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Electric vehicles: Actual market and future prospects, with a focus on battery technology

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Index

Acronymous List

- **ELV** (Electric Vehicles)
- **ICEV** (Internal Combustion Engine Vehicles)
- **BEV** (Battery Electric Vehicles)
- **HEV** (Hybrid Electric Vehicles)
- **PHEV** (Plug-in Electric Vehicles)
- **MHEV** (Mild Hybrid Electric Vehicles)
- **CO_2** (Carbon dioxide)
- **IPCC** (Intergovernmental Panel on Climate Change)
- **NiCd** (Nickel-Cadmium)
- **NiMH** (Nickel-Metal Hydride)
- **Li-ion** (Lithium-ion)
- **LiPo** (Lithium polymer)
- **LFP** (Lithium Iron Phosphate)
- **NMC** (Nichel Manganese Cobalt)
- **BMS** (Battey Management System)
- **LCA** (Life Cycle Assessment)
- **IEA** (International Energy Agency)
- **V2G** (Vehicle to Grid)
- **RPA** (Robotic Process Automation)
- **OTA** (Over-the-air)
- **EBA** (European Battery Alliance)
- **ACEA** (European Automobile Manufacturers' Association)

Abstract

The transition from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) is at the heart of global efforts to reduce carbon emissions and combat climate change. This thesis explores the current state and future prospects of the electric vehicle market, with a particular focus on battery technology, analyzing its impact on the automotive industry and the broader economic landscape. The study begins by introducing the climate crisis and examining how EV adoption can serve as a viable solution to mitigate greenhouse gas emissions. The second chapter provides a historical overview of EV development, classifies different types of electric vehicles, and offers an in-depth comparison of battery technologies. Additionally, it assesses the environmental footprint of EVs versus ICEVs, evaluating CO_2 emissions across their life cycle. The third chapter, which forms the core of this research, presents an extensive analysis of the European EV market, mapping out the entire value chain and identifying key players, industry leaders, and emerging stakeholders shaping the sector. Following this, the fourth chapter investigates the externalities, political advocacy, and geopolitical dynamics that have influenced the European Commission's policies promoting EV adoption. This section critically examines the regulatory frameworks and their economic repercussions on related industries. Finally, the last chapter explores the role of the circular economy in ensuring a smoother transition to electric mobility. It discusses business opportunities and strategic solutions that can offset high initial investments, create new revenue streams, and enhance the long-term sustainability of the EV industry. By offering a comprehensive market analysis, this thesis aims to provide valuable insights into the challenges and opportunities of the European EV sector, highlighting technological advancements, policy interventions, and business innovations that will shape the future of electric mobility.

1. Introduction

Climate change represents one of the most urgent and complex challenges of our time. Defined as a long-term alteration of average weather conditions that characterize different regions of the planet; this change is primarily caused by human activities, particularly the burning of fossil fuels such as coal, oil, and natural gas. These processes release large amounts of greenhouse gases, including carbon dioxide (CO_2), into the atmosphere, trapping heat and increasing the global average temperature.

History of climate change's interest and perception

The interest in climate change is not merely a contemporary concern; it has been a growing topic of scientific inquiry and public awareness since the early 1800s. From Joseph Fourier's initial theories on the greenhouse effect to today's global initiatives, the understanding and importance of climate change have steadily evolved over the centuries.
As said above, the first scientific insights can be traced to Joseph Fourier, who in 1824 proposed the idea that the Earth's atmosphere could trap heat, a phenomenon we now know as the greenhouse effect. Fourier observed that the Earth would be much colder if it weren't for the atmosphere which retains some of the solar heat. In the following years, other scientists like John Tyndall and Svante Arrhenius further developed these theories. Tyndall, in 1859, discovered that certain gases, such as water vapor and carbon dioxide, were particularly effective at absorbing heat. Arrhenius, at the end of the 19th century, calculated that doubling the concentration of CO_2 in the atmosphere could increase the global average temperature by several degrees. Despite these discoveries, public awareness of climate change remained limited for much of the 20th century. It was only in the 1950s and 1960s that the scientific community began to recognize the significant impact of human activities, such as the burning of fossil fuels, on increasing CO_2 concentrations. In the 1970s, this problem began to enter public debate. Scientific reports and international conferences started to emphasize the urgency of addressing global warming. In 1988, the creation of the Intergovernmental Panel on Climate Change (IPCC) marked a turning point, providing periodic and authoritative assessments on the state of the climate and its implications.

In recent decades, the perception of this phenomenon has changed dramatically. Today, thanks to greater media coverage and environmental activism, most people recognize the importance of addressing climate change. Scientific discoveries continue to strengthen our understanding of the phenomenon, highlighting the need for urgent actions to mitigate the negative effects for the planet. In summary, the history of scientific discoveries on climate change and the growing public awareness reflects a long and complex journey. From Fourier's early insights to current global initiatives, our understanding and perception of climate change have evolved significantly, underscoring the importance of collective efforts to protect our environment.

Causes and Impacts of Climate Change

Now let's explain which the possible causes, consequences and solutions are related to this problem.

The most important cause is related to Greenhouse gas emissions, which have led to unprecedented global warming, with an increase in the global average temperature of about 1°C compared to pre-industrial levels. This warming has triggered a series of cascading effects, including the melting of glaciers, rising sea levels, and an increase in the frequency and intensity of extreme weather events such as hurricanes, heatwaves, wildfires, droughts, and floods. These changes not only threaten natural ecosystems but also have severe repercussions on human health, agriculture, food security, and socio-economic stability.
As previously mentioned, one of the key factors of this phenomenon is the combustion of fossil fuels for energy and heat production, resulting in the emission of CO_2 and nitrogen oxides. Another significant cause is deforestation, which reduces the Earth's capacity to absorb CO_2. Trees play a crucial role in carbon sequestration, and their destruction releases large amounts of stored CO_2. Agriculture and intensive livestock farming also contribute to climate disruption. The use of nitrogen-based fertilizers releases nitrogen oxides, a very potent greenhouse gas. The industrial sector is a further contributor to global greenhouse gas emissions. The production of materials such as cement, steel, and plastic require large amounts of energy, often derived from fossil fuels. Additionally, transportation, which uses fossil fuels like gasoline and diesel, releases large quantities of emissions.

This sector accounts for nearly a quarter of global CO_2 related to energy production. Food production contributes to this change not only through direct greenhouse gas emissions but also through deforestation for agricultural expansion and the intensive use of chemicals. Finally, buildings, both residential and commercial, require energy for heating, cooling, and lighting, much of which comes from non-renewable sources.

These causes are interconnected and often overlap, making climate change a complex challenge to address. Reducing emissions requires an integrated approach that involves transitioning to renewable energy sources, protecting forests, adopting sustainable agricultural practices, industrial innovation, and improving energy efficiency.

Solutions for Reducing CO_2 Emissions

To mitigate the effects of this phenomena, it is essential to drastically reduce emissions. Among the most effective solutions are:

1. **Transition to Renewable Energy**: Replacing fossil fuels with renewable energy sources such as solar, wind, and hydroelectric power.
2. **Energy Efficiency**: Improving the energy efficiency of buildings, transportation, and industrial processes can reduce energy consumption and, consequently, emissions.
3. **Reforestation and Afforestation**: Planting new trees and restoring degraded forests can help sequester atmospheric carbon.
4. **Carbon Capture and Storage (CCS) Technologies**: These technologies allow for the capture of CO_2 emitted by power plants and industrial facilities and its storage in underground geological formations.

The Role of Electric Vehicles

Among the proposed solutions, regarding the first and the second one: the adoption of EVs represents a key strategy for reducing CO_2 in the transportation sector, which is one of the largest contributors to global emissions. EVs, powered by rechargeable batteries, do not produce tailpipe emissions during operation, unlike internal combustion engine vehicles that burn gasoline or diesel. Moreover, if the energy used to recharge the batteries comes from renewable sources, the environmental impact of electric vehicles can be further reduced. The widespread adoption of electric vehicles can significantly contribute to reducing emissions, improving air quality in cities, and reducing dependence on fossil fuels. However, to maximize environmental benefits, it is also necessary to address challenges related to battery production and recycling, as well as charging infrastructure. This thesis aims to analyze EV, and the European market segment related to them, focusing on their key components: batteries. These not only represent the technological core of EVs but also determine their costs, range, and environmental impact, making them central to a comprehensive assessment of EV sustainability. However, the picture is complex, as the environmental benefits of EVs come with certain trade-offs, especially when considering the extraction of battery materials, production processes, and eventual disposal. The analysis will also examine the geopolitical factors influencing the adoption of electric vehicles and the development of battery technologies. These geopolitical considerations are especially apparent in the competition for control over essential raw material (such as lithium, cobalt, and nickel) and Europe's efforts to reduce its dependence on imports of critical materials. Furthermore, the expansion of the European EV market requires redefining industrial strategies and regulatory collaboration among member states to maintain a globally competitive automotive industry. In conclusion this thesis will provide a critical overview of electrical vehicles market segment and their batteries, assessing the environmental benefits and limitations of the technology, turning into geopolitical implications and necessary reforms for effective adoption. Finally, it will explore future business opportunities within the circular economy, positioning electric vehicles as an evolving technology requiring an integrated and sustainable approach.

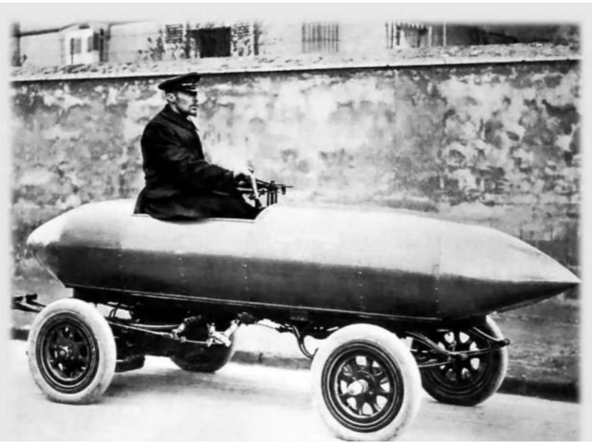
2. Overview of electric vehicles

2.1 History and Development of Electric Vehicles

In common belief, electric cars are seen as a new, cutting-edge technology, something that has only recently been discovered. Generally, this concept is associated with sustainable mobility, a key topic when discussing the reduction of CO_2. The issue of pollution and global warming is indeed one of the most pressing concerns today and is a primary driver behind the transition from combustion engines to electric ones. This connection to such a contemporary issue gives the EV an innovative perception. However interestingly, the electric car was actually invented before the gasoline-powered car. The Battery Electric Vehicle (BEV) was one of the first types of automobiles to be invented. The first battery was created in 1799, and from that moment, the whole world sought to harness this new source of energy. The turning point came with the invention of the first lead-acid battery in 1850. This was a turning point because the lead-acid battery was more efficient and had a higher storage capacity than previous batteries, making it possible to power vehicles for longer periods and with better performance. The first electric vehicles were developed between 1832 and 1839 with the idea of building a "horseless carriage," but the first commercial models were only introduced in 1893. The first example of an electric car can be attributed to the Scottish entrepreneur Robert Anderson, this vehicle was powered by non-rechargeable primary batteries, and it looked more like a carriage than a car. Although it was a significant innovation for its time, the use of non-rechargeable batteries limited the vehicle's practicality, as the batteries had to be replaced once depleted.


One of the first electric vehicles the "horseless carriage".

Thanks to the improvement in battery technology by the French, as mentioned earlier, the first commercial electric vehicles began to circulate around 1890 with a range of up to 30 km and a speed of up to 20 km/h. Additionally, the first electric traction transport vehicles were also experimented with (a bus in Berlin in 1885). Another very important step in the development of this new technology occurred in 1889 with the creation of the “Jamais Content”: an electric car capable of reaching 100 km/h and named the “First Formula 1”. In the same years, Ferdinand Porsche designed the first all-wheel-drive car with an electric motor for each wheel.



La “Jamais Contente” : The first Formula 1.

In the early 1900s, the electric car boom began, and many companies emerged in America as well as in Europe. Among the most important were Anthony Electric, Detroit Electric, and Baker Electric. As for Italy, the leading company in the sector was the Società Torinese Automobili Elettriche (STAE), some models of which are still preserved at the National Automobile Museum of Turin. A very significant fact regarding the superiority of the electric cars over the gasoline ones at that time concerns the overwhelming percentage of BEVs compared to combustion vehicles: 38% for the former and only 22% for the latter; all other vehicles were still powered by steam. The good times for electric cars, however, did not last long. In fact, in the second half of 1800, oil fields were discovered in America, which gradually caused the price of gasoline to drop, and consequently, the price of combustion vehicles compared to those powered by electricity. This, along with some related discoveries, such as the invention of the starter motor, marked the beginning of the era of vehicles powered by fossil fuels. The renewed interest in electric transportation dates back to around 1970, due to the growing attention to the climate crisis and the oil crisis. Increasing investments in the following years led to ever greater advancements in making electric cars an alternative to combustion ones. The most active companies in this regard in recent years have been Toyota, Audi, Tesla, and Chinese car manufacturers (BYD, Leap Motors…). In 2019, Audi launched the e-Tron, the first fully electric SUV. In 2024, about a quarter of the cars registered in Europe were electric. This represents significant growth compared to previous years, despite some fluctuations in specific markets like Germany and Italy.

2.2 Types of electric vehicles (BEV, PHEV, HEV, MHEV)

As previously analyzed, in the current landscape of sustainable mobility, electric vehicles are playing an increasingly central role. However, it is important to recognize that there are different types of electric vehicles, each with specific characteristics and technologies. In this paragraph, the main categories of EVs will be examined, including plug-in hybrid electric vehicles (PHEV), mild hybrid electric vehicles (MHEV), BEV, and hybrid electric vehicles (HEV). This distinction is fundamental to understanding the various technological solutions available and their impact on the environment and energy efficiency. Before delving into the abbreviations for electrified and electric cars, it's important to clarify the two main types of hybrid cars: parallel hybrid and series hybrid. The most common type on the market is the parallel hybrid, where both the internal combustion engine and the electric motor can provide traction to the wheels, either together or separately. This category includes mild hybrids, full hybrids, and plug-in hybrids. The series hybrid, on the other hand, has the electric motor as the sole provider of traction to the wheels, while the internal combustion engine acts only as a generator of electricity for the electric motor and/or the battery. Fuel cell vehicles also fall into this category, but in this case, the internal combustion engine is replaced by a fuel cell powered by hydrogen and oxygen, which generates energy for the battery and the electric motor.

Now let's take a deeper look at the different types of electric vehicles and their substantial differences.

1. BEV - Battery Electric Vehicle: purely electric

BEV , also known as “100% electric” cars, operate solely on energy stored in rechargeable batteries via external sources, such as public charging stations or the domestic electrical grid. These vehicles do not have an internal combustion engine and do not emit exhaust gases. BEVs are ideal for those looking to reduce the environmental impact of local emissions and take advantage of the latest technological innovations in the automotive sector. Additionally, BEVs are often equipped with advanced features such as driver assistance systems, smart connectivity, and over-the-air software updates, which continuously improve the vehicle’s performance and safety. These vehicles represent a sustainable and innovative choice for the future of mobility.

2. PHEV - Plug-in Hybrid Electric Vehicle

PHEV combine an internal combustion engine with one or more electric motors and a battery that can be recharged via an external electric source. This configuration allows PHEVs to operate both as electric vehicles and as combustion vehicles, offering significant versatility. This type of vehicle enables driving in electric mode for short trips and using the combustion engine for longer journeys. PHEVs are perfect for those who want the benefits of an electric car without worrying too much about range.

3. HEV - Hybrid Electric Vehicle

HEV combine an internal combustion engine with one or more electric motors, but unlike PHEVs, they do not require external charging. The battery recharges during driving thanks to regenerative braking systems and the use of the combustion engine. HEVs are ideal for those looking for fuel-efficient cars without having to change their charging habits. Additionally, HEVs offer benefits such as reduced emissions compared to traditional vehicles and greater fuel efficiency. These vehicles are particularly suitable for urban driving, where frequent stops and starts allowing for optimal use of the regenerative braking system. The combination of an electric motor and an internal combustion engine also provides a smoother and quieter driving experience, enhancing overall comfort.

4. **MHEV – Mild Hybrid Electric Vehicle**

These vehicles are not true hybrids. They are equipped with a mild hybrid system, where the electric motor only supports the internal combustion engine, improving fuel efficiency and overall performance. However, the electric motor cannot move the vehicle on its own. In other words, mild hybrid vehicles have an electric system that assists the combustion engine, but they cannot run exclusively in electric mode. Additionally, mild hybrids are often chosen for their ability to reduce fuel consumption and emissions without requiring significant changes in driving habits. These vehicles use a small electric motor and a battery to provide assistance during acceleration and to recover energy during breaking. This system can also improve engine response and make driving smoother. Moreover, mild hybrids are generally more affordable than full hybrids and plug-in hybrids, making them an accessible choice for those looking to improve efficiency without a high investment.

The interesting thing to understand about these different types of vehicles is which ones have the least impact in terms of CO_2 emissions, and which ones can offer the power and range to make them a viable alternative to traditional vehicles:

- BEV do not emit CO_2 during use, as they operate exclusively on electric power. They have a range that varies between 200 and 500 km, with some models exceeding 600 km, and offer high power thanks to the instant torque of electric motors.
- MHEV slightly reduces emissions compared to traditional vehicles but does not eliminate them completely. They do not have significant electric range, and the main power comes from the internal combustion engine, with limited support from the electric motor.
- HEV emits less compared to pure internal combustion vehicles, thanks to the use of the electric motor in certain situations. They have a very limited electric range, generally less than 2 km, and combine the power of the internal combustion engine with that of the electric motor.
- PHEV can operate in electric mode, reducing CO_2 emissions when running without the combustion engine. The electric range varies between 30 and 60 km, and the overall power is a combination of electric and internal combustion power, offering flexible performance.

In conclusion, BEV represent the best choice in terms of environmental sustainability during the utilization. However, these cars differ the most from traditional vehicles and require a higher initial investment, both for purchase and charging infrastructure. Currently, the best compromise for many consumers seems to be PHEV. These vehicles offer significant CO_2 emission reductions when operating in electric mode and provide the flexibility of an internal combustion engine for longer trips. For example, the Jeep Wrangler 4xe PHEV was the best-selling plug-in hybrid in the third quarter of 2024, with nearly 11,000 units sold. This data highlights the preference of customers for vehicles that combine sustainability and efficiency without compromising range and power.

It is crucial to understand the importance of having different types of electric vehicles in order to favor this type of change in the automotive market segment. In recent decades, the transition to more sustainable mobility has become one of the most significant challenges for the carmakers, in particular European ones. Environmental needs and compliance with increasingly stringent regulations and policies have driven automakers to revolutionize the concept of the vehicle itself. However, this revolution could not happen abruptly, in fact the step from traditional engines to electric ones represents not only a technological shift but also a cultural one, requiring customers to abandon deeply rooted habits and confront new doubts and concerns. The diversification of ELV models – BEV, MHEV, HEV and PHEV has been a key response to this complex challenge. Historically, the first significant issue automakers faced was range anxiety. Many potential buyers, even when attracted by the idea of an electric car, feared that the limited electric capacity would not suffice for their daily commuting or, even worse, long-distance trips. At the same time, the charging infrastructure was still in its infancy, making the purchase of a fully electric vehicle a perceived risk for many. To address this problem hybrid vehicles were introduced, combining an electric motor with an internal combustion engine. This technology, pioneering in the early 2000s, represented the perfect compromise for customers. On one hand, it guaranteed greater efficiency and emission reduction; on the other, it allowed reliance on traditional fuel, alleviating any concerns about range.

Over time, technology evolved, and so did consumer expectations. The introduction of plug-in hybrid vehicles marked another step forward in the transition to electric mobility. These models directly responded to the needs of customers who wanted to experience all-electric driving, at least for short distances, without giving up the safety net of an internal combustion engine for longer trips. In many cases, PHEVs acted as a “training ground” for drivers, allowing them to gradually adapt to de dynamics of charging and energy management without depending entirely on public charging infrastructure. In parallel, for markets where electric adoption was still in its infancy, MHEVs were developed as a simpler and more affordable solution. These vehicles, improved fuel efficiency and slightly reduce emissions, offering an accessible entry point for more traditional customers. MHEVS required no significant changes in driver’s habits, maintaining the characteristics of a conventional vehicle but with enhanced efficiency. In this way, they played an educational role, gradually familiarizing customers with the concept of electrification without significant impact on their driving style.

In recent years, with advancements in battery technology and increased investments in charging infrastructure, battery electric vehicles have gained prominence. Automakers recognized that to accelerate the mass production of BEVs, it was necessary to significantly expand the range and make it more accessible. Not only have luxury models been developed. But also, electric vehicles designed for urban mobility and families, thereby broadening the market target. This diversification has addressed different needs: from drivers seeking high performance to those prioritizing low operation costs or a more ecological lifestyle. The success of this strategy lies in its ability to address specific customer concerns. Next-generation BEVs, thanks to improvements in range and charging times, are finally starting to improve the solutions for the problem of range anxiety. Charging infrastructure, despite still limited, is expanding, and many governments are offering economic incentives to facilitate the purchase of electric vehicles and the development of home charging stations. This technological progress has made electric vehicles more mainstream, appealing to an increasingly diverse and broader audience.

In conclusion, the diversification of electrified vehicle models has been crucial in addressing the monumental shift from ICEV to ELV. Each category (MHEV, HEV, PHEV and BEV) has resolved specific issues, progressively and gradually guiding customers toward adopting a sustainable mobility model. This evolution has demonstrated how technological adaptation, and an understanding of consumer needs can go hand in hand, accelerating a change that, in the long run, will be both inevitable and essential.

2.3 Types of batteries used in electric vehicles (Li-ion, solid-state, etc.)

Batteries are the beating heart of EVs, significantly determining their performance and efficiency. Unlike Starting, Lighting, and Ignition (SLI) batteries, which are designed for short bursts of energy, EV batteries must provide continuous and sustained power, like deep-cycle batteries used in other applications. One of the distinctive features of EV batteries is their high power-to-weight ratio, along with high specific energy and energy density. These factors are crucial for reducing the overall weight of the vehicle and enhancing its performance. However, compared to liquid fuels, current battery technologies have lower specific energy, which can limit the range of electric vehicles. Metal-air batteries, which use oxygen from the air as the cathode, are an exception due to their high specific energy. Rechargeable batteries used in electric vehicles include various technologies: lead-acid, nickel-cadmium (NiCad), nickel-metal hydride (NiMH), lithium-ion (Li-ion), lithium polymer (LiPo), zinc-air, and molten salt batteries. Among these, lithium-ion and lithium polymer batteries are the most common in modern electric cars, thanks to their high energy density and low weight. The cost of batteries is a significant component of the price of electric vehicles, influencing their market. However, technological advancements have led to a reduction in battery costs by over 35% between 2008 and 2014. These improvements have been partly driven by the demands of portable electronic devices, such as laptops and smartphones, and the electric vehicle sector has benefited from these innovations. From an operational cost perspective, the electricity required to power an electric vehicle is much cheaper than fuel for internal combustion engines, contributing to overall greater energy efficiency. The market for electric vehicle batteries is rapidly expanding. Additionally, EV batteries are evolving rapidly, with new technologies such as solid-state batteries promising greater safety, longevity, and energy capacity. These developments could further reduce costs and improve the performance of electric vehicles, making them an increasingly attractive choice for consumers.

Here is a list with an overview of the main types of batteries used as electric motors.

1. **Lead-acid Batteries**

Lead-acid batteries are one of the oldest types of rechargeable batteries and are commonly used in various applications. They come in two main types: starting batteries and deep-cycle batteries. Starting batteries are designed to deliver high amounts of power for short periods, making them ideal for automotive engines. They can handle rapid charges and discharge cycles. On the other hand, deep-cycle batteries are designed for sustained energy delivery over longer periods and are commonly used in applications like forklifts and golf carts. These batteries require multi-stage charging and should not be discharged below 50% of their capacity to avoid reducing their lifespan. They have a relatively low specific energy level of 30-40 Wh/kg, which is significantly lower than that of petroleum-based fuels.

Their efficiency ranges between 70-75%, and their storage capacity decreases at lower temperatures. Additionally, using energy to operate a heating system can reduce their efficiency and range by up to 40%. The construction of lead-acid batteries involves lead anode and a lead dioxide-coated cathode, with an electrolyte made of a sulfuric acid solution. This chemical setup allows the battery to convert stored chemical energy into electrical energy for powering electric motors. Despite their modest performance, lead-acid batteries are still used in some low-cost and small electric vehicles due to their affordability and long lifespan. However, they require careful disposal due to their environmental impact.
Typically, they deteriorate after 250-500 cycles, which equates to about 70 km per cycle. While they were the first type of battery used in electric vehicles, their use has significantly declined, and they are now rarely used as the primary energy storage in modern electric cars.

2. Nickel-metal hydride

NiMH batteries are a mature technology used in the automotive sector, particularly in hybrid vehicles like the Toyota Prius. Although they have a lower charge and discharge efficiency (60-70%) compared to lead-acid batteries, they offer a specific energy of 30-80 Wh/kg, which is higher than that of lead-acid batteries. When properly maintained, they can last over 160,000 km and more than ten years. The advantages of NiMH batteries include greater safety, less vulnerability to temperature fluctuations, lower cost compared to lithium-ion batteries, and a higher number of charged cycles, with an average lifespan of 500-2000 cycles. However, they have further disadvantages, not only limited discharge current, high self-discharge rate, and longer charging time; they also suffer from the memory effect, which can reduce performance over time. NiMH batteries have an anode made of metal alloy and a cathode with a high concentration of nickel, with an electrolyte often consisting of diluted potassium hydroxide. Despite their limitations, they have been successfully used in hybrid vehicles, demonstrating good durability and reliability. For example, Toyota offers a 5-year or 100,000 km warranty on the NiMH batteries in its hybrid cars, with the option to extend it for a fee.

