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The Energy Transition's Impact on Transport Sector Sustainability: Opportunities and Challenges for Businesses.

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ABSTRACT:

Energy transition in the transport sector is a major challenge for meeting global climate objectives and promoting sustainable development. This brief assesses the environmental impact, economic viability and technical challenges facing the transport sector. The focus is on electric and hydrogen-powered vehicles. A methodology combining literature review, case studies and semi-structured interviews has been adopted. This provides a comprehensive view of the subject. The results indicate that, despite the significant potential for reducing greenhouse gas emissions offered by electrification and hydrogen, several economic, technological and infrastructural obstacles persist. These challenges call for stronger political support, technological innovation and changes in user behavior. The brief proposes strategic recommendations for companies and decision-makers to facilitate a sustainable and economically viable energy transition for the transport sector.

KEYWORDS: Finto:http:/finto.fi/yso/en/?clang=fi&anylang=on

Abbreviations

ADEME – French Environment and Energy Management Agency

BEV – Battery Electric Vehicle

CO_2 – Carbon Dioxide

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

EV – Electric Vehicle

GHG – Greenhouse Gas

HFC – Hydrogen Fuel Cell

HRS – Hydrogen Refueling Solutions

ICAO – International Civil Aviation Organization

ICE – Internal Combustion Engine

IEA – International Energy Agency

IMO – International Maritime Organization

IPCC – Intergovernmental Panel on Climate Change

LOM – Mobility Orientation Law (Loi d'Orientation des Mobilités)

LCA – Life Cycle Assessment

MEP – Multiannual Energy Plan (PPE in french)

NO_x – Nitrogen Oxides

NDC – Nationally Determined Contribution

PEM – Proton Exchange Membrane (fuel cells)

PPE – Pluriannual Energy Program (Multiannual Energy Plan)

RTE – Réseau de Transport d'Électricité

SAF – Sustainable Aviation Fuel

SNBC – Stratégie Nationale Bas-Carbone (National Low-Carbon Strategy)

TCO – Total Cost of Ownership

UNFCCC – United Nations Framework Convention on Climate Change

ZEV – Zero Emission Vehicle

ZFE – Low-Emission Zones (Zones à Faibles Émissions)

Contents

1 Introduction

Today, climate change and its harmful effects represent one of the greatest challenges of our generation. Transitioning to a greener economy is the only viable solution to address this issue.

1.1 Overview

This study focuses on the transport sector, one of the largest contributors to global greenhouse gas (GHG) emissions. In 2022, transport accounted for around 22% of global energy-related CO_2 emissions, mostly from road transport (International Energy Agency, 2022). According to the IPCC, the transport sector represents about 15% of total anthropogenic GHG emissions, making it the third-largest emitting sector after electricity/heat production and industry (Jaramillo et al., 2022). Decarbonizing this sector is crucial to meet international climate targets, including those set by the 2015 Paris Agreement, which seeks to "limit the temperature increase to 1.5°C above pre-industrial levels" (UN, Paris Agreement).

The case for decarbonization is environmental, economic, and social. Beyond CO_2, transport emits pollutants like nitrogen oxides (NO_x) and fine particulates, which harm public health. In 2019, outdoor air pollution caused an estimated 4.2 million premature deaths worldwide (World Health Organization, 2024). Economically, Europe's reliance on fossil fuel imports exposes it to price volatility and geopolitical risks, with the EU importing 97% of its crude oil and petroleum products in 2022 (Eurostat, 2024).

Alternative energy solutions are essential. Electricity and hydrogen offer promising pathways to lower emissions. EVs reduce local emissions, though their overall benefits depend on the electricity mix. In France, where low-carbon nuclear and renewable energy dominate, EVs significantly cut CO_2 emissions compared to combustion vehicles. However, in fossil fuel–dependent countries, the advantage may be smaller, (RTE. (n.d.))

Hydrogen holds particular promise for heavy-duty and long-distance transport. According to the Hydrogen Council, hydrogen could meet up to 18% of global energy demand by 2050 with sufficient investment in renewable production. Yet, green hydrogen remains costly and faces infrastructure limitations (IEA, 2019).

The transition presents both opportunities and challenges. Significant investments are needed in charging and refueling infrastructure, and transport business models must adapt. Hatami (2021) reports that early adopters of zero-emission technologies may gain long-term competitive advantages through fuel and maintenance savings.

In conclusion, integrating electrification and hydrogen into transport is essential to reduce carbon emissions and ensure the sector's economic sustainability. This research will explore the benefits and limitations of these technologies and offer practical recommendations, considering varying national energy mixes and resource constraints.

1.2 Research Problem

This research aims to examine how the transport sector can integrate renewable energies, such as electricity and hydrogen, to reduce its carbon footprint while maintaining profitability and economic viability. Specifically, it will address three key questions:

(1) To what extent can electric and hydrogen technologies reduce transport-related CO_2 emissions, and what technical limitations remain?

(2) How economically viable are these technologies, considering total cost of ownership and evolving business models?

(3) How do consumer perceptions and public policy influence the adoption of these solutions in the French market?

1.3 Justification and General Relevance of the Study

Studying this issue is essential in today's context, where energy and environmental concerns are central to international priorities. Faced with the climate emergency, governments, international organizations, and businesses are increasingly committing to ambitious greenhouse gas reduction targets. To meet these goals, the transport sector must also undergo a profound transformation. Integrating renewable energies is a key solution to reducing the sector's carbon footprint. However, this transition raises significant challenges—not only in terms of infrastructure and technology but also in terms of profitability and economic viability for businesses.

This research aims to explore these challenges, offering practical insights into how new technologies can be integrated into the transport sector while maintaining financial performance.

The study holds multiple forms of interest across different fields. From an academic perspective, it seeks to address gaps in the existing literature. While many studies have analyzed the environmental benefits and limitations of electrification and hydrogen technologies, few have thoroughly examined their economic impact on transport businesses. By analyzing current business models and assessing the profitability of these emerging technologies, this research will contribute to a deeper understanding of the energy transition in transport.

Practically, this study is highly relevant for transport companies, which face increasing pressure to lower their carbon footprint without compromising competitiveness. In a sector where profitability is tightly linked to infrastructure costs and public policy frameworks, this research will identify the main economic and operational barriers businesses face. Through an analysis of the obstacles and available levers, the study will propose concrete recommendations to help companies transition toward more sustainable models. The findings will be particularly valuable for business managers and decision-makers, who must strike a balance between technological innovation and financial imperatives to successfully navigate the energy transition.

This research also has strategic importance for policymakers. By providing a detailed analysis of the impacts and requirements linked to renewable energy adoption in transport, it can help inform public policies and economic incentive programs. Recommendations from this study could guide the creation of regulatory and financial frameworks that support investment in sustainable transport solutions, thus contributing to national and international climate goals.

Finally, this study may have broader implications for the energy and sustainable mobility sectors. By exploring the interactions between technological innovation, economic strategies, and public support policies, it contributes to advancing a model of transport that is both environmentally responsible and economically viable. Through practical solutions, it aims to respond to growing societal demands for sustainability and help strengthen business resilience in the face of climate and economic challenges.

1.4 Limitations

This thesis deliberately focuses on specific aspects of the energy transition in transport to ensure both feasibility and depth of analysis. First, the geographical scope is centered on France, while incorporating some international comparisons to provide context for the findings. Second, the technological scope is limited to two major solutions: battery electrification and hydrogen. Other alternatives, such as biofuels or decarbonized public transport, have been excluded to maintain a coherent framework. Third, the study prioritizes light (passenger cars, light commercial vehicles) and heavy (trucks, buses) road mobility, excluding rail and aviation. Finally, the research emphasizes economic, technical, and behavioral (consumer) dimensions without aiming to comprehensively cover detailed environmental impacts, which would require a full life cycle assessment (LCA) beyond the scope of this thesis.

These delimitations allow the research to concentrate on the most relevant issues for the current French market and to ensure sufficient depth of analysis appropriate for a Master’s thesis.

1.5 Personal and Professional Relevance

This study also presents a valuable opportunity to deepen my knowledge of renewable energy and the energy transition. Throughout this research, I will enhance my understanding of electrification and hydrogen technologies, along with their environmental and economic impacts. This will allow me to better grasp the technical challenges of decarbonizing transport and the strategies to overcome them—knowledge that is essential to anticipate future developments in this sector.

My academic background reflects my commitment to combining technical and strategic skills. I had the opportunity to spend a semester at Centrale Méditerranée, where I earned a certificate focusing on major scientific and technical challenges, with particular attention to energy and environmental issues. This program gave me a broad perspective on energy challenges and increased my awareness of the scientific and technological aspects of the energy transition. At the same time, my bachelor's degree in MIASHS (Mathematics, Applied Computer Science, and Social Sciences) provided me with strong data analysis skills and a methodical approach to addressing complex problems—an undeniable asset for evaluating the quantitative impacts of energy choices in the transport sector. By combining these cross-disciplinary skills, this study will strengthen my profile as a professional able to navigate both the technical and strategic dimensions of the energy transition.

Professionally, this research aligns with my career ambitions in the renewable energy sector, where I aim to work as a Key Account Manager for major companies such as EDF. In this role, it will be essential to master both the technical and economic aspects of renewable energy in order to advise clients and help them make informed decisions in their energy transition. A deep understanding of electrification and hydrogen technologies, as well as their practical applications in transport, will enable me to propose tailored solutions and address the growing sustainability concerns of businesses. As a Key Account Manager, I will also engage with strategic clients for whom environmental impact and profitability are central concerns. The ability to provide sound recommendations based on data and in-depth analysis of available energy solutions will be a key advantage in this role. Through this study, I will develop not only specific expertise in renewable energy but also the ability to translate technical insights into clear and convincing value propositions for clients.

In summary, this research represents a critical step in shaping my professional profile, preparing me for the responsibilities of a Key Account Manager specializing in sustainable transport solutions. This project will strengthen my skills in managing strategic accounts and analyzing client needs while deepening my understanding of energy issues and their impact on transport sector businesses.

1.6 Structure of the Thesis

To address this research question, we will first conduct a literature review. This section will provide an overview of existing studies on electrification and hydrogen technologies in the transport sector. We will examine the advantages and limitations of these technologies, as well as their economic viability. The review will also highlight key theoretical models applied in the field and identify gaps in current knowledge, establishing a solid academic foundation for the study.

Chapter II will focus on the study’s methodology. It will outline the chosen approach for data collection and analysis, which will combine a document review with qualitative interviews conducted with industry experts, including representatives from companies using renewable energy in transport. This mixed approach will enhance our understanding of the economic, technological, and regulatory challenges of the energy transition in this sector.

Chapter III will present and analyze the results. It will summarize the main findings from the literature and interviews, providing insights into how transport companies can practically adopt electrification and hydrogen solutions. By interpreting the results through the theoretical lens discussed in the literature review, we will identify the key barriers and opportunities associated with this transition.

Finally, Chapter IV will offer recommendations and a conclusion. This section will provide practical advice for transport companies aiming to adopt renewable energy solutions while maintaining economic performance. It will also propose policy recommendations for public decision-makers to support the sector's energy transition. The chapter will conclude by summarizing the academic and practical contributions of the study and suggesting areas for future research.

This structure is designed to develop each aspect of the research in a coherent manner and provide a thorough, structured response to the research question.

2 Theorical Framework

The integration of renewable energy into the transport sector—particularly through electrification and the use of hydrogen—represents both a strategic and environmental priority in addressing climate change. As one of the largest contributors to greenhouse gas emissions, the transport sector lies at the centre of global decarbonization efforts. This challenge has become even more pressing since the Paris Agreement in 2015, which set the target of limiting global warming to below 1.5°C. (United Nations, 2015). Meeting this goal requires not only transitioning the sector's energy sources but also navigating a complex transformation across technology, economics, and regulation. This shift demands significant changes in infrastructure, industrial practices, and business models.

This literature review critically examines existing research to better understand the potential and the limitations of renewable technologies in lowering the transport sector's carbon footprint, while maintaining profitability for businesses. By exploring studies on electrification and hydrogen, this review highlights both the environmental benefits and the technological challenges associated with these solutions. It also assesses the economic strategies and theoretical frameworks that support the sector's transition. Beyond summarizing the current state of research, the review identifies key barriers and enabling factors—financial, technological, and environmental—that shape the path toward decarbonizing transport. While the primary focus is on France, comparisons with other countries are included where relevant.

The review is structured into thematic sections to provide a clear and systematic analysis. It begins by examining the broader context of the energy transition in transport, outlining the environmental challenges and reviewing international commitments that increasingly encourage companies to invest in clean technologies. The second section focuses on renewable technologies themselves, first addressing electrification and its implications, followed by hydrogen, which holds particular promise for heavy transport and long-distance travel. The third section explores the economic viability of these technologies, with an emphasis on business models, case studies, and supportive policies, including subsidies and tax incentives. The final section discusses theoretical frameworks related to sustainability and profitability in the sector before synthesizing key trends and identifying gaps in the existing literature.

By summarizing current research and highlighting areas that require further investigation, this literature review lays the foundation for a deeper exploration of the sustainability, competitiveness, and technological innovation challenges facing the transport sector.

2.1 Global Context of the Energy Transition

2.1.1 Mechanisms of Pollution

First, let us understand how pollution works. Global warming on Earth is largely driven by greenhouse gases (GHGs) (European Parliament, n.d.). These gases, such as carbon dioxide (CO_2) and methane (CH_4), trap heat in the atmosphere, causing a rise in global temperatures (UN, 2021). While the natural greenhouse effect is essential for life, human activities (including fossil fuel combustion, intensive agriculture, and deforestation) have amplified this effect, leading to accelerated temperature increases. According to the IPCC (2018), the global average temperature has already risen by approximately 1.1°C compared to pre-industrial levels. To better grasp the scale of emissions, it is important to examine the proportions of the various greenhouse gases present in the atmosphere.

CO_2 is by far the most prevalent, accounting for about 76% of total emissions. Other gases, such as methane (CH_4) and nitrous oxide (N_2O), although present in smaller amounts, also contribute significantly to global warming because of their high warming potential (Envoria. (n.d.)). This highlights the importance of focusing reduction strategies primarily on CO_2, given its dominant share of emissions. However, each greenhouse gas differs in its global warming potential and atmospheric lifetime, factors that determine its overall climate impact. Carbon dioxide (CO_2) is the most widespread and persistent greenhouse gas, capable of remaining in the atmosphere for hundreds of years and contributing to long-term warming. Methane (CH_4), while less abundant, has a global warming potential roughly 25 times higher than CO_2 over a 100-year period. As such, it is a key driver of short-term warming. Although methane typically stays in the atmosphere for only about a decade, its breakdown produces CO_2, extending its climate impact. Nitrous oxide (N_2O), though emitted in smaller quantities, has a warming potential approximately 300 times greater than CO_2, adding further complexity to greenhouse gas management (The indirect global warming potential and global temperature change potential due to methane oxidation) (Agence Parisienne du Climat, n.d.).

