World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

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Decarbonizing public transport systems in the UK: Initiatives and technologies for reducing carbon emissions

Uthman Opeyemi Abdullahi [1, *], Adnan Adnan [2] and Abdullahi Ayobami Rafiu [3]

[1] *Department of Mechatronics and Computer System Engineering, University of East London.*
[2] *Royal Docks Centre for Sustainability, University of East London.*
[3] *MBA Supply Chain Management, University of East London.*

World Journal of Advanced Engineering Technology and Sciences, 2024, 13(02), 051–058

Publication history: Received on 10 September 2024; revised on 19 October 2024; accepted on 22 October 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.13.2.0505

Abstract

The decarbonization of public transport systems in the UK is a critical step toward achieving the nation's net-zero emissions targets by 2050. This article examines the various initiatives and technologies that are being implemented to reduce carbon emissions from buses, trains, and trams. Focusing on key solutions such as electrification, hydrogen fuel cells, and hybrid systems, it evaluates their potential through a cost-benefit analysis and assesses their impact on environmental sustainability. The paper also explores the UK government's policy frameworks, including the Transport Decarbonisation Plan, which supports the transition toward cleaner, more efficient public transport networks. Through case studies from cities such as London, Glasgow, and Birmingham, the article highlights successful decarbonization strategies, emphasizing the importance of government, industry, and community collaboration. These efforts aim to create a sustainable public transport system that not only meets carbon reduction targets but also enhances urban air quality and public health.

Keywords: Decarbonization; Electrification; Hydrogen Fuel Cells; Policy Frameworks; Cost-Benefit Analysis; Sustainable Transport.

1. Introduction

1.1. Importance of Decarbonizing Public Transport in the UK

The decarbonization of public transport is a key component of the UK's strategy to achieve its net-zero emissions target by 2050. Public transport, including buses, trains, and trams, plays a crucial role in reducing the carbon footprint of urban mobility. By shifting away from fossil-fuel-powered vehicles, the UK can reduce greenhouse gas (GHG) emissions, improve air quality, and contribute to the global fight against climate change. With transportation accounting for around 27% of the UK's total carbon emissions in 2019, public transport decarbonization is an essential element of the broader sustainability agenda (Department for Transport, 2020).

1.2. Overview of Carbon Emissions from Buses, Trains, and Trams

Buses, trains, and trams are significant contributors to the UK's transportation emissions. Diesel-powered buses and trains emit substantial amounts of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM). For example, buses in the UK contribute around 5% of total transport emissions, while rail systems, particularly diesel trains, also add to the carbon footprint (Office for National Statistics, 2021). Trams, while more efficient, still depend on electricity from mixed energy sources, highlighting the need for clean energy integration in public transport systems.

* Corresponding author: Uthman Opeyemi Abdullahi

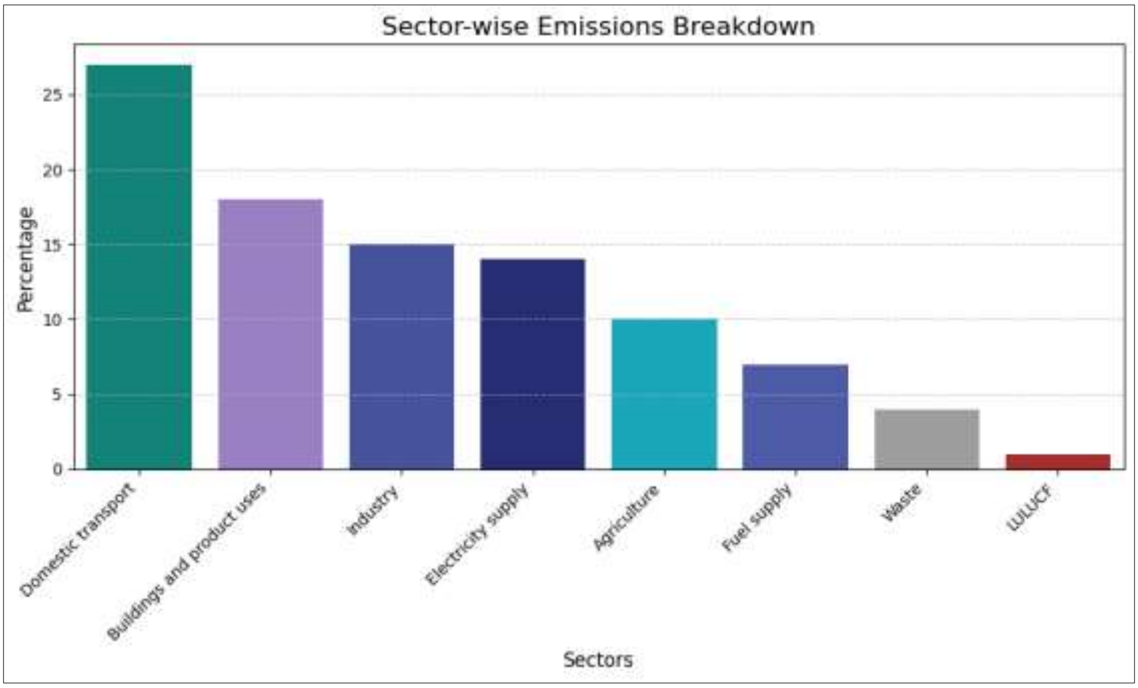
Table 1 Emissions Contribution from Different Public Transport Modes (UK, 2021)

