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A Comprehensive Review of Electric Vehicles

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Abstract— This comprehensive review paper goes substantially into the environment of Electric Vehicles (EVs), starting with a complete advent to what EVs are and the way they paintings. It follows the evolution of these cars from their early beginnings to their modern situation, noting predominant milestones alongside the direction. The article covers the numerous types of EVs which can be to be had now and provides a top-level view of the marketplace as it's far presently. A considerable attention is targeted on the environmental outcomes of EVs, thinking about each their benefits and capability drawbacks. Looking ahead, the report speculates on future trends, along with anticipated technical upgrades and market situations. Additionally, it covers one-of-a-kind troubles that the EV business has, which includes those linked to infrastructure, technology, and economics. The motive of this observe is to give a well-rounded evaluation of the EV quarter, giving essential insights for academics, enterprise professionals, and policymakers alike.

Index Terms— Battery Electric Vehicles (BEVs), Battery Recycling and Second Life, Charging Infrastructure, Emission Reduction, Electric Vehicles (EVs), Fuel Cell Vehicles (FCVs), Hybrid Electric Vehicles (HEVs)

1. Introduction

Emerging as a vital worldwide industry with major influence on the economy and driving progress in research and technology is global automotive. New tech tools meant to protect the occupants as well as those outside on the streets abound on modern cars. Moreover, the increasing count of cars improves our capacity for quick and comfortable travel. However, this rise has also aggravated the issue of air pollution in cities, raising concentrations of several pollutants including Sulphur dioxide, nitrogen oxides, carbon monoxide, and particle matter. Moreover, according to a European Union analysis, road transport alone accounts for more than 70% of all CO2 emissions in the transport sector; transport is thus accountable for roughly 28% of all emissions [1]. Particularly in the transportation industry, reliance on fossil fuels has increased environmental problems like local air pollution, global warming, and resource depletion. For Sri Lanka, this reliance also affects the economy since it imports these fuels somewhat heavily.

One possible answer to solve these financial and environmental problems is electrifying transportation. Rising environmental consciousness, technology developments, market acceptability, government incentives, manufacturing investments, and economic viability all help to drive the march towards electric mobility. Many times, over conventional Internal Combustion Engine (ICE) vehicles, electric vehicles (EVs) present benefits. For example, EVs fuel economy is three to five times better and they are far more energy efficient. They lower oil import reliance, therefore improving energy security. Since EVs have zero-emission, they also help to enhance air quality and fit for metropolitan environments. They are also quieter, which helps to lower noise pollution especially in smaller vehicle types. Regarding industrial development, EVs significantly help to lower battery technology prices, which are essential for industrial competitiveness and the shift to renewable energy [2]. Most people still drive vehicles running on fossil fuels even when Electric Vehicles (EVs) are becoming more popular. Comparatively to conventional fossil fuel vehicles, EVs must contend with life cycle assessment (LCA), recharging infrastructure, and driving range. An electric vehicle's manufacture generates 59% more CO2 emissions than an Internal Combustible Engine Vehicle (ICEV). From tank to wheel, an ICEV releases 120 g/km of CO2; yet, considering the LCA view, this amount increases to 170–180 g/km. Though on a tank to wheel basis EVs produce no CO2, the average CO2 emissions are calculated during the whole life cycle of the vehicle. The energy sources used for producing and running an electric car will considerably affect its whole lifetime CO2 emissions. [3] Running on electricity, which can be derived from sustainable energy, electric vehicles offer a more ecologically beneficial means of mobility. The market nowadays features several versions of electric cars. Among the common kinds are fully electric cars, hybrids that mix small internal combustion engines with electric batteries, and vehicles run by hydrogen fuels cells. Gradually replacing conventional combustion engine cars in the market are these electrically driven forms of mobility [4].

2. EVOLUTION OF ELECTRIC VEHICLES

Several people share credit for developing the first model of an electric car [5]. Early electric motor developer **Ányos Jedlik** from Hungary built a miniature model car driven by his creative motor in **1828**. Four years later, in **1834, Vermont blacksmith Thomas Davenport** created a related contraption running on a small, circular, **electrified track** [6]. Together with his colleague **Christopher Becker**, **Groningen, Netherlands, Professor Sibrandus Stratingh** constructed a small-scale electric vehicle driven by non-rechargeable primary cells in **1834**. Scottish scientist **Robert Davidson** constructed the first known electric automobile in Aberdeen about the same time, in **1837**. Galvanic cells, batteries, drove this car. Later on, **Davidson** built a bigger locomotive called **Galvani** and displayed it at the **Royal Scottish Society of Arts Exhibition in 1841**. Along with basic commutators, the remarkable 7,101-kilogram (7-long-ton) vehicle included two direct-drive reluctance motors with fixed electromagnets acting on iron bars mounted to wooden cylinders on each axle. Over a distance of 2.4 km (1.5 miles), it effectively carried a load of 6,101 kg (6 long tonnes) at a speed of 6.4 km per hour (4 mph). Notwithstanding these successes, the restricted battery capacity prevented its general acceptance. Sadly, railway employees finally demolished it since they thought it would compromise their employment stability.

Scottish inventor **Robert Anderson** also developed a primitive electric vehicle during the years **1832–1839**. England notably obtained a patent for using rails as conductors of electric current in 1840; similar patents were given to Lilley and Colten in the United States in **1847** [7]. Motor vehicles attracted great interest in the late 1890s and early 1900s. Electric battery-powered taxis first appeared near the close of the 1800s. **Walter C. Bersey** assembled a fleet of these cabs in London, which debuted on the city streets in **1897**. The unique humming sound these creative vehicles created soon won them the loving moniker **"Hummingbirds".** Starting with twelve electric hansom cabs**, Samuel's Electric Carriage and Waggon** Company opened business in **New York City** that same year. Running a fleet of up to **62 cabs**, this company stayed until **1898** when its investors restructure it to form the Electric Vehicle Company. Early in the **20th century**, electric cars first showed great success but progressively lost importance in the automotive industry. Several elements influenced this change. Better road infrastructure by the **1920s** called for vehicles with more range than what electric automobiles could provide. Concurrent with the discovery of vast petroleum resources globally, gasoline became more affordable and readily available, hence gas-powered vehicles became preferred for long-distance travel. Constrained by their modest speeds (**usually no more than 24–32 km/h or 15–20 mph**) and limited range (**around 30–40 miles or 50–65 km**), electric automobiles could not match the rising capacity of gasoline-powered equivalents. **American Motors Corporation (AMC)** and **Sonotone Corporation** investigated together in **1959** the prospect of building an electric car driven by a "**self-charging" battery** [8]. Several battery-electric concept automobiles featuring creative concepts and technologies surfaced in the middle of the **1960**s.

2.1. Scottish Aviation Scamp (1965):

- The **Scottish Aviation Scamp** was a forward-thinking electric vehicle. Although it remained a concept, it demonstrated the potential of electric propulsion.
- Unfortunately, it did not progress to mass production, but its design and engineering left a mark on the industry.

Fig. 1. Scottish Aviation Scamp [9].

2.2. Electrovair (1966):

- **General Motors** (GM) experimented with an electric version of one of their gasoline cars, known as the **Electrovair**.
- While it didn't become widely available, the Electrovair represented GM's exploration of electric mobility during that era.

Fig. 2. Electrovair [10].

