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Life Cycle Carbon Footprint Beyond Manufacturing

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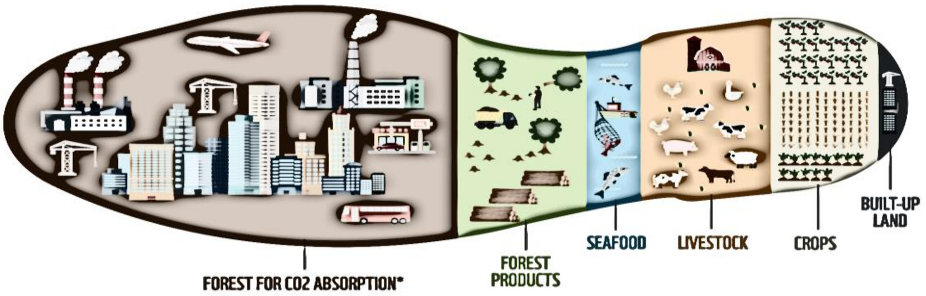
Abstract

In the words of **Jennifer O'Connor**, Epistles "A leading voice on life-cycle assessment offers a call to action for responsible use of LCA for sustainable design."

True sustainability in transportation only involves and benefits from a vision far beyond the usual simplification over a manufacturing-centric look. This thesis throws itself into the complex arena of Life Cycle Carbon Footprint head on by making full use of the Life Cycle Assessment model through rigorous application to the environmental effects of internal combustion engine vehicles and electric vehicles within their entire life cycle. From raw material extraction to the complexity of the manufacturing process to operational energy consumption and end-of-life disposal or recycling, the paper closely investigates each stage with a desire to uncover the subtle realities behind such technologies. The cases draw from around the globe and within India, coupled with insights gained from my professional experience at Peec Mobility, unearthing the complex play of variables that influence lifecycle carbon footprints. The critical review that tackles the challenges in the production of energy-intensive batteries in the case of EVs is the carbon dependency of the dominated power grid for India, and infrastructure disparity in readiness at one go reveals unused potential for the adoption of renewable sources, advancement in circular economy practices, and transformative impact of policy frameworks on lifecycle emissions.

It balances two aspects global benchmark and the Indian scenario presenting a holistic story that underlines the importance of contextual solutions to achieve sustainable transport, which would be the passport to a future transportation system.



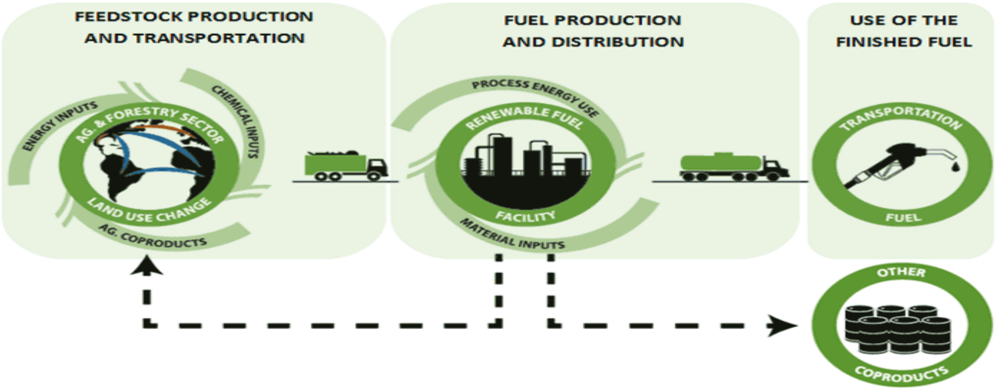
Keywords: Lifecycle, Sustainability, Emissions

INTRODUCTION

As the world dukes it out with climate change, possibly there is more than any immediate need to look at the environmental impacts that run along products and systems. A product's carbon footprint goes beyond the production stage; it runs from raw material extraction to its manufacture, transportation, usage, and eventually disposal. Transportation is another significant source of global GHG emissions. Emissions by them have received attention that is sustained and increasing, as societies are increasingly looking for sustainable solutions. One promising alternative to ICE is electric vehicles, and these are significantly extolled as having an excellent chance of decarbonizing the mobility sector. But closer study shows that while EVs reduce tailpipe emissions, they create enormous environmental trade-offs across other lifecycle stages. The concept of a life cycle carbon footprint is quite critical in understanding the global environmental impacts created by ICE and EV technologies. Therefore, LCCF represents the aggregate greenhouse gases produced at every step of an auto's lifecycle. While usage-phase emissions from ICE vehicles are well established via fossil fuel combustion, the profile for EVs is different. Its usage-phase emissions depend mainly on the carbon intensity of electricity grids, but environmental impacts in production, notably the energy-intensive battery, are major. Added to these considerations are end-of-life recyclability of batteries and waste management, which present unique challenges that will require further innovation and infrastructure development. The LCA model provides a reasonable framework for looking at those impacts. It methodically passes through the environmental footprint of a product from all its lifecycle stages. Thus, it gives a holistic perspective on the sustainability of the product. In transportation, LCA is indispensable in making a fair comparison of the real environmental costs between ICE vehicles and EVs.

1. Understanding the Contextualization of Life Cycle Carbon Footprint

The life cycle carbon footprint (LCCF) is the amount of greenhouse gases emitted by a product from its entire lifecycle, such as raw material extraction and product manufacturing to in-service use and eventual end-of-life disposal. For transportation by itself, this LCCF makes up a holistic view of sustainability, considering emissions above and beyond the simple use of operation by electric vehicles and internal combustion engine-based automobiles. Overall environmental impacts of technological choices are found in the understandings of LCCF. For EVs, whereas operational emissions are significantly much smaller than those for the equivalent ICE vehicle, manufacturing carbon footprint is high. Further, the source of the energy used to charge EVs makes a big difference in total carbon footprint: an EV charged with renewable energies such as solar or wind can have LCCF dramatically smaller than one that relies on coal-based electricity grids.



The contextualization of LCCF will help make informed decisions by policymakers, the manufacturer, and the consumer, focusing on reduction in emissions through efficiency improvement in the battery, increased uptake of renewable energy, and optimizing recycling processes. Through a life cycle perspective, stakeholders can spot the trade-offs, prioritize sustainable practices, and work toward a net-zero future, ensuring that the technologies transitioned from have the supposed end environmental benefits.