3. Sodium-Nickel chloride

Sodium-nickel chloride batteries, also known as ZEBRA (Zero Emission Battery Research Activities) batteries, are a type of energy storage technology that uses molten sodium chloroaluminate ($NaAlCl_4$) as the electrolyte. These batteries consist of a nickel cathode and a dissolved sodium anode, separated by a ceramic ß-alumina membrane that allows ions to pass through but not electrons. One of the main advantages of these batteries is the use of abundant and recyclable materials, making production more sustainable. Additionally, they are very safe due to the stability of the components and offer a lifespan comparable to lithium iron phosphate (LFP) batteries. However, there are also some significant drawbacks. To function properly, they must maintain an internal temperature between 250°C and 270°C, which requires considerable energy consumption for thermal maintenance. Furthermore, if left inactive, they can lose up to 30% of their charge just to maintain the operating temperature. Although the materials are inexpensive, production costs remain high due to the lack of a well-developed production chain. These batteries have been used in specific applications such as electric buses and military vehicles, but their limitations have prevented wider adoption in the automotive sector.

4. Li-ion batteries

Lithium-ion batteries, widely known for their use in laptops and consumer electronics, are the most used batteries for modern electric vehicles. These batteries typically feature a lithium cobalt oxide cathode and a graphite anode, resulting in cells with a high specific energy of over 200 Wh/kg and a high specific power with a charge/discharge efficiency of 80-90%. However, traditional lithium-ion batteries have some drawbacks, including a relatively short cycle life (ranging from hundreds to a few thousand charge cycles) and significant degradation over time. The cathode material is also somewhat toxic. Additionally, these batteries are at risk of catching fire if punctured or improperly charged. They do not accept or provide charges when extremely cold, necessitating a heating system in particularly cold climates. The Tesla Roadster (2008) used groups of traditional "laptop batteries" that could be individually replaced as needed. Recent electric vehicles use new variants of lithium-ion batteries that sacrifice specific energy and power to provide flame resistance, environmental friendliness, rapid charging (in a few minutes), and longer lifespan. These variants (such as phosphates, titanates, and spinels) have demonstrated much longer lifespans. Li-ion are considered the current standard due to their widespread use and success, offering a good balance of performance, high energy density, fast charge and discharge rates, light weight, and sufficient longevity. These batteries have evolved over time, with chemical formulations improving their technical characteristics and optimizing the use of critical materials like cobalt. Currently, lithium-ion batteries with liquid electrolytes are the basis for future solid-state batteries. The average capacity of a lithium-ion battery is between 50 and 80 kWh, allowing a range of 250 to 450 km on a single charge and the average lifespan is about 1000-1500 cycles, equivalent to 8-10 years of use, but this depends on many external factors. Different technologies and chemical compositions influence the characteristics of the batteries, such as energy density, power, safety, and cost.

5. Solid-State Batteries

Solid-state batteries are among the most innovative technologies in the energy storage sector and have the potential to revolutionize multiple industries, including electric vehicles, consumer electronics, and renewable energy storage. Unlike conventional lithium-ion batteries, they use a solid electrolyte instead of a liquid one, offering significant advantages in terms of safety, range, and lifespan. One of their key benefits is higher energy density, which could enable a greater driving range for electric vehicles and faster charging times. Additionally, their safety is significantly improved, as the absence of flammable liquid electrolytes reduces the risk of fires and short circuits. These batteries also promise greater longevity, with a higher number of charge cycles compared to current lithium-ion solutions. However, widespread adoption remains challenging due to high production costs, industrial scalability issues, and limitations in ionic conductivity. To overcome these obstacles, several automotive companies, including Toyota, Volkswagen, BMW, and Mercedes-Benz, are heavily investing in research and development to refine this technology and bring it to market in the coming years.

2.4 Historical Overview of Batteries for Electric Vehicles and the Challenges They Faced and Overcame Through Technological Advancements

The evolution of batteries for electric vehicles represents an important phase of technological innovation and adaptation. After examining the specific technical features of various battery types in the previous section, it is equally important to contextualize their development within a historical framework. Understanding the historical milestones and the challenges that they have faced provides valuable insight into the trajectory of this critical technology. From their inception as rudimentary energy storage solutions to the sophisticated systems that now power millions of electric vehicles worldwide, batteries have undergone transformative changes. These changes were driven by the need to address pressing challenges, such as limited range, high production costs, and safety concerns. Each innovation not only solved immediate technical problems but also paved the way for greater adoption of electric vehicles on a large scale.

Lead-acid ones were the first deployed. Introduced in the 19th century, these batteries powered the first electric vehicles. While innovative for their time, they had significant limitations, however they were relatively inexpensive and easy to produce, making them a necessary choice for early applications. Innovations in lead-acid batteries focused primarily on safety improvements and reducing the need for maintenance, but these batteries soon became obsolete as new technologies emerged. In the 1960s and 1970s, NiCd ones brought significant advancements but introduced new challenges, such as the memory effect. Additionally, the environmental impact of cadmium, a heavy and toxic metal, was a significant barrier. By the 1990s, NiMH emerged as a cleaner and more efficient solution. Used in early hybrid vehicles like the Toyota Prius, NiMH batteries increased range and reduced environmental costs, helping to initiate the era of electrification.

The real turning point came with the advent of lithium-ion batteries in the 1990s and 2000s. With a significantly higher energy density than previous technologies, these batteries enabled electric vehicles to compete with internal combustion engine vehicles in terms of range and performance. However, as said before, they initially presented challenges; the risk of overheating and fires was high due to the unstable chemistry of the cells. Additionally, production costs were prohibitive, limiting widespread adoption. To address these issues, new chemistries, such as lithium-nickel-manganese-cobalt (NMC), were developed, and battery management systems (BMS) were

introduced to monitor safety and optimize performance. These advancements have made lithium-ion batteries the cornerstone of modern electric mobility.
A key variant of lithium-ion batteries is lithium iron phosphate ($LiFePO_4$), introduced in the early 2000s.
These batteries provide enhanced safety due to their more stable chemistry and offer a longer lifespan compared to traditional lithium-ion batteries. While their energy density is slightly lower, they have become a popular choice for applications requiring high safety and reliability, such as electric buses and fleet vehicles.
Today, the future of electric vehicle batteries focuses on solid-state technologies. These ones, still under development, promise to eliminate risks associated with liquid electrolytes, significantly improve energy density, and enable rapid charging times. Solid-state batteries could represent a game changer for the industry, but they still face challenges related to costs and durability.
Alongside these major innovations, other technologies are also being developed, such as lithium-sulfur batteries, which could surpass the energy density of current lithium-ion technologies, and sodium-ion batteries, which provide a more economical solution. Meanwhile, flow batteries, with their scalability and durability, could revolutionize charging infrastructure for electric vehicles.

Battery costs and Safety Problems

As seen in the historical overview and in the descriptions of the particular batteries these products faced and are facing significant problems: the high costs associated with production and the critical safety concerns inherent to battery technology. These issues are intertwined with the progression of the electric vehicle sector, shaping both public perception and market viability.
The financial burden posed by battery production has been a longstanding obstacle to the widespread adoption of electric vehicles. As outlined, lithium-ion batteries, which dominate the current market, require rare and expensive materials such as lithium, cobalt, nickel, and manganese. The mining and processing of these materials often involve complex logistics, as reserves are typically located in remote and politically sensitive regions. Beyond the cost of raw materials, the production process itself demands precision engineering. Batteries must be assembled in highly controlled environments like those used in semiconductor manufacturing, further driving up costs. Although significant strides have been made to reduce battery prices, dropping from approximately $1,700 per kWh in 2010 to projections of $80 per kWh by 2026, cost

remains a key determinant of electric vehicle affordability. Future advancements, such as the adoption of solid-state technologies and alternative chemistries like sodium-ion batteries, hold promises for further cost reductions. Nonetheless, achieving this will require sustained investment in research, scaling production, and developing more efficient supply chains.

In tandem with cost challenges, safety concerns remain a critical issue. Lithium-ion batteries, while efficient and compact, are prone to thermal runaway, a chain reaction that can lead to overheating and, in some cases, fires or explosions. This is primarily due to the highly reactive nature of lithium-ion chemistry and the need to pack cells densely to achieve competitive energy densities. The industry has responded with significant innovations, such as improved BMS that monitor and regulate cell temperatures, as well as the use of less flammable electrolyte materials. Safety concerns extend beyond the vehicles themselves. The storage and transportation of large battery packs pose additional risks, necessitating stringent regulations and specialized handling procedures. Recycling and second-life applications for batteries also require careful management to prevent environmental contamination and ensure worker safety. Despite these challenges, the industry continues to make progress. Collaborative efforts between governments, private companies, and research institutions are driving innovations that address both cost and safety issues. Regulatory frameworks, such as stricter safety standards and incentives for sustainable mining practices, are further aiding in mitigating these barriers.

2.5 Reevaluating the Environmental Impact of Electric Vehicles: A Comprehensive Lifecycle Perspective

The CO_2 emissions Analysis is a key point to assess EVs convenience in terms of sustainability against combustions ones. When evaluating the environmental impact of electric vehicles, it is crucial to go beyond surface-level assumptions and conduct a comprehensive assessment of their entire lifecycle. While EVs are often touted as a cleaner alternative to ICE vehicles due to their lack of tailpipe emissions, a more advanced analysis is required to determine whether they truly deliver significant environmental benefits. This involves considering the full scope of their lifecycle impact, from raw material extraction and production to use and end-of-life stages. The role of batteries is particularly central in this discussion in fact, their production requires large quantities of critical materials like lithium, cobalt, and nickel. Mining and processing these materials can result in significant ecological disruption, greenhouse gas emissions, and social challenges in regions where extraction occurs. Additionally, the high energy demand for battery manufacturing, often reliant on fossil fuels, further complicates the environmental equation.

To truly understand the environmental trade-offs, it is essential to conduct Life Cycle Assessments (LCAs) that include the entire lifespan of both electric and combustion vehicles. These assessments evaluate impacts across all phases (manufacturing, use, and disposal) providing a holistic view of their ecological footprint. Importantly, the extent and boundaries of the LCA play a pivotal role in the conclusions drawn. Narrow LCAs that omit key stages, such as the sourcing of raw materials or battery recycling, can lead to overly optimistic or skewed results. Similarly, regional variations in energy grids and their reliance on renewable or non-renewable sources profoundly influence the environmental benefits of EVs during their operational phase. In this part, will be critically examined the environmental impact of EVs, with a specific focus on their batteries, to challenge the narrative that they inherently offer a substantial ecological advantage over ICE vehicles. By analyzing extensive LCAs and incorporating data on resource extraction, energy consumption, and end-of-life processes, this discussion aims to provide a balanced perspective. While EVs hold great potential for reducing emissions in the long term, understanding their true environmental cost is essential for guiding policy, innovation, and consumer adoption toward more sustainable transportation solutions. EVS are widely regarded as a cornerstone of sustainable mobility due to their lack of direct emissions during operation. However, a comprehensive analysis of their lifecycle impact reveals complexities that challenge this perception.

Raw Material Extraction

One of the most resource-intensive phases of an EV's lifecycle is the extraction of raw materials required for battery production. Lithium, cobalt, nickel, and manganese are critical components, with their extraction processes posing significant environmental and social challenges. For example, lithium mining consumes large amounts of water, up to **2.2 million liters per ton of lithium** extracted. In regions such as South America's "Lithium Triangle," this has led to water scarcity, threatening local ecosystems and communities. CO_2 emissions during this phase for EVs are approximately **15 kg CO_2 per kilometer**, compared to **10 kg CO_2 per kilometer** for ICEVs. This discrepancy arises because ICEVs primarily rely on less intensive processes to extract oil and refine it into fuel. Additionally, the geopolitical concentration of critical material reserves in regions such as the Democratic Republic of Congo for cobalt raises concerns about ethical mining practices and the environmental cost of transporting materials to manufacturing hubs.

Manufacturing

The manufacturing phase of EVs, particularly their batteries, is markedly energy intensive. Producing a single lithium-ion battery pack can emit between **61–106 kg CO_2 per kWh** of capacity, depending on the energy sources used during manufacturing. For a typical 60 kWh EV battery, this equates to emissions ranging from **3.7 to 6.4 tons of CO_2**. Comparatively, the manufacturing emissions for ICEVs are significantly lower, averaging around **4.5 tons of CO_2** per vehicle, as they do not require the complex assembly and controlled environments that battery production necessitates. Advancements in battery chemistries, such as the transition to LFP batteries, are reducing these emissions. Additionally, localized production and reliance on renewable energy for manufacturing can further mitigate environmental impacts. Tesla's Gigafactories, for example, leverage solar and wind power to lower the carbon intensity of battery production.

Operational Phase

The operational phase is where EVs demonstrate their greatest environmental advantage. ICEVs emit approximately **180–200 g CO_2 per kilometer** driven, primarily from fuel combustion. In contrast, EVs emit between **50–90 g CO_2 per kilometer** during operation, with variations depending on the energy mix of the electricity grid. In regions with a renewable-heavy energy grid, such as Norway or Iceland, EV operational emissions can drop as low as **15 g CO_2 per kilometer**. Conversely, in coal-dependent regions like India or parts of the United States, operational emissions for EVs can exceed **100 g CO_2 per kilometer**, narrowing the gap with ICEVs. This underscores the critical role of decarbonizing electricity grids in maximizing the environmental benefits of EVs.

End-of-Life and Recycling

The end-of-life phase presents both challenges and opportunities for EVs. Effective recycling of lithium-ion batteries can recover up to **95% of valuable materials**, significantly reducing the need for virgin material extraction. However, current recycling practices are limited by logistical and economic barriers. Pyrometallurgical recycling, for example, emits **6–8 kg CO_2 per kilogram** of battery recycled, while hydrometallurgical methods are less carbon-intensive but require substantial chemical inputs. Second-life applications for EV batteries, such as stationary energy storage, can extend their utility by 5–10 years, delaying the recycling phase and contributing to grid stability. These applications are particularly impactful in renewable energy systems, where storage is critical for managing intermittency.

Comparative Lifecycle Emissions

When assessed over their entire lifecycle, EVs produce approximately **50–60% fewer greenhouse gas emissions** than ICEVs. For instance:

- **EVs (50 kWh battery, renewable grid):** 15–20 tons of CO_2 over 150,000 km.
- **ICEVs (petrol):** 30–40 tons of CO_2 over the same distance.

However, in regions with carbon-intensive electricity, the lifecycle emissions gap narrows, and the total emissions of an EV can approach those of a highly efficient ICEV.

Until now the discussion was particularly on CO_2 emissions, but there are other forms of pollution that are important. Notably, some researchers argue that EV production, particularly battery manufacturing, contributes to other forms of environmental damage, including water acidification, eutrophication, and increased emissions of toxic substances that pose risks to human health and ecosystems. The last part of these paragraph will analyze different papers focusing on the importance of the regional variability when assessing the CO_2 emissions of a vehicle and in addition, on the other possible effect that all the phases of an ELV can have on the environment, which are not visible through an LCA.

Reduction in CO_2 Emissions

Numerous studies underscore the potential of EVs to reduce CO_2 emissions over their lifecycle. For instance, Ellingsen et al. (2014) conducted a comprehensive LCA comparing EVs with ICEVs. Their findings indicate that EVs powered by renewable energy sources emit **50–60% less CO_2** over their lifecycle compared to ICEVs. However, they also caution that the environmental advantage diminishes in regions heavily reliant on fossil fuels for electricity generation, where the emissions from electricity production may offset operational gains.

Similarly, a study by Dunn et al. (2015) highlights that advancements in battery technology and recycling could further reduce lifecycle emissions. The authors estimate that improvements in hydrometallurgical recycling could lower GHG emissions from battery production by **10–15%**, emphasizing the importance of developing efficient recycling systems.

Increase in Toxic and Harmful Emissions

While EVs excel in reducing GHG emissions, their production processes, especially for batteries, are associated with increased emissions of pollutants that can acidify water, contaminate soil, and harm human health. For example, Romare and Dahllöf (2017) identify that the extraction of lithium and cobalt, key materials for EV batteries, generates substantial amounts of sulfuric acid and other chemicals. These emissions contribute to water acidification and eutrophication, particularly in mining regions.

- **Acidification of Water Resources:** A 2020 LCA study by Liu et al. estimates that the production of lithium-ion batteries results in **70% higher acidification potential** compared to the production of ICEV components. This is due to the leaching of sulfates and the use of acid-based reagents during material processing. This phenomenon has been observed in lithium mining areas such as the Salar de Atacama in Chile, where local water supplies are at risk due to the environmental costs of extraction.
- **Toxic Emissions:** The processing of cobalt, primarily mined in the Democratic Republic of Congo, involves the release of heavy metals such as arsenic and cadmium, which contaminate local water supplies and pose significant health risks. Kim et al. (2016) warn that the expansion of EV production without sustainable supply chain practices could exacerbate these environmental and health issues.

Regional Variability in Environmental Impact

The environmental trade-offs associated with EVs are influenced heavily by regional factors. In countries with stringent environmental regulations and advanced recycling infrastructures, such as Germany or Sweden, the lifecycle impact of EVs is considerably lower. Conversely, in regions where mining and production occur under lax environmental standards, such as parts of Africa and South America, the localized environmental damage can be severe. Moreover, the reliance on coal-powered electricity grids in some regions exacerbates the environmental footprint during the operational phase of EVs. For instance, a study by Bieker (2021) reports that in China, where coal accounts for a significant share of electricity production, the lifecycle CO_2 savings of EVs are reduced by nearly **30%**, while acidification and toxicity potentials remain high.

Policy and Technological Solutions

To mitigate these environmental trade-offs, researchers and policymakers advocate several strategies:

- **Advanced Recycling Technologies:** Hydrometallurgical recycling, which uses aqueous solutions to recover metals, has been shown to reduce harmful emissions compared to pyrometallurgical methods. Armand and Tarascon (2008) estimate that efficient recycling could recover up to **95% of lithium and cobalt**, reducing the need for virgin material extraction.
- **Second-Life Applications:** Using batteries in stationary storage systems before recycling can extend their lifecycle and decrease overall environmental impact. This approach not only delays the acidification impact of battery disposal but also supports renewable energy integration.
- **Sustainable Mining Practices:** Companies and governments must prioritize sustainable mining techniques that minimize water and soil contamination. Initiatives such as the Cobalt Refinery Project in Canada aim to implement closed-loop systems that significantly reduce toxic byproducts.

3. Impact of Electric Vehicles on the Automotive Market

The emergence of electric vehicles has triggered a paradigm shift in the automotive industry, fundamentally altering how vehicles are manufactured, marketed, and consumed. As the global focus on sustainability intensifies, the automotive market is increasingly pivoting away from internal combustion engine vehicles toward electrified alternatives. This transition is driven not only by environmental concerns but also as said before by advancements in battery technology, changes in consumer behavior, and robust policy interventions from governments worldwide. Electric vehicles are no longer a niche product; they have become a core component of automakers' strategies. This shift has influenced the entire supply chain, from the sourcing of critical materials like lithium and cobalt to the development of charging infrastructure. Automakers are investing heavily in research and development to produce EVs that are not only environmentally sustainable but also cost-competitive and appealing to a broad range of consumers. Europe has emerged as an important starter in the adoption and production of EVs, setting ambitious climate targets and incentivizing the transition to electrified mobility. These efforts are transforming the automotive market, with electric vehicles accounting for an increasing share of new car sales. However, this transition also presents challenges, such as the need for extensive charging infrastructure, the pressure on raw material supply chains, and disparities in adoption rates across regions.

3.1 Current State of the Electric Vehicle Market in Europe

The European EV market is at the forefront of the global transition toward sustainable mobility. In recent years, the continent has testified unprecedented growth in EV adoption, driven by ambitious climate policies, significant advancements in battery technology as said before, and changing consumer attitudes. This transformation reflects Europe's commitment to achieving carbon neutrality and reducing its reliance on fossil fuels in the transportation sector. The widespread adoption of EVs in Europe is supported by a combination of regulatory frameworks and financial incentives. Countries across the European Union have implemented measures to encourage the shift away from ICE vehicles, from tax exemptions to subsidies for EV purchases and investments in charging infrastructure. These efforts have been reinforced by the EU's Green Deal and its commitment to a 55% reduction in greenhouse gas emissions by 2030. However, while EV sales have surged in some regions, disparities remain between countries, highlighting challenges previously mentioned. The electric vehicle market in Europe has grown also by shifting consumer preferences. As of 2023, countries such as Norway, Germany, and the Netherlands are pushing the transition to cleaner mobility. EVs now represent over 20% of new car sales across the European Union, a stark contrast to just a few percent a decade ago. The policies have incentivized automakers to ramp up their production of BEVs and PHEVs. In response, almost all major European automakers, such as Volkswagen, BMW, and Stellantis, have unveiled extensive plans to electrify their fleets, with several committing to phasing out internal combustion engine vehicles entirely by 2035. Norway remains the standout performer, with EVs accounting for nearly 80% of new car sales in 2022, thanks to aggressive subsidies and a well-developed charging infrastructure. Other markets, such as Germany and the UK, are catching up, with EV sales reaching 14% and 16%, respectively, in 2022. Despite this progress, there is considerable variation across the continent. Eastern European countries lag behind due to economic barriers, limited infrastructure, and lower consumer purchasing power. Price competitiveness is another critical factor shaping the market. The cost of EVs is declining significantly due to advancements in battery technology and economies of scale, with some models now approaching price parity with internal combustion engine vehicles. Government incentives, such as purchase subsidies and tax exemptions, have further reduced upfront costs for consumers. However, affordability remains a challenge in certain markets, particularly in segments dominated by budget-conscious buyers.

Analyzing the market share of various brands in the European EV segment, it is evident that Tesla initially emerged as the dominant player. In the early years of EV adoption, Tesla capitalized on its technological edge and pioneering innovation, successfully gaining significant market share while traditional automakers remained focused on internal combustion vehicles. The company's early success can be attributed to its ability to introduce a niche product that combined high performance, cutting-edge technology, and an attractive price-to-quality ratio, appealing to early adopters and tech-savvy consumers. However, with the new regulatory targets set by the European Union, European automakers were compelled to make substantial investments to keep pace with the accelerated transition to electric mobility. In response, they developed competitive EV models, aiming to retain market share and challenge the dominance of non-European manufacturers. As a result, what was once a market segment within the broader automotive industry (where Tesla led in BEVs and Toyota dominated in hybrid technology) has evolved into a fully independent market, set to replace conventional combustion vehicles in the coming years.

Despite the initial enthusiasm surrounding EV adoption, the forced nature of this transition has led to growing consumer skepticism. Even with government incentives and subsidies, many European buyers feel pressured to abandon internal combustion vehicles, which have long been integral to the continent's automotive culture. The lack of complete trust in EVs stems from their rapid technological evolution, ongoing infrastructure development, and lingering concerns regarding usability, reliability, and practicality. Moreover, the higher upfront investment required for EV ownership, coupled with uncertainties about charging networks and battery lifespan, has further contributed to hesitation among consumers. Ultimately, these government-driven policies have redefined the EV industry, transforming it from a niche category within the automotive market into a standalone sector. In the coming years, electric mobility will no longer be an alternative but the new standard, marking a fundamental shift in the European automotive landscape.

In January 2025, 124,341 electric vehicles were registered in Europe, marking a 34% increase compared to January 2024. EVs now hold a 15% market share, surpassing diesel cars, which account for 10% of the market. In this expanding European EV market, the main players include Tesla, Toyota, European automakers struggling to maintain market share, and Chinese brands that, after years of heavy investments in innovation, R&D, and favorable political and geographical conditions, are aggressively entering the market. These brands are offering cutting-edge EVs at highly competitive prices, posing a direct challenge to traditional European manufacturers. Leading this push is BYD, which has rapidly gained traction in the region. Europe's legacy automakers are attempting to counter this surge by securing financial support and forming strategic alliances, even with non-European companies. A notable example is the joint venture between Stellantis and Chinese EV manufacturer Leap Motors. This partnership allows Stellantis to leverage its well-established European sales network, while in return, it gains access to critical data and technological insights to improve its product offerings. Despite these efforts, European automakers continue to lose ground, with Tesla and BYD emerging as dominant players in the market.

In February 2025, EV registrations in the 25 EU countries, the UK, Norway, and Switzerland increased by 25%, despite an overall decline in car sales of 3%. This trend is significantly reshaping the hierarchy among major automotive manufacturers, highlighting growing competition between established European brands, emerging Chinese players, and global brands such as Tesla. According to data published by JATO Dynamics (Reuters, 2025), Tesla, as previously analyzed, experienced a sharp decline in sales in Europe in the early months of 2025, falling behind traditional manufacturers like Volkswagen Group and BMW Group, as well as several Chinese brands. In February, Tesla sold fewer BEVs compared to Volkswagen (around 20,000 units) and BMW + Mini (nearly 19,000 units). By contrast, BYD and Polestar recorded significant increases in sales (up by 94% and 84%, respectively), while Xpeng and Leapmotor sold over 1,000 and approximately 900 units, respectively. Regarding Stellantis, the group showed positive signs at the beginning of 2025. In January, it registered 46,413 units in Italy, with a market share of 31.3%, driven by brands like Fiat, Jeep, and Peugeot. However, its performance in the BEV segment has not yet reached the levels of the market leaders, indicating the need to accelerate its electrification strategy to remain competitive (Motori Quotidiano, 2025). Toyota, on the other hand, continues to lead the hybrid market but is working to close the gap in the BEV segment. In January 2025, Toyota and Lexus registered over 11,000 units in Italy, achieving an 8% market share. At the European level, Toyota recorded a 13% growth in the first quarter, with over 100,000 vehicles sold in March alone, reaching a 4.71% market share. However, in 2024, only 1.3% of its global sales were BEVs. To bridge this gap, Toyota announced the launch of nine fully electric models between 2025 and 2026 and the start of BEV production in the UK, with the goal of keeping all eight of its European plants operational during the transition to electrification. In summary, Volkswagen and BMW are leading the European BEV market in the first months of 2025, while Tesla is showing signs of slowdown, also due to reputational issues and increased competition. Chinese brands continue their rise, driven by aggressive pricing strategies and strong investments in technology. Stellantis and Toyota are accelerating their transition to electric mobility, though with different approaches: Stellantis is focusing on a multi-brand and industrial strategy, while Toyota is pursuing a progressive and phased expansion of its BEV lineup. This scenario suggests that future leadership in the European electric vehicle market will be determined by the ability to combine innovation, local manufacturing investments, and a diversified, accessible product offering.

