Electric Vehicle Adoption As Sustainable Solution to Economic Growth and Environmental Challenges in Nigeria

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Abstract
The adoption of Electric Vehicles (EVs) offers a promising solution to address pressing environmental challenges and foster economic growth in Nigeria. This study explores the potential of EV adoption in Enugu State as a sustainable approach to mitigate air pollution, greenhouse gas emissions, and climate change while promoting industrial innovation and job creation. Conventional internal combustion engine vehicles are significant contributors to environmental degradation in the region, exacerbating urban air quality issues and accelerating climate risks. Despite growing global trends in EV adoption, limited infrastructure, high acquisition costs, and low public awareness impede their widespread use in Nigeria.The study investigates the environmental and economic benefits of EVs, emphasizing their role in reducing carbon emissions, fostering sustainable urban mobility, and creating clean energy ecosystems. It also examines global trends in EV adoption, highlighting market growth and technological advancements that enhance the efficiency and accessibility of EVs. Furthermore, the integration of EVs with Intelligent Transportation Systems (ITS) is discussed as a strategy to optimize traffic management, reduce emissions, and align with smart city initiatives.Addressing the barriers to EV adoption requires a collaborative approach involving policymakers, industry stakeholders, and the public. By analyzing challenges such as infrastructure deficits and exploring solutions like renewable energy integration and public awareness campaigns, this study provides actionable strategies to promote EV adoption in Nigeria. The findings underscore the transformative potential of EVs in achieving environmental sustainability and driving economic development in Enugu State and beyond.
Keywords: Electric Vehicles, Adoption, Sustainability, Economic Growth, EnvironmentalChallenges.

Introduction

The automobile industry plays a pivotal role in the global economy and serves as a hub for advancements in Research and Development (R&D). With continuous technological innovation, modern vehicles are equipped with features designed to enhance safety for both passengers and pedestrians (Adler & Mirchandani, 2014). While this progress has brought convenience and improved mobility, it has also exacerbated environmental challenges. The surge in-vehicle use has contributed significantly to urban air pollution, characterized by emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM) (Agarwal et al., 2023). These pollutants not only degrade air quality but also pose health risks and accelerate climate change. Thus, while the automobile industry has revolutionized transportation, it also demands urgent solutions to mitigate its environmental footprint.

Electric Vehicle (EV) adoption presents a promising path toward addressing these challenges. EVs, powered by rechargeable batteries instead of fossil fuels, offer a cleaner and more sustainable alternative. Their ability to reduce greenhouse gas emissions and dependency on non-

renewable resources positions them as a cornerstone of sustainable transportation systems. With rapid advancements in battery technology, EVs are becoming more efficient, cost-effective, and autonomous, aligning with the global push for sustainability (Konig et al., 2021). As the adoption of EVs grows, it is expected to play a crucial role in fostering economic growth by creating new industries and job opportunities while addressing critical environmental challenges.

In Nigeria, particularly in Enugu State, the need for sustainable transportation solutions is evident. Rapid urbanization has led to increased traffic congestion, noise, and air pollution, negatively impacting the efficiency and capacity of transportation systems. Factors such as poorly designed urban road networks, inadequate traffic management systems, and limited public transport options exacerbate these issues. Intelligent Transportation Systems (ITS) have emerged as a potential solution to these challenges, combining advancements in information technology, sensors, and control systems to optimize traffic flow, reduce emissions, and enhance safety (Ravish & Swamy, 2021).

The integration of EVs into ITS frameworks further strengthens the potential for sustainable urban transportation. Autonomous electric vehicles (AEVs), equipped with smart connectivity features, provide innovative solutions to urban mobility issues. They align with the goals of smart city initiatives by reducing carbon emissions and promoting energy efficiency (Saleem et al., 2022). For Enugu State, adopting such technologies is critical for addressing its unique transportation challenges and fostering economic growth through sustainable practices.

Globally, the adoption of EVs has shown a positive trend, with a significant rise in market share over the past decade. Sales of EVs surged by 60% in 2023, and it is projected that the number of EV users will triple by 2030 compared to 2011 (Konig et al., 2021). However, the environmental impact of EV adoption varies across regions, influenced by the energy mix used for electricity generation. In countries like the U.S. and China, the increased use of coal for energy has offset some benefits of EV adoption, emphasizing the need for renewable energy integration to maximize the environmental benefits of EVs (Song et al., 2023).

Electric Vehicle adoption not only addresses environmental challenges but also stimulates economic growth by creating a sustainable energy ecosystem. By reducing reliance on fossil fuels and lowering greenhouse gas emissions, EVs contribute to global efforts to combat climate change while promoting technological innovation and industrial development. For regions like Enugu State, the transition to EVs can serve as a sustainable solution to environmental challenges, paving the way for economic growth through investments in clean energy and infrastructure development.

This study explores the impact of EV adoption on sustainability, economic growth, and environmental challenges in Enugu State, examining its potential to revolutionize transportation systems and contribute to a greener, more prosperous future.

