Chapter

Navigating Sustainability: A Conceptual Exploration of Road Freight Decarbonisation

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Abstract

This chapter underscores the critical importance of embracing alternative fuels, specifically natural gas and hydrogen, as pivotal elements in the concerted effort to decarbonise road freight operations. It accentuates the necessity for collaborative, well-informed decision-making processes to navigate the complexities of this transition successfully. The exploration extends beyond technological considerations to encompass policy-driven initiatives adopted by nations like Norway, India, the USA, the UK, South Africa, and Germany, among others. Notably, it scrutinises instances of demonstrated economic viability associated with specific decarbonisation strategies employed in these regions. Moreover, the chapter advocates for sustained interdisciplinary research efforts to comprehensively address the diverse challenges posed by regional variations, industry-specific requirements, operational environments, cross-cultural influences, and the integration of sustainability metrics. By emphasising the importance of ongoing technological innovation, robust policy frameworks, and thoughtful economic considerations, the chapter envisions a global roadmap for sustainable road freight practices. In essence, it calls for a holistic approach, urging scholars, policymakers, and industry experts to collaboratively shape a sustainable future for road freight that addresses the intricate interplay of technological advancements, policy dynamics, and economic imperatives on a global scale.

Keywords: road freight decarbonisation, alternative fuels, natural gas, hydrogen, policy frameworks, sustainability metrics

1. Introduction

The urgent need to address climate change has led to a detailed examination of various industries' environmental impacts, highlighting transportation as a major contributor to greenhouse gas emissions [1–3]. Among transportation sectors, road freight operations stand out as significant contributors to carbon emissions [4, 5]. In India, road transportation alone accounted for more than 56% of the country's transportation sector emissions in 2019, totalling 2508 million tonnes (Mton), surpassing the global contribution of the entire transportation sector [2]. The transport sector in

India represents 18% of total energy consumption, requiring an estimated 200 Mtoe of energy stock by 2030 if current trends persist [2].

Similarly, China, with the world's largest truck industry, sees over 50% of its total transport emissions originating from road freight [3]. Globally, the transport sector, representing 28% of total energy demand, is projected to contribute up to 10.3 Gt CO_2/year by 2040 [6]. Decarbonising this sector poses formidable challenges due to factors such as high vehicle dependency, widespread use of combustion-based engine technologies, low petroleum costs, and limited alternatives to fossil fuels, and fragmentated operation [1].

The Intergovernmental Panel on Climate Change [7] emphasises that the primary source of carbon emissions in road freight is the combustion of fossil fuels, particularly diesel, leading to the release of carbon dioxide (CO_2) and contributing to global climate change [4, 6, 8–10]. Secondary pollutants, such as nitrogen oxides (NOx) and particulate matter, further impact air quality and public health [2, 5, 11, 12]. Diesel-powered trucks operating in urban areas worsen air quality, posing a threat to public health [6].

Recognising the urgency of addressing this issue, Lee and Kim [13] emphasises the need to transform road freight operations through sustainable practices and technological innovations. Therefore, this chapter aims to provide a foundation for a concise exploration of road freight decarbonisation, covering challenges, strategic approaches, policy frameworks, technological innovations, case studies, and global perspectives. It aligns with the perspective that road freight's heavy reliance on fossil fuels necessitates global efforts to mitigate climate change and enhance environmental sustainability.

Subsequent sections of the chapter encompass methodology, a brief literature review, an investigation into challenges, approaches, and strategies to decarbonise road freight operations. Others comprise global perspectives, case studies showcasing best practices and lessons learned, an examination of future outlook, discussion, and ultimately, a conclusion providing guidance for future studies.

2. Methodology

This chapter employs a conceptual literature review method to furnish an exhaustive comprehension of the intricate domain of road freight decarbonisation [14]. Through amalgamating existing knowledge, this review seeks to elucidate fundamental concepts, burgeoning trends, and crucial lacunae in the literature, thereby establishing the groundwork for a nuanced exploration of sustainability in the realm of road freight. Specifically, the chapter establishes a lucid comprehension of sustainability within the ambit of road freight by scrutinising seminal works and contemporary literature on sustainability. It focuses on how sustainability is conceptualised and applied in the road freight industry. Subsequently, the approach identifies and scrutinises various strategies employed for decarbonising road freight, drawing upon empirical studies, industry reports, and technological advancements. These decarbonisation approaches are categorised into technological, operational, and policy-driven interventions.