This section delves deeper into the intricacies of the industry by examining its value chains in detail. Understanding the EV market requires not only a grasp of its sales performance, policy frameworks, and consumer adoption but also an analysis of the underlying processes and networks that make it possible. The value chains of the EV market encompass a broad spectrum of activities, from the extraction and refinement of critical raw materials to the manufacturing of batteries, motors, and vehicle components, and finally to the distribution and recycling processes. Each link in the chain plays a pivotal role in shaping the sustainability, cost-efficiency, and scalability of electric mobility. These value chains are distinct from those of ICE vehicles, introducing unique challenges and opportunities for automakers, suppliers, and policymakers.

3.2 Supply chain

The supply chain for EVs represents a critical component of the automotive industry's shift toward sustainable mobility. Unlike traditional ICE vehicles, which rely on well-established networks for components such as engines and transmissions, EVs require an entirely different set of raw materials, technologies, and processes. The production of EVs is heavily centered around batteries, which are both the most valuable and complex components in their supply chain. This focus introduces unique challenges, including securing access to critical minerals such as lithium, cobalt, and nickel, and addressing the environmental and ethical concerns associated with their extraction and processing.

Beyond raw material acquisition, the EV supply chain is characterized by the integration of advanced battery manufacturing, electric motor production, and sophisticated electronics. These processes require a high degree of technological expertise and coordination across global networks. Furthermore, as EV demand continues to rise, automakers face increasing pressure to scale up production while ensuring sustainability and cost efficiency. This has led to innovations such as vertical integration, where companies manage multiple stages of production, and the development of localized supply chains to mitigate risks and reduce carbon footprints. In this part, the focus will shift to examining the key elements of the EV supply chain. It will explore the extraction and processing of raw materials, the manufacturing of batteries and other EV components, and the distribution networks that bring these vehicles to market. Additionally, a comparison with the supply chain of ICE vehicles will highlight the unique challenges and opportunities of electrified mobility. By analyzing these aspects, this discussion aims to provide a comprehensive understanding of how the EV supply chain is shaping the future of the automotive industry.

A key point to discuss is that Europe's transition to EVs is fundamentally shaped by its dependence on global markets for critical raw materials. Unlike internal combustion engine vehicles, EVs rely heavily on components such as lithium-ion batteries, which require key minerals like lithium, cobalt, nickel, and manganese. The continent’s limited domestic reserves of these essential materials make it one of the largest importers globally, creating significant vulnerabilities in its supply chain and exposing the European automotive sector to the challenges of globalization. Lithium, for example, is a cornerstone of EV battery production, with demand expected to grow exponentially in the coming years. Europe primarily sources lithium from Australia, the world’s largest producer, which accounts for over half of global lithium production. Chile and Argentina, part of the "Lithium Triangle," also play a crucial role, holding some of the largest reserves of lithium globally and serving as key exporters to European markets. These imports are critical for sustaining Europe’s growing EV market but leave the region vulnerable to price volatility and geopolitical shifts.

Similarly, cobalt, another vital material for battery production, exemplifies Europe’s reliance on external suppliers. The Democratic Republic of Congo is responsible for approximately 70% of the world’s cobalt production. However, this dominance comes with ethical and environmental concerns, including issues of child labor and unsustainable mining practices. Adding to this complexity, China processes the majority of the world’s cobalt, further consolidating its position as a dominant player in the EV supply chain. The situation is no less critical for nickel, which improves battery energy density and performance. Europe sources significant amounts of nickel from Indonesia and the Philippines, with Russia previously being a key supplier before geopolitical tensions, particularly following the invasion of Ukraine, complicated trade dynamics. Graphite, the primary material used in battery anodes, further underscores Europe’s reliance on global imports. With China controlling over 80% of the world’s graphite mining and processing, Europe faces considerable challenges in diversifying its supply sources.

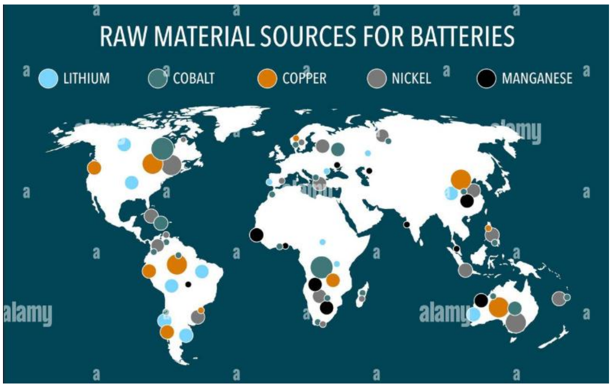
To address these challenges, Europe has begun pursuing several strategies aimed at reducing its dependency on global supply chains. Diversification is a key focus, with European companies increasingly seeking alternative suppliers in Australia, Canada, and Africa to mitigate overreliance on dominant players like China. Efforts are also underway to develop domestic mining projects, particularly for lithium in countries like Portugal and Spain. However, these initiatives remain in their early stages and face regulatory and environmental hurdles.

Recycling is emerging as another critical avenue for reducing dependency. By adopting circular economy principles, Europe aims to recover valuable materials like lithium, cobalt, and nickel from used batteries, which could provide a more sustainable and localized source of these critical minerals. Strategic partnerships, such as those fostered by the EU's Raw Materials Alliance, are also being established to secure long-term access to raw materials and develop a more resilient supply chain. In summary, Europe's reliance on global markets for raw materials underscores a key vulnerability in its EV supply chain. While the region has made strides in advancing its electric vehicle ambitions, reducing this dependency will require substantial investment in domestic resource development, recycling infrastructure, and diversification of supply chains. Only through these efforts can Europe build a sustainable and resilient foundation for its transition to electrified mobility.

On the other hand, the supply chain for internal combustion engine vehicles (ICEVs) has historically been less dependent on global markets than that of electric vehicles (EVs). This distinction stems from several key factors, including the widespread availability of required resources, the simplicity of material sourcing, and the maturity of the traditional automotive supply chain. Together, these elements have allowed ICEVs to operate within a more stable and localized supply framework, in contrast to the complex and globally reliant supply chains necessary for EV production. A cornerstone of the ICEV supply chain is its reliance on petroleum, which serves as the primary fuel source. Unlike the rare materials critical for EV batteries, petroleum is widely distributed across the globe, with significant reserves in regions such as the Middle East, North America, Russia, and South America. This global availability has enabled automotive manufacturers in Europe to secure stable fuel supplies over the decades, even amidst price fluctuations and geopolitical tensions. Furthermore, the oil and gas industry has benefited from over a century of development, resulting in a highly optimized supply chain with established infrastructure for extraction, refinement, and transportation.

Another significant advantage for ICEVs lies in their reliance on common materials such as steel, aluminum, plastics, and rubber. These resources are not only widely available globally but are also extensively produced within Europe, enabling greater regional self-sufficiency for European automakers. For instance, the European steel industry has historically supported the local production of engines, transmissions, and other key components, reducing dependency on imports. This localization of material production and processing has provided European manufacturers with greater control over their supply chains, enhancing resilience and stability. The maturity of the ICEV supply chain is another critical factor that differentiates it from the evolving supply chain of EVs. Over a century of refinement, the ICEV supply chain has become highly standardized and efficient. Automotive manufacturers have developed extensive networks of regional and international suppliers, ensuring a steady and predictable flow of materials and components. This long-standing optimization has allowed ICEV production to scale effectively and adapt to market demands with relative ease. In contrast, the nascent EV supply chain is still grappling with challenges previously mentioned.

In summary, the supply chain for ICEVs has been characterized by its relative simplicity and stability, driven by the widespread availability of resources and the industry's long history of refinement. This contrasts sharply with the supply chain for EVs, which is marked by its reliance on a narrow range of scarce and geographically concentrated materials, introducing significant vulnerabilities. The maturity of the ICEV supply chain has provided automakers with a stable foundation for decades, but as the transition to electrified mobility accelerates, addressing the complexities of the EV supply chain will be critical for ensuring a sustainable and resilient automotive future. Below a graphical representation (by Alamy) of the world raw material mining distribution for the realization of batteries.



It is clearly visible that Europe is almost without resources or processes for the mining and raw materials extraction.

It is really important understand the future developments in this field and the possible solutions: The future of the EV supply chain in Europe is deeply influenced by the growing demand for sustainable mobility and the need to ensure greater resilience and sustainability. Addressing these issues requires a strategic vision that integrates innovation, diversification, and collaboration. As explained before, one of the main issues is the increasing demand for essential raw materials such as lithium, cobalt, nickel, and graphite. According to the International Energy Agency (IEA), Europe's demand for lithium alone is expected to grow more than 18 times by 2040, while cobalt and nickel will also experience significant increases.

To address this situation, a fundamental solution is the diversification of supply sources. Europe is reinforcing partnerships with resource-rich but geopolitically stable countries such as Canada, Australia, and Brazil. These agreements not only ensure more reliable supplies but also help overcome ethical concerns related to cobalt extraction in Congo. Diversification reduces geopolitical risks and promotes a more ethical supply chain. At the same time, Europe is investing in the development of domestic mining projects. Countries like Portugal and Spain have launched initiatives to exploit lithium deposits within their borders, supported by the European Union's Raw Materials Alliance. These projects aim to reduce dependency on imports, but they face significant regulatory and environmental hurdles, including opposition from local communities concerned about the environmental impacts of mining.

Another crucial aspect is the development of a circular economy for EV batteries. By 2040, it is estimated that recycled materials could meet up to 25% of the demand for lithium, cobalt, and nickel in Europe. New recycling technologies, such as hydrometallurgical processes, are improving the efficiency of recovering valuable metals from end-of-life batteries, with recovery rates reaching up to 95%. Additionally, many companies are exploring second-life applications for batteries, such as their use in energy storage systems, extending their lifecycle and reducing the need for new raw materials.

The regionalization of battery production is another step toward making European supply chains more resilient. Currently, global battery production is dominated by Asia, particularly China. However, Europe is seeking to close this gap by building gigafactories in countries like Germany, Poland, and Sweden. The European Union's goal is to produce over 30% of the world's EV batteries by 2030, thereby reducing reliance on Asian imports and decreasing the environmental impact of transporting goods.

Technological innovation is another fundamental pillar for tackling supply chain challenges. New battery chemistries, such as sodium-ion or solid-state batteries, promise to reduce reliance on scarce materials like lithium and cobalt. Sodium-ion batteries, for instance, use more abundant and accessible materials, lowering costs and improving sustainability. Solid-state batteries, on the other hand, offer superior energy densities and increased safety, reducing the quantity of materials required for production. Many European automakers are also adopting vertically integrated models, investing directly in extraction and production operations. Tesla has demonstrated the value of controlling multiple stages of the supply chain, reducing costs and ensuring greater stability. Companies like Volkswagen and Stellantis are following this example by creating joint ventures for battery production and signing long-term contracts with raw material suppliers. Finally, collaboration between automakers and governments is essential to address structural challenges in the supply chain. Initiatives such as the European Green Deal and the Raw Materials Alliance provide a regulatory framework and strategic funding to support the development of infrastructure, sustainable technologies, and ethical sourcing policies. Additionally, the use of digital technologies such as blockchain can improve transparency along the supply chain, ensuring compliance with environmental and social standards.

In conclusion, the future of the EV supply chain in Europe depends on the ability to adopt innovative solutions through source diversification, circular models, investments in emerging technologies, and strategic collaboration. Europe can build a resilient and sustainable supply chain, consolidating its role in the market.

3.3 Battery Manufacturing

Battery manufacturing represents a key element for the entire sector, not only due to its technical importance but also for its impact on costs, innovation, and the overall competitiveness of the final product. Batteries in fact require complex production processes and a strategic approach to resource management. Faced with this challenge, automakers must decide whether to internalize battery production through vertical integration or rely on external suppliers via outsourcing strategies. This strategic decision is not only about economic optimization but also addresses the need to ensure production stability, mitigate vulnerabilities linked to the supply of raw materials, and reduce dependency on external markets as analyzed before. Moreover, the rapid development of emerging technologies and the construction of gigafactories are pushing companies to reconsider their role within the value chain.

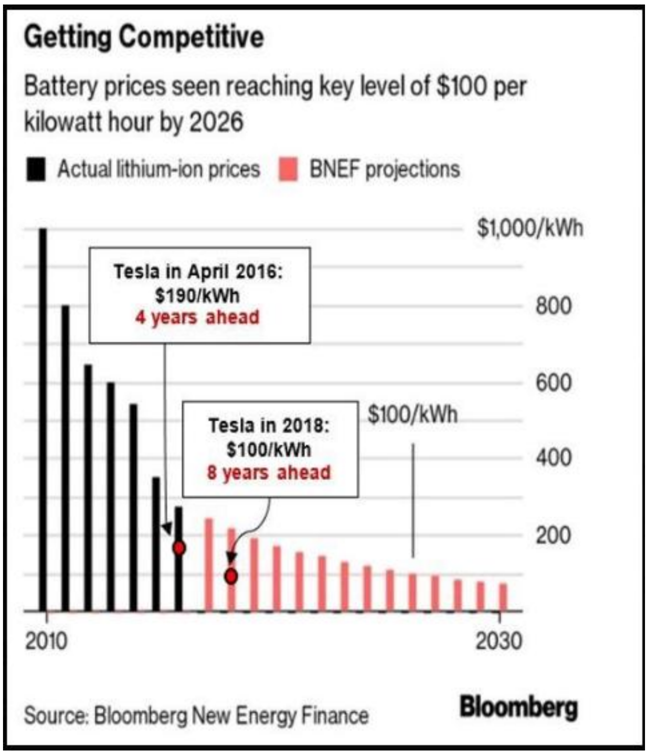
This part will analyze the dynamics of battery manufacturing for electric vehicles, examining how major European automakers are tackling this critical phase. The discussion will explore the implications of vertical integration and outsourcing, assessing the advantages, challenges, and hybrid solutions emerging as strategic responses to balance control, innovation, and flexibility in an industrial context that is rapidly evolving.

Now let’s explain and describe the choice of vertical integration:

Vertical integration in battery manufacturing is a strategic choice that offers automakers the opportunity to gain greater control over one of the most critical components of electric vehicles. This approach involves internalizing various stages of the battery production process, including raw material sourcing, cell manufacturing, and battery pack assembly. Leading automakers such as Tesla, Volkswagen, and BYD have adopted this strategy to secure competitive advantages.
Tesla, for example, has established Gigafactories that enable it to innovate independently, such as developing its advanced 4680 battery cells, which promise higher energy density and lower costs. Similarly, Volkswagen, through its subsidiary PowerCo, is investing heavily in gigafactories across Europe to reduce costs and meet production targets, while BYD exemplifies the benefits of full integration by producing vehicles and batteries in-house, ensuring stability and reducing costs.

V.I. offers automakers several distinct advantages, but it also comes with a series of complex challenges that require careful consideration. One of the primary benefits of vertical integration is the ability to control costs. By internalizing the production process, companies eliminate the profit margins added by external suppliers, allowing for a more streamlined and cost-efficient manufacturing operation. Tesla have demonstrated how this approach can result in significant cost reductions, especially when combined with economies of scale achieved through large-scale facilities like Gigafactories: a 2018 analysis by UBS revealed that Tesla's battery cells cost $111 per kWh, approximately 20% less than LG Chem's $148 per kWh. Further research by Cairn ERA indicated that Tesla pays an average of $142 per kWh for battery cells from suppliers like Panasonic, LG Chem, and CATL, while General Motors pays $169 per kWh, and the industry average is around $186 per kWh.

The following graph represents the reduction of Tesla’s battery prices over the years due to its strategy:



Another significant advantage is the capacity for innovation and customization. This strategy allows automakers to develop proprietary technologies tailored specifically to their vehicle designs, fostering competitive differentiation. Tesla's 4680 battery cells, for example, are a result of its integrated research and manufacturing capabilities. Furthermore, vertical integration enhances supply chain resilience by reducing dependence on external suppliers. Additionally, it supports sustainability goals, as it enables companies to implement environmentally friendly practices throughout the production process, aligning with strict regulatory standards, particularly in Europe.

Despite these advantages, VI is not without its challenges. One of the most significant drawbacks is the high initial capital investment required to establish production facilities. Constructing gigafactories, such as those developed by Tesla or Volkswagen, demands billions of euros in infrastructure, equipment, and training costs. These investments may be prohibitive for smaller manufacturers or those without substantial financial reserves. Moreover, the technological complexity of battery production adds another layer of difficulty. Expertise in materials science, chemical engineering, and precision manufacturing is critical to ensuring high-quality outputs, and acquiring or developing this knowledge can be a slow and costly process. Operational risks also play a major role in the drawbacks of vertical integration. Running large-scale battery production facilities introduces challenges in maintaining quality control and operational efficiency. Even minor inefficiencies or defects can result in significant financial losses or reputational damage. Additionally, automakers that manage their own battery production are directly exposed to the volatility of raw material markets. Fluctuations in the prices of critical inputs can have a direct and immediate impact on production costs, making it difficult to maintain stable pricing models. These advantages and disadvantages illustrate that while V.I. can offer long-term benefits, such as innovation, cost control, and supply chain stability, it is a strategy that demands significant resources and expertise. Automakers must carefully assess their financial and technological capabilities before committing to this approach. For industry leaders like Tesla and Volkswagen, vertical integration has proven to be a viable strategy, but for smaller manufacturers, the risks may outweigh the potential benefits, making outsourcing or hybrid models more suitable alternatives. This balance between control and flexibility defines the ongoing strategic decisions in the rapidly evolving landscape of electric vehicle manufacturing.

On the other hand, relying on external suppliers for battery manufacturing is a strategic choice that offers automakers a range of advantages, particularly in terms of cost efficiency, scalability, and access to specialized expertise. By outsourcing battery production to established suppliers, automakers can focus their resources on core competencies such as vehicle design, assembly, and marketing, without bearing the substantial financial and operational burdens associated with setting up and running large-scale battery production facilities. Suppliers like CATL, LG Chem, Panasonic, and Samsung SDI dominate the global battery market, providing economies of scale and cutting-edge technologies that would be challenging and costly for automakers to replicate in-house. One of the primary benefits of outsourcing is the significant reduction in initial capital investment. Building and equipping gigafactories for battery production requires billions of euros, alongside ongoing costs for research, development, and skilled labor. By leveraging external suppliers, automakers can avoid these high upfront expenses while still securing access to high-quality batteries. Furthermore, outsourcing allows automakers to tap into the technical expertise of specialized suppliers who have extensive experience in battery chemistry, materials science, and manufacturing processes. This collaboration often results in faster innovation cycles, as suppliers are constantly investing in research and development to maintain their competitive edge.

This strategy also provides greater flexibility in responding to market fluctuations and changes in demand. Automakers can scale battery orders up or down based on production needs without the fixed costs and operational constraints associated with owning and operating battery production facilities. For instance, companies like BMW and Mercedes-Benz have successfully partnered with suppliers such as CATL and Samsung SDI, ensuring a steady supply of advanced batteries while maintaining the ability to adjust to evolving market conditions. However, reliance on external suppliers also has its issues. One of the most significant risks is the lack of control over the supply chain. Automakers are dependent on their suppliers to deliver batteries on time and at the agreed-upon quality standards. Disruptions in the supplier's operations (whether due to geopolitical tensions, material shortages, or production issues) can have a direct impact on the automaker's ability to meet production targets. This dependency became particularly evident during the COVID-19 pandemic and subsequent supply chain disruptions, which highlighted the vulnerabilities of globalized supply networks. Another drawback is the potential for higher long-term costs. While outsourcing reduces initial capital expenditures, the per-unit cost of batteries may include supplier markups, eroding cost competitiveness over time. Additionally, as the demand for EVs grows, competition for battery supplies is intensifying, potentially leading to price increases and supply constraints. Automakers that rely heavily on external suppliers may find themselves at a disadvantage compared to vertically integrated competitors who have more direct control over their production; in fact, outsourcing limits the ability of automakers to innovate independently in battery technology. By outsourcing, they may miss opportunities to develop proprietary technologies that could differentiate their products in a competitive market. For instance, while companies like Tesla and BYD are able to tailor their battery designs to specific vehicle models, automakers relying on external suppliers often receive standardized products, which may not fully align with their innovative goals. In summary, relying on suppliers offers companies significant advantages in terms of cost reduction, flexibility, and access to specialized expertise. However, it also its risks as supply chain dependency, potential cost escalations, and limited opportunities for innovation. For automakers with constrained resources or those focused on optimizing their existing operations, outsourcing remains a viable and often necessary strategy. However, as the EV market grows more competitive, companies must weigh these trade-offs carefully, considering whether the long-term benefits of outsourcing align with their broader strategic objectives.

Another crucial factor to consider when evaluating the choice between vertical integration and outsourcing is the role of economies of scale. A 2021 study by Schnell et al. ("Technical economies of scale in lithium-ion battery manufacturing: a process-based cost modeling approach to the minimum efficient scale of production") provides an in-depth analysis of this concept in the context of battery cell manufacturing, aiming to identify the minimum efficient scale required to achieve economically sustainable production in the long term. Although based on an advanced process cost model, the study offers valuable insights for industry players, particularly regarding investment strategies and plant development. Among the key findings, the study highlights that the minimum plant size needed for efficient production is steadily increasing. While today's threshold stands at approximately 1.8 GWh/year for state-of-the-art technologies, this figure is expected to exceed 15 GWh/year in the near future, driven by advancements in materials and manufacturing processes. This growth is primarily associated with increased capacity in roll-to-roll processes used for electrode production, which are identified as the main bottleneck in the manufacturing chain.

This trend has two major implications for the industry:

- **Reduced investment per GWh**: The adoption of advanced materials and optimized processes (such as thicker electrodes and higher roll-to-roll speeds) can significantly lower production costs per GWh, with potential reductions of up to 36% compared to current plants.
- **Increased total investment per plant**: To reach the new minimum efficient scale, companies will have to undertake much larger investments (up to +440%) raising entry barriers for new players and reinforcing market concentration.

In light of these dynamics, the study suggests that:

- **Established firms** must accelerate the industrialization of innovative technologies to maintain a competitive edge.
- **New entrants and smaller players** should seek strategic partnerships with OEMs or institutional investors to share risks and gain access to adequately scaled production facilities.
- **Industrial alliances and joint ventures** will become increasingly important to optimize capacity, lower costs, and stabilize supply chains.

Finally, reducing battery costs through economies of scale is a key lever in enabling a self-sustaining electric vehicle market one that is less dependent on government incentives and more economically viable in the long run.

Below there is an overview of the main players involved in supplying batteries to European automakers.

CATL (Contemporary Amperex Technology Co. Limited)

CATL, headquartered in Ningde, China, is the largest global producer of batteries for electric vehicles. The company leads in the production of lithium-ion and LFP (lithium iron phosphate) batteries, known for their safety and cost competitiveness. With its scale and production capacity, CATL offers economies of scale, making it the primary supplier for several European automakers, including BMW, Mercedes-Benz, and Volkswagen. CATL has also invested in localizing production in Europe, with a facility in Germany designed to meet the growing needs of the European market. The company is renowned for innovation, exemplified by its "Qilin" battery, which offers higher energy density and faster charging times.

LG Energy solutions

Headquartered in Seoul, South Korea, LG Energy Solution is one of the leading players in the lithium-ion battery industry, with a strong presence in the European market. Specializing in pouch and cylindrical cells, LG supplies batteries to manufacturers like Volkswagen, Renault, and Volvo. The company has invested in a large-scale facility in Poland, one of the largest in Europe, to ensure rapid delivery and reduce logistics costs. LG Energy Solution stands out for its robust research and development capabilities, focusing on high-performance batteries designed for premium EV models. The company collaborates closely with its customers to develop tailored solutions that enhance battery efficiency and longevity.

Panasonic

Panasonic, based in Osaka, Japan, is one of the longest-standing and most respected players in the lithium-ion battery industry. The company is best known for its partnership with Tesla, co-establishing Gigafactories in Nevada and other locations. While its primary collaboration is with Tesla, Panasonic also supplies batteries to select European automakers for premium applications, leveraging its expertise in high-energy-density cylindrical cells. Known for reliability and quality, Panasonic continues to push advancements in battery technology to maximize performance and safety.

Samsung SDI

Samsung SDI, part of the Samsung conglomerate, is headquartered in Seoul, South Korea, and is a key player in the lithium-ion battery market. The company produces high-performance prismatic and cylindrical cells, valued for their efficiency and safety. Samsung SDI supplies batteries to brands such as BMW, Audi, and Stellantis and has invested in a facility in Hungary to better serve the European market. The company excels in providing high-performance and energy-efficient batteries with a strong emphasis on safety features. Its strategic European presence makes it a trusted supplier for premium and luxury vehicle segments.

BYD (Build your dreams)

BYD, headquartered in Shenzhen, China, is both an electric vehicle manufacturer and a battery supplier, making it one of the few fully vertically integrated companies in the sector. The company is known for its Blade Battery, an LFP solution, praised for its superior safety and durability. While BYD primarily uses its batteries for its own vehicles, it is expanding its supply business to other automakers, particularly for buses and commercial vehicles in Europe. Its ability to combine innovation with cost-effective production makes it an attractive partner for European manufacturers seeking competitive alternatives.

Northvolt

Northvolt, based in Stockholm, Sweden, an emerging player focused on the sustainable production of lithium-ion batteries. Founded to reduce Europe's reliance on Asian suppliers, Northvolt used renewable energy to power its production facilities, ensuring a lower environmental footprint. The company collaborated with manufacturers such as Volkswagen, BMW, and Volvo and was building gigafactories in Sweden and Germany to strengthen European production capacity. The European player has recently faced a series of significant financial difficulties. In September 2024, the company announced the layoff of 1,600 employees (around 20% of its total workforce) and the suspension of expansion plans for its main plant in Skelleftea, due to weaker-than-expected demand and increasing competition in the battery sector. In November 2024, Northvolt filed for Chapter 11 bankruptcy protection in the United States, reporting debts amounting to approximately $5.8 billion and cash reserves of only $30 million. At the same time, co-founder and CEO Peter Carlsson resigned, highlighting the need for at least $1 billion to ensure the company's operational continuity. Finally, on March 12, 2025, Northvolt declared bankruptcy in Sweden, marking the end of what had once been considered one of Europe's most promising ventures in the global electric vehicle battery market.