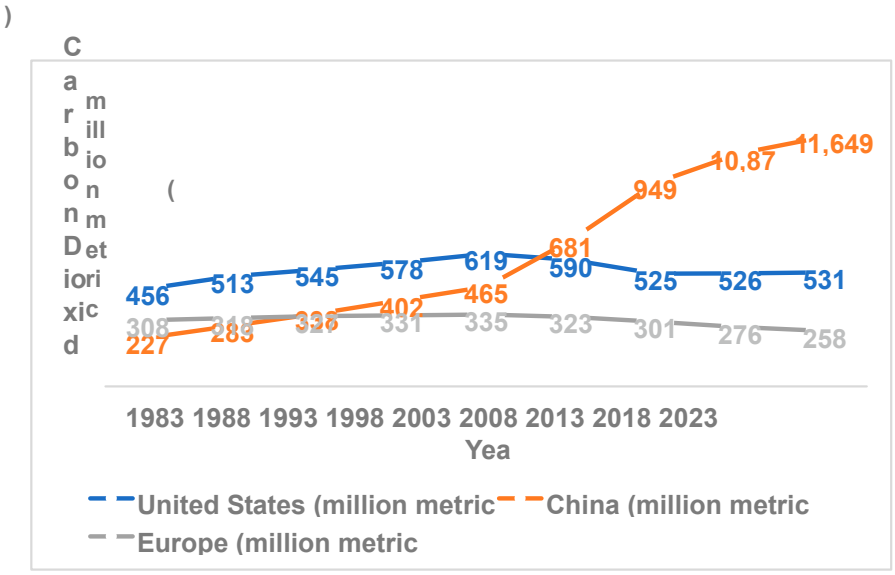

Figure 1. Energy-related carbon dioxide emissions in the US, China, and Europe from 1983 to 2023. Source: Emission Gap Report 2022

Electric vehicles have advantages over conventional cars regarding cost-effectiveness and the environment. EVs might cost more upfront, but they can save drivers money over time thanks to reduced fuel prices and less frequent maintenance needs. Since electric motors have fewer moving parts and require less maintenance, EVs also often have longer lifespans than conventional cars (Grunditz&Thiringer, 2016). Therefore, it's a must to implement electric vehicles all over the world by reducing their adoption challenges.

In this regard, government incentives play a critical role in increasing the sales of electric vehicles by making them more affordable and accessible to the public (Rajaeifar, Ghadimi, Rangei, Wu & Heidrich, 2022). China is a prime example of this, as the government has implemented various policies and incentives to encourage the adoption of electric vehicles. These include financial incentives such as subsidies, tax breaks, and free license plates, as well as non-financial incentives such as preferential access to carpool lanes and free parking (Li, Yang & Sandu, 2018). These incentives have helped to reduce the upfront cost of electric vehicles, making them more competitive with traditional gasoline-powered cars. In addition, government investments in charging infrastructure and research and development have helped to address concerns around range anxiety and the technology's reliability. These incentives have resulted in a surge in electric vehicle sales in China, making it the largest market for electric vehicles globally (Saharan, Bawa & Kumar, 2020). Figure 2depicts the global electric car stock country-wise, including battery electric vehicles(BEVs) and plug-in hybrid electric vehicles (PHEVs). China also holds the largest number of public EV charging stations, as shown in Figure 3.

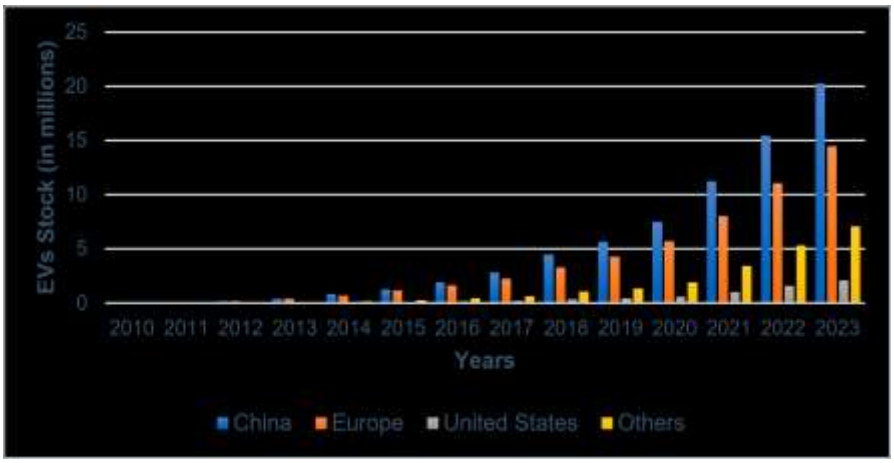

Figure 2. Global electric car stock country-wise, including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Source: Global EV Outlook 2022—Analysis—IEA.

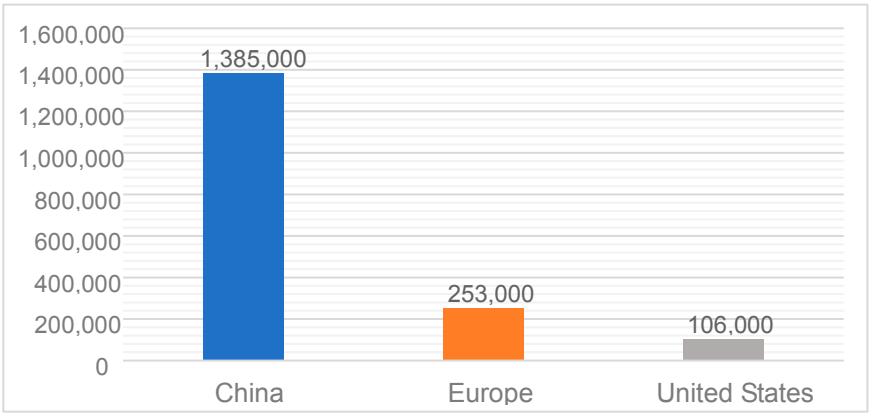

Figure 3. Public EV charging stations (He, Kuo & Wu, 2016).

It's worth noting that these figures are constantly evolving as governments and private companies continue to invest in expanding their EV charging infrastructure. China has been particularly aggressive in building its charging network, intending to have 4.8 million charging points by 2025 (He, Kuo & Wu, 2016). Europe also invests heavily in expanding its charging infrastructure, with plans to have 1 million public charging points by 2025. The US is somewhat behind in the number of charging stations, but the Biden administration has proposed significant funding to help build the country's EV charging network.