Mode of Transport	CO_2 Emissions (Million Tonnes)	NO_x Emissions (%)	PM Emissions (%)
Buses	5.1	17%	10%
Trains (Diesel)	2.8	12%	8%
Trams	0.9	3%	1%

(Sources: Office for National Statistics, 2021; Department for Transport, 2020)

1.3. Purpose and Scope of the Article

This article aims to explore the key initiatives and technologies that can reduce carbon emissions from the UK's public transport systems, with a focus on buses, trains, and trams. The scope includes an evaluation of electrification, hydrogen fuel cells, and hybrid technologies as potential solutions. The article also examines the UK government's policy frameworks, such as the Transport Decarbonization Plan (TDP), that support these transitions. A cost-benefit analysis will be provided to assess the economic and environmental advantages of these technologies. Additionally, the paper will highlight real-world implementation strategies through case studies from UK cities, offering insights into how decarbonization efforts can be scaled nationwide.



(Sources: UK Climate Change Committee, 2022)

Figure 1 UK Carbon Emissions by Sector (2022)

By addressing these key areas, this article will contribute to the ongoing discussion on how the UK can effectively decarbonize its public transport systems while improving urban mobility and environmental sustainability.

2. Policy Frameworks for Decarbonization

2.1. UK Government's Net Zero Strategy

The UK's Net Zero Strategy sets out a comprehensive plan to achieve net-zero greenhouse gas emissions by 2050. The strategy emphasizes the decarbonization of transport as a crucial sector in reaching this goal, with specific targets for reducing emissions from public transport systems. Key commitments include ending the sale of new diesel buses by 2030 and encouraging a transition to electric and hydrogen-powered alternatives. The strategy also focuses on increasing the electrification of rail networks and supporting the development of zero-emission trams (Department for Business, Energy & Industrial Strategy, 2021).

2.2. Transport Decarbonization Plan (TDP)

The Transport Decarbonization Plan (TDP) outlines detailed policies and initiatives to reduce carbon emissions across all transport modes in the UK. For public transport, the TDP targets the complete electrification of buses, with significant investments in charging infrastructure. It also encourages the use of hydrogen fuel cells for long-distance buses and trains, providing flexibility where electrification is not feasible. The TDP supports these efforts with funding and subsidies to help local authorities transition their fleets to low-emission technologies (Department for Transport, 2021).

2.3. Role of Local Authorities and Regional Governments in Supporting Decarbonization Efforts

Local authorities and regional governments play a pivotal role in implementing decarbonization policies at the grassroots level. The UK government provides support to local councils to deliver electric bus services and zero-emission rail projects. Regional transport bodies are also tasked with developing long-term sustainability plans for integrating low-emission vehicles into public transport networks, with a focus on expanding electric vehicle (EV) charging and hydrogen refueling stations (UK100, 2022).

2.4. Subsidies and Incentives For Transitioning to Low-Emission Technologies

To facilitate the transition to low-emission public transport, the UK government has introduced a range of subsidies and incentives. The Zero Emission Bus Regional Areas (ZEBRA) scheme provides funding for local authorities to purchase electric and hydrogen buses. Additionally, grants are available for upgrading existing transport infrastructure to support electric and hydrogen technologies. These financial incentives aim to offset the initial capital costs and make decarbonization more economically viable for transport operators (Department for Transport, 2021).

