



تحليل دورة حياة المركبات الكهربائية تقييم الآثار البيئية والاقتصادية

Lifecycle Analysis of Electric Vehicles: Assessing Environmental and Economic Implications

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Abstract

This research paper presents a comprehensive lifecycle analysis of electric vehicles (EVs) to assess their environmental and economic implications compared to internal combustion engine vehicles (ICEVs). The study examines the entire lifecycle of EVs, from raw material extraction through manufacturing, usage, and end-of-life stages. The environmental analysis highlights the substantial benefits of EVs, including reduced greenhouse gas emissions and lower air pollution, particularly when powered by renewable energy sources. However, it also addresses significant challenges related to the extraction of critical materials like lithium, cobalt, and nickel, which pose environmental and social risks. The economic analysis reveals that while the initial purchase price of EVs remains higher, declining battery costs, lower operational expenses, and supportive government policies contribute to a favorable total cost of ownership (TCO). The research underscores the need for sustainable mining practices, advancements in battery recycling, and robust charging infrastructure to maximize the benefits of EVs. This study concludes that with continued technological advancements and regulatory support, EVs offer a promising pathway towards a more sustainable and economically viable transportation future.

Keywords: Electric Vehicles (EVs), Internal Combustion Engine Vehicles (ICEVs), Lifecycle Analysis, Environmental Impact, Economic Viability, Lithium-Ion Batteries, Raw Material Extraction, Greenhouse Gas Emissions, Total Cost of Ownership (TCO), Battery Recycling, Charging Infrastructure.

ملخص

تقدم ورقة البحث هذه تحليلاً شاملاً لدورة حياة المركبات الكهربائية لتقييم آثارها البيئية والاقتصادية مقارنة بمركبات محرك الاحتراق الداخلي. وتفحص الدراسة دورة حياة المركبات الكهربائية بالكامل، من استخراج المواد الخام إلى التصنيع والاستخدام ومراحل نهاية العمر. ويسلط التحليل البيئي الضوء على الفوائد الكبيرة للمركبات الكهربائية، بما في ذلك انخفاض انبعاثات الغازات المسببة للاحترق العالمي وانخفاض تلوث الهواء، وخاصة عند تشغيلها بمصادر الطاقة المتجددة. ومع ذلك، فإنه يتناول أيضًا تحديات كبيرة تتعلق باستخراج المواد الحيوية مثل الليثيوم والكوبالت والنيكل، والتي تشكل مخاطر بيئية واجتماعية. ويكشف التحليل الاقتصادي أنه في حين يظل سعر الشراء

الأولي للمركبات الكهربائية أعلى، فإن انخفاض تكاليف البطاريات وانخفاض النفقات التشغيلية والسياسات الحكومية الداعمة تساهم في إجمالي تكلفة الملكية المواتية. ويؤكد البحث على الحاجة إلى ممارسات التعدين المستدامة والتقدم في إعادة تدوير البطاريات والبنية التحتية القوية للشحن لتعظيم فوائد المركبات الكهربائية. خلصت هذه الدراسة إلى أنه مع التقدم التكنولوجي المستمر والدعم التنظيمي، توفر المركبات الكهربائية مسارا واعدًا نحو مستقبل نقل أكثر استدامة وقابلية للتطبيق اقتصاديًا.

الكلمات المفتاحية: المركبات الكهربائية، مركبات محرك الاحتراق الداخلي، تحليل دورة الحياة، التأثير البيئي، الجدوى الاقتصادية، بطاريات ليثيوم أيون، استخراج المواد الخام، انبعاثات الغازات المسببة للانحباس الحراري العالمي، إجمالي تكلفة الملكية، إعادة تدوير البطاريات، البنية التحتية للشحن.

Introduction

The transportation sector is a critical contributor to global greenhouse gas (GHG) emissions, responsible for approximately 24% of total emissions in 2019. This sector's significant reliance on fossil fuels has driven the urgent need for cleaner and more sustainable alternatives to mitigate the impacts of climate change and air pollution. Among the proposed solutions, electric vehicles (EVs) have emerged as a promising option due to their potential to reduce emissions and decrease dependency on non-renewable energy sources.

Electric vehicles offer several advantages over internal combustion engine vehicles (ICEVs). Firstly, they produce zero tailpipe emissions, which can significantly improve air quality in urban areas. Secondly, EVs can be powered by renewable energy sources such as wind, solar, and hydropower, further reducing their carbon footprint compared to vehicles that run on gasoline or diesel. As the electricity grid increasingly incorporates renewable energy, the environmental benefits of EVs are expected to grow.

Despite these advantages, the adoption of EVs also presents several challenges. The production of EV batteries requires substantial amounts of raw materials like lithium, cobalt, and nickel. The extraction and processing of these materials can have significant environmental and social impacts, including habitat destruction, water pollution, and labor rights issues in mining regions. Additionally, the manufacturing of EVs, particularly the battery production process, is energy-intensive and generates considerable emissions. Therefore, it is essential to consider the entire lifecycle of EVs to assess their true environmental and economic implications comprehensively.



The primary objective of this research paper is to provide a detailed lifecycle analysis (LCA) of electric vehicles, focusing on both their environmental and economic impacts. By examining real data and referencing existing research, this study aims to offer a comprehensive understanding of the benefits and challenges associated with EVs. The lifecycle analysis will cover four main stages: raw material extraction, manufacturing, usage, and end-of-life. Each stage will be evaluated to highlight the key factors that influence the overall sustainability of EVs.

Understanding the full lifecycle impacts of EVs is crucial for several reasons. Policymakers, industry stakeholders, and consumers need reliable information to make informed decisions regarding the promotion, production, and adoption of EVs. For policymakers, lifecycle analysis can guide the development of regulations and incentives that support sustainable transportation. For manufacturers, it can identify opportunities to reduce the environmental footprint of EV production and improve supply chain sustainability. For consumers, it provides insights into the long-term benefits and potential trade-offs of choosing an EV over a traditional ICEV.

This paper seeks to contribute to the ongoing discourse on sustainable transportation by offering a nuanced perspective on the lifecycle impacts of electric vehicles. Through a comprehensive analysis, it aims to highlight the areas where improvements are needed and where EVs can make the most significant positive impact. By addressing both environmental and economic aspects, this research provides a holistic view of the implications of transitioning to electric mobility.

Methodology

This research employs a comprehensive lifecycle analysis (LCA) framework to evaluate the environmental and economic impacts of electric vehicles (EVs). The analysis is segmented into four primary stages: raw material extraction, manufacturing, usage, and end-of-life. Each stage is scrutinized to provide a detailed understanding of the overall sustainability of EVs compared to internal combustion engine vehicles (ICEVs).