Further, the chapter delves into the economic dimension of transitioning towards sustainable road freight practices. It draws on empirical papers, business case studies, and industry reports to fathom the financial implications for stakeholders in the road freight sector. Following this, the chapter evaluates the environmental consequences of road freight decarbonisation efforts through an examination of life cycle assessments, carbon footprint analyses, and ecological impact studies. This enables an assessment of the overall environmental sustainability of different decarbonisation strategies. Moreover, the chapter scrutinises the role of policies and regulations in shaping road freight decarbonisation by reviewing national and international policy documents. It analyses their effectiveness, challenges, and potential for promoting sustainable practices in the road freight industry. In a similar vein, the chapter identifies and discusses key challenges and associated opportunities with road freight decarbonisation. This is achieved through the synthesis of empirical findings to provide insights into the multifaceted nature of challenges and opportunities in this context.

Finally, the chapter incorporates diverse stakeholders' perspectives to enhance the conceptual understanding of road freight decarbonisation. This is accomplished through the exploration of industry reports and business case studies. In conclusion, the conceptual literature review culminates in a comprehensive synthesis, offering a holistic understanding of road freight decarbonisation within the broader context of sustainability. By traversing the conceptual landscape, this chapter aims to provide a robust foundation for subsequent discussions and analyses in the pursuit of a sustainable future for road freight.

3. Brief literature review

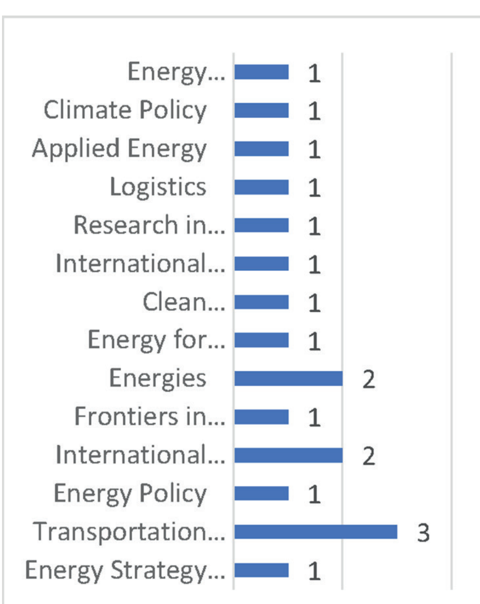
In the pursuit of sustainable road freight, recent studies (e.g., [1, 6, 8, 9, 15]) offer valuable insights into the multifaceted challenges and opportunities within this domain. The collective findings underscore the complexity of road freight decarbonisation, emphasising the intricate interplay of technological, economic, and policy dimensions. Churchman et al. [1] recognise the pivotal role of freight demand segments in influencing decarbonisation strategies. Varied preferences for motive technologies and the potential of containerised rail highlight the need for nuanced, context-specific approaches. Hossain et al. [2] delve into regional specifics, focusing on India's roadmap for 2050. Their emphasis on adopting alternative fuels and advanced technologies aligns with a global push towards sustainability.

Ma et al. [3] conducts a comprehensive Total Cost of Ownership (TCO) analysis, shedding light on the life cycle costs of electric and fuel cell (FC) trucks. The study's emphasis on emission reductions and the role of alternative fuels resonates with Gómez Vilchez et al. [4], who evaluate European decarbonisation trends, highlighting the dominance of natural gas and the imperative for unified policies. de las Nieves Camacho et al. [6] examine hydrogen heavy-duty FC trucks, stressing collaboration, and objective testing for informed decision-making. Haugen et al. [8] tackle hydrogen production challenges, recommending electrolysis as a short-term solution. They identify critical research domains, aligning with Zhang et al. [16], who optimise FC systems in commercial trucks. The potential of hydrogen extends to long-haul strategies, as illustrated by Rohith et al. [17], promoting the platooning of electrified heavy goods vehicles. Rosenberg et al. [18] examine Norway's policy-driven approach, while de Saxe et al. [15] provide evidence of tangible benefits from a 2020 project, demonstrating the economic viability of certain strategies. Barton and Thomson [10] contribute valuable insights into electrification feasibility based on vehicle types and energy needs. Deshpande et al. [19] propose Electric Road Systems (ERS) as economically viable for key transport networks. Studies by Zhang et al. [5] and Melo [9] emphasise the significance of regional and sector-specific approaches. Zhang et al. [5]

advocate for a balanced policy focus in Ireland, while Melo [9] empirical model in Scotland underscores the importance of demand- and supply-led factors in achieving emission reduction targets.