These early electric car concepts paved the way for future developments in the electric vehicle industry [84]. Indeed, none of those early electric car concepts entered widespread production. However, there were some notable developments:

2.3. 1966 Enfield 8000:

- The **Enfield 8000** managed to make it into small-scale production, with a total of **112** units eventually produced.

Fig. 3. 1966 Enfield 8000 [11].

2.4. AMC and Gulton Industries Collaboration (1967):

- In **1967**, **American Motors Corporation (AMC)** collaborated with **Gulton Industries** to create a new battery based on **lithium**.
- They also designed a speed controller under the guidance of **Victor Wouk**.
- An **all-electric 1969 Rambler American station wagon** utilized a nickel-cadmium battery for power.

2.5. AMC's Plug-In Experimental Vehicles:

- **Amitron (1967)**: Another experimental electric vehicle developed by AMC in partnership with Gulton.
- **Electron (1977)**: A similar project exploring electric mobility.

2.6. Tesla Roadster (2008):

- **Tesla Motors**, a California-based electric car manufacturer, began development of the **Tesla Roadster** in **2004**.
- The Roadster marked several milestones:
  - It was the **first highway-legal serial production all-electric car** to use **lithium-ion battery cells**.
  - It achieved a remarkable range of **more than 320 km (200 miles)** per charge.
  - In **2008**, the Roadster was delivered to its first customers, setting the stage for Tesla's impactful journey in the electric vehicle industry [12].

Fig. 4. Tesla Roadster 2008 [13].

Since **2008**, **Tesla** has successfully sold approximately **2,450 Roadsters** across more than **30 countries** until **December 2012**. The Roadster remained available for purchase until early **2012**, when the supply of **Lotus Elise gliders** was depleted. Tesla's contract with **Lotus Cars** for **2,500 gliders** had expired by the end of **2011**. In the U.S. market, orders for the Roadster ceased in **August 2011**. The **2012 Tesla Roadster** was only sold in limited quantities in **Europe**, **Asia**, and **Australia**.

Following the Roadster, Tesla introduced the groundbreaking **Model S**, which made its debut in the U.S. on **June 22, 2012**. The first delivery of a Model S to a retail customer in **Europe** occurred on **August 7, 2013** [14].

In **China**, Tesla commenced deliveries on **April 22, 2014**. Following the Roadster and Model S, the next addition to Tesla's lineup was the **Tesla Model X**. However, in **November 2014**, Tesla faced another delay in starting deliveries to retail customers. The company then announced that Model X deliveries were anticipated to begin in the **third quarter of 2015** [15]. **Norwegian electric vehicles** have enjoyed substantial subsidies for many years, receiving approximately **50%** financial support. Beyond financial incentives, EV owners in Norway also benefit from additional perks, including access to bus lanes and free parking. These advantages have been extended until **2020**.

In **February 2017**, **Consumer Reports** recognized **Tesla** as the leading car brand in the United States, and it secured the **8th** position among global car manufacturers.

Furthermore, the **Nissan Leaf** achieved a significant milestone by surpassing **300,000** units in global sales as of **January 2018** [16].

3. CURRENT STATE OF E-MOBILITY

Although electric mobility has been around for a long time, public acceptance and utilization have now only started. Midway through the 1830s, the first electric vehicles (EVs) started surfaced in the United States. For future markets, EVs—vehicles that substitute an electric motor driven by electricity, stored in an onboard battery pack, for the internal combustion engine—signal a change [17]. Acceptance of electric vehicles depends on government backing; hence, wide market adoption is quite important. Adoption of electric vehicles (EVs) is still in its early phases in developing nations; consumers still consider. Adoption of electric vehicles (EV) is influenced by several elements including low running costs, petrol savings, effective use of energy resources, and low greenhouse gas emissions (GHG [18]). Gradually opening to EVs with growing popularity are developing nations. Changing from gasoline-powered to electric cars is unavoidable. Policies aimed at encouraging EVs are being passed by developing nations; India, for example, plans to deploy EVs by 2030 (NITI Aayog and Rocky Mountain Institute, 2019). The EV market has risen in industrialized nations to rival traditional combustion engine cars [19,20]. Promising sustainability [21–23], developments in lithium-ion battery technology allow EVs and BEVs the possibility to rule future mobility. Many developed nations are significantly funding EV research and development and have measures in place to help its acceptance [24]. With around fifty hybrid models spread across several brands, the market for hybrid vehicles is likewise expanding (U.S. Department of Energy). Manufacturer-Based Offering of AFV and HEV Models Maps Data: US HEV Sales by Model; 2017, [25]. Like the UK's plug-in vehicle award (GOV.UK. Plug-in car and van grants, Driv Transp; 2015, [25]).

Though customer reactions remain a worry, electric vehicles are essential in the worldwide market of today for environmental preservation [27,28]. Understanding consumer interest in moving from gasoline-powered cars to electric vehicles requires study in several disciplines. This study is to create plans to raise consumer pleasure with a wider spectrum of EVs, enhance energy economy, and solve environmental problems [29,30].

Trends now centre on passenger automobiles; predictions and energy system models show that the transportation industry will progressively depend on government initiatives to change vehicle technology [31]. Though still in its early years and presents certain difficulties, the EV market is fast growing all over. Given limited mass production and other variables, high pricing are a major problem [32,33]. In metropolitan regions where longer commute lengths save petrol, energy and the environment, EVs are perfect. These cities can also afford to create required infrastructure including charging stations. Acceptance is slowly rising [34] despite great costs and limited range. The idea of EVs is fresh and calls for time for people as well as countries to adopt this future technology. More infrastructure like batteries and charging stations is required to make EVs reasonably accessible for most people.

EVs offer a sustainable transportation alternative since the usage of fossil fuels and inevitable depletion of them pose global warming and climate change concerns. Though several technologies are still under testing, opinions on an Energy Storage System (ESS) are not clear-cut. Currently best supplied by lithium-ion batteries (LIBs), EVs demand high energy and power densities [35]. The finite and non-renewable nature of fossil fuels such as petrol and petrol will cause prices to rise and thereby increase the cost of conventional vehicles [36]. EVs save the environment from damaging pollutants and provide less travel expenses. Among the several kinds of EVs are hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs [37]). EVs could solve several energies, financial, and environmental problems [38, 39].

3.1. Various parameters that can be considered for consumer trends of EVs.

At the present time, less people embrace and use electric vehicles on the market. Since EVs are new to the market and their current market share is tiny. People must grasp a lot of information, including how beneficial it is for the environment and how, over time, it saves petrol money since current costs are soaring. Understanding consumer setbacks as part of the ambitious marketing aim of EVs and developing them worthy enough to compete with the ICE market helps one make EVs a part of the market [40].

3.1.2. Price range

Any car is bought depending on its value for money or not, hence the rational model of purchasing. Although the first cost of electric vehicles is high and hence, for general consumers, it is a negative view; yet the portion of the future where they would be saving on fuel and efficiency is the positive aspect of EVs [41]. High prices typically concern consumers when purchasing a new commodity since there are very few buyers and thus, the number of reviews and advise about EVs is fewer in the market. They also worry whether to spend such a huge money on a new car that is new to the market. Given their initial high prices, the government should offer loans, subsidies, and other benefits and incentives to attract more customers to purchase EVs since they are good for the environment and also cost-effective in the next future [42]. The graph illustrates in Fig. 5. the sales trend of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) from 2010 to 2022. It shows a significant increase in the number of units sold over this period, with BEV sales (shown in green) substantially outpacing PHEV sales (shown in blue) by 2022. The exponential growth highlights the increasing adoption of electric vehicles globally [43].