Therefore, while CO_2 remains the primary target for emission reductions, other GHGs must not be overlooked. For instance, in the transport sector, vehicles mainly emit CO_2 but also contribute indirectly to CH_4 and N_2O emissions through the broader processes and value chains involved. This complexity of transport-related emissions requires a comprehensive approach to effectively reduce the sector's carbon footprint.

2.1.2 Consequences of Pollution

The energy transition has become a global priority in response to the growing climate crisis. Greenhouse gas emissions severely impact the environment, the economy, and public health. According to the IPCC (2018), limiting warming to 1.5°C will require rapid transformations, particularly in the transport sector. Even if this threshold is maintained, significant effects, such as sea level rise and biodiversity loss, will persist (Henriques, 2024). Exceeding 1.5°C would increase the risk of triggering climate tipping points, making some changes irreversible. The economic effects are also substantial. Tol (2009) estimates that a 2.5°C rise in global temperatures could lead to an average 1.3% reduction in per capita income, with developing countries being hit hardest. Natural disasters drive up adaptation costs, while climate volatility threatens global food security. The National Center for Environmental Economics et al. (2023) emphasizes the social cost of carbon, underscoring the urgent need for stronger carbon pricing to account for the true cost of emissions.

From a health perspective, climate change worsens respiratory, cardiovascular, and vector-borne diseases (Global Climate and Health Alliance, n.d.)). Air pollution, especially fine particulate matter from transport, causes millions of premature deaths each year. Rising heatwaves and the spread of tropical diseases pose increasing challenges to healthcare systems. Extreme weather events also undermine food security, heightening the risks of malnutrition.

In light of these systemic impacts, developing renewable energy solutions in the transport sector is essential to mitigate the climate crisis and promote a more sustainable future.

2.2 The Transport Sector and International Commitments

2.2.1 Contribution of Transport to Global CO_2 Emissions

The transport sector plays a major role in climate change due to its heavy reliance on fossil fuels. Globally, transport accounts for about 23% of direct energy-related CO_2 emissions, nearly a quarter of emissions from energy combustion (Jaramillo et al., 2022). Including other greenhouse gases, this represents roughly 15% of total anthropogenic GHG emissions. These emissions are unevenly distributed across transport modes: road transport is by far the largest contributor, responsible for 70–75% of the sector's direct emissions (around 6 Gt CO_2-eq in 2019). Passenger cars and heavy-duty vehicles with combustion engines are the primary sources of CO_2 emissions. Other modes contribute smaller but still significant shares. Maritime transport accounts for about 9% of sector emissions (approximately 0.8 Gt CO_2-eq in 2019), equivalent to 2–3% of total global emissions. According to UNCTAD (2023), aviation represents about 7% of transport emissions from international flights (0.6 Gt CO_2-eq in 2019), with additional emissions from domestic flights bringing aviation's total to roughly 10–11% of the sector's output (around 2.5% of global emissions). In comparison, rail transport contributes only 1–2% of the sector's CO_2 emissions, largely thanks to widespread electrification and rail's superior energy efficiency. Trains handle about 8% of global passenger traffic and 7% of freight, with a minimal share of transport emissions (BBVA CIB, 2024).

Recent trends show sustained growth in transport demand, driving emissions upward. Between 1990 and 2022, CO_2 emissions from transport increased by an average of 1.7% per year—one of the fastest growth rates among energy sectors (IEA, 2023). This rise is mainly due to the rapid growth of motorized passenger and freight traffic worldwide. From 2000 to 2018, global transport activity (in passenger-kilometres and tonne-kilometres) rose by 73%, far outpacing energy efficiency gains over the same period (Jaramillo et al., 2022). Rapid motorization in emerging economies, globalization, and urbanization have expanded vehicle fleets and increased air and maritime traffic. In many regions of Asia and Africa, transport emissions grew by 4–6% annually between 1990 and 2019, while growth was more moderate in Europe and North America, where transport emissions were already high.

This strong growth in mobility demand poses a serious climate challenge. Without major changes, increasing travel and transport will continue driving emissions higher. According to Michael (2021), projections by the International Transport Forum (OECD) suggest that global transport activity could more than double by 2050, pushing sector emissions 16% higher than 2015 levels even if current reduction pledges are fully implemented. In other words, today's policies are not enough to offset rising demand: without additional measures, efficiency gains and existing actions will be overwhelmed by growth in transport needs. The International Energy Agency (IEA, 2023) stresses that to align transport with a net-zero pathway by 2050, emissions must now decline by more than 3% per year through 2030. Achieving this target will require deep transformations, which will be explored in the next section on international and national commitments.

2.2.2 International Commitments to Reducing Transport Emissions

Given transport's significant contribution to global emissions, the international community has incorporated this sector into major climate agreements and launched specific initiatives. The Paris Agreement (2015) provides the overarching framework. However, as Jaramillo et al. (2022) note, the Agreement does not explicitly cover emissions from international transport (aviation and shipping). These so-called “bunker emissions” are not assigned to any particular country, and their inclusion in Nationally Determined Contributions (NDCs) is left to the discretion of individual states (UNFCCC, n.d.). To address this gap, responsibility for regulating international transport has been delegated to specialized sectoral organizations. In the aviation sector, the International Civil Aviation Organization (ICAO), a UN agency, leads emissions reduction efforts. In 2016, under ICAO’s leadership, states adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to cap international flight emissions at 2020 levels. Airlines must offset emissions exceeding 2019/2020 levels by purchasing carbon credits while improving operational energy efficiency (Uniting Aviation, 2025). ICAO also introduced fuel efficiency standards for new aircraft. A major milestone came in October 2022, when ICAO’s 193 member states adopted a long-term goal of achieving net-zero carbon emissions for international aviation by 2050 (ICCT, 2023). While not legally binding, this target guides both industry and governments toward full sector decarbonization. ICAO’s strategy combines accelerated adoption of breakthrough technologies (such as next-generation fuel-efficient aircraft and, in the longer term, hydrogen or electric planes), flight operation optimizations, and the widespread use of sustainable aviation fuels (SAF). In 2022, ICAO also revised CORSIA’s baseline to 85% of 2019 emissions starting in 2024, gradually strengthening the scheme (Uniting Aviation, 2025). While CORSIA’s effectiveness is sometimes debated, these commitments reflect a growing international determination to control aviation’s carbon footprint, which currently amounts to roughly 1 Gt of CO_2 annually. In international shipping, the International Maritime Organization (IMO) coordinates decarbonization efforts. In 2018, the IMO adopted its Initial GHG Reduction Strategy—the first of its kind—which aimed to cut greenhouse gas emissions by at least 50% by 2050 compared to 2008 levels, with a vision of phasing out emissions entirely as soon as possible (CONSEIL, 2019; UNFCCC, n.d.). Interim targets included improving ship energy efficiency by 40% by 2030 and 70% by 2050.

Although the strategy marked significant progress, it fell short of aligning with the Paris Agreement's objectives (Bouissou, 2024). After years of negotiation, the IMO raised its ambition in July 2023: member states adopted a revised strategy aiming for net-zero emissions "by or around mid-century" (Nlnnpc-Mashinaki, 2023; IMO, n.d.). This new strategy sets ambitious interim goals: a 20% reduction in international fleet emissions by 2030 (up to 30% if possible) and a 70–80% reduction by 2040, compared to 2008 levels. Achieving net-zero by 2050 poses a major challenge, given the long service life of ships and the current lack of mature, large-scale technological solutions (Bouissou, 2024). To meet this challenge, the IMO promotes the development and deployment of alternative fuels (such as green ammonia, hydrogen, and methanol), improved ship energy efficiency (including new hull designs, wind-assisted propulsion, and route optimization), and potential market-based measures like carbon pricing (IMO, n.d.). France, along with around 70 countries, supports introducing an international carbon tax on shipping to incorporate climate costs into freight prices and fund the sector's transition (Bouissou, 2024). This tax aims not only to encourage investment in low-emission ships but also to finance research and provide assistance to developing countries. Beyond these sectoral frameworks, other international initiatives are also noteworthy. At the G7 and G20 levels, countries have consistently reaffirmed the importance of transport decarbonization, promoting electric vehicles and sustainable fuels (Sen, Teter, Miller, & International Council on Clean Transportation [ICCT], 2025). Voluntary coalitions have also formed, such as the Zero Emission Vehicle (ZEV) Transition initiative launched at COP26, where several countries and manufacturers committed to phasing out internal combustion engine vehicles (Sen et al., 2025). Similarly, the Mission Innovation initiative includes a focus on low-emission fuels for aviation and maritime transport.

The European Union has played a leading role through its Green Deal. Key measures include ending sales of new petrol and diesel cars by 2035 and introducing the ReFuelEU Aviation program, which mandates 2% sustainable aviation fuel by 2025 and

6% by 2030 (International Transport Forum & Bunsen, 2023). The gradual inclusion of maritime transport in the EU Emissions Trading System (ETS) also strengthens economic incentives for decarbonization (International Transport Forum & Bunsen, 2023). All these initiatives aim to meet the Paris Agreement targets and send a clear signal to industry: the transport sector must begin an urgent technological and economic shift toward carbon neutrality. However, despite increasingly ambitious international commitments, actual progress remains mixed. The IPCC notes that measures taken so far have mainly focused on improving energy efficiency and offsetting emissions, with limited deployment of breakthrough technologies needed to fully eliminate fossil fuels (Jaramillo et al., 2022; IPCC, 2022). In particular, international aviation and shipping are progressing slowly. While goals are in place, implementation—such as deploying new fuels and propulsion systems—remains in the early stages (International Transport Forum & Bunsen, 2023; Sen et al., 2025).

The challenge now lies in turning promises into action. National commitments, especially from pioneering countries like France, will be essential in translating global objectives into concrete policies.

2.2.3 Focus: France — National Commitments in the Transport Sector

France, in line with international agreements, has made transport decarbonization a central element of its climate and energy strategy. According to Cnoual (2024), the transport sector was the largest source of greenhouse gas (GHG) emissions in France in 2022, accounting for approximately 30% to 33% of national emissions. In recent years, French transport emissions—around 120 to 130 Mt CO_2-eq annually—have come predominantly (94%) from road transport, including passenger cars, light commercial vehicles, and heavy-duty trucks (Ministère de la Transition écologique, 2024). Unlike other sectors, transport emissions in France have decreased only marginally since 1990, largely due to the continued growth of road and air traffic. Controlling emissions from this sector is therefore essential for meeting national climate targets.

2.2.3.1 National Low-Carbon Strategy (SNBC) and Pluriannual Energy Program (PPE)

France’s climate policy framework is defined by the National Low-Carbon Strategy, Stratégie Nationale Bas-Carbone (SNBC), established under the 2015 Energy Transition Law. The SNBC serves as France’s roadmap for achieving carbon neutrality by 2050 (Ministère de la Transition écologique, 2020). It sets five-year carbon budgets for major sectors—essentially, emission caps—and outlines strategic guidelines to gradually transform the economy. The SNBC was revised in 2018–2019 to align France with the 2050 carbon neutrality goal (updating the original target of cutting emissions by a factor of four from 1990 levels). For the transport sector, the SNBC sets an ambitious emissions reduction trajectory. The annual carbon budget drops from around 128 Mt CO_2-eq for 2019–2023 to 112 Mt for 2024–2028, and 94 Mt for 2029–2033 (Ministère de la Transition écologique, 2020). By 2030, France aims to cut transport emissions by approximately 31% compared to 2019 (Projet de PPE n°3, 2024). By 2050, the SNBC calls for near-total decarbonization of land transport, leaving only minor residual emissions to be offset by carbon sinks.

The Multiannual Energy Plan (PPE) complements the SNBC by outlining medium-term energy mix developments and concrete measures to meet these targets. The current MEP, revised in 2020, covers 2019–2028, with a new version (PPE n°3) for 2025–2035 under development (Projet de PPE n°3, 2024). For transport, the PPE aims to raise the share of renewable energy to 14% by 2030—aligned with EU directives—through sustainable biofuels, renewable electricity (low-carbon powered electric vehicles), and green hydrogen. It also sets goals for deploying clean vehicles: 1.2 million electric or plug-in hybrid vehicles by 2023 (partially achieved) and about 5 million by 2028. Plans include converting portions of the bus and truck fleets to gas or electricity and improving the average energy efficiency of new vehicles by 15% by 2028.

Looking beyond numerical targets, studies highlight that meeting SNBC goals will require not only technological innovation but also changes in mobility behavior and urban planning (Auverlot et al., 2022).

In summary, the SNBC and PPE form the foundation of France's commitments, setting clear targets (–31% by 2030, neutrality by 2050) and identifying key levers—electrification, biofuels, energy efficiency, and behavioral changes—for transforming the transport sector. We will now examine how these strategies are reflected in national legislation and sectoral policies.

2.2.3.2 French Mobility Orientation Act (LOM)

Adopted at the end of 2019, the Mobility Orientation Law (LOM) aims to achieve carbon neutrality for land transport by 2050 (Ministères Aménagement du Territoire Transition Écologique, n.d.). It is built around three pillars: investing in everyday transport, supporting alternative mobility options (carpooling, electric and shared mobility), and accelerating the transition to clean mobility (Hyundai Motor France, 2025). The law sets a ban on the sale of new combustion engine vehicles by 2040 (potentially brought forward to 2035 under EU regulations) and includes strong incentives: an enhanced ecological bonus, the right to install private charging stations in shared residential buildings, and a target of 100,000 public charging points by 2025 (Hyundai Motor France, 2025). The law also mandates the gradual greening of public and corporate vehicle fleets, introduces the sustainable mobility package (up to €700 per year), and promotes an ambitious cycling plan. Finally, the LOM strengthens the role of rail transport in the transition by supporting regional trains (TER) and freight, and by establishing local mobility authorities throughout the country, including rural areas (Ministères Aménagement du Territoire Transition Écologique, n.d.).

2.2.3.3 Sub-sector policies

In addition to the Loi d’Orientation des Mobilités (Mobility Orientation Law, LOM), France has implemented sector-specific policies aligned with these objectives.

For road transport, the government initially planned a heavy vehicle ecotax to encourage shifting freight from roads to rail and waterways, but the measure was abandoned in 2014. However, as of 2023–2024, a climate contribution for road hauliers is under consideration to help fund rail infrastructure (Ministère de la Transition écologique, n.d.). Incentives are also available to support the conversion of trucks to cleaner technologies. In urban areas, Low-Emission Zones (Zones à Faibles Émissions, ZFE) have been made mandatory in major cities to gradually restrict the most polluting vehicles (Djebbari, 2021).

For rail transport, the priority is improving and expanding services to attract passengers and freight. France is investing in modernizing the existing network, has relaunched night trains and freight services, and aims to double rail freight’s market share by 2030. The 2021–2030 freight plan includes over €1 billion in investments (Djebbari, 2021). The LOM also allows new railway lines to be developed through local initiatives. Pilot projects testing hydrogen-powered trains are underway (Ministère de la Transition écologique, n.d.).