In the raw material extraction phase, the environmental impacts of mining and processing key materials such as lithium, cobalt, and nickel, which are essential for EV batteries, are examined. Data for this stage is sourced from peer-reviewed articles and industry reports, which provide insights into the ecological and social consequences of mining activities.

The manufacturing stage focuses on the energy consumption and emissions associated with producing EV components, particularly the lithium-ion battery. Studies by Ellingsen et al. (2014) and other relevant research are utilized to quantify the environmental footprint of



battery production. Lifecycle inventory databases such as Ecoinvent offer additional data on the emissions and resource use during the manufacturing process.

For the usage phase, the analysis compares the operational efficiency and emissions of EVs and ICEVs. The assessment includes real-world data on energy consumption, emissions during vehicle operation, and the electricity grid mix's influence on overall emissions. Information from government databases like the U.S. Department of Energy's Fuel Economy website is employed to ensure accurate and up-to-date comparisons.

The end-of-life stage evaluates the processes involved in recycling and disposing of EV components, with a particular emphasis on battery recycling technologies. The study reviews advancements in recycling methods and their effectiveness in reducing environmental impact. Data from recent research on battery recycling processes, such as hydrometallurgical and pyrometallurgical methods, are analyzed to understand the potential for resource recovery and pollution reduction.

Environmental Impact Analysis

The environmental impact analysis of electric vehicles (EVs) encompasses the entire lifecycle, from raw material extraction through manufacturing, usage, and end-of-life. This analysis aims to understand the environmental benefits and challenges associated with EVs, providing a comprehensive assessment of their sustainability compared to internal combustion engine vehicles (ICEVs).

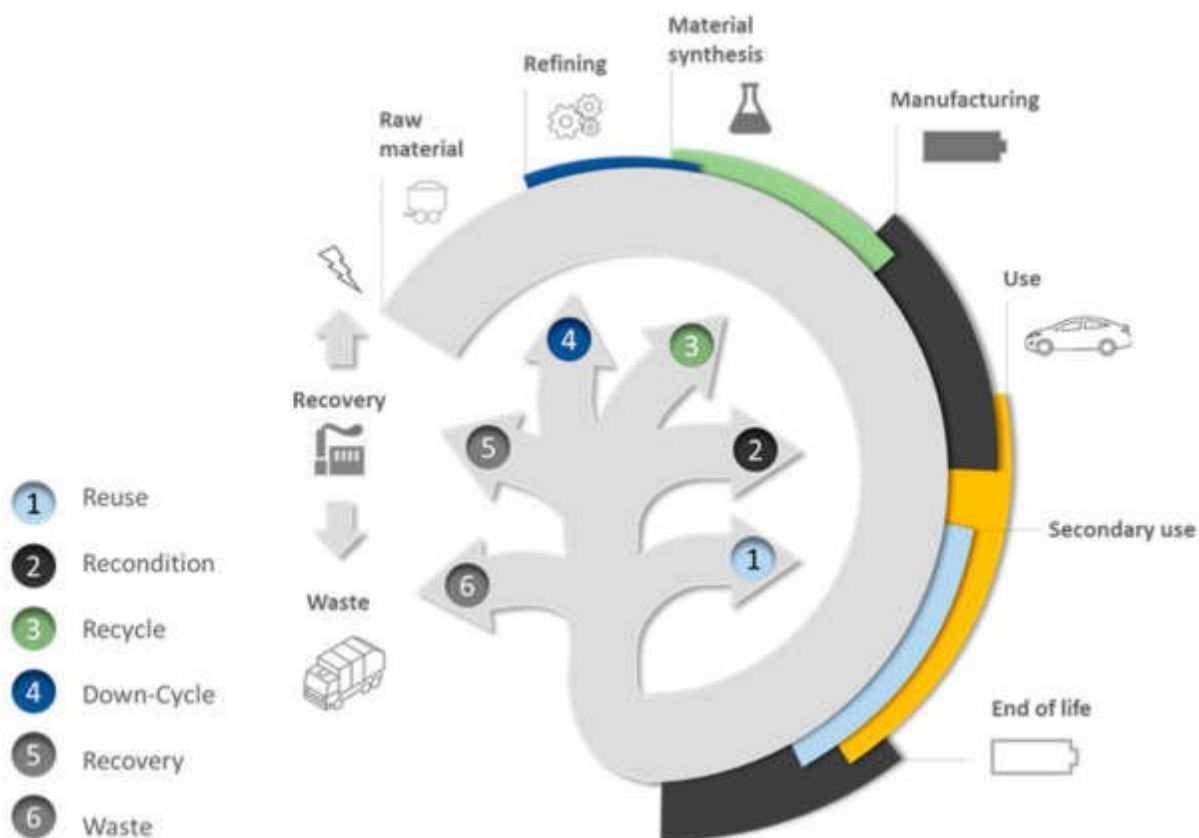


Figure 1 lifecycle stages of EVs. raw material extraction, manufacturing, usage, and end-of-life [29].

The extraction of raw materials for EV batteries, such as lithium, cobalt, and nickel, has significant environmental and social implications. Lithium is predominantly extracted from brine pools in South America, particularly in Chile, Argentina, and Bolivia. The extraction process involves pumping lithium-rich brine to the surface and allowing it to evaporate in large ponds, which consumes large quantities of water. This method can lead to the depletion of local water resources and negatively impact the surrounding ecosystems and communities. Flexer et al. (2018) highlight that the high-water demand for lithium extraction poses a severe threat to the arid regions where these operations are located [2]. Cobalt is primarily mined in the Democratic Republic of Congo (DRC), where mining activities are associated with severe environmental degradation and human rights abuses. The extraction process often involves artisanal and small-scale mining, which can result in significant soil and water pollution due to inadequate regulation and oversight. Amnesty



International (2016) reports that cobalt mining in the DRC has led to extensive environmental damage and raised serious concerns about child labor and unsafe working conditions [3].

Nickel mining and processing generate substantial CO₂ emissions and cause soil and water pollution. The environmental impact is particularly pronounced in regions with less stringent environmental regulations. Norgate et al. (2007) provide a detailed assessment of the environmental footprint of nickel refining, noting significant emissions and resource use during the process [4].