Capros et al. [20] advocate for a model-based analysis to decarbonise the EU economy, stressing the cost significance of timely access to decarbonisation options. Sharmina et al. [21] introduce a new framework for monitoring and assessing mitigation progress, aligning with the call for integrated models and highlighting untapped mitigation opportunities. In conclusion, this critical synthesis calls for continued interdisciplinary research, integrating technological innovation, regional specifics, policy frameworks, and economic considerations. Practical implementations and pilot projects, similar to de Saxe et al. [15], should be encouraged to validate theoretical models. Furthermore, a focus on social science aspects, as highlighted by Churchman and Longhurst [22] is crucial for understanding business transitions and ensuring consumer-centric sustainability. Future studies should aim for a holistic understanding of road freight decarbonisation, fostering collaboration between academia, industry, and policymakers to drive sustainable change.

Moreover, we explore current trends in academic publications within the road freight decarbonisation debate. This section focuses on presenting and summarising observed patterns, frequencies, and themes with limited subjective opinions. Our review of the timeline and article distribution indicates an increasing trend in research output, highlighting the subject's growing relevance. Most publications (9) are from Elsevier Ltd., followed by MDP and Taylor and Francis Ltd., with 4 and 2 publications, respectively, alongside others. Similarly, the review papers are 16 articles and 2 review papers in the specified context. The distribution of articles by journals provides an overview of the sources contributing to research in energy, transportation, and related environmental topics (see **Figure 1a**). The methodology employed in the reviewed articles encompass scholarly literature examination, quantitative analysis through engineering and statistical modelling, as well as simulation techniques, and qualitative investigation through interviews (see **Figure 1b**). Finally refer to **Table 1** for the full meaning of abbreviations.



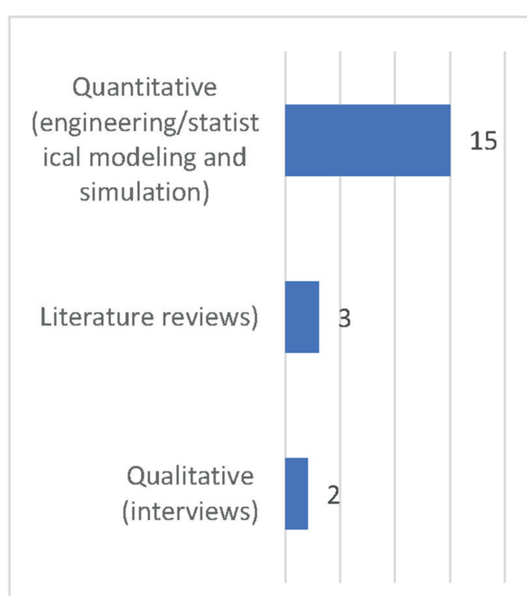


Figure 1.
Publication trend by journals and research methods.

Abbreviation	Full meaning
EV	Electric vehicles
IPPC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
WHO	World Health Organisation
ISO	International Organisation for Standardisation
ITF	International Trust Fund
USDE	U.S. Department of Energy
LNG	Liquefied natural gas
LRC	Low Carbon Logistics (LRC)
HGV	Heavy goods vehicles
LGV	Light goods vehicles
FCEV	Fuel cell electric vehicle
FC	Fuel cell
CO_2	Carbon dioxide
NOx	Nitrogen oxides
GHG	Greenhouse gas
ICEs	Internal combustion engines
CE	Circular economy
TCO	Total Cost of Ownership

Table 1.
Abbreviations and their full meanings with references.

4. Understanding the challenge

4.1 Emission sources in road freight

Understanding and mitigating road freight emissions necessitates addressing various sources across the supply chain, including vehicle fuel combustion, manufacturing, maintenance, infrastructure, idling inefficiencies, and suboptimal logistics practices [7, 13, 21, 22]. To formulate effective strategies, it is crucial to acknowledge and target these points. In road freight operations, where diesel in heavy-duty trucks is a major emission source [23], efficient fuel combustion is paramount (see **Figure 2**—Interlink transport coal in the PBS pilot project). This process, occurring within internal combustion engines, involves chemical reactions between fuel hydrocarbon molecules and oxygen, impacting carbon dioxide (CO_2) emissions per unit of energy [24]. Modern trucks use advanced technologies to enhance combustion efficiency and reduce emissions [25]. Life cycle assessment (LCA) methodologies, considering the entire life cycle, guide sustainable solutions [24]. Environmental impact regulations, like those by the European Commission, aim to mitigate traditional fuel combustion effects [26]. With a growing emphasis on alternative fuels like electric vehicles, hydrogen fuel cells, and biofuels [23], the road to decarbonising road freight involves considerations of fuel combustion efficiency, emissions, regulatory frameworks, alternative fuels, technological innovations, and holistic environmental impact assessments.