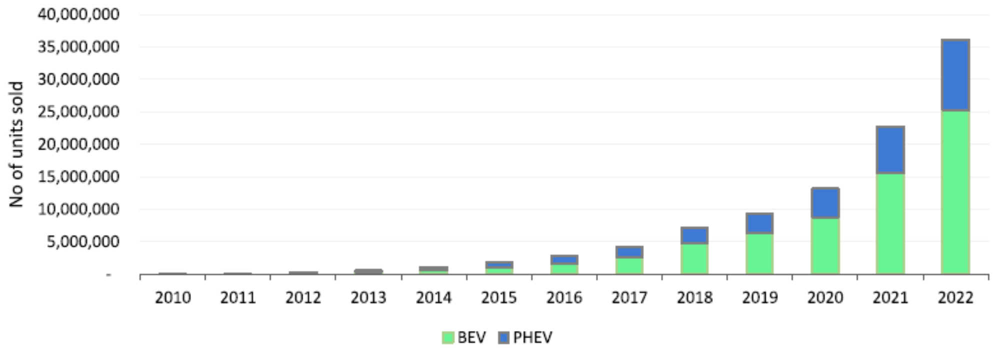


Fig. 5. Types of EVs sales [43].

3.1.3. Social and psychological acceptance

What does the social view of the say or what does one believe in? This is really important in guiding our decision. Thus, society is the most significant factor influencing the choice of any good. To a significant extent, information and understanding influence the market of electric vehicles. Adoption of EVs would change depending on the personal knowledge of the person about EVs. Thus, it is imperative that the government informs the general people about the advantages of EVs [44,45]. The phenomena of "range anxiety" among so many people result from the vehicles' present battery range not being as high as that of ICEVs and so runs out on the road [44,46].

3.1.4. Charging station availability

Right now, the infrastructure for charging stations is poor throughout developing nations since EVs are new on the market. Consumers would be less likely approach charging stations as their distance is also larger and there are somewhat few of them. The users also noted that they had to spend more time at the charging center than at convenience fuel-filling stations [47]. These charging stations were constructed in either empty parking lots, offices, or leisure centers. The restricted number of stations influences this charge time; so, their infrastructure should be expanded. One would need a license to obtain a charging station built at home; the procedure is difficult and costly as well as requires a lot of investment also [48, 49]. The graph shows a significant rise in charging stations and electricity demand for electric vehicles (EVs) from 2010 to 2025, indicating the need for expansion of charging infrastructure and sufficient energy supply to meet future demands [43].

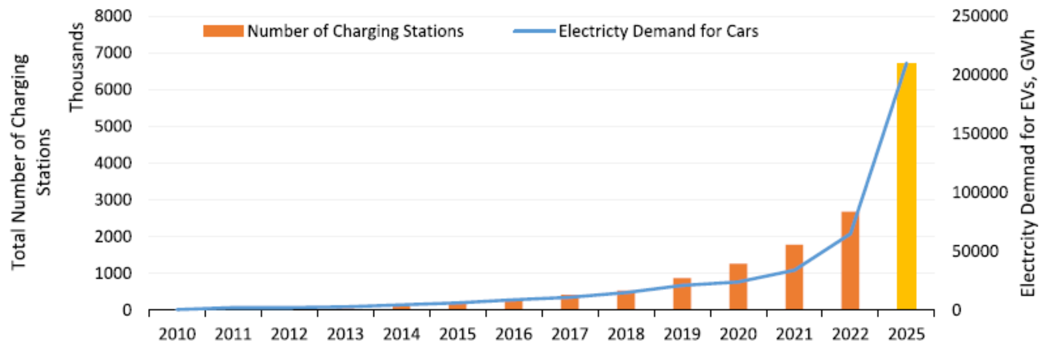


Fig. 6. Charging Station and Electricity Demand for cars increment over the years [43].

3.1.5. Battery-related concerns

Buyers of electric vehicles (EVs) are mostly concerned about this, so it causes uncertainty. Reports of several aspects of the battery raising questions abound. Concerns about the design, packaging, and even the materials utilized in the battery have been voiced by people [49,50]. People are worried since every EV needs a particular charger and all of the vehicles lack a common charger [49,51]. This raises questions among people since they worry the presence of a compatible charger in their vicinity or anywhere, they would want to travel [49,51]. Another issue that has been brought up is that establishing several charging stations calls for parallel investment and also not all locations are suitable for setting up these stations, for example, densely populated areas are not fit enough to set up a charging station, even though it is that place which will have more vehicles and will require more charging stations [49,52].

3.2. Global outlook for faster EV adoption

Rising worries about air quality and climate change, many nations have acted aggressively to lower emissions generally from different industries and transportation industry is one of those. Globally, good incentives policies and laws have been applied to reduce the emissions from the transport industry [53]. Success of all early-stage electric car programmers depends on both financial and legal incentives. Financial incentives include subsidized charging, lowered license fees, and subsidies for EV purchase and leasing can become financially unsustainable as the number of EVs rises, though. Once EV acceptance transcends early adoption, some tools—like assigning road space to EVs—become useless. Beyond some of these advantages, it is challenging to go on especially considering that cutting rewards immediately could compromise efforts at market growth. Therefore, many governments have found their toughest obstacle in deciding the suitable incentives for electric vehicles after their first introduction [54,55]. Fig. 7 shows global electric vehicle (EV) sales from 2016-2023, with China leading, followed by Europe and the US. This trend is driven by increased consumer interest and supportive policies [56].

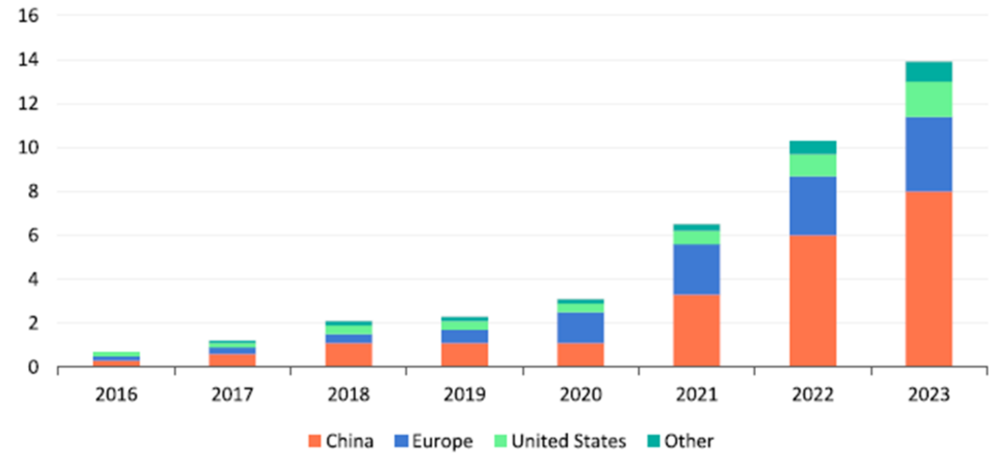
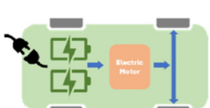
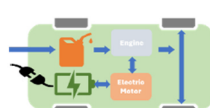
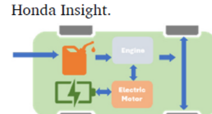


Fig. 7. EVs sales data globally [56].