Vehicles that operate on electricity rather than petrol or diesel fuel are known as electric vehicles (EVs). There are several EV kinds, each with a unique engine and settings (Yang, Long & Li, 2016). According to their engine technology and settings, electric cars are categorized in the following manner in detail (Figure 4):

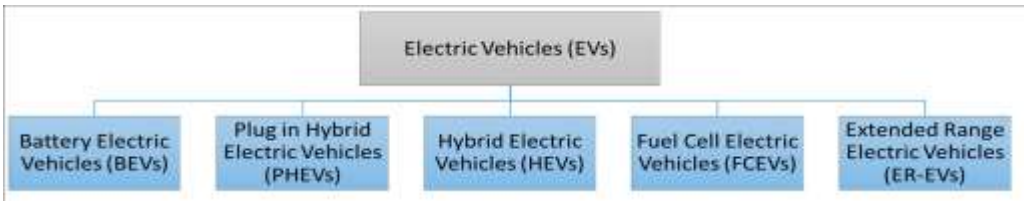

Figure 4. Classification of Electric Vehicles (EVs) according to engine technology and settings.

Statement of the Problem

The increasing environmental challenges, including air pollution, greenhouse gas emissions, and climate change, have necessitated urgent action to adopt sustainable solutions for energy and transportation systems. In Enugu State, Nigeria, reliance on conventional internal combustion engine vehicles contributes significantly to these environmental issues, exacerbating poor air quality and accelerating environmental degradation. Despite growing awareness of these challenges, the adoption of Electric Vehicles (EVs), which offer a cleaner and more sustainable alternative, remains limited in the region.

Furthermore, the economic potential of EV adoption, such as job creation, technological innovation, and reduced dependency on fossil fuels, has not been fully explored or harnessed in Enugu State. The lack of adequate infrastructure, high costs of EV acquisition, and insufficient public awareness hinder the widespread adoption of EVs, leaving the region dependent on unsustainable transportation methods.

This situation underscores a critical problem: the failure to embrace EVs not only perpetuates environmental degradation but also limits opportunities for economic growth and sustainable development. Addressing this gap requires a comprehensive understanding of the barriers to EV adoption and the potential socio-economic and environmental benefits that could arise from transitioning to electric mobility in Enugu State. This study seeks to investigate these challenges and propose strategies to promote EV adoption as a sustainable solution to the environmental and economic issues facing the region.

Objectives of the Study

1. The primary objective of this study is to shed light on the challenges surrounding the adoption of electric vehicles and suggest effective strategies for their successful implementation.
2. To explore how have electric vehicles contributed to reducing carbon emissions, and what is their global market share trend over time
3. To investigate electric vehicle adoption and implementation by providing evidence-based insights and recommendations. The study represents a significant step towards understanding the challenges and opportunities associated with electric vehicle adoption and implementation.

Research Questions

1. What are the main challenges and facilitators of electric vehicle implementation in Nigeria, and what collaborative efforts are necessary for successful integration?
2. How have electric vehicles contributed to reducing carbon emissions, and what is their global market share trend over time?
3. What are the potential future research directions for electric vehicles in Nigeria, with a focus on improving battery technology, addressing range anxiety, reducing charging times, and promoting EVs?

Benefits of Electric Vehicles

Environmental Benefits

Since EVs don't emit tailpipe emissions, they don't contribute to air

pollution or greenhouse gas emissions. Even when fossil fuels are needed to generate energy to power the EV, it emits less pollution than a typical gas-powered vehicle (Li, Khajepour & Song, 2019).

Lower Operating Costs

Compared with regular cars, EVs offer lower running costs. In general, electricity is less expensive than petrol or diesel, and as electric vehicles have fewer moving components, they require less maintenance. Due to electric motors' excellent durability compared with internal combustion engines, they also often have a longer lifespan (Li, Khajepour& Song, 2019).

Energy Independence

Renewable energy sources, including solar or wind power, may power EVs. This lessens reliance on fossil fuels and may increase the sustainability of energy use (Li, Khajepour& Song, 2019).

Efficiency

Compared with conventional cars, EVs are more efficient. The efficiency of the power plant will also affect the well-to-wheel (WTW) effectiveness. Compared with diesel cars, which vary from 26% to 38%, the overall WTW productivity of petrol vehicles range from 12% to 28%. In comparison, the WTW efficiency of EVs powered by natural gas power plants ranges from 14% to 30%, while EVs powered by renewable energy show an overall efficiency of up to 70% (Li, Khajepour& Song, 2019).

Smooth and Quiet Operation

EVs operate significantly more quietly and smoothly than conventional cars because electric motors generate less vibration and noise. This may result in a more relaxing and pleasurable driving experience (Li, Khajepour & Song, 2019).

Convenience

EVs may be charged at residences or public charging stations, so going to the petrol station is no longer necessary. Additionally, many EVs include capabilities that enable drivers to remotely warm up or cool the cabin, which may be helpful in extremely hot or cold weather (Li, Khajepour& Song, 2019).

Performance

Electric motors can produce instant torque, allowing EVs to accelerate quickly. They could also have a lower centre of gravity, making them more manoeuvrable and stable (Li, Khajepour& Song, 2019).

Challenges of Adopting Electric Vehicles

Public sector operators in the EV market include utilities, state and municipal governments, and private sector players, including EV service contributors, fleet workers, and individual car holders. Variable adopters, such as private automobile owners, managers of private business fleets, and public fleets, make varied operational decisions. Following the types and distribution of adopters, at-home charging, public charging, and battery-swapping stations should be optimized for the charging models. The customer type is also connected to incentive programs and infrastructure deployment (Lv& Shang, 2023). An overview of the EV service industry's members and some of the key problems they deal with is shown in Figure 5.

