Road Traffic
Management Corporation

NEV

NEW ENERGY VEHICLE
RESEARCH REPORT

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Executive Summary

South Africa faces a dual and interlinked crisis: persistently high road traffic fatalities and an urgent need to transition its transport sector towards cleaner, more sustainable energy systems. South Africa's road safety crisis, marked by 12,172 fatalities in 2024, is characterised by human error, ageing vehicle fleets, infrastructure deficits, and socioeconomic inequality, all of which are identified as dominant contributing factors. Concurrently, global momentum towards decarbonisation is accelerating the adoption of new energy vehicles (NEVs), raising a critical policy question: can South Africa's transition to cleaner vehicle technologies also deliver meaningful road safety benefits?

Road Safety Crisis

Road traffic fatalities in South Africa, predominantly attributable to human factors (88.3%) and disproportionately affecting pedestrians (45.1%), are exacerbated by vulnerabilities in an ageing, fossil-fuel-dependent vehicle fleet, including mechanical breakdowns (International Energy Agency, n.d.). Emerging evidence also points to indirect effects of traffic-related emissions, which may impair cognitive performance and reaction times through air pollution exposure, potentially elevating human error risks in high-exposure areas (e.g., Sager, 2019). In exploring alternative energy sources, such as carbon-based e-fuels, biofuels, hydrogen and electrification, NEVsprovide pathways to enhance vehicle reliability, reduce emissions (and associated health risks), and support integration of advanced driver assistance systems (ADAS) for collision avoidance and mitigation of human error (Brynolf et al., 2022). Prioritising energy transitions alongside infrastructure improvements and behavioural interventions in high-risk areas could lead to measurable reductions in fatalities (Holmatov & Hoekstra, 2020).

Alternative Fuels Analysis

Carbon-based e-fuels and selected biofuels emerge as transitional solutions with relevance to South Africa's ageing internal combustion engine fleet. While these fuels are less efficient from a well-to-wheel energy perspective, they offer short-term benefits by improving fuel quality, reducing certain mechanical failure risks, and enabling emissions reductions without requiring immediate vehicle or infrastructure replacement. Their strategic use could therefore support safety and environmental gains in regions unlikely to electrify rapidly.

NEVs and Safety Synergies

This study examines South Africa's readiness to adopt NEVs, specifically electricity, hydrogen, carbon-based e-fuels, and biofuels in a manner that improves road safety outcomes while supporting environmental and economic objectives. Using a mixed-methods approach combining extensive desktop research with a nationally representative survey of 3,547 respondents, the research assesses vehicle performance, maintenance reliability, mechanical failure risk, behavioural factors, and infrastructural readiness across different energy pathways.

From a vehicle design perspective electricity-powered NEVs enhance stability through low centres of gravity and regenerative braking, reducing brake wear and improving vehicle control (Brightmile, 2020), yet quiet operation elevates safety risks for pedestrians (Autel Energy, 2024). Optimal portfolios blend BEVs/hybrids (Battery Electric Vehicles) for urban use with FCEVs/e-fuels (Fuel Cell Electric Vehicle), cutting lifecycle-wide emissions by 70-96% and reducing mechanical failures.(IEA, 2022a).

Contextual adoption of NEVs and alternative fuel solutions

The findings indicate that no single energy solution is sufficient for South Africa's diverse transport landscape. Battery electric vehicles (BEVs) offer the strongest long-term potential for emissions reduction and improved vehicle safety, particularly through the integration of advanced driver-assistance systems and digital safety technologies.

However, their immediate safety benefits are constrained by electricity supply instability, limited public charging infrastructure, affordability barriers, and uneven geographic access. E-fuels, biofuels as well as hydrogen fuel cell vehicles show promise for long-distance and heavy-duty applications but remain economically and infrastructurally unviable for large-scale deployment in the short to medium term.

Challenges and Recommendations

Socioeconomic barriers, grid instability, and knowledge gaps impede adoption, necessitating subsidies, refuelling stations in hotspots, and public education campaigns (Naamsa, 2023). Policies should mandate e-fuel blending, localise manufacturing, and enforce roadworthiness for safety gains (ITF, 2023; National Treasury, 2024). This road-safety-centric strategy positions e-fuels as pivotal to a longer term decarbonised, fatality-reduced mobility by 2030 and beyond (IRENA, 2022a).

Survey results further reveal low public awareness and understanding of NEVs in South Africa, particularly regarding safety implications, maintenance requirements, and total cost of ownership. This knowledge gap represents a significant barrier to adoption and underscores the need for targeted public education, especially in high-risk and vulnerable communities.

Importantly, the research demonstrates that road safety benefits do not automatically flow from cleaner propulsion technologies. The greatest safety gains associated with NEVs arise from vehicle modernisation, improved maintenance reliability, and embedded digital safety systems rather than from fuel type alone. Without deliberate policy alignment, NEV adoption risks replicating existing crash patterns driven by behavioural risk, inadequate enforcement, and unsafe road environments.

The study concludes that South Africa is partially ready for a transition to new energy vehicles but requires a coordinated, safety-centred strategy to realise their benefits fully. A phased, multi-technology approach is recommended, integrating electrification with transitional fuels, accelerating fleet renewal, prioritising vehicle safety standards, and aligning infrastructure development with high-fatality sectors. Crucially, NEVs

must be positioned not only as a climate intervention necessity but as a road safety, public health, and socioeconomic development instrument.

1.5 Research methodology

A mixed-methods approach was utilised for this study, which included comprehensive desktop research and an anonymous online survey. The desktop research consisted of reviewing academic papers, intergovernmental reports, government documents, news articles, commercial analyses, and industry reports. An anonymous online survey was conducted with 3,547 respondents. The sample was demographically representative of South Africa, collected from September to October 2025. The survey assessed NEV awareness, potential road safety benefits, key concerns, supportive government policies, and adoption barriers.

Chapters 2–5 examine alternative fuel solutions for vehicles, starting with hydrogen in Chapter 2, followed by carbon-based e-fuels, biofuels, and electricity. Each chapter analyses these options through technical, environmental, and commercialisation perspectives.