SK On

SK On, a division of the South Korean conglomerate SK Group, is a rapidly growing battery supplier specializing in high-performance lithium-ion batteries with a focus on energy density and longevity. The company supplies batteries to Hyundai and Ford and is expanding its European footprint to attract more local customers. SK On's ability to develop innovative battery chemistries and scalable production solutions positions it as a key player in meeting the needs of next-generation electric vehicles.

Envision AESC

Envision AESC, headquartered in Yokohama, Japan, is a global producer in lithium-ion battery with a strong commitment to sustainability. The company supplies batteries to Nissan and other European automakers, with production facilities in the UK and France. Envision AESC is recognized for its focus on quality and reducing environmental impact through optimized manufacturing processes and innovative materials. With its extensive industry experience, Envision AESC remains a trusted supplier for the European market.

The EV battery market is highly competitive regarding battery supply, with a few key players dominating the landscape. Each supplier brings unique strengths and challenges, shaping their position in this critical sector. Comparing CATL, LG Energy Solution, Panasonic, Samsung SDI, BYD, and Northvolt reveals distinct approaches to cost, innovation, production capacity, and alignment with the needs of European automakers.

CATL stands out as the largest global battery manufacturer, leveraging its scale to achieve unmatched cost efficiencies. With costs consistently under **$100 per kWh**, CATL is a leader in affordability, making it an attractive partner for mass-market EV production. Its investment in European production, including a facility in Germany, strengthens its local presence and reduces logistical complexities. However, its focus on LFP technology, while cost-effective, may limit its appeal for premium automakers seeking higher energy density solutions.

LG Energy Solution, on the other hand, excels in supplying high-performance batteries tailored for premium vehicles. Its pouch and cylindrical cell technologies are popular among European brands like Renault and Volvo, ensuring strong relationships with high-end automakers. With an estimated cost of **$130-$140 per kWh**, LG balances quality with competitive pricing. Its strategic location in Poland provides logistical advantages, yet its slightly higher costs compared to CATL limit its mass-market competitiveness.

Panasonic, known primarily for its partnership with Tesla, remains a benchmark for premium battery technology. Its cylindrical cells offer superior energy density, making them ideal for luxury EVs. However, Panasonic’s focus outside Europe and its reliance on Tesla constrain its broader market influence. With costs around **$150 per kWh**, Panasonic is less competitive for automakers prioritizing cost efficiency over performance.

Samsung SDI occupies a middle ground, serving premium brands like BMW and Audi with high-quality prismatic and cylindrical batteries. Its Hungarian plant enhances its European operations, but its smaller scale compared to CATL and LG Energy Solution affects its pricing power. Costs ranging from **$140-$150 per kWh** position Samsung SDI as a strong contender for premium segments but less so for cost-sensitive markets.

BYD is a unique case, combining vehicle manufacturing with battery production to achieve remarkable efficiency. Its Blade Battery, based on LFP chemistry, is celebrated for safety and longevity. With costs as low as **$95-$110 per kWh**, BYD is highly competitive. However, its limited supply to external automakers and primary focus on its own vehicles restrict its broader impact on the European market.

Northvolt, was the only European supplier among the key players, focuses on sustainability and localized production. While its costs were higher, estimated at **$150-$180 per kWh**, it appealed to automakers like Volkswagen and Volvo, who value environmental responsibility and alignment with European regulatory goals. As it scaled its production, It had the potential to become a significant competitor, but a bad management related to the sales forecasts and the strength of competitors conducted this company to bankruptcy.

Considering all factors, CATL emerges as the most competitive supplier overall, particularly for automakers targeting affordability and scalability. Its unmatched production volume, aggressive pricing, and commitment to European infrastructure make it a clear leader in the mass-market segment. For premium automakers, however, LG Energy Solution and Samsung SDI provide the best balance of performance and quality, offering advanced technologies tailored to high-end vehicles. Ultimately, the choice of the “best” supplier depends on an automaker’s strategic priorities, whether they lean toward cost leadership, technological innovation, or sustainability. However, in the current landscape, CATL's combination of scale, cost efficiency, and local investments positions it as the most versatile and dominant supplier in the European EV market.

3.4 Technological Innovation along the Electric Vehicle Value Chain

Technological innovation is the driving force behind the transformation of the EV industry, influencing every stage of the value chain. From the extraction of raw materials to battery production, from motor design to recycling and material reuse, technological progress has revolutionized this rapidly growing market. In a context where EVs represent not only a response to increasing environmental concerns but also an economic and industrial challenge, innovations along the value chain play a crucial role in reducing costs, improving performance, and ensuring sustainability. A central aspect of this transformation lies again in batteries, as already examined, the technological core of electric vehicles. In recent years, battery-related technologies have undergone significant evolution, with the introduction of new chemistries, such as solid-state and sodium-ion batteries, which promise greater energy density and lower costs. In parallel, BMS are becoming increasingly advanced, ensuring higher efficiency and operational safety. But innovation is not limited to batteries: electric motors are also evolving, with a focus on reducing weight, improving energy efficiency, and decreasing reliance on rare materials. Another cornerstone of technological advancement is charging infrastructure, which is critical to accelerating EV adoption. The proliferation of rapid and wireless charging stations, along with the integration of Vehicle-to-Grid (V2G) technologies, is redefining how vehicles interact with the energy system. These innovations not only reduce charging times but also create new opportunities to optimize energy resource usage. Innovation also extends to the production phase, where the adoption of smart manufacturing technologies, advanced automation, and digital twins is transforming traditional factories into more efficient and flexible production ecosystems. These advancements not only cut costs and production times but also enhance the overall quality of the product.

Finally, the focus on sustainability has led to new solutions for battery recycling and material reuse, making the lifecycle of electric vehicles more circular. Advanced technologies for recovering critical materials and second-life applications for batteries are helping to reduce environmental impact and dependence on new resources. This section will explore these key areas of technological innovation, analyzing how they are redefining the electric vehicle value chain in Europe. The aim is to understand how these advancements are consolidating the competitiveness of the European industry, addressing market and environmental challenges, and paving the way for a more sustainable future.

Battery Management Systems (BMS): The Brain of Electric Vehicle Batteries

The history of Battery Management Systems (BMS) is closely intertwined with the evolution of battery technology, reflecting the growing need to manage and optimize the increasingly complex demands of modern energy storage systems. Initially, batteries were relatively simple devices used in basic applications, and their management relied on manual monitoring or basic circuit designs. However, as rechargeable battery technologies advanced, particularly with the introduction of lithium-ion batteries, the need for sophisticated systems to regulate and protect these energy sources became evident. The concept of battery management began gaining traction in the late 20th century with the rise of industrial applications using lead-acid and nickel-cadmium batteries. During this period, early BMS designs were rudimentary, focusing on basic monitoring of charge levels and providing minimal protection against overcharging or overheating. These systems were sufficient for stationary applications but lacked the complexity to handle more dynamic use cases, such as those in portable electronics or electric vehicles. In the 1990s, the introduction of lithium-ion batteries revolutionized the energy storage industry. While lithium-ion offered significantly higher energy density and lighter weight compared to earlier chemistries, it also introduced new challenges. Lithium-ion batteries are highly sensitive to temperature, voltage fluctuations, and overcharging, which can lead to reduced lifespan, safety risks, or catastrophic failures such as thermal runaway. To address these issues, manufacturers began developing more advanced BMS technologies. Initially, these systems were designed for consumer electronics, such as laptops and mobile phones, where compact and efficient battery management was critical. The growing demand for reliable, long-lasting batteries in these devices accelerated innovations in cell monitoring, thermal regulation, and charge control.

The early 2000s marked a crucial step for BMS development with the rise of hybrid and fully electric vehicles. Automakers quickly recognized that the success of electric mobility depended on the ability to manage large, multi-cell battery packs effectively. Unlike single-cell batteries in consumer devices, EV batteries consist of hundreds or even thousands of interconnected cells, each requiring precise monitoring and regulation. Early adopters, such as Tesla, invested heavily in BMS technology to maximize range, improve safety, and ensure reliability. Tesla's innovative approach to battery management, including over-the-air updates to optimize BMS performance, set a benchmark for the industry and demonstrated the critical role of this technology in making EVs viable for the mass market. As the EV industry grew throughout the 2010s, BMS systems became more sophisticated, incorporating features like cell balancing, predictive maintenance, and real-time communication with vehicle control systems. Advances in artificial intelligence and machine learning further enhanced the capabilities of BMS, allowing for adaptive management based on usage patterns and environmental conditions. These innovations not only improved battery performance but also reduced costs by extending battery lifespans and minimizing the risk of failure.

In recent years, the role of these systems has expanded beyond ensuring safety and efficiency to support broader energy management objectives. For example, modern BMS systems facilitate integration with Vehicle-to-Grid (V2G) technologies, enabling EV batteries to store surplus renewable energy or supply electricity back to the grid during peak demand. This dual functionality positions EVs as a critical component of future smart energy networks. Additionally, the push toward sustainability has driven the development of these technologies that track battery usage across their lifecycle, aiding in recycling and second-life applications for spent batteries. Today, BMS technology continues to evolve, adapting to emerging battery chemistries such as solid-state and sodium-ion batteries, which require different management strategies. As the world accelerates its transition to renewable energy and electric mobility, the BMS remains at the heart of this transformation, ensuring that batteries are not only safer and more efficient but also better aligned with the environmental and economic goals of the future. Performance optimization is another critical role of the BMS. By balancing the energy output of individual cells, the system ensures uniformity within the battery pack. This balancing act maximizes energy usage and contributes to longer driving ranges, a key factor for EV consumer adoption. Additionally, the BMS manages the state of charge (SOC) and state of health (SOH) of the battery, providing real-time data to drivers and optimizing charging and discharging cycles to extend battery lifespan.

Despite these advancements, challenges remain. The increasing complexity of EV batteries, with higher energy densities and multi-cell configurations, places significant demands on BMS design and performance. Ensuring precise cell monitoring and effective thermal management across larger packs require continuous innovation. Furthermore, cybersecurity has become a growing concern, as the integration of connected technologies makes BMS systems vulnerable to potential hacking or data breaches. The choice between outsourcing BMS development or producing it in-house is shaped by an automaker’s strategic goals and available resources. Established suppliers like Texas Instruments and Analog Devices offer reliable and scalable solutions, enabling manufacturers to concentrate on other aspects of electric vehicle production. On the other hand, automakers with significant research and development capabilities, such as Tesla and Volkswagen, view BMS as a critical area where they can innovate and achieve a competitive edge. Developing BMS internally gives automakers the flexibility to innovate more rapidly, customize systems to fit their specific platforms, and maintain control over valuable intellectual property. Outsourcing, however, allows manufacturers to benefit from the specialized expertise and economies of scale of established suppliers, often resulting in lower costs and faster implementation. Ultimately, both approaches have their strengths, and the decision reflects each automaker's overall strategy for innovation and integration in the EV industry. For companies that prioritize customization and control, in-house development is becoming an increasingly popular choice. Meanwhile, others continue to collaborate with trusted suppliers, relying on their proven capabilities to deliver cost-effective and dependable BMS solutions.

V2G technologies

Before going deeper into V2G technology, it is essential to examine the current state of the electricity grid used to power EVs. With the increasing adoption of EVs, the electricity grid has taken on a central role in the transition to sustainable mobility. Originally designed to meet traditional consumption demands (residential, commercial, and industrial), the grid now faces a growing need to accommodate EV charging, a challenge that requires significant infrastructure upgrades and new management strategies.

The widespread adoption of EVs has led to a substantial increase in electricity demand, particularly during peak hours. Charging a vehicle can draw between 50 kW and 350 kW of energy per session. In some European regions where EV penetration is high, this additional demand is putting pressure on existing grid infrastructure, especially in areas where renewable energy sources dominate the energy mix. One of the primary obstacles is the uneven development of charging infrastructure. Urban areas and major highways benefit from a greater number of charging stations, while rural or remote regions often lack adequate facilities, creating "charging deserts." This disparity limits EV accessibility for many potential users. Furthermore, the type of charging infrastructure varies widely (from slow Level 2 chargers to ultra-fast DC chargers) impacting the grid's ability to efficiently handle peak loads.
Additionally, a significant portion of the electricity used for EV charging comes from renewable

energy sources, particularly in Europe, where policies strongly promote the use of solar and wind energy. While this reduces the carbon footprint of EV charging, it presents challenges due to the intermittent nature of renewables. For example, solar energy production peaks during the day, while most vehicles are charged at night, leading to a mismatch between energy availability and demand. To address these issues, smart grids, which leverage digital technologies to monitor and manage energy flow, are becoming essential for integrating EVs into the electricity system. These grids enable energy providers to track consumption in real time, predict demand patterns, and optimize electricity distribution. Furthermore, smart grids facilitate innovative solutions like V2G technology, which allows vehicles to store energy and return it to the grid during times of high demand.

As EV adoption accelerates, the modernization of the electricity grid and the integration of smart technologies will be crucial in ensuring a reliable and efficient energy supply, pushing the way for a sustainable future in mobility.

How V2G Supports the Electric Grid

- **Optimizing Renewable Energy Use**
  One of the main challenges of renewable energy sources like solar and wind is their variability. V2G provides a solution to this intermittency: when renewable energy production exceeds demand, EVs can store the excess energy. This stored energy can then be supplied back to the grid during periods of low renewable production, improving the integration of renewables into the energy mix.
- **Cost Reduction for Users and Grid Operators**
  For EV owners, V2G can become a source of income. Vehicle owners can sell the energy stored in their batteries during high-demand periods, earning credit or financial compensation. For grid operators, using EVs as distributed energy sources helps avoid costly investments in new infrastructure to handle peak loads.
- **Enhancing Grid Resilience**
  V2G enhances the resilience of the electric grid by decentralizing energy distribution. In the event of outages or blackouts, vehicles can supply local power, ensuring continuity for

homes, businesses, or entire communities. This feature is particularly useful in vulnerable areas or during extreme weather events.

Technological Evolution and Challenges of V2G

While V2G holds significant promise, several technical and operational challenges need to be addressed for full implementation:

- Battery Wear: Feeding energy back into the grid involves additional charge and discharge cycles, which can accelerate battery degradation. However, advancements in battery management systems are already mitigating these effects.
- Standardization and Infrastructure: V2G requires compatible bidirectional chargers and global standardization to ensure interoperability between vehicles, grids, and energy providers.
- User Awareness and Acceptance: Many EV owners are still unaware of V2G's benefits or are concerned about its impact on battery longevity. Financial incentives and educational campaigns will be key to encouraging adoption.

The Impact of V2G on the Future Grid

This technology not only addresses challenges related to EV charging and grid management but also serves as a cornerstone for creating a smarter, more sustainable, and resilient energy system. It is one of the most promising innovations in the field of electric mobility and energy management. However, despite its revolutionary potential, its adoption is currently limited to pilot projects and experimental initiatives, primarily concentrated in countries at the forefront of the energy transition, such as Denmark, the United Kingdom, Japan, and certain states in the United States. These projects demonstrate V2G's effectiveness in balancing energy supply and demand, better integrating renewable sources, and improving grid resilience, but large-scale implementation remains a future goal.

Currently, the penetration of V2G technology is hindered by several challenges. The lack of bidirectional charging infrastructure, the still high costs of compatible chargers, the absence of harmonized regulations, and limited public awareness are among the main obstacles. While some automakers, such as Nissan, have integrated V2G functionalities into their vehicles, the number of electric cars equipped for this technology represents only a small fraction of the global EV fleet. Looking to the future, projections indicate that V2G could become a standard technology within the next 10-15 years, driven by several key factors. First, technological advancements and the increased production of bidirectional chargers will lead to significant cost reductions, making V2G more accessible for both consumers and energy providers. Second, government policies will play a crucial role in promoting adoption through financial incentives, clear regulations, and investments in infrastructure. Finally, the growing adoption of electric vehicles will serve as a natural catalyst, increasing the number of potential participants in the V2G system.

The timeline for widespread V2G adoption also depends on the ability of electricity grids to adapt to this technology. The transition to more advanced smart grids, equipped with real-time monitoring and management systems, will be essential to integrate millions of electric vehicles as distributed energy resources. Additionally, public education will be critical: many EV owners are still unaware of V2G's benefits, both economically and environmentally. Financial incentives and awareness campaigns could accelerate consumer acceptance of this technology. In the long term, V2G has the potential to radically transform energy management. By 2040, it is estimated that a global fleet of V2G-enabled electric vehicles could provide between 20 and 30 TWh of energy to the grid, reducing the need to build new power plants and significantly improving the efficiency of renewable energy use. Consumers could earn between €500 and €1,000 annually by selling energy back to the grid, while carbon emissions would be further reduced thanks to smarter and more sustainable energy utilization. In conclusion, V2G technology has the potential to revolutionize the global energy system, but its widespread adoption requires a coordinated approach among governments, industries, and consumers. With the right investments, technological innovations, and targeted policies, V2G could become an essential component of a more resilient, sustainable, and future-ready electricity grid.

Technological Innovation in Electric Vehicle Production: Smart Manufacturing and Digital Twin

Beyond the innovations in battery management and the electric grid, technological development is also fundamental in the production of vehicles. The automotive industry is undergoing an unprecedented transformation, driven by the growing adoption of EVs. At the heart of this revolution lies technological innovation in production, which is redefining traditional industrial processes through the adoption of cutting-edge solutions such as smart manufacturing, advanced automation, and digital twin technology. These innovations not only enhance production efficiency but also help reduce costs, shorten production times, and ensure increasingly high-quality standards. The transition to digital and automated technologies enables automakers to adapt rapidly to the demands of a constantly evolving market while maintaining a focus on sustainability and competitiveness.

The integration of tools such as the Internet of Things (IoT), artificial intelligence (AI), and digital simulations has transformed traditional factories into interconnected production ecosystems capable of responding flexibly to demand fluctuations and optimizing resource use. In this part, the thesis will analyze in detail the main technologies shaping the future of electric vehicle production. We will explore how smart manufacturing enables real-time control of production lines, how advanced automation improves precision and efficiency, and how the digital twin stands out as one of the most promising innovations for simulating and optimizing production processes. Together, these tools not only make the creation of more accessible and sustainable electric vehicles possible but also redefine the role of the automotive industry in the era of electric mobility.

Smart manufacturing: a Revolution in production processes

Smart manufacturing represents a fundamental evolution in modern industry, integrating advanced digital technologies to improve the efficiency, flexibility, and sustainability of production processes. Numerous articles, including the following:

- *Kang, H.S., Lee, J.Y., Choi, S.S., Kim, H., Park, J.H., Son, J.Y., Kim, B.H. e Noh, S.D. (2016) 'Smart Manufacturing: Past Research, Present Findings, and Future Directions'*
- *Mittal, S., Khan, M.A. e Wuest, T. (2016) 'Smart Manufacturing: Characteristics and Technologies', in Rivest, L., Bouras, A. e Louhichi*
- *Zhang, Y., Ren, S., Liu, Y. e Si, S. (2017) 'Smart Manufacturing and Intelligent Manufacturing: A Comparative Review', Engineering*

highlight the key characteristics and applications of this innovation, analyzing how it is transforming the global industrial landscape.

According to a review in *“Smart Manufacturing: Past Research, Present Findings, and Future Directions”*, the roots of smart manufacturing lie in the convergence of traditional automation and emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics. These tools enable factories to operate more intelligently by collecting and analyzing real-time data to optimize production and reduce waste.

The Core Technologies of Smart Manufacturing

Internet of Things: The Backbone of Smart Factories

The Internet of Things connects machines, sensors, and devices across the production floor, creating a real-time network of interconnected systems. This connectivity allows manufacturers to gather vast amounts of data, providing unprecedented visibility into operations. IoT systems enable continuous monitoring and real-time feedback, which improves both efficiency and product quality. In Germany, Siemens has pioneered the use of IoT in its factories, particularly in the electronics sector. Through its "Digital Enterprise" initiative, Siemens has deployed IoT-enabled systems that allow its factories to achieve near-zero downtime by predicting equipment failures before they happen. This predictive maintenance capability has resulted in significant cost savings and productivity improvements. In the automotive sector, Volkswagen has integrated IoT technology into its production facilities as part of its Industry 4.0 strategy. The company’s smart factories use IoT sensors to monitor every stage of vehicle assembly, ensuring precision and reducing waste.

Artificial Intelligence: Enhancing Decision-Making and Automation

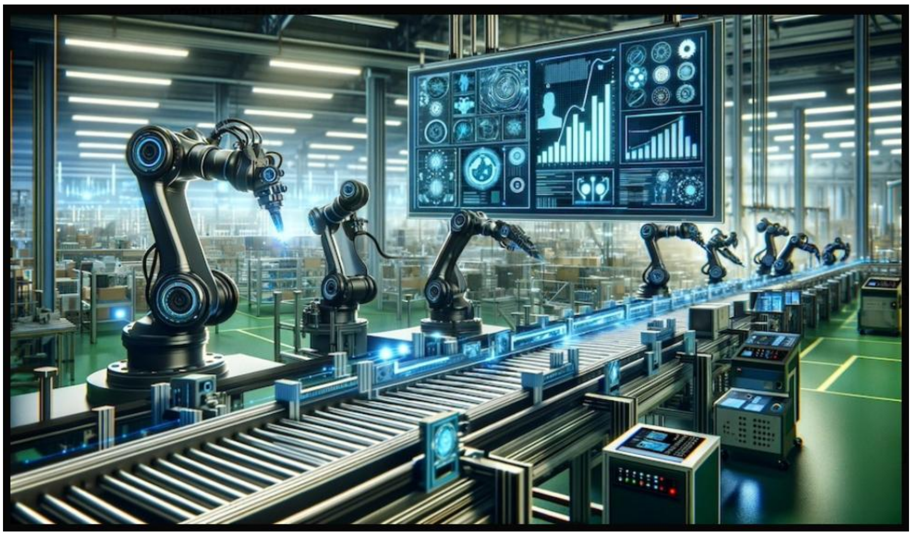
Artificial intelligence is a cornerstone of smart manufacturing, enabling advanced automation and data-driven decision-making. AI-driven systems can learn from historical data, identify patterns, and make real-time adjustments to optimize production processes.

AI applications in smart manufacturing include:

- **Automated quality control**: AI-powered vision systems inspect products for defects at speeds and accuracies beyond human capability.

- **Process optimization**: Machine learning algorithms continuously adjust production parameters to improve efficiency and reduce energy consumption.
- **Demand forecasting**: AI models analyze market trends and customer behavior to predict demand, helping manufacturers avoid overproduction.

French aerospace manufacturer Airbus uses AI to improve quality control in aircraft assembly. Through machine learning algorithms, Airbus can detect micro-defects in components that would be difficult for human inspectors to identify, ensuring higher safety standards in its aircraft. Similarly, Renault employs AI in its assembly lines to optimize the welding process of car bodies. By analyzing data from thousands of welding points, AI systems adjust welding parameters in real time, ensuring consistent quality across all vehicles.



Big Data Analytics: Turning Data into Actionable Insights

Big data analytics play a crucial role in smart manufacturing by processing and analyzing the enormous volumes of data generated by IoT devices and other sources. This data-driven approach helps manufacturers gain deeper insight into their operations, identify inefficiencies, and implement targeted improvements.

Big data analytics can be used to:

- **Monitor production performance**: Dashboards provide real-time KPIs, enabling managers to track productivity and quickly address any deviations.

- **Optimize supply chains**: Advanced analytics models help manufacturers predict supply chain disruptions and develop contingency plans.
- **Enhance sustainability**: By analyzing energy consumption patterns, manufacturers can implement measures to reduce their environmental footprint.

The integration of these technologies is reshaping traditional factories into highly efficient, flexible, and sustainable ecosystems. By enabling real-time monitoring, predictive maintenance, and advanced decision-making, smart manufacturing addresses the challenges of modern industry, including rising consumer expectations, the need for customization, and environmental sustainability. The combination of IoT, AI, and big data analytics ensures that smart manufacturing not only improves operational efficiency but also creates opportunities for innovation and competitive advantage. As these technologies continue to evolve, they are expected to become even more integral to the future of production, enabling industries to thrive in an increasingly dynamic and demanding global market.

Digital Twin technology

Digital Twin technology is an innovation that creates a virtual replica of a physical object, process, or system, enabling real-time monitoring, simulation, and analysis. Unlike traditional models, a digital twin is a dynamic representation that continuously updates its virtual state based on real-world data collected through sensors and IoT devices. The fundamental concept of this technology is to bridge the physical and digital worlds, allowing for enhanced insights and decision-making capabilities. By using advanced data analytics and machine learning algorithms, digital twins can simulate how a physical asset will behave under different scenarios, helping industries predict failures, optimize performance, and improve efficiency. Originally developed for aerospace applications, DT has expanded into various sectors, including manufacturing, healthcare, energy, and, more recently, the automotive industry. The evolution of this technology has been driven by the convergence of IoT, big data, and artificial intelligence, which together provide the computational power and connectivity required to make real-time digital replicas feasible.