The manufacturing phase of EVs, particularly the production of lithium-ion batteries, is energy-intensive and generates considerable emissions. The production of EV batteries is one of the most critical factors contributing to the overall environmental footprint of EVs. According to Ellingsen et al. (2014), the manufacturing of lithium-ion batteries contributes significantly to greenhouse gas emissions, with estimates ranging from 150 to 200 kg CO₂-equivalent per kWh of battery capacity [7]. This high energy demand is primarily due to the processes involved in extracting, refining, and assembling the battery components. Besides batteries, the production of other EV components also involves significant energy consumption and emissions. However, advancements in manufacturing technologies and the increasing use of renewable energy in production facilities are helping to mitigate some of these impacts.

The usage phase of EVs presents several environmental advantages over ICEVs, primarily due to their higher energy efficiency and zero tailpipe emissions. EVs convert approximately 60% of the electrical energy from the grid to power at the wheels, compared to about 20% for gasoline vehicles. This higher efficiency results in lower overall energy consumption during the vehicle's operational life. The emissions during the usage phase of EVs depend heavily on the electricity mix used for charging. In regions with a high share of renewable energy, EVs can significantly reduce greenhouse gas emissions compared to ICEVs. For instance, in Norway, where most electricity is generated from hydropower, EVs emit approximately 50 g CO₂-equivalent per kilometer, compared to 120 g CO₂-equivalent per kilometer for ICEVs [15]. However, in regions reliant on coal-fired power plants, the emissions reduction potential of EVs is less pronounced.

The end-of-life stage involves the recycling and disposal of EV components, particularly the batteries. Proper management of this phase is crucial to minimizing environmental impact. Advances in battery recycling technologies are essential for recovering valuable materials and reducing the environmental footprint of EVs. Hydrometallurgical and pyrometallurgical processes are the most common methods for recycling lithium-ion



batteries, with the potential to recover metals like lithium, cobalt, and nickel. However, the current recycling rates are relatively low, and significant improvements are needed to make the recycling process more efficient and environmentally friendly. Improper disposal of EV batteries can lead to soil and water contamination due to hazardous materials such as lead, cadmium, and organic electrolytes. Ensuring proper disposal and recycling practices is essential to mitigating these risks [14].

Raw Material Extraction

Extraction of raw materials necessary for production of electric vehicle (EV) batteries, including lithium, cobalt, and nickel, involves significant environmental and social implications. Each of these materials is critical for the functionality and performance of lithium-ion batteries, which are the predominant energy storage solution in EVs. However, the extraction processes for these materials often result in considerable environmental degradation and social challenges.

Lithium is primarily extracted from brine pools in South America, notably in the "Lithium Triangle" of Chile, Argentina, and Bolivia. The extraction process involves pumping lithium-rich brine from underground reservoirs to the surface, where it is allowed to evaporate in large ponds. This method can lead to the depletion of local water resources and negatively impact the surrounding ecosystems and communities. Figure 2 illustrates the regions of lithium extraction and the associated environmental impacts. Flexer et al. (2018) emphasize that the high-water demand for lithium extraction can lead to the depletion of aquifers, negatively impacting both local communities and ecosystems. The evaporation process also releases harmful chemicals into the environment, which can lead to soil and water contamination [2].



Figure 2 Environmental Impact of Lithium Extraction [30]

Cobalt is predominantly mined in the Democratic Republic of Congo (DRC), accounting for approximately 60% of global supply. The mining of cobalt in the DRC is often carried out through artisanal and small-scale mining (ASM), which is poorly regulated and involves hazardous working conditions. Amnesty International (2016) reports that cobalt mining in the DRC has led to significant environmental degradation, including deforestation, soil erosion, and water pollution. Additionally, ASM practices have been linked to severe human rights abuses, including child labor and unsafe working environments. These conditions raise serious ethical concerns about the sustainability of cobalt extraction for EV batteries [3].

Nickel is another essential component of EV batteries, particularly in high-energy-density batteries. The environmental impact of nickel mining and processing is substantial, involving large-scale open-pit mining operations and energy-intensive refining processes. Norgate et al. (2007) note that nickel mining generates considerable CO₂ emissions and leads to soil and water contamination due to the release of sulfur dioxide and other



pollutants. The extraction process often results in significant habitat destruction and biodiversity loss, especially in regions with less stringent environmental regulations [4]. The environmental and social implications of raw material extraction for EV batteries are profound. The water-intensive nature of lithium extraction threatens water security in already arid regions, while the environmental degradation associated with cobalt and nickel mining poses significant ecological risks. Furthermore, the social challenges, particularly those related to cobalt mining in the DRC, highlight the need for more sustainable and ethically responsible mining practices. These issues underscore the importance of developing alternative extraction methods, improving regulatory frameworks, and enhancing recycling technologies to mitigate the environmental and social impacts of raw material extraction. Addressing the environmental and social challenges associated with raw material extraction for EV batteries requires a multifaceted approach. One potential solution is the development of more sustainable extraction methods. For instance, direct lithium extraction (DLE) technologies are being explored as a means to reduce water consumption and environmental impact compared to traditional evaporation ponds. Additionally, enhancing the efficiency and scalability of battery recycling processes can help recover valuable materials and reduce the demand for virgin raw materials [14]. Improving the regulatory frameworks governing mining activities is also crucial. Stricter environmental regulations and enforcement can mitigate the ecological impact of mining operations, while international standards and certifications can help address social issues, including labor rights and community impacts. Companies involved in the EV supply chain must also take responsibility for ensuring that their sourcing practices are sustainable and ethically sound [3].

Manufacturing

The manufacturing phase of electric vehicles (EVs) is critical to their overall lifecycle environmental impact, primarily due to the production of lithium-ion batteries. This phase encompasses the extraction and processing of raw materials, the synthesis of battery chemicals, and the assembly of battery cells and packs, all of which contribute significantly to the environmental footprint of EVs.

Lithium-ion batteries are the most substantial component of the EV manufacturing environmental footprint due to their energy-intensive production processes. The lifecycle assessment (LCA) of lithium-ion batteries reveals significant greenhouse gas emissions associated with their production. Ellingsen et al. (2014) estimate that producing a lithium-ion battery results in emissions ranging from 150 to 200 kg CO₂-equivalent per kWh of

battery capacity [5]. This high energy demand is largely due to the processes involved in extracting and refining the raw materials, such as lithium, cobalt, and nickel, and the energy-intensive stages of cathode material production and cell assembly. The environmental impact of battery manufacturing varies significantly depending on the energy mix used in the production facilities. For instance, in regions where the electricity grid is predominantly powered by fossil fuels, the carbon footprint of battery production is higher compared to regions that rely on renewable energy sources. As a result, the geographic location of battery manufacturing facilities plays a crucial role in determining the overall environmental impact.