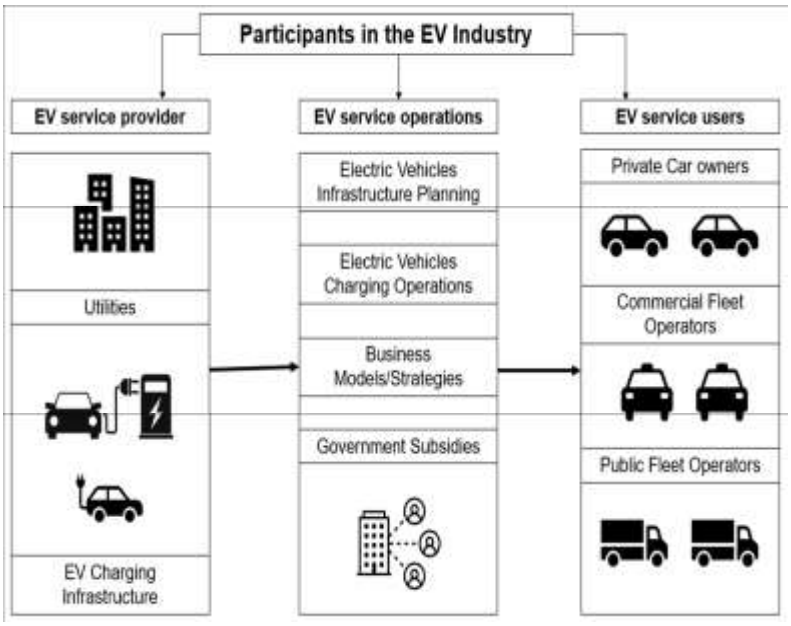

Figure 5. EV service operations/participants.

Charging Infrastructure

EV-related technologies are still developing; hence, their future course is yet unknown.

For instance, one of the most important elements influencing EV acceptance is the battery performance, which is still not at its peak. Despite recent advancements in the construction of charging infrastructure, it is still not as accessible or practical as conventional petrol stations. This can make it challenging for EV drivers to locate charging outlets when needed, especially when travelling long distances or in remote places. The speed of battery recharging is another ambiguous technological aspect. It has long been anticipated that fast and secure charging will let Electric vehicles replace Individually Constructed Vehicles. Global-scale fast charging would, however, increase the stress on the electric grid and, as a result, pose several stability issues for power systems. Another source of misunderstanding in technical standards is those for charging interface standards. Prior agreement on recharging standards will be essential for developing the EV market, as more diverse standards require more significant infrastructure expenditure. Additionally, many charging standards make producing their goods more challenging for EV suppliers and automakers.

Interconnected Public Policies

The EV industry is still in its infancy, given the total dominance of Individually Constructed Vehicles in the international car market. The public sector has a crucial role in encouraging the use of EVs. Many nations are implementing various policies to make it easier for EVs to be introduced and consolidated into the market. These rules and associated laws cover gasoline taxation, carbon emission controls, public charging infrastructure, monetary incentives and public subsidies, and support for electric vehicle study and development. Incorporating three interconnected factors—investment in electric vehicle charging infrastructure, state subsidies, and public acceptance of EVs—will help to increase EV adoption. Various new decision-making difficulties must be resolved for these policies to be successfully implemented. Public policymaking is complicated and made more difficult by the

high levels of uncertainty and market dynamics for EVs.

Business Strategies

How a firm or group of businesses provides one or more goods or services is called its

Business strategy

The EV sector has suggested cutting-edge ownership models, including battery swapping and EV sharing, to address problems such as range anxiety and high upfront costs. For this, the Beijing EV firm, a top electric vehicle manufacturer in China, set up battery-switching places for electric taxi cabs in 2015. Sinopec, a firm benefiting from a vast transportation network, worked with Beijing Electric Vehicle Company to implement these stations (He, Kuo & Wu, 2016).

Vehicle sharing is a well-liked type of business where people hire automobiles for brief intervals, frequently per hour/day. Customers can access a sizable fleet of automobiles by signing up for a car-pooling program and paying a yearly fee. EV sharing mixes the business concepts of EVs and automobile sharing. Many local states are increasingly pushing electric vehicle-sharing schemes by providing numerous forms of monetary incentives because of the growth of the sharing economy. This approach is appealing since it enables users to utilize EVs on a budget. Car2go, a division of Daimler AG, runs a car-sharing program with all-electric fleets in San Diego (USA), Amsterdam (The Netherlands), and Stuttgart (Germany) (Gu, Rao, Zhou & Lu, 2023).

Therefore, it is probable that developing business strategies will provide several approaches to get over obstacles to broaden EV implementation. However, specialists and scholars must examine the pertinent issues with these service operations' business models.

Strategies for Overcoming Challenges

It is generally known that; as compared with cars powered by internal combustion engines (ICEs), electric vehicles (EVs) have the potential to provide significant societal and personal advantages. Recent research has looked at the many obstacles EVs encounter and has typically determined that the most common ones are cost, range, infrastructure for charging, and customer perceptions.

Compared with refueling ICEVs, the range of BEVs is presently constrained, and charging still takes much longer. As a result, route design is excessively optimistic, and some routes are too lengthy for battery electric vehicles (BEV). Therefore, this research paper proposes suitable strategies for implementing electric vehicles (EVs) in Nigeria.

Charging Infrastructure

Since electric vehicles often have a smaller driving range than conventional vehicles, their owners may be concerned that they may run out of juice before reaching their destination. Even though the range of EVs is expanding, some drivers, particularly those who need to go long distances, still find it challenging. However, the consumer will be aware of the open slots if they can reserve charging times in advance. Customers can thus research alternative slots besides those already waiting in line. By answering consumers' queries and easing their worries over the charging network, good charging infrastructure will also help to reduce their "range anxiety".

