preferred to increase the speed rather than the moment of inertia. Modern high-speed flywheels use composite materials that can withstand centrifugal forces and, most importantly, very high peripheral speeds, with the limit being around 800 m/s [22]

I.10.4- Electric Motors Used in Electric Vehicles

It is a very simple component at the heart of the electric vehicle, and its operating principle is primarily based on electromechanical interaction. It is used to convert electrical energy from the source into mechanical energy used to propel the vehicle during traction phases, or conversely, to convert mechanical energy into electrical energy during braking phases, allowing for energy recovery (regeneration). During braking, the mechanical chain partly becomes the power source, and the main energy source (battery) becomes the receiver. [23]

a - DC Motor (Direct Current Motor)

Since the energy source from the battery is direct current (DC), choosing a DC motor seems like an obvious choice. Historically, drives using DC motors were employed early in electric vehicles because they offer simple speed control. Additionally, this type of motor has excellent characteristics for electric propulsion (the torque curve is very favorable at low speeds). However, their production is costly and requires maintenance of the brush- commutator system. Their speed is limited, and they have a low specific power, generally ranging from 0.3 to 0.5 kW/kg, while gasoline engines typically have a specific power of around 0.75 to 1.1 kW/kg. This makes them less reliable and unsuitable for this application area . [23]

b - The Asynchronous Motor (Induction Motor)

- **Stator:** The stationary part of the motor. It has three windings (or coils) that can be connected in either a star (Y) or delta (Δ) configuration, depending on the power supply network.
- **Rotor:** The rotating part of the motor. Cylindrical in shape, it can either have a winding (typically three-phase, like the stator) connected via three slip rings and brushes, or a squirrel-cage rotor, which is inaccessible and made of conductive aluminum bars. In both cases, the rotor circuit is short-circuited (either by rings or a rheostat [24].

The asynchronous machine, due to its simplicity of manufacturing and maintenance, is currently the most widespread type of machine in the industrial sector and offers significantly better performance than other types of machines. However, these machines have a lower specific torque, efficiency, and power factor compared to permanent magnet machines

c - The Synchronous Motor

Although more delicate to control, more expensive, and potentially less robust, the synchronous motor has become the preferred choice in electric and hybrid vehicles. The synchronous machine offers the best efficiency in both motor and generator modes. The synchronous motor consists, like the asynchronous motor, of a stator and a rotor separated by an air gap. The only difference lies in the design of the rotor [25] .

d - The Permanent Magnet Synchronous Motor (PMSM)

It is the most popular motor for driving electric vehicles because it offers better performance in terms of efficiency, torque, and power density. Additionally, it requires little maintenance and is relatively easy to control. However, the production cost, which primarily depends on the quality of the magnets, is among the highest

e - The Switched Reluctance Synchronous Motor (SRSM)

The rotor of this type of motor does not contain magnets or excitation windings. The torque is generated solely by the reluctance effect. The stator is similar to that of most alternating current machines.

The rotor is designed in such a way that the ratio between inductance in the direct axis and the quadrature axis (Ld/Lq) is as high as possible. The operating speed range at constant power is directly related to this ratio. The same applies to the power factor (the higher this ratio, the greater the power factor). Achieving a high (Ld/Lq) ratio introduces manufacturing challenges that negatively impact the cost.

I.11 - Advantages and Disadvantages of Electric Vehicles

I.11.1 - Advantages

Electric cars offer several advantages that make them superior to internal combustion vehicles, which can be listed as follows:

- **Electric vehicles are free of noise pollution**, as they operate in complete silence.
- **They offer a pleasant driving experience**, with a smooth ride characterized by continuous and progressive acceleration, since the motor never stalls (no clutch involved).
- **The technical architecture of electric vehicles is simple**, consisting of around 6,000 fewer parts than a conventional car.
- **They are easier to maintain**, with operating costs reduced by 30 to 40% (for example, electric motors don’t require oil changes). Additionally, breakdowns are three times less frequent.
- **Electric vehicles do not consume energy in traffic jams or during braking**in fact, they recharge during deceleration—making them highly suitable for urban environments, which are expected to become the dominant living spaces in the future (megacities).
- **The energy efficiency of electric motors is three times higher than that of combustion engines.**
- **Starting the vehicle is very quick and easy**—just press a button, eliminating common cold-start issues in winter.
- **They reduce dependence on petroleum**

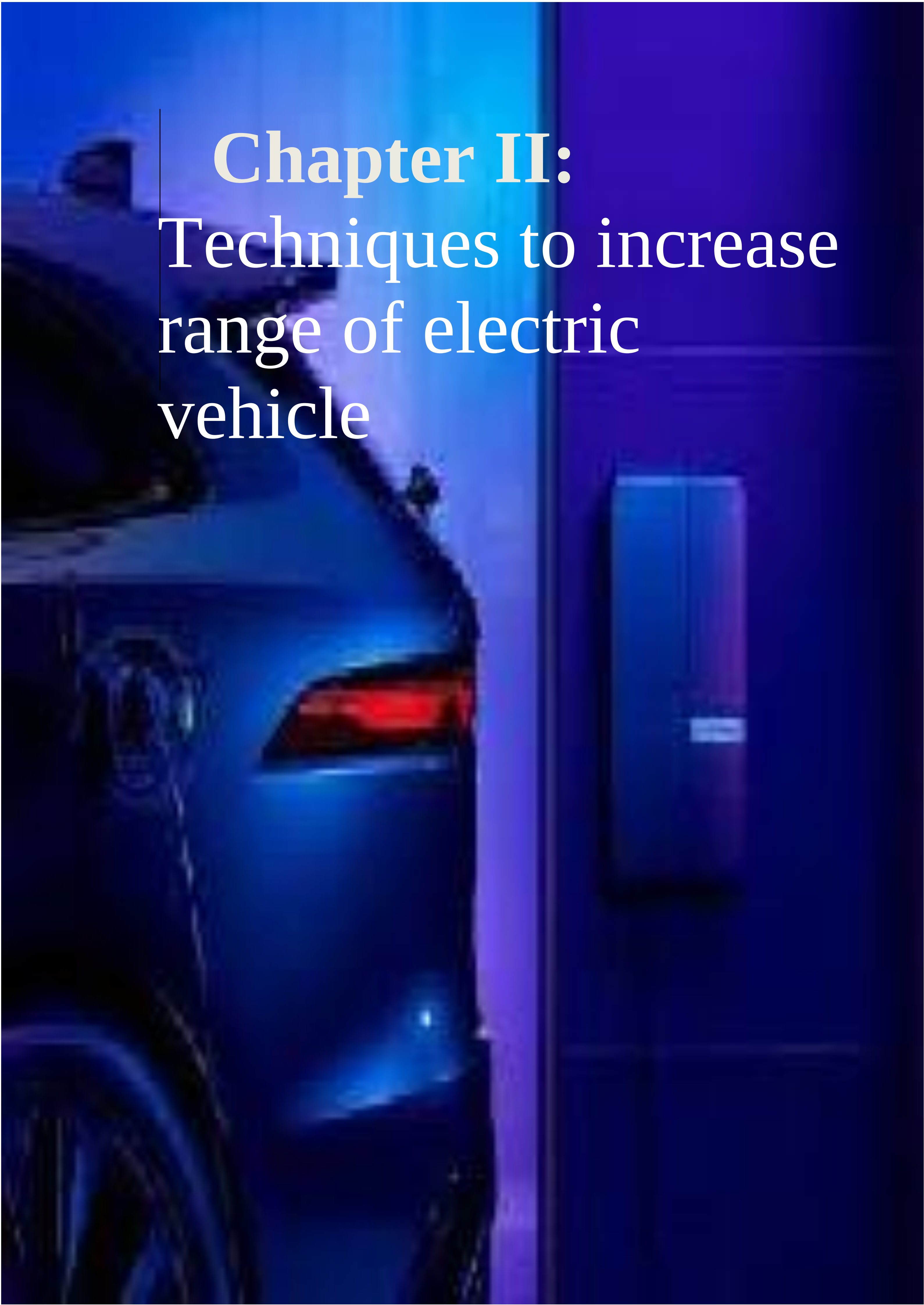
I.11.2- Disadvantages

Just as electric cars offer many advantages, they also have some drawbacks:

- **Limited driving range (autonomy)** remains a major concern.
- **Weight is a critical factor**—the vehicle must be as light as possible, since the heavier it is, the more energy it requires, reducing its range.
- **As with most innovative products, the cost is often high**, so electric cars tend to be expensive.
- **Battery charging time is still relatively long.**
- Additionally, **electric motors do not generate heat during operation**, meaning the vehicle's cabin isn't naturally heated. As a result, using systems for comfort—like heating, air conditioning, or the radio—**drains the battery faster**.
- **The lifespan of the battery and the power of electric motors** are still somewhat limited compared to traditional technologies

I.12 - Conclusion

In this chapter, we presented a state-of-the-art review of electric vehicles (EVs) and their development throughout history. We then outlined the different types of EVs and their classification based on energy sources. The chapter also covered the architecture of EV drivetrain systems, focusing on the various technologies employ



Chapter II:

Techniques to increase range of electric vehicle

II.1. Introduction

Electric vehicles (EVs) have become a cornerstone of sustainable transportation, offering an eco-friendly alternative to internal combustion engines. However, one of the most common concerns among EV owners and potential buyers is the range; and how can the car travel long distances on a single charge. While battery technology continues to improve, maximizing the distance your electric car can travel still depends heavily on a combination of driving habits, vehicle maintenance, and smart energy management. In this guide, we'll explore practical strategies to extend your EV's range, and reduce "range anxiety" during longer trips.

The driving range of an electric vehicle (EV) is one of the most critical performance factors influencing consumer acceptance. A key determinant of this range is the quality and performance of the battery. In this chapter we focus how battery characteristics affect vehicle range.

II.2. Factors affecting the range of an electric vehicle

The range of an electric vehicle is one of the most significant challenges facing users of these vehicles. Range is measured by the distance a vehicle can travel before the battery needs to be recharged. This challenge stems from a combination of interconnected factors that directly impact energy efficiency . [27]

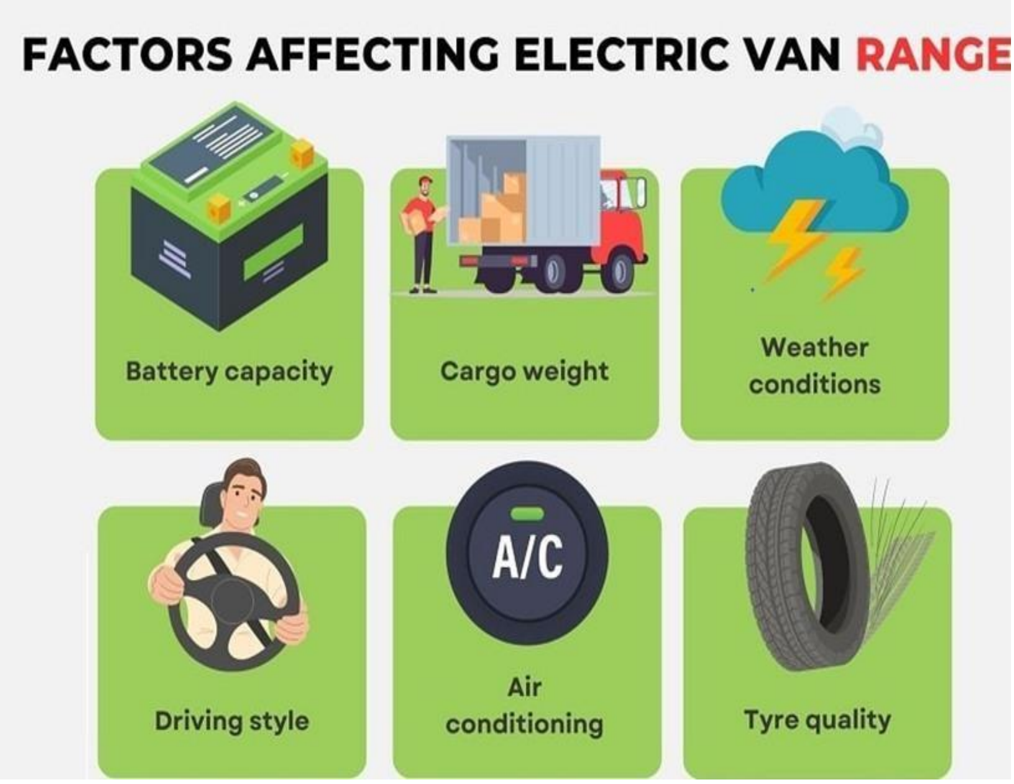


FIG II.1 Most important factors affecting the electric car [27]

II. 2.1. Temperature and climate

Temperature and climate are key factors that significantly impact the range and performance of an electric vehicle. Lithium-ion batteries, used in most electric vehicles, are susceptible to both high and low temperatures, reducing driving range and increasing energy consumption.

➢ Effect of cold weather on electric cars

At low temperatures, chemical reactions within the battery slow down, increasing its internal resistance and reducing its ability to store and deliver energy. This results in a reduction in driving range of up to 30% or more in some cases. For example, a study by the Norwegian Automotive Federation showed that a Tesla Model S lost 16.4% of its driving range in winter. Additionally, charging the battery in cold weather requires longer, as the battery needs to warm up before it can accept a full charge. This increases recharging time and impacts user comfort.

Figure II. 2 : Effect of cold weather on electric car charging **[27]**

The central grey layer is the solid-state separator which, on its own, acts both as a separator between the anode and cathode and as an electrolyte. It therefore becomes the intermediary through which the ions move and also has the properties of electrical

- Use battery preheating while charging to maintain an optimal temperature.
- Reduce the use of in-car heating systems, such as the cabin heater, as they consume additional energy.
- Avoid driving at high speeds, as this increases energy consumption.

- Check tire pressure regularly, as low pressure reduces energy efficiency.

➢ Effect of hot weather on electric cars

At temperatures above 35°C, electric vehicle batteries begin to overheat, increasing internal resistance and reducing battery efficiency. This results in a range reduction of up to 31% at 38°C. For example, a study showed that an electric vehicle with a nominal range of 450 kilometers may only have an actual range of 310 kilometers at 38°C. Furthermore, ion movement within the battery increases rapidly at high temperatures, preventing effective bonding between ions and the anodes and cathodes, leading to reduced battery life.

FIG II.3 –Effect of hot weather on electric cars [27]

➢ Tips for dealing with the effects of temperature on an electric in hot weather

- Use air conditioning with caution, as it increases energy consumption.
- Avoid leaving your car in sunny areas for extended periods.
- Use tints or curtains to reduce heat entering the cabin.
- Check your car's cooling system regularly to ensure its efficiency.

II.2.2. Road quality

Road quality is a key environmental factor that directly affects the range and efficiency of an electric vehicle. The effects of road surface conditions vary in terms of fluidity and resistance, affecting energy consumption and driving range

➢ Paved and smooth roads

- It provides low rolling resistance, reducing energy consumption.
- It allows for efficient use of the regenerative braking system, which contributes to increased range.
- It is ideal for continuous, high-speed driving.

The Firefly electric car is designed for urban roads and cities as it is a car designed for public roads only.

***FIG II.4 – Firefly electric road car* [29]**

➢ off-road or unpaved roads

- It increases rolling resistance due to uneven terrain.
- It requires additional energy for acceleration and deceleration, resulting in reduced range.
- It limits the effectiveness of the energy recovery system due to repeated acceleration and deceleration**.**

As a result, we must use vehicles specifically designed for these types of roads, such as the Mercedes-Benz EQC 4×4², which is a practical vehicle designed for off-road and natural terrain such as mountains, swamps, and sand. It is considered one of the best electric vehicles designed for off-roading.

***FIG II.5 –Mercedes-Benz EQC 4×4² prototype.* [29]**

➢ Winding or sloped roads

- It requires frequent gear changes, which increases energy consumption.
- It may affect the vehicle's stability and energy recovery efficiency.

➢ Tips for improving electric vehicle range on different roads

- **Choosing the right road:** Prefer paved, level roads when planning long trips.
- **Drive carefully:** Avoid sudden acceleration and deceleration, especially on rough roads.
- **Perform regular maintenance:** Check tires regularly and ensure they are at the correct pressure.
- **Using the energy recovery system effectively:** Take advantage of slopes and braking to recover the maximum amount of energy.

II.2.3. Speed and driving style

Speed and driving style significantly influence the range and efficiency of an electric vehicle. These factors affect energy consumption and, consequently, the distance the vehicle can travel before needing to be recharged.

Speed is a major factor affecting the energy consumption of an electric vehicle. The higher the speed, the greater the air resistance (aerodynamic drag), which requires more energy to maintain speed, thus reducing range. For example, decreasing speed from 105 Km to 80 Km can increase range by up to 30%.

Driving style is a critical factor in determining the range of an electric vehicle.

Aggressive driving, such as sudden acceleration and hard braking, consumes more energy, reducing range. On the other hand, gradual acceleration and balanced braking contribute to improved energy efficiency and increased range.

By adopting a moderate driving style and controlling speed, energy efficiency can be improved and the range of an electric vehicle can be increased, contributing to a more efficient and sustainable driving experience

- **Tips for Improving Range**
  - **Drive Smoothly**: Avoid sudden acceleration and deceleration.
  - **Control Cruise:** Maintain a constant speed as much as possible.
  - **Use Regenerative Braking:** Take advantage of the regenerative braking system when decelerating.

Table II.* 1 : *Comparison of different speeds and their effect on range

The influencing factor	**Impact on energy consumption**	**Expected range (miles)**	**The observer**
High speed (70-75 km)	Increase energy consumption by up to 30%	Reduce range by up to 30%	Increased air resistance leads to greater energy consumption.
Average speed (50-60 km)	Moderate energy consumption	medium range	Balance between energy consumption
Aggressive driving (sudden acceleration and deceleration)	Increase energy consumption by up to 30%	Reduce range by up to 30%	Sudden acceleration and deceleration result in greater energy consumption.
Smooth driving (gradual acceleration and deceleration)	Low energy consumption	Low energy consumption	Smooth driving helps reduce energy consumption and increase range.

II .2.4. Weight and pregnancy

Weight and payload are significant factors influencing the range and efficiency of an electric vehicle. The heavier the vehicle or the load being transported, the more energy it consumes, reducing the distance the vehicle can travel before needing to be recharged.

Electric vehicles require more energy to move additional weight. According to a study by the American Automobile Association (AAA), the range of a Ford F-150 Lightning pickup truck decreased by 24.5% (from 445Km to 335 Km) when loaded with 630KG of weight, roughly 70 bags of soil or 20 bags of concrete mix. By comparison, the U.S. Department of Energy estimates that adding 45KGto a vehicle's weight reduces its fuel efficiency by 1%, meaning that a 14% increase in weight could reduce efficiency by up to 14%.

FIG II.6– Effect of load on the electric car battery **[32]**

The effect of load and weight on the electric car through its effect on the battery by increasing energy consumption from the battery as a result of the increase in torque and rotation, which drains the battery in the fastest time.

- ***Table II.2 : Impact of Load on Electric Vehicle Range***

Load Type	**Weight (KG)**	**Range Impact**	**Notes**
Light Load	200–500	Slight Decrease	Minimal effect on energy consumption and driving capability
Moderate Load	500–1000	Noticeable Decrease	Significant increase in energy consumption and reduced range
Heavy Load (Near Maximum Capacity)	1400+	Significant Decrease	Range reduced by up to 24.5%, as observed in the Ford F-150 Lightning test

By considering these factors and taking appropriate measures, the impact of weight and load on an electric vehicle’s range can be reduced, improving its efficiency and reducing the need for frequent recharging.