2. Understanding the Life Cycle Assessment (LCA) Model

Recently, sustainable industries have picked up immense speed across the globe, and the Life Cycle Assessment (LCA) framework proved to be an instrumental tool to gauge environmental impacts. LCA offers a highly detailed overview of the ecological impact by assessing any product, process, or service at all stages of its life cycle. The transportation industry is of particular significance as the environmental costs of conventional and electric vehicles extend beyond the manufacturing horizon into the usage, maintenance, and final disposal stage of any vehicle.

2.1 Conceptualization and Structure

An LCA is thus an organized framework that must have a detailed quantification and evaluation of environmental impacts that are associated during each stage of a product's life cycle. Unlike other traditional assessments, which focus on a single stage like the production stage, LCA encompasses every phase; therefore, it provides a holistic view of a product's sustainability. The LCA structure can be broken down into five independent stages:

1st Stage; Raw Material Extraction

This encompasses procuring raw materials that will be used in the production of the product. For vehicles, it would include extracting metals like lithium, cobalt, or nickel for battery usage in EVs or extracting crude oil and refining it to gasoline for ICE vehicles. Environmental costs like energy-intensive processes in mining, habitat destruction, water contamination, and large amounts of carbon dioxide emitted into the environment. For instance:

Lithium Mining: Lithium is an essential material in EV batteries, which involves water-intensive processes. It induces groundwater depletion and ecological disruption in mining regions such as South America's Lithium Triangle.

Petroleum Extraction: The extraction, refining, and shipment of crude oil for use by ICE vehicles involve some emissions and an oil spill risk, which threatens marine ecosystems in some additional ways.

2nd Stage; Manufacturing and production

The manufacturing phase, therefore, involves converting raw materials into parts that can be used to form the final product and assembling these components. The latter is energy-intensive and has a high carbon footprint. This stage is particularly energy-intensive in the production of EVs for battery manufacturing.

EVs: Battery production contributes the most to emissions. For example, the production of a 60 kWh EV battery will have emissions equated to 9–15 metric tons of CO_2 through the process consumed in its manufacture.

ICEs: The production of ICE automobiles has fewer emissions than EVs, but the assembly process, material utilization, and painting process contribute to the overall footprint.

3rd stage; Transport and Distribution

Once produced, the automobiles are shipped to dealerships or customers. At this stage, there is emission from shipping, trucking, or air transport. Automakers often source components from different parts of the world, increasing emissions through long-distance transportation. For instance, EV batteries are often produced in one country, shipped to another for vehicle assembly, and then distributed globally.

Firms operating localized production facilities, exemplified by Tesla's Giga factories, have aimed to diminish emissions by streamlining production and assembly operations.

4th stage; Utilization Stage

Usage constitutes the highest and longest period in a vehicle's life cycle. This is also when vehicles release most of their emission, either direct or indirect from the consumption of energy.

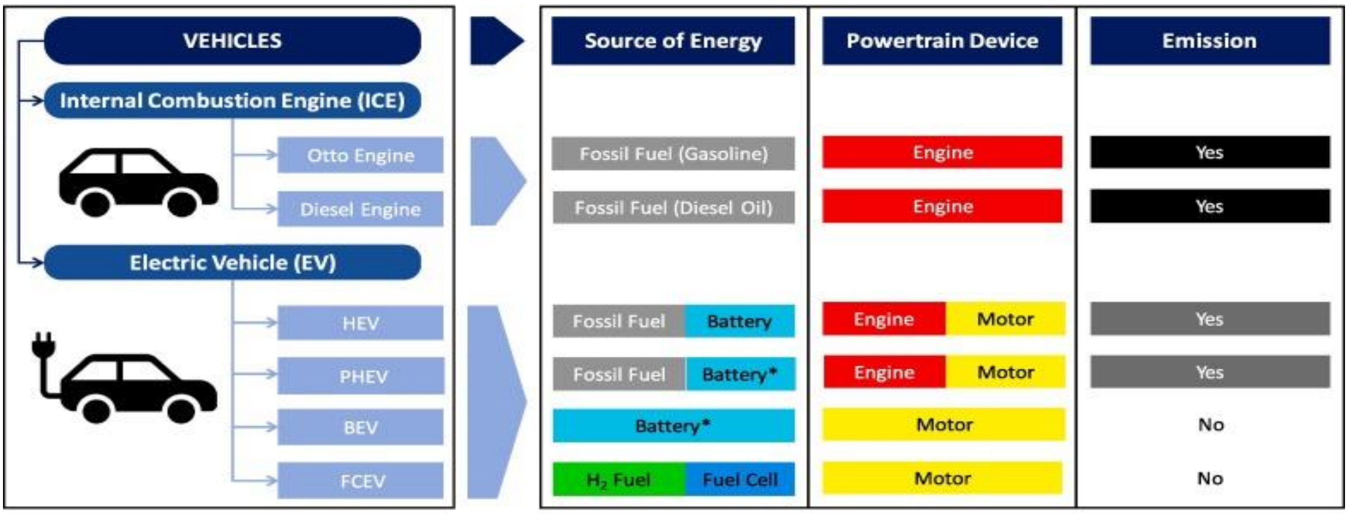
2.2 ICE v/s EV's

Internal Combustion Engines (ICEs):

Vehicles whose types of engines use fossil fuels for burning to generate mechanical energy include petrol, diesel, and natural gas. The combustion process gives large quantities of GHGs emitted during the combustion process that consist of CO2, CO, and NOx. The greenhouse gas most involving carbon dioxide is key in global warming, and NOx causes the formation of smog and also presents a risk to health issues about respiratory functions. In addition, particulate from the exhaust emitted by ICE exacerbates air quality degradation, thereby creating public health issues. For instance, a typical petrol-fueled car emits about 120 grams of CO2 per kilometre, depending on which fuel efficiency is deployed. So, the high mileage of ICEs aggravates such impacts over their operational life. In general, these are not hard to recycle from a materials recovery point of view. Steels, aluminium, and other metallic components can be easily recycled. Difficulties arise in handling streams for used motor oil, transmission fluids, etc. In most cases, metal recycling from ICE vehicles is over 90%, but the contribution of recycling to environmental impacts, such as energy consumption associated with smelting, also needs to be accounted for.