Figure 2.
Interlink transport coal in the PBS pilot project (source: [15]).

Vehicle manufacturing and maintenance are integral to road freight's carbon footprint. Energy-intensive production processes and material extraction contribute to emissions. Life cycle assessment (LCA) studies, such as Hawkins, Singh [24], provide insights into the environmental impact of manufacturing. Material selection and lightweighting strategies inform emission rates [25]. Efficient maintenance practices, including predictive maintenance, can reduce emissions [27] Circular economy principles in manufacturing and maintenance optimise designs for longevity and recycling, mitigating environmental impact [28]. Decarbonising road freight involves a shift to electric vehicles, with the [7] highlighting their manufacturing and maintenance efficiency. Optimising manufacturing processes and embracing sustainable maintenance practices contribute to a more environmentally sustainable road freight industry.

Infrastructure construction and maintenance, energy-intensive processes, contribute substantially to emissions [29]. Integrating intelligent technologies like condition monitoring and predictive maintenance is essential [30]. Sustainable practices, such as incorporating alternative materials and construction technologies, are pivotal [31]. Green corridors, wildlife-friendly structures, and strategic investments in multimodal transportation systems are essential for sustainable infrastructure [32]. Infrastructure development and maintenance need careful consideration for road freight decarbonisation. Implementing sustainable practices, exploring alternative materials, and adopting innovative technologies are fundamental steps towards a more ecologically sound road freight industry.

Vehicle idling and operational inefficiencies significantly contribute to carbon emissions in road freight. Reducing idling time, optimising routes, and improving load factors are direct approaches to mitigate emissions [33]. Technologies like telematics and connectivity enable real-time monitoring, contributing to decarbonisation by enhancing efficiency [34]. Smart logistics, incorporating real-time tracking and supply chain optimisation through IoT and AI, addresses inefficiencies [35]. Idling regulations, anti-idling technologies, and emission standards drive the adoption of fuel-efficient technologies [26, 36]. Addressing idling and operational inefficiencies is pivotal for road freight decarbonisation, and integrating technological solutions, smart logistics, and regulatory measures contributes to sustainable freight operations.

Inefficient cargo capacity utilisation and the transportation of empty containers contribute to increased carbon emissions. Optimising return journeys, implementing smart logistics, and collaborative initiatives enhance operational efficiency [37, 38]. Integrating technological solutions like telematics and route optimisation is essential. Regulatory measures incentivising or mandating reduced empty haulage and underutilised capacity contribute to road freight decarbonisation [38]. A multifaceted approach, including technological solutions, collaborative freight initiatives, and regulatory measures, is essential for mitigating these inefficiencies and achieving road freight decarbonisation.

Inefficient logistics practices, including suboptimal route planning and excessive inventory, contribute to increased carbon emissions. Efficient resource utilisation, technology integration, alternative fuel adoption, green logistics initiatives, collaboration, and regulatory compliance are crucial elements driving sustainable practices in road freight [13]. Aligning logistics and supply chain practices with environmental goals is a critical prerequisite for achieving meaningful decarbonisation. Likewise, a comprehensive understanding of diverse emission sources is essential for designing effective decarbonisation strategies for road freight.

4.2 Lifecycle assessment (LCA) in road freight

Life cycle assessment (LCA) is a holistic approach that evaluates the environmental impact of road freight activities from production to end-of-life, covering stages such as raw material extraction, manufacturing, transportation, use, and disposal [39]. LCA identifies key points in the life cycle, directing decarbonisation efforts towards impactful stages like fuel combustion, manufacturing, and logistics [39]. Additionally, LCA facilitates the comparison of technologies, fuels, and operational practices, aiding decisions on cleaner alternatives in the road freight sector [39].

LCA's significance lies in exposing carbon emissions associated with fuel combustion in road freight vehicles. Decarbonisation guided by LCA can focus on enhancing combustion efficiency, transitioning to alternative fuels, and adopting electric or hybrid vehicles [24]. Manufacturing emerges as a vital contributor to life cycle emissions, and LCA guides the selection of sustainable materials, lightweighting strategies, and eco-friendly manufacturing processes to reduce environmental impact [24] . LCA underscores logistics and supply chain practices as critical components affecting overall environmental impact. Insights can drive the adoption of smart logistics strategies, route optimisation, and collaborative efforts within the supply chain to enhance decarbonisation [40].