The manufacturing of other EV components and the vehicle assembly process also contribute to the environmental impact, although to a lesser extent than battery production. Components such as electric motors, power electronics, and lightweight materials are integral to EV design and performance. The production of these components involves the use of various metals and materials, each with its own environmental footprint. For instance, the production of lightweight aluminum and high-strength steel used in EV bodies requires substantial energy, but helps reduce the overall vehicle weight, thereby improving efficiency and reducing emissions during the usage phase.

The vehicle assembly process for EVs, which includes activities such as stamping, welding, painting, and final assembly, consumes energy and produces emissions. However, advancements in manufacturing technologies, such as increased automation and energy-efficient manufacturing practices, are helping to mitigate these impacts. Companies like Tesla and BMW are investing in renewable energy sources for their production facilities to further reduce the carbon footprint of EV manufacturing [13].

When we comparing the manufacturing impacts of EVs to those of internal combustion engine vehicles (ICEVs), it is essential to consider the lifecycle perspective. Although the production of EVs, particularly their batteries, tends to be more energy-intensive and emission-heavy than that of ICEVs, the overall lifecycle emissions of EVs can be lower due to their superior efficiency and lower emissions during the usage phase. According to Hawkins et al. (2013), despite higher emissions during the manufacturing phase, EVs offset these emissions during their operational life through reduced tailpipe emissions and higher energy efficiency [1]. This trade-off underscores the importance of viewing vehicle impacts from a full lifecycle perspective rather than focusing solely on the manufacturing stage.

Efforts to Reduce Environmental Impact

Efforts are already being made to reduce the environmental impact of EV production. One of these is the utilization of renewable energy sources instead of the grid for manufacturing power. For example, Tesla's Nevada Gigafactory is being built to run on 100% renewable energy, meaning battery manufacturing will be done with an extremely low carbon footprint [14]. On the other hand, improvements can be effected on the battery technology. In fact, the development of more sustainable battery chemistries is currently under development, with projects focusing on solid-state batteries as well as batteries that significantly curtail or remove the use of critical materials like cobalt. Such innovations may reduce the environmental footprint of battery production through a reduction in the use of high-impact materials, and through improved general energy efficiency. Recyclability of the battery and reuse of the materials in the batteries have also been substantially experimented with. The development of efficient recycling means helps in recovery and reuse of most of the valuable materials in the battery. This will lessen the demand for new materials and hence cut the accompanying environmental impacts from their extraction and processing. According to Gaines (2014), recycling has the potential to reduce environmental burdens and improve material resource efficiency in the EV industry [14].

Usage

EVs are generally more energy-efficient than ICEVs. Electric motors in EVs convert approximately 60% of the electrical energy from the grid to power at the wheels, compared to about 20% for gasoline vehicles. This efficiency translates into lower overall energy consumption during the vehicle's operational life. According to the U.S. Department of Energy, EVs typically use about 0.3 kWh of electricity per mile, whereas gasoline vehicles consume about 1.7 kWh per mile when converted to equivalent energy units [16].

The greenhouse gas (GHG) emissions during the usage phase of EVs depend on the carbon intensity of the electricity used for charging. In regions where the electricity grid is predominantly powered by renewable sources, such as hydropower, wind, or solar, the emissions associated with EVs are substantially lower. For instance, in Norway, where most electricity is generated from hydropower, EVs emit approximately 50 grams of CO₂-equivalent per kilometer, compared to 120 grams of CO₂-equivalent per kilometer for ICEVs [15]. Conversely, in regions reliant on coal-fired power plants, the emissions reduction potential of EVs is less pronounced. In such areas, the carbon intensity of electricity generation can offset some of the environmental benefits of EVs. The environmental benefits of EVs during their usage phase vary significantly across different

regions. Table 1 illustrates the estimated GHG emissions from EVs and ICEVs in various regions, highlighting the importance of the local electricity mix.

Table 1 Estimated Greenhouse Gas Emissions from EVs and ICEVs in Various Regions [15][17][18]

Region	Primary Energy Source	EV Emissions (g CO ₂ -eq/km)	ICEV Emissions (g CO ₂ -eq/km)
Norway	Hydropower	50	120
United States	Mixed (Natural Gas, Coal, Renewables)	120	250
China	Coal	180	260
Germany	Mixed (Coal, Renewables)	130	220
France	Nuclear, Renewables	60	200

Another consideration during the usage phase is battery degradation. Over time, the capacity of lithium-ion batteries decreases, which can reduce the driving range of EVs and necessitate more frequent charging. This degradation is influenced by several factors, including the number of charge cycles, charging patterns, and environmental conditions. Research by Berti et al. (2019) indicates that the average lithium-ion battery retains about 80% of its capacity after 8 years of use [19]. This reduction in capacity can impact the overall efficiency and convenience of EVs but does not typically lead to significant increases in operational emissions.

EVs generally require less maintenance than ICEVs due to fewer moving parts and the absence of components such as oil filters and exhaust systems. The reduced need for maintenance translates into lower operational costs over the vehicle's lifetime. A study by Palmer et al. (2018) found that the total cost of ownership (TCO) for EVs is often lower than for ICEVs, especially when accounting for savings on fuel and maintenance [20]. These economic benefits further enhance the attractiveness of EVs from a consumer perspective and contribute to their growing adoption.

End-of-Life

The electric vehicle (EV) end-of-life (EOL) involves decommissioning, recycling, and component disposal, particularly lithium-ion batteries. Proper management of this phase is necessary to reduce the environmental footprint and to ensure the recovery of valuable materials. Close attention to the issues related to EV disposal and recycling will ensure the full realization of green benefits from EVs.

Battery Recycling Technologies

Since lithium-ion batteries form the core technology of EVs, they contain valuable metals in the form of lithium, cobalt, nickel, and manganese. Recycling such batteries will help recover these metals and reduce the impact of raw material extraction on the environment. Currently, the available technologies for recycling lithium-ion batteries fall under two categories: hydrometallurgical and pyrometallurgical. The former involves a series of processes in which metal is leached from the battery components through the use of chemical solvents. The key advantage of this process lies in the fact that it is able to recover a high percentage of metals with a low input of energy. According to Gaines (2014), about 95% of lithium and cobalt can be recovered using this technology [21]. Still, the implementation of the process presents potential environmental and safety issues because of the strong acids and other chemicals used. Pyrometallurgical technologies involve the smelting of battery components at a high temperature to separate the metals. The process is effective in the recovery of the valuable metals but is energy-intensive and may release a considerable amount of greenhouse gases. Regardless, this method remains one of the most used technologies because of its scalability and its robustness. According to Wang et al. (2019), improvements in the pyrometallurgical process continue to be developed to reduce emissions and improve energy efficiency [22].