Electric Vehicles (EVs):

In stark contrast, EVs produce no tailpipe emissions, which makes them attractive for reducing urban air pollution. However, the overall environmental impact during the usage phase is intricately tied to the energy mix of the electricity grid. In regions with renewable energy-dominated grids, such as Norway or Iceland, EVs offer substantial lifecycle emissions reductions compared to ICEs. Indirect emissions can add up while charging the batteries of EVs, offsetting its benefits. For example, in a coal-based grid, the emissions from charging an EV could be equal to or even higher in comparison to the frugal ICE vehicle. In addition to GHG implications, the electricity demand of EVs puts pressure on the grid infrastructure, possibly increasing dependence on peaking power plants at peak-demand times. This underlines the significance of decarbonising the grid in step with EV adoption for them to fully realise the potential to reduce lifecycle emissions.



VEHICLES	Source of Energy	Powertrain Device	Emission
Internal Combustion Engine (ICE)			
Otto Engine	Fossil Fuel (Gasoline)	Engine	Yes
Diesel Engine	Fossil Fuel (Diesel Oil)	Engine	Yes
Electric Vehicle (EV)			
HEV	Fossil Fuel Battery	Engine Motor	Yes
PHEV	Fossil Fuel Battery*	Engine Motor	Yes
BEV	Battery*	Motor	No
FCEV	H_2 Fuel Fuel Cell	Motor	No

*Completed with Plug In

End-of-Life Stage for (ICE's)

The end-of-life stage includes decommissioning, recycling, or disposing of a vehicle and also extracting valuable materials from it. Even though, on average, it makes up for a lesser share of the overall lifecycle emissions compared to the usage phase, it is highly challenging and full of prospects to make the vehicle more sustainable.

Electric Vehicles (EVs):

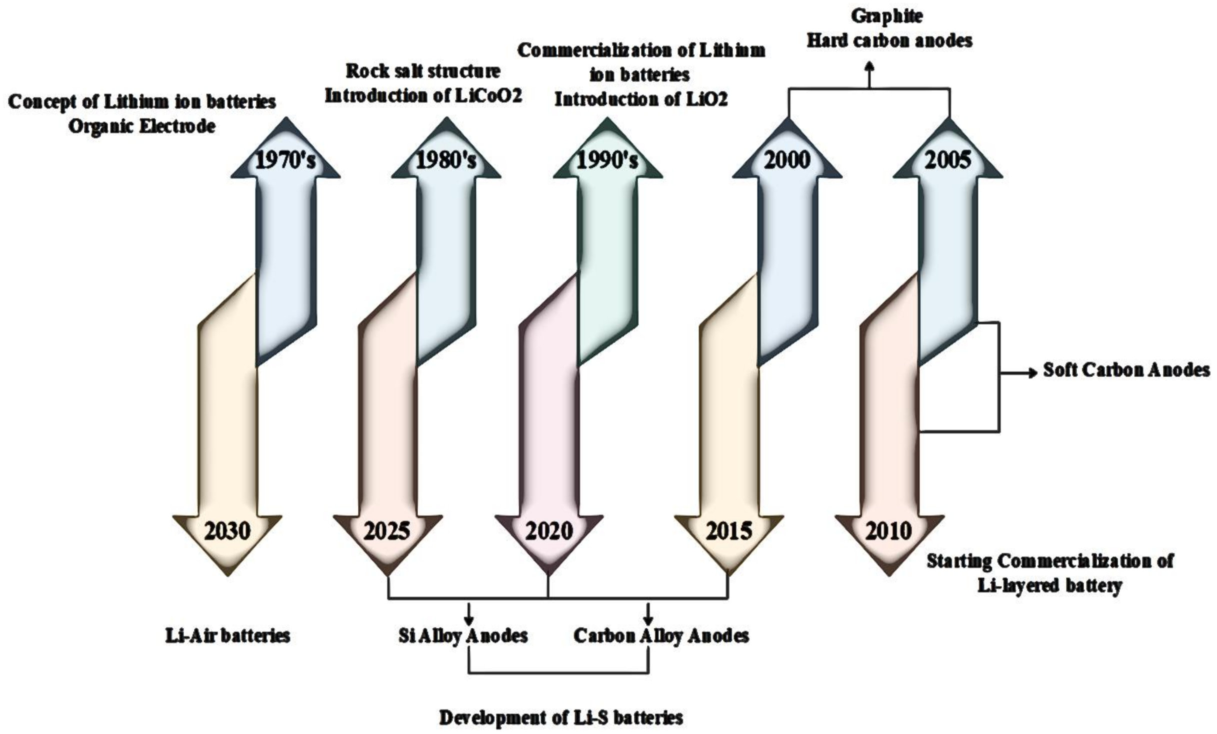
The end-of-life stage for EVs is much more complex with big lithium-ion batteries. Lithium, cobalt, and nickel are incorporated into batteries; thus, the valuable metals could potentially be recovered and recycled. In most regions, especially developing countries such as India, battery recycling infrastructure remains embryonic. Improper disposal of EV batteries carries a serious risk to the environment in addition to soil and water contamination by harmful substances consisting of lithium and manganese; the recycling process is highly energy-intensive and not yet optimized for efficiency.

Coming to the International System, Norway is a good example of the potential EVs can show in creating an almost negligible lifecycle carbon footprint with nearly 98% of its electricity coming from renewable sources. Recycling and second-life applications add further value to sustainability aspects. Another example is the regional differences in the U.S. drive the importance of grid composition. The heavily renewable-heavy-dependent state of California more clearly demonstrates the environmental advantages of EVs, whereas coal-dependent states leave a much more modest gap between ICE and EV lifecycle emissions.

3. Resource intensity and ecological footprint

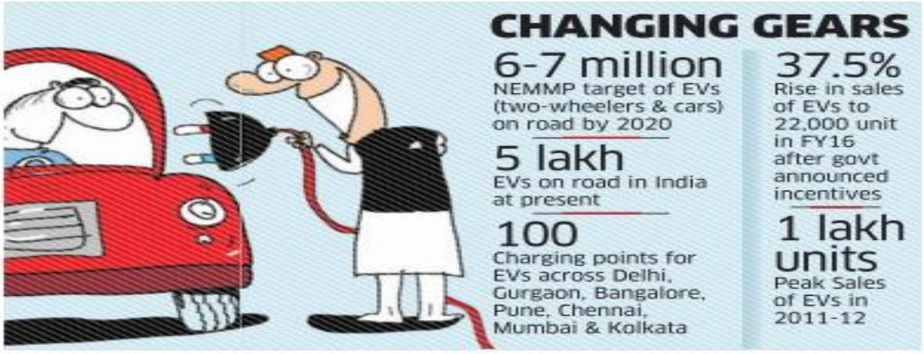
ICE vehicles have been the backbones of automotive transport for well over a century, with manufacturing processes that are relatively streamlined and optimized. The production processes for ICE vehicles are less energy intensive than those of EVs, mainly because the drivetrain is not complex compared to those used in EVs, and no massive battery system is needed. The ecological consequence of ICE manufacturing arises mainly from the raw materials extracted for its assembly such as steel, aluminum, and plastic and the emissions that accompany it. EVs are more resource- and energy-intensive, primarily because lithium-ion battery packs are integral to functionality. The battery manufacturing process includes extraction, purification, and assembly, and each one of the processes is associatzd with significant costs in environmental terms. For example,