Chapter 2: Hydrogen As An Alternative Fuel Solution

This section provides an overview of hydrogen as an alternative to fossil fuels for vehicular applications, including its definition and attendant advantages and challenges. The initial subsection delineates hydrogen's historical development and its pertinence to decarbonisation efforts. Subsequent technical considerations examine its carbon profile, colour-based classifications, demand dynamics in industrial and transportation sectors, and associated costs. The commercialisation dimension addresses pertinent policies, infrastructural exigencies, and trade mechanisms.

2.1 History of hydrogen and discoveries

Hydrogen is frequently regarded as an indispensable energy carrier for a decarbonised society. It was formally identified as a distinct element in 1766 by Henry Cavendish (Concawe, 2022). The inaugural application of hydrogen in transportation transpired in Paris in 1783, when Jacques Charles engineered and piloted the world's first hydrogen balloon. Throughout the latter part of the eighteenth century, hydrogen-based transportation innovations predominantly centred on balloon propulsion, marking the inception of aerial travel (Aviationfile, 2020). Hydrogen technology did not extend to terrestrial vehicles until the early nineteenth century. In 1801, Humphry Davy conceptualised the hydrogen fuel cell (FC). This technology would subsequently enable substantial electrical power generation for vehicular applications, while Sir William Robert Grove materialised it as the gas voltaic battery in 1842. In 1807, Isaac de Rivaz constructed the de Rivaz engine, the pioneering ICE and four-wheeled vehicle powered by a hydrogen-oxygen mixture (Mercedes-Benz Group, 2023). Pivotal discoveries and applications of hydrogen technology spanning the past five centuries are depicted in Table 1.

Table 1: Timeline – The Historical Journey of Hydrogen in Transportation

TIME FRAME	KEY DISCOVERIES/USES OF HYDROGEN TECHNOLOGY
1800's	The beginning
1806	First hydrogen-powered engine developed
1860	The hippomobile debuts
1889	The first hydrogen fuel cell was conceived
1900's	Gasoline overtakes hydrogen
1941	Russia converts 200 gasoline-powered trucks to hydrogen
1960	GE produced a fuel-cell power system for NASA.
1966	GM's Electrovan is one of the first FCEVs
1980	The US Navy studies using fuel cells to power submarines
1988	Iceland announces plans to create a hydrogen economy
1999	The first commercial vehicle hydrogen station opens in Germany
2000's	Modern fuel cells revolutionise hydrogen technology
2018	Hydrogen plants begin to spread internationally
2020	Major automakers invest in hydrogen vehicle development
June 2021	40,000 + passenger FCEVs are on the open road in select markets globally

Source: FASTECH (2023)

2.2 Discoveries that made the commercialisation of hydrogen possible

Hydrogen attained commercial significance through the pivotal 1910 Haber-Bosch process (a Nobel Prize in Chemistry patent), in which substantial quantities of hydrogen are synthesised from nitrogen derived from ambient air to yield ammonia (NH_3) (Thyssenkrupp, 2023). The salience of this innovation resides in ammonia's efficacy as an energy carrier, facilitating the long-distance transport of hydrogen in a more compact form. During the 1950s, hydrogen fuel cells (FCs) found application in industrial equipment and vehicles, including tractors, forklifts, and welding apparatus; in 1966, General Motors (GM) introduced the Chevrolet Electrovan, the inaugural hydrogen FC-powered vehicle. Although FCs had been explored since the early nineteenth century, GM pioneered the integration of hydrogen FCs to propel vehicular wheels directly (Eberle et al., 2012).

2.3 The need for commercial hydrogen as a clean source of energy

Contemporary interest in the hydrogen economy emerged in 1970, aimed at decarbonising diverse economic sectors, including transportation, and mitigating climate change (Jones, 1970). The 1990s witnessed significant advances in fuel cell technology, as Ballard Power Systems, a Canadian firm specialising in proton exchange membrane fuel cells, successfully increased hydrogen's power density from 200 watts per litre to 1,500 watts per litre. This breakthrough facilitated simplified storage, transportation, and utilisation of hydrogen. More than two centuries after the inception of hydrogen-powered vehicles and nearly five decades following General Motors' debut of the first hydrogen fuel cell prototype, leading original equipment manufacturers (OEMs), such as Toyota, Hyundai, and Honda, commenced commercial deployment of hydrogen fuel cell vehicles (FCVs) (J.D. Power, 2022).

2.4 Technical considerations:

2.4.1 Definition

Hydrogen (element symbol H, atomic number 1) constitutes the lightest, simplest, and most abundant element, manifesting as a colourless, odourless gas at room temperature that reacts with oxygen to yield water (Concawe, 2022). It predominantly occurs in combination with oxygen in water and in organic materials such as living plants, coal, and petroleum, making it abundantly available (Los Alamos National Laboratory, n.d.). Nonetheless, hydrogen's boiling point, marking the transition from gas to liquid, remains exceedingly low at -268.9 °C. Coupled with its high flammability, these properties render hydrogen hazardous to handle, necessitating rigorous safety protocols and sophisticated infrastructure (Concawe, 2022).

2.4.2 Carbon profile

Efficiency

Hydrogen can be utilised in two principal configurations for vehicle propulsion: via an ICE, operating on a hydrogen-oxygen mixture, or through a fuel cell (FC) that drives an electric motor (Brynolf et al., 2022). As an energy carrier for transport, hydrogen is currently significantly more effective in fuel cell vehicles than in ICE applications, owing to the higher overall efficiency and zero tailpipe emissions associated with fuel cell systems (Ghadikolaei et al., 2021). Fuel cells are regarded as among the most efficient and least polluting power sources available, capable of delivering superior energy efficiency and energy density (i.e., the amount of energy stored per unit mass or volume) relative to many conventional technologies. The dominant fuel cell technology in the transport sector is the proton exchange membrane fuel cell (PEMFC), which can be started from cold and emits only water as a by-product. PEMFCs are electrochemical devices that utilise hydrogen and exhibit an energy density approximately three times that of diesel or gasoline, such that 1 kilogram of hydrogen used in a fuel cell to power an electric motor yields an energy output roughly equivalent to that provided by 3 litres of diesel (Aminudin et al., 2023).