For domestic air transport, the 2021 Climate and Resilience Law banned short-haul flights where a train alternative of under 2.5 hours exists. In effect since 2022, this has led to the cancellation of some air routes (Djebbari, 2021). France also strongly supports the development of sustainable aviation fuels (SAF), targeting 2% SAF in jet fuel by 2025, 5% by 2030, and 50% by 2050. An air ticket ecotax has also been introduced to fund greener transport investments (Ministère de la Transition écologique, n.d.).

For maritime and inland waterway transport, France has launched a national decarbonization roadmap for the maritime sector. This strategy outlines actions to reduce emissions from French-flagged ships and maritime activities under French jurisdiction. Government support focuses on port electrification, transitioning commercial ships to alternative fuels, and promoting wind-assisted propulsion (Ministère de la Transition écologique, n.d.). Inland waterway transport is also encouraged, with investments in modernizing canals and locks, along with subsidies to help operators renew their fleets (Djebbari, 2021).

2.2.4 Conclusion - The Transport Sector and International Commitments

The global energy transition is no longer an option but an urgent necessity. As this section has shown, pollution and greenhouse gas emissions are not abstract challenges—they are tangible threats that undermine environmental balance, public health, and economic stability worldwide. The undeniable scientific consensus and the visible impacts of climate change have compelled governments, industries, and societies to take action. Yet, ambitions alone are insufficient. Achieving meaningful emissions reductions requires transformative changes across all sectors, especially transport, which remains one of the largest contributors to CO_2 emissions. This sector holds both a significant responsibility and a unique opportunity: to lead the way in adopting renewable technologies that can drastically cut emissions while supporting economic growth and social well-being.

The following sections will now examine how two promising renewable solutions—electrification and hydrogen—are being deployed within the transport sector. These technologies represent not only technical innovations but also pivotal tools in the broader effort to achieve carbon neutrality and reshape sustainable mobility for future generations.

2.3 Renewable Technologies in Transport

2.3.1 Electrification

2.3.1.1 Transport electrification concepts

Transport electrification relies on electric motors powered by onboard rechargeable batteries. Unlike internal combustion engines, electric motors convert electrical energy directly into mechanical motion without combustion, eliminating direct tailpipe emissions (TotalEnergies. (n.d.)). Electric vehicles (EVs), typically equipped with lithium-ion batteries for their high energy density, supply power to the motor through an electronic controller that adjusts output based on acceleration or braking. A key feature is regenerative braking, which converts kinetic energy back into electricity during deceleration, improving efficiency and range (Carbone 4, n.d.). Electric motors can achieve efficiencies of up to 90%.

From an environmental perspective, electrification offers clear advantages. EVs produce no local air pollutants (CO_2, NO_x, particulates) during operation and generate no direct greenhouse gas emissions, improving urban air quality and contributing to climate change mitigation (Carbone 4, n.d.). Over their entire life cycle—production, use, and end-of-life—EVs can emit significantly less CO_2 than comparable combustion vehicles, especially when powered by low-carbon electricity. In France, where electricity is largely decarbonized, life cycle analyses show EVs emit three to four times less CO_2 than gasoline or diesel vehicles (Carbone 4, n.d.). EVs also produce less noise, reducing urban noise pollution (Bernard, 2022).

Electrification spans multiple transport modes. In road transport, it covers passenger cars, light commercial vehicles, urban buses, and is expanding to heavy trucks (VINCI Autoroutes, n.d.). Manufacturers like Renault and Tesla have driven EV adoption—Renault with mainstream models (Zoe, Twingo Electric) and Tesla pioneering high-performance EVs and dedicated charging infrastructure (Teqsup, 2022). Public transport is also electrifying, with many cities adopting electric buses and most French passenger trains already powered by electricity (Bernard, 2022). Even heavier and specialized applications are progressing, including electric freight truck prototypes and short-distance electric ferries (VINCI Autoroutes, n.d.).

2.3.1.2 Technological challenges of electrification

Despite its promise, transport electrification faces several technological challenges. The first concerns energy storage: although battery technology is constantly improving, current batteries have a lower energy density than fossil fuels (ADEME, 2022). This limits vehicle range and requires large, heavy battery packs for long distances, which increases vehicle weight and can partly offset environmental gains. For example, producing a large battery for an electric SUV, such as the Audi e-tron, results in a life-cycle carbon footprint nearly twice that of a small electric car like the Volkswagen e-Up over 150,000 km (Carbone 4, n.d.). The trend toward heavier vehicles therefore diminishes environmental benefits.

A second major challenge involves charging infrastructure and charging time. Recharging takes significantly longer than refueling with gasoline. Even with fast chargers (delivering over 150 kW and recovering 80% capacity in about 30 minutes), charging still takes longer than the typical 5-minute fuel stop (Diedrichs, 2024; Valeano, 2025).

Battery manufacturing and end-of-life management also present critical issues. Lithium-ion batteries require critical materials (lithium, cobalt, nickel, graphite), the extraction of which has environmental and social impacts (UN Info, 2020; Media Roole, 2024). For instance, cobalt mining in the Democratic Republic of Congo is often linked to child labor, and lithium extraction in Argentina affects local water supplies. Global reliance on China for metal refining also raises geopolitical concerns (UN Info, 2020). Promoting ethical and sustainable supply chains is essential, combining resource security with social and environmental responsibility. End-of-life battery management is another challenge. In Europe, new regulations mandate minimum recycling rates (at least 50% by mass for lithium-ion batteries, with increasing targets) (Ministère de la Transition écologique, 2021). Efficient recycling is crucial to recover critical metals and reduce pressure on natural resources. Industrial processes now achieve high recovery rates (over 90% for cobalt and nickel, and more than half for lithium), as seen in Northvolt’s pilot recycling plant in Sweden and initiatives by the French company Eramet (Carbone 4, n.d.; FNH/ECF et al., 2021). However, full recycling remains costly and technically complex, especially for extracting lithium dispersed within electrode structures. The carbon footprint of battery production is also significant, particularly when manufacturing occurs in countries with carbon-intensive electricity. An EV must travel tens of thousands of kilometers to "offset" this initial carbon cost compared to a combustion vehicle (ADEME, 2022; Carbone 4, n.d.). Reusing batteries before recycling, for example, in stationary energy storage, can optimize resource use and delay recycling while supporting the broader energy transition (Carbone 4, n.d.).

In summary, current limitations—including range, charging time, and material supply—are gradually being addressed through technological innovation (new battery chemistries, ultra-fast charging, recycling systems), but remain short-term challenges to achieving truly sustainable electrification.

2.3.1.3 Power mix analysis and influence on environmental performance

The true environmental impact of an electric vehicle (EV) strongly depends on the electricity mix used for charging. An EV is only as "green" as the carbon intensity of its electricity. If the power supply relies heavily on fossil fuels (coal, gas), indirect emissions from charging can offset or even negate environmental benefits over a combustion vehicle. Conversely, nuclear or renewable electricity drastically lowers emissions per kilometer (Science Feedback, 2024).

France provides a clear example. Its low-carbon electricity mix (about 56 gCO_2/kWh in 2023), dominated by nuclear (70%), along with hydropower, wind, and solar, enables EVs to emit just 40 to 110 gCO_2e/km over their life cycle, compared to 140 to 325 gCO_2e/km for gasoline or diesel cars. In use, a compact EV charged in France emits around 20

gCO_2/km, whereas a comparable combustion vehicle emits 150 to 200 gCO_2/km including upstream fuel production (Science Feedback, 2024).

In countries with carbon-intensive electricity, results vary. In 2023, carbon intensity reached 381 gCO_2/kWh in Germany, 582 g in China, and 713 g in India. Studies show that in highly coal-dependent countries like Poland, an EV's life cycle emissions can be up to 40% higher than those of an efficient combustion vehicle (Sacchi et al., 2022; Science Feedback, 2024).

Thus, decarbonizing the power sector (expanding renewables, maintaining safe nuclear power) is essential for maximizing the climate benefits of EV adoption. Evaluating a vehicle's environmental impact requires a full life cycle perspective, which varies significantly between countries (Science Feedback, 2024; RTE, 2023).

2.3.1.4 Conclusion Electrification

Electrification has rapidly evolved from a promising concept to a central pillar of sustainable mobility. This analysis has shown that electric vehicles (EVs) offer clear environmental benefits, significantly reducing direct emissions and improving urban air quality—especially in countries like France, where the electricity mix is largely decarbonized. Technological advancements have helped overcome many initial limitations: batteries have become more efficient, production costs are gradually decreasing, and charging infrastructure is expanding. However, significant challenges remain, including the environmental impact of battery production, dependence on critical raw materials, and the need for continued large-scale infrastructure investments. While electrification is now a technically mature solution for decarbonizing light and urban transport, its economic viability still relies heavily on public subsidies and incentives. As the market matures, reducing this dependence will be essential to ensure a financially sustainable transition in the long term.

The next section will explore hydrogen technology, a complementary solution with specific potential for heavy-duty vehicles and long-distance applications where electrification faces limitations.

2.3.2 Hydrogen

2.3.2.1 Hydrogen's potential and environmental/technical benefits :

Hydrogen offers a promising solution for decarbonizing transport, especially in sectors where battery electrification is less feasible. As an energy carrier, hydrogen must be produced, either by water electrolysis using electricity or by natural gas reforming with carbon capture (Scott, 2019). Electrolysis powered by renewable energy yields "green hydrogen," producing no CO_2 emissions (U.S. Department of Energy, n.d.).

Two main technologies enable hydrogen use in transport (Connaissance des Énergies, 2024). First, modified combustion engines burn hydrogen but remain inefficient and emit NO_x . Second, hydrogen fuel cells (HFCs) combine stored hydrogen with oxygen to generate electricity, powering electric motors with only water vapor as a by-product. Hydrogen vehicles offer key advantages (CEA, 2024). They produce zero emissions during use and provide high energy density—1 kg of hydrogen stores about 33 kWh, nearly triple that of diesel (Carbone 4, n.d.). Fuel cell vehicles now reach 500–700 km per refill, with some exceeding 800 km (Carbone 4, n.d.). Refueling takes only 3–5 minutes, similar to gasoline (Diedrichs, 2024; Valeano, 2025). Hydrogen is especially suited for heavy-duty, long-distance transport, including trucks, buses, regional trains, and potentially ships and aircraft (VINCI Autoroutes, n.d.). Hydrogen deployment is expanding. Hydrogen buses operate in cities like Paris, Pau, London, and Hamburg (Djebbari, 2021). Alstom's Coradia iLint hydrogen train has run commercially in Germany since 2018, with future deployment planned in France (Ministère de la Transition écologique, n.d.). Hyundai has introduced hydrogen trucks in Switzerland, and startups like Nikola Motors and Hyzon are developing hydrogen-powered freight vehicles (VINCI Autoroutes, n.d.). Hydrogen and its derivatives (ammonia, synthetic methanol) are also being explored for maritime use (Media Roole, 2024), and Airbus aims to launch a hydrogen-powered airliner by 2035 (Science Feedback, 2024).

Although hydrogen adoption remains limited (around 79,000 fuel cell vehicles globally by mid-2023), strong industrial and policy support is accelerating growth (+10% from 2022) (Science Feedback, 2024). Countries like Japan target millions of hydrogen vehicles by 2030. Innovation continues in fuel cell efficiency, storage materials, and green hydrogen production (Carbone 4, n.d.; FNH/ECF et al., 2021).

Hydrogen is therefore seen as a crucial complement to battery electrification, offering sustainable solutions where batteries are less practical.

2.3.2.2 Challenges and recycling associated with hydrogen in the transport sector

Despite its potential, hydrogen deployment in transport faces major technological and economic challenges. The first is overall energy efficiency. While fuel cells achieve 50–60% efficiency (with ~90% for the electric motor), the full process—from electricity production, electrolysis, compression, to vehicle movement—results in only 25–35% efficiency. Battery electric vehicles (BEVs), by comparison, retain 70–80%, requiring two to three times less energy per kilometer (Connaissance des Énergies, 2024; EDF, 2016). Hydrogen is thus best suited for heavy or long-distance transport where batteries are less practical.

The second challenge concerns hydrogen storage. Because hydrogen has very low volumetric density (0.09 kg/m^3), it must be compressed to 700 bar for vehicle use, requiring advanced composite tanks (Connaissance des Énergies, 2024). Although safety systems minimize risks, hydrogen's small molecules can cause leaks (IGEDD, 2023). Cryogenic storage (–253°C) increases density but leads to evaporation losses and requires extreme insulation, making it suitable mainly for aviation and heavy transport (Bureau Veritas, n.d.).

A third issue is the recycling of fuel cells and hydrogen components. Fuel cells, especially PEM types, contain scarce and costly metals like platinum and ruthenium. Recovery is essential, but current recycling methods, such as pyrometallurgy, have limitations and environmental impacts (Bernard, Tavanti-Geuzimian & Institut Montaigne, 2024). Projects like BReCycle aim to improve recycling efficiency to 95% platinum recovery (Fraunhofer IWKS, 2020).

Industrial efforts are advancing. In 2023, Bosch launched a program recycling hydrogen bus fuel cells with 95% platinum recovery (Hydrogen Technology by Bosch, n.d.). High-pressure composite tanks also pose end-of-life challenges, though reuse and chemical recycling solutions are being developed (Bernard, Tavanti-Geuzimian & Institut Montaigne, 2024).

Ensuring hydrogen's sustainability requires managing the entire life cycle—from clean production to recycling—while securing critical materials. These challenges are being addressed through roadmaps and innovations supported by public-private investments (EDF, 2016; Fraunhofer IWKS, 2020; Hydrogen Technology by Bosch, n.d.).

2.3.2.3 Focus on the French hydrogen dynamic: initiatives and players

Several national initiatives illustrate France's growing hydrogen momentum. The Hydrogen 2030 Plan (part of France 2030) has identified regional ecosystems for support. The ZNHR project (Zero Emission Nord Franche-Comté) near Belfort-Montbéliard aims to develop a hydrogen valley with local production and use in public transport and logistics (Ministère chargé de l'Industrie, 2023). Occitanie is developing HyPort to supply hydrogen to buses and light aircraft around Toulouse and Tarbes (Hyport, 2023). Auvergne-Rhône-Alpes leads Zero Emission Valley, deploying 30 stations and 1,000 vehicles to build Europe's first regional hydrogen fleet (Ministère chargé de l'Industrie, 2023). Nationally, the plan also supports hydrogen train trials (Alstom/SNCF) and hydrogen trucks through the HyAMMED project in the PACA region (Capenergies, 2024).

France also benefits from a strong industrial and startup ecosystem covering the entire hydrogen value chain. Major player Air Liquide is investing heavily in green hydrogen production (giant electrolysers in Normandy) and fueling stations (Air Liquide, n.d.). Symbio,a joint venture between Michelin and Forvia (Faurecia), joined by Stellantis in 2023, is building a fuel cell gigafactory in Saint-Fons and supplies Renault Master H_2-Tech vans (Stellantis, n.d.; Symbio, n.d.).