Global Data: Manufacturing a 60-kWh battery pack for an electric vehicle (EV) requires the emission of hundreds of kilograms of CO2, equivalent to between 9–15 metric tons, depending upon efficiency in manufacturing, choice of materials, and regional energy supplies. This is around a third of an EV's total lifecycle emissions, also including generation emissions when in use for electricity. Available research suggests that emissions in battery production are primarily due to energy-intensive production steps, for example, synthesis of cathode and electrolyte materials and assembly of the cell. Regions using coal and other fossil fuels for electrical generation intensify this carbon legacy. While electric vehicles reduce tailpipe emissions compared to ICEs, battery manufacturing emissions are significant, thus, emphasizing the necessity for supply chain decarbonization. A transition towards renewable energy sources in manufacturing and optimization in the recycling of batteries will significantly reduce lifecycle emissions. Available research suggests that the lifecycle advantage of EVs over ICE vehicles may continue to improve as energy grids become greener and battery recycling scales up. The proposed reductions in GHGs may be as high as 50–70% over time.



Material Requirements: The latest development of electric vehicle batteries required the mining and processing of essential minerals such as lithium, cobalt, and nickel. Related to them are serious environmental impacts. Mining harms habitats, pollutes water, and releases massive amounts of carbon. For instance, to extract one ton of lithium, about 500,000 gallons of water are needed. This can also mean scarce freshwater supplies in arid locations like the Atacama Desert. Cobalt mining, mostly concentrated in the Democratic Republic of Congo, does not have good labour or deforestation practices. Nickel mining leads to soil and water degradation because of acid leaching. All these processing steps require energy-intensive refinement steps, releasing yet more CO2, particularly in regions where the energy grids have strong commitments to fossil-based fuels. Coming full circle, mitigation aspirations involve early research into families of battery chemistry, including lithium-iron-phosphate (LFP) and developments in the solid state, all of which reduce dependency on rare or environmentally unfriendly materials. Additionally, the incorporation of circular economy practices, such as enhanced recycling and use of spent batteries, can also neutralize the negative environmental impacts of new mineral extraction. Scaling the practices of sustainable mining and the new concepts in innovative battery designs will remain key to reducing the ecological footprint of EVs.

Indian Context: In India, the carbon intensity of manufacturing EV batteries is high because the country's energy mix is dominated by coal-fired electricity contributing to 70 per cent of the energy mix. Therefore, making an EV battery domestically is perhaps 20-30% more carbon-intensive than in a purer energy grid, such as Norway or Sweden, which is largely fed by renewable resources. For instance, the production of a 60 kWh battery in India would emit about 18-20 tonnes of CO2, whereas in cleaner grids, it would be around 9-15 tonnes of CO2. This gap therefore necessitates a change in India's direction towards more environmentally friendly energy sources. Such policy interventions and financial incentives, like the National Electric Mobility Mission Plan (NEMMP) and those for renewable energy, attempt to address such challenges, yet large-scale implementation remains a challenge. Gaining momentum in setting up gigafactories dependent on renewable energy sources - and specifically designed under schemes like Production Linked Incentive (PLI) for advanced chemistry cells - offers a cheerful possibility for India to reduce emissions. Stacked with technological improvements in recycling batteries and second-life applications, these practices would reduce the lifecycle carbon emissions from EVs in India by considerable margins. However, for it to acquire a stamp of global competitiveness and sustainability, clean energy infrastructure investments and a local, eco-friendly supply chain supply would be necessary.