Proper tire pressure is crucial to maintaining the energy efficiency of an electric vehicle.
Even a slight drop in pressure can increase rolling resistance, resulting in greater energy consumption and reduced range. This has an impact through:

Increased rolling resistance: Improperly inflated tires deform more, resulting in increased friction with the road and additional energy consumption.

It also affects range: A study has shown that low tire pressure can reduce the range of an electric vehicle by up to 4%.

- *Table II.3 : Impact of Load on Electric Vehicle Range*

Load Type	Weight (KG)	Range Impact	Notes
Light Load	200–500	Slight Decrease	Minimal effect on energy consumption and driving capability
Moderate Load	500–1000	Noticeable Decrease	Significant increase in energy consumption and reduced range
Heavy Load (Near Maximum Capacity)	1400+	Significant Decrease	Range reduced by up to 24.5%, as observed in the Ford F-150 Lightning test

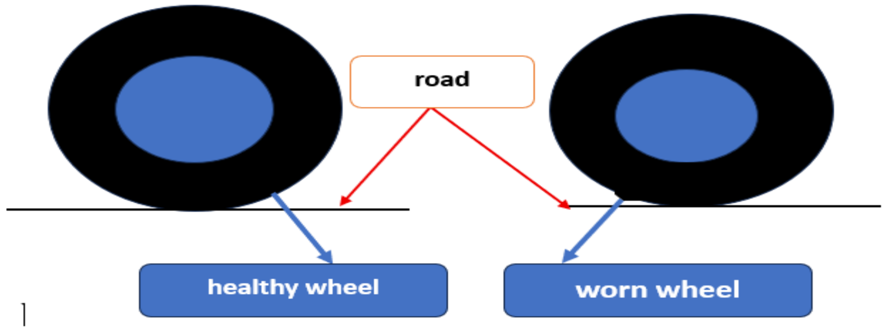
By considering these factors and taking appropriate measures, the impact of weight and load on an electric vehicle’s range can be reduced, improving its efficiency and reducing the need for frequent recharging.

II.2.5 Tire pressure and technical condition

Proper tire pressure is crucial to maintaining the energy efficiency of an electric vehicle. Even a slight drop in pressure can increase rolling resistance, resulting in greater energy consumption and reduced range. This has an impact through:

Increased rolling resistance: Improperly inflated tires deform more, resulting in increased friction with the road and additional energy consumption.

It also affects range: A study has shown that low tire pressure can reduce the range of an electric vehicle by up to 4%.



(a) Full wheels *(b) Empty wheels*

FIG II. 7– Effect of tire pressure on the range of an electric vehicle

II.2.6 Battery status

Battery health is a key factor that directly affects the range and efficiency of an electric vehicle. Studies indicate that deteriorating battery health can significantly reduce driving range. The battery is the most expensive component in an electric vehicle, accounting for between 50% and 70% of the vehicle's price. Although the average battery life is between 8 and 15 years, misuse or harsh environmental conditions can cause it to deteriorate more quickly, reducing driving range. Studies indicate that low temperatures significantly reduce the range of an electric vehicle. For example, at 15°C, the range can drop to 54% of the advertised range. Even at moderate temperatures, such as 21.5°C, the range can reach 115% of the advertised range. However, at high temperatures, such as 37.8°C, the range can drop to as much as 31%. Regarding long-term maintenance of an electric car battery, car owners should only rely on Level 3 fast charging in cases of extreme necessity, such as while traveling. They should therefore rely primarily on Level 1 and Level 2 charging. This is easy, as the Level 1 charging rate available from a regular electrical outlet is adequate for most car owners' daily driving range. All they need to do is leave the car charging overnight. Level 2 charging, which can be installed at home, is suitable for charging a suitable range in a short time and for frequent travelers. Level 3 charging from private stations, which can charge 80 to 100% in many cars in half an hour, should only be relied upon when absolutely necessary.

The scientific reason is that lithium-ion car batteries, like smartphone batteries, lose cells with each charging cycle, reducing the number of rechargeable cells. Level 3 fast charging causes these cells to be lost at a greater rate with each charging cycle, unlike Level 1 and Level 2 charging.

FIG II.8– Measuring battery efficiency during charging **[33]**

Therefore, it is necessary while planning a long trip to maintain the battery of the electric car, as maintaining the battery charge level requires the temperature control system and several other systems that operate while the electric car is stopped and require a charge in the battery. Therefore, the battery of the electric car should never be left empty or completely full. Since you can set up the car’s charging system and monitor it from a smartphone, it is recommended to set the charging system to always keep the car’s charge level between 25 and 75%. Therefore, if the charge drops below 75%, the car is charged. The importance of this range is that if the power is cut off, the car has until the charge drops to 25%, and then the charging system returns to work and raises the car to the 75% level or the specified level.

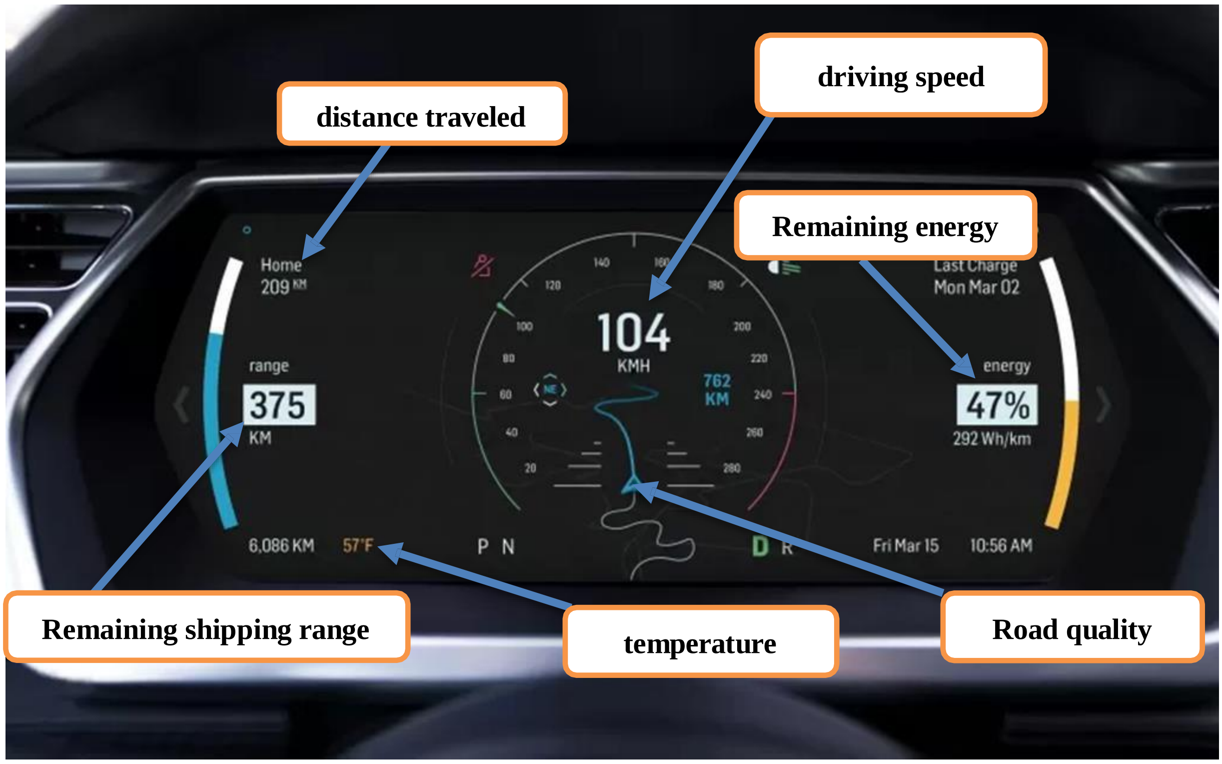


FIG II.9– Elements on the dashboard of an electric vehicle [35]

II.3. Battery operation

A battery is a complex cycle that converts chemical energy into electrical energy. It involves two important processes: discharging and charging. During the discharging process,
a small portion of the energy is converted to heat. During the charging phase, electrical energy is converted to chemical energy, and another portion to heat. Effective heat management during the discharging and charging processes is essential to ensure optimal battery performance and safety.

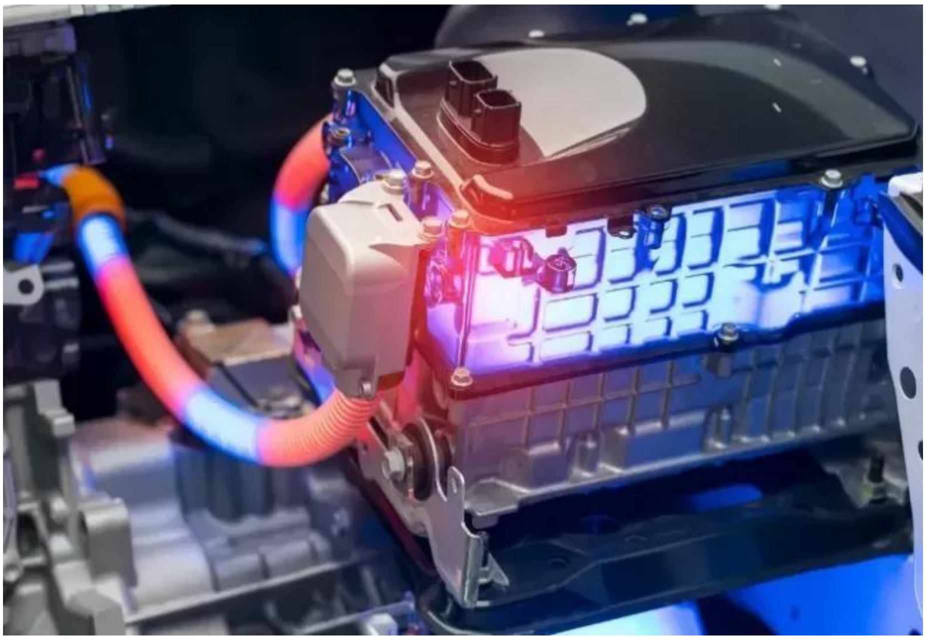


FIG II.10 – Designing better batteries for electric cars [35]

II.4. Three types of battery cells with the difference

There are three types of electric vehicle battery cells: cylindrical, prismatic, and pocket. All of these batteries are made of lithium ions with a specific type of casing. Each type of battery has a specific chemical composition, size, capacity, and lifespan, making it more or less suitable for electric vehicles. Understanding the differences shows why manufacturers prefer one battery over another. Each type has advantages and disadvantages, and the material aspect plays a role in how these ions are made as they have been developed over the years.

. Understanding these differences helps explain why manufacturers might prefer one type over another.

FIG II.11 – Designing better batteries for electric cars [32]

Table II.4: Comparison of EV Battery Cell Types

Feature	Cylindrical Cells	Prismatic Cells	pocket Cells
Shape	Round tubes	Rectangular	Flexible foil pouch
Energy Density	High per unit volume	Moderate	Highest
Mechanical Stability	High	Moderate	Low
Thermal Stability	High	Moderate	High
Thermal Stability	High	Moderate	High
Manufacturing Maturity	Well-established	Developing	Developing
Cost	Low	Moderate	High
Weight	Moderate	High	Low

Cylindrical

- **Chemical Composition**

The chemical composition of lithium-ion (Li-ion) battery cells varies depending on the cathode material used. The cathode is a critical component that influences the battery's energy density, lifespan, cost, and safety. Below is an overview of the most common cathode chemistries used in EV batteries

- **Size & Capacity**:Standard sizes include 18650 cell (2,300–3,600 mAh), 21700 cell (4,000–5,000 mAh), and 46800 cell (26,000 mAh).
- **Lifespan**: Up to 25,000 charge cycles.
- **Advantages**: High energy density per unit volume, robust mechanical and thermal stability, well-established manufacturing processes, and lower cost.
- **Disadvantages**: Gaps between cells in battery packs can reduce overall energy density.
- **Applications**: Widely used in EVs like Tesla, offering a balance between performance and cost

Prismatic

- **Chemical Composition**

Prismatic cells are a type of lithium-ion battery cell characterized by their flat, rectangular design, which allows for more efficient space packing within battery packs. These cells are manufactured using different chemistries, which affects their performance and cost.

- **Size & Capacity**: Larger than cylindrical cells, with capacities ranging from 20,000 mAh to 30,000 mAh.
- **Lifespan**: Approximately 2,000 charge cycles.
- **Advantages**: Efficient use of space due to flat design, fewer electrical connections needed, and moderate cost.
- **Disadvantages**: Potential for overheating and density inconsistencies; shorter lifespan compared to cylindrical cells.
- **Applications**: Common in EVs from manufacturers like BMW and Volkswagen

pocket

- **Chemical Composition:** Pouch cells are a type of lithium-ion battery cell characterized by their flexible, flat design, which allows for more efficient space-filling within battery packs. These cells use a multi-layer composite casing, typically consisting of an outer layer of nylon, a middle layer of aluminum, and an inner layer of polypropylene or similar materials.
- **Size & Capacity**: Flexible design allows for various shapes and sizes, with capacities comparable to cylindrical cells.
- **Lifespan**: Around 2,000 charge cycles.
- **Advantages**: Lightweight, high energy density, and adaptable to different designs.
- **Disadvantages**: Lower mechanical stability, requiring additional structural support; higher manufacturing costs.
- **Applications**: Used in portable devices and some EVs, offering design flexibility.

II.5. Cell components

Battery cells in electric vehicles consist of several key components that work together to store and provide the energy needed to power the vehicle. Here's an overview of these components:

- **Main components of battery cells in electric vehicles**

- **Anode (negative electrode)**

Usually made of graphite or other carbon materials.

Stores lithium ions during charging.

- **Cathode (positive electrode)**

Composed of materials such as nickel manganese cobalt oxide (NMC) or lithium iron phosphate (LFP).

It is the primary source of energy in the cell.

- the cathode and anode in a galvanic cell with the reaction

$$\mathbf{Zn(s) + CuSO4(aq) \rightarrow ZnSO4(aq) + Cu(s)} \qquad \mathbf{(II.1)}$$

- The cathode is Cu(s), and the anode is Zn(s)

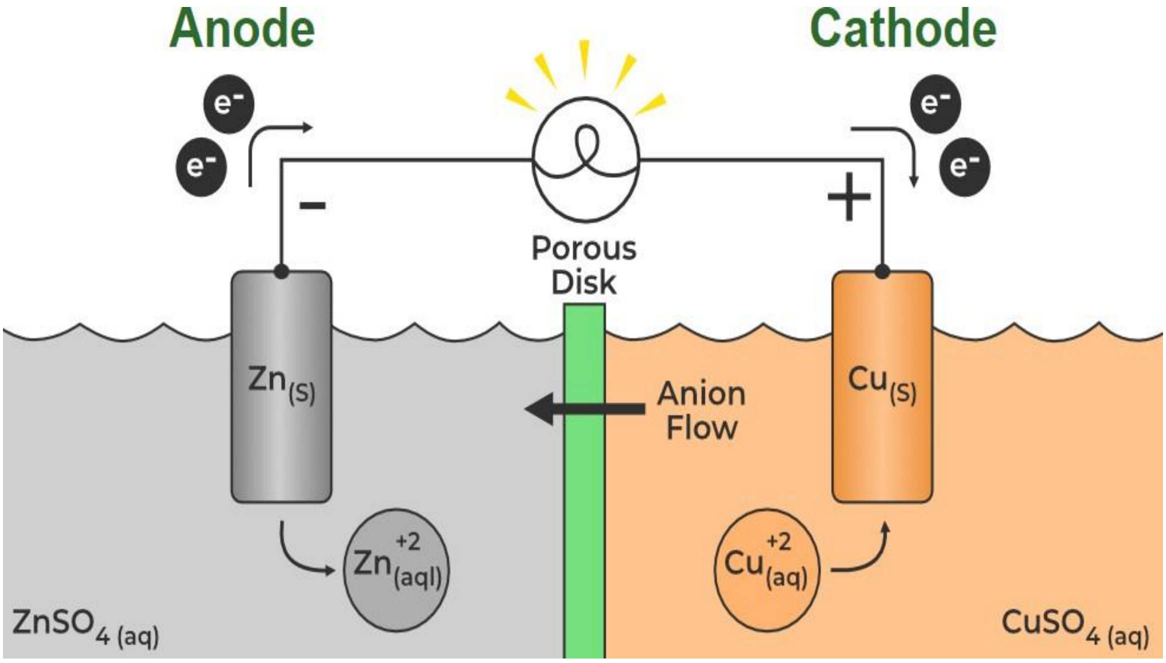


FIG II.12– Cathode and Anode [32]

- **Electrolyte**

A solution containing lithium ions that allows ions to move between the anode and cathode.

It is usually made of organic compounds containing lithium salts.

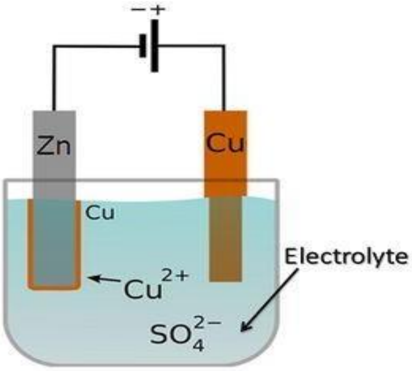


FIG II.13 – Electrolytes process **[32]**

- **Separator**

A thin layer of electrically non-conductive material, such as polyethylene or polypropylene.

It prevents direct contact between the anode and cathode, preventing short circuits.

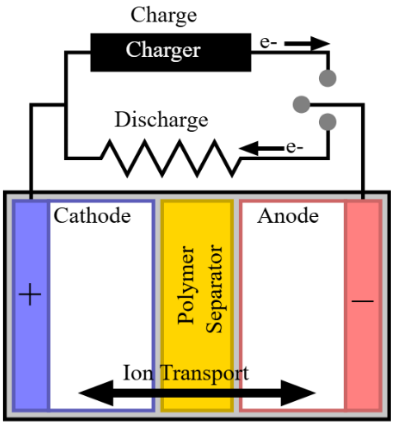


FIG II.14 – Diagram of a battery with a polymer separator **[32]**

- **Outer casing**

Made of materials such as aluminum or stainless steel.

It provides mechanical protection for the cell and maintains its structural stability.

- **Battery Management System (BMS)**

An electronic system that monitors the status of the cells, ensures charge balance, and protects them from overcharging or over discharging

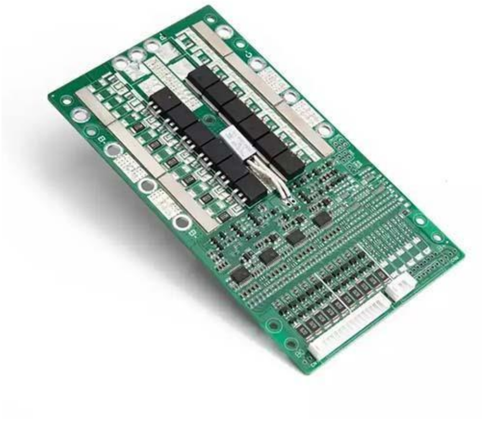


FIG II.15– Battery Management System (BMS) [38]

II.6. Electrical and chemical concepts of battery electronics

Batteries, like electric cells, are electrochemical generators. In other words, they produce electricity from chemical reactions. This phenomenon is studied and developed in a scientific field called "electrochemistry," which focuses on the relationship between chemistry and electricity. Electrochemistry describes the reactions and phenomena that occur at the atomic level when two conducting systems meet. These reactions and phenomena are chemical reactions associated with mutual exchanges of electrical energy. These exchanges, whether electronic or ionic, occur when one or more electrons transfer their charge, resulting in electricity.