There are several ways to effectively alleviate range anxiety, even if it makes customers unhappy and presents an economic hurdle to EV adoption.

First, fast DC charging is a practical method for reducing the time it takes to recharge and extending the range when travelling between cities by highway. Various driving styles have various energy and recharge requirements; thus, EV infrastructure

planners should consider this. Properly and dynamically building EV recharging infrastructure helps alleviate range anxiety (Lv, Qiao, Cai & Wang, 2021).

Second, a mathematical vehicle model that can forecast "real road" driving energy consumption and drivable range may be utilized to estimate accurate energy consumption and drivable range.

Third, developing countrywide charging stations can also help alleviate range anxiety, but this cannot be done without government incentives or public-private collaboration.

Finally, range anxiety can be decreased by using a network path selection model. For EV drivers, this model chooses the quickest and best route using an algorithm. These models, meanwhile, might be improved by judging the exit time and duration of a stop at a charging station. The driving range can be increased by employing series, parallel, and series-parallel charging arrangements with extremely efficient electric motors. To partially alleviate range anxiety, some EV manufacturers even provide complimentary rental automobiles for local trips outside the EV range (Lv& Shang, 2023).

Balancing Auxiliary Loads

Auxiliary loads greatly impact how much energy electric cars use, which cuts down on how far they can go. First, heavy auxiliary loads drain batteries in city driving circumstances, reducing the EV's range. The driving range decreases by 17.2–37.1% (under simulated settings) when the AC is activated in the summer. Similar to how EVs employ PTC (Positive Temperature Coefficient) heaters, the range spans from 17% to 54% (under simulations) owing to the need for heating in the cold (Mckinsey Report, 2023). Second, when electric cars are driven at highway speeds, the effects of auxiliary loads such as air conditioning and heating have not yet been fully investigated. Finally, there are significant differences in the impact of supplementary loads in a lab setting and on actual roadways. Under ideal conditions, such as with little auxiliary loads and the help of a regenerative brake system (RBS), electric vehicle producers may achieve low energy consumption and an extended driving range; nevertheless, this ideal outcome is different when EVs are driven on highways amongst towns.

One way to address the problem of limited range and high energy usage brought on by auxiliary loads is to utilize a heat pump to heat EVs in the winter. This can increase the driving range by 7.6–21.1% thanks to a higher heating coefficient of performance (CoP). The vapour compression cycle of a heat pump oversees both cooling and heating. Additionally, a four-way valve that reverses refrigerant flow is included. Additionally, its coefficient of performance is 1% greater than that of PTC heaters. Additionally, a precise assessment of EVs' heating and cooling demands may significantly reduce the energy used by the AC system. An appropriate energy management technique can also lower the total energy consumption when cooling. Consequently, a suitable energy management strategy may regulate energy use instead of the ON/OFF technique (He, Yin, Wang & Yang, 2016).

Another approach is the system configuration that has been suggested, which uses a traction shaft to clutch the AC compressor motor during braking intervals. This method not only helps the EV to weigh less but also uses less energy (Pevec, Babic, Carvalho, Ghiassi, Ketter&Polobrik, 2020).

Improved Battery Technology

The limitations of battery technology are one of the main obstacles to the widespread use of electric vehicles (EVs). The present battery design for EVs has a poor energy density,

which impacts the vehicle's driving range (Pelletier, Jabali, Laporte & Veneroni, 2017). To improve EV efficiency, a variety of

battery technologies and combinations have been created over time. Users see electric vehicles as a real alternative to internal combustion engine vehicles because of the development of better, more affordable, and higher-capacity batteries, which will increase vehicle autonomy.Since batteries are vital to EVs, more manufacturers (such as LG, Panasonic, Samsung, Sony, and Bosch) are investing in creating better, more affordable batteries.

The battery bundle is the costliest part of any EV. For instance, the Nissan LEAF's lithium-ion batteries originally accounted for one-third of the total cost of the car. However, it is anticipated that this cost will gradually decrease; as of the end of 2014, the battery pack cost around $500 per kWh (half the price in 2009); now, the price per kWh is $200, and it is anticipated to drop to approximately $100 in 2025. The fact that Tesla Motors is creating a "Mega factory" to lower manufacturing costs and enhance battery output is another piece of data supporting the trend towards lower battery costs (He, Yin, Wang & Yang, 2016).The price of EVs would naturally decrease because of decreasing battery costs, making them more competitive with other types of cars.Enhancing EV Charging Procedures—Battery Switching Stations

To lessen range anxiety, battery swapping stations might be utilized in place of battery charging stations. Standard, fully charged batteries are kept on hand at battery switching points for EV drivers to swap out and continue their trip quickly. In this way, EVs at a charge station along a highway can be changed immediately. The battery changing stations' operational mechanism is depicted in Figure 7. This technology of charging EVs instantly is already being used by Tesla and U.S. and European battery vendors (Yang, Guo & Zhang, 2017).

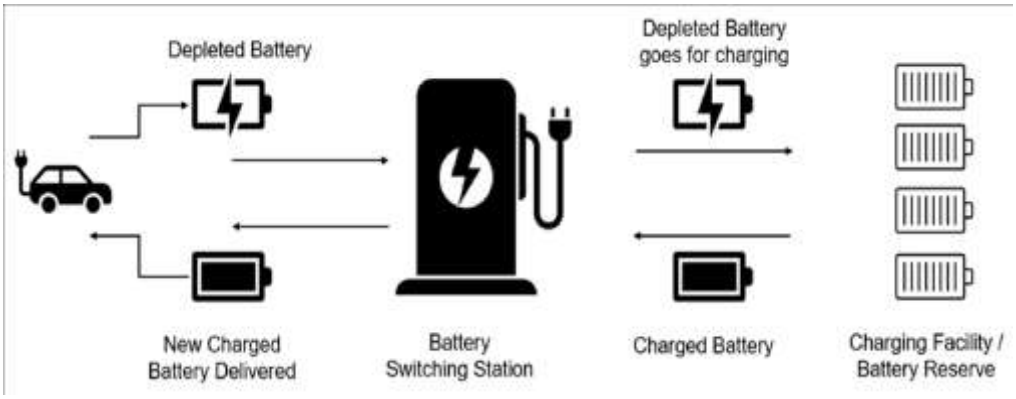

Figure 7. The battery changing stations' operational mechanism.