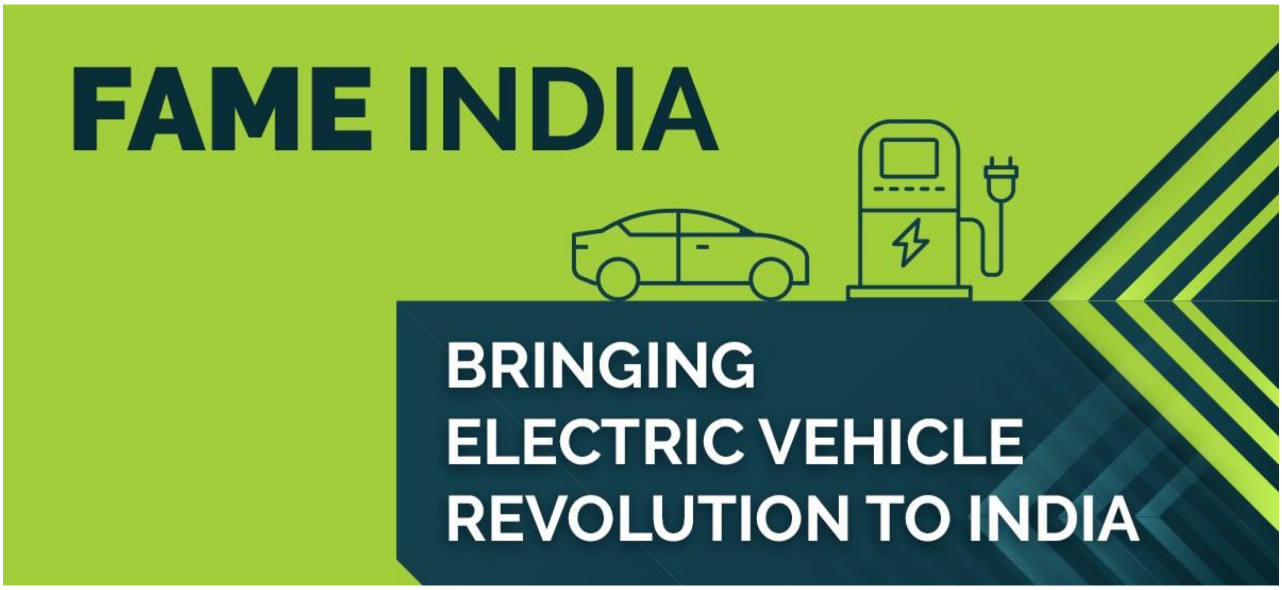
3.1 Recent Developments

Innovations in the type of battery chemistry, new ones including solid-state batteries, and alternative options like lithium iron phosphate, change the energy storage game: helping with issues related to resource dependency and ecological damage. Replacing liquid electrolytes with solid materials, solid-state batteries promise greater energy density, faster charging, and enhanced safety while reducing reliance on cobalt metal found in scant, finite amounts everywhere in the world. Incidentally, LFP still relies on more readily available materials than the other versions, which keeps costs lower and makes it particularly appealing for large-scale applications in EVs and Grid Storage. Manufacturers have also been following these innovations with a line of renewable powered Gigafactory that cut emissions during production, using solar, wind or hydroelectric energy powering the plant to reduce the carbon footprint of making the battery. This synthesis of technological innovation and sustainable practice is the decisive step toward a greener, more efficient future in the energy sector.

Case Studies

Case Study 1: F.A.M.E. India Scheme and Its Role in Accelerating Electric Vehicle Adoption

Indian transport is at a par with sectoral transformation as it is adopting electric vehicles with open arms. The country stands at a critical juncture, with the establishment of ambitious targets to reduce greenhouse gas emissions and a decrease in reliance on fossil fuels, while leading the EV manufacturing process in the world. However, dependence on coal-generated electricity and poor infrastructural facilities have seriously affected the development process, not to mention the environmental implications associated with the manufacture of electric vehicle batteries. This case study analyses the myriad dimensions that bear upon India's electric vehicle trajectory-from policies to market forces to challenges-influencing transition.



Context and Strategic Importance

India is one of the fastest-growing automobile markets; transport or transportation accounts for around 14% of the total carbon emission. The government is eager to embrace EVs in consideration of its international commitments towards reducing escalating global warming up to 1.5°C so that extreme climatic conditions can be avoided. Mass penetration of EVs reduces air pollution considerably from the urban areas since vehicle pollution is one of the major aggravating factors in such towns. These notwithstanding, however, the share of EVs in the Indian vehicle market remains miniscule, with EVs accounting for less than 1% of passenger vehicle sales since 2023. More significantly, notable improvements have been made in the two and three-wheeler EV segments, but its overall penetration is far off the scale from what would be required to impact the environment meaningfully. The Indian Government has also undertaken several initiatives to overcome the barriers for adoption of EVs. The most central among these is FAME- Faster Adoption and Manufacturing Hybrid and Electric Vehicles, which launched in 2015. Consumer subsidies featured in the initial phase of FAME, but FAME-II was more robustly designed with features including public transport electrification, such as buses and three-wheelers, along with establishing charge infrastructure.

The PLI program complements the FAME initiative, enabling incentives for domestic manufacturing of advanced battery technologies. The Centre has also published draft guidelines related to Extended Producer Responsibility or EPR to ensure manufacturers decide for safe recycling and disposal of EV batteries. Delhi, Karnataka, and Maharashtra have formulated their own policies regarding EVs. State-specific policies have incorporated tax sops and subsidies for building charging points, in addition to mandating that public transport fleets are made electric.

Market Dynamics and Passenger Vehicles

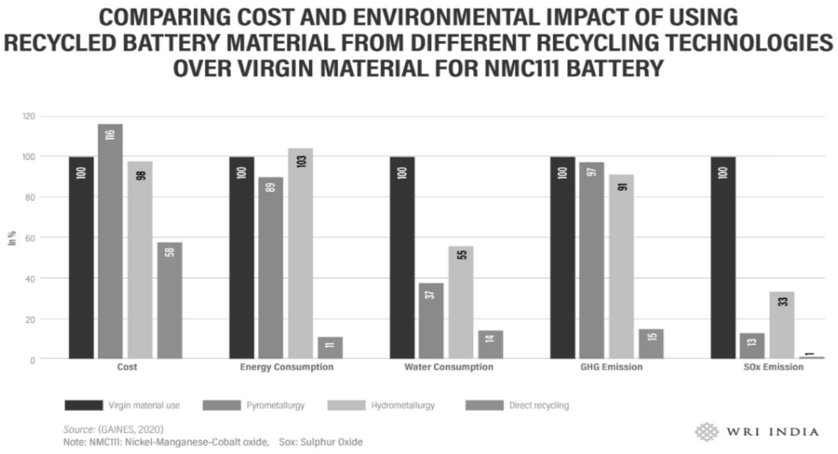
Electric vehicle passenger car take-up has been slow, mainly on account of extremely high introductory costs and anxiety about driving ranges with inadequate charging infrastructure. Although government incentives have reduced the gap in prices between electric vehicles and internal combustion engine vehicles, they are still too expensive for most middle-income individuals. The positives, however, may be mitigated by the fact that premium -endorsed segments like Tata Motors, MG, and Hyundai are catching up faster. Two-wheelers and three-wheelers seem to be big hits because they happen to be cheaper options and ideal for short distances. More than 15 percent of the two-wheeler registrations in Delhi are electric, and this seems to explode exponentially. Electric buses have been an area of focus for FAME-II, and the states have also received subsidies for procurement. Urban cities such as Mumbai and Bengaluru have successfully inducted electric buses into their fleets, marking early success.

Lifespan emissions and energy mix

While EVs are lauded for their zero tailpipe emissions, the environmental benefits are undermined by India’s coal-heavy energy grid. Over 60% of India’s electricity is generated from coal, resulting in significant lifecycle emissions for EVs. Studies show that, in coal-dependent regions, EV emissions during manufacturing and charging can equal or exceed those of fuel-efficient ICE vehicles. However, battery production contributes a considerable share toward this problem. It alone constitutes around 60% of the total emissions generated by an EV's production process. Lithium-ion batteries-the heart of any modern electric vehicle-need mining and processing of lithium, cobalt, and nickel. The process is energy-consuming and harmful to the environment. The government is thus seriously considering renewable energy-based solutions for EV charging. The emerging trends are solar-powered charging stations and grid-scale battery storage systems. First, India has renewable energy capacity of more than 130 GW and is projected to almost double that by 2030-an achievement that could considerably lessen the carbon footprint of EVs.