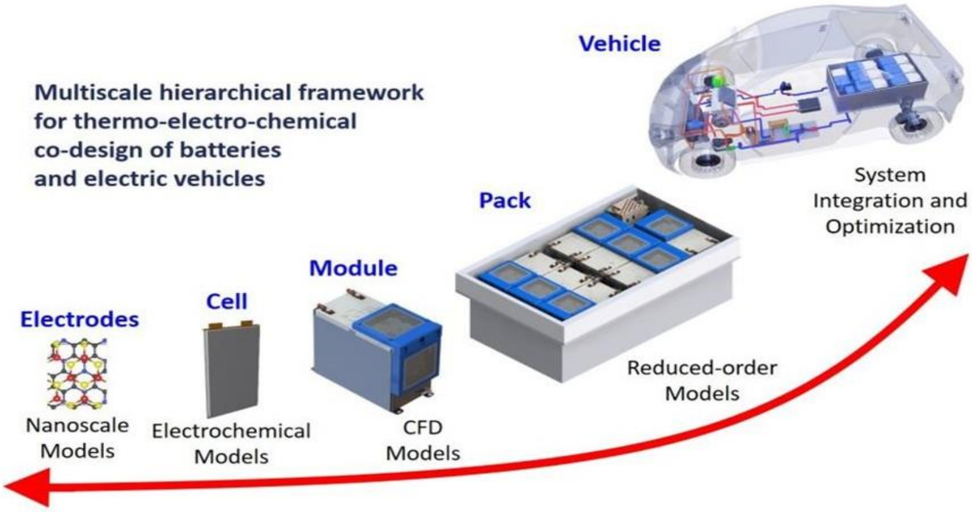
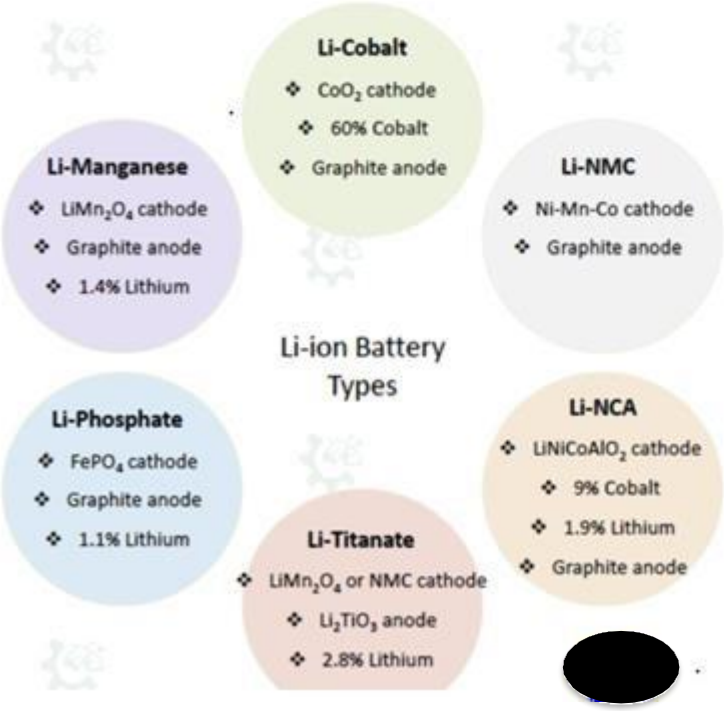


FIG II.16– Battery from fabrication to integration [38]

II .7. Materials and elements of batteries

Main electrochemical materials in batteries are categorized into three primary components: the anode, cathode, and electrolyte. Each component plays a crucial role in the battery's performance, energy density, and safety; we can found various types of batteries such:

- **Lead-acid battery**
- **Nickel/Cadmium (Ni-Cd)**
- **Nickel-metal hydride (Ni-Mh)**
- **Lithium/Ion (Li-Ion)**
- **Lithium/Polymer (Li Po)**
- **Lithium/iron/Phosphate (LFP)**
- **Lithium/Metal Polymer (LMP)**
- **Nickel/Manganese/Cobalt (NMC)**
- **Nickel/Cobalt/Aluminum (NCA)**
- **Lithium/Cobalt/Oxide (LCO)**



[redacted]

FIG II.17– Different types of materials in battery **[40]**

II.7.1. Lithium-ion

The lithium-ion (Li-ion) batteries have advanced technology in portable electronic devices, electric vehicles (VE) and energy storage. It is recommended for energy efficiency, performance and durability

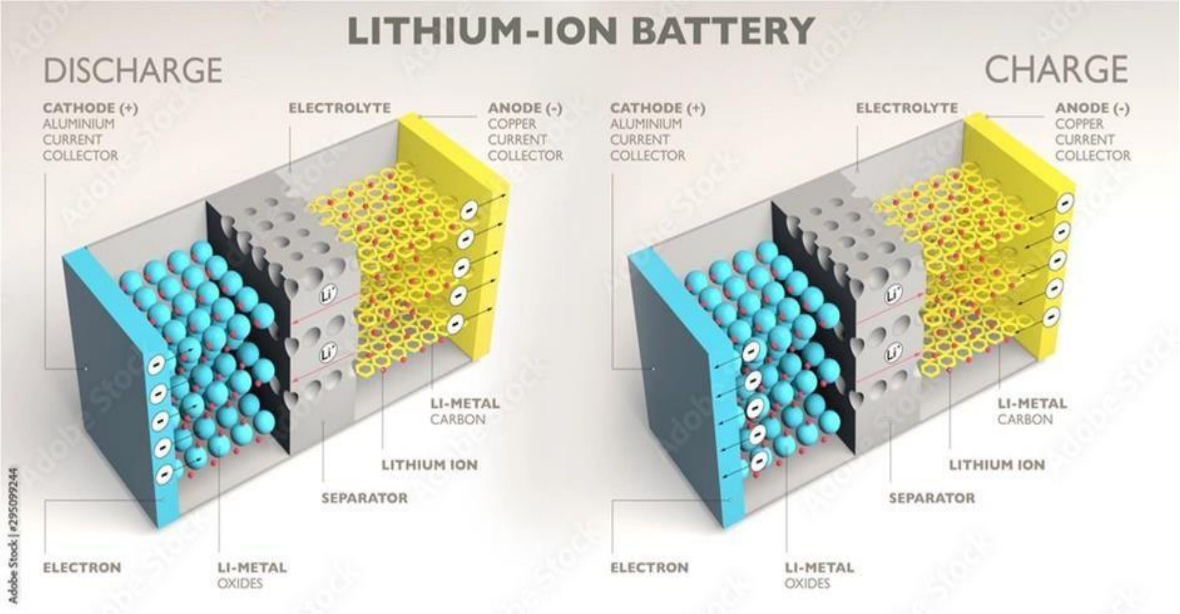


FIG II.18 – Li-ion battery diagram **[40]**

II.7.2. Lithium/Polymer (Li Po)

Lithium Polymer (LiPo) batteries are a type of rechargeable battery that uses a polymer electrolyte instead of the liquid electrolyte found in traditional lithium-ion batteries. This design allows for a lightweight, flexible, and compact battery structure, making them ideal for applications where space and weight are critical consideration

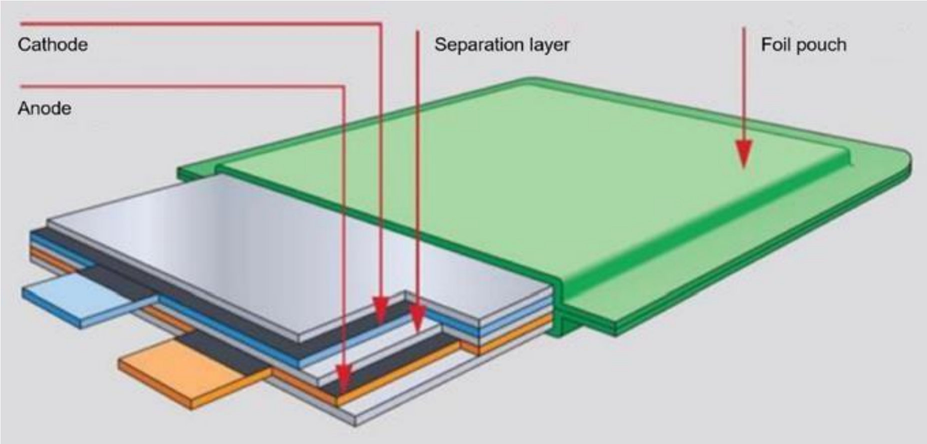


FIG II.19 – Lithium Polymer Battery **[40]**

II.7.3. Lithium/iron/ Phosphate (LFP)

$LiFePO_4$ batteries are a type of lithium-ion battery that uses lithium iron phosphate as the positive electrode (cathode) and graphite carbon as the negative electrode (anode). These batteries boast high-temperature resistance, long service life, and stable performance, making them an ideal choice for electric vehicles.

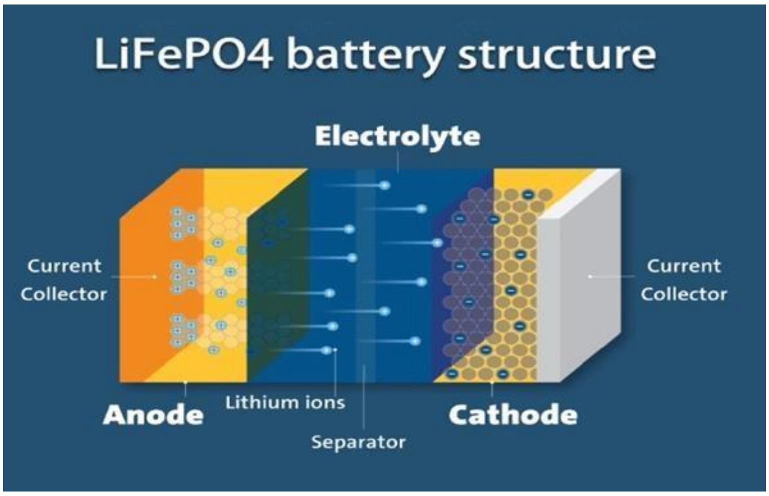


FIG II.20 – LifePO4 Battery [41]

II.7.4. Lithium/Metal Polymer (LMP)

A lithium/metal/polymer (LMP) battery is an advanced type of lithium battery that uses lithium metal as the anode (negative electrode) and a solid polymer electrolyte. These batteries feature a solid-state design that enhances safety and efficiency, making them a promising option for advanced energy applications.

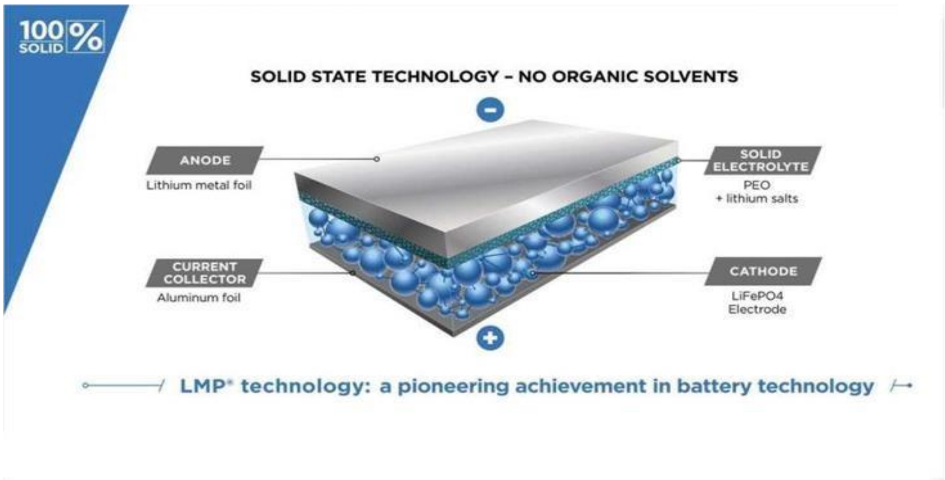


FIG II.21 – Lithium Metal Polymer (LMP) Battery [41]

The three main types of lithium batteries used in electric vehicles: Lithium-Ion (Li- ion), Lithium Polymer (LiPo), and Lithium Iron Phosphate ($LiFePO_4$), highlighting their pros, cons, and suitability for EV applications. We found another types of battery based on Lithium, table *II.4* resume the comparison between them

- ***Table II.5: Battery Comparison Table***

Feature	**Li-ion (Lithium Cobalt Oxide)**	**LiPo (Lithium Polymer)**	**$LiFePO_4$ (Lithium Iron Phosphate)**
Energy Density	High (150–250 Wh/kg)	High (150–200 Wh/kg)	Moderate (90–120 Wh/kg)
Cycle Life	500–1,000 cycles	300–500 cycles	2,000–5,000 cycles
Safety	Moderate (risk of thermal runaway)	Moderate (risk of swelling and fire)	High (non-flammable, thermally stable)
Nominal Voltage	3.6–3.7 V	3.7 V	3.2 V
Weight & Size	Light and compact	Lightweight and Flexible	Heavier and bulkier
Temperature Range	0°C to 45°C	0°C to 45°C	-20°C to 60°C
Cost	Moderate	Higher due to customization	Lower over lifespan
Environmental Impact	Higher due to cobalt use	Higher due to cobalt use	Lower (no cobalt, easier recycling)
Best EV Application	High-performance EVs	Lightweight EVs	Long-range, safety-prioritized EVs

II.7.5. Comparison of different EV battery technologies

Modern electric vehicles primarily rely on Li-ion variants, with NMC and NCA being common in high-performance applications and LFP gaining popularity due to safety and cost advantages. Older types like NiMH, Ni-Cd, and lead-acid are largely phased out from EVs but remain in niche or hybrid applications. Solid-state batteries such as LMP show promise for the future, offering high energy and safety but are not yet widely adopted due to cost and scalability issue.

➢ ***Table II.6: Battery Comparison Table***

Battery Type	**Chemistry**	**Energy Density (Wh/kg)**	**Cycle Life**	**Thermal Stability**	**Cost**	**Typical Use**	**Key Features**
Lead-Acid	$Pb\text{-}PbO_2$	30–50	500–1,000	Good	Very Low	Golf carts, early EVs	Heavy, low energy, highly recyclable
Nickel/Cadmium (Ni-Cd)	Ni-Cd	40–60	1,000–2,000	Moderate	Moderate	Rarely used in EVs	Toxic cadmium, memory effect
Nickel-Metal Hydride (Ni-MH)	Ni-MH	60–120	500–1,000	Good	Moderate	Hybrids (e.g., Prius)	Robust, safer than Ni-Cd
Lithium-Ion (Li-ion)	Varies (e.g., LCO, NMC)	150–250	1,000–2,000	Moderate	High	Most modern EVs	High efficiency, common
Lithium-Polymer (Li-Po)	Li-ion polymer	100–200	500–1,000	Moderate	High	Drones, e- bikes, some EVs	Flexible shape, light weight
Lithium Iron Phosphate (LFP)	$LiFePO_4$	90–160	2,000–5,000	Excellent	Low	Tesla (Model 3 SR), BYD	Very safe, long life, lowerrange
Lithium Metal Polymer (LMP)	Solid-state	200–300 (potential)	3,000+ (projected)	Excellent	Very High	Bolloré Bluecar (limited)	Solid electrolyte, emerging tech
Nickel Manganese Cobalt (NMC)	$LiNiMnCoO_2$	150–220	1,000–2,000	Moderate	High	EVs (VW, BMW, Hyundai)	Balanced performance
Nickel Cobalt Aluminum (NCA)	$LiNiCoAlO_2$	200–260	1,000–2,000	Moderate	High	Tesla (Model S/X)	High energy, long range
Lithium Cobalt Oxide (LCO)	$LiCoO_2$	150–200	500–1,000	Poor	High	Electronics, rarely EVs	High energy, low safety

The Ragone diagram is a crucial tool for comparing the performance of various energy storage technologies, including batteries, by plotting specific energy (Wh/kg) against specific power (W/kg). This logarithmic chart helps visualize the trade-offs between energy capacity and power delivery, guiding the selection of appropriate technologies for specific applications

Specific energy is used as an indicator of the amount of energy that can be stored per unit mass, reflecting the length of time a device can operate. Conversely, specific power is used as a measure of the speed at which this energy can be delivered—in other words, how quickly a system responds to instantaneous loads.

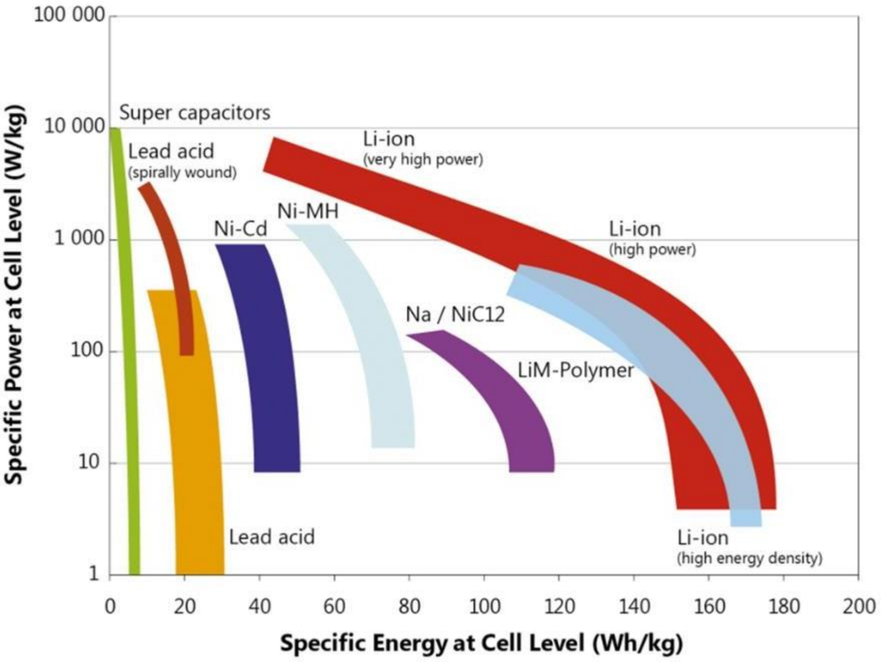


FIG II.22 –Ragone chart depicting the range of specific energy and power levels achievable by current generation battery cell technology.
***Note that the specific energy and power of the final assembled battery pack will be lower than that of the con* [45]**

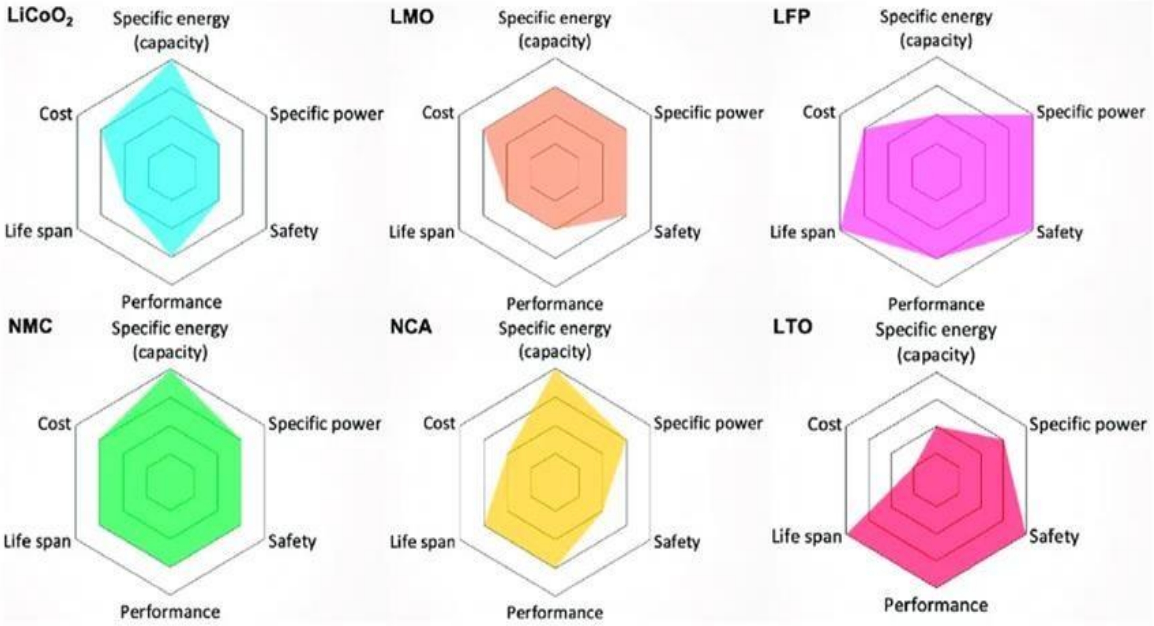


FIG II.23 –Comparison of lithium-ion (Li-Ion) technology. (a) LCO;
***(b) LMO; (c) LFP;(d) NMC; (e) NCA; (f) LTO* [45]**

II.8. Solid-state batteries

Solid-state batteries (SSBs) represent a significant advancement over traditional lithium-ion batteries, primarily by replacing the flammable liquid electrolyte with a solid electrolyte. This innovation enhances safety, energy density, and longevity, making SSBs particularly promising for applications in electric vehicles (EVs), aerospace, and consumer electronics Solid-state batteries replace the liquid electrolyte used in traditional lithium-ion batteries with a solid electrolyte. This design enhances energy density, safety, and longevity, making them a compelling option for EVs and other application

FIG II.24 –Solid-State Batteries [49]

II.8.1. Working Principle of Solid-State Batteries

Solid-state batteries represent a significant advancement in energy storage technology, particularly for electric vehicles (EVs). They differ from traditional lithium-ion batteries by using a solid electrolyte instead of a liquid or gel, leading to improved safety, higher energy density, and longer lifespan.