Key components of a digital twin include:

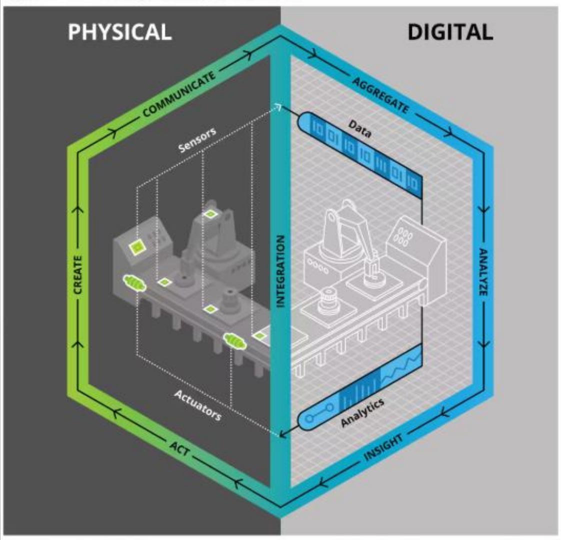
1. **Physical entity**: The real-world object or system being modeled (e.g., a vehicle, a factory, or a production line).
2. **Virtual model**: A detailed, data-driven digital representation of the physical entity.
3. **Data connection**: The integration of real-time data from sensors, IoT devices, and other sources into the virtual model.
4. **Analytics and simulation**: Advanced algorithms and machine learning tools that analyze the data, predict future performance, and offer optimization recommendations.

Digital Twin technology is increasingly being adopted in the automotive sector, where precision, reliability, and innovation are crucial. By creating virtual models of vehicles, production lines, and even individual components, automotive manufacturers can test new designs, optimize production processes, and improve vehicle performance without the costs and risks associated with physical prototypes. One of the key applications in the automotive industry is in vehicle design and testing. Traditional design cycles require multiple iterations of physical prototypes, which are expensive and time-consuming to produce. With this new technology, manufacturers can simulate the behavior of a new design under various conditions, reducing the number of physical prototypes needed. This accelerates the development process and lowers costs.

Predictive maintenance is another significant application. By using DT of production equipment and vehicles, manufacturers can monitor their condition in real time, predict when a failure is likely to occur, and carry out maintenance before a breakdown happens. This reduces downtime and maintenance costs, improving overall efficiency. A notable example in Europe is Rolls-Royce, which employs Digital Twin technology in its manufacturing processes for jet engines and high-performance automotive components. By using real-time data from sensors embedded in physical components, Rolls-Royce can predict maintenance needs, optimize fuel efficiency, and improve the reliability of its engines.

In the context of smart factories, this innovation plays a crucial role in process optimization. As highlighted in “A Comprehensive Review of Digital Twin -- Part 1: Modeling and Twinning Enabling Technologies”, manufacturers such as Volkswagen and BMW have implemented digital twins to simulate entire assembly lines, allowing them to identify bottlenecks, test different configurations, and improve overall productivity without disrupting actual operations. Despite its numerous advantages, the adoption of Digital Twin technology is not without challenges. As noted in *“Digital Twin: State-of-the-Art Review of Its Enabling Technologies”*, one of the primary hurdles is the high cost of implementation, particularly for small and medium-sized enterprises (SMEs). Additionally, the integration of data from various sources requires robust IT infrastructure and advanced data management capabilities. However, with increasing investment in Industry 4.0 technologies and support from government initiatives, such as the European Union’s Horizon Europe program, the barriers to adoption are gradually being lowered. Over the next decade, it is expected that Digital Twin technology will become a standard tool in the automotive industry, driving further innovation and efficiency.

Figure 1. Manufacturing process digital twin model



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Advanced automation

Advanced automation refers to the integration of cutting-edge technologies, such as robotics, AI, and machine learning, into industrial processes to enhance productivity, efficiency, and flexibility. Unlike traditional automation, which relies on predefined rules and static processes, advanced automation systems are capable of learning, adapting, and making decisions in real time based on data-driven insights. Historically, automation has evolved through several phases, starting with simple mechanization during the Industrial Revolution, progressing to programmable logic controllers (PLCs) and robotics in the mid-20th century, and culminating in today's sophisticated smart factories powered by Industry 4.0 technologies. As highlighted in the paper *"Adaptive Automation: Status of Research and Future Challenges"*, early automation systems were rigid and required human intervention for any changes. However, the integration of AI and IoT has enabled the development of adaptive systems that can dynamically adjust their operations to changing conditions.

One of the key advancements in recent years is Robotic Process Automation (RPA), which automates repetitive tasks in administrative and manufacturing environments. While RPA focuses on rule-based processes, advanced automation incorporates AI-driven decision-making, making it suitable for complex and unpredictable tasks.

The core technologies in advanced automation are:

- **Artificial Intelligence and Machine Learning**
  The paper "Integration of Artificial Intelligence and Robotic Process Automation: A Comprehensive Review" discusses how AI enhances RPA by adding cognitive capabilities, such as natural language processing (NLP) and image recognition, making automation more versatile and intelligent.
- **Industrial Robotics**
  Advanced robotics includes both fixed and collaborative robots (cobots) designed to work alongside human operators. These robots are equipped with sensors and AI algorithms that allow them to perform tasks with precision and adapt to changing environments. In Europe, companies like KUKA and ABB have pioneered robotic solutions for various industries, including automotive manufacturing.

- **Adaptive and Flexible Automation Systems**
  Adaptive automation refers to systems that can modify their behavior in real time based on feedback from the environment. This approach is critical in dynamic production environments where conditions can change rapidly. The study "Towards Autonomous Systems: Flexible Modular Production Systems Enhanced with Large Language Model Agents" highlights how AI-driven adaptive systems improve flexibility and reduce downtime in production lines.

Europe has been a leader in adopting advanced automation technologies, driven by the region’s strong emphasis on innovation, quality, and sustainability. The European Union’s Horizon Europe program has allocated significant funding for research and development in advanced automation, aiming to enhance the competitiveness of European industries on a global scale. Several major automotive manufacturers in Europe, including Daimler and Stellantis, have invested heavily in advanced automation technologies to modernize their production facilities and meet the growing demand for electric and autonomous vehicles. By adopting flexible and adaptive automation systems, these companies have been able to reduce costs, increase production efficiency, and improve product customization. Moreover, the adoption of advanced automation aligns with Europe’s sustainability goals. By optimizing resource usage and reducing waste, these technologies contribute to a more sustainable manufacturing process. For example, Audi has implemented AI-driven energy management systems in its factories, significantly reducing energy consumption and carbon emissions.

Image of a cobot

New technologies, such as those discussed in this section, play a crucial role in the production of EVs and ICE vehicles. However, their importance and impact are significantly greater in the production of electric vehicles due to several factors related to the intrinsic characteristics of these vehicles, the production processes, and market demands.

Complexity of Critical Components

The production of electric vehicles involves the manufacturing of highly specialized components, such as batteries and energy management systems, which require high levels of precision and control. Regarding batteries, which are the core of electric vehicles, cell production demands sterile and controlled environments, along with advanced technologies to ensure consistency and safety. Technologies such as digital twins enable the simulation and optimization of each stage of battery production, reducing defects and improving energy efficiency. Furthermore, electric motors, unlike combustion engines, have fewer moving parts but require extreme precision in the manufacturing of coils and magnets. The use of cobots and advanced automated systems helps maintain exceptionally high-quality standards. For combustion engine vehicles, although engine production also demands precision, it is a more mature and well-established process, with less need for innovation and customization.

Need for Continuous Innovation

The constant evolution of the EV market requires rapid innovations in terms of range, performance, and charging times. This necessitates greater flexibility in production lines and the continuous adaptation of technologies. For example, smart manufacturing technologies enable the quick customization of electric vehicles according to customer needs and the introduction of new variants without requiring a complete redesign of production lines. In contrast, the production of combustion engine vehicles is now standardized and benefits less from these technologies, as the innovations introduced are less frequent and primarily focus on incremental improvements rather than radical transformations.

Impact on Sustainability

One of the primary goals of this emerging market is to reduce environmental impact, not only during the use of the vehicle but also throughout its production. New technologies play a key role in making production processes more sustainable. Energy optimization is crucial; thanks to advanced automation systems and real-time monitoring enabled by smart manufacturing, electric vehicle factories can reduce energy consumption and minimize waste. For example, some Tesla and Volkswagen plants in Europe utilize renewable energy systems combined with digital twin technologies to optimize production and lower CO_2 emissions. Additionally, recycling and reuse are supported by new technologies. The production of electric vehicles requires a significant amount of critical raw materials, such as lithium and cobalt. Digital twin technologies and big data analytics allow for the optimization of material usage and the development of efficient recycling processes. In contrast, while sustainability is also a key objective in the production of combustion engine vehicles, their environmental impact is inherently higher due to direct CO_2 emissions during operation.

Customization and Production Flexibility

Electric vehicles allow for a higher level of customization compared to combustion engine vehicles, as manufacturers can offer variants with different battery capacities, motor configurations, and charging systems. Advanced automation technologies and digital twin systems enable rapid reconfiguration of production lines to accommodate new product variants without significant interruptions. This is essential in a market where the demand for customization is high and constantly growing. In contrast, customization options for combustion engine vehicles are more limited, mainly concerning engine variants and optional features, which reduces the importance of advanced technologies in managing production lines.

Safety and Quality

Safety is a crucial element in EV production, particularly concerning batteries, which can pose significant risks in the event of malfunction. The use of AI and big data analytics allows for monitoring every stage of battery and electronic component production, identifying potential anomalies and defects before they become a problem. This approach is essential to ensuring the long-term safety of electric vehicles. In combustion engine vehicles, quality control processes have been well-established over decades of production experience. While advanced automation can further enhance these processes, its overall impact is less significant compared to the production of electric vehicles.

In conclusion the innovations of Smart Manufacturing have a more significant impact on electric vehicles than on internal combustion engine vehicles ICEVs due to the need to quickly adapt to new production and technological standards. While the ICEV industry has developed over the course of a century, EV production had to rapidly integrate advanced technologies such as automation, artificial intelligence, the Internet of Things, and digital twin systems. These innovations have enabled greater production efficiency, cost reduction, and quality improvement. A crucial aspect of this transformation is the production of lithium-ion batteries, which require highly precise processes to ensure safety and efficiency. The integration of IoT sensors and AI allows real-time monitoring of cell quality, while automation in assembly reduces the risk of malfunctions and enhances safety. Additionally, the modular design of EVs has encouraged the adoption of Smart Manufacturing, allowing rapid reconfiguration of production lines, the use of 3D printing and additive manufacturing, and the optimization of supply chain management through Big Data analytics. Another key factor is the digitalization of vehicles: EVs are natively connected, supporting over-the-air (OTA) software updates, advanced energy management, and integration with autonomous driving systems. This has necessitated the implementation of high-tech production lines capable of handling the increasing complexity of both software and hardware components. Finally, the need to reduce production costs has made Smart Manufacturing even more crucial for EVs. Process automation, workforce reduction, and supply chain optimization have significantly lowered battery costs, which account for up to 40% of the total vehicle cost. Although the ICEV industry has also benefited from Smart Manufacturing, these innovations have been essential for EVs to ensure economic sustainability and technological competitiveness. The integration of Industry 4.0 technologies has allowed the EV market to grow rapidly, improving accessibility and accelerating the transition towards electric mobility.

3.5 The final part of the Value chain: Sales

The final part of the electric vehicle value chain concerns the sales and distribution process, a crucial element for the success of any product on the market. EV sales present specific characteristics and challenges that set them apart from the sale of internal combustion engine vehicles. This segment of the value chain involves not only the final transaction between manufacturer and customer but also marketing strategies, innovative business models, government incentives, and the network of dealerships and after-sales services.

In recent years, the electric vehicle sales market has experienced exponential growth, however, to ensure the success of EV sales, automakers must address new challenges related to consumer perception, charging infrastructure, and high initial costs. Sales represent the final, yet no less important, phase of the EV value chain. This stage plays a crucial role in the commercial success of the product and in promoting the widespread adoption of electric mobility. Compared to internal combustion engine vehicles, selling electric vehicles requires higher initial costs, the need for adequate charging infrastructure, and the importance of effectively communicating technological innovations to potential customers.

Before discussing the various sales strategies, which also differ from those of internal combustion engine vehicles, it is important to provide an overview of one of the main aspects in which to invest in a rapidly growing market like that of electric vehicles: **marketing**. EV marketing plays a key role in promoting sustainable mobility in Europe, pushing automotive manufacturers to thoroughly rethink their strategies compared to those used for ICE vehicles. The growing demand for environmentally friendly transportation solutions and government incentive policies are trying to create a favorable environment, but the electric vehicle market requires innovative marketing approaches to address specific challenges related to consumer perception, higher initial costs, and the need for adequate charging infrastructure.

The first change concerns **value communication**: while the marketing of combustion engine vehicles has historically focused on elements such as performance, reliability, and design, EV marketing emphasizes sustainability, long-term savings, and technological innovation. Advertising campaigns aim to educate consumers about the environmental benefits of EVs, such as reduced CO_2 emissions, and the economic advantages of lower maintenance costs and the use of electricity instead of fossil fuels. For example, according to a Nielsen analysis in *"The EV Revolution Requires*

New Marketing Strategies", the most effective marketing strategies in the EV sector include transparent communication about the total cost of ownership and clear information on available charging solutions. This approach helps reduce customer concerns related to vehicle range and the availability of charging infrastructure.

Another distinctive feature of electric vehicle marketing compared to combustion engine vehicles is the **high degree of customization and digitalization of offers**. Automotive manufacturers like BMW and Volkswagen have introduced digital platforms that allow customers to configure their vehicles according to personal needs, with the possibility of post-sale software updates that add new features. This strategy, made possible by the advanced electronics present in electric vehicles, allows the product to remain up to date over time, enhancing the customer experience and increasing the perceived value of the vehicle. In contrast, for combustion engine vehicles, customization is often limited to standard options and rarely extends to digital features that can be implemented after purchase.

An additional strategy is to establish **strategic partnerships with energy providers** and technology companies to develop widespread charging networks and home charging solutions. For example, many automakers offer packages that include the installation of home wallboxes, making the purchase of an electric vehicle more convenient and practical. Furthermore, the sale of electric vehicles heavily leverages government incentives available in many European countries, clearly communicating to the end customer the potential savings through purchase discounts, tax exemptions, and reduced operating costs. For combustion engine vehicles, these opportunities are much more limited, as government policies aim to discourage their use in favor of low-emission solutions.

Finally, sustainability becomes the key element of branding. In electric vehicle marketing, sustainability is not just an added value but a fundamental pillar of the brand. Automakers are investing heavily to associate their brand with an image of innovation and environmental responsibility. This is reflected not only in advertising campaigns but also in corporate policies aimed at reducing the environmental impact.

New Business models for electric vehicles sales

The growing adoption of EVs is driving automakers to fundamentally rethink traditional business models. Unlike internal combustion engine vehicles, EVs require innovative strategies that go beyond merely selling the vehicle, focusing on digital services, charging infrastructure, subscription plans, and new direct-to-consumer sales approaches. The analyzed papers and articles highlight how these strategies are essential for competing in an increasingly sustainability-driven market. One of the most innovative business models introduced with the rise of EVs is **direct-to-consumer sales**, an approach successfully adopted by Tesla. Unlike the traditional dealership-based model, direct sales allow vehicle manufacturers to maintain full control over the purchasing experience, offering transparent pricing and reducing operational costs. Moreover, this approach enables a direct relationship with the customer, improving after-sales service and providing remote software updates to add new features to vehicles already sold. Some European automakers, such as Volvo and Polestar, are gradually adopting this model for their electric vehicles, creating digital platforms that allow customers to configure and purchase vehicles directly online. This strategy represents a significant departure from the traditional dealership model, which still remains important for handling maintenance and service management.

A key concept in new business models for EV is the rise of **Digital Services**. With the increasing digitalization of the automotive industry, many automakers are adopting business models based on digital services. Modern electric vehicles, equipped with advanced connectivity systems and driver assistance technologies, offer the unique possibility of post-purchase software updates and the addition of new features over time. This strategy not only enhances the user experience but also opens up new revenue streams for manufacturers through digital service subscriptions and premium functionalities. One notable example is Volkswagen's strategic initiative, **"**NEW AUTO**"**, which aims to transition the company from being a traditional car manufacturer to a provider of integrated mobility services. The goal is to generate approximately 20-30% of the company's future revenue from digital services by 2030. This includes offering OTA updates, enabling customers to unlock features such as enhanced autonomous driving capabilities, improved infotainment systems, or even battery performance upgrades. The shift towards digital service-based business models provides automakers with a steady stream of recurring revenues. Unlike the traditional one-time sale of a vehicle, digital services allow manufacturers to maintain long-term relationships with customers. By offering periodic updates and new features, automakers can keep vehicles technologically relevant for a longer period, avoiding customers’ doubts about their decreasing value due to the continuous innovation of the product and increasing the perceived value of the product, boosting brand loyalty. For example, Tesla, a pioneer in this approach, regularly releases OTA updates that enhance vehicle performance, add new entertainment options, and improve existing safety features. This strategy has significantly contributed to Tesla's high customer satisfaction and retention rates. According to a study by McKinsey, automakers that successfully implement digital service models can increase their average revenue per vehicle by 15-20% over their lifecycle. At the core of this new business model is vehicle connectivity, which enables real-time data collection and remote management of software. Automakers can analyze this data to improve product performance, predict maintenance needs, and offer tailored services to individual customers. Additionally, the data collected can be monetized in partnership with other industries, such as insurance companies and smart city initiatives. For instance, some automakers are exploring partnerships with insurance providers to offer usage-based insurance models, where premiums are adjusted based on real-time driving data collected from the vehicle. This approach not only benefits the customer with potentially lower insurance costs but also provides a new revenue source for manufacturers.

Another important aspect of digital service models is the introduction of subscription-based services. Instead of paying in front of certain features, customers can opt to subscribe to them on a monthly or annual basis. For example, BMW has introduced a subscription model for features such as heated seats and advanced driver assistance systems. While initially met with skepticism, this model allows customers to access premium features without a significant upfront cost, making high-end options more accessible. According to a report by Boston Consulting Group (BCG), the global automotive digital services market is expected to reach a value of $310 billion by 2030, driven by increasing demand for connected services and the proliferation of subscription-based models. Also, long term-benefits for Automakers are a consequence of the business digitalization. This approach to business not only diversifies revenue streams but also extends the lifecycle value of each vehicle. By continuously offering new features and improvements, automakers can mitigate the depreciation of their products, making them more appealing in the used car market. Additionally, digital services create a competitive advantage in a market where innovation and customer experience are key differentiators.

Another emerging business model in the EV market is represented by **integrated mobility solutions**. These new business models, which include car-sharing services and long-term rentals, by bundling additional services such as maintenance, insurance and access to charging networks, provide a comprehensive and hassle-free experience, making EVs more appealing to a wider audience. As cities increasingly prioritize green mobility and impose restrictions on ICE vehicles, consumers (especially those in urban areas) are seeking more convenient and sustainable alternatives to private car ownership. In response, automakers are embracing shared mobility services, which allow users to rent EVs for short periods, either by the minute, hour, or day, via mobile apps. A prominent example is Renault's Zity, a car-sharing platform operating in cities such as Madrid and Paris. This service not only reduces urban congestion and pollution but also familiarizes users with EV technology, helping to overcome common concerns about range and charging. Similarly, BMW, through its DriveNow service (now part of Share Now, following a merger with Daimler's Car2Go), provides a fleet of electric and hybrid vehicles available for short-term rental in several European cities. These services have been pivotal in promoting EV adoption by offering an affordable and flexible alternative to outright purchase, thus lowering the psychological and financial barriers associated with electric mobility.

In addition to car sharing, subscription models are gaining traction as another innovative approach to EV sales. Unlike traditional leasing or purchasing, subscription plans offer a more flexible and inclusive experience. Consumers pay a fixed monthly fee that typically covers vehicle use, maintenance, insurance, and access to charging infrastructure. This model provides an all-inclusive solution, removing the complexity of owning and managing a vehicle. An example of this approach is Care by Volvo, which offers consumers the option to drive various models, including fully electric ones, with all expenses bundled into a single monthly payment. This service has found significant success in markets such as Germany and the UK, where flexibility and convenience are highly valued. High upfront costs, concerns about battery life, and uncertainties about charging infrastructure remain significant deterrents for potential buyers, but by providing access to EVs without requiring full ownership, automakers can offer a low-risk way for consumers to experience the benefits of electric mobility.

In addition to vehicle sales, strategies are emerging also based on **pay-per-use and subscription plans**. These models are designed to meet the diverse needs of consumers by allowing them to choose between paying for the actual use of charging stations or subscribing to monthly plans that offer discounted rates or unlimited access to the charging network. Already adopted by leading operators such as Ionity and Enel X, these solutions are revolutionizing how users interact with EV charging services. The pay-per-use model stands out for its flexibility, offering users the option to pay only for the energy consumed or the time spent at the charging station. This option is particularly suitable for drivers who primarily charge their vehicles at home or work and use public charging stations infrequently. For example, Ionity, one of Europe’s top high-power charging operators, applies a per-kilowatt-hour tariff, allowing customers to access its charging points without long-term contracts. However, for users who frequently rely on public charging stations, pay-per-use may become less cost-effective compared to subscription models, which offer lower per-session costs and greater predictability. Meanwhile, subscription models are becoming increasingly popular, particularly among regular EV drivers. These plans involve a fixed monthly fee and offer either reduced rates or unlimited access to the charging network, providing significant savings for users who charge their vehicles frequently. A notable example is the JuicePass program by Enel X, which offers various subscription levels fitting with customers' charging needs. Higher-tier plans provide unlimited charging at a fixed monthly cost, enabling users to manage their expenses with greater precision while eliminating concerns about fluctuating energy prices.

Beyond the economic aspects, pay-per-use and subscription models play a relevant role in creating an integrated ecosystem of electric mobility services. Automakers, energy providers, and EV manufacturers are collaborating to offer increasingly comprehensive and interconnected solutions. Some automakers, such as Audi and Hyundai, have already begun including discounted or free charging plans for a limited period after purchasing a new EV, making it easier for new customers to transition to electric mobility. Despite significant progress, challenges remain. One of the main issues is interoperability among different charging networks. Currently, many operators manage closed networks, requiring users to subscribe to multiple plans to access all available stations. To address this problem, initiatives are underway to establish roaming agreements between operators, allowing users to access various networks with a single subscription or account. This improvement would be crucial in providing a smoother charging experience and further encouraging EV adoption. The future prospects for these business models are highly promising. According to a Bloomberg NEF report, the global market for EV charging infrastructure is expected to exceed $200 billion by 2030, driven by the growing demand for public charging solutions and the continuous expansion of charging networks. In Europe, where policies supporting sustainable mobility are particularly advanced, these business models will play a key role in facilitating the transition.

The Role of Government Incentives in Electric Vehicle Sales

Government incentives are another instrument that has played a crucial role in promoting the adoption of electric vehicles across many European countries. Given the higher upfront cost of EVs compared to ICE vehicles, these measures have significantly contributed to making EVs more affordable for a growing number of consumers. Direct incentives, such as purchase subsidies and tax reductions, have been introduced to stimulate demand and accelerate the transition. These initiatives can be broadly categorized into direct financial incentives and supportive policies. The former includes purchase subsidies, tax exemptions, and annual fee reductions, while the latter involves benefits such as free or discounted parking, preferential access to low-emission zones (LEZs), and tax relief for companies that renew their fleets with electric vehicles. For instance, in Germany, the government offers a bonus of up to €9,000 for the purchase of an EV, divided between state contributions and manufacturer discounts. This policy has had a substantial impact on the market, leading to a 60% increase in EV sales in 2022 compared to the previous year, making Germany the largest EV market in Europe. In France, a maximum €7,000 ecological bonus is available for EV purchases, with additional incentives for scrapping older, more polluting vehicles. These measures have driven rapid EV adoption, with sales accounting for 13% of total new registrations in 2022, up from 7% just two years earlier. In Italy, the government introduced the Ecobonus, which provides up to €6,000 for purchasing an EV and scrapping an ICE vehicle. Although the initial impact was less pronounced than in Germany and France, the Italian incentives have significantly boosted EV registrations, particularly in northern regions, where infrastructure and environmental awareness are more advanced.

These economic drives have proven to be a powerful turning point for EV sales. In European countries offering substantial incentives, EV sales have grown by an average of 45% annually over the past five years. These figures highlight how reducing the perceived upfront cost is critical to encouraging consumers to switch to electric mobility. In addition to direct ones, supportive policies have enhanced EV ownership experience by lowering operating costs and improving convenience. For example, in many Italian and French cities, free access to low-emission zones and discounted parking rates provides EV users with tangible advantages over ICE vehicle owners, particularly in urban areas. While these policies have positively impacted EV sales, there are concerns about their long-term sustainability. Offering high subsidies for an extended period places a significant financial burden on public budgets, especially as the EV market expands. Some governments, such as Norway's, have started to phase out direct incentives, focusing instead on infrastructure development and stricter environmental regulations for ICE vehicles. Another key challenge is the availability of a comprehensive and reliable charging infrastructure. While financial incentives can lower the initial cost barrier, the widespread adoption of EVs also depends on the availability of sufficient charging facilities. For this reason, many countries are simultaneously investing in both incentives and the development of public and private charging networks. In the short term, government support will remain crucial in driving the growth of the EV market in Europe. However, as battery prices decline and EV costs near those of ICE vehicles, dependence on financial help is likely to decrease, making room for policies aimed at enhancing infrastructure and broader adoption measures. According to McKinsey projections, by 2030, the total cost of ownership (TCO) for electric vehicles is expected to fall below that of ICE vehicles in most major European markets, even without subsidies. This anticipated change could lead governments to shift their focus from direct financial assistance to usage-based benefits and investments in charging networks and related infrastructure.