Considering the entire life cycle, LCA supports the argument for extending the operational lifespan of road freight vehicles. Maintenance and repair strategies, informed by LCA, contribute to reducing the need for frequent replacements and associated manufacturing emissions [41]. In summary, life cycle assessment stands as a crucial tool for evaluating and comprehensively addressing the environmental impact of road freight operations. Its holistic perspective, hotspot identification, and comparative analysis offer valuable insights crucial for effective decarbonisation, supporting optimisation of fuel combustion, sustainable material selection, efficient logistics practices, and the extension of vehicle lifespan—critical elements in achieving meaningful road freight decarbonisation.

5. Strategic approaches and global perspective

5.1 Strategic approaches

Decarbonising road freight is a complex challenge demanding strategic solutions across the entire supply chain. This assessment explores key strategies such as alternative fuels, advanced vehicles, modal shift, intermodal optimisation, green logistics initiatives, and regulatory compliance. Each strategy is evaluated for effectiveness, feasibility, and broader industry impact.

- *Alternative fuels*: the integration of alternative fuels, including liquefied natural gas (LNG), hydrogen, and electricity, stands out as a pivotal strategy for reducing carbon emissions in road freight. Despite challenges such as infrastructure needs and initial costs, alternative fuels significantly contribute to lowering the carbon intensity of freight operations. The success of this strategy is amplified when combined with logistics optimisation, advanced vehicle technologies, and regulatory compliance.

- *Advanced vehicle technologies*: innovations in engine efficiency, aerodynamics, and drivetrain optimisation play a crucial role in enhancing fuel efficiency and aligning with decarbonisation goals. Challenges like upfront costs and charging infrastructure gaps exist, but the overall impact on emission reduction is noteworthy. The synergy of advanced vehicle technologies with alternative fuels and logistics optimisation maximises their effectiveness in addressing various facets of carbon emissions in the road freight sector.

- *Modal shift and intermodal optimisation*: modal shift involves redirecting freight to more sustainable modes, such as rail and water transport. Intermodal optimisation integrates different transportation modes for efficiency gains. Despite challenges like infrastructure limitations, both strategies complement each other, offering a diversified and environmentally sustainable freight transportation system. Successful implementation requires supportive policies, regulations, and strategic planning.

- *Green logistics initiatives*: green logistics efforts focus on optimising vehicle fleets, adopting alternative fuels, and leveraging intermodal transport. Energy-efficient technologies and last-mile delivery solutions contribute to decreasing emissions per unit of freight transported [42, 43]. Digital technologies, including real-time tracking and data analytics, play a pivotal role in enhancing efficiency. Overcoming challenges requires collaborative efforts from stakeholders, governments, and policymakers.

- *Regulatory compliance and advocacy*: regulatory compliance involves meeting emission standards to ensure environmentally acceptable road freight operations. Advocacy complements this by influencing policymakers to institute incentives and support the transition to cleaner alternatives. Effective advocacy addresses challenges related to enforcement and industry resistance. International collaboration is essential for harmonising regulations globally and achieving meaningful reductions in carbon emissions.

In conclusion, decarbonising road freight requires a holistic and integrated approach that combines these strategies. Each element contributes uniquely, and their collective implementation is key to achieving substantial and sustainable reductions in carbon emissions within the global road freight sector. Policymakers, industry stakeholders, and international bodies must collaborate to create an environment conducive to embracing these decarbonisation measures.

5.2 Global perspectives

This section explores the pivotal role of decarbonising road freight in addressing global climate change and sustainability. The literature review sheds light on key trends, challenges, and opportunities influencing the international landscape. A notable global trend is the increasing adoption of electric vehicles (EVs) in road freight, backed by significant investments from governments and industries, essential for reducing reliance on fossil fuels and mitigating carbon emissions. Additionally, the integration of advanced technologies like autonomous and connected vehicles, telematics, and real-time analytics is gaining traction globally, enhancing operational efficiency and fuel savings.

However, a significant challenge on a global scale is the insufficient charging infrastructure for EVs, emphasising the need for a robust and accessible charging network to fully exploit the potential of electric road freight [36]. Inconsistencies in policies across regions present obstacles to global road freight decarbonisation, underscoring the importance of harmonising regulations and emission standards worldwide [26]. Due to the global nature of road freight, increased international collaboration is considered necessary, enabling the sharing of best practices, technological innovations, and policy frameworks to expedite the decarbonisation process [44].