A solid-state battery consists of three primary components:

- **Cathode (Positive Electrode)**: Typically made from lithium-based compounds such as lithium iron phosphate (LFP), nickel manganese cobalt (NMC), or lithium manganese oxide (LMO).

- **Anode (Negative Electrode)**: Often constructed from pure lithium metal, which allows for a higher energy density compared to graphite used in conventional batteries.

- **Solid Electrolyte**: A non-flammable, solid material that conducts lithium ions between the anode and cathode. This electrolyte can be made from ceramics, sulfides, or phosphates.

During charging, lithium ions move from the cathode to the anode through the solid electrolyte. During discharge, the ions flow back to the cathode, releasing stored energy as electricity.

II.8.2. Advantages of Solid-State Batteries

- **Higher Energy Density**: Utilizing lithium metal or high-silicon anodes, SSBs can achieve energy densities exceeding 350 Wh/kg, surpassing the typical 150–250 Wh/kg of conventional lithium-ion batteries.
- **Enhanced Safety**: The absence of liquid electrolytes eliminates risks associated with flammability and leakage, significantly reducing the potential for thermal runaway.
- **Extended Cycle Life**: SSBs demonstrate improved durability, with some designs targeting over 1,000 charge cycles with minimal degradation.
- **Operational Stability**: These batteries maintain performance across a wide temperature range, from -30°C to 60°C, making them suitable for diverse environmental conditions.

II.8.3. A Notable Developments in Solid-State Battery Technology

- **Solid Power**: Based in Colorado, Solid Power is developing sulfide-based solid electrolytes for all-solid-state batteries. Their lithium metal and high-silicon anode cells have achieved energy densities up to 440 Wh/kg and over 1,000 charge cycles. Solid Power plans to commence pilot production in 2025, with integration into EVs by 2027–2028.
- **QuantumScape**: In partnership with Volkswagen, QuantumScape is focusing on ceramic-based solid-state batteries using lithium metal anodes. Their technology aims for high energy and power density with rapid charging capabilities.
- **Toyota**: Toyota plans to introduce solid-state batteries in EVs by 2027, targeting a range of up to 1,000 km and charging from 10% to 80% in approximately 10 minutes.
- **BYD**: BYD's "Super-e" system aims to provide a range of 400 km with just five minutes of charging, showcasing the potential for ultra-fast charging in solid-state battery technology.

II.8.4. Comparison between solid-state batteries and lithium-ion batteries, focusing on key aspects relevant to electric vehicles (EVs):

With the rapid expansion of the electric vehicle (EV) market, the need for more efficient and safer battery technologies has become critical. Lithium-ion batteries are currently the most widely used option, offering a good balance between efficiency, weight, and cost. However, this technology faces challenges such as safety risks resulting from the use of liquid electrolytes, and limited energy density and lifetime.

Solid-state batteries (SSBs) have emerged as a promising solution to overcome these limitations. They replace liquid electrolytes with non-flammable solid materials, increasing safety and enabling lighter, more energy-efficient designs. This comparison focuses on key technical aspects such as energy density, charging speed, cycle life, safety, operating temperature range, and cost to assess the readiness of solid-state batteries to become a future alternative to lithium-ion batteries in the EV industry**.**

- ***Table II. 7: Comparison Table: Solid-State vs. Lithium-Ion Batteries***

Feature	**Solid-State Batteries**	**Lithium-Ion Batteries**
Energy Density	250–800 Wh/kg	160–250 Wh/kg
Cycle Life	8,000–10,000 cycles	1,500–2,000 cycles
Charging Speed	12–15 minutes to 80%	30–45 minutes to 80%
Safety	Higher (non-flammable solid electrolyte)	Moderate (flammable liquid electrolyte)
Operating Temp.	-30°C to 60°C	0°C to 45°C
Cost	$800–$1,200 per kWh (currently) DZD104037,55	$100–$150 per kWh DZD13004,69
Commercialization	Expected around 2026–2027	Widely available and established

Solid-state batteries have the potential to revolutionize energy storage solutions thanks to their superior safety, efficiency, and performance. With continued research and development, these batteries are expected to play a pivotal role in the future of electric mobility and beyond.

II.9.Most important leading companies in the electric car industry

Leading electric vehicle manufacturers such as Tesla, BYD, and Mercedes EQ are seeking to improve the range of their electric vehicles by adopting advanced technologies in the areas of batteries, aerodynamics, propulsion systems, and software. Below is a review of the latest studies and technologies used.

II.9.1. Tesla

Tesla is constantly striving to improve the range of its electric vehicles by adopting advanced technologies in the areas of batteries, aerodynamics, propulsion systems, and software.

- **Improved motors and inverters:** Tesla has improved the efficiency of its motors from 80% to 90%, increasing range by up to 18%. Inverters also achieve efficiency of up to 99% in some cases.
- **Use of a heat pump:** Tesla uses a heat pump instead of traditional electric heating, reducing energy loss at low temperatures and increasing efficiency by up to 300%.
- **Improved aerodynamic design:** The Model 3 has been updated with aerodynamic improvements, such as reduced air resistance, resulting in a 10% range increase.
- **Software and over-the-air updates:** Tesla provides periodic software updates to improve energy consumption and battery management, which contributes to increased range

FIG II.25 – Tesla Model 3 Performance **[50]**

II.9.2. BYD

Chinese company BYD is a leading company in the electric vehicle industry, continuing to develop innovative technologies to increase the range and performance of its electric vehicles.

The latest technologies adopted by the company

- **E-Platform 3.0**

BYD's e-Platform 3.0 platform is a significant step forward in electric vehicle development. BYD features:

- **Blade Battery**

BYD's Blade battery is one of the latest battery technologies. It features:

High safety, as the battery passes harsh tests such as puncture and bending without ignition or smoke.

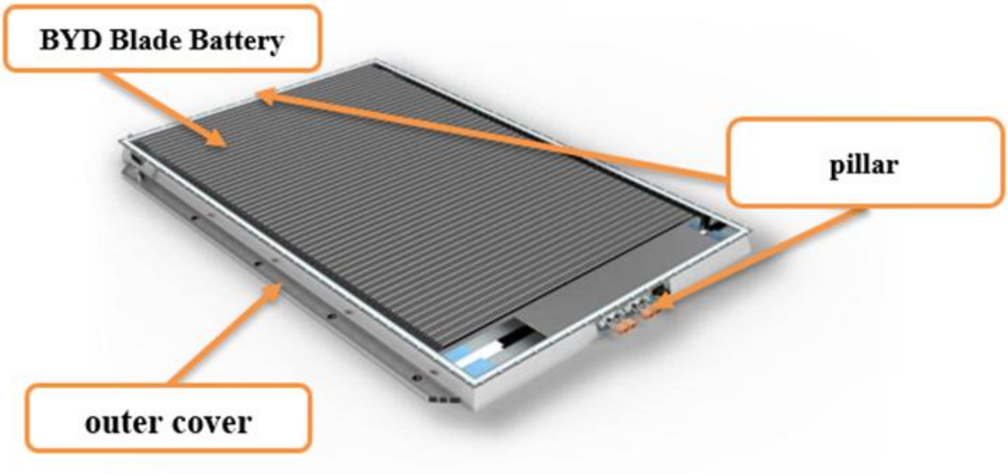


FIG II.26– BYD's Blade battery **[50]**

Space efficiency, as the battery's design improves space utilization by more than 50% compared to conventional batteries. The long-range battery contributes to a range of more than 565 km in some models.

- **Ultra-fast Charging**

BYD offers ultra-fast charging technology with a capacity of up to 1,000 kW, allowing the car to charge for a distance of 470 km in just 5 minutes.

➢ **BYD's distinctive models**

BYD offers a variety of electric vehicles that showcase its advanced technologies:

- **BYD Han EV:** A luxury sedan with long range and powerful performance.
- **BYD Tang EV:** A family-friendly electric SUV with spacious interiors and outstanding performance.
- **BYD Atto 3:** A compact SUV that offers a balance between performance and price.
- **BYD Seagull:** A compact electric vehicle suitable for urban driving.

- **BYD Yangwang U8:** A luxury SUV that offers advanced technologies and powerful performance.

BYD demonstrates its commitment to delivering high-performance and reliable electric vehicles, making them a compelling choice for consumers seeking innovation and efficiency.

FIG II.27 – Model BYD SEAL [50]

II.9.3. Mercedes EQ

It's a line of luxury electric vehicles offered by Mercedes-Benz, featuring advanced technologies aimed at improving driving range and energy efficiency. Here's a look at some of the key models and technologies.

- **Battery and Range Technologies**

- **EQS Sedan:** The EQS 450+ features a 107.8 kWh battery, offering a range of up to 563 km according to EPA standards.
- **EQS SUV:** The EQS 450+ SUV offers a range of up to 491 km, while the EQS 580 4MATIC® SUV offers a range of up to 459 km.
- **EQE Sedan:** The EQE 350 features a range of up to 491 km, while the EQE 500 4MATIC® offers a range of up to 418 km.
- **EQB SUV:** The EQB 250 offers a range of up to 394 km, while the EQB 350 4MATIC® offers a range of up to 365 km.

- **Range-enhancing technologies**

Advanced energy recuperation system: The EQS 2025 features an enhanced energy recuperation system that enables deceleration of up to 3 m/s², helping recover more energy during braking.

- **ECO driving mode:** The ECO driving mode helps reduce energy consumption by adjusting driving style and optimizing energy recovery.
- **Intelligent motor control:** In 4MATIC® models, the front motor automatically disengages in low-load conditions to reduce energy consumption.

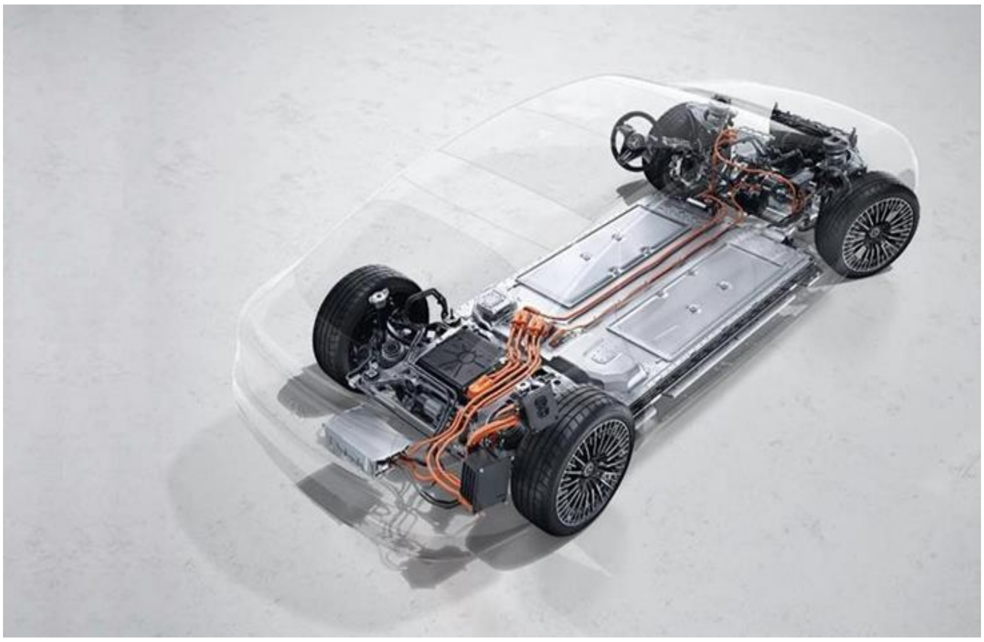


***FIG II.28* – Mercedes *EQS SUV* [50]**

Mercedes-Benz is pursuing new technologies such as solid-state batteries, which promise significant increases in energy density and safety. Initial tests show these batteries could provide a driving range of up to 1,000 km. These technologies are expected to revolutionize the electric vehicle

Mercedes-Benz is actively developing solid-state battery technology, aiming to enhance electric vehicle (EV) performance and safety. In September 2024, the company partnered with U.S.-based startup Factorial Energy to co-develop the "Solstice" battery, a lithium-metal solid-state battery featuring a novel dry cathode design. This collaboration is part of Mercedes-Benz's strategy to lead in battery technology and accelerate its transition to electric mobility.

➢ ***Table II.8: Comparison Table: Solid-State vs. Lithium-Ion Batteries***

Company	Key Technology	EPA Range	Fast Charging	Highlights
Tesla	High-efficiency powertrains, Heat Pump system	Up to 643 km (Model S Long Range AWD)	Supercharger V3 (up to 250 kW)	94% efficiency, 4680 battery development underway
BYD	Blade Battery, e-Platform 3.0	Up to 696km (Seal EV)	500 kW ultra-fast charging	50% space utilization increase, 1 million km lifespan
Mercedes EQ	Regenerative braking, ECO driving mode	Up to882km (EQS 450+ 4MATIC)	Not specified	34–44 kWh/100 miles consumption, premium comfort

➢ **Additional Notes:**

- **Tesla:** Features advanced motor and heating technologies, contributing to increased energy efficiency.
- **BYD:** Offers ultra-fast charging technologies, reducing downtime and increasing user comfort.
- **Mercedes EQ:** Focuses on passenger comfort and luxurious design, with improvements in energy consumption.

II.10. Role of Battery Quality in Range Optimization

The driving range of electric vehicles (EVs) is a critical factor influencing consumer adoption and the broader transition to sustainable transportation. A pivotal determinant of this range is the quality and performance of the battery system. High- quality batteries, characterized by superior energy density, efficiency, thermal stability, and longevity, are essential for maximizing the driving distance achievable on a single charge.

Recent advancements in battery technology have underscored the importance of these attributes. For instance, research indicates that lithium-ion batteries can retain approximately 90% of their capacity after 100,000 kilometers and about 87% after 300,000 kilometers, with an annual degradation rate of just 1.8 %. Moreover, studies have demonstrated that optimal battery thermal management strategies can significantly enhance battery lifespan and performance, thereby contributing to extended vehicle range.

Furthermore, the impact of environmental conditions on battery performance cannot be overlooked. Variations in ambient temperature can lead to significant fluctuations in battery efficiency, with reductions in driving range observed under extreme cold conditions.

This section delves into the specific battery characteristics that influence EV range, examining how advancements in battery chemistry, thermal management, and system integration contribute to enhanced performance and extended driving distances.

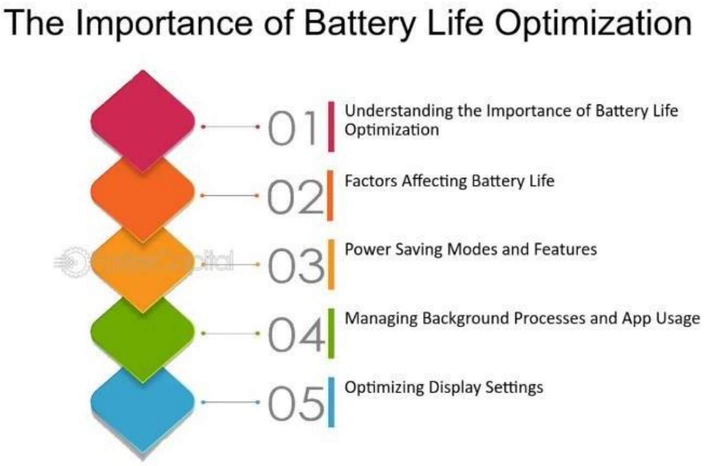


FIG II.29 –Importance Of Battery Life Optimization **[58]**

II.10.1 - Energy Density

Energy density is a fundamental parameter in evaluating the performance of batteries, particularly in the context of electric vehicles (EVs). It refers to the amount of energy a battery can store per unit of mass (gravimetric energy density) or volume (volumetric energy density). Higher energy densities enable EVs to achieve longer driving ranges without increasing the size or weight of the battery pack.

Recent advancements in battery technology have led to significant improvements in energy density. For instance, between 2008 and 2020, the volumetric energy density of lithium-ion batteries increased from 55 watt-hours per liter to 450 watt- hours per liter. This enhancement allows for more compact and lighter battery designs, contributing to overall vehicle efficiency.
The specific energy of lithium-ion batteries varies depending on the chemistry used. For example, lithium iron phosphate (LFP) batteries typically offer specific energies around 150 Wh/kg, while nickel manganese cobalt (NMC) batteries can achieve over 300 Wh/kg . These differences influence the choice of battery type based on the desired balance between energy capacity, cost, and thermal stability. [28]

Understanding and optimizing energy density is crucial for the development of EVs that meet consumer expectations for range and performance. Ongoing research aims to further enhance energy density through innovations in materials and battery design, paving the way for more efficient and accessible electric transportation solutions.