Although this process has a good potential for material recovery, the recycling rate of EV batteries is relatively low. Firstly, tediousness emanates from the complex and variegated designs of batteries. Secondly, the economic barriers such as fluctuating prices for the recovered materials and the high costs in the recycling processes; this includes the high amounts for accessibility to recycling facilities, with the collection and transportation posing a critical issue. Collection of spent batteries from far-scattered locations and transportation to the recycling facilities in a safe and environmentally sound manner is an arduous and expensive process. Furthermore, the hazardous properties of the constituents of the batteries impose tough observance to the safety and environmental regulations during handling and transportation. Inadequate disposal of EV batteries can have dire environmental implications. Batteries, if inadequately disposed of or not recycled, are capable of emitting hazardous materials, including heavy metals and organic electrolytes,

into the environment. This further results in the pollution of the soil and water to pose risks for the ecosystems and human health. For instance, lead and cadmium, which are common in the batteries, have been noted to cause "unusually high environmental pollution and severe health problems when let out in the environment" [23].

To address such inappropriateness, broad policy and regulatory frameworks are necessary so that the government and regulatory authorities enact and enforce regulations that are potent of creating incentives for recycling. One of the major policy responses is in the form of EPR schemes. EPR is the concept that the producers have the ultimate concern, right from the extraction of the raw materials to the end-of-life phase, over the life of their products. In EPR schemes, the producers are made to have incentives to design batteries that can be easily recycled and to invest in recycling infrastructure. The European Union has made the lead in developing such regulations. For example, the EU Battery Directive mandates that at least 50% by weight from batteries be recycled and capping off hazardous materials from disposal [24]. Other regions have recently started passing that kind of legislation to accommodate for sustainable disposal and recycling of EV batteries.

Research and development of battery recycling technologies are necessary for the advancement of efficiency and the environment under battery recycling. For example, the development of up-coming technologies, including direct recycling. It targets to recover and re-apply low processing battery components. Direct an essential element of recycling is the reconditioning of the battery cells and the components to re-introduce by the new batteries. It implies that more of the original value in the material is retained, and energy is conserved. In addition, automation together with the use of artificial intelligence has enhanced battery sorting and disassembling, improving recycling, which has a high output within a concise period. Chemical processes have been innovated to get an agent that is less noxious, and that is environment-friendly in hydrometallurgical recycling [25].

Economic Impact Analysis

The economic impact of electric vehicles (EVs) spans various aspects, including manufacturing costs, total cost of ownership (TCO), job creation, and the broader economic implications of transitioning from internal combustion engine vehicles (ICEVs) to EVs. This section provides a comprehensive analysis of these factors, drawing on real data and references to illustrate the economic benefits and challenges associated with EVs.

The production of EVs, particularly the manufacturing of lithium-ion batteries, involves significant costs. Battery costs have been a major barrier to the widespread adoption of EVs. However, recent advancements in battery technology and economies of scale have

led to a substantial decrease in battery prices. According to BloombergNEF, the average price of lithium-ion batteries dropped from \$1,100 per kilowatt-hour (kWh) in 2010 to approximately \$137 per kWh in 2020, and it is projected to fall below \$100 per kWh by 2023 [11]. Despite these reductions, the initial manufacturing cost of EVs remains higher than that of ICEVs. This is primarily due to the cost of raw materials, battery production, and the need for specialized manufacturing processes. However, as battery costs continue to decrease and manufacturing processes become more efficient, the price gap between EVs and ICEVs is expected to narrow.

The total cost of ownership (TCO) of EVs is a critical factor influencing consumer adoption. TCO includes the purchase price, fuel costs, maintenance expenses, and resale value. Several studies have shown that, despite higher upfront costs, EVs tend to have a lower TCO over their lifetime compared to ICEVs. Fuel costs for EVs are significantly lower than for ICEVs, as electricity is generally cheaper than gasoline or diesel. Additionally, EVs have fewer moving parts and require less maintenance. A study by Palmer et al. (2018) found that the TCO for EVs can be up to 15-30% lower than for comparable ICEVs, particularly when accounting for fuel savings and lower maintenance costs [20]. Maintenance costs for EVs are lower because they do not require oil changes, have fewer fluids to replace, and experience less wear and tear on components such as brakes due to regenerative braking systems. These factors contribute to a lower TCO, making EVs an economically attractive option for consumers.

The transition to EVs is expected to have significant implications for job creation and the broader economy. The EV industry is creating new jobs across the board, in battery manufacturing, vehicle assembly, charging infrastructure, and related sectors. According to the International Energy Agency, the shift to EVs could create up to 10 million new jobs worldwide by 2030 [18]. On the other hand, the transition to EVs may also offer challenges to traditional automotive industries, especially in regions widely based on ICEV manufacturing. Particularly alarming are the prospects in areas where such job displacement would occur. The skills required for the production of EVs are generally unlike skills required for ICEVs. This calls for workforce retraining and the outlay of large investments in new manufacturing technologies.

The massive shift towards EVs can realize high economic values through the reduction of greenhouse gas emissions and improvement in public health. Lower emissions would result in better air quality, a situation that would see health costs reduced through the decline of respiratory and cardiovascular diseases. As discussed by Holland and associates in 2016, the health cost saved by the US up to the year 2030 through a reduction in air pollution



shall be \$13 billion annually. Diversified energy sources and the high use of domestically produced electricity will ensure that there is reduced reliance on fossil fuels and, consequently, reduced economic exposure to fluctuations in oil prices.

Government incentives influence the rate at which the market for EVs develops. Tax credits, rebates, and subsidies reduce the implied cost of purchasing EVs, making them competitive against ICEVs. For example, the federal government of the U.S. provides \$7,500 as a tax credit against buying a new EV, with some more being offered by other several states in their country [27]. These incentives have spurred market growth along with investments in charging infrastructure. Sales of EVs worldwide have been growing very fast, whereby in 2020, the sales grew by 43%, despite the economic downturn caused by the COVID-19 pandemic. It is further estimated that sales in EVs will reach 30 million per annum by the year 2030, accounting for an approximately 30% new vehicle sale share, according to IEA projections [18].

Discussion

Now, with respect to the life cycle assessment of electric vehicles, environmental benefits and economic constraints are shakingly equalized. Electric vehicles can be considered as an option to reduce greenhouse gas emissions and improve air quality, more so in the case of their end-of-life stage, as tailpipe emission will be minimized to zero. However, this directly tethers on environmental benefits, most especially on the carbon intensity of their electricity generation, and there is even an impulse to switch on to renewable sources. In some potential environmental impacts of the life cycle, certain cobalt mining areas pose critical environmental impacts, and water depletion in lithium-rich regions due to the extraction of raw material for electric vehicle manufacturing. These issues should be handled properly with sustainable mining and raw material sourcing, as well as an ethical supply chain.