Opportunities lie in promoting multimodal transportation solutions integrating road, rail, and waterway transport, with coordinated global efforts having the potential to optimise supply chain logistics and contribute to overall emission reduction [37]. Stringent emission standards are becoming prevalent worldwide, with governments recognising the necessity of regulating road freight vehicle emissions to achieve climate goals [26]. Many countries are introducing incentives and subsidies to encourage the adoption of cleaner technologies in road freight, aligning with the global push for sustainable transportation [45]. The global outlook for road freight decarbonisation reflects a dynamic landscape, marked by a shift towards electric

Region	Challenges	Opportunities	Strategies
North America	• Lack of comprehensive EV charging infrastructure • Policy fragmentation	• Abundance of renewable resources • Innovation hubs	• Collaboration on charging infrastructure • Advocacy for unified emission standards
Europe	• Urban congestion • Transition period for traditional fleets	• Extensive rail and waterway networks • Strong regulatory framework	• Urban logistics innovations • Incentive programs
Asia-Pacific	• High urbanisation rates • Diverse economic realities	• Growing middle class • Innovation in emerging economies	• Sustainable urban planning • Technology transfer and collaboration
Africa	• Insufficient road infrastructure • Economic constraints	• Leapfrogging technologies • Infrastructural development	• Regional collaboration • Economic empowerment

Table 2.
Overview of the regional road freight decarbonisation efforts.

vehicles, advanced technology integration, and supportive policies. Despite challenges, international collaboration and concerted efforts can unlock opportunities for sustainable road freight operations worldwide. In summary, this section underscores the global necessity of decarbonising road freight while highlighting variations in challenges, opportunities, and strategies across distinct regions, focusing on North America, Europe, Asia-Pacific, and Africa (refer to **Table 2**).

6. Case studies of best practices, lessons learned, and future outlook

6.1 Case studies of best practices and policies

HJF Transports BVBA, a burgeoning family enterprise in Belgium with around thirty trucks, grapples with operational cost management and carbon emission reduction challenges [43]. In a strategic alliance with Shell Belgium, a prominent natural gas supplier, the company is transitioning its truck fleet to liquefied natural gas (LNG), perceived as a competitive and sustainable alternative to diesel. As per Shell's report, 11 out of HJF Transports' 30 trucks exclusively run on LNG, with plans for further investment in the LNG network across Belgium, the Netherlands, Germany, France, and Poland. Mr. Fossoul, the company's representative, underscores the limited public awareness of LNG's efficiency and sustainability, emphasising the imperative for increased investment in this alternative [46].

Amid uncertainties and mounting diesel costs, HJF Transports perceives LNG as the optimal solution for immediate and sustainable fleet operations. The company's commitment to environmental sustainability aligns with its 2018 investment strategy in LNG-powered trucks, a decision made in partnership with Shell Belgium. The success of the current LNG-powered trucks validates the company's choice to invest in a more sustainable solution. The ongoing collaboration between HJF Transports and Shell is characterised as a true partnership, with Shell incorporating customer requests and operational realities into the development of new services. HJF Transports plans to expand its LNG-powered fleet, leveraging Shell's growing pan-European LNG network facilitated by the Shell LNG card [46]. The company's proactive approach demonstrates its dedication to a sustainable business model amidst the challenges of rising diesel costs and environmental responsibility (see **Figure 3**).

Likewise, according to the Foresignt [47], Low Carbon Logistics (LRC) research has significantly influenced UK government policies, transforming the official approach to carbon auditing road freight transport [47]. It has offered guidance to the industry on measuring and managing CO_2 emissions, establishing the industry and government-endorsed target to reduce the carbon intensity of road freight transport. Responding to this research, the Freight Transport Association (FTA) initiated the Logistics Carbon Reduction Scheme (LCRS) in 2010. Collaborating with the FTA, the LRC adapted its freight decarbonisation model to meet LCRS needs and assessed how the UK road freight system should transform to achieve the CO_2 reduction target set by the 2008 Climate Change Act.