Most conventional vehicles can operate on any of the three fuels: petrol, diesel, and petrol, as shown by comparing traditional petrol stations and battery switching stations. Battery switching stations need to handle a broad range of batteries, and they may run out of one type periodically. This might cause EV drivers to get anxious. Batteries come in various kinds: configurations, energy, and power densities.

EV drivers will be able to monitor the several battery types that are accessible thanks to smartphone applications developed by battery switching facilities. Even better, they may store extra batteries in advance to replace their exhaust ones. Giving the battery switching locations and the electric vehicle driver a communication platform can significantly reduce waiting times and eliminate range anxiety. This enables the driver to go beyond the usual velocity range of the vehicle.

However, this can present further issues for the battery switching stations, as they might need to keep many more batteries on hand to service clients, especially if some switch batteries numerous times daily. Multiple approaches can be used to solve this issue. The possibilities include limiting the number of swaps executed daily, adding a fee for each extra swap executed within a single day, penalizing customers for exceeding their daily limit, etc. As indicated, imposing fines may deter people from implementing EVs, so we need to consider which solutions are workable. Furthermore, the inconsistency of some battery types being available is another issue with battery switching stations. Due to the possibility that switching stations do not always have enough charged batteries, it might be challenging to service all their clients/EV drivers (Yang, Guo & Zhang, 2017).

An EV battery-swapping station operator must continually modify charging and swapping guidelines to account for changing energy prices and save operational costs. A novel queuing network model with a service quality guarantee was used to research the optimal charging procedures for battery swapping stations. They also updated the model to incorporate battery-swapping facilities and renewable energy in the power system to flatten the power generation curve by considering locations and billing orders.

In this regard, it is worth noticing that battery-swapping technology has gained significant traction in China. One of the key players in this space is NIO, a Chinese EV manufacturer, which has implemented battery-swapping stations across China. These stations are fully automated and use a robotic arm to remove the depleted battery from the EV and replace it with a fully charged one. NIO claims that the entire process takes less than five minutes, providing a convenient and efficient way for EV drivers to continue their journey. They have installed over 1323 battery swapping stations across China as of March 2023.

Given China's success in deploying battery-swapping technology, other countries could benefit from learning and adopting similar techniques. Battery swapping provides a convenient and efficient alternative to traditional charging methods, which could help accelerate the adoption of electric vehicles and reduce reliance on fossil fuels.

Discussion

The analytical arrangements of the key studies are offered in this section to address all the research questions.

What are the main challenges and facilitators of electric vehicle implementation in smart cities, and what collaborative efforts are necessary for successful integration?

The findings highlight several challenges to the adoption of Electric Vehicles (EVs) in Nigeria, aligning with broader global issues identified in the literature. These challenges include range anxiety, high costs, inadequate charging infrastructure, battery performance, and low public awareness and acceptance. While these barriers are significant, the findings also suggest practical solutions and strategies to overcome them, which align with ongoing research in the field. Range anxiety, one of the major concerns for EV users, is primarily due to limited battery capacity. As noted, advancements in battery technology can significantly extend driving

ranges, alleviating this concern. The development of more efficient and cost-effective batteries, as shown in Figure 6, highlights the progress in battery technology from 1980 to 2025. These advancements also have the potential to reduce vehicle costs and improve overall convenience by enabling faster charging and extended battery life. This finding aligns with Bonges and Lusk's (2016) assertion that better battery technology is pivotal for improving EV adoption. Moreover, integrating renewable energy sources for charging further supports sustainability goals, reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Inadequate charging infrastructure remains a critical barrier to EV adoption in Nigeria. The proposed strategies in Section 4, such as strategically deploying charging stations in parking lots, public spaces, and highways, address this issue effectively. The use of flow and network stability models for infrastructure development is a progressive approach, ensuring that charging stations are not only accessible but also capable of meeting demand without disrupting the grid. The suggestion to incorporate battery swapping stations provides an alternative to traditional charging, potentially reducing range anxiety further. These strategies are consistent with global best practices in urban planning and sustainable mobility development.

The findings emphasize the need to integrate EVs into public transportation systems and urban planning. Promoting the use of electric buses and trains can significantly reduce personal vehicle usage and associated carbon emissions. This approach not only addresses environmental challenges but also aligns with sustainable urban development goals. However, as Bonges and Lusk (2016) highlight, successful integration requires robust policy frameworks and incentives to encourage investment in EV-friendly infrastructure and technologies. Low public awareness and acceptance of EVs remain significant barriers. Addressing this challenge requires targeted education and awareness campaigns to inform the public about the economic and environmental benefits of EVs. Such initiatives can foster a cultural shift toward sustainable transportation and enhance acceptance levels. These findings align with previous research by Bonges and Lusk (2016), which underscores the importance of technological advancements, infrastructure development, and public acceptance in overcoming barriers to EV adoption. The emphasis on renewable energy integration and innovative infrastructure solutions, such as battery swapping stations, complements existing research and offers practical pathways to mitigate challenges specific to Nigeria.

Overall, addressing these challenges through technological innovation, strategic infrastructure deployment, and public policy alignment can facilitate the widespread adoption of EVs, promoting sustainable economic growth and environmental preservation in Nigeria.