On the flip side, however, upfront costs for electric vehicles are higher than for internal combustion engine vehicles. However, in line with an exponentially rising battery technology, the battery prices have fallen steeply. As battery prices reduce and production gets more efficient, EVs will become more and more cost-competitive. The rising electric vehicle industry has created many new jobs, though ICEV-dependent areas will suffer when workers must make the transition. The operability of EVs is, on the other hand, highly energy-efficient, and their TCO is below ICEVs due to low-cost fuel and low maintenance. Again, though, the situation will depend on the carbon intensity of the grid and the strength of policies supporting clean energy. Moreover, concerns associated with battery



degradation and end-of-life underline the necessity to have a supportive recycling infrastructure and regulatory framework to minimize risks to the environment.

This shift to the electric vehicles means the total shift economically: from reduced fuel costs to the structures used in this shift, all embracing a shift in culture and a change of lifestyle. This adoption of EVs will pass through a tight vertex of government incentives and policy initiatives that must be designed to provide strong bases for infrastructural support. However, the issues always crop up when addressing issues related to environmental and economic disparities between the regions and industries. Coordinated policies and support schemes by policymakers and manufacturers with full participation of many consumers are mandatory for the realization of potential that EVs hold in achieving set sustainability goals. Electric vehicles will play the central role, through continued innovation, investment, and regulatory support, in observing a cleaner and more sustainable future.

Environmental Benefits and Challenges

Though the EV would grant immense environmental benefits pertaining to greenhouse gas emission reduction and better air quality, it also poses significant environmental challenges that require to be mitigated to leverage the potential of the EV in climate change and sustainability. One of the most convincing evidence on the environment gains by EVs is their potential to provide significant reductions in greenhouse gas emissions. Unlike ICEVs that burn fossil fuels and emit CO₂ and other pollutants directly from their tailpipes, EVs have zero tailpipe emissions. This attribute is important in areas with high vehicular traffic, where vehicular emissions emerge as the most potent source of degradation to ambient air quality. According to the IEA, compared to a similar ICEV and considering a global average electricity mix, a typical EV reduces CO₂ emissions by approximately 50-60% [18].

The nonexistence of tailpipe emissions with respect to EVs leads to better air quality, specifically in areas characterized by high vehicular traffic. This is because ICEVs emit pollutants such as NO_x and PM that are considered precursors to the formation of smog and also contribute to respiratory diseases. With the wide-scale deployment of EVs, such pollutants would subsequently decline, leading to lessened health impacts. According to a study conducted by Holland et al. in 2016, societal benefits accruing from health through better air quality, using a scenario where EV deployment increases in the European Union, would lead to annual savings of up to €13 billion in healthcare costs by 2030 [26].

EVs are inherently more energy-efficient than ICEVs. Electric drive is 2-3 times more efficient than internal combustion engines. Approximately, 60% of electrical energy from the grid is converted into power at the wheels by electric motors, while gasoline engines convert only about 20% of energy from gasoline into power [27]. This increased efficiency also means that EVs would use up a less significant amount of energy to travel an equivalent distance, thereby lowering the overall consumed energy and, in the process, the need for fossil fuels.

However, the extraction of the raw materials needed in EV batteries, especially lithium, cobalt, and nickel, comes with adverse environmental issues. Lithium, primarily from the Lithium Triangle countries of Chile, Argentina, and Bolivia, is extracted by the pumping of lithium-rich brine from underground reservoirs to evaporate in large ponds. The process is water-intensive, therefore majorly threatening local water supplies, especially in arid regions. Flexer et al. (2018) bring the negative environmental effects to the fore in their study linking lithium extraction to water resource depletion and potential soil and water contamination [1].

Cobalt mining, especially in the Democratic Republic of Congo, is not only accompanied by environmental destruction but also severe social problems. It is known as rolex mining and is individual scale-based in the DRC, where it has been devastatingly accused of the severe erosion of soils, deforestation, and water contamination. Also, Amnesty International (2016) shows that cobalt mining in the DRC is linked to human rights violations, including child labor and dangerous working conditions and, therefore poses ethical concerns regarding cobalt's extractability for use in EV batteries [3].

This then means that EV batteries' production is energy-demanding and, by itself, accounts for a substantial fraction of the total environmental footprint of EVs. In the manufacturing of lithium-ion batteries, constituting the most dominant battery technology applied in electric vehicles, raw materials need to be mined and processed. Raw material mining and processing are energy-intensive, and in the process, these processes account for massive emissions. As determined by the estimate by Ellingsen et al. (2014), 150 to 200 kCO₂-eq is emitted in a kWh battery capacity for the manufacturing of lithium-ion batteries, these constituting an essential fraction of EV lifecycle emissions [5].

The environmental benefits accruing from the use of EVs are directly related to the source of energy that charges the batteries. In countries where the primary source of power is from renewable sources like hydropower, wind, or solar, GHG emissions related to EVs are significantly diminished. This similarly diminishes in regions with large power generation capacities from coal-fired thermal power plants. This variation underscores the need for

rapid adoption of cleaner sources of energy, which will be crucial to unlock much of the potential of EVs with regard to benefits that stand to accrue to the environment.

The end-of-life phase of EV batteries presents both challenges and opportunities. Proper recycling of lithium-ion batteries is important to recover valuable materials and at the same time abate the environmental impact. Currently, recycling by hydrometallurgical and pyrometallurgical processes can recover close to 100% of lithium and other metals, such as cobalt and nickel. Nevertheless, recycling rates are quite low, and there is a lot of ground to be covered to ensure the process is efficient and environmentally friendly. Without good management, EV batteries can cause soil and water contamination from their hazardous materials; hence, hard regulations and recycling infrastructures are needed. Improper disposal of EV batteries will also cause soil and water contamination with hazardous materials and, therefore, will require tight regulatory frameworks and recycling infrastructure [21].