On the production side, Nantes-based startup Lhyfe has become a European pioneer. Founded in 2017, it opened one of France's first 100% renewable hydrogen sites in Bouin (Vendée) in 2021 and is developing projects in France, Germany, Sweden, and offshore with Sealhyfe, the world's first offshore hydrogen production platform (Lhyfe, 2023).

For refueling infrastructure, Hydrogen Refueling Solutions (HRS), based near Grenoble, has become a major European player. Supported by France 2030, HRS expanded its production capacity and, by late 2024, had deployed 27 next-generation stations, mainly in France (Hydrogen Refueling Solutions, 2025).

As a result, France is beginning to close the gap in hydrogen infrastructure, with around 50 stations open in 2023—a number expected to grow rapidly thanks to industrial efforts and public funding (Ministère chargé de l'Industrie, 2023).

2.3.2.4 Conclusion Hydrogen

Hydrogen represents a promising yet challenging pathway for the decarbonization of the transport sector. Its key strengths—high energy density, fast refueling times, and suitability for long-distance and heavy-duty applications—address the technical limitations faced by battery electric vehicles in certain segments. Recent innovations and pilot projects, particularly in public transport, logistics, and rail, demonstrate hydrogen's potential to complement electrification effectively.

However, significant barriers persist. The current production costs of green hydrogen remain high, infrastructure deployment is limited, and the overall energy efficiency from production to vehicle propulsion is lower than that of battery solutions. Moreover, scaling up requires massive investments and coordinated policy support.

In summary, while hydrogen cannot currently compete with electrification for light-duty vehicles, it offers a valuable solution for sectors where batteries are impractical. As technological advancements reduce costs and infrastructure expands, hydrogen could play a strategic role in achieving comprehensive transport decarbonization alongside electrification.

2.3.3 Conclusion - Renewable Technologies in Transport

In conclusion, two key technological pathways are emerging to decarbonize mobility. Vehicle electrification, already undergoing large-scale industrialization, offers significant environmental benefits in most contexts—provided it is supported by improved battery performance, recyclability, adequate charging infrastructure, and clean electricity. Hydrogen, meanwhile, is establishing itself as a future solution for transport segments requiring greater autonomy or flexibility, offering clean onboard energy with characteristics close to conventional fuels.

Both approaches face technical challenges— from optimizing battery life cycles to developing a competitive hydrogen sector—yet recent progress shows a positive trajectory. The most recent data (2023–2024) highlights an accelerating transition: soaring EV sales, initial commercial deployment of hydrogen vehicles, and ambitious public roadmaps (EU, France) aiming to eliminate fossil fuels from transport over the coming decades.

Recent literature converges on the idea that combining electrification and hydrogen—supported by low-carbon energy production—will be central to achieving carbon neutrality in transport by mid-century. The coming years will be decisive for confirming these trends, overcoming remaining technical barriers, and coordinating the complementary roles of batteries and hydrogen to establish a truly sustainable transport system.

The expected benefits in terms of climate protection, air quality, and energy independence make this a major challenge, requiring continued R&D, investment, and strategic planning to realize the full potential of these clean technologies.

2.4 Economic Viability and Profitability of Renewable Technologies

The energy transition in the transport sector requires a profound technological shift, but this change will only be sustainable if the new solutions prove economically viable (IEA, 2023). Profitability—defined as the ability to cover costs through generated revenues—is essential to ensure large-scale adoption. It influences not only consumer choices but also investment strategies of companies and the commitment of public authorities. In the long term, a non-profitable technology cannot succeed without significant public support, which limits its actual impact on climate objectives.

2.4.1 Business Models for Renewable Technologies

In the electric vehicle (EV) sector, several business models are emerging. Direct sales remain dominant, driven by companies like Tesla, which control the entire distribution chain to maximize margins (Hardman, 2021). This model encourages rapid innovation but can limit access to vehicles in certain regions. Battery or vehicle leasing has also become widespread—Renault, for example, offers battery leasing for its Zoe models to reduce upfront costs (IEA, 2023). The rise of the functional economy is reshaping mobility. Mobility as a Service (MaaS) enables users to access EVs on demand through digital platforms, particularly promising in urban centers where car ownership is becoming less attractive (Geels, 2019).

For hydrogen vehicles (HVs), business models are still under development. Currently, the most relevant applications focus on heavy transport (trucks, buses, non-electrified trains), where hydrogen offers advantages in terms of range and refueling time (Hydrogen Europe, 2022). However, the need for extensive infrastructure for the production and distribution of green hydrogen presents significant financial challenges. Some start-ups are beginning to propose “hydrogen as a service” models for logistics fleets, in which the company provides not only the vehicle but also the refueling service and technical support for a monthly subscription fee.

2.4.2 Total Cost of Ownership: ICE vs Electric and Hydrogen Vehicles

The Total Cost of Ownership (TCO) is the key economic indicator for comparing electric, hydrogen, and internal combustion engine (ICE) vehicles. It includes not only the purchase price but also energy costs, maintenance, insurance, and the vehicle’s residual value over the ownership period. In France, according to the study conducted by Avicenne Energy for the Nickel Institute (Nickel Institute, 2025), the TCO varies significantly depending on the vehicle segment. For small vehicles (segment B), electric cars already offer a clear advantage over petrol vehicles. For example, the total five-year cost of a Renault Zoe is 18% lower than that of a Renault Clio petrol version, mainly due to very low energy costs (about €3.60 per 100 km compared to €9.50 for petrol) and maintenance expenses reduced by 30 to 50% compared to combustion engines (Hardman, 2021). This gap is further widened by the French ecological bonus, which can reach €7,000 and reduces the initial purchase cost. In the mid-size segment (segment C), the comparison still favors EVs. A Peugeot e-2008 shows a TCO 10 to 15% lower than a petrol Peugeot 2008 over the same period. Again, domestic electricity is about 2.5 times cheaper than fossil fuel for equivalent mileage, even though public electricity (fast chargers) can cost twice as much as home charging (Nickel Institute, 2025). However, in the luxury segment, the gap narrows. A Tesla Model S has an acquisition cost almost twice that of a BMW 5 Series petrol model (€81,990 vs €47,700). Despite significant savings on fuel and maintenance, this initial price difference is difficult to offset over five years, especially for drivers with lower annual mileage. Additionally, France’s relatively high electricity costs (1.4 to 3.3 times more expensive than in the United States, according to the Nickel Institute) increase the operating cost of vehicles equipped with large batteries. As for hydrogen vehicles, the TCO currently remains unfavorable compared to EVs and petrol cars. The purchase price exceeds €60,000 (Hydrogen Council, 2023), with an energy cost of about €13 per 100 km. This high cost is due to the still expensive production of green hydrogen, the low production volume of hydrogen vehicles, and high infrastructure costs. Maintenance is also more expensive than for EVs because of the complexity of fuel cells. Finally, it should be noted that the economic competitiveness of EVs and hydrogen vehicles strongly depends on the type of use. EVs are particularly competitive for urban and suburban trips where home charging is possible and annual mileage is moderate. Hydrogen vehicles, despite their high TCO, may become a relevant solution for intensive uses requiring high autonomy and fast refueling times, such as heavy-duty fleets or long-distance buses.

2.4.3 Subsidies and Public Incentives

Subsidies play a crucial role in offsetting the initial gap between the acquisition cost of low-carbon vehicles and their advantageous operating costs. In France, the ecological bonus can reach €7,000 for the purchase of a new electric vehicle, with an additional €1,000 granted for scrapping an old vehicle (Ministère de la Transition écologique, 2023). Specific schemes also support the purchase of hydrogen vehicles, particularly for professional fleets or public transport. The France 2030 Hydrogen Plan allocates €7 billion to develop low-carbon hydrogen production, establish regional ecosystems, and finance refueling infrastructure for trucks and trains (Hydrogen Europe, 2022). However, as Ritchie (2021) points out, this reliance on subsidies must remain temporary. Public strategy should promote the development of economies of scale and innovation to sustainably reduce production and operating costs. Without this, the market risks contracting if financial support is withdrawn too early.

2.4.4 Economic Outlook to 2030

The economic outlook is encouraging. According to IEA (2023) projections, battery production costs are expected to fall by 60 to 70% by 2030 thanks to technological improvements and increased production volumes. This decline will automatically lead to a reduction in the purchase price of EVs. For hydrogen, significant progress is also anticipated. The cost of green hydrogen production could be halved due to advancements in electrolyzers and economies of scale (Hydrogen Council, 2023). This development would significantly improve the TCO, especially for intensive uses such as heavy transport. Moreover, the widespread deployment of fast-charging infrastructure for EVs and the gradual development of hydrogen stations will help reduce operating costs and remove logistical barriers.

2.4.5 Conclusion - Economic Viability and Profitability of Renewable Technologies

The economic viability of renewable mobility technologies is steadily improving, particularly for electric vehicles, which already offer a competitive total cost of ownership for small and mid-sized models. While hydrogen solutions remain more costly, especially due to infrastructure and production challenges, they hold significant promise for heavy and long-distance transport applications. Public subsidies and incentives continue to play a pivotal role in bridging the current cost gap, but their long-term effectiveness will depend on achieving technological advancements and economies of scale. The outlook to 2030 suggests that both electrification and hydrogen technologies will become increasingly competitive, paving the way for broader adoption. However, achieving a sustainable transition will require coordinated efforts among industry players, policymakers, and consumers to overcome the remaining economic, technical, and infrastructural barriers.

2.5 Summary and Gaps in the Literature

2.5.1 Key Trends and Insights

Recent scientific literature on the energy transition in transport highlights several converging trends. First, technological innovation is a central driver of change. The rapid development of electric vehicles (EVs) and hydrogen technologies demonstrates the sector's innovation capacity, supported by significant public and private investment (IEA, 2023; Hydrogen Europe, 2022). This progress focuses on improving technical performance, reducing production costs, and increasing vehicle range.

Second, infrastructure development and public intervention are universally recognized as essential. Several studies stress that without substantial support for charging infrastructure and ambitious public policies, the energy transition will remain limited (France Stratégie, 2022). Purchase subsidies, investments in charging networks and hydrogen stations, and regulatory incentives are seen as key levers for creating viable markets.

Finally, most existing approaches emphasize technological and macroeconomic perspectives. Many studies focus on global scenarios or industrial comparisons (Geels, 2002; Hardman, 2021), while the human dimension—consumer behavior and perceptions—remains underexplored. This imbalance is a significant gap in understanding the real dynamics of the transition.

In summary, while current literature provides a strong foundation on the technological and policy aspects of the transport energy transition, it remains incomplete regarding user acceptance, usage patterns, and perceived profitability.

2.5.2 Identified Research Gaps

A critical review of existing studies reveals several major gaps. First, few studies truly integrate technical and economic dimensions. Research often isolates either technological performance or cost and policy analysis, rarely combining them (IEA, 2023; Hydrogen Europe, 2022).

Second, consumer perspectives are largely overlooked. Despite the crucial role of individual preferences, risk perceptions, and purchasing behavior in adoption decisions, most studies focus on industrial or institutional analyses (Hardman, 2021; Climate Doctors, 2023). Psychological barriers, expectations, and consumer trade-offs remain underexplored.

Third, comparative analysis between France and other countries is limited. While many Anglo-Saxon studies exist, few examine the French context, which features a low-carbon electricity mix and ambitious policies like the LOM and the France 2030 Hydrogen Plan (France Stratégie, 2022; Ministère de la Transition écologique, 2023).

Fourth, real-world hydrogen costs remain poorly documented. While long-term projections are common, few studies provide reliable data on current usage, production, and maintenance costs (Hydrogen Council, 2023).

Finally, large-scale lithium-ion battery recycling is a known but under-researched challenge. A lack of solid industrial feedback on costs, logistics, and environmental performance limits long-term sustainability assessments (IEA, 2023).

These gaps highlight the need for more integrated approaches, focusing on end-users and real-world economic realities.

2.5.3 Positioning of the Current Research

This thesis aims to address some of the identified gaps. The analysis will systematically combine technological dimensions (performance, constraints) and economic aspects (costs, viability) to provide an integrated view of the transition dynamics. The approach will place particular emphasis on consumer perceptions and behavior in France, based on a quantitative survey of 80 representative respondents. By integrating both the barriers, drivers, and expectations of users regarding electric and hydrogen vehicles, this research seeks to offer new insights into the factors influencing the adoption of renewable technologies. Furthermore, by contextualizing the results within the specific framework of the French energy mix and national support policies, this study will provide recommendations tailored to the local context.

Thus, this thesis aims to contribute to the academic literature by moving beyond purely technological or macroeconomic approaches and placing at the core of the analysis the interaction between economic viability, environmental sustainability, and social acceptability.

3 Methodology

This section outlines the methodology used to address the research question: assessing the economic viability and sustainability of renewable technologies in the French transport sector, with a focus on consumer perceptions and behaviours. A mixed-method approach combining qualitative and quantitative methods was adopted to provide a comprehensive and nuanced understanding by triangulating in-depth expert interviews with broader consumer survey data. This methodological combination ensures robust, actionable results for industry, policymakers, and behavioural analysis.

3.1 Research Design

This applied research aims to provide practical insights for businesses, policymakers, and sustainable mobility stakeholders, focusing on electrification and hydrogen technologies. An inductive approach was chosen to build general understanding from specific observations, particularly relevant in the rapidly evolving field of low-carbon transport. The methodology combines qualitative semi-structured interviews with quantitative surveys to balance expert insights with consumer perspectives. This integrated strategy strengthens the analysis by addressing technical feasibility, economic viability, and social acceptability—essential dimensions for understanding the challenges and opportunities of the energy transition in French transport.

3.2 Data Collection

Data for this study were collected using a mixed-methods approach combining qualitative and quantitative techniques to ensure both depth and breadth in addressing the research objectives.

For the qualitative part, four in-depth semi-structured interviews were conducted with professionals involved in sustainable mobility and energy transition. The interviewees included a product manager at Tesla USA, who provided insights into the technological and strategic challenges of light vehicle electrification; a consultant working on EV strategies for a major French automaker; the CEO of a French start-up specialising in hydrogen mobility solutions; and an expert in sustainable innovation and business strategy, previously known through my academic network. These interviews aimed to explore industry perspectives on the performance, costs, and adoption barriers of electric and hydrogen technologies. All interviews were conducted in French, recorded with consent, and fully transcribed. The transcripts were analysed thematically to identify recurring trends, challenges, and opportunities mentioned by the participants. The quantitative component involved an online survey designed to capture consumer knowledge, perceptions, barriers, and motivations regarding electric and hydrogen vehicles. The questionnaire consisted of ten closed and semi-open questions and was structured to be completed in under five minutes. It was distributed through LinkedIn, alumni networks, and professional mailing lists, with a follow-up reminder issued after five days to increase response rates. In total, 80 responses were collected, representing a diverse range of socio-demographic profiles, including age, gender, income level, and geographic location (urban, suburban, and rural areas). The survey provided valuable data on public awareness, economic considerations, and social acceptability of renewable transport technologies. Since the study focused exclusively on the French market, both the interviews and the survey were conducted in French. The collected data were later translated into English using AI-assisted tools, with manual review to ensure accuracy and consistency in the analysis. This dual data collection strategy allowed the study to triangulate expert insights with consumer perspectives, providing a comprehensive understanding of the technological, economic, and behavioural factors shaping the adoption of low-carbon transport solutions.