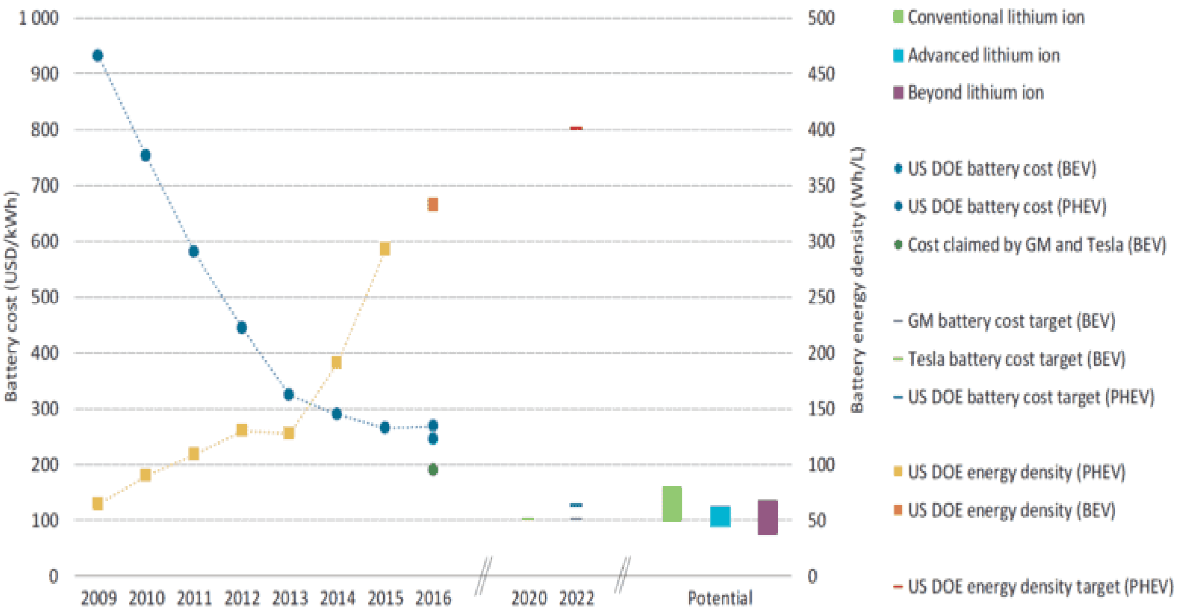


FIG II.30–Importance – Graph of electric vehicle battery cost and power density 2009 to 2016 [59]

II.10.2 - Battery Efficiency:

Battery efficiency refers to a battery's ability to convert stored energy into usable electrical energy with minimal loss. This efficiency is crucial for applications like electric vehicles (EVs), portable electronics, and grid energy storage, as it impacts performance, longevity, and energy consumption.[59]

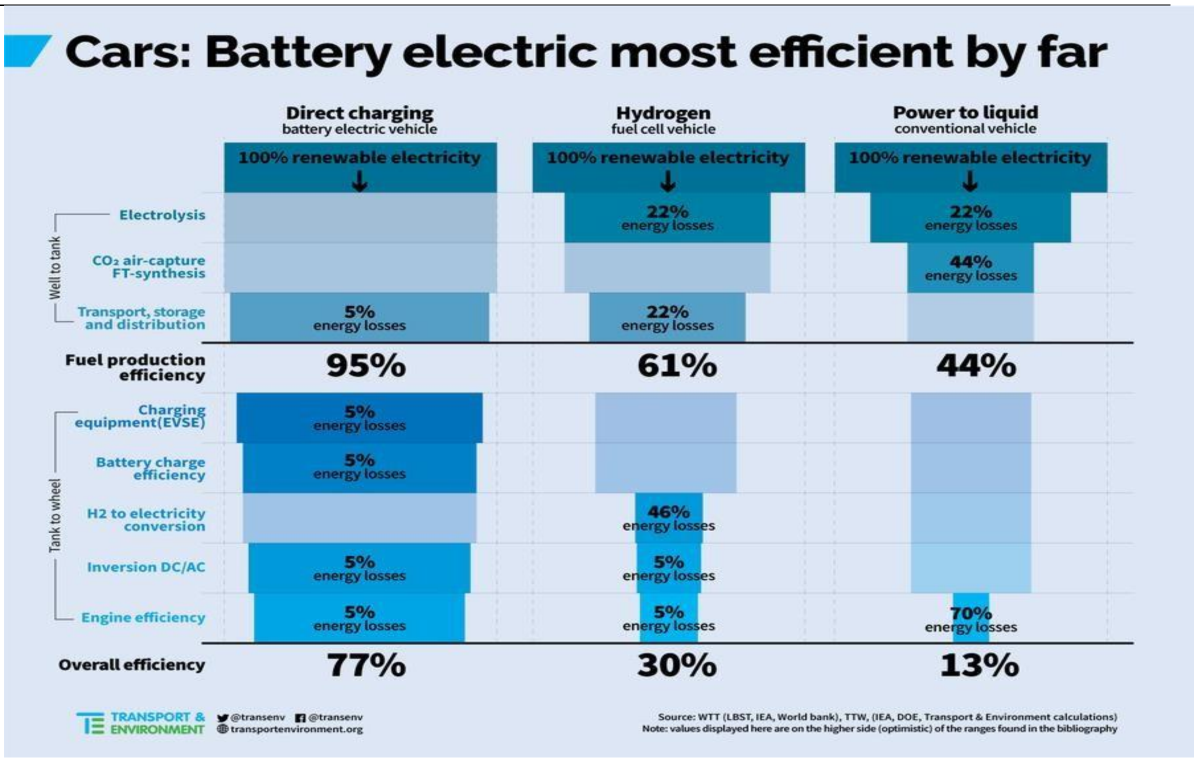


FIG II.31– Battery Electric most efficient by far [59]

Key Types of Battery Efficiency

- **Coulombic Efficiency**
    - Measures the ratio of charge delivered during discharge to charge received during charging.
    - High coulombic efficiency indicates minimal energy loss during cycling, which is vital for optimizing battery performance.
- **Charge Efficiency**
    - Indicates how effectively a battery converts input energy into stored energy.
    - Lithium-ion batteries typically have charge efficiencies ranging from 90% to 95%, while lead-acid batteries may have lower efficiencies between 70% and 85%.
- **Round-Trip Efficiency**
    - Refers to the ratio of energy output during discharge to energy input during charging.
    - Lithium-ion batteries generally exhibit round-trip efficiencies above 80%, making them suitable for applications requiring frequent cycling

Factors Influencing Battery Efficiency

- **Internal Resistance**: Higher internal resistance leads to energy losses as heat, reducing overall performance.
- **Temperature**: Extreme temperatures can affect battery performance and efficiency.
- **State of Charge (SoC)**: Maintaining an optimal SoC is crucial for battery health and performance.
- **Battery Age**: Overcharging, fast-charging, and extreme temperatures can accelerate battery aging, impacting efficiency.

Enhancing Battery Efficiency

- **Optimal Charging Practices**: Avoid overcharging and deep discharging to prolong battery life.

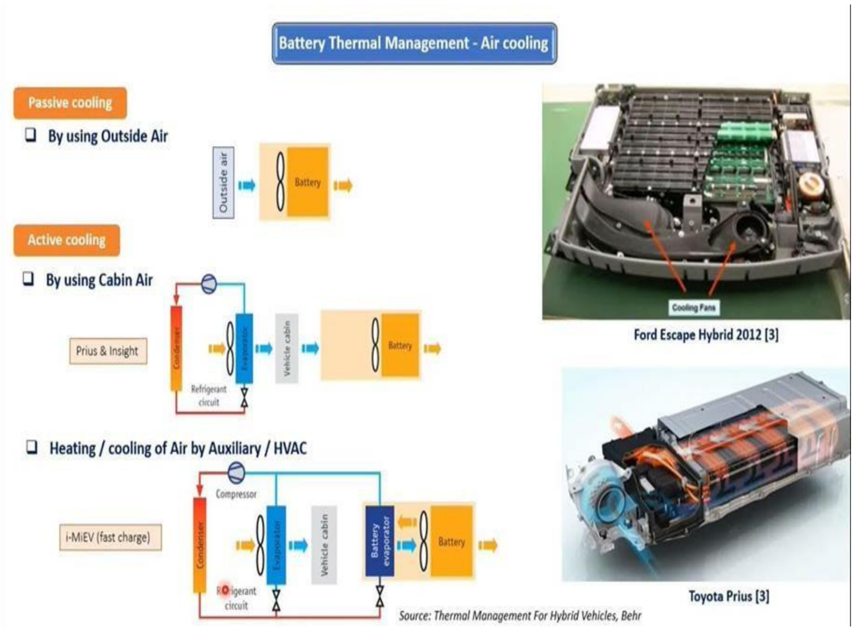
- **Temperature Management**: Maintain batteries within recommended temperature ranges to prevent performance degradation.

- **Advanced Charging Algorithms**: Implement intelligent charging protocols that adjust based

- **Material Innovations**: Developing new materials and manufacturing techniques can improve battery performance and efficiency

II.10.3.Thermal Management

Is a critical aspect of electric vehicle (EV) and energy storage systems, ensuring that batteries operate within optimal temperature ranges [30]. Effective thermal management enhances performance, extends lifespan, and improves safety by preventing issues like thermal runaway.



Source: Thermal Management For Hybrid Vehicles, Behr

FIG II.32 –Battery Management Systems- Thermal Management and Architect **[61]**

II.11. Battery Management Systems (BMS)

play a crucial role in ensuring the safety, efficiency, and longevity of the battery pack. The BMS monitors key parameters such as voltage, current, temperature, and the State of Charge (SOC) for each cell within the battery. It balances the cells to ensure uniform performance, protects the battery from unsafe conditions like overcharging or overheating, and manages power flow to optimize energy use. In modern EVs, the BMS also communicates with the vehicle's control systems and chargers to provide real-time data and control signals. Without an effective BMS, the performance and safety of electric vehicles would be severely compromised, making it an essential component in any EV powertrain. Is an electronic system used to manage rechargeable batteries, such as lithium-ion batteries found in electric vehicles. Its primary goal is to ensure the safe and long-lasting use of the battery by continuously monitoring and estimating its state, calculating secondary data, reporting system status, controlling the battery’s environment, balancing cells, and providing protection. [31]

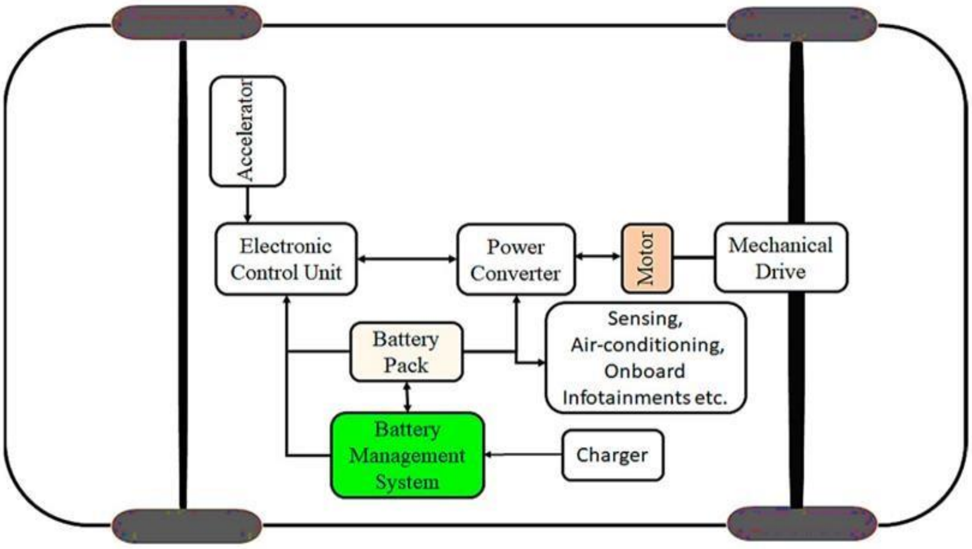


FIG II.33 –EV power distribution network **[61]**

The BMS performs essential functions such as monitoring voltage, current, and temperature; estimating the State of Charge (SOC) and State of Health (SOH); balancing individual cells to prevent overcharging or deep discharging; and managing thermal conditions to prevent overheating. It also offers protection against unsafe operating conditions like overcurrent, high temperatures, and voltage irregularities. Additionally, the BMS communicates with external systems like the vehicle control unit or charger to ensure proper operation.[32]

In electric vehicles, the BMS plays a critical role in maximizing battery performance, enhancing safety, and extending battery lifespan.

II.11.1. AI improvements to BMS strategies (smart BMS)

Artificial Intelligence (AI) is significantly improving Battery Management System (BMS) strategies, leading to what is often referred to as **Smart BMS**. These AI-enhanced systems go beyond traditional BMS functionalities by incorporating data-driven decision-making, real-time adaptability, and predictive capabilities

- **State Estimation Enhancements**

Traditional BMS methods (e.g., Kalman filters) estimate:

- **State of Charge (SOC)**
- **State of Health (SOH)**
- **State of Power (SOP)**

AI improvements:

- **Machine Learning (ML) models** (e.g., neural networks, support vector machines) trained on large datasets improve the accuracy of SOC/SOH predictions.
- **Deep Learning models** can identify complex nonlinear relationships between temperature, current, voltage, and capacity.

➢ **Battery Health Prediction and Prognostics**

Predicting when a battery will fail or degrade below usable limits is critical.

AI techniques used:

- **Time-series forecasting** (LSTM, RNNs)
- **Reinforcement Learning (RL)** for adaptive learning
- **Anomaly detection** using unsupervised ML to detect early signs of failure

Example Use Cases:

- **Tesla and Rivian:** Use AI-enhanced BMS for EV battery optimization.
- **Grid-scale batteries:** AI helps balance demand response, life extension, and predictive maintenance.
- **Consumer electronics:** Smart BMS can tune performance for individual user habits.

II.10.2. Operating principle of Battery Management Systems (BMS) in Electric Vehicles (EVs)

Is based on the continuous monitoring, control, and protection of the battery pack to ensure its safety, performance, and longevity. The BMS constantly measures important parameters such as voltage, current, temperature, and the State of Charge (SOC) of each cell in the battery. It performs cell balancing to maintain equal voltage levels across all cells, preventing damage from overcharging or deep discharging. The system also manages thermal conditions by activating cooling or heating mechanisms to keep the battery within a safe temperature range. In addition, the BMS detects faults or irregularities, such as short circuits or temperature spikes, and takes immediate protective actions. It communicates with other vehicle systems to coordinate energy flow and provides real-time diagnostics. In summary, the BMS functions as the brain of the battery system, ensuring reliable and efficient performance in all driving conditions. [33. 61]

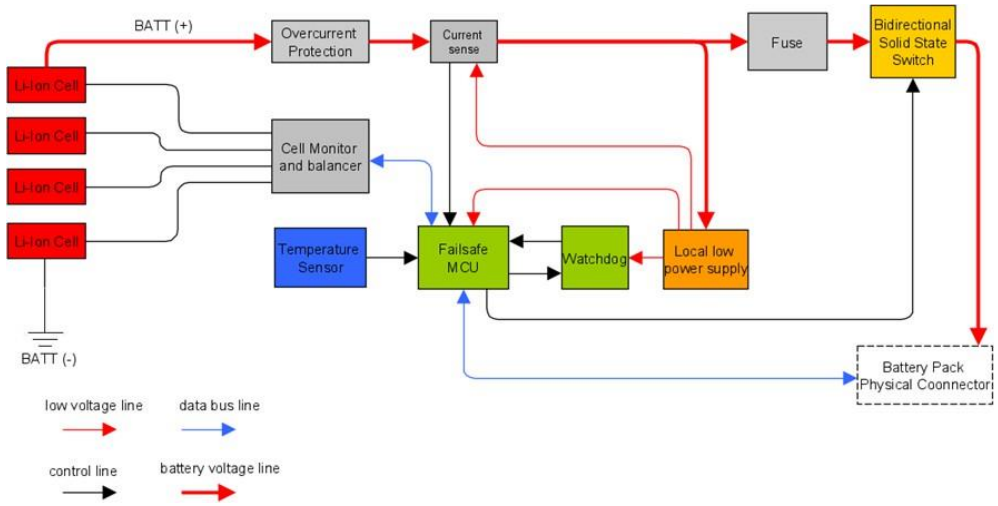


FIG II.34–BMS diagram **[61]**

II.10.3. Electrical Equations

A. State of Charge (SOC).

Measures how much energy remains in the battery

This method is widely used due to its simplicity and cost-effectiveness. However, it is sensitive to initial SOC errors and current measurement inaccuracies. Over time, these errors can accumulate, leading to drift in SOC estimation

$$\mathrm{SOC}(t) = \mathrm{SOC}(t_0) - \frac{1}{3600 \cdot Q} \int_{t_0}^{t} (I_{\mathrm{bat}} - I_{\mathrm{loss}})\, dt \qquad \textbf{(II.2)}$$

- **SOC(t):** State of charge at time (t)
- **I(t) :** Current (positive for discharge)
- **C nominal:** Nominal capacity of the battery

-Space Representation:

- SOC is computed by integrating the current over time, similar to Coulomb Counting.
- The voltage across each RC parallel is simulated as

$$\frac{dV_{c,i}}{dt}(t) = -\frac{1}{R_i C_i} V_{c,i}(t) + \frac{1}{C_i} i(t) \qquad \textbf{(II.3)}$$

II.10.4. Electrical Equations

A. State of Health (SOH).

Indicates the battery’s remaining usable capacity:

$$\mathrm{SoH_c} = \left(\frac{Q_{\mathrm{cc}}}{Q_{\mathrm{nc}}}\right) \times 100$$

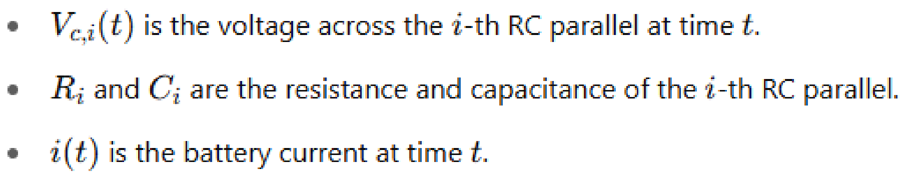
(II.4)

- Cactual**:** Current capacity

II.12. Advanced materials (e.g., silicon anodes, graphene)

Silicon anodes, in particular, offer a significantly higher theoretical capacity—up to ten times greater than traditional graphite anodes—which can substantially increase energy density and extend the driving range of EVs. However, silicon expands during charging, which can cause structural issues, so researchers are developing composite materials to stabilize it. Graphene, a single layer of carbon atoms arranged in a honeycomb structure, is another breakthrough material due to its exceptional electrical conductivity, mechanical strength, and thermal properties. It can be used in electrodes, current collectors, and even in thermal management layers to improve overall battery efficiency, reduce charging times, and enhance safety. The integration of these advanced materials is critical to improving battery performance, lifespan, and enabling more compact, lightweight EV designs.[34]

Advanced materials like silicon anodes and graphene are revolutionizing electric vehicle (EV) battery technology by significantly enhancing energy density, charging speed, and overall performan



- $V_{c,i}(t)$ is the voltage across the i-th RC parallel at time t.
- R_i and C_i are the resistance and capacitance of the i-th RC parallel.
- $i(t)$ is the battery current at time t.

- **Silicon Anodes:**

Silicon anodes offer a substantial increase in energy density compared to traditional graphite anodes. While graphite has a theoretical capacity of about 372 mAh/g, silicon can theoretically deliver up to 4200 mAh/g, enabling batteries to store more energy without increasing size .
This enhancement leads to longer driving ranges and reduced charging times for EVs. However, silicon's high capacity comes with challenges. During charging cycles, silicon expands by up to 300%, causing mechanical stress that can lead to cracking and capacity loss [34]. To address this, researchers are developing solutions such as silicon nanowires and composite materials that incorporate graphene to improve structural integrity and conductivity .