How have electric vehicles contributed to reducing carbon emissions, and what is their global market share trend over time?

Electric vehicles (EVs) have emerged as a significant contributor to reducing carbon emissions, aligning with global efforts to mitigate climate change and promote sustainable development. The findings indicate that the adoption of EVs has grown steadily, with a remarkable 60% surge in sales as of 2023, resulting in 1 in 7 automobiles produced globally now being electric. This upward trend in EV adoption reflects a growing recognition of their environmental and economic benefits, as well as advancements in supporting technologies and infrastructure.

The transition from internal combustion engine (ICE) vehicles to EVs plays a crucial role in reducing carbon emissions. Traditional gasoline and diesel

vehicles are significant contributors to air pollution and greenhouse gas emissions, with transportation accounting for a substantial share of global energy-related emissions. The adoption of EVs directly offsets these emissions by replacing ICE vehicles. Furthermore, as the electricity grids powering EVs become increasingly cleaner—through the integration of renewable energy sources like solar, wind, and hydropower—the carbon footprint of EVs continues to decline.

Figure 1, which illustrates energy-related carbon dioxide emissions in the U.S., China, and Europe from 1983 to 2023, underscores the impact of EV adoption in reducing emissions in regions with robust EV markets. These findings are consistent with research by Bonges and Lusk (2016), which highlights the potential of EVs to transform the transportation sector and significantly lower global carbon emissions.

The findings also emphasize the rapid expansion of the EV market. The steady growth of EV market share over the past decade demonstrates increasing consumer acceptance, policy support, and advancements in technology. In regions such as China, Europe, and the U.S., supportive policies—such as subsidies, tax incentives, and stringent emission regulations—have accelerated EV adoption. The classification of EVs into battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) highlights their varied applications, catering to diverse consumer needs and preferences, as shown in Figure 2.

These findings align with previous research, including Bonges and Lusk (2016), which emphasizes the dual impact of EVs: reducing carbon emissions and fostering economic growth. The link between EV adoption and lower greenhouse gas emissions is well-documented, with studies showing that regions with higher EV penetration tend to report significant reductions in transportation-related emissions. For instance, the International Energy Agency (IEA) has noted that global EV deployment could reduce carbon emissions by approximately 1 gigaton annually by 2030, aligning with the trends depicted in the findings.

Despite their environmental benefits, the findings acknowledge that achieving even greater emissions reductions depends on the continued decarbonization of electricity grids. In regions heavily reliant on fossil fuels for electricity generation, the environmental advantages of EVs are less pronounced. However, as renewable energy adoption accelerates, the lifecycle emissions of EVs will decrease further. The findings align with previous research that highlights the transformative potential of EVs in reducing carbon emissions and fostering sustainable development. The global market share trend of EVs underscores their increasing prevalence and the pivotal role they play in achieving climate targets. By addressing challenges such as energy grid decarbonization and improving battery technology, EVs can continue to drive significant environmental and economic benefits globally.

What are the potential future research directions for electric vehicles in Nigeria, with a focus on improving battery technology, addressing range anxiety, reducing charging times, and promoting EV adoption?

The findings point to the need for further research in key areas that can accelerate the adoption of electric vehicles (EVs) in Nigeria. These areas include improving battery technology, addressing range anxiety, reducing charging times, and promoting EV adoption through innovative strategies. While EV technology has made significant progress globally, challenges specific to Nigeria's socio-economic and infrastructural context present opportunities for focused research.

Battery technology is at the heart of EV performance and adoption. The findings emphasize the need for research on advanced

battery chemistries, such as solid-state batteries, which offer higher energy density, longer lifespans, and enhanced safety compared to current lithium-ion batteries. These advancements could reduce EV production costs, making them more affordable and accessible to the average Nigerian consumer.

In consonance with previous research, studies by Wang et al. (2021) have identified battery costs as a critical factor influencing EV affordability. Moreover, addressing issues related to battery recycling and second-life applications aligns with sustainability goals and minimizes the environmental impact of widespread EV adoption.

Range anxiety, a common concern for potential EV users, is especially pronounced in Nigeria due to limited charging infrastructure. Future research could explore innovative solutions such as:

- Battery swapping stations: Reducing downtime for users by allowing quick battery replacements.
- Energy-efficient EV designs: Developing vehicles optimized for Nigerian road conditions and traffic patterns to maximize range.

These strategies align with findings from Bonges and Lusk (2016), which advocate for the integration of both technological and infrastructural solutions to alleviate range anxiety.

Fast-changing technology is crucial for improving the convenience of EVs. Research into ultra-fast chargers and grid-stabilizing technologies can help address the challenges associated with high electricity demand during peak charging hours. Collaborations with renewable energy providers, such as solar farms, could also enable localized, off-grid charging solutions, reducing reliance on Nigeria's often unreliable power grid.

Promoting EV adoption requires a multi-faceted approach, including policy interventions, public awareness campaigns, and infrastructure investments. Future research could focus on the following areas:

- Policy frameworks: Exploring subsidy models, tax incentives, and import duty reductions for EVs and related components.
- Public awareness: Understanding consumer perceptions and designing educational campaigns tailored to address local misconceptions about EVs.
- Localization of EV production: Developing local manufacturing and assembly capacities to lower costs and create jobs, as suggested by Ogunleye et al. (2022).

While these research directions align with global trends, unique challenges in Nigeria include unreliable electricity supply, limited technical expertise, and high initial costs of EV infrastructure development. Addressing these issues requires collaborative efforts between government agencies, private investors, and international stakeholders.

The findings align with prior research in emphasizing the importance of improving battery technology, reducing range anxiety, and enhancing EV infrastructure to promote adoption. They also underscore the necessity of tailoring solutions to Nigeria's specific challenges, such as unreliable power grids and limited public awareness. By addressing these areas through targeted research and innovation, Nigeria can leverage EV technology to achieve both environmental sustainability and economic growth.