Battery Recycling and Second Life Applications

This will generate about 128 GWh of recyclable batteries per year in India's EV market by 2030, a 6,400% increase from the 2024 level. Recyclability will not only help recover materials but also reduce damage to the environment and facilitate a circular economy. Of course, it is still a baby industry because more recycling units are set up for lead-acid batteries than for lithium ion. It is this realization that the Indian government has been localizing battery recycling to reduce dependency on imports and ensure environmentally responsible disposal of battery waste. Initiatives such as the Make in India and Atmanirbhar Bharat are contributing positively to developing indigenously made EV batteries, making components, and creating a self-sustaining ecosystem for producing EVs in the country, which would include recycling infrastructure. Starting localized battery recycling facilities is an important objective since it results in solving the environmental impact that discarded electric vehicle batteries pose, not to mention contributing to developing employment in the recycling sector.



COMPARING COST AND ENVIRONMENTAL IMPACT OF USING RECYCLED BATTERY MATERIAL FROM DIFFERENT RECYCLING TECHNOLOGIES OVER VIRGIN MATERIAL FOR NMC111 BATTERY

Source: (GAINES, 2020)
Note: NMC111: Nickel-Manganese-Cobalt oxide, Sox: Sulphur Oxide

(Source; WRI India)

Another major challenge for electric vehicle adoption in India is the deficiency in suitable charging infrastructure. Such huge land areas of a lack of public charging stations create a very big problem for any potential buyer of electric vehicles. While such adoption is on the rise in cities, it usually lags behind concerning facilities for charging stations. Further, the situation becomes even more grave in rural areas where gaps in infrastructure are starkly visible.

It incurs a substantial investment in charging stations and doesn't have a normative protocol of charging, which poses a huge challenge to the expansion of charging infrastructure. The government of India has therefore developed some rules and financial incentives to be provided for the establishment of charging stations primarily along highways. This government plan for the charging station network is expected to increase convenience and consumer confidence, leading to electric vehicle ownership being more viable for Indian drivers.

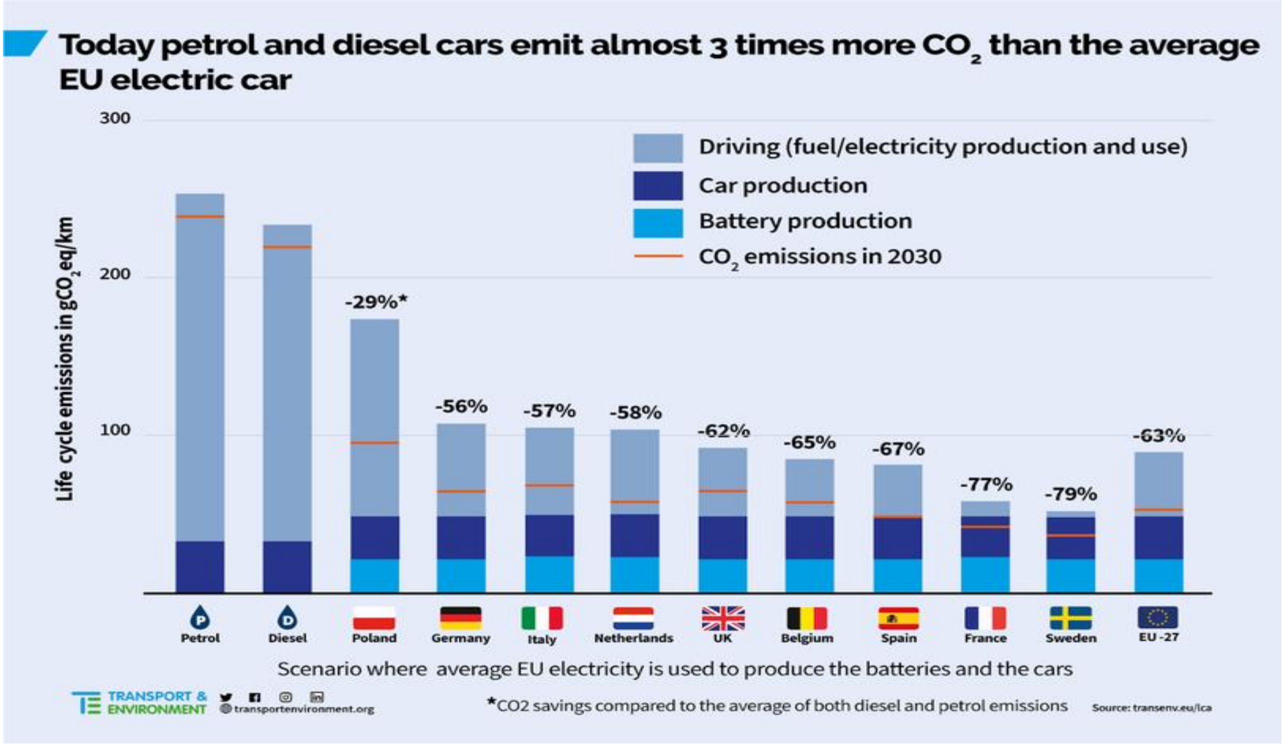
To conclude, the transformation of India to an electric vehicle nation is crucial to reach the environmental goals, but there are still many challenges. Addressing the nation's dependence on coal for electricity generation, the poor availability of charging infrastructure, and the ecological implications surrounding battery production and disposal are critical for the full realization of the electric vehicle. It is India's turn to make the highway to a more sustainable future of EVs. That means swift integration into renewable energy, expansion of battery recycling initiatives, and enhancement of charging infrastructure.

Case Study 2: Comparative Analysis of Carbon Footprints; ICE vs. EV in the EU and US.

The transition from ICE vehicles to electric vehicles is strategically relevant for lessening dependence on fossil fuels and improving air quality while mitigating climate change. Some factors may determine the environmental footprint of transition including electricity sources used for charging the vehicle, the processes involved in manufacturing the automobiles as well as general emissions over the lifecycle of the vehicle. ICE vehicles have been on the roads for more than a century, producing CO2 as a byproduct of gasoline or diesel combustion. A contemporary gasoline-fueled car emits about 2.3 kilograms of CO2 in a litre. Hence, by use and efficiency, the annual emissions would be around 4,000–6,000 kilograms of CO2. In addition, manufacturing an ICE vehicle involves material extraction and production, which accounts for 15–20% of its total lifecycle emissions. A carbon footprint dominated by its operational emissions does not explain the balance between cleaner operation and manufacturing complexity for ICE versus EVs.