Table 2 Summary of Key UK Policies for Public Transport Decarbonization

Policy	Description	Key Target Date
Net Zero Strategy	National plan to achieve net-zero emissions by 2050, with targets for transport	2050 (Net Zero)
Transport Decarbonisation Plan	Detailed plan to decarbonize buses, trains, and trams through electrification and hydrogen fuel cells	2030 (End of new diesel bus sales)
ZEBRA Scheme	Financial support for local authorities to procure zero-emission buses	Ongoing (2021-2025)
Grants for EV Infrastructure	Incentives for installing charging and hydrogen refuelling infrastructure	Ongoing
Local and Regional Authority Role	Decentralized implementation of transport decarbonization efforts	Ongoing

3. Technological Solutions for Decarbonization

3.1. Electrification

Electrification is one of the primary technological solutions for reducing emissions in public transport systems. Battery-powered electric buses, trains, and trams are becoming increasingly popular due to their zero tailpipe emissions and reduced dependence on fossil fuels. Electric buses have been widely adopted in cities such as London, where the government has committed to a fully electric bus fleet by 2037 (Transport for London, 2020). Similarly, electrification of train networks is underway, with a significant push toward replacing diesel-powered trains with electric alternatives on major rail routes.

To support this transition, the development of charging infrastructure is crucial. Public charging points for buses and depots with overnight charging facilities are required to ensure operational efficiency. Additionally, grid readiness, involving upgrades to electricity distribution networks, is essential to manage the increased demand for power from electric transport systems (National Grid, 2021).

3.2. Hydrogen Fuel Cells

Hydrogen fuel cells offer a promising solution for long-range buses and trains, where battery technology may not be sufficient due to weight and range limitations. Hydrogen-powered buses are already in use in cities like Aberdeen, where hydrogen refueling stations have been set up as part of the UK's Green Hydrogen strategy (Aberdeen City Council, 2021). Hydrogen fuel cells produce electricity by combining hydrogen and oxygen, emitting only water vapor, which makes them ideal for decarbonizing public transport.

However, challenges in hydrogen production and distribution need to be addressed. Most hydrogen is still produced from fossil fuels, so transitioning to green hydrogen (produced using renewable energy) is essential for achieving true decarbonization. Additionally, infrastructure for hydrogen distribution, including refueling stations, must be expanded to support widespread adoption (Hydrogen Council, 2021).

3.3. Hybrid Technologies

Hybrid technologies, which combine traditional internal combustion engines with electric power, offer an interim solution for reducing emissions. Hybrid buses, for example, can operate in electric mode in urban areas to reduce pollution and switch to conventional fuel for longer journeys. This technology has been adopted in several UK cities as a bridge toward fully electric transport (Low Carbon Vehicle Partnership, 2020).

Hybrid trains, such as those used on non-electrified rail lines, reduce fuel consumption by using electric power when available and diesel engines where electrification is not present. These systems provide flexibility while infrastructure for full electrification is still being developed.

3.4. Emerging Technologies

Beyond electrification and hydrogen fuel cells, other emerging technologies are being explored for decarbonizing public transport. Solar-powered trams, for instance, use photovoltaic cells to generate electricity for tram operation. In some parts of the world, autonomous electric vehicles are being trialled for public transport services, which could further reduce emissions and improve energy efficiency (UITP, 2021).

Alternative fuel technologies, such as biofuels and synthetic fuels, also hold potential for reducing carbon emissions. While not entirely carbon-neutral, they offer lower emissions than conventional fossil fuels and can be used in existing engines with minimal modifications.

4. Cost-Benefit Analysis

4.1. Initial Costs vs. Long-term Savings

The upfront capital costs of electrifying public transport systems and adopting hydrogen fuel cell technologies are significant. These costs include purchasing new electric or hydrogen-powered vehicles, retrofitting existing infrastructure (charging or hydrogen refueling stations), and upgrading the grid for increased energy demand. For instance, the cost of an electric bus is approximately £340,000–£440,000, significantly higher than a diesel bus (Sustainable Bus, 2020). Hydrogen buses can cost even more due to the complexity of the fuel cells.

Despite the high initial costs, long-term savings in operational expenses are substantial. Electric buses offer lower fuel costs, with electricity being cheaper than diesel, and reduced maintenance expenses due to fewer moving parts. Similarly, hydrogen fuel cell buses are expected to provide savings in fuel consumption as hydrogen production becomes more efficient. Over time, these savings can offset the upfront investments and reduce the total cost of ownership (Cambridge Econometrics, 2021).

4.2. Environmental and Social Benefits

The decarbonization of public transport brings notable environmental and social benefits. One of the primary advantages is the reduction of greenhouse gas emissions. Electrification and hydrogen fuel cells produce zero tailpipe emissions, contributing significantly to the UK's net-zero carbon goals. According to the UK Government's Transport Decarbonization Plan, transitioning to electric buses and hydrogen trains could reduce emissions by up to 76% by 2050 (Department for Transport, 2021).