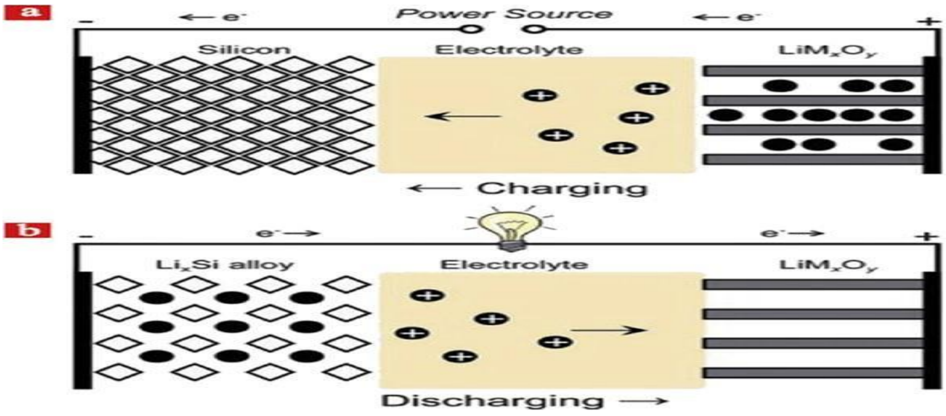


FIG II.35–Schematic of a lithium battery containing a Si anode and lithium metal oxide cathode during charging and discharging. **[63]**

- **Graphene:**

Graphene, a single layer of carbon atoms arranged in a two-dimensional lattice, is renowned for its exceptional electrical conductivity, mechanical strength, and thermal properties. Incorporating graphene into battery electrodes enhances electron and ion transport, leading to faster charging times and improved cycle stability. Moreover, graphene's flexibility and strength contribute to the structural stability of batteries, reducing the risk of degradation over time. Its lightweight nature also aids in reducing the overall weight of EVs, contributing to improved efficiency and performance[34].

In summary, the integration of silicon anodes and graphene into EV batteries represents a significant advancement in energy storage technology. While challenges such as silicon's volume expansion and the cost of graphene production remain, ongoing research and development are paving the way for more efficient, durable, and sustainable EV batterie

The integration of advanced materials like silicon anodes and graphene into EV batteries holds the promise of significantly enhancing performance, efficiency, and sustainability. While challenges such as material expansion in silicon and production costs in graphene exist, ongoing research and technological advancements are paving the way for overcoming these obstacles. The future of electric vehicles increasingly relies on these innovations to meet the growing demand for higher performance and environmentally friendly transportation s

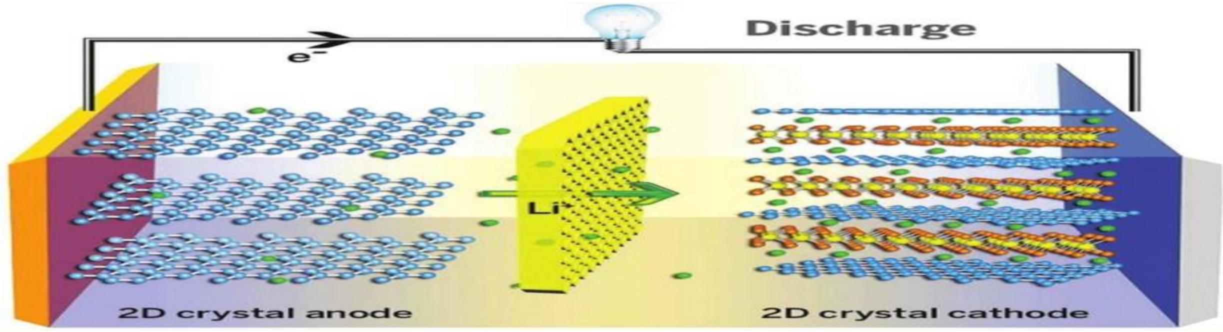


FIG II.36–Schematic A typical BMS block diagram **[63]**

- ***Table II.9 : Comparison of Advanced Battery Materials and Technologie***

Criteria	Graphene	Silicon Anodes	Solid-State Batteries	Lithium-Ion Batteries
Primary Role	Conductive additive / electrode enhancement	Anode material (negative electrode)	Next-generation battery technology	Current mainstream battery technology
Energy Density	Improves capacity when combined with cathodes	Very high (up to 10x graphite)	Very high (up to 2x Lithium-Ion)	Medium to high
Cycle Stability	Very high	Poor (expands up to 300%, causing damage)	Very high	Moderate over time
Safety	Not directly a safety factor	Not directly a safety factor	Very safe (non-flammable)	Moderate (risk of thermal runaway)
Charging Speed	Enhances conductivity and charge rates	Potential for fast charging, but challenges exist	Potentially very fast	Moderate
Weight	Extremely lightweight	Heavier than graphene	Light to moderate (depends on solid materials)	Moderate
Electrical Conductivity	Excellent	Moderate (requires additives)	Depends on the solid electrolyte Used	Good
Commercial Readiness	In R&D phase	In development and early deployment	Early commercial stage	Fully commercial and widely used
Cost	Currently expensive	Medium to high cost	Very high at present	Lower (benefits from economies

- **Note:**

This table compares material-level innovations (Graphene and Silicon Anodes) with system-level technologies (Solid-State vs. Lithium-Ion batteries). While materials like graphene and silicon are components that enhance battery performance, solid-state and lithium- ion refer to the overall battery architecture. These materials can be used within both types of battery systems depending on the design.

II.13. CATL (Contemporary Amperex Technology Co., Ltd.)

CATL (Contemporary Amperex Technology Co., Ltd.), the world's largest electric vehicle battery manufacturer, announced plans to mass-produce solid-state batteries by 2027.

In January 2024, CATL announced its joining of the China Solid-State Battery Collaborative Innovation Platform (CASIP), which includes companies such as BYD, CALB, EVE Energy, SVOLT, Gotion High-Tech, and automotive companies such as Nio. This alliance aims to develop solid-state battery technology and establish a local supply chain by 2030.

Global Expansion: CATL continues to expand its global operations and plans to establish a joint venture plant in Indonesia with a production capacity of 15 GWh, expected to begin production in 2027.

While CATL strives to make significant progress in the solid-state battery field, technical and economic challenges may impact the speed of achieving its stated goals. The company is expected to continue investing in research and development, focusing on improving performance and reducing costs, to meet the growing demand for advanced battery technologies in the future. CATL's advancements in solid-state batteries

CATL is developing batteries with an effective energy rating of up to 500 Wh/kg, and has proven its effectiveness and achieved a 40% certification rate for active electrolyte-based batteries.

FIG II.37–Most powerful battery produced by CATL
[65]

II.13.1. CATL Battery Company Develops New Technology

Chinese battery supplier CATL has launched a new technology it calls the "super hybrid battery," promising a pure-electric range for plug-in hybrids that will outperform many battery-powered electric vehicles. Officially dubbed the Freevoy Super Hybrid Battery, the wild prediction suggests a battery technology that addresses nearly all the challenges facing current battery technology. The Freevoy battery will enable plug-in hybrids and extended-range electric vehicles (EREVs)—those with range extenders like the Scott Motors Traveler Harvester and Ram 1500 Ram Charger—to travel up to 402 km on electricity alone, offering a driving range of up to a week on a single charge. The technology company also claims faster charging speeds (280 km/h in just 10 minutes of charging) and the ability to operate in extremely cold environments, maintaining a “smooth driving experience” in low temperatures. The Freevoy battery aims to solve three major problems typically associated with plug-in hybrids and alternative fuel electric vehicles:

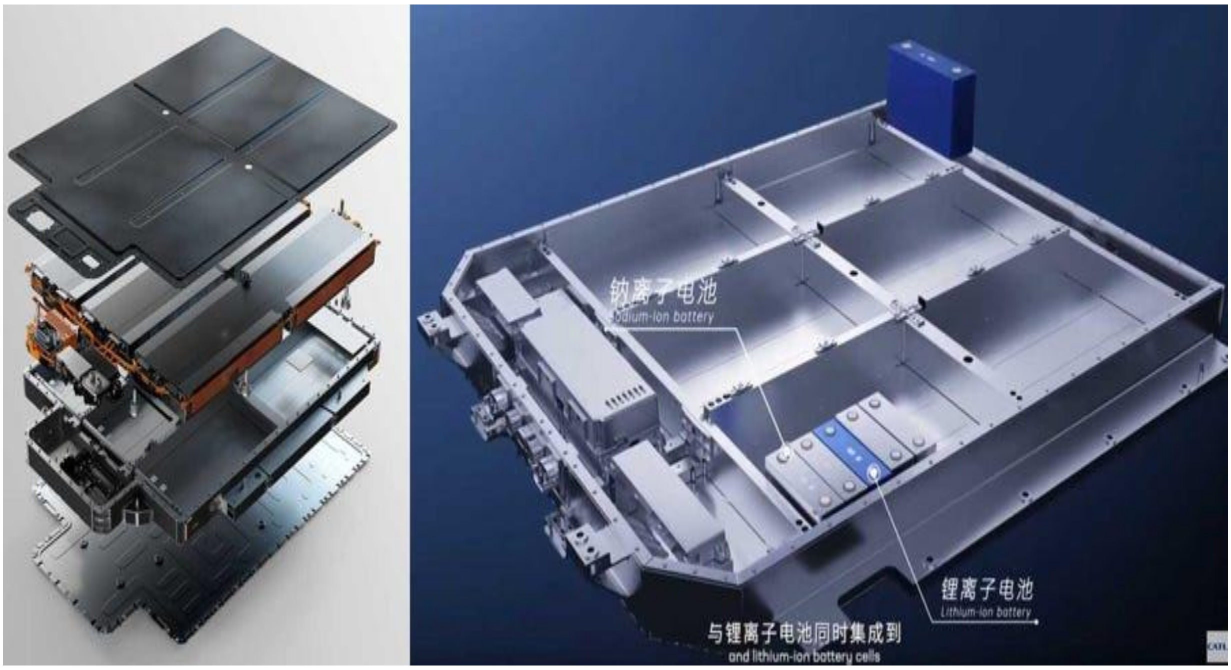


FIG II.38–Super Hybrid Battery **[65]**

II.13.2. New technology work (super hybrid battery)

CATL uses surface modification technology on the battery cathode, combined with a high-voltage electrolyte formulation that creates a protective nano-layer. Sounds complicated? It is, but it essentially prevents unwanted reactions from consuming energy that could be better used to propel the vehicle, making the battery more efficient at charging and discharging. CATL combines the best of its lithium-ion battery development with its sodium-ion technology, combining series and parallel connections between cells to improve performance across a wide range of scenarios.

II.14. Standalone Electric Vehicle (EV) Charging Station

Standalone EV charging stations refer to dedicated charging sites that are not part of another business infrastructure, like gas stations, malls, or supermarkets. They are also known as independent or dedicated charging station

These are locations designed solely for EV charging. They are:

- Not linked to other commercial services.
- Often placed along highways or in strategic standalone locations.
- Equipped with various types of charging units (slow, medium, and fast – AC/DC).

FIG II.39–Electric Vehicle (EV) Charging Station [70]

II.14.1. Main Component

It is a group of units connected to each other that form the charging station.

- **Charging units** (AC or DC)
- **Power transformers** and distribution equipment
- **Electronic payment systems** (card, app, QR code)
- **Surveillance and security systems**
- **Canopies or solar panels**
- Optional extras: Wi-Fi, waiting area, mini caf

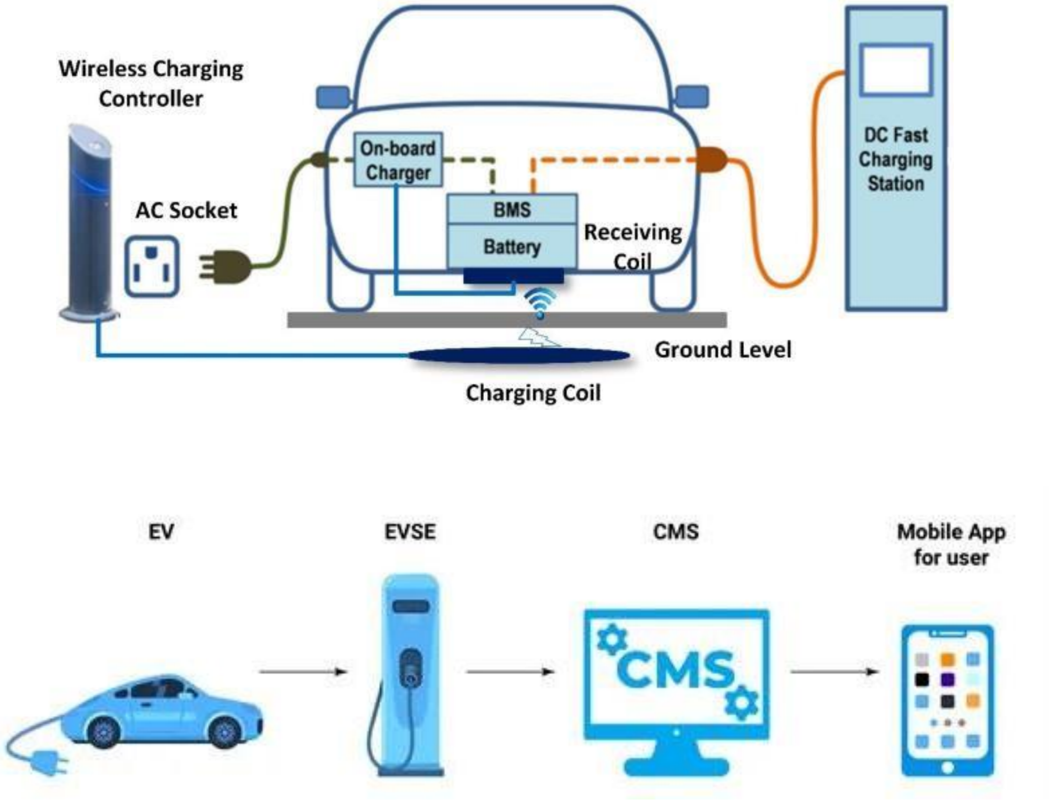


FIG II.40–Electric car charging station components and their uses **[70]**

II.14.2. Types of Charging

Standalone EV charging stations usually offer multiple levels of charging to accommodate different vehicle types and user needs. These are typically categorized by charging speed, power output, and current type (AC or DC).

- ***Table II. 10Types of Charging:***

Type	**Approx. Duration**	**Power Output (kW)**	**Typical Use Case**
Slow Charging (AC)	6–12 hours	3–7	Homes or workplace parking
Medium Charging (AC)	2–4 hours	11–22	Public parking areas
Fast Charging (DC)	20–60 minutes	50–150+	Highways and travel routes

Providing multiple charging levels at autonomous electric vehicle charging stations ensures flexibility, accessibility, and convenience for all types of electric vehicles. As the electric vehicle market grows, the ability to provide efficient and scalable charging options will be essential to supporting the transition to sustainable transportation and meeting the diverse needs of modern electric vehicle drivers.

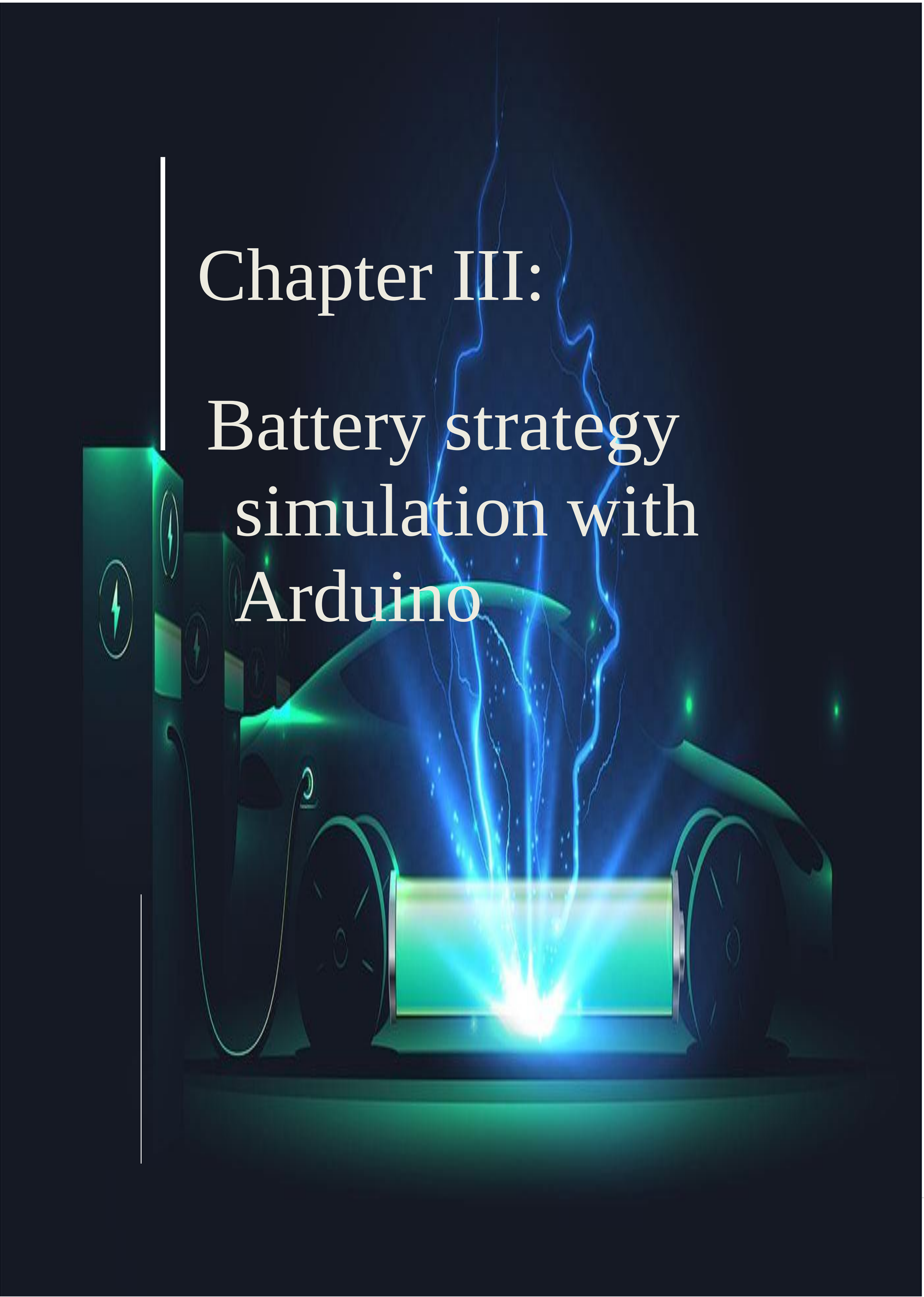
II.15. Conclusion

In this chapter, we review the factors influencing electric vehicles, especially batteries, which play a significant role in this industry. We note their types and compare them to all the technological developments. We also highlight the most important companies in this field, touching the most important recent developments, without neglecting the role of charging stations. Competition between car companies to enter the race for development and progress, as each company seeks to highlight its most important contributions.

Electric vehicles have also witnessed remarkable development over the past decade through artificial intelligence, keeping pace with the development of charging and control processes, and others. This points out to the importance to this advanced information, we will discuss the role of artificial intelligence in this industry in the next chapter.