4. Types of electric vehicles

Electric vehicles are often categorized as hybrid electric vehicles (HEVs) and solely electric vehicles depending on the main propulsion method, energy storage systems, and fuel delivery systems. Mild, full, or plug-in hybrids—which combine internal combustion engine (ICE) systems with electric motor (EM) technologies—can also be further classified from HEVs. Advanced full-HEVs including Internet of Things (IoT), artificial intelligence (AI), and wireless charging capabilities [57] are being developed in order to meet the zero emissions target. Table 1 provides a brief summary of the types of EVs; Fig. 8 shows the differences in electrification among the many types of EVs.

Table 1: Classification of EVs [58,59].

Battery Electric Vehicles (BEVs)	Plug-in Hybrid Electric Vehicles (PHEVs)	Hybrid Electric Vehicles (HEVs)	Fuel Cell Electric Vehicles (FCEVs)
A BEV is a fully electric vehicle that operates entirely on electricity stored in a rechargeable battery. Unlike internal combustion engines (ICEs), they do not emit any tailpipe emissions. Examples include the Tesla Model 3, Nissan Leaf, and Chevrolet Bolt.	PHEVs combine an electric motor and a gasoline or diesel engine. They can run on electric power from their batteries for a certain range and then switch to the internal combustion engine. PHEVs can be charged via an electric outlet. Examples include the Toyota Prius Prime and Ford Escape PHEV.	HEVs have both an electric motor and an internal combustion engine. They use the electric motor to assist the engine and improve fuel efficiency but cannot be charged externally. HEVs are self-charging, generating electricity through regenerative braking and the engine. Examples include the Toyota Prius and Honda Insight.	FCEVs use hydrogen gas to produce electricity through a fuel cell stack, which then powers an electric motor. They produce only water vapor as a by-product and have a longer range than many BEVs. Examples include the Toyota Mirai and Hyundai Nexo.
			

4.1. Full-Hybrid EVs

Combining several technical systems results in hybrid electric vehicles (HEVs), which run the drivetrain from either dual or more sources of energy. To run the car environmentally friendly, HEVs combine an electric motor (EM) with an internal combustion engine (ICE). Car companies trying to satisfy the growing demand for higher fuel economy have embraced full-HEVs in great numbers. These vehicles can run either separately or in unison by means of separate electrical paths for the ICE and the EM. While maintaining performance, this design can increase fuel economy by up to forty percent. An extra energy storage device included in full-HEVs solves running out of fuel during transit [60].

In Series Full-HEVs, the internal combustion engines (ICEs) and electric motors (EMs) collaborate in a sequential manner within the vehicle's mechanism to propel the vehicle. The ICEs generate mechanical energy, which is then transformed into electrical energy for the drivetrain's use. Mostly to charge the batteries, this approach turns alternating current (AC) into direct current (DC) using an AC-DC converter [61]. Operating independently but coupled through a mechanical coupler, the propulsion systems of the internal combustion engine (ICE) and the electric motor (EM) operate parallel full-HEVs. This design enables both the ICE and EM to cooperatively contribute to the vehicle's traction power [62]. The term "series-parallel EV" refers to the tandem hybrid electric vehicle, which incorporates both series and parallel drivetrains into a single system. This enables the vehicle to benefit from the combined features of both configurations [63].

A gear assembly unit links the initial element, which is an engine powered by combustion, to a generator. Following this, there is an electric apparatus constituted of a motor, a battery, and a generator [64]. Advanced Full-HEVs are an evolution of the standard full hybrid electric vehicles, which typically encounter challenges such as bulkiness, higher costs, limited range, and less powerful engines. These cars can overcome the problems by including artificial intelligence and a hybrid energy storage system, therefore turning into advanced full-HEVs. At the tailpipe, the hybrid energy storage technology reduces pollutants and improves drive economy. Moreover, the incorporation of intelligent technology improves HEVs' charging system, dependability, and power output. Advanced full-HEVs will be developed using Internet of Things (IoT), artificial intelligence, wireless charging, and cloud computing to reach zero emissions [65].

4.2. Plug in Hybrid Vehicles

Plug-in Hybrid Electric Vehicles (HEVs), a type of HEVs, contain an Energy Storage System (ESS) that may be externally charged. When the battery is low, these vehicles automatically convert to using fuel, offering increased travel lengths [66]. Plug-in Hybrid Electric Vehicles (PHEVs) predominantly rely on electric power, which necessitates them to have larger batteries compared to standard HEVs. When the battery level is low, PHEVs use the internal combustion engine (ICE) to either boost the vehicle's performance or recharge the battery. Initially, PHEVs operate on electric power. Their batteries can be charged directly from the electrical grid or through energy recaptured during regenerative braking. In areas where electricity is produced from relatively clean energy sources, PHEVs and fully electric vehicles generally emit fewer pollutants from the exhaust to the wheels than conventional gasoline or diesel vehicles [67].

4.3. Pure Electric Vehicles

Often referred to as "pure electric vehicles," battery electric vehicles (BEVs) run on totally rechargeable batteries for their powertrain. Comparatively to conventional energy conversion technologies, these batteries are seen as more environmentally benign. But in recent years, considerable concern has been raised about the environmental effects of battery manufacture and their degradation over time. These batteries are capable of being recharged through a charging port using electricity from the grid or alternative power sources [68]. Battery electric vehicles, unlike traditional internal combustion engines, take a bit longer to charge. The drivetrain of a battery-electric vehicle efficiently converts electrical energy into mechanical energy with minimal loss [69].
Key feature of fuel-cell electric vehicles (FCEVs), sometimes referred to as fuel cell vehicles (FCVs), is fuel cells. The core of the power system of the vehicle is produced by these cells by chemical reactions [70]. Often known as hydrogen fuel cell vehicles, fuel-cell electric vehicles (FCEVs) run hydrogen as the main fuel to start the chemical reaction in fuel cells generating energy. An electric motor running on this electrical power drives the wheels. The Polymer Electrolyte Membrane Fuel Cell (PEMFC) is particularly ideal for vehicle usage because to its high-power density, operational temperatures ranging from 60 to 80 degrees Celsius, and less degradation compared to other types of fuel cells [71-74].

Fuel-cell hybrid electric vehicles (FCHEVs) are a new vehicle concept that results from altering the power system of fuel-cell electric cars (FCEVs). This design adds an auxiliary Energy Storage System (ESS) to boost the fuel cell's functionality. Batteries or ultracapacitors, which may be charged and discharged dependent on the vehicle's power demand and flow, are utilized as the ESS [75]. To ensure that a vehicle runs efficiently and without issues when powered primarily by a fuel cell, with an Energy Storage System (ESS) consisting of either a battery or an ultracapacitor, it's necessary to overcome a number of obstacles. The benefit of these types of vehicles is their ability to produce electricity on their own without releasing any carbon emissions, thereby reducing their carbon footprint more effectively than other electric vehicles (EVs) [76].