A fuel cell is an electrochemical energy conversion device - it utilizes hydrogen and oxygen to generate electricity, heat and water.

1 The hydrogen atoms enter at the anode.

2 The atoms are stripped of their electrons in the anode.

3 The positively charged protons pass through the membrane to the cathode and the negatively charged electrons are forced through a circuit, generating electricity.

4 After passing through the circuit, the electrons combine with the protons and oxygen from the air to generate the fuel cell's byproducts: water and heat.

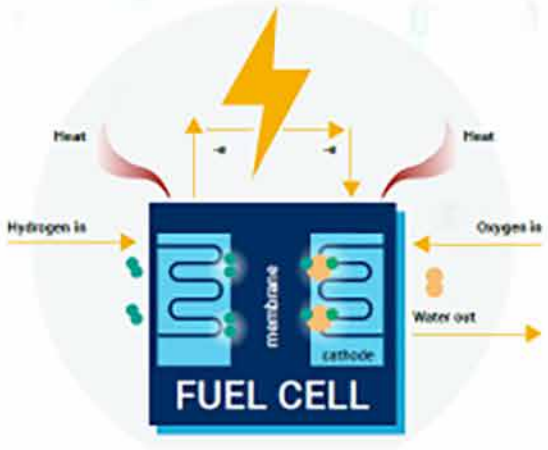

Image source: FCHEA

Figure 1: How fuel cells work

Enabler of the clean energy transition

The environmental performance of hydrogen-fuelled vehicle technologies is directly contingent on the primary energy source and the production pathway used to generate molecular hydrogen. At present, the majority of hydrogen is produced via steam methane reforming of natural gas and coal gasification, both of which are associated with substantial carbon dioxide (CO_2) emissions. Future demand, however, is expected to be dominated by zero-carbon, or so-called green, hydrogen generated from renewable energy sources such as wind and solar, thereby targeting net-zero emissions across both production and end use. Green hydrogen accounted for only 0.03% of global hydrogen supply in 2020 (IEA, 2021b). Expansion plans for hydrogen production, therefore, centre on electrolysis powered by electricity from variable renewable energy sources (World Nuclear Association, 2021). The prospects for fully green hydrogen becoming a commercially viable low-carbon energy vector are thus critically dependent on the scale and reliability of renewable energy capacities available for its production.

Figure 2: Decarbonisation process for FCEVs

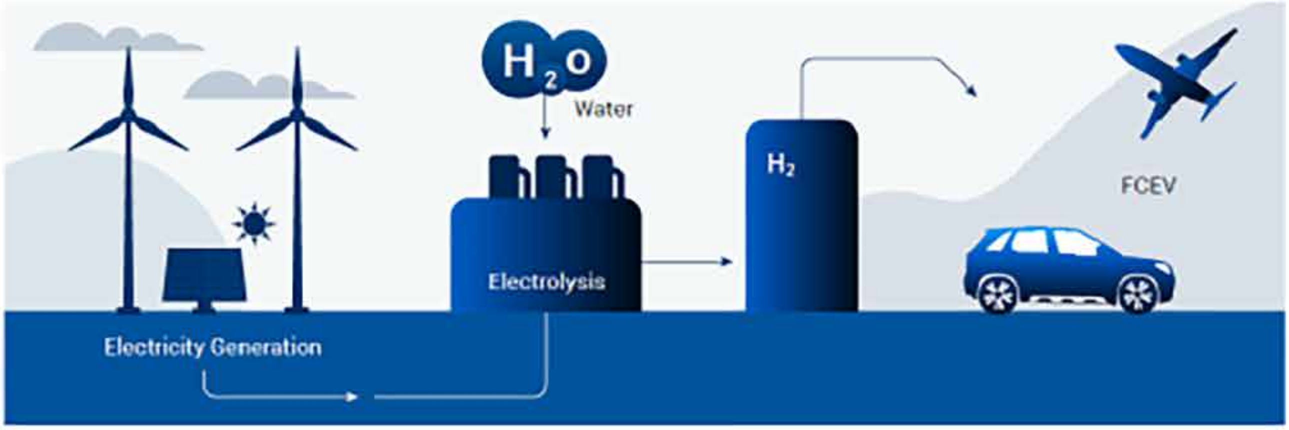

Image source: MysticB

2.4.3 Hydrogen colour spectrum

In the energy sector, colour codes are used to distinguish hydrogen variants based on their production methods. Although hydrogen combustion yields solely water as a byproduct, the carbon intensity of its production process varies considerably. Table 2 delineates the principal hydrogen categories, elucidating the attendant benefits and challenges in achieving carbon neutrality.

Table 2: Hydrogen colour spectrum

BLACK HYDROGEN

Definition	Hydrogen made from fossil fuels
Process	Gasification
Source	Black (bituminous) coal
Advantages	• The traditional process of making hydrogen • Infrastructure in place
Challenges	Environmentally damaging, as both the CO2 and carbon monoxide generated during the process are not recaptured.

BROWN HYDROGEN

Definition	Hydrogen made from fossil fuels
Process	Gasification
Source	Black (lignite) coal
Advantages	• The traditional process of making hydrogen • Infrastructure in place
Challenges	Environmentally damaging, as both the CO2 and carbon monoxide generated during the process are not recaptured.
Example in use	Japan and Australia have entered a brown coal-to-hydrogen partnership project, which will use brown coal in Australia to produce liquefied hydrogen, which will then be shipped to Japan for low-emission use.

PINK HYDROGEN

Definition	A viable carbon-free energy source using nuclear energy
Process	Electrolysis of water
Source	Nuclear energy
Advantages	Potential for the exceptionally high temperatures from nuclear reactors to be used in alternative hydrogen production through steam production for more effective electrolysis.
Challenges	• Nuclear power is complex and hugely costly to build • Nuclear energy generates vast amounts of hazardous waste

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BLUE HYDROGEN

Definition	• Low CO2 production route • Proposed as a lower-emissions hydrogen compared with grey hydrogen
Process	
	• Steam methane reforming in natural gas with carbon capture (85% - 95%) and storage to reduce emissions • Gasification with carbon capture (85% - 95%) and storage to reduce emissions.
Source	• Methane • Coal • Natural Gas
Advantages	• Less costly than green hydrogen • Captures resulting CO2 emissions before they hit the atmosphere • Captured CO2 can be condensed and stored underground or used as a feedstock for several industrial applications
Challenges	According to a study by Howarth and Jacobson (2021), total CO2 emissions in the production of blue hydrogen are only 9% - 12% less than those of grey hydrogen. Energy is needed to capture the CO2, and this electricity is produced from burning additional natural gas, increasing fugitive methane emissions that are higher than those of grey hydrogen. The study found that the greenhouse gas (GHG) emissions of blue hydrogen are over 20% more than burning coal or natural gas for heat, and over 60% more than burning diesel oil.