Table 2 Comparison of Key Environmental Impacts of EVs and ICEVs

Impact Area	EVs (Electric Vehicles)	ICEVs (Internal Combustion Engine Vehicles)
Greenhouse Gas Emissions	Lower overall, but varies with electricity source	Higher due to direct tailpipe emissions
Air Quality	Improved, zero tailpipe emissions	Poorer, high NOx and PM emissions
Energy Efficiency	Higher (~60% grid to wheels)	Lower (~20% fuel to wheels)
Raw Material Extraction	Significant environmental impacts (lithium, cobalt, nickel)	Moderate, primarily related to fuel extraction
Manufacturing Emissions	High (battery production)	Moderate to high
End-of-Life	Recycling challenges, potential for contamination	Established recycling, but environmental risks remain

Economic Viability

The economic viability of electric vehicles (EVs) is a multifaceted issue that encompasses the initial costs of purchasing EVs, the operational and maintenance expenses, and the broader economic impacts on industries and employment. This analysis provides a comprehensive look at these factors, highlighting the economic benefits and challenges associated with the transition to electric mobility.

The upfront cost of EVs has historically been higher than that of internal combustion engine vehicles (ICEVs), primarily due to the expensive lithium-ion batteries that power them. However, over the past decade, there has been a significant reduction in battery costs. According to BloombergNEF, the average price of lithium-ion battery packs dropped from \$1,100 per kilowatt-hour (kWh) in 2010 to approximately \$137 per kWh in 2020, with expectations of falling below \$62 per kWh by 2030 [11]. This decline in battery costs has made EVs more competitive in terms of price and is expected to lead to price parity with ICEVs in the near future.

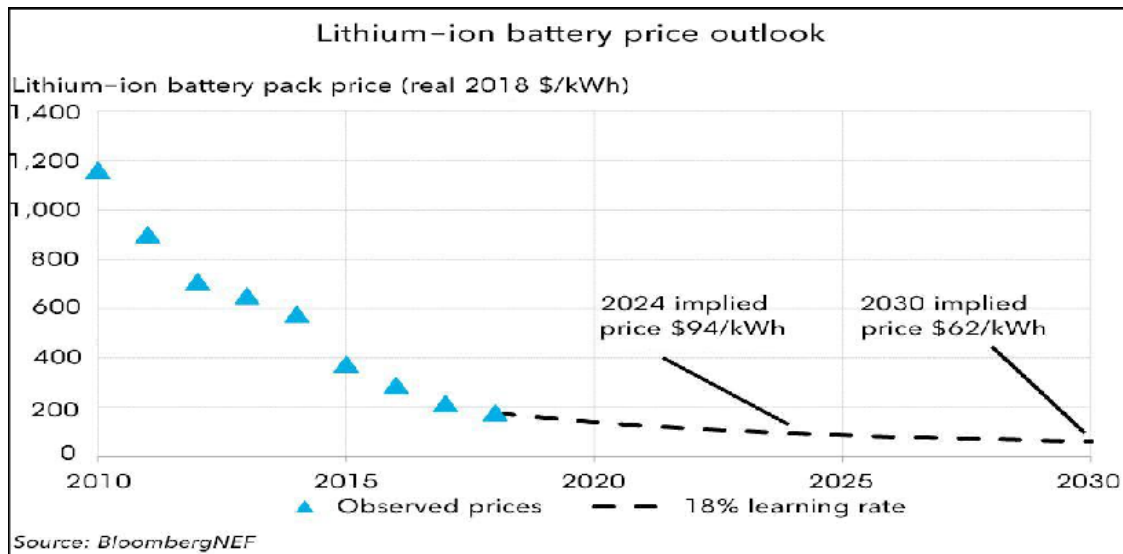


Figure 3 cost of lithium-ion battery packs from 2010 to 2020 with projected costs up to 2025 – 2030. From [31]

One of the significant economic advantages of EVs is their lower operational costs. EVs have fewer moving parts compared to ICEVs, resulting in reduced maintenance and repair costs. For instance, the U.S. Department of Energy (DOE) reports that the scheduled maintenance costs for light-duty EVs are about one-third those of similar ICEVs. Additionally, the cost of electricity per mile for EVs is typically lower than the cost of gasoline or diesel. The DOE estimates that fueling an EV cost about half as much as fueling

a conventional vehicle, assuming average U.S. electricity and gasoline prices. These lower running costs enhance the economic attractiveness of EVs over their operational life. When we considering the total cost of ownership (TCO), which includes the purchase price, fuel costs, maintenance, insurance, and depreciation, EVs often present a more favorable economic proposition over the vehicle's lifespan. A 2020 study by the International Council on Clean Transportation (ICCT) compared the TCO of EVs and ICEVs in major European markets and found that EVs were already cost-competitive with ICEVs, largely due to lower running costs and government incentives. These findings suggest that as battery costs continue to decline and more efficient EVs are developed, the TCO will become even more advantageous for EVs.

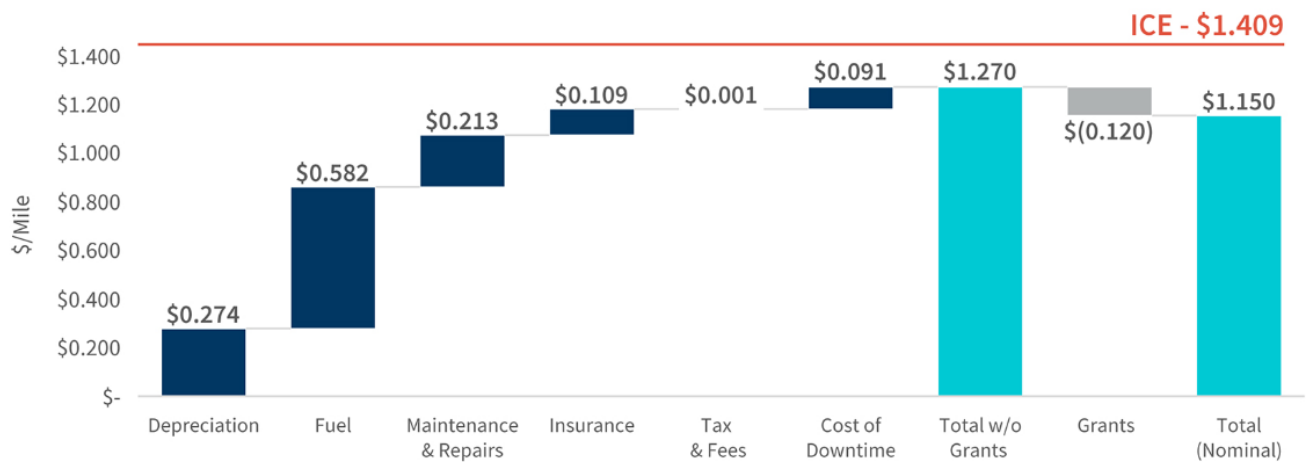


Figure 4 Total cost of ownership (TCO) of EVs vs. ICEVs, including purchase price, fuel costs, maintenance, and other expenses over a typical vehicle lifespan from FTI consulting [32]