Future Research Recommendations

Despite significant advancements in the evolution and development of electric vehicles (EVs), several challenges persist, offering opportunities for innovative research. This section outlines key areas for future exploration, focusing on improving EV batteries, integrating artificial intelligence (AI) into EV systems, and developing effective public policies to promote EV adoption.

EV Batteries: Recent Developments and Innovations

Batteries are a critical component of EVs, contributing significantly to both the vehicle's cost and performance. While current lithium-ion batteries dominate the market, ongoing research aims to develop technologies that exceed their capabilities in terms of durability, energy density, and charge/discharge efficiency (Bonges& Lusk, 2016).

Future research should focus on exploring new materials and technologies, such as graphene-based batteries. Graphene, a lightweight material with high thermal conductivity, offers potential breakthroughs in quick charging and heat management. For example, Graphenano, a Spanish company, has developed a prototype graphene battery with a range of 800 km and a charging time of just 5 minutes using high-power outlets (Pevec et al., 2020). While still in the experimental phase, graphene batteries could achieve a specific energy of up to 6.4 kWh/kg, revolutionizing EV performance.

Research in this domain should aim to:

- Develop cost-effective manufacturing processes for graphene batteries.
- Improve battery recycling and lifecycle management to ensure sustainability.
- Enhance thermal management systems to prevent power loss during fast charging.

o 2. Artificial Intelligence in EV Systems

The integration of artificial intelligence (AI) offers transformative potential for EV systems. AI can address critical issues such as battery thermal management, intelligent routing, and efficient power generation. Yuvaraj et al. (2022) proposed a machine learning-based routing model to optimize energy consumption across road segments, while Park and Kim (2020) demonstrated the use of artificial neural networks (ANNs) to regulate battery temperatures efficiently.

Future research directions in AI and EVs include:

- Streamlining battery charging: AI can enable early booking of charging points, power balancing, and adaptive charging based on user behavior.
- Enhancing power grid efficiency: Predictive AI models can analyze mobility patterns and forecast energy demand, ensuring grid stability.
- Advancing Internet of EVs (IoEVs): The IoEVs ecosystem could unlock new applications and services, revolutionizing transportation systems.

Additionally, innovative cooling systems, such as distributed forced convection for batteries, could ensure uniform temperature regulation, reducing energy losses and extending battery life (Hossain et al., 2023).

3. Public Policies and Subsidies

Government subsidies play a pivotal role in accelerating EV adoption, particularly among consumers with limited budgets. While the impact of subsidies on EV production has been explored, there remains a research gap in designing subsidy programs that balance the objectives of manufacturers, retailers, and consumers.

Game theory models offer a promising approach to analyze these dynamics. For instance, subsidies can influence production levels, pricing strategies, and consumer demand across supply chain structures. Future research should:

- Investigate optimal subsidy structures to maximize consumer surplus and market demand.
- Evaluate the interplay between subsidies for battery electric vehicles (BEVs) and internal combustion vehicles (ICVs).
- Assess the long-term impact of subsidies on the automotive sector's transition to sustainable energy sources.

Developing effective public policies will require interdisciplinary collaboration among economists, policymakers, and engineers to ensure subsidies are targeted, equitable, and effective in achieving environmental and economic goals.

Future research into EVs should prioritize technological advancements in batteries, AI integration, and policy development. By addressing these areas, researchers can pave the way for a more sustainable and efficient transportation future, particularly in regions like Nigeria where EV adoption faces unique challenges.

Conclusions

The paper discussed electric vehicles (EVs), their benefits and potential, and the obstacles to their adoption and integration into Nigeria such as range anxiety, infrastructure, and battery cost. The study indicates that integrating EVs into Nigeria can create sustainable economic growth and an efficient urban environment with lower operating costs, reduced greenhouse gas emissions, and improved air quality. Nigeria can overcome the challenges associated with EV adoption by developing robust charging infrastructure, implementing smart grid technologies, and utilizing data analytics. By promoting the use of EVs in Nigeria, we can build more livable and sustainable cities that prioritize the health and well-being of residents while reducing our carbon footprint.

Implementing electric vehicles (EVs) faces challenges such as high upfront costs, limited driving range, charging infrastructure inadequacy, and public perception. However, these challenges can be addressed via government policies, private sector investment, and public education to increase EV adoption, develop new business models that enable EV use, invest in charging infrastructure, improve battery technology and charging speeds, and increase awareness about the benefits of EVs. Overcoming these challenges can accelerate the transition to sustainable economic growth,and transportation systems, and mitigate climate change impacts.

The article discusses strategies to promote the adoption of electric vehicles (EVs) as a sustainable mode of transportation, economic growth, and solutions to environmental challenges. These strategies include supportive policies and regulations, investment in charging infrastructure, and public education and outreach initiatives. Governments can help by providing financial incentives, mandating minimum EV sales targets, and funding charging infrastructure. Private companies can invest in charging infrastructure, develop new business models, and partner with automakers to promote EV adoption. Public education programs can help overcome obstacles such as range anxiety and a lack of knowledge about the benefits of EVs. By implementing these strategies, we can transition to a more sustainable transportation system while reducing our dependence on fossil fuels and combating climate change.

The future of electric vehicles looks positive with advancements in battery technology, charging infrastructure, and supportive policies. Battery prices are expected to drop significantly, making EVs more affordable and convenient for consumers. Switching to EVs can help reduce reliance on fossil fuels and combat climate change, and incorporating them into Nigeria'sprograms can improve efficiency. As the market grows, we can expect new models with improved driving ranges and faster charging times, potentially including self-driving EVs.

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