TURQUOISE HYDROGEN

Definition	CO2 -free production route
Process	Pyrolysis
Source	• Methane • Natural Gas
Advantages	According to Diab et al. (2022), turquoise hydrogen exhibits substantially lower energy density compared to green hydrogen (10–30 kWh/kg H_2 versus 50–60 kWh/kg H_2). The authors performed a sensitivity analysis of the environmental metric time-horizon and methane emissions, demonstrating that the carbon intensity of turquoise hydrogen production is 88.3–90.8% lower than that of grey hydrogen. Moreover, the utilisation of renewable natural gas yields a negative carbon intensity for hydrogen (–4.09 to –10.40 kg CO_2e/kg H_2 at 100% renewable natural gas), the lowest among grey, blue, and green variants, thereby underscoring turquoise hydrogen's prospective role in facilitating the energy transition.
Challenges	Technical challenges of handling solid carbon: Once a reaction occurs over a conventional solid catalyst, the carbon quickly deposits on the surface of the catalyst, which deactivates it.

YELLOW HYDROGEN

Definition	Hydrogen made through electrolysis of water using solar power Relatively new term
Process	Electrolysis
Source	Solar energy
Advantages	Process occurs without emitting GHG emissions
Challenges	While solar power can reduce water usage by almost 15% compared to coal and natural gas power plants, a substantial amount of water consumption occurs, nonetheless.

GREEN HYDROGEN

Definition	• Carbon-free production route • Only type produced in a climate-neutral manner.
Process	Polymer electrolyte membrane electrolysis – the use of an electric current to split water into hydrogen and oxygen with no GHG emissions, provided the electricity used to power the process is entirely from renewables.
Source	Renewable Energies: • Solar • Wind
Advantages	Good alternative to grey and blue (the only type of hydrogen produced in a carbon-neutral manner).
Challenges	High production costs – currently too costly to be a viable renewable and carbon-neutral alternative.

Source: (Switzer Manufacturing Company, n.d.)

2.4.4 Hydrogen demand

Hydrogen demand in industry

Global hydrogen demand rose by approximately 3.0% in 2022 relative to the preceding year, attaining 95 million tonnes (Mt). As illustrated in Figure 3, demand remains predominantly concentrated in conventional industrial and refining applications, with the majority of production derived from fossil fuels, thereby perpetuating greenhouse gas (GHG) emissions. In 2022, activity in low-emission hydrogen production for end-use sectors, including shipping, chemical manufacturing, and refining, increased. The 'Other' category in Figure 3 encompasses emerging applications across industries such as transport, construction, and power generation; within this segment, which accounted for less than 0.1% of global demand in 2022, the preponderance is allocated to road transport, specifically FCEVs employed in heavy-duty, long-haul trucking in China. The International Energy Agency (IEA) anticipates demand to surpass 150 Mt by 2030, representing nearly 1.6 times 2022 levels, with the bulk of expansion stemming from established applications and approximately 30% from novel uses, including road vehicles (IEA, 2022a).

Figure 3: Global hydrogen demand by sector in the Net-Zero Scenario (2020-2030):

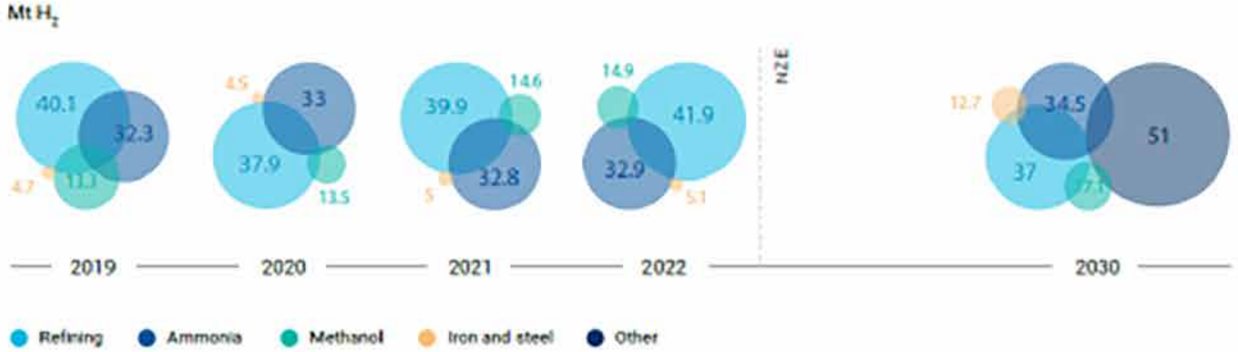
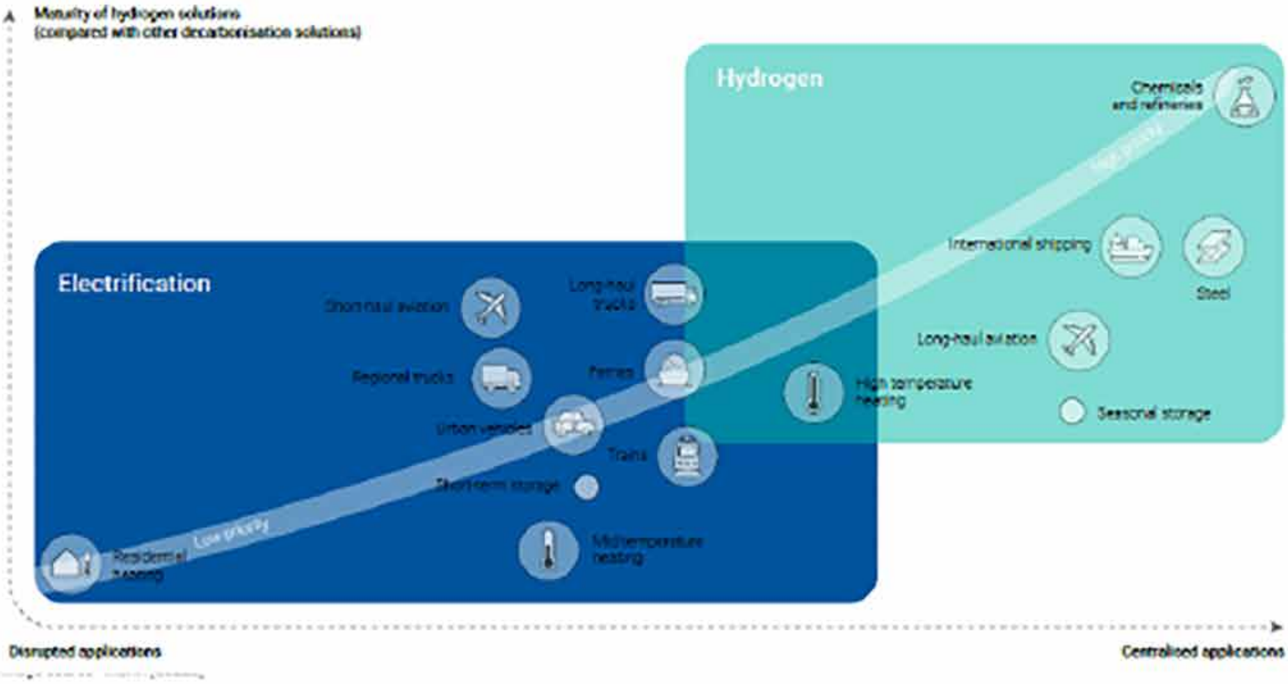