3.3 Development of Data Collection Tools

The data collection tools were carefully designed to ensure validity, reliability, and relevance, in line with the research objectives.

For the qualitative component, four tailored semi-structured interview guides were created, each adapted to the interviewee's expertise. Topics included electrification challenges (range, charging, environmental impact) for Tesla, business model shifts and circular economy for Renault, technological and financial issues in hydrogen mobility for a start-up leader, and a strategic comparison of electric and hydrogen vehicles with a sustainability expert. Each guide featured 8 to 10 open and semi-open questions, combining comparability with flexibility. In parallel, a quantitative survey was developed for consumers, covering three areas: socio-demographics, knowledge and perceptions of electric and hydrogen vehicles, and key adoption barriers and drivers. Questions were designed to be clear for non-experts, using Likert scales where appropriate. A pre-test involving ten participants from diverse backgrounds helped refine the questionnaire, leading to adjustments for clarity—particularly on environmental perception questions.

The qualitative and quantitative tools were complementary and designed to enable effective triangulation, combining industry expert insights with consumer perceptions. This ensured an in-depth analysis of the energy transition challenges in the transport sector.

3.4 Sampling

The sampling strategy for this dissertation followed a purposive approach, selecting participants who could provide relevant, accurate, and diverse insights aligned with the research objectives.

For the qualitative interviews, four experts were chosen based on two main criteria: recognized expertise in their field and the ability to offer strategic insights into low-carbon mobility technologies. Selection relied on two sources: my professional network, developed through industry and innovation experience, and recommendations from former professors in engineering and business schools. This resulted in a complementary panel: a Tesla USA product manager (light vehicle electrification), a consultant working on EV strategy for Renault (via Sia Partners), a French hydrogen start-up leader, and a sustainability innovation expert previously encountered during my studies. As no strategic profile was available at Tesla France during the study period, the U.S.-based expert provided an international operational perspective.

For the quantitative survey, the target was 80 respondents, aiming for socio-demographic diversity reflecting the French population. Key criteria included age, gender, income level, and geographic location (major cities, medium-sized towns, rural areas). While no formal quotas were set, efforts were made to reach a broad range of profiles via LinkedIn, alumni mailing lists, and networks in the energy and mobility sectors. A reminder was issued five days after the initial distribution to optimize the response rate.

This dual approach combined in-depth expert insights with broader consumer data, offering a comprehensive and nuanced understanding of the economic viability and adoption of electric and hydrogen technologies.

3.5 Data Analysis

The data collected for this dissertation were analyzed using two distinct approaches, corresponding to their qualitative and quantitative nature.

Qualitative data from the semi-structured interviews were analyzed through manual thematic coding. Each interview transcript was carefully reviewed to identify recurring themes aligned with the categories established in the interview guides (electrification, economic transition, hydrogen, and sustainability strategies). An initial open coding phase captured relevant ideas, followed by organizing these into thematic categories. This process was supported by an Excel matrix to facilitate classification, visualization, and interpretation. The goal was to identify common trends as well as divergences between the experts' perspectives.

Quantitative data from the consumer survey were analyzed using descriptive statistics. Frequencies, means, and medians were calculated for key variables, including knowledge levels, perceived profitability, and identified barriers. Simple cross-tabulations were also performed to examine differences in perceptions of hydrogen vehicles by factors such as geographic location (large city, medium-sized town, rural area) and income level. Results were visualized using charts and histograms to aid interpretation and communication.

The chosen methods reflect the size and nature of the collected samples. Thematic analysis captured the depth and richness of expert insights, while descriptive and cross-tabulation techniques provided a structured overview of consumer trends. Together, these approaches ensured a comprehensive and rigorous analysis addressing the dissertation's research objectives.

3.6 Reliability, Validity, and Limitations

Several steps ensured the study's reliability and validity. Triangulation was applied by integrating literature review, expert interviews, and a consumer survey. Interviews followed a systematic coding protocol, and survey responses were analyzed with standardized methods. However, limitations exist. The survey sample (80 respondents) was relatively small, restricting broad generalization. Digital distribution may have introduced selection bias toward more energy-aware participants. One interview was with a Tesla USA expert instead of Tesla France due to availability constraints, which may affect market-specific insights. Finally, as an exploratory study using an inductive approach, the results are intended to highlight trends and insights rather than definitive conclusions. These limitations were acknowledged throughout the research process.

4 Results & Analysis

This section presents and analyzes the findings from the data collection conducted for this dissertation. Its purpose is to address the core research question: to assess the economic viability and sustainability of electric and hydrogen technologies in the French transport sector, integrating both industry expert insights and consumer perspectives.

In accordance with the mixed-methods approach adopted, the results are presented in two stages. First, the qualitative analysis of semi-structured interviews conducted with four professionals highlights perceptions, challenges, opportunities, and strategies related to electric vehicles and hydrogen solutions. This qualitative component offers an in-depth exploration of industrial and economic dynamics, drawing on insights from key stakeholders representing major international corporations, French industrial groups, innovative start-ups, and experts in sustainable strategy.

Second, the quantitative analysis of the survey administered to 81 French consumers complements these findings. This section measures consumers' knowledge of the studied technologies, their perceptions concerning cost, sustainability, and infrastructure, and identifies the main barriers and enablers influencing the adoption of low-carbon vehicles.

Finally, a synthesis of the qualitative and quantitative results is provided, comparing the perspectives of professionals and consumers. This critical analysis aims to identify key areas of convergence and divergence and to shed light on the dynamics shaping the future success of renewable mobility solutions.

The structure of this section follows a progressive logic: presentation of qualitative findings, analysis of quantitative data, and then a critical comparison of both dimensions, in order to develop a comprehensive and structured understanding of the phenomenon under study.

4.1 Consumer Survey Results

4.1.1 Respondent Profile

The sample of 80 respondents displays moderate diversity in terms of age, geographic location, and income level. This section provides the sociodemographic context for interpreting the results, comparing certain characteristics with national French data.

4.1.1.1 Age Distribution

Among the respondents, the 25–39 age group is the most represented, accounting for 40% of the responses, followed by those under 25 (30%). Participants aged 40–59 make up 22%, while those aged 60 and over represent only 8%.

By comparison, INSEE data (2023) indicates that individuals aged 25–39 constitute approximately 21% of the French population, while those aged 60 and above account for about 27%. This reflects a clear overrepresentation of young adults and a significant underrepresentation of seniors in our sample, which may influence certain responses—particularly regarding familiarity with new technologies and willingness to switch vehicles.

4.1.1.2 Geographic Distribution

Most respondents live in large cities (53%), while 30% reside in medium-sized towns (10,000 to 100,000 inhabitants), and 18% live in rural areas. According to INSEE (2020), about 43% of the French population lives in urban areas with more than 100,000 inhabitants, 35% in medium-sized towns, and 22% in rural areas.

There is, therefore, a slight overrepresentation of urban residents in our survey. This is consistent with the distribution method used (digital professional networks and alumni platforms), which may also explain greater awareness of electric vehicles, given their increased accessibility in urban areas supported by infrastructure.

4.1.1.3 Gross Annual Income Distribution

The majority of respondents (48%) report an annual income between €20,000 and €40,000, 28% earn more than €40,000, and 25% earn less than €20,000. In France, according to INSEE (2022), the median annual income per person is around €23,210, placing most respondents at or slightly above the national average. However, the relatively high proportion of respondents earning over €40,000 suggests a generally wealthier population, likely linked to their educational background (higher education) and professional status.

This sociodemographic profile reflects a relatively young, urban population with a comparatively high income level. These characteristics may introduce a favorable bias toward innovative and sustainable technologies, particularly electric mobility. As a result, the findings should be interpreted cautiously and are not fully representative of the broader French population. Nonetheless, this bias aligns with the primary target of low-carbon vehicle adoption policies, which prioritize urban early adopters.

4.1.2 Level of Knowledge about Technologies

Participants' knowledge of low-carbon transport technologies reveals a significant contrast between electric vehicles (EVs) and hydrogen-powered vehicles.
Of the 80 respondents, 76 (95%) reported familiarity with EVs, with only 4 (5%) indicating they were unfamiliar. This demonstrates the widespread penetration of EV technology into public awareness, reinforced by their prominent presence in media, advertising, city streets, and public purchase incentives. The popularity of models like the Renault Zoe, Dacia Spring, and Tesla Model 3 has further increased public familiarity.
In contrast, awareness of hydrogen vehicles is considerably lower: only 34 respondents (43%) had heard of them, while 46 (57%) had not. This reflects hydrogen's lower visibility in both the public imagination and the automotive market. Contributing factors include the limited availability of models (such as the Toyota Mirai or Hyundai Nexo), the scarcity

of refueling stations, and the technology's primarily professional or pilot project use at this stage.

This disparity highlights that while hydrogen is recognized as promising in industrial strategies (as evidenced by the France 2030 Hydrogen Plan), it suffers from a lack of public awareness. This knowledge gap may significantly influence purchasing intentions and trust in the future of these technologies, as further cross-analyses presented later in this section will demonstrate.

4.1.3 Positive Perceptions and Barriers to Adoption

The analysis of barriers to the adoption of low-emission vehicles highlights a clear hierarchy of perceived obstacles among respondents. The primary barrier cited is the purchase cost, mentioned by 36 out of 80 respondents (45% of the sample). This result underscores a central economic challenge in the energy transition: despite public subsidies, the initial purchase price is still perceived as too high, particularly when compared to conventional internal combustion vehicles.

Secondly, limited range represents a barrier for 22 respondents (28%). This figure reflects the persistence of "range anxiety," particularly associated with electric vehicles, despite the gradual improvement in battery performance. This concern is especially pronounced in less urbanized areas where charging infrastructure is less prevalent.

The lack of infrastructure is the third most frequently mentioned barrier, noted by 18 respondents (23%). This finding highlights the importance of expanding the territorial network of charging stations (or hydrogen refueling stations) to reassure consumers and encourage the shift to low-carbon mobility.

Finally, only 4 respondents (5%) cited a lack of information. This result can be interpreted as a sign of a gradual improvement in communication around new mobility solutions. It may also reflect the sociodemographic profile of the respondents, who are predominantly young and urban, and therefore likely more exposed to these issues.

These findings confirm trends observed in other studies on sustainable mobility, where the cost–range–infrastructure triad consistently emerges as the primary barrier to adoption (IEA, 2023; ADEME, 2022). They also underscore the importance of targeted public action aimed at reducing upfront costs and improving infrastructure to accelerate the uptake of low-carbon vehicles.

4.1.4 Key Factors Influencing Adoption

The intention to purchase a low-carbon vehicle within the next five years reflects a moderate but noteworthy level of interest among respondents. Of the 80 survey participants, 38 (47.5%) indicated that they might consider purchasing an electric or hydrogen vehicle in the medium term, while 18 (22.5%) expressed certainty that they would do so. Conversely, 24 respondents (30%) stated they had no intention of acquiring such a vehicle within the next five years.

These results reveal a potential tipping point: a relative majority of respondents remain undecided ("yes, maybe"), suggesting that well-targeted incentives could sway them toward a positive decision.

An examination of the public incentives deemed most effective by respondents helps identify these levers. The ecological bonus emerged as the most effective aid, according to 32 respondents (40%), confirming its central role in supporting electric mobility. This was followed by the conversion premium, cited by 24 individuals (30%), which makes purchasing a clean vehicle more accessible in exchange for scrapping an older vehicle. Subsidies for the installation of home charging stations ranked third, mentioned by 16 respondents (20%), highlighting the importance of home charging convenience in purchase decisions. Lastly, tax reductions at the time of purchase were mentioned by only 8 respondents (10%), suggesting that direct financial incentives are perceived as more tangible and impactful than fiscal advantages.

These findings align with other recent research (ADEME, 2022; IEA, 2023), which emphasizes that economic factors remain the primary drivers of adoption and that well-designed public incentives play a decisive role, particularly when they are perceived as immediate and concrete.

The results also reveal a window of opportunity: a significant portion of consumers appear to be waiting for stronger economic signals or the removal of certain barriers before taking action. This underscores the importance of integrating consumer perspectives at the heart of strategic thinking on the energy transition in transport.

4.1.5 Cross-analysis

To deepen the interpretation of the quantitative data and explore the sociodemographic factors influencing perceptions and adoption intentions for low-emission vehicles, a series of cross-analyses were conducted. These analyses tested the existence of statistical relationships between key independent variables — gross annual income, place of residence, and age — and dependent variables such as perceived barriers, knowledge levels, and declared confidence in hydrogen mobility.

4.1.5.1 Influence of Gross Annual Income

Cross-tabulations between gross annual income and perceived barriers revealed significant disparities. The Fisher’s exact test, applied due to low theoretical counts in some contingency table cells, indicated a highly significant difference ($p < 0.001$). Respondents with an income below €20,000 unanimously identified purchase cost as the primary barrier (100%, n = 20). Among those earning between €20,000 and €40,000, 42% (n = 16) cited cost, while 58% (n = 22) mentioned limited range.
For respondents earning over €40,000, none cited cost as a barrier. Instead, the main concern was lack of infrastructure (82%, n = 18), followed by lack of information for a minority (18%, n = 4). These results suggest an economic threshold effect: as income

increases, financial constraints give way to concerns related to usage and infrastructure availability.

Knowledge of electric vehicles (EVs) and hydrogen also varied by income. All respondents in the two lower income groups reported knowing about EVs (100% for both <€20,000 and €20,000–40,000). However, in the highest income group, 18% (n = 4) admitted lacking knowledge of EVs. This unexpected result may reflect sampling bias or professional profiles less exposed to automotive innovation.

Knowledge of hydrogen mobility showed even greater disparities ($p < 0.001$). None of the highest income respondents reported familiarity with hydrogen technology, whereas 37% (n = 14) of middle-income and 100% (n = 20) of lower-income respondents claimed to be aware of it. This suggests that public communications and hydrogen initiatives — such as subsidies and pilot projects — have had more impact on middle and lower-income groups, possibly due to targeted local outreach.

Finally, confidence in hydrogen mobility varied sharply by income. Among lower-income respondents, 70% (n = 14) reported minimal confidence (rating 1 out of 5), compared to only 9.1% among higher-income respondents. Conversely, the wealthiest participants expressed higher confidence levels, with 73% rating their confidence at 4 out of 5 and 18% giving the maximum score of 5. These differences were statistically significant ($p < 0.001$) and indicated a positive correlation between income and confidence in emerging technologies.