Chapter III:

Battery strategy simulation with Arduino



III.1. Introduction

Electric vehicles in our time suffer from estimating the distance traveled to reach the charging station, and the big problem is the charging time that worries the drivers of these vehicles, as the development witnessed by electric vehicles during the past years made them vehicles that keep pace with the age of technology, and this is through programming them on artificial intelligence through advanced technologies and software, as I present in this project programming the Arduino system for an electric vehicle that depends on two batteries and a smart solar panel located on the roof of the vehicle's outer body, in order to obtain a greater distance.

In electric vehicles, the battery management system (BMS) is integrated with the Arduino board, which is good to battery performance and efficiency. The BMS monitors battery status, such as voltage, current, and temperature balances the different cells to optimize their lifespan. By connecting to the Arduino board, experts collect and analyze this data, allowing it to perform functions such as cutting off AC power when recalibrating or providing cooling.

III.2. Arduino IDE

Arduino The Arduino IDE (Integrated Development Environment) is the official, open-source environment used for programming Arduino boards. This programming environment was developed by the Arduino project team in 2005 as part of an initiative to simplify microcontroller programming. The primary goal was to make programming easier for students, beginners, and hobbyists without a deep background in programming or embedded systems.

The program was initially developed as part of an academic project at the Interaction Design Institute Ivrea in Italy. It was designed to be easy to use and supports coding using a C/C++-like language, making it an effective tool for learning programming and controlling electronic devices.

The Arduino IDE provides a simple, easy-to-understand interface, containing the basic tools needed to write code (sketch), compile it, and upload it directly to the Arduino board via USB. It also includes ready-made software libraries that allow users to control various electronic modules (such as sensors, motors, and displays) without having to write code from scratch.

- **Key Features of the Arduino IDE:**
  - It's free and open-source, allowing users to view, modify, or develop the source code.
  - Broad operating system support: It runs on Windows, macOS, and Linux.

- A large global community contributes to library development, project sharing, and technical support.

- It's easy to learn and implement, thanks to the ready-made examples available within the program.

- Thanks to these features, the Arduino IDE has become the first choice for educational projects and technological applications based on embedded systems and automation.

FIG. III. 1–Arduino Uno Rev3

➢ **Types of Arduino Boards:**

Among the most popular types available are:

- **Arduino Uno:** The most widely used, suitable for beginners.
- **Arduino Mega:** Contains a larger number of ports, used for larger projects.
- **Arduino Nano:** Small in size, suitable for portable projects or projects that require a small amount of space.
- Arduino Leonardo, Arduino Due, Arduino Micro, and others.

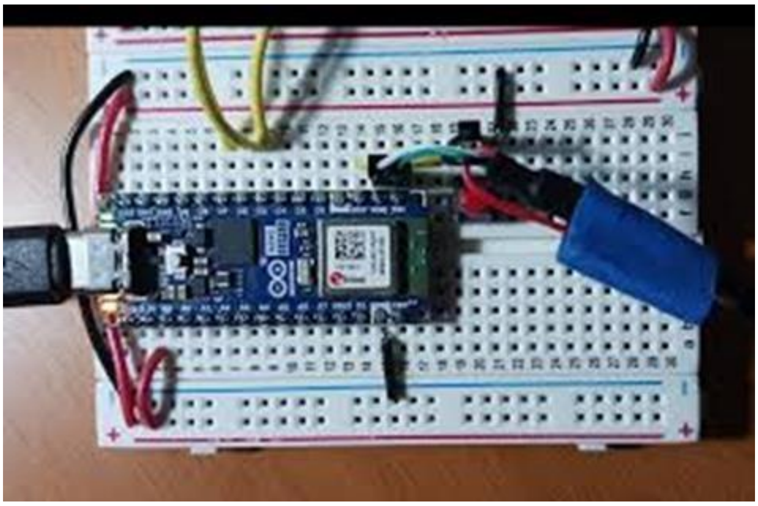
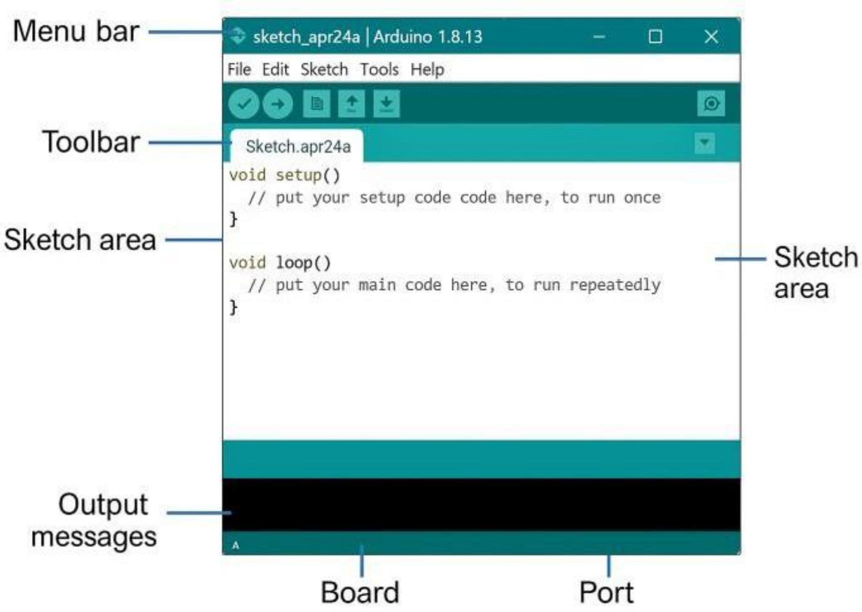


FIG. III. 2– Arduino programmer

III.3. Arduino IDE Components

As of 2023, the following names stood out as leading suppliers in the EV battery sector, marking their prominence within the industry:

- **Arduino IDE Components:**
  - **Toolbar:** Contains basic control buttons such as:
  - **Verify:** To check the code for errors.
  - **Upload:** To upload the code to the board.
  - **New:** To create a new project.
  - **Open:** To open a previous project.
  - **Save**: To save the project.
  - **Serial Monitor:** To monitor data exchanged between the computer and the board via the USB port.
- **Sketch Area:** This is the area where the user writes the code for the project. Each project on the Arduino is called a "Sketch."
- **Output Window:** Displays error messages or the upload status to the board.
- **Tools Menu:** Allows the user to select the type of Arduino board being used, the serial port (COM port), and other settings such as the processor type.



```
void setup()
  // put your setup code code here, to run once
}

void loop()
  // put your main code here, to run repeatedly
}
```

FIG. III. 3–Arduino software interface

III.4. Modern Electric Vehicle Project

In recent years, the world has witnessed increasing interest in developing sustainable and environmentally friendly means of transportation, given the environmental and economic challenges facing societies. Among these means, solar-powered electric vehicles stand out as innovative solutions that combine energy efficiency and environmental conservation.

This project aims to design and implement an electric vehicle equipped with a smart charging system based on solar panels, using an Arduino board as the primary control element. The vehicle will be equipped with two batteries for energy storage, one of which is charged by the other using a smart solar panel located on the roof of the vehicle. When the second battery is discharged, it acts as a charger for the vehicle to reach a charging station. This system will contribute to improving energy efficiency, increasing range, and promoting environmental sustainability.

- **Project objectives include:**

Design of a smart charging system: Develop a charging system based on solar panels using maximum power point tracking (MPPT) algorithms to ensure efficient battery charging.

Management: Use an Arduino board to monitor battery status, regulate charging and discharging, and ensure that overcharging and deep discharge do not occur.

Performance improvement: Design a system that enables the vehicle to operate efficiently using solar energy, while still being able to charge and travel long distances.

III.5. Components for an advanced electric car

To create an electric car with two batteries, a smart solar panel, and an Arduino module, we integrate the power, electronics, and control systems into a single project, following a systematic process based on the characteristics and roles of each component.

➢ **Power System**

- **Batteries:**

They can be lithium-ion or advanced CATL batteries. They can be connected in series to increase voltage or in parallel to increase capacity. The battery size depends on the motor's power and the desired range (for example: 12V 10Ah x 2).

- **Smart Solar Panel:**

A small solar panel (usually 6V–12V, depending on the design) with a smart power tracking module (MPPT) to optimize charging from the solar panel. Sun tracking sensors automatically direct the panel toward the sun for optimal performance.

➢ **Control System (Arduino)**

An Arduino module of the Arduino UNO or Nano type.This module is used to manage and distribute power, control the motor, charge the batteries, and monitor system performance. Auxiliary electronic components also play an active role through control units, such as a solar charging module (such as a TP4056 or a small MPPT module).Motor controller (Motor Driver - L298N or BTS7960).Voltage/current monitoring module (INA219 or ACS712).Electronic switch (Relay Module or MOSFET).

➢ **Drive system**

The electric motor is a motor compatible with brushed or brushless DC motors. It is compatible with both batteries.

- **Sensors**
  - **Sun sensor (LDR x 4):** To track the direction of the sun and automatically move the panel.
  - **Temperature sensor:** This sensor is crucial for operation by monitoring the temperature of the battery and motor.
  - **Charge sensor (Battery voltage):** To measure the charge level.
- **Display and monitoring screen:** An OLED or LCD screen displays information such as the battery charge percentage, charging current, and speed.
- **Control software (Arduino code)**
  - Reads inputs from the sensors.
  - Controls power distribution (between the batteries and the solar panel).
  - Intelligently manages battery charging.
  - Starts the motor when needed.
  - Displays information on the screen.

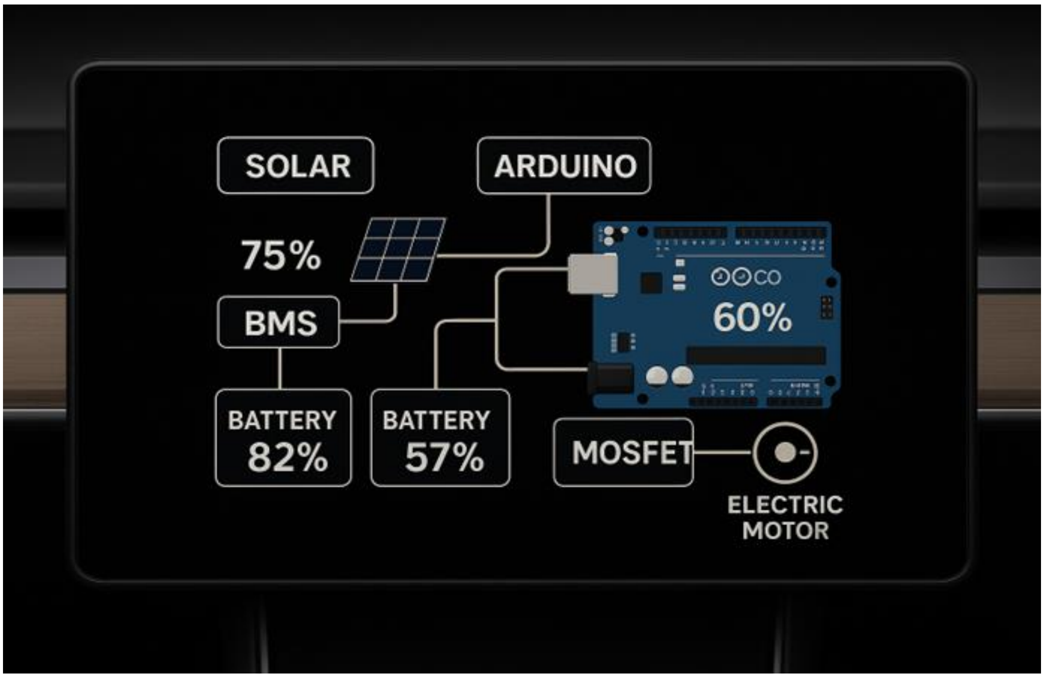


FIG. III. 4– Control panel

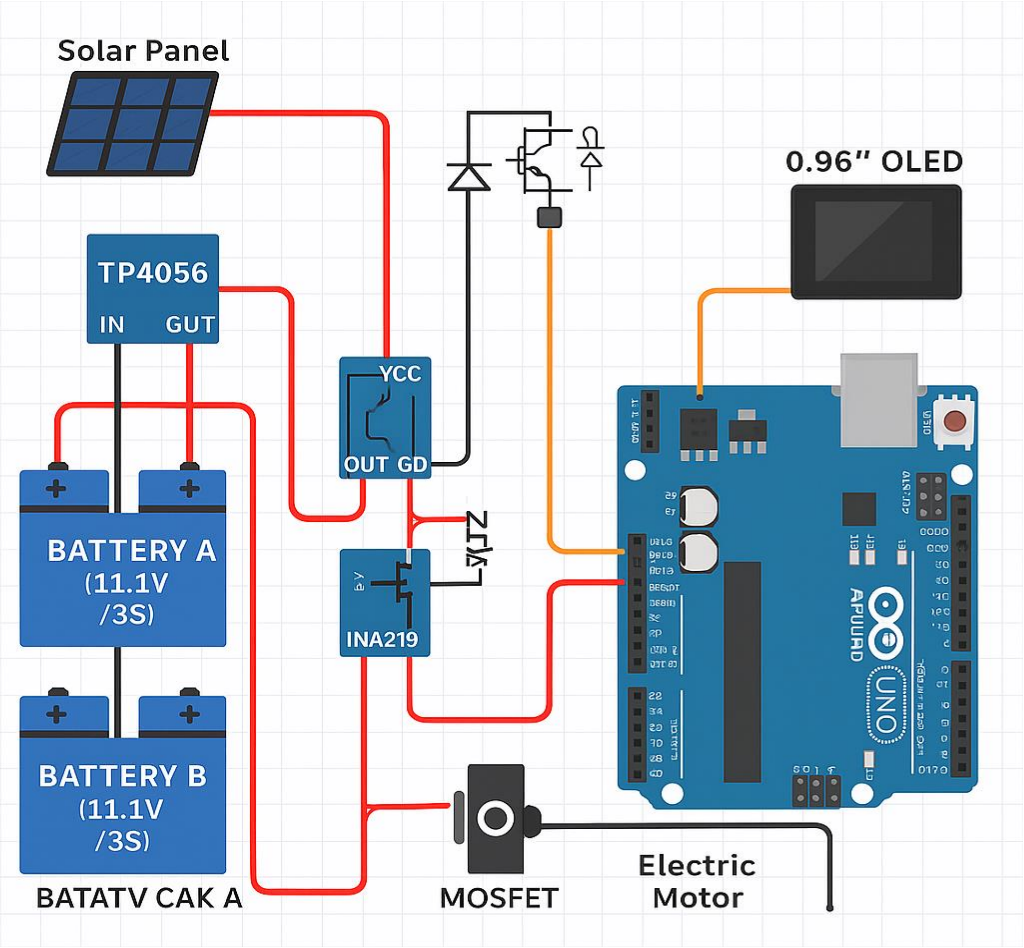


FIG. III. 5–Electrical connections of elements

III.6. Electric vehicle operation

A 3D mode ***FIG. III.7***– l of an electric car. This diagram can be effectively applied to represent a smart battery management system (BMS). This system is connected to the car to ensure the car continues to operate even when the battery is depleted, monitoring voltage and current and using solar power as an additional charging source. The two lithium-ion batteries are installed inside the car as power sources. They are connected via MOSFET transistors, so the appropriate battery is selected based on its state. The car's DC motor is connected directly to the MOSFET (as shown in the figure ***FIG. III. 6***). The car operates solely on the active battery. The Arduino Nano module: Mounted in front of the main display, it monitors voltage and current using the INA219 program. This module controls battery switching via signals to the MOSFET transistors. The smart solar panel mounted on the car's roof charges the unused battery via an OLED display mounted on the car's body. It displays:

Battery voltage 1 and 2, current drawn, and charging or alert status.

The battery currently in use. Simulates the functions of car systems such as Tesla and BYD.

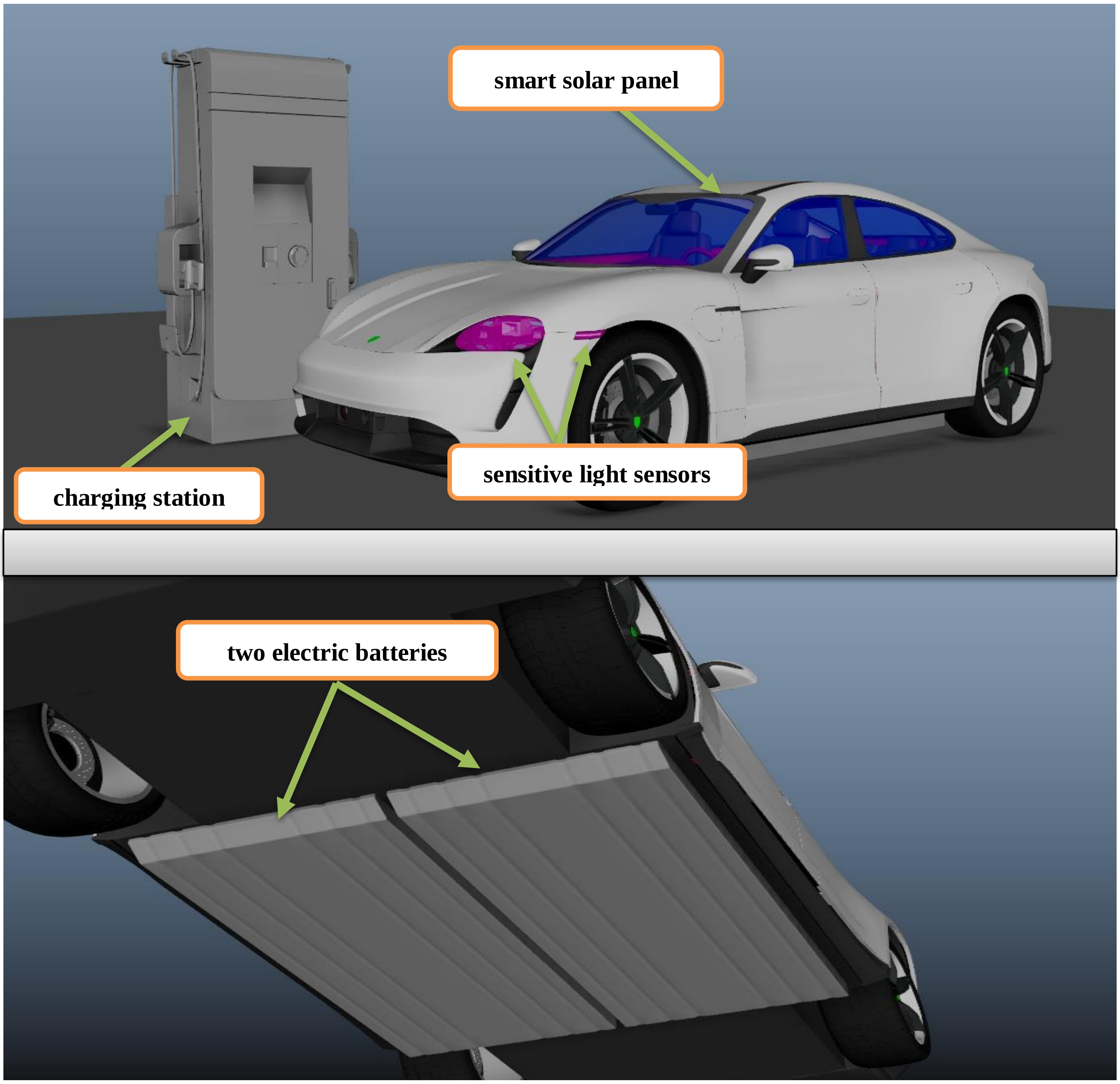


FIG. III.6– Model of the advanced electric car

III.7. Algorithms needed to monitor batteries and control charging.