Image source: Mystic8

According to IRENA (2022a), hydrogen is projected to satisfy 12.0% of global energy demand by 2050, with the most substantial expansion anticipated in refining, steel production, and international shipping (see Figure 4). The trajectory of hydrogen demand in the automotive sector will depend on the expeditious commercialisation of emerging technologies.

Figure 4: Green hydrogen priority sectors



Hydrogen demand in the automotive industry

Several Original Equipment Manufacturers (OEMs) are actively promoting hydrogen-fuelled vehicles, utilising either ICEs or FCs, to consumers, driven by increasingly stringent greenhouse gas (GHG) emissions regulations. Table 3 delineates the applications of both technologies.

Table 3: Application of hydrogen ICEs and Hydrogen FCs

	Advantages	Disadvantages
Hydrogen ICE	Leverages existing technology and infrastructure similar to those of conventional spark-ignition engines. Benefits from comprehensive established service networks. Demonstrates optimal efficiency under elevated loads, rendering it particularly suitable for heavy-duty trucks.	When derived from green hydrogen, it emits negligible quantities of CO_2 but generates nitrogen oxides (NO⊠), necessitating exhaust after-treatment systems to mitigate NO⊠ emissions. Exhibits a greater propensity for utilising non-green hydrogen variants, given that internal combustion engines can accommodate lower-grade hydrogen feedstocks.
Hydrogen FC	When derived from green hydrogen, the sole emission comprises water vapour. Exhibits superior efficiency at low loads, such as those encountered in passenger vehicles. Harnesses energy via regenerative braking during short duty cycles, thereby enhancing overall system efficiency.	Exhibits elevated costs attributable to the exigency of novel technological paradigms. Necessitates supplementary resources, including precious metals such as platinum and iridium, which serve as catalysts in fuel cells and specific water electrolysis systems.

Source: Cummins and TWI Global (2022)

Hydrogen fuel cell vehicles (FCVs) are particularly suited for lighter payloads, prompting most OEMs to prioritise their development for passenger vehicle applications. FCVs are often compared with BEVs, as both deliver zero tailpipe emissions and use electric motors for propulsion. The principal distinction resides in FCVs' superior driving range, approaching 500 kilometres, and their capacity for refuelling in under 10 minutes (Manoharan et al., 2019). The ensuing discussion delineates select OEMs presently investing in hydrogen technology for passenger vehicles.

2.5 GAC Motor Ammonia Engine

Guangzhou Automobile Group Co., Ltd. (GAC Motor) unveiled the inaugural ammonia engine for passenger vehicles in June 2023. Diverging from conventional approaches that entail cracking ammonia into hydrogen for fuel cell operation, GAC Motor has adapted it for use in modified combustion engines.

2.5.1 Advantages

GAC Motor claims a peak power output of 120 kilowatts (kW) and a 90% reduction in greenhouse gas (GHG) emissions compared with conventional fuels (Bloomberg, 2023a).

2.5.2 Disadvantages

Prevailing ammonia production predominantly relies on the high-emission Haber-Bosch process (Bloomberg, 2023a).

2.6 BMW iX5 Hydrogen Pilot Fleet

In February 2023, BMW introduced the inaugural hydrogen-operated BMW iX5 model following four years of development. A limited fleet of 100 units has been deployed to evaluate the feasibility of hydrogen fuel cell (FC) technology in passenger vehicles.

2.6.1 Advantages

The refuelling process requires only five minutes, with the refuelling port positioned identically to that of the conventional combustion-engine X5 (BMW Group, 2023).

2.6.2 Disadvantage

The paucity of supporting infrastructure is anticipated to impede widespread adoption of this technology.

2.7 Renault Scenic Vision

Electric Concept with Hydrogen Fuel Cell Range Extender. The Renault Scenic Vision concept vehicle, anticipated to debut in France in 2024, incorporates a compact recyclable battery (40 kWh) augmented by a hydrogen fuel cell (FC) range extender, capable of extending the range by an additional 800 km via a 15 kW FC unit.

2.7.1 Advantages

This configuration synergistically integrates hydrogen FC technology with battery capacity via a range-extender mechanism, enabling refuelling in less than 5 minutes (Renault, 2023).