The Role of Dealership Networks and After-Sales Service in Electric Vehicles

Despite the growing trend of direct-to-consumer sales models, dealership networks remain essential for many automakers, particularly in the area of after-sales service. Dealerships play a crucial role not only in selling vehicles but also in providing ongoing support to customers, including training them in the correct use of electric vehicles and charging infrastructure, as well as offering specialized maintenance for complex components such as batteries and electric systems. These tasks require highly skilled personnel, prompting significant investments from manufacturers in training programs to ensure high-quality after-sales services. Automakers like Renault and Volkswagen are leading the way in developing comprehensive training programs for their dealership staff. Renault has trained over 30,000 employees within its network to provide expert maintenance and support for its E-Tech electric vehicles. This investment is aimed at enhancing the quality of after-sales service and building customer trust during the transition to electric mobility. The Volkswagen Group has undertaken an extensive employee training initiative to prepare its workforce for electric vehicle production and maintenance. In Zwickau, one of the group's key EV production hubs, nearly 7,770 employees have participated in specialized courses that incorporate advanced tools such as virtual reality to improve their technical capabilities. This program underscores Volkswagen's commitment to equipping its workforce with the skills needed to handle the challenges of EV production and service. MoreoDA, a subsidiary of Volkswagen, has expanded its training offerings through the ŠKODA Academy, introducing digital courses specifically designed for electric mobility. These programs are targeted at students, apprentices, and employees, ensuring that all levels of the workforce are adequately prepared for the demands of EV service and support. Proper training enables dealership staff to educate customers on key aspects of EV ownership, such as optimal charging practices and the benefits of using home charging stations or public infrastructure. Additionally, dealerships act as a point of contact for any technical issues, offering reassurance to customers by providing timely and efficient maintenance services. Furthermore, as EV technology continues to evolve rapidly, dealerships with well-trained personnel can help mitigate potential concerns related to battery longevity and performance.

3.6 Challenges in Consumer Perception of Electric Vehicles in the European Market

Despite the growing momentum, due to all strategies explained before, significant barriers still hinder their widespread adoption, many of which are rooted in consumer perception and hesitation toward this emerging technology. While government incentives, expanding charging infrastructure, and advancements in battery technology have contributed to increased interest in EVs, potential buyers often remain skeptical. This skepticism stems from various concerns, which continue to pose challenges for the EV market in Europe.

One of the most critical issues is **range anxiety**, a common fear among consumers regarding the limited driving range compared to traditional internal combustion engine vehicles. Although modern EVs have seen significant improvements in range, this concern persists, particularly in regions where charging infrastructure is still under development. Another major barrier, as already mentioned, is the **high upfront cost**. Despite declining battery prices and substantial government incentives, EVs generally remain more expensive than their counterparts. Many consumers are unsure whether long-term savings on fuel and maintenance justify the initial investment, leading to hesitation in making the switch. Additionally, concerns about the **availability and convenience of charging infrastructure** remain prevalent. While major cities in Europe have made progress in deploying public charging stations, rural areas often lack sufficient infrastructure, making potential buyers question whether owning an EV would be practical for their daily needs. There is also a notable **lack of consumer knowledge and familiarity** with EV technology. Many potential buyers feel uncertain about key aspects such as charging procedures, battery lifespan, and maintenance requirements. This unfamiliarity can create a psychological barrier, as consumers may prefer to stick with the more familiar ICE vehicles they have used for years. Lastly, the **perceived environmental impact** of electric vehicles has become a point of debate. While they are marketed as eco-friendly alternatives, concerns regarding the environmental cost of battery production and disposal have led some consumers to question the overall sustainability of this technology.

In the following sections, these issues will be explored in greater detail, analyzing how they affect the adoption of EVs in Europe and what measures could be taken to overcome them. Understanding and addressing these concerns will be essential for manufacturers and policymakers aiming to foster greater acceptance of electric vehicles in the European market.

Range anxiety

Range anxiety is simply the fear that an EV battery may run out of power before reaching a charging station; it represents one of the most significant psychological and practical barriers to the widespread adoption of electric vehicles in Europe. Despite significant technological advancements in terms of range and the continuous development of charging infrastructure, this concern remains prevalent among potential EV buyers, influencing their purchasing decisions. One of the primary factors contributing to range anxiety is the limited perception of the actual range of electric vehicles. Although the latest EV models offer ranges between 400 and 600 km on a single charge value comparable to those of internal combustion engine vehicles for daily use, many consumers still perceive these figures as insufficient. According to a BloombergNEF study (‘Sentiment towards battery electric vehicles falls in Europe, according to car buying intentions survey’), approximately 50% of potential buyers in Europe believe that the current range is inadequate for long-distance travel, especially in countries such as Germany, France, and Italy, where long-distance mobility is common. Another significant finding from the study concerns the perception of "declining" battery range over time. Many consumers fear that, after a few years of use, the battery’s capacity will decrease significantly, further reducing the vehicle’s range. Although real data shows that modern lithium-ion batteries retain over 80% of their capacity even after 8 to 10 years of use, this concern continues to negatively affect public perception. According to a study conducted by Geotab on over 6,000 electric vehicles from various brands and models, the average annual battery degradation rate is 2.3%. This means that after 8 years of use, the remaining battery capacity exceeds 80% of its initial capacity, ensuring sufficient range for most daily uses. In modern lithium-ion batteries are designed to last between 1,500 and 2,000 full charging cycles, which corresponds to approximately 300,000 to 500,000 km of driving, depending on the vehicle and usage conditions. This data suggests that the lifespan of the batteries can far exceed the vehicle's typical service life. Additionally, some manufacturers, such as Tesla and Nissan, offer battery warranties covering up to 8 years or 160,000 km, with a guarantee that the remaining capacity will not fall below 70%. These warranties aim to reassure consumers about the long-term durability of the batteries.

In addition, automakers also provide several recommended best practices for users to extend the lifespan batteries:

1. **Avoid frequent fast charging**: While fast charging stations are highly convenient, excessive use can accelerate battery degradation due to the heat generated during the process.
2. **Maintain charge levels between 20% and 80%**: To reduce chemical stress on the cells, it is advised to avoid consistently charging the battery to 100% or completely discharging it.
3. **Charge in moderate temperature environments**: High temperatures can speed up the aging process of battery cells. Therefore, it is preferable to charge the vehicle in cool or shaded locations during summer.

Despite real-world data demonstrating that battery degradation is not a significant issue for most users, and these recommended practices by automakers, negative perceptions remain widespread. A 2022 Nielsen survey (European Consumer EV Survey: Range Anxiety and Perception Trends) revealed that approximately 45% of potential buyers in Europe fear that the vehicle's range will decline rapidly over time, making EV ownership less appealing compared to ICE vehicles. This perception directly affects the resale market for EVs. Many consumers believe that used EVs have a substantially lower value than ICE vehicles, fearing that the battery might be near the end of its useful life. However, the EV used car market is evolving rapidly. Platforms like Renault Refactory and Nissan Used Program offer certified used electric vehicles with guaranteed battery performance, helping to alleviate consumer concerns.

Availability and convenience of charging infrastructure

The analyzed papers highlight that, despite significant progress in urban areas, the availability and convenience of charging infrastructure remains one of the main concerns for potential electric vehicle buyers in Europe. This issue significantly impacts their perception and adoption, particularly in rural and peripheral areas. In major European cities, thanks to government policies, a relatively dense network of public charging stations has been established, encouraging EV purchases. According to a BloombergNEF study, in 2023, (Global EV Infrastructure Outlook) the number of public charging points in key European metropolitan areas grew by 35% compared to the previous year. However, in less densely populated areas, such as rural regions in Italy, France, and Spain, the charging network is still insufficient, posing a significant obstacle to the expansion of the EV market as mentioned in "European Automobile Manufacturers' Association (ACEA) (2023). *Overview of EV Charging".* Another issue highlighted by the literature is the disparity in access to fast and ultra-fast charging stations. Although slow chargers are more numerous, fast chargers (capable of charging a vehicle to 80% in about 30 minutes) are less widespread and often concentrated along major highways (Transportation Research Part A (2023). *Public Perception of EV Charging and Its Impact on Adoption)*. This limits the practicality of EVs for long-distance travel, prompting many consumers to continue preferring ICE vehicles for convenience. Additionally, the need for better interoperability among different charging networks is emphasized. As previously analyzed, many public charging network operators in Europe are currently offering independent access systems, requiring separate subscriptions or the use of specific payment apps. This fragmented system further complicates the charging experience for users, increasing uncertainty and hindering large-scale EV adoption (McKinsey & Company (2023). *Electric Vehicle Adoption: Infrastructure Challenges in Europe)*. Finally, the perceived convenience of home charging varies greatly depending on the residential context. In urban centers with multi-story buildings, many potential buyers do not have access to private parking where a home wallbox could be installed, making home charging less accessible compared to single-family homes in suburban areas. Furthermore, negative perceptions about charging times are amplified by the lack of consistency in the charging experience. Not all stations provide the same power output, and many vehicles cannot fully utilize the capacity of ultra-fast chargers. For instance, a vehicle with a maximum charging capacity of 100 kW will see no additional benefit from using a 350-kW station, resulting in longer charging times compared to higher-end models capable of handling greater power. This variability frustrates consumers, who find it difficult to accurately estimate how long a charging session will take. Another factor contributing to user hesitation is the non-linear charging curve. While the initial phase, up to 80%, occurs at a relatively fast pace, the final 20% takes significantly longer due to the need to balance the battery cells, ensuring both safety and longevity. Although this behavior is well understood by industry professionals, it remains less clear to consumers, who often perceive a full charge as unnecessarily slow and inconvenient. Lastly, psychological factors play a key role. Even when charging times can meet the daily needs of most users (such as overnight charging providing full range for the next day) the necessity of planning stops during long trips or spending extra time at a charging station continues to act as a mental barrier to purchasing an EV. According to a McKinsey survey (*How European consumers perceive electric vehicles)*, around 55% of European consumers still consider current charging times too long to justify switching from internal combustion engine vehicles, despite the potential environmental and economic advantages. In conclusion, while EV charging times have significantly improved thanks to technological advancements and the expansion of fast-charging networks, they remain a major deterrent for many potential buyers. Overcoming this obstacle requires continued investment in ultra-fast charging infrastructure, better consumer education on charging procedures, and increased standardization of the charging process.

Since the development of charging infrastructure is a crucial condition for overcoming customer hesitancy regarding the purchase of electric vehicles, it is essential to understand in detail the current European landscape. Despite the total number of public charging points in the European Union surpassing 900,000 in 2024, their distribution remains heavily concentrated in just a few member states. Specifically, the Netherlands, Germany, and France alone host approximately 61% of all charging stations across the EU, highlighting a significant asymmetry compared to other countries (European Commission, 2024). In Italy, the number of charging points reached 64,024 as of December 31, 2024, marking a 36% increase compared to 2023 (Motus-E, 2024). However, in relative terms, the country still lags behind. With only 70 points per 100,000 inhabitants and 8 points per 100 km of road network, Italy ranks second-to-last in Europe in terms of infrastructure density—far behind countries like the Netherlands (104 points/100 km) and Denmark (31 points/100 km) (EAFO, 2024). The geographical distribution is also uneven: 57% of charging stations are concentrated in Northern Italy, compared to 20% in the Center and 23% in the South, thus amplifying regional disparities (Motus-E, 2024). This imbalance is also evident in terms of municipal coverage: in the North, about 60% of municipalities have at least one charging station, whereas in the South, fewer than 50% of municipalities are equipped with such infrastructure. Lombardy stands out as the leading region 17% of the national total. Conversely, southern regions like Basilicata and Sardinia show significantly lower coverage, with more than 65% of municipalities lacking charging infrastructure. This infrastructural disparity may discourage the adoption of electric vehicles in less serviced regions.

As previously explained another critical issue is the limited diffusion of fast-charging stations: across Europe, only around 11% of public charging points are capable of delivering a full charge in under an hour (European Alternative Fuels Observatory, 2024). This severely limits EV adoption for long-distance travel and penalizes users with urgent charging needs. To address these challenges, strategic initiatives such as the IONITY network have emerged, a joint venture between several automakers (BMW, Volkswagen, Ford, Hyundai, Kia) aimed at building a high-power European network with charging speeds up to 350 kW, specifically designed for long-distance driving. At the same time, Tesla continues to expand its Supercharger network, offering high-performance, fast, and reliable charging solutions.

In conclusion, Europe is progressing at uneven speeds in the deployment of charging infrastructure. While some countries are investing in widespread, fast, and technologically advanced networks, others, such as Italy, still need to bridge a significant gap. To ensure a fair and sustainable transition, a joint effort from governments, industry stakeholders, and EU institutions is essential to increase territorial coverage, average charging power, and accessibility in rural or underserved areas, thereby pushing widespread acceptance of electric vehicles.

High upfront cost

The high upfront cost is the most recognized obstacle to the adoption of EVs. Although they should offer long-term savings due to lower maintenance and fuel costs, their higher purchase price compared to ICE remains a deterrent for many potential buyers. A study conducted across several European markets, including Italy and Germany, highlighted that a significant portion of consumers considers government incentives essential to make EV purchases more competitive (Platform for Electromobility. (2022). *New consumer study shows that the EV transition is inevitable*).

In key markets such as France, Germany, and the Netherlands, EVs are still perceived as too expensive compared to traditional models. The average price of an EV currently stands at around €55,000, while the price level perceived as acceptable by consumers is approximately €36,000, known as the "tipping point" the point at which purchasing an EV becomes economically viable for most buyers (KPMG. (2023). *Charging ahead: Addressing the EV cost hurdle)*.

If we analyze in more detail and compare the prices of the two types of vehicles in Europe reveal significant differences, particularly in the segments of compact cars, mid-size sedans, and compact SUVs. This gap is mainly due to the high production costs of batteries and the insufficient economies of scale for EVs, although this situation is expected to change as technological advancements continue and production volumes increase. In the compact car segment, a model like the Renault Clio starts at approximately €18,000, while its electric counterpart, the Renault Zoe, starts at around €33,000, showing a price difference of over 70% (Platform for Electromobility. (2022). *New consumer study shows that the EV transition is inevitable*）. Similarly, in the mid-size sedan segment, the BMW 3 Series, with a starting price of €40,000, is significantly cheaper than the BMW i4, the electric version, which starts at over €60,000, representing an increase of around 50% (KPMG. (2023). *Charging ahead: Addressing the EV cost hurdle*). In the compact SUV category, the Audi Q3 is priced at around €35,000, whereas the electric Audi Q4 e-tron starts at approximately €45,000, indicating a 28% price difference (McKinsey & Company. (2023). *The Future of Electric Vehicle Pricing in Europe*). Although EVs have a higher upfront cost, long-term economic benefits, such as lower maintenance and refueling expenses, can partially offset this price gap. Additionally, many European governments offer substantial incentives, including direct rebates and tax reductions, to promote the purchase of electric vehicles, thereby lowering the perceived cost for consumers (European Automobile Manufacturers' Association (ACEA). (2023). *Comparative Analysis of ICEV and EV Pricing Trends)*. Despite these efforts, a McKinsey survey highlights that the purchase price remains one of the main barriers to EV adoption, as many customers still prefer ICE vehicles due to their lower initial cost. In the future, the price gap between ICEVs and EVs may narrow, driven by increased production and growing competitiveness in the battery market. Battery costs are expected to decrease significantly by 2030, making EVs more affordable and encouraging wider market adoption.

On the other hand, regarding external competitors in recent years, the global automotive industry has seen a growing presence of foreign EV manufacturers entering the European market, particularly from China. These new players are challenging traditional automakers on both technological and economic fronts, offering EV models at significantly lower prices compared to ICEVs and European EVs. A key factor in this competition is pricing. Chinese manufacturers, such as MG, BYD, and NIO, can offer electric vehicles at considerably lower costs than their European counterparts. A clear example is the MG4 Electric, a compact segment C vehicle priced at approximately €30,000. In contrast, the Volkswagen ID.3, a comparable model from a European brand, starts at around €38,000, resulting in a price difference of more than 20% （McKinsey & Company. (2023). *Electric vehicle pricing and competition*). This aggressive pricing strategy aims to capture a substantial portion of the European market, appealing to consumers looking for more affordable electric mobility solutions.

Despite the competitive pricing, Chinese manufacturers face significant challenges in the European market. The European Union recently introduced tariffs on imported Chinese EVs, with additional duties ranging from 7.8% to 35.3%, to protect the local automotive industry (European Automobile Manufacturers' Association (ACEA). (2023). *Analysis of European automotive policies and tariffs*). These additional costs could reduce the price gap between Chinese and European EV models, potentially weakening the pricing advantage of Chinese manufacturers.

The perceived environmental impact and the lack of trust from customers

Sergio Marchionne, former CEO of Fiat Chrysler Automobiles, frequently expressed doubts and reservations about the transition to electric vehicles. In a 2017 speech delivered during the conferral of an honorary degree in Mechatronic Engineering at the University of Trento, he highlighted the numerous challenges associated with the large-scale adoption of this technology. According to Marchionne, while electric vehicles represent a technologically advanced step toward reducing urban emissions, they risk being a "double-edged sword." He emphasized that the energy required to recharge EVs largely comes from fossil fuels, limiting their overall positive impact on the environment. Without a simultaneous transition to renewable energy sources, the overall benefits could be minimal or even negative. He also pointed out the high production costs associated with electric vehicles, which inevitably translate into higher retail prices, making them less accessible to consumers. Another concern he raised was related to employment in the automotive sector: the differing production requirements of electric vehicles compared to traditional ones could lead to a significant reduction in jobs. Marchionne concluded his speech by stressing the urgent need to address issues related to the production and distribution of electricity before promoting a full-scale transition to electric mobility. Without an integrated approach that considers the entire energy supply chain, the shift to electric vehicles might fail to deliver the anticipated environmental benefits.

The views expressed by the former CEO of FCA highlight key concerns that shape customer perceptions of EVs. One of the primary psychological barriers to widespread EV adoption is the belief that the electricity required for charging largely depends on non-renewable energy sources. While EVs produce no direct emissions, the energy powering them is often generated from fossil fuels, such as coal or natural gas, especially in countries where renewable energy integration remains limited. Another significant concern relates to the potential economic impact of transitioning to EVs. Many consumers fear that the shift to electric mobility could result in job losses within the traditional automotive sector. This is particularly concerning in regions where the manufacturing of ICEVs plays a critical role in local economies. This issue is particularly prominent in Europe, where countries like Germany and Italy have long-standing traditions of internal combustion engine production. EVs, with their simpler mechanical design, require fewer components, which could lead to a reduced need for labor. These changes raise concerns not only among industry employees but also among consumers, who may view the adoption of EVs as potentially harmful to economic stability. Automakers have started addressing these challenges by investing in employee reskilling and creating new opportunities in areas like battery production and advanced electronic systems. However, this transformation requires time, collaboration, and support from governments, unions, and companies to ensure a smooth transition.

Additionally, the environmental benefits of EVs are often questioned due to the reliance on fossil fuel-based electricity. This skepticism is exacerbated by limited awareness of advancements in renewable energy. For instance, countries such as Norway and Germany are making significant strides in integrating wind and solar power into their grids, making EVs a greener choice in those regions. However, in other areas, a lack of awareness about such developments contributes to consumer uncertainty, creating a psychological barrier to EV adoption. Statements by influential industry leaders like Sergio Marchionne can further impact public trust in EVs. When experts highlight challenges such as high production costs, dependence on fossil fuels, and inadequate infrastructure, their words can amplify existing doubts among consumers, discouraging them from considering an EV as their next vehicle. This hesitation is particularly evident in emerging markets and among customers who may not be fully informed about the advancements and benefits of EV technology. Expert critiques often serve as indicators of broader industry readiness, leading some buyers to postpone their purchase until perceived issues are resolved. To address these concerns, automakers must focus on transparent and proactive communication strategies. Highlighting technological improvements, infrastructure expansion, and sustainability initiatives can help shift consumer perception.

4. Geopolitical and Regulatory Analysis

This chapter gives an overview of the most important initiatives taken by the EU in order to reduce CO_2 emissions, the players and the externalities which play a crucial role in this transition and the consequences which these policies performed and are performing in the European market labour.

4.1 Introduction: The historical European Commission's Initiative on Climate Policies

The European Commission has taken a leading role in advancing environmental policies to combat climate change and reduce CO_2 emissions. This commitment is rooted in efforts initiated in the 1990s, driven by the growing awareness of human activities' impact on the environment. A turning moment was the ratification of the Kyoto Protocol in 1997, which marked the start of a worldwide structured approach to reducing greenhouse gases. Since then, the European Union has launched several ambitious initiatives, including the introduction of the first Emissions Trading System (EU ETS) in 2005. This mechanism established limits on emissions for businesses while promoting the trading of carbon credits. Over time, the transportation sector became a primary focus of European policies. In 2009, the Commission adopted specific regulations to reduce CO_2 emissions from passenger vehicles, setting progressively stricter targets for manufacturers. These measures pushed the development of more efficient and sustainable vehicles. The launch of the European Green Deal in 2019 further intensified these efforts, aiming to achieve climate neutrality by 2050. A cornerstone of this plan is the "Fit for 55" package, which aims to cut emissions by 55% by 2030 compared to 1990 levels. The plan also includes targeted actions for the automotive sector, such as phasing out internal combustion vehicles by 2035 and expanding infrastructure for electric vehicles. A distinctive feature of European policies has been the combined use of incentives and regulations. Alongside investments in clean technologies and subsidies for adopting electric vehicles, penalties were imposed on those failing to meet emission targets. This approach has driven a gradual yet significant transformation in the European automotive sector, fostering innovation and sustainability. The European Commission's actions have not only aimed to mitigate the effects of climate change but have also reshaped the industrial and social landscape of the continent, positioning Europe as a global leader in the transition toward a sustainable economy. Through a mix of strategic vision and targeted policies, the EU has charted a clear path toward a low-carbon future.

The efforts have focused on a range of particular sectors to tackle the challenges posed by CO_2 emissions. As previously mentioned, one of the main areas of intervention is the transport sector, which accounts for a significant portion of greenhouse gas emissions in Europe. The European Commission has introduced stringent regulations on emissions from passenger cars and vans, promoting the transition to electric and hybrid vehicles. Measures such as the regulation on alternative fuels infrastructure have supported the expansion of electric vehicle charging stations along major road networks, while also encouraging sustainable mobility through investments in public transportation and rail projects. Simultaneously, actions have been initiated to improve the environmental impact of air and maritime transport, sectors traditionally more challenging to decarbonize. Another area closely related to this sector is the energy one, which is responsible for the majority of emissions in Europe and represents a cornerstone of EU policies. Through the promotion of renewable energy sources such as wind, solar, and green hydrogen, the Commission has launched this transition. Regulations such as the *Renewable Energy Directive* and the *Clean Energy for All Europeans Package* have incentivized the production and use of clean energy, while energy efficiency has been promoted as a crucial tool to reduce overall consumption.

The industrial one has also received significant attention as one of the most emission-intensive areas. The *European Union Emissions Trading System (EU ETS)* introduced a mechanism to cap emissions from heavy industries, fostering investments in innovative technologies such as carbon capture and utilization (CCUS). Furthermore, the introduction of the *Carbon Border Adjustment Mechanism (CBAM)* aims to reduce the risk of "carbon leakage" by taxing imported products based on their environmental impact, ensuring a level playing field for European companies.
The building sector, which consumes about 40% of Europe’s total energy, has been targeted with initiatives to improve energy efficiency and reduce emissions. The *Energy Performance of Buildings Directive* has encouraged the renovation of existing buildings, promoting the use of sustainable materials and technologies. These measures aim to make buildings not only less energy-intensive but also more comfortable and cost-efficient for residents.
Agriculture, which contributes a considerable share of methane and nitrous oxide emissions, has been addressed through policies for more sustainable land and water management. The promotion of organic farming and the adoption of precision farming technologies have helped mitigate environmental impact, while synthetic fertilizers are being progressively replaced with lower-emission alternatives. Lastly, the waste sector has seen the implementation of the *Circular*

Economy Action Plan, aimed at reducing waste generation and promoting recycling. Particular attention has been given to the sustainable management of electronic waste and batteries, minimizing greenhouse gas emissions from landfills and increasing the recovery of valuable materials. In summary, the European Commission has adopted a multidimensional approach to tackle climate challenges, targeting key sectors with integrated policies and innovative solutions. This strategy not only reduces emissions but is also profoundly transforming Europe's economic and social fabric.

All these sectors are closely connected to the automotive one, placing automakers crucial for the transition. These companies, more than any other, have had to adapt their strategic visions to align with the new European targets. However, these regulations have not always been carefully designed to allow a gradual adaptation for the various market players. This has led to a downsizing of the European automotive market in terms of sales, profitability, and the redefinition of its key players. The result has been the emergence of new multinational corporations formed through the merger of historic brands, as well as the entry of competitors from other continents, particularly China, Japan, and America.

4.2 European Policies for CO2 Emissions

This paragraph will address and describe the main policies issued by the European Union regarding the regulation of CO_2 emissions for vehicles and the future targets to be achieved under these regulations.

A key element of the strategy to achieve the goals of the European Green Deal and climate neutrality by 2050 is the Regulation (EU) 2019/631, adopted on April 17, 2019, serves as the foundation of this approach. It establishes stringent targets for the average CO_2 emissions of new passenger cars and vans. The regulation outlines two main milestones: by 2025, emissions must be reduced by 15% compared to 2021 levels, while by 2030, the targets become even more ambitious, requiring a 55% reduction for cars and a 50% reduction for vans. Specifically, the 2025 target imposes a limit of approximately 81 g/km for passenger cars and 125 g/km for vans, based on reference values of 95 g/km and 147 g/km respectively, set for 2021. By 2030, these thresholds will need to be further lowered, forcing manufacturers to develop increasingly advanced and sustainable technologies. The regulation stipulates that average CO_2 emissions must be calculated annually for each manufacturer, based on total vehicle sales and the average weight of the fleet. This method ensures fair treatment across different manufacturers by accounting for fleet variations. However, companies failing to meet the specified limits face severe penalties: €95 for each gram of CO_2 above the limit per vehicle sold. These fines serve as a strong incentive for automakers to invest in research and development of more efficient technologies. To support the achievement of these goals, the regulation also introduces incentive mechanisms, such as credits for low- and zero-emission vehicles. Manufacturers exceeding a minimum sales threshold of ZLEVs, set at 15% of total sales by 2025, can earn credits to offset emissions from other vehicles in their fleet, thereby reducing the risk of penalties. Additionally, the super credit system rewards the sale of electric vehicles proportionally, further encouraging the shift towards low-emission mobility. This regulation not only sets targets but also provides for periodic reviews to adjust the objectives based on technological progress and market conditions, ensuring they remain realistic and achievable. Its implementation drives manufacturers to improve vehicle efficiency while fostering a supportive environment for the development of supporting infrastructure, such as charging networks for electric vehicles. In conclusion, Regulation (EU) 2019/631 represents a milestone in European environmental regulation, establishing clear objectives and effective tools to reduce emissions in the transport sector. Despite being ambitious, this regulation is vital for promoting a sustainable transition, contributing to reduced environmental impact and technological innovation in one of the most critical sectors for the continent's decarbonization.