EVs, which lack tailpipe emissions, offer operational advantages but have challenges of their own. Their environmental impacts largely depend on the carbon intensity of the electricity grid used for charging. For instance, EV operation carbon savings are decreased in comparison with California's renewable heavy versus areas relying on coal in parts of the US Midwest. There's also the matter of manufacturing: The lithium-ion battery in an EV might produce as much as 50% more emissions than building an ICE vehicle. This is because mining and processing those materials lithium, nickel, and cobalt is energy intensive. Although they produce more at first, on average, they generally emit much less, especially if the grid is a low-carbon source, which is well the case for most of the EU. For instance, an EV in Europe that draws from a renewable mix of 2022 levels- 40 per cent as renewable and 25 per cent nuclear-would have much lower lifetime emissions than an ICE vehicle. On the flip side, the fossil fuel dependence on the US grid is mostly skewed; while California leads at more than 30% renewables, states like Texas relying on coal and natural gas, ensure that in those regions, higher lifecycle emissions for EVs will be felt.

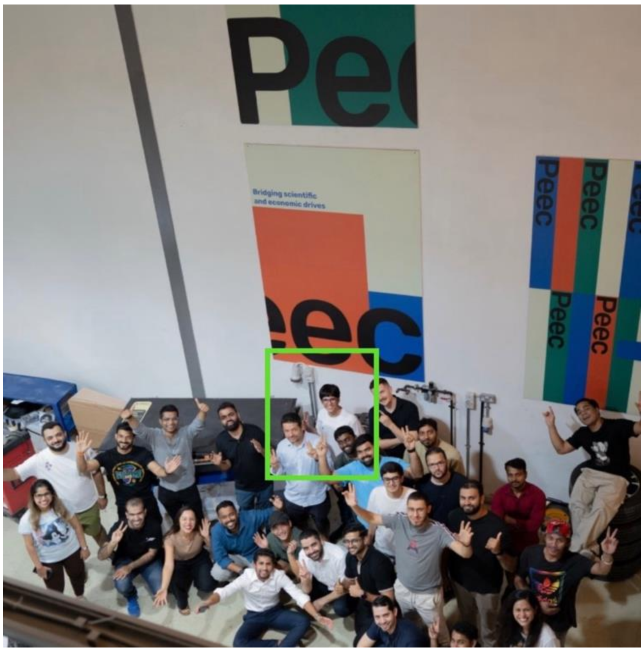
The obvious carbon emissions difference between the European Union and the United States alone underscores the substantial impact regional energy frameworks exert. EU's policies on renewables and nuclear energy ensure a massive inflow of clean energy; thus, EVs represent a much cleaner solution. For example, in Norway - where nearly 100% of electricity comes from hydropower - under perfect conditions, lifecycle emissions are the least for EVs. In Germany, with partial coal dependence, carbon emissions from EVs have been significantly reduced by using renewable energy.



Contrasted with those in the US, disparities are much starker; across different regions, EV emissions can vary as much as 60%, according to the Union of Concerned Scientists. Though EVs will still do better than their ICE counterparts over their lifetimes even in coal-heavy regions, that margin is significantly smaller than it would be if the power grid were greener. The ongoing transition towards renewable energy in these two areas suggests a future where the environmental benefits of EVs continue to grow, making them a more integral part of slowing down global transportation emissions.

4. Personal Insights

Amid electrification of a Fiat 500L with Peec Mobility. I performed many responsibilities over multiple months, including car disassembly, bespoke component design, and support in integrating EV systems. The focus has been on CAD, utilizing Fusion 360 to design as well as further elaborating various components, primarily a sheet-metal compressor bracket, in which both material efficiency and strength are stringently considered. I worked with the existing vehicle components so that the electric vehicle drivetrain and its accompanying systems would be integrated. In addition, I was involved in solving structural problems, such as corrosion issues. I prepared technical documentation in terms of DFMEA and assembly guides for manufacturing and assembly purposes. That way, I got hands-on experience with both the technological and collaborative aspects of electrifying an automobile and learned how to apply theoretical engineering principles in pragmatic applications.



However, the experience was not without its challenges, particularly in terms of processes of data collection and analysis. Trying to electrify the Fiat 500L proved challenging because of numerous issues related to introducing electric vehicle systems into an existing framework of the vehicle. Such challenges as rust repair, missing equipment, and delays in testing critical elements, such as the battery testing system, have presented huge impacts on the progress of the project. These challenges often wiped out the accuracy and comprehensiveness of information that I needed to move forward with the design and assembly phases. Through these challenges, however, I gained significant knowledge of the complexities involved in automotive electrification while developing skills in navigation over the uncertainties of a dynamic resource-constrained environment. I became conscious of how policy and technology were reshaping the face of sustainable transportation. As communities move progressively into embracing electric vehicles in curbing emissions, the transition is not only seen to be shrouded with technological challenges but has also environmental trade-offs. The process of electrification demands careful consideration of the entire product lifecycle-from raw material extraction and manufacturing to usage, maintenance, and eventual disposal, especially recycling of the batteries.

Overall, within the larger framework of sustainability, life at Peec Mobility helped me establish the practical application of technology with the theoretical concept of life cycle carbon footprint (LCCF). Electrified vehicles would lead to lower emissions in use, but manufacturing poses far more severe environmental challenges, mainly since the production of batteries requires very high energy inputs that have a substantial carbon footprint. Moreover, the source of power used to charge an EV determines much of its total carbon footprint; an EV charged with renewable sources such as solar or wind power would have a substantially lower LCCF compared to one charged with coal-based electricity. This link between policy, technology, and environmental outcomes made me understand why a life cycle perspective needs to be included in decision-making related to sustainable transportation. The role of the policymaker should, therefore, be taken with utmost importance in promoting the inclusion of renewable energy; improving recycling of batteries; and providing manufacturer incentives to optimize the efficiency of the electrification process. This would be about the internship, giving a deeper understanding of the need for technology and policy to collaborate effectively to reduce the impact of the transportation industry on the environment and fast-track movement toward a net-zero future.

5. The Future of Sustainable Transportation

Further developing the EV technologies field is an important factor for the future of sustainable transportation. Advances in the fields of battery efficiency and energy storage, charging infrastructures, and vehicle designs, have contributed to significant growth in the EV sector over the last decade. The great technological leap in electric vehicles is better, more efficient batteries.