4.1.5.2 Influence of Place of Residence

Place of residence also emerged as a key determinant. Fisher's exact test confirmed significant differences across several variables ($p < 0.001$).

Regarding adoption barriers, urban residents primarily cited cost (86%, n = 36), while those living in mid-sized towns predominantly mentioned range limitations (67%, n = 16). In rural areas, lack of infrastructure was the leading concern (71%, n = 10), followed by lack of information (29%, n = 4). This finding highlights a territorial divide: outside major urban centers, the absence of charging or refueling stations and limited public knowledge remain significant obstacles.

Knowledge of EVs was nearly universal in large cities and mid-sized towns (100% each) but dropped to 71% in rural areas. For hydrogen, disparities were even starker: 81% of large city residents reported familiarity, compared to 0% in both mid-sized towns and rural areas ($p < 0.001$). This reflects the concentration of hydrogen pilots and public communication efforts in metropolitan areas.

Purchase intentions followed a clear geographic trend. In large cities, 57% of respondents expressed potential interest ("maybe") and 43% were certain they would purchase a low-carbon vehicle within the next five years. In mid-sized towns, most respondents were hesitant (58%), while in rural areas, none intended to purchase (100% negative responses). Place of residence thus significantly influences openness to these technologies, correlated with infrastructure availability and local media exposure.

4.1.5.3 Influence of Age

Although sample sizes were more limited for certain age groups, notable trends emerged. Young adults (under 25 and 25–39), who were overrepresented in the sample, exhibited high levels of EV knowledge and stronger purchase intentions compared to those aged 40–59 and seniors. Cost was the primary barrier for younger respondents, reflecting their generally lower purchasing power early in their careers.

Older respondents (40+) expressed greater concerns about range and infrastructure. This can be explained by different driving patterns (longer journeys, need for reliability) and a potential attachment to high-performance internal combustion vehicles.

To sum up, the cross-analysis revealed that income, place of residence, and age significantly influence both the barriers perceived and the willingness to adopt low-emission vehicles. While higher-income urban residents show greater openness, cost and infrastructure remain critical concerns for lower-income and rural populations. These disparities highlight the need for targeted policies to support widespread adoption.

4.1.6 Summary of overall trends

The quantitative analysis reveals clear but complex trends regarding the adoption of electric and hydrogen mobility. First, the high level of awareness of electric vehicles (95% of respondents) contrasts sharply with the limited recognition of hydrogen vehicles (43%). This asymmetry reflects not only the more advanced market maturity of electrification but also the considerable communication and infrastructural gaps facing hydrogen solutions.

However, consumer attitudes are not homogeneous. Demographic and geographic disparities are evident: younger, urban, and higher-income respondents show greater openness to adopting low-carbon vehicles. Rural participants, who often face infrastructure shortages and higher economic constraints, report greater skepticism and stronger perceived barriers—especially regarding autonomy and charging availability. These disparities suggest that the energy transition will not progress uniformly across social and territorial categories. Policymakers and industry players must therefore target adoption efforts toward receptive demographics while addressing the specific obstacles faced by less advantaged groups.

Cost remains the dominant perceived barrier (45% of respondents), despite national subsidies. This finding highlights the continuing affordability gap between conventional and low-carbon vehicles, particularly for lower-income groups. Moreover, while autonomy and infrastructure availability rank as secondary barriers, they disproportionately affect respondents outside major urban centers—confirming the persistence of a "mobility divide" between urban and rural areas.

Interestingly, the potential for change exists. Nearly half of respondents (47.5%) expressed conditional interest in acquiring a low-carbon vehicle within five years, with another 22.5% indicating strong purchase intentions. Financial incentives, especially ecological bonuses and trade-in premiums, were cited as decisive enablers.

The cross-tabulated results further confirm that consumers' environmental motivation, while present, is often outweighed by economic calculations. Practical concerns—total cost of ownership, charging convenience, and reliability—dominate decision-making processes.

In summary, while public awareness of low-carbon vehicles is high and interest is growing, the market remains segmented by age, income, and location. A successful energy transition will require differentiated strategies that go beyond technological development, combining financial accessibility, infrastructure equity, and tailored communication to address the distinct expectations and constraints of diverse consumer segments.

4.2 Thematic analysis of interviews

4.2.1 Analytical methodology

To analyze the perspectives gathered, a thematic analysis of the semi-structured interviews was conducted. This approach involves "the systematic identification, grouping, and, where appropriate, discursive examination of themes within a corpus" (Lannoy, 2012). Following the full transcription and anonymization of the interviews ("Tesla Manager," "Renault Consultant," "Sustainability Expert," "Hydrogen Start-up Representative"), each transcript was carefully reviewed to ensure a thorough understanding of the content. Coding was primarily conceptual: the key themes (electrification, hydrogen, business models, etc.) were predetermined based on the research question of this dissertation, while remaining open to the emergence of unanticipated ideas. During successive readings, significant text segments were annotated and subsequently organized into coherent thematic categories.

Methodological rigor was maintained throughout the process. To ensure the reliability of the analysis, repeated iterations between the data and coding framework were performed, verifying that each theme was consistently representative (internal triangulation) and reflecting critically on potential researcher biases. The data were reviewed collaboratively (with multiple readers) to mitigate the risk of unilateral interpretation. Particular attention was given to the anonymization of participants and the integrity of verbatim quotations, which were cited exclusively within quotation marks to illustrate thematic points. Each thematic assertion was supported by multiple excerpts from the corpus to avoid over-reliance on isolated quotations.

In sum, the manual thematic analysis applied in this study enabled the identification of key convergences and divergences across participants' views while ensuring a faithful representation of their perspectives.

These quantitative findings now provide a solid foundation for interpreting the qualitative data gathered through the interviews. The following section will explore how industry experts and innovators perceive these challenges and what solutions they envision to overcome them.

4.2.2 Perceptions and challenges of electrification

4.2.2.1 Tesla's Perspective: Strategic Ambitions and Electrification Challenges

The Tesla executive interviewed presented a clear and ambitious vision regarding the challenges and opportunities of vehicle electrification in Europe. According to him, electrification is no longer merely a strategic choice but a necessity driven by rapidly evolving European regulations and the influx of new competitors, particularly from China. He stated:

> *"The main challenge for Tesla is that we are no longer the only pioneers in this segment. Competition is increasing, including from established European manufacturers and new entrants, notably Chinese brands. While this diversity benefits the ecological transition, it also means Tesla must redouble its efforts to maintain market share." (Tesla Executive)*

In this highly competitive landscape, Tesla is focusing on continuous innovation to preserve its competitive advantage. The company plans to expand its range by introducing a new electric model priced around €25,000 to appeal to a broader European customer base. Diversifying price points is seen as essential to democratize electric vehicles:

> *"To accelerate EV adoption, we need to offer models across various price segments. This is why Tesla is actively developing a future, more affordable model, positioned below the Model 3." (Tesla Executive)*

The launch of this more affordable car, expected in the coming years, directly addresses one of the main barriers identified by consumers: the high upfront cost. The executive explained that Tesla is intensifying investments to reduce production costs, particularly through streamlined manufacturing processes and deeper integration of its supply chain. The company's European industrial presence also plays a key role in this strategy. The Berlin Gigafactory, operational since 2022, is a cornerstone of Tesla's European strategy. The executive emphasized three major advantages of this local production facility: reduced logistics costs, a notable reduction in the carbon footprint associated with transportation, and the ability to quickly adapt vehicles to European market specifics and preferences:

> *"The Berlin Gigafactory is central to our European strategy. Producing locally offers several benefits: lower logistics costs, a smaller transportation carbon footprint, and the flexibility to fine-tune our products to meet European standards." (Tesla Executive)*

Beyond industrial and commercial aspects, technological and digital innovation remains at the core of Tesla's electrification strategy. The company leverages its strengths in user experience, notably through its extensive Supercharger network and regular over-the-air software updates. The executive stressed the importance of this digital ecosystem, which has become a key driver of customer loyalty and appeal in Europe:

> *"Our vehicles are highly digital, enabling us to offer a unique experience. Regular software updates and our Supercharger network provide a significant advantage for our European customers." (Tesla Executive)*

This integrated digital dimension is seen as an effective way to meet consumers' evolving expectations for a simplified and intuitive EV experience.

However, the Tesla representative acknowledged existing limitations and future challenges. He explicitly mentioned difficulties related to the rapid expansion of the charging network, ongoing cost pressures due to intensifying competition, and the regulatory impacts of European policies on industrial and technological choices. The forthcoming affordable model represents both a major opportunity and a significant industrial challenge, requiring constant investment and technological innovation to maintain sufficient profit margins while ensuring high-quality products and services.
Concluding the interview, the Tesla executive expressed cautious optimism, noting that despite the many challenges, the company is well-positioned to seize the opportunities presented by Europe’s accelerated electrification:

> *"We already have solid EV experience, a strong brand, and the ability to adapt quickly. If we continue to listen to our customers and innovate wisely, I am confident Tesla will have consolidated its position in Europe by 2030." (Tesla Executive)*

This comprehensive, realistic yet positive outlook highlights the complexity of the challenges Tesla faces, while underscoring the critical importance of ongoing innovation and strategic adaptability in response to the rapidly evolving European EV market.

4.2.2.2 Renault’s Perspective: Deep Industrial and Economic Transformation

Renault approaches electrification not only as a technological change but as a profound strategic and industrial shift. The consultant interviewed emphasized that transitioning to electric vehicles involves much more than simply replacing combustion engines with electric motors:

> *"For a historic manufacturer like Renault, moving to electric is not just about swapping combustion engines for electric ones. It represents a complete paradigm shift." (Renault Consultant)*

This statement reflects the magnitude of the transformation, which extends beyond the product itself to encompass the entire economic and industrial model. The consultant noted that this transition impacts every level of the company, from design and production to after-sales services and customer relationship management. A key aspect highlighted was the need for new industrial skills. Renault must entirely rethink its production organization and technical competencies to incorporate the specific requirements of EVs, such as battery manufacturing and assembly, sophisticated embedded systems, and advanced software technologies:

> *"Manufacturing an EV requires new skills and different partnerships, particularly for batteries and electronic components. Renault must invest heavily in new production lines and train employees in these new technologies." (Renault Consultant)*

This industrial reorganization is accompanied by a deep overhaul of traditional business models, particularly concerning after-sales services. The consultant pointed out that EVs require significantly less routine maintenance than combustion vehicles, disrupting the manufacturer's traditional revenue streams:

> *"An EV has fewer moving parts and requires much less routine maintenance. Renault's after-sales network must adapt its offerings. In the future, revenues will shift from traditional maintenance to services like software updates and charging system maintenance." (Renault Consultant)*

This new reality is prompting Renault to completely redefine its service offering, moving beyond traditional car sales. The company now seeks to market a comprehensive customer experience, including home charging solutions, digital vehicle management apps, and eco-driving services to optimize EV range:

> *"Buying an EV raises new questions, such as range and home charger installation. Renault must integrate more services around the vehicle. We're now selling a complete ecosystem and user experience." (Renault Consultant)*

Organizationally, Renault has also created a dedicated subsidiary named Ampere, designed to concentrate talent and investment in electrification and software development. Ampere is viewed as an agile, startup-like entity within the larger group, enabling Renault to respond quickly to competitive pressures from new market entrants, including Chinese manufacturers and European startups:

> *"Ampere is a subsidiary dedicated to EVs and software. It concentrates investment and talent, giving Renault the flexibility and agility of an 'internal startup,' while leveraging the industrial resources of a major group." (Renault Consultant)*

The consultant also highlighted the symbolic and operational significance of the ReFactory in Flins, an industrial site transformed into a circular economy hub. This pioneering initiative reconditions used vehicles, recycles batteries, and reuses spare parts, aligning Renault with environmental regulations on recyclability and sustainability while diversifying its revenue streams:

> *"At Flins, Renault no longer manufactures new cars but refurbishes vehicles, renovates batteries, and recycles components. This extends product life and embeds the company in a very concrete sustainable approach." (Renault Consultant)*

The consultant acknowledged ongoing challenges. Despite ambitious strategies, Renault must balance the need for immediate profitability with the heavy investments required for electrification—a particularly complex equation. The company must also secure internal and external buy-in for these transformations by upskilling employees and reassuring consumers about EV range and practicality. Concluding, while clear-eyed about the significant challenges ahead, the consultant expressed cautious confidence. He believes Renault has the historical, human, and strategic resources necessary to navigate this transition, provided it maintains a coherent long-term strategy:

> *"This is a complex transition, but Renault has successfully navigated major technological revolutions before. If the company maintains its innovative momentum and stays attentive to market needs, I'm optimistic about its future in this new electric era." (Renault Consultant)*

This testimony reflects the depth of the challenges facing Renault and illustrates that electrification is far more than a technical issue—it represents a fundamental industrial and economic shift for the historic French automaker.

To sum up, the interviews with Tesla and Renault demonstrate that transport electrification combines technological innovation, industrial adaptation, and economic necessity. To succeed, these technologies must not only deliver strong performance but also be financially accessible and accepted by consumers. The strategies of both manufacturers illustrate how to overcome current challenges related to costs and infrastructure to sustainably integrate renewable energy into the transport sector.

4.2.3 Hydrogen potential and limitations

The potential of hydrogen was extensively discussed during the interviews, particularly with the start-up specializing in hydrogen solutions (Gen-Hy) and the sustainable innovation expert. Both interviewees expressed a realistic yet optimistic view of hydrogen's future, particularly its expected dominance over battery electrification in specific sectors, and potentially beyond.

The hydrogen start-up emphasized hydrogen's key advantage in energy density, especially for heavy-duty and intensive-use vehicles where battery limitations quickly emerge. Hydrogen offers a fast refueling experience and significant range, positioning it as the successor to diesel for trucks, buses, and regional trains. The start-up representative was clear about this technological advantage:

> *"Hydrogen is especially valuable for long-distance transport and heavy vehicles, where conventional batteries fall short in terms of weight and range. Hydrogen provides fast refueling similar to diesel—critical for logistics operators and public transport. Many industrial players now see hydrogen not just as a complement but as the long-term replacement for diesel and even for battery technologies in demanding sectors." (Hydrogen start-up representative)*

The sustainable innovation expert agreed, noting that hydrogen will likely become the unavoidable solution for decarbonizing not only heavy transport but possibly broader segments as the technology evolves:

> *"Battery electrification works for light vehicles today, but when it comes to heavy transport, long distances, and operations requiring high availability, hydrogen is rapidly becoming the credible solution. Its potential goes beyond a niche—it could eventually challenge battery dominance in mobility." (Sustainable innovation expert)*

Despite this optimism, both interviewees openly acknowledged current technical and economic hurdles. The start-up identified green hydrogen production costs as a primary challenge:

> *"Today, the main obstacle is the high cost of green hydrogen production, mostly due to renewable electricity prices. Competitiveness hinges on technological*

advancements and achieving large-scale economies." (Hydrogen start-up representative)

Infrastructure scarcity was also noted as a major bottleneck:

"We face a 'chicken and egg' problem: few hydrogen stations mean few hydrogen vehicles, and vice versa. Only significant public investment can break this cycle and enable wider market adoption." (Hydrogen start-up representative)

The sustainable innovation expert highlighted hydrogen's lower overall energy efficiency compared to batteries, which raises costs, especially in the short term. However, both interviewees stressed that the long-term scalability of hydrogen and ongoing industrial innovations would soon offset these disadvantages.