The European Green Deal

After focusing on and introducing policies specifically targeting electric vehicles, it is essential to provide a broader overview of the strategic foundation sustaining all the regulations driving this transformation. These measures aim to counteract climate change and pursue the overarching goal of reducing greenhouse gas emissions: The European Green Deal.

Introduced by the European Commission in December 2019 under the leadership of President Ursula von der Leyen, the plan sets an ambitious target of achieving climate neutrality across Europe by 2050, aligning with the objectives of the Paris Agreement. This comprehensive initiative stems from increasing recognition of the need for immediate action against climate change, coupled with political and social demands from citizens, environmental organizations, and member states. Far from being solely an environmental blueprint, the Green Deal encompasses a broad range of initiatives designed to transform key sectors. It seeks to revolutionize energy production and consumption, redefine transportation systems, and optimize the use of natural resources. Among its core focus areas, several stand out as pillars of strategy.

Renewable Energy and Energy Transition.

Two key directives guide this transition:

- Renewable Energy Directive (RED II): Introduced as part of the broader Clean Energy Package for All Europeans, the directive establishes binding targets to increase the share of renewable energy within the EU's overall energy mix. By 2030, at least 32% of the EU's energy consumption must come from renewable sources, reflecting the Union's commitment to the Paris Agreement and its long-term ambition for climate neutrality as outlined in the Green Deal. One of the directive's critical features is the distribution of responsibilities among member states through National Energy and Climate Plans (NECPs). Each country must detail how it intends to contribute to the overall target, ensuring a collective approach to the renewable energy transition. In addition, RED II promotes the integration of renewable energy across various sectors, including electricity generation, heating and cooling, and transport. RED II also introduces measures to empower consumers and small-scale energy producers. Citizens and local communities are encouraged to participate in the energy transition through initiatives like self-consumption projects and renewable energy cooperatives, ensuring a more inclusive approach. The directive is dynamic, with provisions for regular updates to reflect evolving technological and economic conditions. As part of the Fit for 55 packages, the EC has proposed increasing the renewable energy target to 40% by 2030.
- Clean Energy for All Europeans Package: It is a comprehensive legislative framework designed to modernize the EU's energy systems. Adopted in 2018, at its core the package emphasizes the creation of a fully interconnected and competitive energy market. By improving cross-border energy infrastructure, the package ensures a seamless flow of renewable energy between member states, reducing inefficiencies and promoting greater market stability. A key principle of the package is the prioritization of energy efficiency, which it views as essential for achieving emissions reductions. The package also seeks to empower consumers by giving them more control and transparency over their energy

choices. Simplified processes for switching suppliers, clear billing systems, and opportunities for renewable self-consumption allow individuals to play an active role in the energy transition. Furthermore, the package removes barriers to the adoption of renewable energy technologies by addressing administrative hurdles and promoting competitive auction systems for renewable energy projects. Another focus is the decarbonization of the heating and cooling sectors, which account for a significant portion of the EU's energy consumption. The package encourages integrating renewable energy into these systems, supporting innovations such as district heating and the use of heat pumps.

Through funding initiatives and incentives, the EU supports infrastructure and research projects, such as offshore wind farms in the North Sea and the deployment of green hydrogen. These efforts are particularly focused on replacing fossil fuels in hard-to-decarbonized sectors, such as heavy industry.

Circular Economy and Waste Management

The transition to a circular economy model is a central pillar of the European Green Deal. This approach aims to revolutionize traditional production and consumption patterns by focusing on waste reduction and maximizing the reuse of resources. The Circular Economy Action Plan, introduced in 2020, targets material-intensive sectors such as electronics, textiles, construction, and batteries, promoting recycling and reuse practices to minimize waste generation. One of the primary goals of this plan is to significantly reduce the volume of waste produced by requiring companies to design more durable, repairable, and recyclable products. These measures are intended to extend product lifespans and improve resource efficiency. Another critical aspect is the sustainable management of specific waste categories, including electronic waste and batteries, which are pivotal for the future of electric mobility. Such initiatives are essential for curbing emissions associated with landfill disposal and recovering critical materials like lithium and cobalt, which can be reintegrated into production cycles. These actions have a dual impact: on the one hand, they help alleviate pressure on natural resources, preserving them for future generations; on the other, they enhance the competitiveness of European businesses, enabling them to position themselves as global leaders in an increasingly sustainability-oriented economy. In this way, the circular economy is not only an opportunity to mitigate environmental impacts but also a strategic factor for the economic and industrial revitalization of the European Union.

Biodiversity and Sustainable Agriculture

This approach is primarily based on the 2030 Biodiversity Plan and the Farm to Fork Strategy, two interconnected initiatives aimed at preserving natural ecosystems, improving food security, and promoting low-impact agricultural practices. The Biodiversity Plan focuses on increasing the area dedicated to organic farming, with a target to reach 25% by 2030. This transition seeks to reduce the use of harmful chemicals and foster an agricultural system that respects biodiversity. Organic farming relies on natural techniques that enhance soil fertility, reduce water pollution, and contribute to a better balance between human activities and the environment. To support this transformation, the EU has allocated significant funding through the Common Agricultural Policy (CAP), encouraging farmers to adopt more sustainable methods and diversify crops to reduce dependence on monocultures that deplete the soil. Another key objective is to reduce pesticide use by 50% and the use of chemical fertilizers by 20% by 2030. The excessive use of these substances has contributed to ecosystem degradation, water pollution, and the loss of animal and plant species. EU is promoting the introduction of environmentally friendly alternatives, such as biopesticides and organic fertilizers, while supporting research and development in this field. In parallel, the Farm to Fork Strategy encourages the development of precision farming systems that leverage digital technologies and data analysis to optimize resource use, minimize waste, and reduce environmental impacts. These initiatives go beyond addressing the climate crisis, as they also have a significant impact on food security by enhancing both the quality and availability of agricultural products. Additionally, the promotion of sustainable farming practices plays a key role in improving the economic and social conditions of rural communities. By promoting new employment opportunities and reducing reliance on intensive, polluting agricultural methods, these measures contribute to the overall well-being of these regions. The integration of sustainable agricultural practices with biodiversity conservation policies exemplifies how a holistic approach can tackle environmental challenges while simultaneously bolstering the economic and social resilience of rural areas.

4.3 The role of Externalities and of Advocacy

This paragraph will delve into the causes that led the European Commission to act and influence the automotive market through the previously mentioned policies. Both indirect causes from an economic system perspective, linked to externalities, and those related to geopolitical and advocacy interests will be analyzed.

Externalities

Climate change is one of the most pressing global challenges, and the European Union has identified the transport sector as a major contributor to CO_2 emissions. Approximately one-quarter of Europe's total greenhouse gas emissions are attributed to transport, with road transport being the primary source. This not only exacerbates the greenhouse effect but is also closely linked to rising average temperatures, biodiversity loss, and an increase in extreme weather events such as floods, droughts, and heatwaves, all of which have significant economic and social consequences. Another critical issue is air quality, which is heavily affected by emissions from transportation, particularly in densely populated urban areas. Internal combustion engine vehicles ICEVs emit not only CO_2 but also fine particulate matter (PM2.5), nitrogen oxides (NOx), and other pollutants that adversely impact human health. These emissions are strongly associated with an increase in respiratory and cardiovascular diseases. According to data from the European Environment Agency, air pollution is responsible for approximately 400,000 premature deaths annually across the continent. This alarming figure underscores the urgent need for targeted measures to improve air quality and safeguard public well-being, especially in urban areas that are most vulnerable to these risks. The economic implications of this situation are equally significant. According to the World Health Organization, the costs associated with air pollution in Europe exceed €500 billion annually, including both direct healthcare expenses and economic losses due to reduced workplace productivity. This scenario has prompted the European Commission to implement stringent regulations aimed at reducing CO_2 emissions in the transport sector and encouraging the adoption of zero-emission technologies, such as electric vehicles. These measures not only address the need to protect the environment but also represent a strategic step toward improving public health and lowering the costs associated with managing the consequences of pollution.

The effects of air pollution extend far beyond premature deaths, impacting a significant portion of the population with chronic illnesses and disabilities that severely compromise quality of life. Conditions such as asthma, chronic bronchitis, heart disease, and strokes have become increasingly prevalent, particularly among vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions. These health issues, closely tied to poor air quality, place immense pressure on national healthcare systems, leading to higher costs for medical treatments, hospital admissions, and medications. In addition to health impacts, air pollution negatively affects workplace productivity. It results in increased absenteeism due to illness and reduces the physical and cognitive performance of workers exposed to high pollution levels. A study by the European Respiratory Society estimates that the economic cost of productivity losses in Europe exceed 150 billion annually. This substantial economic burden serves as a strong motivator for governments to invest in cleaner technologies and preventive measures to improve air quality.

An additional externality is energy dependency and geopolitical security.
Europe has long been reliant on fossil fuel imports, with the transport sector accounting for a significant share of oil consumption. Before the 2022 energy crisis, the EU imported more than 60% of its oil and 40% of its natural gas, with a heavy dependence on external suppliers such as Russia, the Middle East, and North Africa. The invasion of Ukraine revealed just how fragile Europe's energy security truly was: within a few months, Russia drastically cut natural gas supplies, leading to price increases of over 400% in less than a year. To address this emergency, many European countries were forced to adopt extraordinary measures, including energy rationing, the reactivation of coal-fired power plants, and emergency imports of liquefied natural gas (LNG) from the United States and Qatar. To address this situation of instability, the EU has responded by accelerating decarbonization policies and transitioning to renewable energy, recognizing the reduction of fossil fuel dependence as not only an environmental concern but also a matter of strategic security. In addition to the previously analyzed "European Green Deal", another key initiative is the REPowerEU Plan, an emergency strategy aimed at cutting dependence on Russian gas by two-thirds by 2025. This plan promotes the expansion of renewable energy sources and improvements in energy efficiency. Moreover, many EU member states are securing agreements with new suppliers, including the United States, Norway, Algeria, and Qatar, to diversify their energy sources and reduce reliance on a limited number of exporters. As a result, the

electrification of transport is not just a response to climate change, but also a means of reducing oil dependency. Currently, the transportation sector accounts for over 70% of oil consumption in Europe, making its transformation essential to reducing exposure to global market fluctuations. Electric vehicles powered by locally produced renewable energy would significantly decrease the demand for fossil fuels, ensuring greater stability for European markets. However, this transition must extend beyond private mobility. Energy-intensive sectors, such as heavy industry and public transportation, are also gradually adopting zero-emission solutions. On the other hand, is also important to notice, as already explained in “Supply chain chapter”, that with EVs, Europe should not be dependent from market fluctuations’ price due to other countries, during the transportation phase; but these issue remain for European companies in the supply chain in order to reach the materials for the battery production. Indeed, to enable and sustain this transformation, it is also crucial to invest in building an independent supply chain and pushing the construction of facilities in order to produce the batteries in the European continent. This requires research and development investments to improve battery technology and develop innovative energy storage solutions. Solar and wind power, while sustainable, face the challenge of intermittency, which can be mitigated by next-generation batteries and large-scale energy storage systems. Addressing these externalities and overcoming such challenges offers both geopolitical and economic advantages. Investing in renewable energy reduces the need for costly imports. Furthermore, the EU's leadership in ecological transition strengthens its global standing, positioning it as a benchmark for climate policies and a hub for technological advancements. From an industrial perspective, this transition also stimulates new employment opportunities and pushes technological innovation, particularly in emerging sectors such as battery production and artificial intelligence for energy management.

Another factor driving the European Commission to focus on EVs and decarbonization is the potential transformation of the European labor market, with the creation of new job opportunities and the redefinition of the skills required in the industrial sector. According to a study by the European Commission, the growth of the renewable energy sector, battery production, and charging infrastructure could generate up to one million new jobs by 2030 (European Commission, *EU Energy Dependence and Diversification Strategy*, 2022). This expansion impacts several key areas. The first key aspect concerns the production of batteries and components for EVs. Specifically, the rising demand for lithium-ion batteries for electric vehicles is driving the establishment of gigafactories across Europe, such as Northvolt's plants in Sweden, Volkswagen's facilities in Germany, and ACC's operations in France. These factories require thousands of workers skilled in chemistry, materials engineering, and automation. Additionally, the expansion of solar and wind energy production and the deployment of public and private charging networks are creating jobs for technicians, engineers, and specialized installers. The European Battery Alliance (EBA) estimates that over 800,000 skilled workers will be needed in the battery and EV charging sectors by 2025. Finally, the growing demand for critical raw materials such as lithium, cobalt, and nickel has led the EU to develop strategies for material recycling and recovery, generating employment opportunities in the circular economy. Companies like Umicore and BASF are investing in advanced recycling facilities to create a more sustainable and self-sufficient battery supply chain in Europe.

Despite these emerging opportunities, the transition from ICEVs to EVs also presents significant challenges for the traditional automotive industry. EVs require fewer mechanical components, which in turn reduces the demand for labor compared to conventional vehicles. According to a study by McKinsey (International Monetary Fund, "Impact of Energy Crisis on European Economies", 2023), the automotive sector could lose up to 500,000 jobs in the coming years due to the decline in internal combustion engine and transmission manufacturing. Countries with a strong industrial heritage, such as Germany, Italy, and France, are expected to be the most affected by this transition, as many manufacturing plants remain heavily reliant on internal combustion engine production. To mitigate the impact of this shift, the EU is actively promoting professional retraining programs (reskilling and upskilling) to support workers transitioning from traditional industries to emerging sectors. These initiatives focus on training employees in electrical engineering, mechatronics, and digital technologies to align with the evolving demands of the automotive industry. For example, Germany has allocated €2 billion to training programs specifically aimed at workers in the automotive sector, ensuring a smoother transition to the electric mobility era.

The role of Advocacy

In addition to the external economic factors that have indirectly influenced the European automotive sector, as previously analyzed, significant importance must also be given to the pressures exerted by various lobbying groups, which have sought to steer the European Commission's decisions in alignment with their own interests. Industrial and environmental lobbying groups have played a significant role in shaping the European Union's energy and climate policies, exerting pressure both legislatively and through media campaigns to accelerate the transition toward sustainable energy sources. Organizations such as **Eurelectric**, **WindEurope**, **SolarPower** Europe, and environmental advocacy groups like **Transport & Environment** have been instrumental in promoting more ambitious policies, working directly with the European Commission, the European Parliament, and national governments. The organizations advocating for the transition to electric mobility have employed various tools to influence EU policy decisions:

- **Consultations with the European Commission**: Industry organizations actively participated in public consultations on key regulations such as the Renewable Energy Directive (RED II) and the Fit for 55 packages, providing data and recommendations to strengthen the adoption of renewable energy.
- **Awareness campaigns and media lobbying**: Groups like WindEurope funded studies and reports to highlight the economic and employment benefits of renewables, emphasizing that wind energy alone could generate over 450,000 jobs by 2030.
- **Direct advocacy with European Parliament members**: Organizations like Eurelectric and other associations lobbied legislators to push for stricter CO_2 emission regulations in the energy and transport sectors.
- **Collaborations with companies and stakeholders**: Certain lobbying groups partnered with automotive manufacturers, tech companies, and financial institutions to develop sustainable business models and support investments in clean technologies.

In practice, environmental lobbying groups, particularly Transport & Environment (T&E), played a crucial role in the negotiations leading to the ban on the sale of internal combustion engine cars by 2035. T&E published several reports demonstrating that electric vehicles could reduce emissions by 70% compared to internal combustion engines and led advocacy campaigns pressuring governments to prevent exemptions in favor of synthetic fuels. This lobbying effort helped persuade initially skeptical countries, such as Germany, to accept the final agreement.

Another notable example is the influence of SolarPower Europe and Eurelectric in shaping the revision of the Renewable Energy Directive. Initially, the European Union had set a target of 27% renewable energy by 2030, but persistent lobbying efforts from these organizations led to an increase in the target to 32%. These advocacy groups provided data and analysis demonstrating that a higher share of renewables would not only be economically beneficial but also significantly reduce Europe's reliance on imported fossil fuels. Eurelectric has also actively advocated policies aimed at expanding charging infrastructure for electric vehicles. Their efforts contributed to the inclusion of a target of 3 million charging points by 2030 within the Alternative Fuels Infrastructure Regulation (AFIR), reinforcing the EU’s commitment to facilitating the transition to electrified mobility.

Finally, the renewable energy sector and certain advanced industrial sectors have actively backed the implementation of the Carbon Border Adjustment Mechanism (CBAM), a carbon pricing system applied to high-emission imports. Approved by the EU in 2023, this measure was advocated as a strategy to prevent industrial relocation to countries with weaker environmental regulations while safeguarding European businesses investing in decarbonization efforts.

The reasons behind lobby support for the transition to renewable energy are diverse and extend beyond environmental concerns:

- **Economic interests and market opportunities**: Decarbonization presents a massive economic opportunity. Global investments in renewable energy could exceed $10 trillion by 2050, and European companies aim to establish themselves as leaders in this sector.
- **Reducing energy dependence**: The 2022 energy crisis exposed Europe's vulnerability to gas and oil imports. Accelerating the shift to renewables is also a strategic move to enhance energy independence and security.
- **Public pressure and regulatory changes**: Growing environmental awareness and consumer demand for sustainable products are driving companies to adapt and remain competitive in a rapidly evolving market.
- **Public funding and incentives**: EU investment programs such as Next Generation EU and the Just Transition Fund provide billions of euros to support decarbonization, encouraging businesses to invest in clean energy technologies.

However, this transition to electric mobility has not been supported by all organizations. Several lobbying groups have attempted to slow down, modify, or oppose the climate policies adopted, concerned about the economic and structural impacts these transformations could have on specific industrial sectors. Among the most active groups trying to influence the decarbonization process are heavy industry associations, the automotive sector, and major fossil fuel corporations. The ACEA has emerged as one of the most vocal critics of the European Union's emission reduction policies, particularly regarding the ban on the sale of internal combustion engine vehicles set for 2035. Leading European car manufacturers, including Volkswagen, Stellantis, and BMW, initially raised concerns about the feasibility of the targets imposed by the EU, warning that a rapid transition could jeopardize hundreds of thousands of jobs and create financial difficulties for companies that have yet to complete their industrial conversion. A concrete example of ACEA's lobbying efforts was the push for exemptions regarding synthetic fuels (e-fuels). Through intense lobbying, supported by the German government, a compromise was negotiated to allow the use of e-fuels beyond 2035, provided they are produced exclusively with renewable energy. This outcome illustrates how car manufacturers have worked to shape European regulations, aiming to maintain multiple technological pathways and reduce their exclusive reliance on electric vehicles.

Also, industries characterized by high energy consumption, such as cement, steel, and chemicals, have raised similar concerns regarding the rapid pace of decarbonization. Organizations like CEMBUREAU, representing the European cement industry, and Eurofer, the association for the steel sector, have argued that a stringent emissions reduction framework could put European manufacturers at a disadvantage compared to competitors from regions with more soft environmental policies, such as China and the United States. To mitigate the economic impact of these policies, industry lobby groups have actively pushed for measures that soften regulatory pressures. Their efforts have focused on securing subsidies for the adoption of low-emission technologies, maintaining free emission allowances under the EU Emissions Trading System (ETS), and advocating for the implementation of the Carbon Border Adjustment Mechanism (CBAM). The latter introduces tariffs on carbon-intensive imports, aiming to create a level playing field for European industries while preventing carbon leakage.

In addition, significant force opposing the energy transition has been the oil and gas industry, which has actively sought to delay or redirect the shift toward renewable energy sources. According to a report by InfluenceMap, leading fossil fuel corporations such as Shell, BP, ExxonMobil, and TotalEnergies have allocated billions of euros to lobbying efforts aimed at preserving the role of natural gas as a transitional energy source and securing incentives for expanding gas infrastructure. A central objective of these companies has been the inclusion of natural gas in the EU Green Taxonomy, a classification system that defines sustainable investments. Through extensive political lobbying, they successfully influenced the European Commission to designate natural gas as a transitional energy source in 2022, even if with specific conditions related to reducing methane and CO_2 emissions. Furthermore, fossil fuel lobbyists have worked to delay the phase-out of public subsidies for fossil fuels, arguing that a rapid transition could lead to drastic increases in energy costs for both businesses and consumers. The energy crisis of 2022 reinforced this stance, prompting certain governments to temporarily deprioritize renewable energy investments in favor of securing immediate energy supplies.

4.4 The impact of the transition on the European automotive market segment

This course set by the European Community is well-defined and determined, but it has not been implemented in a particularly gradual manner. As a result, it has had and continues to have a significant impact on businesses reliant on fossil fuel consumption across the continent. In particular, major and long-established automotive groups and brands have faced considerable challenges, such as allocating substantial resources toward the transition to electric mobility. Automotive giants like Volkswagen, Stellantis, BMW, Mercedes-Benz, and Renault have announced multi-billion-euro investment plans in research and development of new platforms for EVs, the construction of gigafactories for battery production, and the expansion of charging infrastructure. For example: Volkswagen has allocated over €180 billion by 2027 to accelerate EV production and strengthen its battery supply chain, Stellantis, through its Dare Forward 2030 plan, has committed more than €30 billion to electrification, aiming for 100% electric vehicle sales in Europe by 2030, Renault has established the Ampere division, entirely dedicated to EVs, with the goal of making electric vehicle production more competitive and reducing costs.
As previously discussed, changes are evident throughout the entire value chain of the automotive market segment, forcing industry players to adopt strategic initiatives. One of the key areas of transformation is the supply chain, where companies have launched plans for battery production and supply chain reorganization. Regarding battery production, manufacturers have entered into

partnerships with specialized companies and developed gigafactories to reduce reliance on Asian suppliers. The EBA has been a driving force in establishing a European battery industry, leading to the development of gigafactories such as Northvolt in Sweden, ACC in France and Germany, and Volkswagen in Germany. At the same time, the supply chain reorganization has been driven by the fact that electric vehicles require fewer mechanical components, creating challenges for suppliers specializing in engines, transmissions, and exhaust systems. While some companies have successfully adapted by shifting to EV component production, others have faced closures and layoffs due to the reduced demand for traditional automotive parts. Another critical factor is the automation and digitalization of manufacturing; EV production demands a higher level of technological integration, requiring advanced skills in robotics, artificial intelligence, and software management. As a result, many automakers are investing in workforce training programs to equip employees with the necessary expertise to operate in a more automated and digitalized production environment.

The shift towards decarbonizing the automotive sector and reducing reliance on fossil fuels is undoubtedly a necessary step. However, as previously mentioned, the approach taken by the European Commission has revealed significant challenges. The raw enforcement of stringent targets, without providing companies with sufficient time to adapt, has placed substantial economic and employment pressures on industry. A lack of flexibility and compensatory measures has further complicated this transition, making it more disruptive than necessary. Rather than adopting a more gradual strategy that would have allowed European manufacturers to adjust progressively, the EU implemented rigid regulations that have increased both competitive and strategic risks for the sector. The main consequences of this lack of flexibility include a massive restructuring of the labor market, with new opportunities emerging while many existing job positions become obsolete. Another significant dynamic resulting from this situation is the loss of competitiveness among European companies, to the advantage of emerging Chinese and American automakers, leading to a decline in market share within the continent.

Employment impact

This aspect, previously discussed as an externality capable of influencing the vision and decisions of the European Commission, represents a controversial dynamic. On the one hand, its effect appears positive, as demonstrated by the EBA’s estimate of 800,000 new job opportunities in the battery manufacturing sector. On the other hand, these new positions require specific skills, highlighting a mismatch between the current workforce's competencies and those demanded by emerging technologies. While workers in the traditional automotive sector possess expertise in metalworking, mechanical assembly, and internal combustion engine manufacturing, the evolving electric mobility industry requires advanced knowledge in electrical engineering, mechatronics, software development, and energy management. This skills gap is creating significant challenges in workforce retraining, slowing down occupational transitions and leaving many workers in a precarious situation.

As previously analyzed, there is a pressing need for strong support from the European Union, not only for businesses but also for member states, to fund reskilling and upskilling programs. These initiatives are crucial for developing a workforce that is aligned with innovation and the technical demands of the new industrial landscape. Different EU countries are adopting varied approaches to address this issue. For instance, Germany has allocated over €2 billion for training and retraining programs aimed at transitioning automotive workers into roles focused on electrification and digitalization. In France, the industrial retraining plan provides incentives for companies that implement internal employee training programs, promoting a gradual rather than abrupt transition. Meanwhile, Italy has launched partnerships with universities and research centers to offer specialized training courses on skills related to electric mobility.
Automakers are also playing a crucial role in managing this transition by launching internal reskilling programs for their employees. Major groups such as Volkswagen, Stellantis, Renault, and Mercedes-Benz have established training initiatives aimed at developing advanced skills in battery production, electronics, and software management for electric vehicles. However, not all companies have the necessary resources to undergo this transformation. Many small and medium-sized enterprises within the supply chain face significant challenges, risking their autonomy and survival in the evolving market. The most notable corporate initiatives have come from Volkswagen, Renault, and Stellantis. Volkswagen has established a dedicated training academy for electric vehicles, offering specialized courses on battery technology, digitalization, and industrial automation. Renault, through its Ampere division, is restructuring its workforce training to align employees with new production requirements. Stellantis has introduced a targeted reskilling program for workers in transitioning plants, focusing on new automotive technologies and software.

Despite these efforts, greater collaboration between automakers, national governments, and the European Union remains essential. Without a coordinated approach, the transition risks reshaping the labor market in a way that benefits only certain categories of workers while leaving many others at a disadvantage.