Going government policies and incentives also play a huge role in improving the economic viability of EVs. Most countries provide such subsidies, tax rebates, and grants that make the effective purchase price of EVs lesser. For example, in the U.S., buyers are eligible to receive a federal tax credit of \$7,500 or less, depending on battery capacity and manufacturer. Similar incentives are deployed in the European Union and in other parts of the world, which amplify the economic attractiveness of electric vehicles. Linkages of EVs to the broader economy have implications for employment and industries. While the EV industry poses opportunities in new areas such as battery manufacturing, software design, and charging infrastructure, the traditional automotive industry—which heavily relies on ICEV manufacturing—is bound to be negatively affected. The likely economic disruptions

and job losses in regions where the manufacturing of ICEVs is currently based are seen with declines in sales and eventual shutdowns of particular facilities, where these facilities are located. Investments in retraining and reskilling of workers are therefore required in order to take up these new opportunities that will be seen in the chain of electric vehicle production.

A very vital component of the economic viability of EVs is charging infrastructure. An adequate, reliable, and widely distributed charging network is essential in supporting large numbers of EVs on the road. Therefore, it is not only essential for EV adoption, but it also creates business opportunities in construction, technological development, and maintenance services. According to McKinsey & Company, the global EV charging infrastructure market will increase in size and is estimated to be close to \$500 billion by 2040. Such growth would underline the significance of infrastructure investment for the economic sustainability of the EV transition.

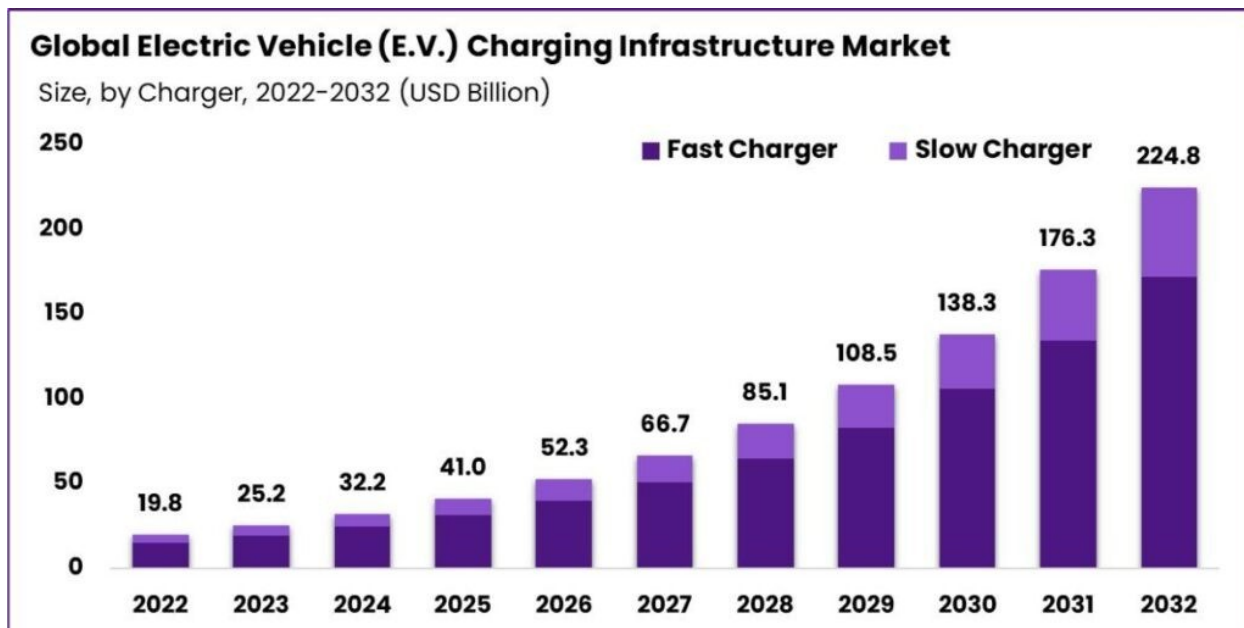


Figure 5 Global EV Charging Infrastructure Market Growth [33]

Table 3 Economic Comparison of EVs and ICEVs

Aspect	EVs (Electric Vehicles)	ICEVs (Internal Combustion Engine Vehicles)

Initial Purchase Cost	Higher, but declining	Lower
Fuel Costs	Lower (electricity)	Higher (gasoline/diesel)
Maintenance Costs	Lower	Higher
Total Cost of Ownership (TCO)	Becoming more favorable	Higher over the vehicle's lifespan
Government Incentives	Available in many regions	Fewer, mostly emissions-related penalties
Impact on Employment	New opportunities, but transition needed	Established, but potentially declining
Charging/Fueling Infrastructure	Growing, requires investment	Established, widespread

Conclusion

Electric vehicles (EVs) have both environmental and economic implications when compared to internal combustion engine vehicles (ICEVs). If the sources of power are renewables, such a shift is prospective for the environment, like lesser generation of greenhouse gases and less air pollution in operation. However, offsetting numerous environmental benefits is the significant challenge with raw material extraction for battery manufacturing and electric power-hungry manufacturing processes. In terms of environment, this is a nice fact. On the economic side, EV viability has become much better than 10 years ago, through the dropping cost of batteries, lower operational costs, and general government support. Purchasing prices are higher than that of ICEVs, but with a progressively lower TCO caused by reduced costs of fueling and maintaining. Government incentives and public investments in charging infrastructure further enhance the economic attractiveness of EVs and widen their adoption.

Changes in the automobile industry would mean transformative changes in industries and employment, with gradual increases in job opportunities for industries like battery manufacturing, software development, charging infrastructure, etc. but at the same time, would mean job displacement in the traditional automotive values chain, which may strain the industry without proper retraining and upskilling. Environmental and social impacts



from mining of raw materials for EV batteries stress that sustainable, ethically responsible mining should be conducted in parallel with developments in battery recycling. These are paramount concerns for long-term sustainability of EVs and the ecological footprint of their supply chains.

In general, the results of the present study suggest that further technological development, along with regulatory and infrastructural improvement, is crucial to fully exploit the benefits of EVs and deal with their associated problems. By these means, a transition to electric mobility, although pegged on improved economic viability by sustainable operation, can play a significant role in global efforts toward climate change mitigation and work against the view of promoting a world fit for the future. Some incontestable challenges, but more important, promise through this large-scale lifecycle analysis of electric vehicles: through innovation and continuing commitment, EVs are only a step closer to a more sustainable and economically viable future in transportation.

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