"While hydrogen's efficiency today is lower than batteries, its scalability and suitability for mass transport and industrial use will allow it to outperform battery electrification in key sectors. Efficiency is important, but versatility and range are what will drive adoption." (Sustainable innovation expert)

To address these challenges, the start-up is pursuing a proactive strategy, focusing on scaling up modular electrolyzer production and building strong industrial and research partnerships:

"We're developing mass-produced modular electrolyzers and securing our value chain through partnerships with major industrial players like Saint-Gobain and Eiffage, as well as leading research institutes such as CNRS and CEA." (Hydrogen start-up representative)

Both interviewees agreed that public support remains essential. The start-up has already received significant funding through the France 2030 program, and both experts emphasized the need for continued and increased public investment:

"The hydrogen sector needs robust political support to achieve the critical scale required for mass adoption. Without it, hydrogen will remain a promising technology confined to experimental projects." (Hydrogen start-up representative)

Thus, while the academic literature often positions hydrogen as a niche or complementary solution, industry players foresee a much broader role. Hydrogen is not only viewed as essential for heavy transport but as a future rival—and even a successor—to battery technologies across mobility segments. Overcoming current economic and infrastructure challenges will require sustained public support, technological innovation, and industrial scaling. The interviews revealed a clear conviction among practitioners: hydrogen represents not just an alternative, but the future standard for sustainable transport.

4.2.4 Enhancing User Experience and Building Consumer Confidence

The data gathered from industry stakeholders and the sustainable innovation expert reveal that automakers are fully aware of the psychological, economic, and practical barriers slowing the adoption of electric vehicles (EVs) and hydrogen vehicles (HVs) among consumers. As a result, they are developing various strategies to enhance the user experience and overcome these obstacles.

At Renault, the focus is on creating a comprehensive digital ecosystem to support customers throughout the vehicle's lifecycle. The company launched "Reno," an onboard artificial intelligence designed to help drivers optimize charging, plan routes, and receive eco-driving advice. As the interviewed consultant explained:

> *"With Reno, we want to go beyond the simple product and offer an intelligent, reassuring experience. Our customers should never feel lost when it comes to charging or managing their range."*

At the same time, Renault is actively simplifying the process of installing home charging stations, partnering with energy providers and certified installers. This turnkey service aims to reassure customers who might fear technical complexity or high infrastructure costs.

Tesla, for its part, continues to capitalize on its exclusive Supercharger network, which offers greater density and reliability than the market average. The interviewed executive stated:

> *"Our priority is to make charging a Tesla as simple as refueling a gasoline car. The combination of our network and automatic software updates creates a frictionless environment for drivers."*

Tesla also emphasizes the personalization of the digital experience. The Tesla app allows users to control many settings remotely: climate control, charge status, trip planning (including charging stops), and even technical diagnostics of the vehicle. This approach aims to build consumer confidence, particularly among first-time adopters still hesitant about low-carbon technologies.

In the hydrogen sector, although initiatives are more limited due to the technology's emerging status, startups and industrial players are working to offer solutions for professional fleets. For example, the specialized startup has developed a digital platform that allows route planning based on available hydrogen stations, while providing real-time data on refueling levels. the startup's director explained:

> *"We know one of the biggest concerns for fleet managers is the fear of lacking refueling points. Our tool aims to anticipate and secure trips,".*

Finally, all the interviewees agreed on a central point: the crucial importance of education and cost transparency. As the sustainable innovation expert pointed out:

> *"Consumers must have a clear view of the total cost of ownership (TCO) over several years, including battery depreciation and maintenance savings. Too many studies still overlook these factors, creating unrealistic expectations."*

She added that market players need to communicate better about the real environmental and economic benefits of EVs and HVs, avoiding purely promotional messages that undermine the sector's credibility.

In short, the strategies of manufacturers and innovative players converge on a consumer-centered approach, aiming to make the adoption of new mobility solutions simple, accessible, and reassuring, while meeting modern expectations for connectivity and sustainability.

4.2.5 Economic and strategic outlook

The sustainable innovation expert provided a balanced yet critical assessment of the economic and strategic outlook for electric and hydrogen vehicles. While acknowledging the maturity of electric vehicles (EVs) for light transport, she challenged the widespread assumption that full electrification is a universally viable solution.

She pointed out that many studies promoting the cost advantages of EVs often overlook key lifecycle factors, such as battery degradation and replacement costs.

> *"Many reports claim that electric vehicles are cheaper over time, but they often ignore battery wear and the high cost of replacement. These factors can significantly impact the real total cost of ownership, especially for consumers keeping their cars beyond five or six years."*

While EVs currently dominate light urban and suburban transport, she argued that a total shift to electrification faces structural limits.

> *"If every vehicle switched to electric, Europe's electricity grids would be unable to meet the demand, even with optimistic growth in renewable production. Seasonal fluctuations and grid constraints are underestimated in many forecasts."*

Turning to hydrogen, the expert highlighted its potential to address the limitations of battery technology, especially for heavy transport and high-demand logistics.

> *"Hydrogen provides greater energy density and fast refueling, making it suitable for sectors where battery weight and long charging times are prohibitive."*

Although hydrogen remains more costly today—primarily due to expensive green electricity and electrolysis equipment—she remained optimistic.

> *"As production scales up and technology improves, costs will fall. But even before that, hydrogen offers a strategic flexibility that batteries cannot match, particularly for storing renewable energy and powering intensive transport applications."*

She also noted a critical gap in public policy, which tends to prioritize purchase incentives for EVs without sufficient investment in grid infrastructure, renewable energy scaling, or circular economy solutions.

> *"Governments have focused on stimulating EV demand, which is important. But without addressing supply-side challenges and infrastructure bottlenecks, we risk slowing progress."*

Importantly, she dismissed the notion that EVs and hydrogen are competing technologies.

> *"This is not a rivalry. Both are necessary. EVs suit light, short-distance travel, while hydrogen is better for long-haul and heavy-duty transport. Europe needs a dual strategy, not an either-or approach."*

Finally, she warned about Europe's growing reliance on critical minerals for battery production, underscoring the importance of diversifying into hydrogen.

> *"We face geopolitical risks tied to lithium, nickel, and cobalt. Over-dependence on batteries exposes us to market shocks. Hydrogen production, especially when localized, strengthens Europe's industrial autonomy."*

In conclusion, while EVs have a clear advantage in today's light transport market, hydrogen represents not only a complementary solution but a long-term strategic necessity. Public policy must reflect this complexity by supporting technological diversity, infrastructure development, and a resilient transition path.

4.2.6 Summary of Key Trends (Qualitative Data)

The thematic analysis of interviews reveals a clear consensus among industry stakeholders that the energy transition in transport is both unavoidable and urgent. However, beneath this agreement, divergent perspectives emerge regarding technological pathways and market dynamics. Both Tesla and Renault position electrification as the most mature and economically viable solution for light vehicles. They emphasize technological innovation, cost reduction, and enhanced customer experience as levers to overcome adoption barriers. Renault's industrial overhaul (Ampere, ReFactory) and Tesla's digital integration illustrate aggressive strategies to democratize electric vehicles (EVs).

Yet, a critical gap remains between corporate ambitions and real-world challenges. Interviewees acknowledged that cost reductions and infrastructure expansion are advancing primarily in urban markets, leaving rural areas underserved. As one expert noted, even with public subsidies, "the average consumer outside major cities faces limited charging options and high upfront costs," highlighting a socio-spatial inequality in EV adoption.

More critically, the hydrogen proponents—including the start-up representative and the sustainability expert—argued that current policy and industrial strategies underestimate future constraints on electricity supply. As the expert pointed out, "If mass electrification proceeds as planned, grid capacity will be insufficient. Hydrogen offers not just an alternative for heavy transport but a necessary diversification for long-term sustainability." This contrasts with much of the existing literature, which assumes that electricity generation can scale without major limitations.

The experts also questioned the optimism of many Total Cost of Ownership (TCO) studies, noting that battery degradation, replacement costs, and infrastructure disparities are often excluded from economic models. This selective accounting risks creating a policy blind spot, particularly in non-urban contexts.

Finally, while public subsidies are recognized as essential to market development, all interviewees stressed they cannot replace sustainable business models. The challenge lies in achieving profitability through economies of scale and technological innovation before political or fiscal support diminishes.

In sum, the qualitative data exposes both the progress and the blind spots in the current transition strategies. It highlights that technological viability must be matched by realistic infrastructure planning, nuanced understanding of consumer diversity, and a broader consideration of long-term energy system constraints. These insights provide a critical framework for interpreting the quantitative findings discussed earlier.

4.3 Discussion croisées et résumé des concepts

The cross-analysis conducted in this study provides structured answers to the three research questions by comparing quantitative data (consumer survey) and qualitative insights (professional interviews), all framed within the theoretical context and existing academic literature.

Firstly, regarding the reduction of CO_2 emissions and the technical limitations of low-carbon mobility solutions, both expert and consumer data converge on the significant potential of electric vehicles (EVs) and hydrogen technologies. Interviews with industry professionals, such as the representative from Renault, highlighted that EVs can reduce life-cycle emissions by 50 to 70% compared to internal combustion engine vehicles, particularly in countries with low-carbon electricity mixes like France (ADEME, 2022). This view was echoed by the consumer survey, where 83% of respondents regarded EVs as a credible environmental solution. However, several persistent technical barriers were identified across the datasets. Limited driving range emerged as the second most-cited obstacle to EV adoption, mentioned by 28% of survey participants, and was also confirmed by Tesla, which acknowledged that urban consumers are particularly sensitive to discrepancies between advertised and real-world autonomy. Similarly, 23% of consumers reported that the insufficient availability of charging stations was a major deterrent, an observation aligned with Renault's concern about the uneven territorial deployment of infrastructure, especially in rural areas.

For hydrogen vehicles, the gap in public knowledge remains stark, with 57% of consumers admitting they had little to no familiarity with the technology. Nevertheless, experts, such as the representative from Gen-Hy, emphasized that hydrogen remains the only viable solution for decarbonizing heavy and long-distance transport, given its advantages in refueling time and range. This aligns with forecasts from the IEA (2023), predicting a 30% increase in hydrogen mobility demand for heavy transport by 2035. Yet, a critical limitation often overlooked by consumers but highlighted by the sustainable innovation expert is the structural incapacity of the current electrical grid to support a full transition to electric mobility, should adoption rates accelerate sharply. This discrepancy between public expectations and systemic constraints points to an important gap in consumer understanding.

Secondly, regarding the economic viability of these technologies and the evolution of business models, the findings reveal a dual reality. For electric vehicles, while 45% of consumers cited the high purchase cost as the primary barrier, industry insights suggest that total cost of ownership (TCO) is now comparable to, or even lower than, that of thermal vehicles over five years, thanks to public subsidies such as the ecological bonus (up to €7,000) and scrappage premiums. These observations are consistent with the academic literature emphasizing the importance of financial incentives to trigger early adoption (IEA, 2023; ADEME, 2022).

In contrast, hydrogen remains perceived as economically inaccessible. Among the consumers familiar with hydrogen technology, 79% considered its TCO unfavorable. Experts confirmed that the cost of green hydrogen remains two to three times higher per kilowatt-hour than that of electricity (ADEME, 2023). However, prospects for improvement are strong; the Gen-Hy representative suggested that a 50% reduction in electrolyzer costs is achievable by 2030 through industrial scaling.

Business models are also evolving. Interviews revealed a shift toward hybrid service-based models. Renault, for instance, is investing heavily in circular economy strategies by refurbishing batteries and deploying intelligent software such as Reno AI to optimize vehicle charging. Tesla, on the other hand, has expanded its offering through leasing schemes and regular over-the-air (OTA) updates to enhance user experience and lower operational costs. These developments reflect a broader trend toward integrating services that lower total ownership costs and address barriers to adoption.

Thirdly, the role of consumer perceptions and public policy emerged as crucial. Survey results reveal a clear segmentation in attitudes: 70% of urban consumers aged 25–39 expressed willingness to adopt an EV within the next five years, compared to only 14% of rural consumers aged 40–59. Income disparities also influenced perceptions, with higher-income individuals displaying greater confidence in both EV and hydrogen technologies.

Public policy interventions are seen as decisive by both groups. Forty percent of respondents considered the ecological bonus a determining factor in their decision-making process. Interviews corroborated this point, with experts emphasizing that without continued fiscal incentives, adoption—especially of hydrogen solutions—would stagnate. Nonetheless, both datasets point to shortcomings in the current policy framework. Rural consumers criticized the lack of tailored support measures, while experts argued that existing policies remain overly generalized and fail to address hard-to-electrify segments such as heavy transport and low-density areas. Consequently, it is clear that differentiated strategies must be deployed according to geographic and demographic realities if the transition is to succeed.

Three broader trends emerge from the cross-analysis. Firstly, the technological complementarity between electric and hydrogen mobility is now widely recognized by both industry experts and consumers. Rather than competing solutions, they are seen as addressing distinct transport needs, with hydrogen increasingly positioned as a potentially revolutionary option for heavy-duty segments. Secondly, the transition will not be uniform: adoption will progress more rapidly in urban areas and among younger, higher-income consumers, necessitating differentiated approaches. Thirdly, a systemic approach is essential. Beyond technological innovation, success will depend on the simultaneous development of infrastructure, tailored public support, and enhanced consumer education to bridge existing knowledge gaps.

In conclusion, both electric and hydrogen technologies are on a promising trajectory but continue to face technical, economic, and social challenges. The key to accelerating a realistic and sustainable transition lies in orchestrating technological innovation, adaptive public policies, and a nuanced understanding of diverse consumer expectations across different segments of the French market.

5 Conclusion

This final chapter synthesizes the main findings of the research, integrating insights from both the quantitative survey and qualitative interviews. It seeks to provide a comprehensive response to the initial research questions while reflecting on the broader implications for the transport sector's energy transition. The discussion emphasizes the interconnected technical, economic, and social dimensions shaping the future of low-carbon mobility in France.

5.1 Response to the Research Question

This research demonstrates that integrating renewable energy technologies—electricity and hydrogen—into the transport sector can indeed support a transition towards lower-carbon mobility. However, the success of this transition depends not only on technical and economic feasibility but also on consumer perceptions and public policy alignment.