The threat of new non-European players

The impact of this direction taken by the European Commission is not limited solely to the new dynamics affecting the labor market but also extends to a reduction in the European market share of continental companies. This is due to the entry of new players from other continents, who are increasingly gaining importance and credibility in the electric vehicle landscape. The rise of these new players stems from a well-defined strategic approach, primarily characterized by timely investments in innovation. In the early 2000s, the global automotive industry was still dominated by internal combustion engines. However, certain American and Chinese companies took a forward-thinking approach by channeling resources into electric mobility. A notable example is Tesla, established in 2003 with the ambition of developing high-performance electric vehicles. The introduction of the Tesla Roadster in 2008 marked a turning point, proving that an electric car could rival traditional combustion engines in both range and performance.

Tesla Roadster 2008.

In 2009, China launched the NEV (New Energy Vehicles) incentive program, heavily funding the development of electric vehicles and an internal battery supply chain. The NEV program is a Chinese government initiative designed to accelerate the growth and adoption of BEVs, PHEVs, and fuel cell electric vehicles. This strategy aligns with China's broader goal of reducing reliance on fossil fuels, improving air quality, and establishing itself as a global leader in electric mobility. The program is structured around five key pillars:

- **Direct Subsidies for Manufacturers and Buyers:** The government introduced generous state incentives for purchasing electric vehicles, covering up to 40% of the sale price in some cases. These subsidies were granted based on the vehicle's driving range—the longer the range, the higher the incentive.
- **Mandatory Quotas for Automakers:** In 2017, was implemented the NEV quota system, requiring automakers to ensure that a minimum percentage of their vehicle sales consisted of electric models to avoid penalties. This policy pushed both Chinese manufacturers and foreign companies operating in China, such as Volkswagen and General Motors, to heavily invest in electric mobility.
- **Investment in the Battery Supply Chain:** The government financed and supported the development of gigafactories for battery production, enabling companies like CATL and BYD to become global leaders in the sector. Additionally, local content requirements were imposed to favour domestic companies in battery component manufacturing, reducing reliance on foreign suppliers.
- **Expansion of Charging Infrastructure:** China has developed the largest public charging network in the world, with over 5.2 million charging stations installed by 2023. Chinese cities have also introduced incentives to encourage the installation of charging points in residential areas and public parking lots.
- **Restrictions on Internal Combustion Vehicles in Major Cities:** Several large cities, including Beijing, Shanghai, and Shenzhen, have implemented strict regulations limiting the registration of new gasoline and diesel vehicles, accelerating the transition to electric mobility.

These government measures have proven highly effective, leading to an exponential growth in China's EV market, making it the largest electric vehicle market in the world, accounting for over 60% of global EV sales in 2023. Additionally, Chinese companies such as CATL, BYD, and Gotion now control a significant share of global EV battery production. At the same time, however, in the early 2000s, European automakers were still primarily focused on diesel engines and plug-in hybrids, rather than BEVs. Their main priority was optimizing internal combustion engines, partly due to their strong dependence on traditional suppliers.

Between 2010 and 2018, Tesla and Chinese manufacturers strengthened their competitive advantage. As previously mentioned, China leveraged government support, while Tesla boosted its performance through innovation and scalability. The American company developed its own Gigafactories for large-scale battery production, significantly reducing manufacturing costs compared to European competitors, who were still dependent on external suppliers. Additionally, Tesla created its own Supercharger network, providing customers with an exclusive charging infrastructure that enhanced the EV driving experience. In contrast, Europe’s public charging infrastructure remained fragmented.

Another crucial factor was the Volkswagen Dieselgate scandal, which accelerated the transition to electric vehicles in Europe but also exposed the European automotive industry's reluctance to seriously invest in electrification before that point. The Dieselgate scandal is an industrial fraud case involving Volkswagen in 2015. The German company was accused of manipulating emissions tests for diesel engines by installing illegal software in its vehicles, which altered nitrogen oxide (NOx) emission data during regulatory approval tests. Today, European automakers are striving to catch up, but they face several challenges. 80% of global battery production is still concentrated in China, meaning that European manufacturers remain dependent on pricing and supply chains controlled by Chinese companies such as CATL and BYD.

Additionally, European carmakers, with their long-standing history and rigid structures, struggle to quickly adapt and transition their production compared to their younger and more flexible competitors. Meanwhile, Tesla and Chinese manufacturers like BYD, NIO, and XPeng have adopted aggressive strategies, reducing costs through vertically integrated supply chains and government subsidies. On the other hand, the EU is considering protective measures against Chinese EV imports to safeguard the European automotive industry. However, such actions could drive up electric vehicle prices for European consumers. In conclusion, over the past decades, the electric mobility sector has undergone significant evolution, driven primarily by companies that have anticipated market changes and invested with a long-term vision. While European automakers were still focused on optimizing internal combustion engines, these companies decisively invested in research and development of electric vehicles, laying the foundation for their current leadership.

A key element of this competitive advantage has been the massive government support received by both China and the United States. The support policies implemented in these countries have been far more aggressive than those of the European Union, allowing local manufacturers to develop rapidly and gain significant market shares. In China, for instance, substantial state subsidies and favourable regulations have created an ideal ecosystem for the growth of companies such as BYD, NIO, and XPeng, further consolidating their position in the global market. This government support combined with V.I strategies has allowed them to lower production costs and offer electric vehicles at more competitive prices than their European counterparts. Another distinguishing factor is corporate structure. Chinese and American startups have proven to be more flexible and responsive compared to European automotive giants, which must navigate bureaucracy, labour unions, and a more conservative corporate culture. Their ability to quickly adapt to new market trends has enabled these companies to innovate at a faster pace and capture market share in a relatively short period.

Lastly, the focus on technology has been another key strength. While European automakers initially concentrated their efforts on improving combustion engines, companies like Tesla, NIO, and XPeng immediately invested in advanced software, autonomous driving, and next-generation batteries. This strategy has enabled them to provide consumers with more innovative products, offering better performance and an enhanced driving experience compared to traditional models. In summary, the current dominance of Tesla and Chinese manufacturers in the electric mobility sector is not coincidental but rather the result of targeted strategies, early investments, and greater business agility. To close the gap, European automakers must accelerate their transition, invest in emerging technologies, and adapt their production structures to compete effectively with these new global market leaders.

5. Circular Economy and Future Business

5.1 Introduction

In recent years, the automotive industry has faced increasingly complex challenges related to the transition towards more sustainable and less resource-dependent production models. Traditionally, the automotive sector has followed a linear model, based on the principle of "take, make, dispose": raw materials are extracted, transformed into components, and assembled into vehicles, which, at the end of their lifecycle, become waste that is difficult to manage. This system has led to intensive resource exploitation and a growing amount of waste, with significant environmental and economic impacts. To address these challenges, a new paradigm is emerging: the Circular Economy. This approach is based on sustainability, efficiency, and reuse, aiming to keep materials and components in use for as long as possible, reducing the need for new resource extraction and minimizing waste. In the automotive sector, this means rethinking the entire vehicle lifecycle with strategies such as reusing and recycling raw materials, extending product lifespan, and integrating more sustainable production processes. The application of Circular Economy principles to the automotive industry becomes even more relevant with the transition to EVs. The shift to electrification brings new challenges, particularly related to the production and disposal of lithium-ion batteries, which contain critical materials such as lithium, cobalt, and nickel. Moving from a linear to a circular model in the EV sector presents concrete opportunities to reduce transition costs, improve sustainability, and make the industry more resilient to fluctuations in the raw materials market. Adopting a circular model in this industry means rethinking the entire production ecosystem, from designing vehicles with more sustainable and easily recoverable materials to implementing second-life strategies for EV batteries and developing advanced recycling processes to reduce dependence on virgin raw materials. This transformation is not only an environmental necessity but also a business opportunity for companies in the sector, allowing them to lower production costs, access new revenue streams, and comply with increasingly stringent global environmental regulations.

This chapter will analyse the main circular economy strategies applied to the electric vehicle industry, highlighting the business opportunities that can help offset the investments required for the transition from internal combustion engines to electric propulsion. Topics such as battery management innovations, critical raw material recycling strategies, retrofit solutions, and shared mobility models will be examined, demonstrating how Circular Economy can become a key factor in ensuring a sustainable and competitive future for the automotive industry.

5.2 Business Opportunities to offset the investments

Given the substantial and unavoidable investments required by this forced or at least accelerated transition, it becomes crucial to identify alternative business models that can initially offset the overall costs of EV production and R&D, and in the long term, as the sector evolves, generate sustainable revenue streams. Another critical aspect to consider is that the responsibility for end-of-life vehicles falls on the manufacturer, including all associated disposal costs. As a result, minimizing these costs and even turning them into sources of revenue is becoming an increasingly strategic priority for the automotive industry and beyond. This section will explore and analyse various Circular Economy business opportunities that automakers are integrating into their long-term strategies, highlighting how these models can contribute to cost reduction, sustainability, and new profit avenues.

Second Life

One of the most relevant challenges due to the transition to the electric mobility is in managing the end-of-life phase of lithium-ion batteries. After approximately 8 to 10 years of operation in electric vehicles, these batteries experience a decline in capacity, often dropping below 80%, making them less efficient for propulsion. However, despite this reduction in performance, they still retain a significant energy storage potential, making them ideal for second-life applications. This approach aligns seamlessly with the principles of the Circular Economy, aiming to extend product lifespans and minimize waste. One of the most promising reuse strategies for decommissioned EV batteries is their integration into energy storage systems. These systems allow batteries to store renewable energy such as solar and wind power—and release it when demand is high, or supply is low. Additionally, they play a crucial role in grid stabilization, helping balance energy fluctuations and enhance reliability.

By repurposing used batteries for stationary storage solutions, the demand for new battery production can be significantly reduced, lowering the environmental footprint associated with the extraction of critical raw materials like lithium, cobalt, and nickel. Moreover, these second-life batteries can be utilized in industrial and residential sectors to optimize self-consumption of renewable energy, decreasing reliance on traditional power grids. A concrete example of this

approach is the "Second Life" project by Enel, which has implemented a battery storage system in Melilla, Spain, using retired EV batteries. With a 4 MW capacity, this system provides 15 minutes of backup power in case of grid disconnection, ensuring continuity of supply and improving network resilience (Enel, 2022). Through second-life applications, EV batteries can have their operational lifespan extended, lowering disposal costs and unlocking new business opportunities. Instead of being discarded as waste, they can be transformed into valuable economic assets, reinforcing sustainability while enhancing the efficiency of the energy sector.
Several second-life business models have emerged as viable solutions for extending the useful life of EV batteries. Among them, partnerships with energy utilities have gained traction, as automakers collaborate with energy companies to repurpose used batteries for large-scale energy storage systems. A notable example is Nissan, which has partnered with Wykes Engineering in the UK to integrate second-life batteries from Jaguar I-PACE electric SUVs into the national power grid, helping improve energy efficiency and stability (Infobuild Energia, 2023). Another promising business model involves residential energy storage solutions. In addition to large-scale infrastructure projects, several companies are developing home-based storage systems using second-life batteries. These systems allow owners of solar panel installations to store surplus energy for later use, optimizing self-consumption and reducing dependency on the power grid.

Recycle and Material recovery

A key component of the circular economy is the sustainable management of critical raw materials, particularly in the EV industry. One of the most pressing challenges involves end-of-life battery recycling and extracting value from recovered components. To address this, automakers are implementing strategies to minimize disposal costs while maximizing economic efficiency. Among these strategies, vertical integration of recycling operations and the formation of joint ventures with specialized firms are proving to be highly effective. These initiatives not only help reduce environmental impact but also create significant economic opportunities within the growing market for critical raw materials. Integrating battery recycling within automakers' operations allows companies to internalize disposal processes, reducing reliance on third-party suppliers while improving resource management. Establishing in-house recycling plants enables manufacturers to recover and reuse valuable materials such as lithium, nickel, and cobalt, lowering production costs and ensuring a more stable supply chain for battery production. Beyond managing battery recycling internally, another highly effective strategy is forming joint ventures with companies specializing in battery recovery and processing. These collaborations optimize recycling technologies, allow for knowledge sharing, and help reduce operational costs by leveraging the expertise of established industry players.

An example of such a strategic collaboration is the partnership between Jaguar Land Rover (JLR) and the UK-based company Altilium. This initiative focuses on testing EV batteries manufactured using recycled materials from older Jaguar I-PACE models. The project aims to prove the feasibility of large-scale recycled battery production, reducing reliance on virgin materials while lowering carbon emissions by 60% (Reuters, 2024). Additionally, automakers like Renault are investing in in-house recycling plants and forming partnerships with innovative startups to optimize the recovery of critical materials and establish a direct presence in the battery recycling market (Qualenergia, 2023).

A notable example of vertical integration in battery recycling is Mercedes-Benz's newly established battery recycling facility in Kuppenheim, Germany. This advanced plant employs a mechanical-hydrometallurgical process, enabling it to recover over 96% of valuable materials, including lithium, nickel, and cobalt, which are then reintegrated into the production of new battery cells (Industria Italiana, 2024). This approach demonstrates how vertical integration can transform recycling from a cost burden into a profitable resource, offering a competitive edge to manufacturers that invest in sustainable recycling technologies.

Battery Remanufacturing and Retrofit as Key Strategies

One of the most impactful strategies within the circular economy framework is battery remanufacturing, a process that restores the original performance of used or end-of-life batteries. This approach extends battery lifespan while reducing the demand for new raw materials, thereby mitigating the environmental footprint associated with the production of new batteries. A prominent example of battery remanufacturing is the SUSTAINera Circular Economy Hub, established by Stellantis in Mirafiori, Turin. Inaugurated in 2023, this 73,000-square-meter facility represents an investment of €40 million and focuses on the remanufacturing of electric motors, transmissions, and high-voltage batteries. Additionally, the HUB is involved in vehicle reconditioning and dismantling, aiming to reintegrate recovered materials into the production cycle for new vehicles and components. The overarching objective is to extend the lifespan of vehicle components, aligning with the principles of sustainability and waste reduction (Stellantis, 2023).

Another key strategy in the circular economy is the retrofit of internal combustion engine (ICE) vehicles into fully electric models. This process involves removing the traditional engine and replacing it with an electric motor, alongside the installation of a suitable battery pack. By doing so, existing vehicles can be repurposed, eliminating the need for new manufacturing while significantly reducing emissions.

The retrofit of corporate and commercial vehicle fleets presents significant business potential, offering several advantages:

- **Lower Operating Costs**: EVs have lower maintenance and fuel costs compared to ICE vehicles, due to fewer moving parts and the relatively lower cost of electricity compared to fossil fuels.
- **Compliance with Environmental Regulations**: Many cities worldwide are introducing low-emission zones, where ICE vehicles are subject to restrictions or penalties. Converting fleets to electric ensures compliance with regulations, allowing businesses to continue operations without additional costs or limitations.
- **Preservation of Investments**: Instead of purchasing new EVs, companies can convert existing specialized or high-value vehicles, maintaining their operational capabilities while making them more sustainable.

Several companies and startups are investing in the retrofit sector, demonstrating the potential of this business model:

- **Clipper Automotive**: This UK-based company specializes in converting London's diesel-powered taxis into electric vehicles. This initiative extends the lifespan of iconic black cabs while significantly reducing urban emissions (The Guardian, 2024).
- **RBW EV Cars**: A British startup that retrofits classic sports cars with modern electric drivetrains, combining vintage aesthetics with cutting-edge EV technology. Recently, RBW expanded its operations by supplying electric drivetrain components to other automakers, proving that retrofit can also support B2B solutions (Reuters, 2024).

Circular Economy in EV Component Manufacturing

The transition to electric mobility is not only about replacing internal combustion engines with batteries but also involves rethinking the entire production process to make it more sustainable and resource efficient. One of the fundamental principles of the circular economy is reducing the need for virgin raw materials by incorporating recycled materials into new vehicle production. This practice not only minimizes resource depletion but also reduces the carbon footprint of manufacturing:

Steel and aluminum are among the most energy-intensive materials used in car manufacturing. By using recycled steel and aluminum, automakers can significantly cut down emissions and energy consumption. Studies show that recycling steel reduces energy use by over 70%, while recycling aluminum cuts energy consumption by up to 90% compared to extracting virgin materials. Many EV manufacturers have begun integrating these materials into their vehicles to enhance sustainability. For instance, Tesla and BMW have committed to using high percentages of recycled aluminum and steel in their vehicle frames and battery casings. BMW’s i Vision Circular concept car, unveiled in 2021, is designed with 100% recycled and recyclable materials, demonstrating how the industry can move toward a fully circular production model.

Beyond metals, recycled plastics, fabrics, and composites are becoming essential in EV interiors and battery enclosures. Companies like Volvo and Polestar are increasingly relying on recycled ocean plastics and plant-based materials for seats, dashboard panels, and carpets, significantly reducing plastic waste in landfills and oceans. By leveraging recycled materials, automakers are not only cutting emissions and resource consumption but also meeting growing consumer and regulatory demands for sustainability.

Another key approach to enhancing circularity in EV production is the implementation of modular design principles. Modularity allows for easier replacement, upgrading, and reuse of components, extending the lifespan of vehicles and reducing electronic waste.

Advantages of Modular EV Design:

- **Extended Vehicle Life**: With interchangeable and upgradable battery packs, motors, and interior components, vehicles can be updated rather than discarded, significantly reducing waste.

- **Simplified Maintenance**: Modular components make repair and maintenance more efficient, lowering costs for consumers and reducing vehicle downtime.
- **Efficient Material Recovery**: When vehicles reach their end-of-life stage, modular designs facilitate disassembly, improving the recovery and recycling of valuable materials.

Renault’s "Re-Factory" initiative in France is a prime example of circularity through modular vehicle production and refurbishment. The facility specializes in repairing and reconditioning EV batteries, upgrading vehicle software, and even remanufacturing key components to extend product life. Renault has also introduced the "Battery-as-a-Service" model, allowing customers to swap and upgrade battery packs instead of replacing entire vehicles, promoting circularity at the consumer level.

Incorporating circular economy principles into corporate ESG (Environmental, Social, and Governance) strategies is becoming essential for automakers. Investors and consumers increasingly demand sustainability, and regulations worldwide are tightening around carbon neutrality, waste reduction, and ethical material sourcing.

How Automakers Are Aligning Circular Economy with ESG Goals:

- **Reducing Carbon Emissions**: Automakers are setting science-based carbon reduction targets by integrating recycled materials, energy-efficient production methods, and battery recycling initiatives into their supply chains.
- **Improving Resource Efficiency**: Companies like Stellantis, Volkswagen, and Ford are investing in closed loop recycling systems, ensuring that production waste is reused within their own facilities.
- **Social and Ethical Responsibility**: Many companies are focusing on ethical raw material sourcing, especially for lithium, cobalt, and nickel in EV batteries. Circular economy initiatives, such as battery remanufacturing and second-life applications, reduce dependency on environmentally damaging mining operations.

5.3 Conclusions and Future Perspectives

As explained in this chapter, shift to electric mobility is not just about advancing technology, it demands a complete rethinking of how vehicles are designed, built, and managed throughout their lifespan. The circular economy presents a practical and necessary approach, instead of treating end-of-life vehicles and components as waste, the industry is beginning to recognize their potential for reuse and recovery. Practices such as battery remanufacturing, vehicle retrofitting, and modular design are proving to be essential in making the most of existing materials, while also lowering costs and expanding access to electric mobility. At the same time, the use of recycled materials in new vehicle production is reshaping manufacturing processes, making them more sustainable without compromising performance or safety. Beyond technical innovations, the integration of CE principles into corporate ESG policies is driving further progress. Companies that embrace closed-loop production systems, responsible sourcing of raw materials, and second-life applications for key components are not only meeting regulatory requirements but are also positioning themselves for long-term success in an increasingly competitive market.

The commitment to circularity will be a defining factor in the sustainability of electric mobility. As new technologies emerge, collaboration between automakers, policymakers, and technology providers will be key to scaling up circular economy solutions. Investing in remanufacturing hubs, modular vehicle architectures, and advanced recycling systems will allow the industry to minimize waste, reduce environmental impact, and drive economic growth. Ultimately, the future of electric mobility will not be determined solely by the number of EVs on the road but by how well these vehicles and their components are integrated into a truly circular system. Moving toward waste-free, resource-efficient, and low-emission production is no longer just an aspiration but an essential step.

Conclusions

This thesis provides a depth analysis of the key aspects of electric vehicles, with a particular focus on the European market, examining both growth opportunities and challenges. The starting point of this research is the urgent need to reduce CO_2 emissions to combat climate change, which has shifted from being a distant concern to an immediate priority. Given this reality, the study explores the role of the European Union, which has positioned itself as a global leader in emissions reduction by implementing ambitious regulations and policies aimed at accelerating the transition to electric mobility. Following this introduction, the thesis examines the history of electric vehicles, revealing that their origins are precedent internal combustion vehicles. This challenges the common perception of EVs as a purely futuristic technology. The research also delves into the diversification strategies adopted to facilitate a gradual shift from ICEVs to ELVs, analyzing the range of electrified models available, from mild hybrid electric vehicles to fully electric battery electric vehicles. A key section of the thesis is dedicated to battery technology, the defining component of electric vehicles. The study traces the evolution of battery innovations, from early lithium-ion solutions to emerging solid-state batteries, which have the potential to shape the future of mobility. Each battery type is examined in terms of cost, safety, and environmental impact, with particular attention given to their lifecycle, efficiency, and limitations. A crucial part of this evaluation involves a comparative environmental impact analysis between electric and combustion engine vehicles, incorporating research that extends the Life Cycle Assessment methodology beyond just the usage phase to include battery production and raw material extraction. The thesis then shifts to an in-depth examination of the European electric vehicle market, covering the entire value chain, from supply chains to sales strategies, while drawing comparisons to the well-established internal combustion vehicle market. A significant focus is placed on the competitive imbalance between European manufacturers and foreign competitors, highlighting how Tesla and Chinese automakers such as BYD, NIO, and XPeng have capitalized on early investments in electrification, allowing them to secure a significant market share. Meanwhile, traditional European automakers are facing considerable difficulties in keeping pace with this shift, as they attempt to recover lost ground. Another key aspect of the study explores European policies and their impact on the automotive industry. The European Commission’s aggressive regulations and incentives have played a crucial role in shaping the sector’s future, but their rapid implementation has also created challenges, particularly for legacy manufacturers. To

better understand this dynamic, the thesis investigates the externalities and advocacy efforts that have influenced EU decision-making. This transition is not only reshaping industrial competition, but it is also impacting the labour market, creating new job opportunities while simultaneously threatening traditional roles. The shift towards electrification and battery-focused industries demands a more skilled workforce, requiring significant investment in training and reskilling programs to prevent widespread job losses. Moreover, the study highlights how the strict EU emissions targets have contributed to a decline in market share for long-established European automakers, while foreign manufacturers (particularly from China) have gained a stronger foothold. While this presents a serious challenge for Europe's traditional automotive industry, it also opens the door to new business opportunities, particularly in the circular economy.
The final section of the thesis examines circular economy strategies as a means to offset transition costs and create new revenue streams. Concepts such as battery remanufacturing, the retrofitting of combustion engine vehicles, and raw material recycling are becoming increasingly important in ensuring a more sustainable and cost-effective transition. To take full advantage of these opportunities, automakers are actively working to build stronger collaborative networks and joint ventures, with the aim of turning end-of-life vehicle management into a valuable economic resource rather than a financial burden.

Despite the undeniable reality of climate change, this thesis raises concerns regarding how this transition is being managed by policymakers and regulatory bodies. One of the most significant issues highlighted is the actual reduction in emissions achieved by electric vehicles compared to internal combustion engine vehicles as analyzed through LCA studies. While EVs indeed offer a lower carbon footprint during their usage phase, the environmental costs of battery production and raw material extraction significantly offset these savings. The mining and processing of critical raw materials such as lithium, cobalt, and nickel not only generate substantial CO_2 emissions but also pose serious environmental and social risks, including habitat destruction, soil degradation, and water pollution. Additionally, the environmental impact of EVs extends beyond CO_2 emissions. The production of batteries and other EV components leads to the release of harmful substances into the environment, contributing to phenomena such as water acidification and soil contamination, which can have detrimental effects on both ecosystems and human health. These issues raise questions about the long-term sustainability of EV manufacturing and the need for more responsible supply chain management. Another major challenge is the inadequacy of charging infrastructure, which remains one of the biggest barriers to widespread EV adoption. As previously discussed, charging station density across most European countries is insufficient to support a full-scale transition to electric mobility, particularly in rural and suburban areas, where the disparity is even more pronounced. This lack of infrastructure, combined with range anxiety, uncertainty regarding the durability and resale value of EVs, and general skepticism toward such a rapidly evolving product, contributes to a hesitant consumer base. This consumer skepticism translates into low adoption rates, with many potential buyers either postponing their switch to electric or opting for non-European manufacturers that offer more affordable alternatives. The ability of Chinese automakers to offer technologically advanced EVs at significantly lower prices has intensified competition, putting European manufacturers under pressure. This situation not only threatens the market share of traditional brands but also raises concerns about the long-term economic competitiveness of the European automotive industry. The European government must find a delicate balance between its decarbonization goals and the need to maintain the competitiveness of the continent's automotive industry. This cannot be achieved solely through subsidies but will require significant public investments aimed at improving charging infrastructure and increasing the density of charging stations, particularly in underserved areas. Additionally, policymakers could consider introducing more flexible targets to allow European automakers a smoother adaptation period, preventing sudden disruptions in the industry while maintaining the momentum of the transition. On the other hand, automakers must adopt new industrial strategies to remain competitive in a rapidly evolving market. A key priority will be localizing battery production in Europe to reduce dependence on China and secure a stable supply of critical raw materials. At the same time, manufacturers should push for a more diversified business model, incorporating innovative solutions such as battery leasing, battery swapping, and shared mobility services, which could make EV adoption more financially accessible for consumers. Another crucial aspect will be the advancement of battery technology, with a strong focus on solid-state batteries and other sustainable alternatives that can enhance performance, safety, and cost-effectiveness. Additionally, automakers must leverage circular economy opportunities, maximizing the remanufacturing and recycling of batteries and other vehicle components to reduce waste, lower production costs, and establish new revenue streams. By adopting these strategies, both governments and manufacturers can contribute to a more sustainable and economically viable transition, ensuring that European industry remains a strong competitor in the global electric mobility landscape

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