The research's impact is evident in various arenas, including influencing the Department of Energy and Climate Change (DECC)'s 2050 Pathways Analysis, which relied on LRC's work for setting emission levels. The LRC's freight decarbonisation model played a pivotal role in shaping the Fourth Carbon Budget by the Committee on Climate Change (CCC), contributing to the UK's efforts to tackle climate change. Additionally, the LRC's analytical framework for assessing logistics-related

Figure 3.
HJT vehicle fleet and Shell LNG plant (source: [46]).

externalities at a country level has been adopted and refined by large EU-funded projects and applied in reports for the UK Commission for Integrated Transport. Furthermore, the LRC's research scrutinised CO_2 emissions from road haulage operations, prompting methodological changes in compiling CO_2 data for the National Atmospheric Emissions Inventory. The research demonstrated that decarbonising the road freight sector might be less challenging than anticipated. Notably, the LRC's work has influenced industry practices, government policies, and international initiatives, showcasing its multifaceted and profound impact on the road freight sector's journey towards decarbonisation.

6.2 Lessons learned

The road freight sector, a linchpin in global trade, faces a transformative shift towards sustainability due to environmental concerns like carbon emissions and air pollution. Global initiatives are underway to usher in ecologically conscious practices, encompassing technological integration, collaborative efforts, regulatory backing, and innovative financial models. Workforce training, gender equality, lifecycle assessment, sustainability metrics, and adaptability are also crucial dimensions. Electric vehicles (EVs) are key to reducing carbon emissions. Azapagic and Perdan [48] emphasise electric trucks and vans powered by batteries or hydrogen fuel cells as alternatives to diesel. Hybrid systems, combining internal combustion engines with electric power, enhance fuel efficiency. Fuel-efficient technologies, aerodynamic enhancements, lightweight materials, and advanced engine management systems optimise fuel consumption. Telematics and connectivity solutions use real-time data analytics for efficient fleet management. Autonomous vehicles offer increased efficiency and reduced fuel consumption.

Exploring alternative fuels like compressed and liquefied natural gas provides cleaner-burning options. In urban logistics, electric cargo bikes and drones reduce congestion and emissions. Successful decarbonisation relies on strategic technology selection, adaptability, investment planning, financial viability, data-driven decision-making, stakeholder collaboration, employee training, change management, regulatory compliance, scalability, replicability, continuous improvement, and innovation. Selecting technologies based on operational needs, adapting to innovations, and conducting thorough assessments contribute to successful integration. Infrastructure planning and collaboration are crucial for an accessible charging network. Real-time data analytics and predictive modelling optimise routes and reduce energy consumption. Investing in training programs, robust financial planning, and supportive regulations are key factors for success. Collaboration with stakeholders, continuous monitoring of technology performance, flexibility, life cycle assessments, and transparent sustainability metrics enhance stakeholder trust. Pilot programs assessing feasibility and effectiveness contribute to widespread impact. Lessons from successful initiatives underscore the importance of these factors in the road freight sector's journey towards decarbonisation.

6.3 Future outlook

The future of road freight decarbonisation holds promise with the integration of emerging technologies and anticipated policy developments. This outlook envisions a transformative shift towards sustainable practices, driven by advancements in technology and a supportive policy landscape.

6.3.1 Emerging technologies

The electric vehicle (EV) landscape is set for rapid growth, fuelled by advancements in batteries, improved charging infrastructure, and increased energy density (see **Figure 4**). Solid-state batteries and fast-charging technologies, highlighted by Rai et al. [49], promise to enhance the viability of EVs in road freight. Meanwhile, the integration of autonomous and connected technologies, as discussed by Thomopoulos et al. [50], is poised to revolutionise route planning and fleet efficiency. Ongoing research into alternative fuels like green hydrogen and advanced biofuels, along with innovations in propulsion systems, offers credible substitutes for traditional diesel. The potential of hydrogen fuel cells and improved engine designs plays a pivotal role in achieving carbon-neutral road freight, according to Kühnbach et al. [51].

6.3.2 Anticipated policy development

The future policy landscape is expected to introduce stricter global emission standards for road freight vehicles, fostering the adoption of cleaner technologies and penalising carbon-intensive practices [26]. Governments are likely to provide increased incentives and subsidies for the transition to low-emission and zero-emission vehicles, particularly in areas like fleet electrification, charging infrastructure

Figure 4.
An overhead centenary implementation of ERS. Source: Siemens Mobility GmbH, 2022, as cited in [19].

development, and sustainable transportation research [23]. Anticipated policies also suggest a shift towards integrated multimodal transportation solutions, promoting a balanced combination of road, rail, and waterway transport to reduce the overall carbon footprint [38]. Looking ahead, a collaborative approach leveraging emerging technologies and evolving policies, especially the convergence of electric and autonomous vehicles, is poised to drive innovation in the road freight sector, contributing significantly to global decarbonisation efforts.