2.7.2 Disadvantages

A substantial proportion of Renault's sales occur in Africa and Latin America, regions where large-scale hydrogen infrastructure development remains unlikely in the near term.

Manoharan et al. (2019) estimate that by 2030, fuel cell (FC) costs will become more competitive relative to ICEs, driven by technological advancements and greater availability. Consequently, hydrogen holds substantial potential as a primary fuel source for personal vehicles by the 2030s. At present, however, the elevated costs associated with hydrogen fuel cell vehicles (FCVs) constitute one of the technology's principal impediments, as elaborated below.

2.8 Cost challenges

Hydrogen production costs

In most countries, green hydrogen production has remained commercially unviable owing to insufficient governmental support and elevated production costs; however, this paradigm is shifting with the introduction of incentives in select regions (PIIE, 2023). The subsequent section examines policies and strategies poised to render green hydrogen economically feasible in due course. As depicted in Figure 3.4.6, green hydrogen production costs are projected to decline from the current range of USD 3.20–7.70 per kg to USD 1.30–3.30 per kg by 2060, thereby enhancing affordability and expediting the energy transition (IEA, 2019a).

Figure 5: Global average levelized cost of hydrogen production by energy source and technology (2019 and 2050)

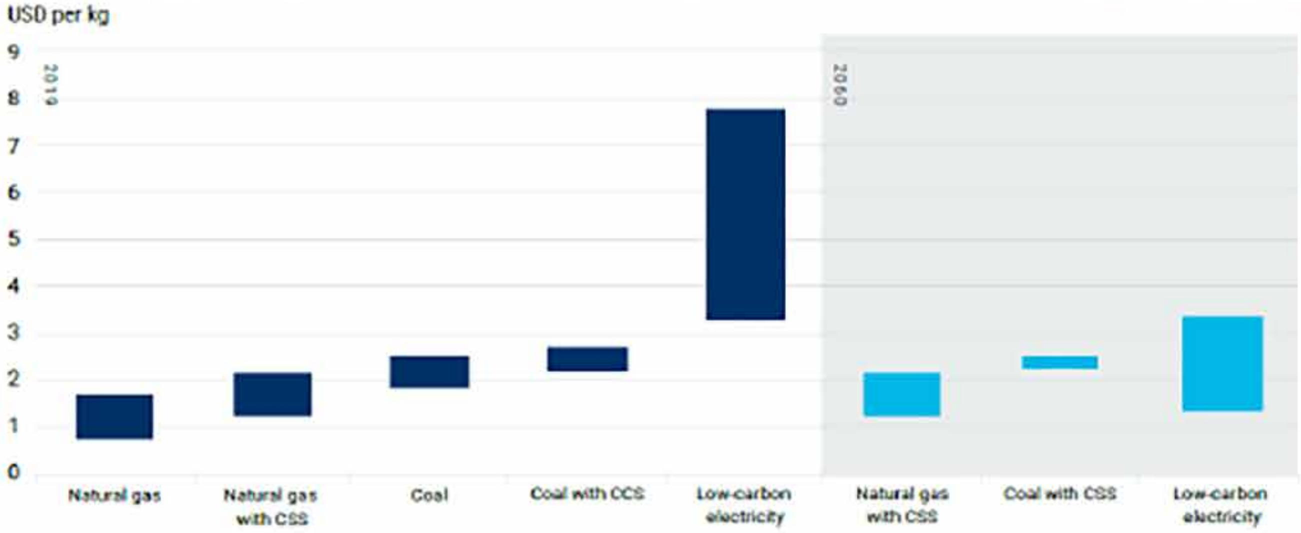


Image source: IEA (2019a). Licence: CC BY 4.0

Hydrogen FC costs

FCEVs offer a potential advantage over BEVs in terms of lower lifecycle costs. Initial fuel cell expenditures have decreased due to sectoral advancements and improved performance, thereby reducing operational and maintenance costs. The long-term viability of hydrogen FCEVs is anticipated to improve through ongoing cost optimisation, refinements in purification techniques, and routine vehicle upkeep (Fakhreddine et al., 2023). Concurrent efforts seek to curtail the utilisation of platinum group metals, a principal constituent of hydrogen-fuelled polymer electrolyte membrane fuel cells, to foster more economical, sustained applications. Moreover, collaborative efforts among governments, universities, and industry are advancing research and development initiatives to develop low-cost fuel cell stacks, balance-of-plant components, and high-volume manufacturing processes to reduce aggregate system costs (US Department of Energy, n.d.). The subsequent section elucidates specific national and international policies and strategies that are propelling hydrogen deployment in the global transportation sector.

2.9 Hydrogen commercialisation

Hydrogen policies and strategies

Achieving advanced commercialisation of green hydrogen production and utilisation necessitates substantial governmental support. The following outlines key taxes, subsidies, and strategies for hydrogen production and vehicular applications, as implemented by frontrunner entities advancing cleaner energy paradigms. Figure 6 illustrates nations that have formally promulgated hydrogen strategies, the preponderance of which reside in Europe.

Figure 6: Countries that have released national hydrogen strategies

Image source: Mystic8

2.10 European Union and Schengen Area: Integration of Carbon Credits and Hydrogen Subsidies

- **Emissions Trading System (ETS):** This carbon pricing mechanism effectively elevates the cost of fossil fuels by imposing financial penalties on emissions (PIIE, 2023).
- **Emissions Allowance Tightening:** Allowances covering industrial emissions have attained a milestone price exceeding €100 per metric tonne (PIIE, 2023).
- **Hydrogen Production Subsidies:** Designed to enhance the competitiveness of green hydrogen, the EU Innovation Fund intends to implement a series of production subsidies via competitive tenders, offering a fixed premium per kilogram of green hydrogen for a decade (PIIE, 2023).
- **Germany:** Hydrogen vehicles are exempt from circulation tax for 10 years (PIIE, 2023).
- **Norway:** FCEVs benefit from reduced fees for public parking, ferries, and toll roads (PIIE, 2023).

2.11 *United States: Emphasis on Hydrogen Production Credits*

The 2022 Inflation Reduction Act (IRA) establishes substantial tax credits for hydrogen production, offering USD 3.00 per kg for green hydrogen over 10 years, with reduced credits for less clean hydrogen variants (White House, 2023). The Congressional Budget Office (2022) estimates the aggregate 10-year cost of these IRA hydrogen production subsidies at USD 13.2 billion.