In addition to cutting carbon emissions, these technologies improve urban air quality by reducing the pollutants associated with diesel engines, such as nitrogen oxides (NOx) and particulate matter (PM). Cleaner air directly benefits public health, reducing respiratory conditions like asthma and cardiovascular diseases, particularly in densely populated urban areas (Health Effects Institute, 2020).

4.3. Case Study: Cost-Benefit Analysis of London's Electric Bus Fleet Transition

London's transition to an electric bus fleet provides an excellent example of a cost-benefit analysis. The city has committed to making its fleet fully electric by 2037, with over 300 electric buses already in operation as of 2022 (Transport for London, 2022). The capital costs of acquiring these buses and building charging infrastructure have been offset by substantial long-term savings. TfL estimates that operational savings could reach £65,000 per bus over a 12-year period due to lower fuel and maintenance costs. Furthermore, the transition has resulted in significant reductions in air pollutants, contributing to the city's environmental goals.

Table 3 Comparative Cost-Benefit Analysis of Electrification and Hydrogen Solutions for Public Transport

Category	Electrification	Hydrogen Solutions
Initial Capital Costs	High (vehicle cost: £340,000–£440,000 per bus)	Very High (higher cost for fuel cell vehicles)
Fuel Costs	Lower (cheaper electricity vs. diesel)	Moderate (depends on hydrogen production)
Maintenance Costs	Lower (fewer moving parts, reduced wear)	Moderate (complex fuel cells, regular upkeep)
Environmental Benefits	Zero emissions, cleaner air, reduced carbon output	Zero emissions, potential for green hydrogen
Operational Range	Limited by battery capacity (100-300 km)	Longer range (300-500 km)
Infrastructure Requirements	Charging stations, grid upgrades	Hydrogen production, refuelling infrastructure
Long-term Savings	Significant (fuel and maintenance savings)	Moderate (fuel savings depend on hydrogen price)

5. Implementation Strategies

5.1. Short-Term Implementation

In the short term, decarbonization of public transport can be initiated through pilot projects and testing of new technologies. Many UK cities are already trialing electric and hydrogen buses to evaluate performance, reliability, and operational costs. For example, the Zero Emission Bus Regional Areas (ZEBRA) scheme provides funding for pilot projects aimed at deploying electric buses (Department for Transport, 2021).

Another short-term strategy involves upgrading existing fleets to hybrid or low-emission vehicles. This can serve as a transitional step, reducing emissions while the full electrification or hydrogen infrastructure is developed. Hybrid buses, which combine diesel engines with electric motors, have already been successfully integrated into many UK cities as part of broader emission-reduction programs (LowCVP, 2020).

5.2. Long-Term Strategies

Long-term decarbonization strategies focus on full electrification of bus, train, and tram fleets, as well as the integration of hydrogen fuel cell technologies for longer-range transport. The UK government has set a target of achieving a fully electric bus fleet by 2037 (Department for Transport, 2021). Long-term investment in nationwide charging and refueling infrastructure is critical to support these goals. The UK's strategy includes expanding high-power charging networks and hydrogen refueling stations to ensure the availability of alternative fuel sources across the country.

Table 4 UK Government's Long-Term Targets for Public Transport Electrification

Target	Deadline
Fully electric bus fleet	2037
Electrification of all major rail routes	2040
Hydrogen fuel cell integration for buses	Ongoing, target by 2050

5.3. Collaboration

The transition to low-emission public transport requires collaboration across multiple sectors. Partnerships between government, the private sector, and local authorities are essential for accelerating this shift. Local governments can implement low-emission zones, incentivize electric vehicle (EV) adoption through subsidies, and provide grants to support the installation of charging infrastructure. The private sector can play a crucial role by investing in R&D for innovative transport solutions, while transport operators and energy companies can work together to establish reliable charging and refueling networks (National Grid, 2021).

Government policy frameworks, such as the Transport Decarbonization Plan, encourage collaboration by setting out clear objectives for all stakeholders. This joint approach is crucial for overcoming barriers to implementation, such as cost, technical limitations, and regional variations in infrastructure readiness.

5.4. Challenges

Despite progress, several challenges remain. A significant funding gap still exists between the required investment for nationwide decarbonization and available resources. While government subsidies, like the ZEBRA scheme, help, further investment is required to scale up charging and hydrogen infrastructure (Transport for the North, 2020).

Technical limitations also pose hurdles. Battery technology continues to evolve, but current electric vehicle ranges are still limited, particularly for heavy-duty buses and trains. Hydrogen fuel cells offer greater range, but the infrastructure for hydrogen production and distribution is not yet fully established.