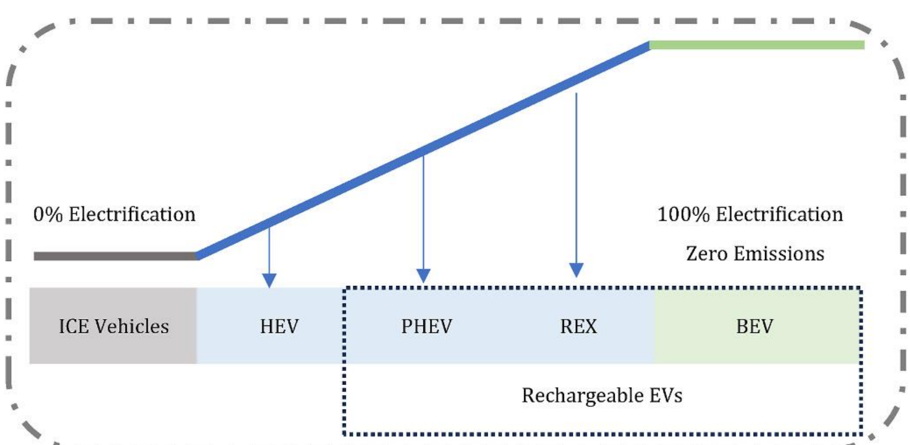


Fig. 8. Various EVs classification [77].

5. ENVIRONMENTAL IMPACT

Particularly battery electric vehicles, or BEVs, electric cars (EVs)—especially have zero exhaust emissions and less greenhouse gas emissions when run on renewable energy sources than internal combustion engine vehicles (ICEVs [78]).Apart from operational emissions, they affect manufacturing, consumption, and disposal as well. Particularly battery manufacture, which greatly adds to CO2 emissions [79,80], the production phase of electric vehicles might be energy intensive. The environmental advantages of EVs rely on the energy mix utilized for charging; renewable energy sources can considerably reduce emissions as compared to fossil fuels [78]. Although these operations can potentially contribute to emissions, recycling and appropriate end-of-life management of EV batteries are absolutely essential for reducing environmental concerns and reclaiming valuable resources [81,82]. Furthermore, circular economy approaches emphasizing resource efficiency, extending material life cycles, and closed-loop recycling are crucial to improve the sustainability of EVs; wrong application might result in higher environmental consequences [83,84]. Standardized approaches and thorough life-cycle analyses (LCAs) are required to guarantee that CE techniques successfully lower the general environmental impact of EVs [85,86].

5.1. Positive Impact of EV's

Some electric vehicles (EVs) choose lead-acid batteries due to their reliability, wide accessibility, and cost-effectiveness. However, in places like the EU and USA, over 99% of lead-based batteries are currently successfully collected and recovered. This percentage is substantial in comparison to other items. Indeed, in the majority of advanced countries, approximately 95% to 99% of used batteries undergo recycling [1]. Unlike conventional internal combustion vehicles, electric vehicles (EVs) have become a model of sustainability and environmental care since they do not spew toxic compounds into the air. Beyond only employing hybrid or electric vehicles, this sustainability includes their design, the materials utilized in their manufacture, the energy footprint during their usage, and the consequent component recycling.

Solar and wind power among other renewable energy sources could be stored to lower charging costs[87-91] or to meet demand during times of highest need. About the infrastructure required for the deployment of electric vehicles, environmentally friendly solutions are being investigated. With an eye towards solar photovoltaic modules, Bhatti et al [92] synthesis several facets of EV charging, including environmental and financial effects of grid-powered photovoltaic EV charging. Likewise, Calise et al. [93] provide a sustainable mobility paradigm based on EVs, photovoltaic energy, and energy storage devices, so demonstrating that solar energy can satisfy a major share of the summertime overall energy consumption. Recycling presents chances to recover valuable materials [94] and lower life cycle costs.

Adoption of cleaner vehicles, including battery electric vehicles (BEVs), offers a possible way to lower the environmental effects of road traffic and, hence, the environmental impact of cities [95]. BEVs run without tailpipe greenhouse gas emissions during operation [81] and run on electricity kept in rechargeable batteries for propulsion. Consequently, the mix of the electricity consumed in the area where they are used [95] determines their emissions. The usage of BEVs might halve GHG emissions compared to a similar fleet of internal combustion engine vehicles (ICEVs) [96] with the expected rise in renewable energy sources (RES) by 2030.

The sustainable development of BEVs [97] depends on applying circular economy (CE) strategies targeted on resource efficiency—through narrowing of total resource consumption, prolonging the use cycle of raw materials and products, slowing down overall resource consumption, and enabling closed-loop recycling[98-100]. One important environmental strategy [101], which promotes battery lifespan extension and repurposing [95], is lowering reliance on virgin raw materials by building secondary supply chains for important and unique metals in the automotive sector. Although recycling might possibly lower the overall impact by 1.5 kg CO_2 eq./kg, some recycling techniques can add up to 2 kg CO_2 eq./kg due to great energy expenditure and low recovery rates [103-104].

5.2. Negative Impact of EV's

In the past, the main problem with these batteries was the environmental impact caused by their creation, consumption, disposal, and recycling operations. Lead, an essential element, can have significant health consequences.

Recent research, meantime, have started to doubt EVs' general environmental impact and sustainability. Three main phases define these issues: (i) their production technique; (ii) their use over their lifetime; and (iii) their disposal and recycling [105-108]. Regarding manufacturing, some studies indicate that, mostly owing to battery manufacture, producing an electric car can demand more than twice the energy required to produce a conventional vehicle [105-106]. Along with current battery manufacture technologies, the mining and processing of minerals vital for EV batteries—lithium, copper, cobalt, manganese, and rare earth elements like neodymium—can require between 350 and 650 Megajoules per kWh [13]. Moreover, every kWh of battery capacity generates 150 to 200 kg of CO_2 emissions; so, a 22 kWh BMW i3 battery may emit about 3 tons of CO_2.

Regarding the use of electric vehicles, a major issue is the great demand for electricity needed to charge them, especially considering their increasing spread [14]. The generating source of this electricity determines its environmental effect. EVs do not produce greenhouse gases or NO_2, hence their environmental advantages are lessened even if the power needed for charging could come from fossil fuels. For example, coal and gas [107] account for around half of Germany's generating of energy. Thus, the utilization of renewable energy for production as well as charging EVs is absolutely vital.

Regarding EV disposal, appropriate recycling is crucial for the effective application of this technology since once the batteries reach the end of their lifetime, they can cause an environmental risk. Some of these incentives, meanwhile, might have unexpected effects, such lower toll income from exempting EVs from toll charges [108]. Furthermore, noted is a 3.6% drop in public transport use in Norway, possibly connected to the fast increase in EV sales since the economic advantages and more comfort of EVs could result in lower public transport use [109]. Designed for great autonomy and electrical power, BEV batteries comprise complicated manufacturing techniques and diverse chemistries that greatly affect their environmental performance [110]. For instance, depending on the chemistry used [111] the production impact of a lithium-based battery can vary from 40 kg to 350 kg CO2 per kWh of battery capacity. Furthermore, displaying considerable fluctuation in recycling methods and related environmental effects [112] is the end-of-life (EOL) management of these batteries.