2.12 *South Korea: Premier Subsidies for Fuel Cell Electric Passenger Vehicles*

In November 2022, South Korea promulgated new policy directions for the hydrogen economy, aimed at establishing a clean hydrogen supply chain and fostering a globally preeminent hydrogen industry (MOTIE, 2022). These encompass three principal growth strategies, denominated as "3UP":

- **Scale-Up:** Seeks to augment the clean hydrogen ecosystem through the development of a global supply chain and the generation of substantial demand in power generation and transportation sectors. The Ministry of Trade, Industry and Energy (MOTIE, 2022).
- **Build-Up:** Endeavours to institute a comprehensive legal framework for distribution infrastructure, thereby expediting clean hydrogen utilisation. This encompasses the construction of the world's largest liquid hydrogen plant and fuelling station, an ammonia and liquid hydrogen receiving terminal, and a hydrogen pipeline network; further provisions include inaugurating a hydrogen bid market, enacting hydrogen business legislation, and implementing a clean hydrogen certification system The Ministry of Trade, Industry and Energy (MOTIE, 2022).
- **Level Up:** Aspires to attain technological innovation commensurate with positioning South Korea as the paramount global hydrogen powerhouse (MOTIE, 2022).

The Ministry of Trade, Industry and Energy has articulated an action plan targeting the production of 30,000 hydrogen-powered commercial vehicles by 2030, the erection of 70 liquid hydrogen fuelling stations, and the integration of clean hydrogen into the national energy mix, constituting 7.1% of the national energy mix by 2036. South Korea presently offers the most generous subsidies for fuel cell electric passenger vehicles, concomitant with an expansion of the roster of stations eligible for subsidies covering hydrogen procurement costs (MOTIE, 2022).

2.14 *China: Implementation of One of the Largest Global Hydrogen R&D Strategies*

Substantial funding is being allocated to initiatives prioritising hydrogen utilisation, with 16 provinces and cities inaugurating five-year plans that incorporate this technology.

Within China's extant Five-Year Plan (2021–2025), hydrogen constitutes one of the six designated industries of the future (IRENA, 2022a).

The deployment of hydrogen vehicles receives fervent endorsement in alignment with municipal carbon-neutrality objectives. According to IRENA (2022a), China has operationalised approximately 8,400 FCEVs, the third-largest fleet worldwide, succeeding South Korea and the United States, and aspires to introduce an additional 2,500 hydrogen fuel cell-powered vehicles in 2023, escalating to 1 million by 2030, supported by 1,000 refuelling stations.

China's preeminent manufacturer of hydrogen fuel cells for vehicular applications, Shanghai Sinofuelcell, anticipates a more than twofold increase in sales throughout 2023, propelled by Beijing's advocacy of hydrogen integration into its carbon-neutrality ambitions by 2060 (SCMP, 2023).

2.15 Hydrogen infrastructure and transportation

In the contemporary global market, hydrogen production occurs near demand centres. Jurisdictions endowed with robust liquid natural gas (LNG) infrastructure, such as Europe, can facilitate hydrogen conveyance via blending. This interim stratagem entails the admixture of hydrogen into natural gas pipelines, utilising existing infrastructure (IEA, 2021a). As hydrogen attains greater commercial maturity and intersectoral demand burgeons, specialised transportation networks will be imperative to accommodate the growth of cross-border commerce (IEA, 2021a).

One prevalent methodology for hydrogen conveyance involves liquefaction, in which hydrogen is converted to a liquid state to facilitate maritime transport, and then reconverted to a gaseous state at the destination. The principal impediment is the need to maintain liquid hydrogen at -252.87°C within fully insulated storage vessels, thereby escalating transportation costs. Before large-scale liquid hydrogen shipping becomes feasible, exporters must overcome the attendant technical impediments (IEA, 2021a).

Given hydrogen's inherently volatile properties, its manipulation necessitates bespoke infrastructure, apparatus, and personnel training. Consequently, ammonia, derived from lower-carbon blue or green hydrogen, emerges as a markedly more practicable energy carrier for long-distance maritime voyages, serving as a viable surrogate for direct hydrogen transport. In regions such as Asia, where supply chains and liquefied natural gas (LNG) infrastructures lag behind their European counterparts in maturity and ubiquity, leveraging ammonia supply chains affords superior efficiency (IEA, 2021a).

These conveyance modalities are depicted in Figure 7.

Image source: Hystic8

2.17 Green Hydrogen Hubs

A salient catalyst for hydrogen advancement lies in the establishment of hubs, integrated networks of producers and consumers interlinked via specialised infrastructure, in which participants capitalise on agglomerated expertise and reduced costs. As illustrated in Figure 8, optimal functionality of green hydrogen hubs requires several prerequisites, including favourable geographic positioning with robust connectivity, sophisticated pipeline corridors, and advanced terminal and logistics infrastructure. Numerous global ports, particularly advanced, integrated smart ports, are expanding their capacity for renewable energy production, handling, and storage, including green hydrogen, thereby positioning themselves as pivotal export hubs (Notteboom and Haralambides, 2023).

Figure 8: Requirements for green hydrogen hubs

Image source: Notteboom and Haralambides (2023)

Proximity to green hydrogen hubs confers a strategic advantage for hydrogen fuel stations, as the principal impediment to the broad adoption of hydrogen-fuelled vehicles remains the elevated costs of hydrogen production and delivery to refuelling sites (Isenstadt and Lutsey, 2017). Geographic contiguity to such hubs thus positions select nations and regions favourably. China, Japan, and South Korea rank as the foremost trio globally in the deployment of hydrogen refuelling stations, with China accounting for approximately one-third of the worldwide total (Hydrogen Fuel News, 2023). This pre-eminence correlates with China's robust policy framework and industrial cultivation of pivotal hydrogen clusters, the Bohai Circle, Yangtze River Delta, and Pearl River Delta, which lead advancements in hydrogen technology research, development, and implementation (Peng and Bai, 2022).