Public acceptance is another challenge. The success of these initiatives hinges on the public's willingness to embrace new technologies and support sustainable practices. Public perception of EV reliability, charging convenience, and cost savings can either drive or hinder the transition.

6. Case Studies

6.1. London: Transition to Electric Buses and the Ultra Low Emission Zone (ULEZ)

London is leading the charge in public transport decarbonization with its transition to electric buses and the introduction of the Ultra Low Emission Zone (ULEZ). The city now operates over 500 electric buses, making it one of the largest electric bus fleets in Europe. The ULEZ, which covers central London and charges vehicles that do not meet strict emission standards, has significantly reduced air pollution and encouraged the use of electric and low-emission vehicles (Transport for London, 2022). This policy has resulted in a 44% reduction in roadside nitrogen dioxide (NO_2) levels in the ULEZ area since its launch in 2019 (Greater London Authority, 2021).

6.2. Glasgow: Deployment of Hydrogen-Powered Buses

Glasgow has been at the forefront of hydrogen fuel cell bus deployment in the UK. In 2020, the city launched a fleet of hydrogen-powered buses as part of its efforts to reduce carbon emissions and air pollution. These buses offer a range of over 300 km per refueling, making them ideal for longer urban routes where electric buses might struggle due to limited range. The buses are refueled at Scotland's first hydrogen production and refueling facility, highlighting Glasgow's commitment to becoming carbon-neutral by 2030 (Scottish Government, 2021).

6.3. Birmingham: Electrification of Local Rail Networks

Birmingham is focusing on rail electrification as a key part of its decarbonization strategy. The city's local rail network, including the Cross City Line, is undergoing electrification to reduce the reliance on diesel-powered trains. This initiative aligns with the UK government's goal to phase out diesel-only trains by 2040 (Department for Transport, 2020). Electrifying rail networks will not only cut emissions but also provide a more efficient and reliable service. Birmingham's efforts are part of a broader West Midlands initiative to become a low-carbon transport hub, supported by significant government investment in electrification projects.

Table 5 Summary of Case Studies Highlighting Decarbonization Success in UK Cities

City	Decarbonization Initiative	Outcome
London	Transition to electric buses, ULEZ	44% reduction in roadside NO_2 levels, one of Europe's largest electric bus fleets (TfL, 2022).
Glasgow	Deployment of hydrogen-powered buses	Zero-emission buses with over 300 km range, supporting Glasgow's carbon-neutral goals (Scottish Government, 2021).
Birmingham	Electrification of local rail networks	Progress toward eliminating diesel trains by 2040, improving rail efficiency and reducing emissions (DfT, 2020).

7. Conclusion

7.1. Summary of Key Findings

The transition to decarbonized public transport systems in the UK is a multifaceted effort that requires robust policy support, significant cost investments, and technological innovation. Policies such as the Ultra Low Emission Zone (ULEZ) in London, coupled with government subsidies and incentives, have proven instrumental in reducing emissions. Moreover, technological advancements, particularly in electric and hydrogen-powered vehicles, have demonstrated significant cost savings in terms of fuel efficiency and reduced maintenance costs. For instance, London's transition to electric buses has resulted in lower operational expenses while improving urban air quality. Case studies from cities like Glasgow and Birmingham further illustrate the effectiveness of strategic investments in hydrogen and electrification technologies.

7.2. Emphasis on Innovation and Collaboration

The journey toward decarbonizing public transport requires continued innovation across various technologies, such as the development of more efficient batteries, expansion of hydrogen production facilities, and integration of alternative fuel sources like solar power. Collaboration between the government, private sector, local authorities, and energy companies will be critical in accelerating the transition. For example, partnerships between transport operators and energy providers can enhance the development of refueling and charging infrastructure, ensuring that future demand is met. Furthermore, local governments play a crucial role in implementing low-emission zones and supporting public transport operators with financial incentives to adopt green technologies.

7.3. Outlook on the Future of Decarbonizing Public Transport Systems in the UK

Looking ahead, the decarbonization of the UK's public transport systems is promising, with the government's ambitious targets set for 2037 and beyond. However, challenges such as infrastructure development and public acceptance remain. To overcome these, continuous investment in research and development, as well as public education campaigns, will be necessary. The future will likely see the widespread adoption of electric and hydrogen fuel cell technologies, and with the right support, the UK can establish itself as a leader in sustainable public transport, setting a global standard for decarbonization efforts.

Compliance with ethical standards

Acknowledgments

The authors would like to thank the Royal Docks Centre for Sustainability without whom we could not deliver our programmes and develop a draft for challenges and opportunities facing hybrid and electric vehicles integration into the public transport system.

Disclosure of conflict of interest

The authors have declared that no competing interests exist.

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