This code reads the voltage, current, and temperature of each battery, calculates the percentage of charge (SOC), and displays it on an LCD screen. It also controls the on/off switch using a relay and alerts the user with a buzzer when the charge level drops below 20%.

To improve charging performance, a Maximum Power Point Tracking (MPPT) algorithm, such as the Perturb and Observe (P&O) algorithm, can be incorporated to adjust the charging process from solar panels.

```cpp
#include <LiquidCrystal_I2C.h>

const int voltagePin = A0; // Battery voltage sensor
const int currentPin = A1; // Battery current sensor
const int pwmPin = 3;      // PWM output to MOSFET gate

LiquidCrystal_I2C lcd(0x27, 16, 2); // LCD display

float voltage, current, power, previousPower = 0;
int dutyCycle = 128; // Initial duty cycle (50%)

void setup() {
  lcd.begin(16, 2);
  lcd.backlight();
  pinMode(pwmPin, OUTPUT);
  analogWrite(pwmPin, dutyCycle);
}
void loop() {
  voltage = analogRead(voltagePin) * (5.0 / 1023.0) * 5.0; // Convert to voltage
  current = analogRead(currentPin) * (5.0 / 1023.0) * 5.0; // Convert to current
  power = voltage * current; // Calculate power

  // Perturb and Observe MPPT algorithm
  if (power > previousPower) {
    dutyCycle++; // Increase duty cycle
  } else {
    dutyCycle--; // Decrease duty cycle
  }
  previousPower = power;

  // Limit duty cycle to prevent over-driving the MOSFET
  dutyCycle = constrain(dutyCycle, 0, 255);
  analogWrite(pwmPin, dutyCycle);
  // Display information on LCD
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("V: " + String(voltage, 1) + "V");
  lcd.setCursor(0, 1);
  lcd.print("I: " + String(current, 1) + "A");

  delay(1000); // Update every second
}
```

FIG. III. 7–System operation algorithm in Arduino programming language

III.8. Digital process control

The Arduino board serves as the main controller for this system, reading inputs from digital push buttons that allow the user to select the appropriate power source. When a button is pressed, the Arduino activates or deactivates the relay connected to the selected power source, enabling power to be directed to the batteries or electrical loads as needed. System status, such as voltage, current, and percentage of charge (SOC), is displayed on an LCD screen, enabling the user to continuously monitor performance.

To improve charging efficiency, a Maximum Power Point Tracking (MPPT) algorithm can be integrated with the Arduino, enabling the maximum possible power to be extracted from the solar panels and directed to the batteries. This algorithm contributes to reducing waste and improving overall system efficiency.

By combining digital manual control with smart charging technologies, an integrated and flexible power system can be achieved that meets the needs of modern electric vehicles, contributing to enhanced sustainability and reducing reliance on conventional energy sources**.**

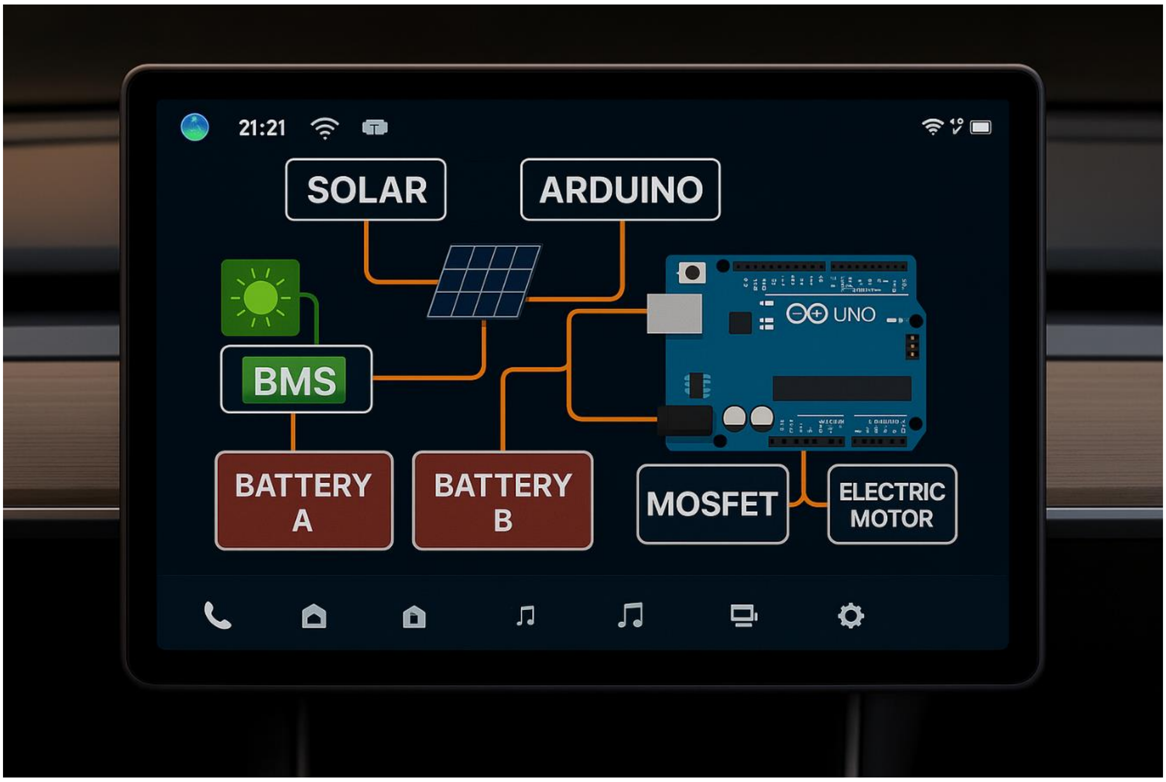


FIG. III.8–System control panel

In conclusion, the use of an Arduino board to digitally control an electric vehicle equipped with two connected batteries and solar panels demonstrates significant potential for improving energy efficiency; providing flexible and sustainable solutions. By integrating technologies such as smart charging control, switching between different power sources, and digital data display, an integrated and efficient energy system can be achieved. These solutions contribute to reducing dependence on traditional energy sources and promoting environmental sustainability, making them an important step toward a greener, more energy-efficient future.

III.9. Smart Charging Station

In the context of developing innovative solutions to accelerate the adoption of electric vehicles, the Battery Swapping System is an advanced solution that allows drivers to replace depleted batteries with fully charged ones in record time, improving operational efficiency and reducing downtime.

When the vehicle arrives at the swapping station, the charge status of the two connected batteries is determined. If the charge level is low, the system uses a mechanical or robotic mechanism to lift the depleted batteries and replace two fully charged batteries. This process typically takes less than 5 minutes, allowing the driver to resume their journey without any significant delay.

This technology represents an advanced step towards improving the electric vehicle experience, as it contributes to reducing downtime, lowering initial vehicle costs, and enhancing environmental sustainability through the periodic reuse of batteries. Despite the challenges related to standardization and infrastructure development, these solutions hold promise for accelerating the adoption of electric vehicles and enhancing energy efficiency.

➢ **Main System Components**

- **Swapable Battery Modules:** These batteries are designed to standardized standards to ensure compatibility with various types of electric vehicles.
- **Automatic Battery Swapping Station:** Contains a mechanical or robotic mechanism to remove old batteries and install new ones quickly and efficiently.
-
- **Digital Payment System:** Allows drivers to pay the swap fee via mobile apps or electronic payment cards, making the process easier and faster.

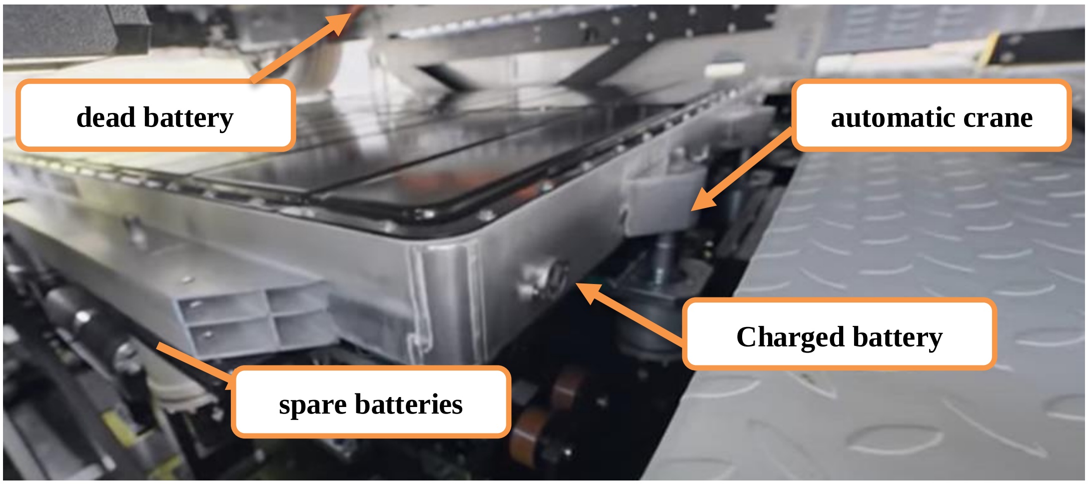


FIG. III.9–Smart battery swap charging station

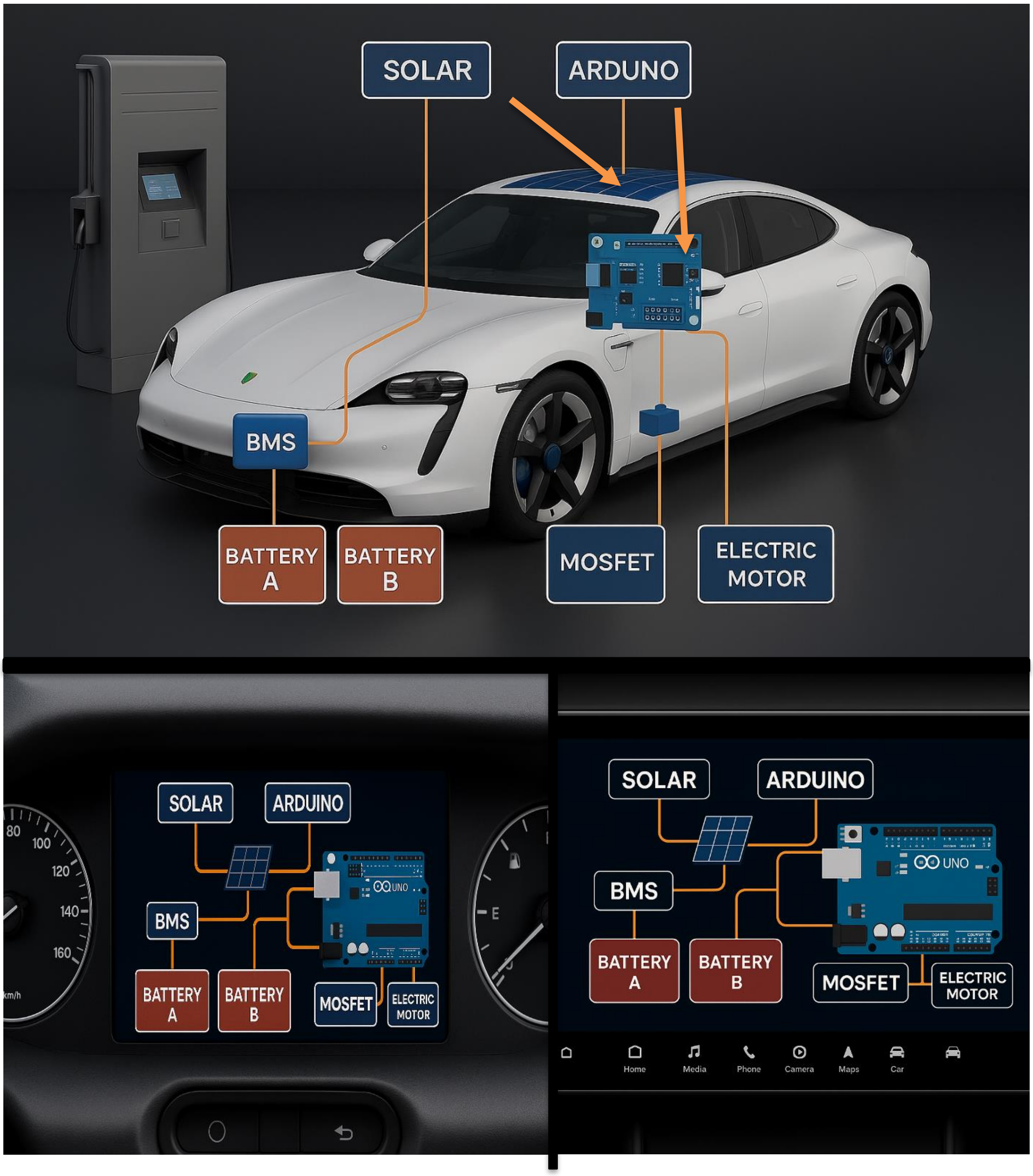


FIG. III.10–Final model

III. 10. Conclusion

In this chapter, we review an electric vehicle equipped with two batteries and a smart solar panel, powered by a BMS and Arduino. We touch on the operation of this system and the components and features that can play a significant role in this industry. We highlight the working method, utilizing artificial intelligence through the Arduino program, without neglecting the role of smart charging stations, to which we have dedicated a section. Based to the information collected in this project presented, we can do more researches to develop a smart robust controlling system.

General conclusion

Growing need for environmentally friendly and energy-efficient transportation, electric vehicles (EVs) have emerged as a promising solution that meets sustainable development requirements and reduces dependence on fossil fuels.

we reviewed the fundamental aspects of EV development, from their technical architecture to power sources and control and monitoring systems. We also discussed the factors affecting EVs, including external factors such as climate, temperature, and road conditions, as well as internal factors such as the battery, wheels, and weight.

We focused specifically on the development of batteries, a vital component in the performance of EVs. We discussed their characteristics, types, and associated challenges such as thermal balance, service life, and energy efficiency. Lithium-ion batteries are among the most prominent solutions currently being used, with future aspirations toward more advanced and safer technologies. Solid state batteries give a new solution to EVS safety and less impacts to environment.

We also highlighted the importance of the new programing technics like Arduino system in the field of EVs through the Battery Management System (BMS) in maintaining battery health and achieving optimal performance; in addition, IA can develop EVS performances. In this context, we designed a prototype based on an Arduino board that enables energy monitoring and conversion while analyzing operational data, enabling efficient communication between vehicle electrical system components for greater efficiency.

This project demonstrates that the use of open platforms such as Arduino in electric vehicle applications can accelerate innovation and provide practical solutions to technical problems.

These innovations contribute to a cleaner, safer, and more sustainable future for a world that is witnessing significant development in this industry. These solutions offer additional benefits, such as:

- Transition to the electric vehicle industry by enacting strict regulations for manufacturers and guiding them towards this field.
- Development and construction of the necessary structures for electric vehicle users.
- Supporting users of these vehicles through tax reductions.

- Low charging costs compared to fossil fuels.
- Supporting research and development centers in all industrial environments dedicated to this category by spreading the culture of electric cars and their importance for maintaining environmental balance.
- Developing and recycling batteries, making them semi-sustainable, and shifting

Finally, we hope this work will constitute a useful scientific contribution to electric vehicles field and serve as a basis for more advanced future projects that contribute to supporting the transition to clean and smart transportation.

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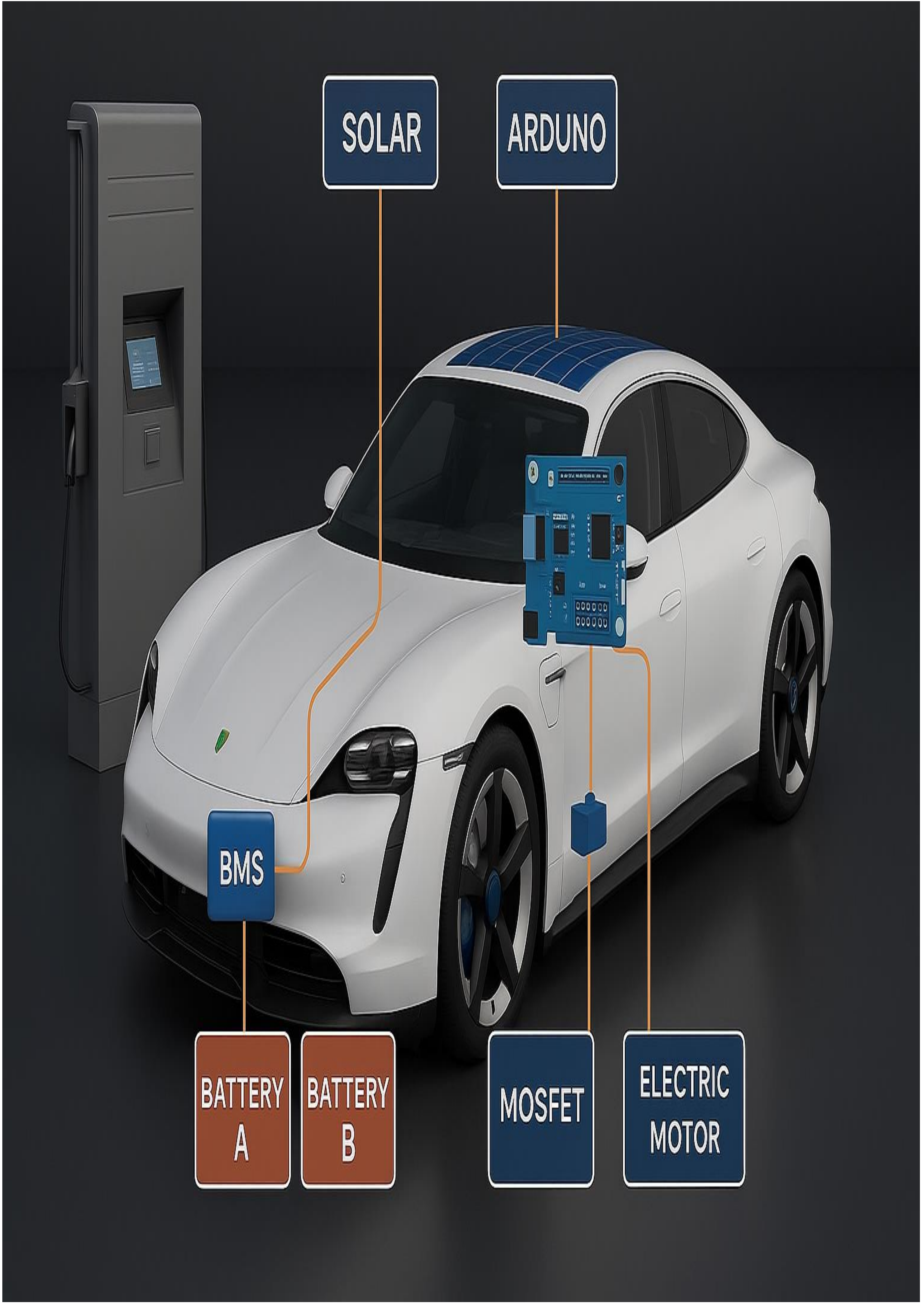
SOLAR
ARDUNO
BMS
BATTERY A
BATTERY B
MOSFET
ELECTRIC MOTOR