Lithium-ion batteries, the most widespread kind currently used in EVs, have come down in price and become thousands of per cent more energy-dense and even more robust. New variants of them, like solid-state batteries, promise to hold higher energy densities and charge faster. Advances in recycling processes for batteries promise a reduction in environmental impact through EV production. Probably the biggest fear that has restrained the wide adoption of EVs was concern about how far an electric vehicle could travel before it needs a recharge. Through advancements in technology, mileage potential in electric cars has been profoundly improved due to the advent of new, better-designed battery management systems. Virtually all new models can now travel over 400 miles on a single charge and have become more equal with ICE engines. Besides, the further addition of rapid charging networks and advancements in wireless charging will reduce recharging time even more and make things much more convenient for EV users.

Not only is the battering ram of new technologies on batteries but new vehicle design concepts are also headed linearly for efficiency and cost in carbon fibre or aluminum; the lightweight material destined to make more use of it already helps cut vehicle weight and leads the way further in EVs' performance and range. Smarter integration in terms of autonomous driving and V2G will let EVs do more than take their occupant efficiently: let him or her participate in a wider energy system.

The optimal environmental benefits of EVs are achieved when they are supplied with clean, renewable energy. The carbon footprint of EVs largely relies on the mix of electricity grid used to charge. Regions whose electricity is mainly sourced from fossil fuels may have net emissions greater than those from areas powered by renewable energy. Integrating more renewable sources into the grid and, in so doing, facilitate greater sustainability potential for electric transportation. Solar, wind, hydro, and geothermal sources can significantly reduce EV carbon intensity. A home-based solar panel system can charge an EV with zero emissions; that is an extremely advantageous environmental circumstance over conventional fossil fuel-powered vehicles. It opens another kind of feedback loop that would benefit both parties: owing to the wide-spaced deployment of more EVs, such a demand for renewable clean electricity would expand the infrastructure. Conversely, the use of renewables means a lesser carbon footprint for the EVs; hence, increasing their sustainability factor.

Policymakers will have to make further strides to reach full environmental potential through an acceleration of renewable energy transition. This will incorporate incentives for wind and solar power, improvement of the current energy storage technologies, and modernizing the grid to adequately accommodate decentralized, renewable sources of power.

Policy Recommendations for India

India has very specific issues in driving adoption toward sustainable transportation and the widespread penetration of electric vehicles forms an important part of the nation's climate action plan. Significant policy interventions and considerable investments in infrastructure, technology, and public awareness, however, are likely required to create substantial penetration of EVs in India. Some key policy recommendations follow.

Subsidies and Incentives; Already the Indian government has formulated programs like the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme offering market and financial incentives with incentives for those purchasing electric vehicles. All such schemes need to be expanded, more so on mass markets, to make EVs affordable to the 'common man'. Such incentives will include direct cash subsidies, reductions in tax, and incentives for car makers to make models of EVs affordable.

Battery Recycling and Domestic Manufacturing; India must look towards building a domestic battery manufacturing ecosystem to avoid over-reliance on imports. Therefore, the vulnerability factor in the supply chain would be reduced for the industry. In an endeavour towards the creation of a proper battery recycling ecosystem that is sustainable, it shall decrease the environmental footprint of EVs and complete the circular model of economy.

Supply: The supply of renewable energy capacity should be developed for a sustainable supply of energy and enable the adoption process in India. This is with investment in abundant sources of solar and wind resources and upgrading its energy network to absorb the intermittency of such sources, about the aim and scale as set out by the country's renewable energy targets.

Infrastructure Development: Surely, the lack of charging infrastructure remains the largest barrier to the widespread uptake of EVs in India. Policymakers must engage with private sector companies for the development of an adequate charging network in both urban and rural areas. Public-private collaborations related to charge infrastructure can be in the form of incentives granted by the government for establishing EV charging stations as well as subsidies on residential charging infrastructure.

Public Awareness and Education; More public awareness about the long-term benefits of EVs would increase its adoption rate. The Indian government can, in collaboration with automobile companies, initiate awareness-educative campaigns among people to make them aware of the environmental as well as economic benefits of a change over to EVs. Moreover, incentives for the purchase of second-hand EVs would reduce the entry barrier for many potential customers.

6. Conclusion

Without a doubt, EVs are surely environmentally friendly at least regarding emissions during operation compared to the conventional ICEs. Significant factors are involved in the net environmental impact of EVs, and among these, are electricity generation for charging, efficiency of the vehicle being charged, and manufacturing processes used to produce the vehicles. For example, in the EU where renewable energy is gradually being combined with the grid, carbon emissions of EVs are being hugely reduced overall.

In any case, the carbon advantages of the EV are modest whereas electric generation remains heavily dependent on fossil fuels, as is typically the case in the US or India.

Batteries for EVs, charging infrastructure, and vehicle design are now substantially more commercially viable and efficient compared to earlier times. Additionally, with the increase of renewables in the grid, the carbon intensity of charging an EV falls further down, making it better environmentally. This helps paint a place for EVs at the core of sustainable transportation everywhere.

Only a proper life cycle assessment of the environmental impact of transportation could fathom if electric vehicles can be sustainable. Operational emissions of EVs are significantly lower than those of ICE vehicles; however, production emissions are much higher, especially in battery production. However, such a situation is soon bound to change with advancements in production processes and the invention of recycling technologies for batteries. It focuses on the totality of the vehicle's whole life cycle, from raw material extraction to end-of-life disposal or recycling in addition to tailpipe emissions. Those factors facilitate an easier comprehension of a new, more holistic context into which environmental impacts fall, or how much more sustainable EVs can be.

Call to Action

Speed up the adoption of electric vehicles; for Governments, the private sector, and consumers to meet and form a sustainable transportation solution for the near future. Policymakers need to focus on price reduction of electric vehicles, increase charging points available, and increase the proportion of renewable energy fed into the grid. Companies manufacturing vehicles should put all their sweat into introducing new, better battering and vehicle designs and manufacturing processes.

Consumers are also to be considered as playing a role in recognizing the long-run benefits of EVs and considering them as an option to replace conventional vehicles. Only an integrated approach that challenges the adoption of EVs on both technological and infrastructural levels and integrates solutions of clean energy into the transportation ecosystem will support the transition towards sustainable transportation. A future of mobility is sustainable only when considered from a lifecycle perspective, enhancing opportunities for minimization of environmental footprints and steps toward a cleaner, more sustainable world. Therefore, the integration of electric vehicles into worldwide transport systems heals climate change and makes sustainability apparent. This could be through a full-lifecycle approach and continuous technological innovations along with every sector's strong support; eventually, emissions from carbon will decrease dramatically, and the futures of generations to come will be clean and greener.

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