Still, careful planning of advances in resource efficiency helps to prevent rebound effects. Inappropriate implementation of CE techniques can unintentionally raise BEV's overall environmental effect. For example, employing a large percentage of recycled materials in battery manufacture without considering other life-cycle factors can lower battery lifespan and energy efficiency, therefore raising the total environmental impact [83][84]. Moreover, CE innovations that concentrate just on lowering GHG emissions could result in environmental burden shifting, in which case fixing one environmental issue generates negative effects in other sectors or life-cycle stages [113]. Consequently, a thorough environmental study of CE techniques applied to the design and life-cycle management of EV batteries demands a systems-thinking approach supported by strong, holistic science-based tools like life-cycle assessment (LCA) [85][56] Although many studies on the LCA of BEVs have been done, CE techniques based on these studies are hardly applied. Reviewing 51 LCA studies on the global warming potential of BEVs and ICEVs, Hawkins et al. [114] underlined the lack of standardizing and the great heterogeneity in assumptions, like power consumption, which ranged from 0.10 to 0.24 kWh/km.

In their assessment of 79 LCA research on BEVs, Nordelöf et al. [115] observed that LCA approaches devoid of future time perspectives hinder the long-term environmental performance analysis of BEVs. Marmiroli et al.[116] also express this issue. Another difficulty stressed by Dillman et al. [95]—who examined 25 papers to provide a framework for prospective LCA computations—is the quality and granularity of main data. Reviewing 103 papers on BEV resource efficiency, Dolganova et al. [117]and D'Adamo and Rosa [118] examined the EOL processes of BEVs by means of 171 articles, respectively, revealed that these studies sometimes lack a comprehensive picture of CE. The literature shows a great worry regarding the variation of LCA results for BEVs and their batteries, which demands the creation of criteria and rules to harmonize CE assessments and LCA approaches. But LCA studies on BEVs may center on EOL management , which results in partial analyses of life cycle impacts and maybe negative sustainability-oriented decisions from their limited scope [120]. Below Fig. 9 compares conventional gasoline vehicle emissions to battery-electric vehicles in EU-28, Germany, France, and the US, showing significant reductions in EV emissions, with France showing the highest reduction (-78%) [121].

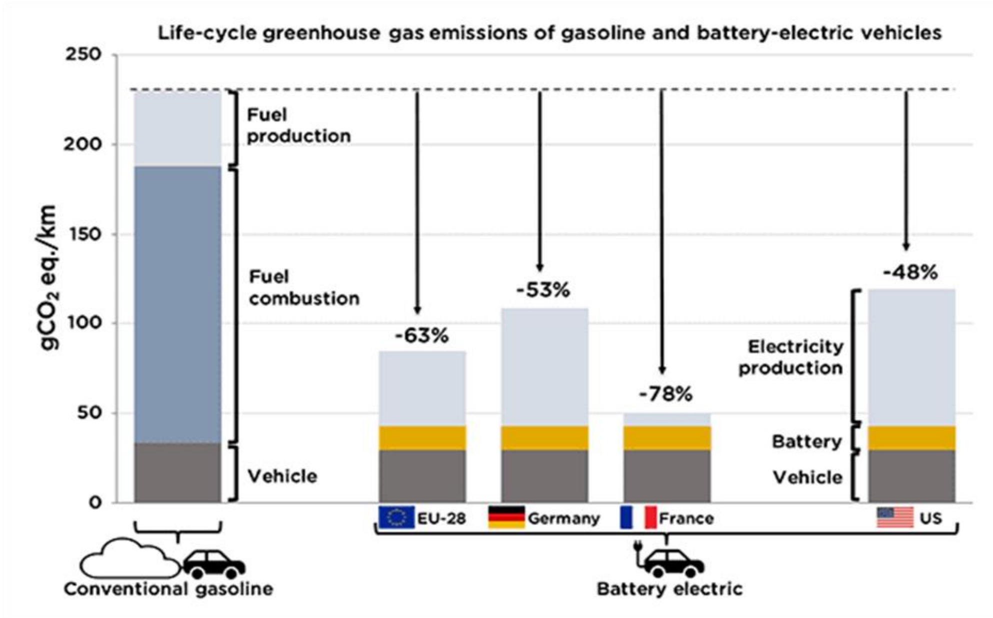


Fig. 9. Life cycle greenhouse gas emission of gasoline and EVs [121].

6. Future Trends of Electric Vehicles

In today's world, a significant number of Original Equipment Manufacturers (OEMs) are engaged in the production of Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), and Fuel Cell (FC) vehicles. The stock of battery-powered and plug-in hybrid EVs exceeded 2 million units in 2016 [122].With worldwide sales over 750,000 units [122] and a 33% rise over 2015 [123], the EV market reached a new high in 2016. China leads the globe in electric car stock, then the US. Many sources indicate that the market's future expansion is bright; some estimates of a worldwide EV stock by 2020 (Fig. 11) point to 20 million units. However, the current global electric car stock represents only 0.2% of the total number of passenger light-duty vehicles in circulation [122]. These forecasts are based on the assumption that they can be achieved as long as they continue on their current trajectory. Assuming that all the underlying conditions are met, it's more pragmatic to envision a scenario where the rise in electrified vehicles is projected to be between 9 million and 15 million units by 2020 [123]. Fig. 10 shows the electric vehicle (EV) market in 2016 showed varying adoption rates across different regions, with China and the US leading the way. Norway led with 29.0% of its market, followed by Iceland and the Netherlands [122] and Fig.11 shows the growth of electric car inventory up to 2030, based on various scenarios and targets, including the Paris Declaration and EV30@30 campaign. Historical data and cumulative country targets indicate a significant increase in adoption.

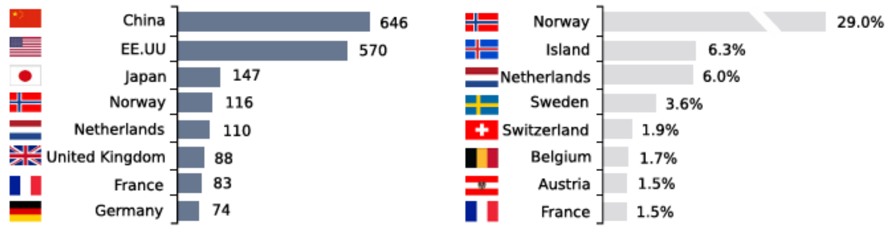


Fig. 10. Electric vehicle market in 2016 [122].

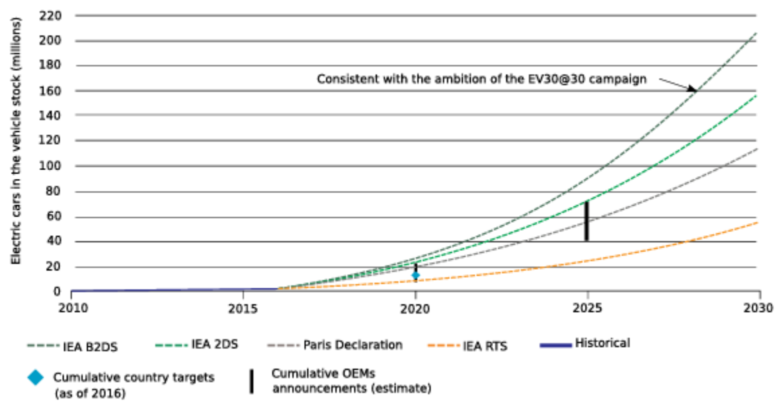


Fig. 11. Illustrates the projected growth patterns for the inventory of electric cars up to 2030, as predicted by pertinent authorities [122].