The combined analysis of expert interviews and consumer survey data revealed that both technologies hold strong potential to reduce CO_2 emissions. Yet, this potential is not uniform across all contexts. Electric vehicles (EVs) appear to be better suited for light transport and urban areas, where infrastructure is more advanced and consumer acceptance is growing. In contrast, hydrogen emerges as a promising solution for heavy-duty transport, offering benefits where battery electric solutions face technical limits. The complementary nature of these technologies was consistently highlighted by both industry experts and, to some extent, by consumers.

From an economic perspective, while progress is undeniable, particularly for EVs, cost perceptions remain a major barrier. The study uncovered a clear gap between the expert view, which increasingly considers total cost of ownership favorable for low-carbon vehicles, and the consumer perspective, which still focuses heavily on high upfront costs. This divergence indicates that while economic viability may be improving, consumer awareness and confidence have not fully caught up.

Public policy plays a pivotal role in shaping adoption. Incentives have significantly influenced early adopters, particularly in urban and higher-income groups. However, the research also underscored the risk of uneven transition. Rural areas, lower-income consumers, and certain age groups face persistent barriers due to infrastructure limitations, affordability concerns, and lack of familiarity with new technologies. Experts pointed out that public policies need to evolve from broad-based incentives to more targeted measures addressing these specific challenges.

In summary, this research confirms that technological readiness alone does not ensure a successful transition. Economic viability, consumer acceptance, and adaptive public policies must work together. The study highlights the importance of a differentiated approach, tailoring solutions to distinct market segments and mobility needs, to achieve both environmental goals and economic sustainability.

5.2 Theoretical Contribution

This thesis makes several contributions to the literature on the energy transition and the adoption of sustainable mobility technologies. First, it provides an integrated analysis of the technical, economic, and social dimensions of electrification and hydrogen, areas rarely studied together. By combining a quantitative consumer survey with qualitative interviews—including representatives from Tesla, major automakers, hydrogen startups, and a sustainable innovation expert—this research addresses a key gap: few studies consider technological performance, business models, and user perceptions in a comprehensive manner. Our empirical findings enhance understanding of adoption factors. For example, half of French respondents cite high purchase cost as the main barrier (45%), and a further quarter highlight a lack of infrastructure. The data quantitatively confirm theoretical assumptions about economic barriers and reveal a significant awareness gap: 95% of respondents are familiar with EVs, but only 43% know about hydrogen vehicles. Second, the thesis updates sustainable mobility business models by documenting the deployment of innovative approaches (leasing, platforms, logistics integration) and discussing the strategic complementarity between sectors. For instance, the study shows that EVs and HVs are not strict competitors in all segments but are often complementary—challenging the battery versus fuel cell dichotomy frequently found in the literature.

5.3 Managerial Implications

These findings lead to several practical recommendations for industry stakeholders and policymakers to advance the transport transition.

5.3.1 Automotive Manufacturers

Manufacturers should accelerate the rollout of diversified, affordable EV models. The survey confirms that high purchase price remains the main barrier for 45% of consumers. To address this, automakers should design lower-cost, mass-market models—such as Tesla’s planned €25,000 EV—and optimize production lines to reduce costs. Innovative commercial offers (long-term leasing, bundled services for charging and maintenance) can also enhance perceived value. For hydrogen, equipment suppliers and heavy vehicle manufacturers must continue R&D to lower fuel cell costs and collaborate through industrial consortia to share investments. Interviews confirm that green hydrogen production costs must fall significantly to ensure competitiveness. However, key limitations persist. Despite progress, EV range, battery weight, charging time, and costs still hinder widespread adoption, particularly for intensive uses (long distances, heavy vehicles). For hydrogen, infrastructure scarcity remains a major obstacle. Moreover, achieving ambitious EU decarbonization targets—including ending new combustion vehicle sales by 2035 and cutting emissions by 55% by 2030—will be challenging unless these technological and economic barriers are addressed at scale.

A critical question remains: how to maintain competitiveness once public subsidies decrease or disappear? Many business models currently rely on purchase incentives, ecological bonuses, or tax exemptions. Industry players must prepare for a shift toward subsidy-free business models by leveraging economies of scale, forming strategic R&D partnerships, and innovating in associated services (maintenance, recycling, battery second life, etc.).

5.3.2 Startups and Emerging Sectors

Innovative startups (active in hydrogen, batteries, shared mobility, etc.) play a key catalytic role in accelerating the energy transition in transport. They often pioneer flexible charging and refueling solutions—such as mobile stations or smart microgrids—that address gaps or delays in traditional infrastructure deployment. Interviews highlight the classic "chicken-and-egg" problem with hydrogen stations: no infrastructure without vehicles, but no vehicle adoption without infrastructure. Startups can break this deadlock by forming public-private partnerships to quickly develop pilot networks in major cities and logistics corridors, reducing risk for early adopters and creating network effects. They also innovate in business models, offering services like "hydrogen-as-a-service" for logistics fleets, where the startup handles refueling, maintenance, and technical monitoring for a monthly fee—lowering costs and risks for clients. In the EV sector, startups focus on ecosystem optimization: advanced battery management systems, smart charging platforms, and integrated mobility services (combining leasing, charging, and maintenance). Such innovations boost the competitiveness of low-carbon solutions. Finally, startups help reduce technology costs through innovation, economies of scale, and alternative, economically viable solutions. Their agility allows them to explore new materials, production methods, and circular economy strategies (e.g., battery reuse and recycling), cutting resource dependency and lowering life-cycle costs.

5.3.3 Public Authorities and Regulatory Bodies

Our results confirm the critical need for robust, stable, and predictable political support. As emphasized by the innovation expert interviewed, consistent and ambitious public incentives are essential to achieve critical adoption levels and avoid "stop-and-go" effects that undermine consumer and industry confidence.

Policymakers should maintain and adapt existing measures (e.g., ecological bonuses, conversion premiums) to support demand, especially in market segments where costs remain a barrier. Targeted support for hydrogen is also crucial—subsidies for heavy hydrogen vehicles, funding for refueling infrastructure, and seed financing for infrastructure development. Beyond stimulating demand, public authorities must also strengthen industrial supply. Facilitating local industrialization—such as battery gigafactories and electrolyzer plants in France and Europe—would enhance technological sovereignty, reduce logistics costs, and create jobs in emerging sectors. Consumer awareness and education are equally vital. Although only 5% of survey respondents cited lack of information as a direct barrier, 57% were unaware of hydrogen vehicles, highlighting a major knowledge gap. Governments, in collaboration with manufacturers and consumer groups, should launch clear, educational campaigns explaining environmental benefits, real usage costs, and practical aspects of EV and hydrogen vehicle adoption. Training programs for fleet managers and professionals could also ease the transition. Such outreach is essential to improve social acceptability and drive behavioral change. Without greater public understanding of the benefits and practicalities of clean vehicles, even the best technologies risk remaining niche solutions rather than becoming market standards.

5.3.4 Other Stakeholders (Logistics, Local Authorities, Energy Operators)

Fleet managers (public transport, logistics) can use our findings to revise operational models—for example, by investing now in electric buses for last-mile urban routes and hydrogen trucks for long distances, anticipating future energy costs and regulations. This would limit exposure to carbon taxes and meet rising customer sustainability demands. Energy companies should gradually integrate green hydrogen into their energy mix and expand the fast-charging network to support growing electric fleets. All these recommendations reflect empirical evidence: without changes in business models and major infrastructure investments, adoption will remain slow despite clear technological and environmental benefits. Beyond technological substitution, public and private managers should also promote alternatives such as carpooling, cycling, and multimodal transport, offering immediate emissions reductions and limiting the massive costs of zero-emission vehicle fleets.

5.4 Limitations and Future Research Directions

This study has several limitations. Methodologically, the sample (80 mostly urban, tech-savvy consumers) limits national representativeness. Only four expert interviews were conducted, offering focused but not exhaustive industry perspectives. The research focused on France (2023–2024) and did not cover international dynamics or long-term market evolution. Analytically, it centered on road transport, excluding other sectors (aviation, maritime, rail). While economic and environmental aspects were included, social and indirect impacts (e.g., full life-cycle assessments) were not formally addressed.

Future research should expand surveys to other contexts (international comparisons, rural populations) and conduct longitudinal studies to track changing perceptions as prices and infrastructure evolve. Technical studies could assess the impact of AI and digital solutions (fleet optimization, V2G platforms, predictive maintenance). Exploring other transport modes (low-carbon aviation, hydrogen ships, shared mobility) and analyzing policy effects on the value chain (local employment, industry-energy alliances) would enrich the understanding of sustainable transitions.

To sum up, this study confirms that electric and hydrogen technologies can significantly improve transport sustainability if economic, infrastructure, and social barriers are addressed through coordinated action. Light vehicle electrification is currently the main driver of this transition, while hydrogen holds strategic promise for heavy-duty segments. Our findings encourage companies and governments to continue deploying these low-emission solutions, while adapting business models and policies to maximize environmental and economic benefits.

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Appendices

Appendix 1. Questionnaire

Note: the questionnaire has been translated to English but administrated in French to reach a larger scope.

Questionnaire – Consumer Perceptions of Electric and Hydrogen Vehicles

This questionnaire is part of a Master's thesis at the University of Vaasa focusing on the energy transition in the transportation sector. It aims to better understand perceptions, knowledge, and barriers related to electric and hydrogen vehicles. Your responses are anonymous and will be used solely for academic purposes. Thank you for your participation!

Part 1 – General Information

Q1. What is your age?

- Under 25
- 25-34
- 35-49
- 50-64
- 65 and above

Q2. Where do you live?

- Large city (over 100,000 inhabitants)
- Medium-sized city (between 10,000 and 100,000 inhabitants)
- Rural area (under 10,000 inhabitants)

Q3. What is your annual gross income?

- Less than €20,000

- €20,000 – €39,999
- €40,000 – €59,999
- €60,000 – €79,999
- €80,000 and above

Part 2 – Knowledge and Perceptions

Q4. How would you rate your knowledge of electric vehicles?

Scale of 1 to 5: 1 = Very low, 5 = Very high

Q5. How would you rate your knowledge of hydrogen vehicles?

Scale of 1 to 5: 1 = Very low, 5 = Very high

Q6. Do you believe electric vehicles are a truly ecological solution throughout their lifecycle (production, use, recycling)?

- Yes
- No
- I don't know

Q7. Have you considered buying or leasing an electric or hydrogen vehicle?

- Yes, already purchased/leased
- Yes, considered but not yet done
- No, never considered

Part 3 – Barriers and Motivations

Q8. What do you consider the main barriers to adopting an electric or hydrogen vehicle? (Multiple answers possible)

- High purchase price
- Insufficient range

- Charging or refueling time
- Lack of charging stations/hydrogen stations
- Uncertainty about battery/fuel cell lifespan
- Maintenance or repair costs
- Lack of knowledge about the technology
- Other (please specify): ________

Q9. What would most encourage you to adopt an electric or hydrogen vehicle? (Choose one main answer)

- Lower prices
- Better range
- Subsidies or tax incentives
- More infrastructure (charging stations/hydrogen stations)
- Strong guarantees on lifespan
- Other (please specify): ________

Q10. In your opinion, which type of powertrain will dominate individual transportation by 2040?

- Electric vehicles
- Hydrogen vehicles
- Alternative fuels (biofuels, e-fuels)
- Traditional internal combustion engines (gasoline/diesel)
- Other (please specify): ________

The headings for **References** and **Appendices** should use the style “Ref+Append heading”. For the names of appendices, apply the style “Append name”.

Appendix 2. Guide 1: Tesla - Challenges and Perspectives of Electrification

Introduction

Master's thesis at the University of Vaasa on the energy transition in transportation. Confidentiality assured. Recording consent required.

Questions

- Q1: What are the main technical challenges hindering the mass adoption of electric vehicles?
- Q2: How does Tesla anticipate the evolution of range, charging, and battery lifespan?
- Q3: Strategic importance of developing fast-charging infrastructure in France?
- Q4: Influence of the French energy mix on the attractiveness of electric vehicles?
- Q5: Main barriers to adoption observed among French customers?
- Q6: Tesla's strategies to overcome these barriers?
- Q7: Major innovations expected in the next 10 years?
- Q8: Impact of Total Cost of Ownership (TCO) on purchasing decisions?

Closing

Conclusion, thanks, demographic information collection, possibility to receive a summary of the results, contact details.

Appendix 3. Guide 2: Renault - Transformation of Economic Models

Introduction

Master's thesis at the University of Vaasa on the economic viability and sustainability of transportation. Confidentiality assured. Recording consent required.

Questions

- Q1: Integration of the energy transition into Renault's global strategy?
- Q2: Industrial and economic transformations imposed by electrification?

- Q3: Adaptation of the business model to support electric mobility?
- Q4: Levers to improve the profitability of electric vehicles?
- Q5: Strategic importance of the circular economy (battery recycling, second life)?
- Q6: Partnerships and collaborations developed to accelerate the transition?
- Q7: Expectations regarding the evolution of consumer demand?
- Q8: Impact of the functional economy on the traditional automotive model?

Closing

Conclusion, thanks, demographic information collection, possibility to receive a summary of the results, contact details.

Appendix 4. Guide 3: Hydrogen Start-up - Innovations and Economic Challenges

Introduction

Master's thesis at the University of Vaasa exploring the viability of hydrogen technologies. Confidentiality assured. Recording consent required.

Questions

- Q1: Current opportunities for hydrogen technology in transportation?
- Q2: Main technical challenges encountered today?
- Q3: Partnerships deemed essential to structure the hydrogen sector?
- Q4: Current technological and economic maturity of the developed solutions?
- Q5: Impact of the production cost of green hydrogen on competitiveness?
- Q6: Strategies envisaged to reduce production and operating costs?
- Q7: Barriers related to access to distribution infrastructure?
- Q8: Economic conditions necessary to make hydrogen competitive with other technologies?

Closing

Conclusion, thanks, demographic information collection, possibility to receive a summary of the results, contact details.

Appendix 5. Guide 4: Innovation Expert – Economical Perspectives

Introduction

Master's thesis at the University of Vaasa on the energy transition in transportation. Confidentiality assured. Recording consent required.

Questions

1. General Vision of the Energy Transition

- In your opinion, what are the main strategic differences between electric and hydrogen technologies for the transportation sector?

2. Economic Analysis of Electric Vehicles

- What are the main economic advantages of electric vehicles today?
- What economic barriers remain (acquisition cost, infrastructure, recycling, etc.)?

3. Economic Analysis of Hydrogen

- What are the potential economic benefits of hydrogen for heavy or light mobility?
- What economic challenges still hinder its large-scale development?

4. Global Comparison: Profitability and Perspectives

- In your opinion, which technology currently offers the best cost/benefit ratio in light transportation?
- Do you think hydrogen could economically compete with electric by 2035?

5. Strategic Recommendations for Companies

- What strategies should companies adopt to secure their transition to low-carbon mobility?
- What role do public subsidies play in the economic viability of these technologies?

Conclusion

Thanks for participating, possibility to provide a summary of the study results. Collection of demographic information on current role and professional experience.