7. Discussion and conclusion

7.1 Discussion

The chapter presents a stimulating analysis of the intricate aspects surrounding the sustainability of road freight. Employing a conceptual review method, it sheds light on key concepts, emerging trends, and critical gaps, delivering a nuanced exploration of sustainability concerns within the road freight sector. Commencing with the establishment of a clear understanding of sustainability within the context of road freight, the chapter engages with seminal works and contemporary literature to delve into the conceptualisation and application of sustainability. This not only lays the foundation for subsequent discussions but also emphasises the significance of defining sustainability in the evolving landscape of freight transportation.

A pivotal facet of the chapter involves the identification and analysis of diverse strategies for decarbonising road freight, categorised into technological, operational, and policy-driven interventions [25, 37, 43]. The implications extend beyond immediate environmental concerns, encompassing the socio-economic dimension of the freight sector and stressing the necessity for a multifaceted approach in addressing challenges posed by carbon emissions. The exploration of the economic dimension enriches the discourse by spotlighting the financial implications for stakeholders in the road freight sector [28]. This economic scrutiny aligns with the broader discourse on the green economy, highlighting the imperative of sustainable practices that strike a balance between environmental and economic considerations [37].

Moreover, the chapter critically assesses the environmental consequences of road freight decarbonisation efforts, utilising lifecycle assessment, carbon footprint analyses, and ecological impact studies [24, 40, 41, 48]. The implications extend beyond immediate environmental impact, contributing to the broader discourse on sustainable practices in transportation and emphasising the interconnectedness of environmental concerns with global sustainability goals. By scrutinising the role of policies and regulations, the chapter underscores the significance of government intervention in shaping road freight decarbonisation [21, 44]. This aligns with broader literature discussing the regulatory framework's role in promoting sustainable practices across industries, emphasising the need for collaborative efforts between policymakers and industry stakeholders. The identification and discussion of challenges and opportunities associated with road freight decarbonisation add a layer of realism to the conceptual exploration [26, 37, 42, 45]. This discussion aligns with broader literature on sustainability marked by both obstacles and potential breakthroughs.

Furthermore, the incorporation of diverse stakeholder perspectives enriches the conceptual understanding of road freight decarbonisation [31, 33, 35, 46, 47]. This emphasis on stakeholder engagement resonates with broader discussions in the literature on the importance of inclusive decision-making processes for effective sustainability initiatives. In summary, the implications of the issues covered in this chapter resonate with broader literature on sustainable transportation, green logistics, and the global shift towards more eco-friendly practices [37]. The interconnectedness of environmental, economic, and social aspects aligns with the holistic approach advocated in the broader literature [33, 37]. Against this backdrop, the implications highlighted underscore the urgency of addressing road freight sustainability as an integral part of broader global sustainability efforts.

7.2 Conclusion and direction for future studies

In the quest for a sustainable future in road freight, this chapter underscores the complex nature of decarbonisation, emphasising the need to tailor strategies to specific regional and industry contexts while integrating innovation and community engagement. The findings advocate for comprehensive approaches, highlighting the importance of clear reporting, sustainability metrics, and cross-cultural understanding to facilitate effective road freight adaptations. The review serves as a guiding resource, steering stakeholders towards collaborative solutions and stressing the necessity to customise decarbonisation efforts across diverse regions, industries, and operational contexts. Industry-specific approaches, aligned with operational environments, are deemed crucial for ensuring supply chain resilience. The roles of technological integration, cultural awareness, community engagement, and sustainability metrics are pivotal in optimising the environmental impact of road freight [37].

The future study agenda recommends prioritising tailored strategies for different regions, industries, and operational contexts to enhance the efficacy of decarbonisation initiatives, streamline logistics, and address specific challenges across diverse settings. The comprehensive research dimensions include investigating regional variations, analysing industry-specific adaptations, assessing operational environment considerations, scrutinising cross-cultural perspectives, and evaluating the integration of sustainability metrics using mainly qualitative research approach to help map the 'how' issues affecting road freight decarbonisation. Additionally, the chapter calls for future research to encompass emissions quantification, lessons learned transferability, sustainability beyond carbon reduction, ongoing commitment to learning, obstacle navigation, benchmarking, inspiration for similar efforts, and examining advocacy resulting from successful initiatives. In summary, adopting a multidimensional research approach is crucial for comprehensively addressing regional, industry-specific, and operational variations, contributing to the development of targeted and context-specific strategies for sustainable road freight practices globally.

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Conflict of interest

None.

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