The most prevalent technologies in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) are Permanent Magnet Synchronous Machines (PMSMs) and Induction Machines (IMs) [124]. This is primarily due to their high efficiency and superior power density, which is especially important in HEVs because of their limited space. Specifically, Interior PMSMs are used because their additional reluctance torque allows for a higher power density than Surface Mounted PMSMs [125]. However, technologies that don't rely on rare-earth magnets are becoming more popular [126,125,127] due to the scarcity, price volatility, and high costs associated with these materials (neodymium and, in smaller amounts, dysprosium and terbium) [127–131].Among these, the mature squirrel cage IM [133–137] is rather popular in the automotive sector. The scientific community is also attracted by alternative electric machine technologies as Switched Reluctance Machines (SRM) [138–142] and Ferrite-based Permanent Magnet Assisted Synchronous Reluctance Machines (PM-assisted SynRM) [143–147].

TABLE 2: The progression of battery capacity from the mid-1980s to the present [148].

Vehicle	Year	Capacity (kWh)
Audi duo	1983	8
Volkswagen Jetta citySTROMer	1985	17.3
Volkswagen Golf	1987	8
Škoda Favorit	1988	10
Fiat Panda Elettra	1990	9
General Motors EV1	1996	16.5
Audi duo	1997	10
General Motors EV1	1999	18.7
General Motors EV1	2000	26.4
Tesla Roadster	2006	53
Smart ed	2007	13.2
Tesla Roadster	2007	53
BYD e6	2009	72
Mitsubishi i-MiEV	2009	16
Nissan Leaf	2009	24
Tesla Roadster	2009	53
Mercedes-Benz SLS AMG E-Drive	2010	60
Tata Indica Vista EV	2010	26.5
Volvo C30 EV	2010	24
Volvo V70 PHEV	2010	11.3
BMW ActiveE	2011	32
BMW i3	2011	16
BYD e6	2011	60
Ford Focus Electric	2012	23
Renault Zoe	2012	22
Tesla Model S	2012	40, 60, 85
BMW i3	2013	22
BYD e6	2013	64
Volkswagen e-Golf	2013	26.5
Renault Fluence Z.E	2014	22
Tesla Roadster	2014	80
Chevrolet Spark EV	2015	19
Mercedes Clase B ED	2015	28
Tesla Model S	2015	70, 90
BYD e6	2016	82
Chevrolet Volt	2016	18.4
Tesla Model 3	2016	50, 75
Tesla Model X	2016	90, 100
BMW i3	2017	33
Ford Focus Electric	2017	33.5
Jaguar I-Pace	2017	90
Nissan Leaf	2017	40
Tesla Model S	2017	75, 100
Audi e-tron	2018	95
Kia Soul EV	2018	30
Nissan Leaf	2018	60
Renault ZOE 2	2018	60
Renault ZOE 2 rs	2018	100
Tesla Model 3	2018	70, 90
Mercedes-Benz EQ	2019	70
Nissan Leaf	2019	60
Volvo 40 series	2019	100
Audi e-tron	2020	95
BMW i3	2020	42
Hyundai Kona e	2020	64
Mercedes EQC	2020	93
Mini Cooper SE	2020	32.6
Peugeot e-208	2020	50
Volkswagen ID.3	2021	77
Ford Mustang Mach-E	2021	99
BYD ATTO 3	2022	60
BYD Seal	2022	82
Tesla Roaster	2022	200

Today, one of the significant challenges is the storage difficulties associated with high costs. This issue can only be addressed through the advancement and enhancement of battery technology to achieve a higher energy density [148], [149]. Batteries with high energy density and large capacities can be an effective solution to the common problem of range anxiety. It can also enhance the reliability of EVs and reduce the frequency of charging cycles, thereby extending battery life and delaying maintenance needs. The progress in battery capacity for EVs over the years is outlined in Table-2. The high internal resistance of contemporary batteries presents another challenge as it can result in extended charging times, excessive heat generation, safety concerns, and reduced battery life. This is a significant limitation in the EV industry today. The development of battery technology to lower internal resistance can lead to less heat generation, prevent energy losses, make batteries more repairable, ensure shorter charging times, and improve charging and discharging efficiency [150].

7. CHALLENGES

One major financial obstacle are electric cars (EVs). Lack of maturity in EV technology has caused many issues, hence it is difficult to compete with more reasonably priced conventional vehicles driven by internal combustion engines (ICEs). The development of electric vehicles needs for cooperation among several players, especially the government. Although national policies have great influence on the EV industry, they also have significant financial consequences. For example, China, the second-largest economy in the world, is quite important in promoting electric vehicles all around [151]. Being one of the main producers of oil worldwide, the emergence of electric vehicles (EVs) would have a big impact on China's petroleum industry, hence indirectly affecting their economy [152]. Reducing the cost of electric vehicles (EVs) and quickening the speed of EV technological development will help to appeal them more to the general people. Currently the primary barrier keeping EVs from entering the current market is their high selling price [153].

7.1. Battery

Regardless of their use, the cost of batteries has always been a significant concern. In recent years there has been a notable decrease in battery prices while their energy density has been gradually increasing. This trend has contributed to the expansion of the electric vehicle (EV) market. Despite the reduction in battery costs, economically manufacturing batteries on a large scale remains a challenge due to the high costs associated with the use of expensive materials and advanced processes in EV applications. Current technologies are not yet capable of producing high-performance batteries using traditional materials. The batteries used in EVs need to have a high energy capacity to enable a longer range, which necessitates the use of certain quality materials in their construction, thereby increasing the cost [154]. The lithium-ion (Li-ion) batteries used in EVs present a very concerning supply chain issue. It has been reported that the extraction of cobalt, the essential component of the rechargeable Li-ion batteries, is linked to child labor [155]. The cost of cobalt has increased fourfold due to a rapid surge in demand for the mineral in recent years. The Democratic Republic of Congo (DRC) mines two-thirds of the world’s cobalt, and the fact that children often work in these artisanal mines alongside adults presents both ethical issues and economic challenges for multinational corporations. “The cost of cobalt has increased fourfold due to a rapid surge in demand for the mineral in recent years. The Democratic Republic of Congo (DRC) mines two-thirds of the world’s cobalt, and the fact that children often work in these artisanal mines alongside adults presents both ethical issues and economic challenges for multinational corporations [156]. The difficulties faced in battery development closely mirror the economic challenges associated with electric vehicles (EVs) mentioned earlier. According to Li and Ouyang, lowering the cost of EV batteries could reduce the overall expenses for consumers, thereby making it more feasible for them to afford the higher costs associated with battery charging [157]. The elevated cost of batteries is why electric vehicles (EVs) will continue to be more expensive than traditional internal combustion engine (ICE) vehicles in the near future, even with government purchase subsidies available in many countries. The sole method to lower the price of EVs is to enhance and broaden the production line to increase the production volume of EVs, thereby making them more affordable for the market. Some research suggests that for EVs to penetrate the mass market without government purchase subsidies, the cost of batteries must be significantly reduced first [154]. The Fig. 8 bar graph illustrates a considerable expansion in battery sales across several sectors from 1990 to 2022+, with a noteworthy spike starting around 2010. The sectors include Commercial EVs, Passenger EVs, E-buses, Two/Three-wheelers, Automotive (all), Stationary storage, Consumer electronics, and Other and blue arrow represents a growth rate of 33% per year. This demonstrates the increased demand for energy storage options[155].

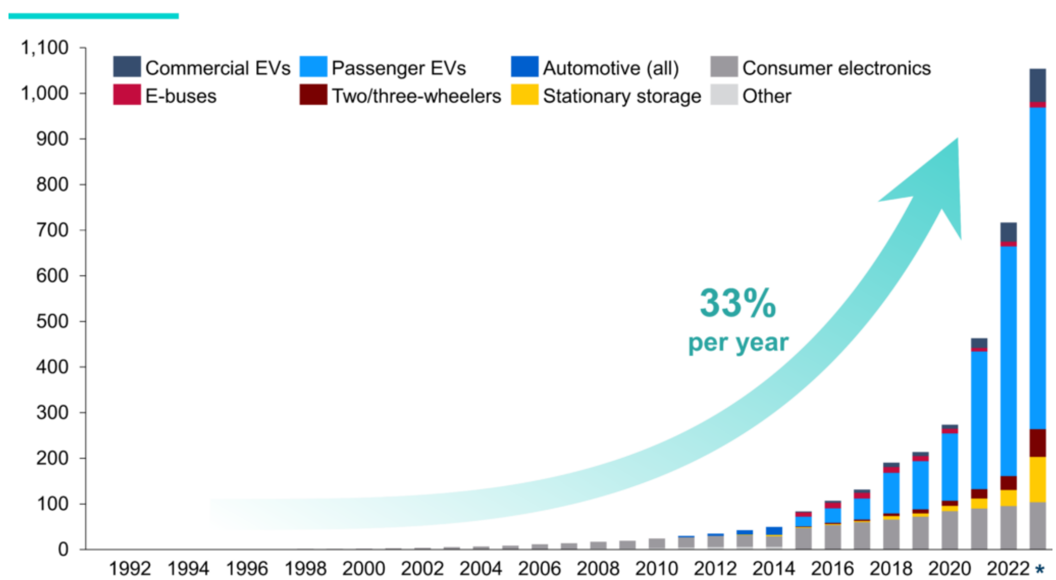


Fig. 12. Global battery sales by sector, GWh/y [155]

7.2. Charging Infrastructure

The charging infrastructures for electric vehicles (EVs) can be categorized into public, semi-public, and private categories according to their accessibility. Public charging infrastructures are usually found in public parking lots and are accessible to all users. Conversely, semi-public charging infrastructures are restricted to a particular demographic. Private charging infrastructures are those installed in private garages or homes. Private charging infrastructures are more numerous than public ones, as they are more accessible and favored by EV users [156,158]. Nevertheless, it’s widely recognized that public charging infrastructures play a vital role in promoting the use of electric vehicles (EVs) and in alleviating the ‘range anxiety’ experienced by EV users [159]. The cost of charging, subsidies for building and operating, and the number of charging units have a direct relationship with the profit of the charging infrastructure. However, factors such as charging demand, location, and the number of electric vehicles (EVs) interact with the profit in more complex ways. For example, the revenue and number of charging units are heavily influenced by the charging demand, which in turn impacts the capital cost of the charging infrastructure [160]. Setting up charging infrastructures in city centers and urban locations provides convenient access for electric vehicle (EV) users, but it often involves higher land lease costs. On the other hand, to alleviate the 'range anxiety' of EV users, it's important to have charging infrastructures in both urban and rural areas [161,162].

7.3. Environmental

Using electric vehicles (EVs) instead of internal combustion engine (ICE) vehicles improves environmental quality. EVs, which are powered by batteries and emit no tailpipe emissions, are considered eco-friendly. The burning of petroleum in ICE vehicles releases harmful toxins into the air, which are detrimental to both humans and the environment. However, it's important to note that the process of generating power to charge EVs also results in the emission of greenhouse gases, which contribute to global warming [163]. The operational principle of electric vehicles relies on electrical energy, which leads to a decrease in the demand for petroleum. Consequently, the energy storage systems in electric vehicles have a minimal effect on environmental pollution. However, the manufacturing and processing of these energy storage systems, as well as the disposal of electrochemical batteries, could lead to respiratory, pulmonary, and neurological health issues. Therefore, safety precautions must be prioritized during the production of energy storage systems, particularly batteries [164]. Given that electric vehicles (EVs) emit no tailpipe emissions, it's crucial to comprehend and pinpoint the potential environmental impact stemming from the generation of electrical power. The batteries in an EV need to be recharged once their capacity is exhausted, which can be accomplished at a charging station. These stations draw electrical energy from local power grids to recharge EVs, a process that results in a significant amount of carbon being released into the environment. Fig 13 illustrates the CO2 intensity generated by an electrical grid in Iceland from January 2011 to June 2015, with each data point representing the daily average CO2 intensity. Fig.13 line graph illustrates the changes in CO2 intensity, measured in grams per kilowatt-hour (gCO2/kWh), over a five-year period. This data is vital for understanding the environmental impact of electricity generation and feeds discussions on sustainable energy policies. The graph provides as a visual representation of the trends in carbon emissions, which is a significant part of measuring the ecological footprint of electric networks [165].

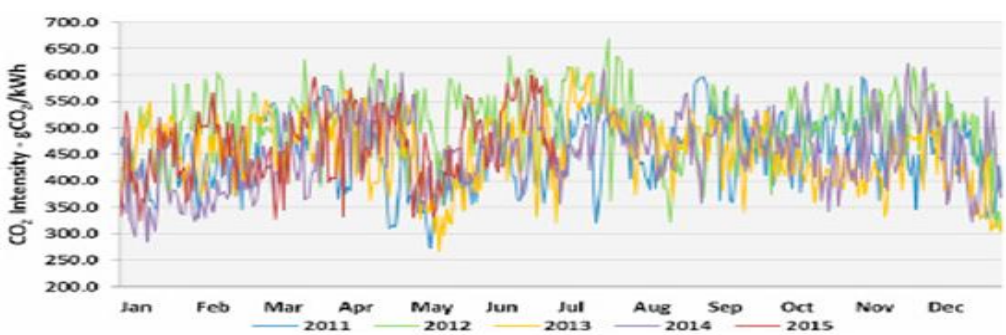


Fig. 13. CO2 intensity produced from an electric grid from 2011 – 2015. [165]

It has also been determined that as the energy consumption (in kWh) increases, the total amount of CO2 emissions also rises. It can be inferred that the CO2 emissions are influenced by the charging consumption of each individual electric vehicle (EV), which impacts the overall energy usage. The cumulative emission of CO2 over an EV's lifespan will result in noticeable environmental changes [165].

8. CONCLUSION

The paper emphasizes the transforming power of electric vehicles in changing our transportation systems and supporting environmental sustainability. From the progression of EVs to the development of several kinds of EVs, it recognizes the main success achieved on the sector. Emphasizing the need of a fair viewpoint considering the complete lifetime of EVs, the environmental benefits and drawbacks of choosing EVs are stressed. Driven by ongoing innovation and growing market demand, the paper projects exciting prospects in the EV industry ahead. However, it also cautions against the challenges that could hinder the general adoption of EVs, including infrastructural limitations, battery technology constraints, and cost problems. The paper concludes with a call for continued study, policy support, and business collaboration to overcome these challenges and realize the full potential of EVs. This comprehensive review serves as a useful resource for anyone interested in the future of sustainable transportation.

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