2.18 Hydrogen trade and supply chains

Hydrogen predominantly constitutes a localised and regional commodity, disseminated proximate to its production clusters, with the majority eschewing long-distance transportation owing to formidable logistical impediments and prohibitive costs (IRENA, 2022a). Nevertheless, an incremental proliferation of bilateral trade and cooperation accords is emerging, positioning salient regional producers, such as Latin America, North Africa, and Australia, as pivotal exporters to demand-centric regions like Europe and the Asia-Pacific, where endogenous production capacities prove inadequate. Figure 9 delineates principal hydrogen trade corridors, both extant and prospective, encompassing their origin and destination locales.

Figure 9: Major hydrogen trade supply corridors

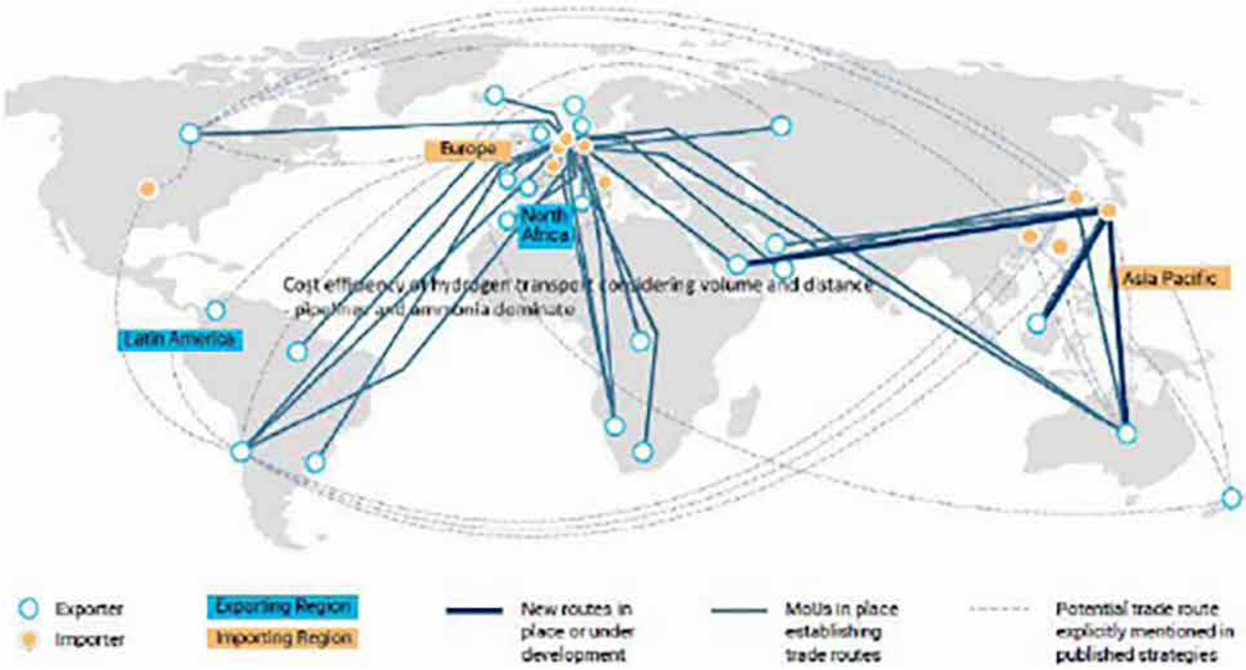


Image source: IRENA (2022a)

Chapter 3: Carbon-Based E-fuels As An Alternative Fuel Solution

3.1 Background of carbon-based e-fuels

Definition

Carbon-based e-fuels offer the distinct advantage of chemical compatibility (often indistinguishable from conventional fossil fuels), facilitating their seamless integration into existing transport infrastructures. These fuels function as "drop-in" alternatives, requiring minimal, if any, modifications to ICEs while leveraging established fuel distribution networks and refuelling stations. The principal technical and economic hurdles pertain to upstream production processes rather than downstream deployment or end-use applications (ITF, 2023).

Carbon sources

- Carbon capture at source

Approximately one-third of anthropogenic carbon dioxide emissions originate from fossil fuel power plants, where flue gas concentrations typically range from 8 to 10% (Jiang et al., 2010). Capturing CO_2 from these high-concentration point sources prevents its atmospheric release and enables its utilisation as a feedstock for carbon-based e-fuels. However, as climate mitigation strategies reduce emissions from such facilities, long-term e-fuel production will necessitate carbon capture from lower-concentration industrial sources and ambient air via direct air capture (Jiang et al., 2010).

- Direct air capture

Atmospheric carbon dioxide concentrations have risen from pre-industrial levels of 260-280 ppm to approximately 416 ppm (Senecal & Leach, 2021). Despite these levels exerting catastrophic climatic effects, they remain remarkably dilute for capture purposes, equivalent to just 0.04%, in stark contrast to the 8-10% concentrations in industrial flue gases. The chemical inertness of CO_2 further complicates direct air capture, which relies principally on absorption or adsorption methodologies (Senecal & Leach, 2021)

Figure 10: Absorption v adsorption

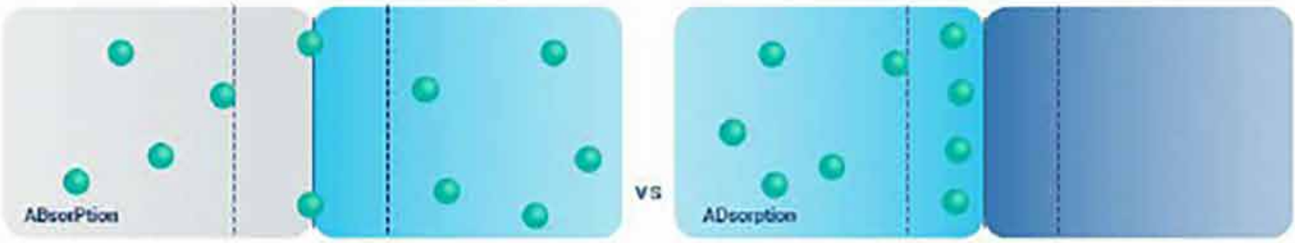


Image source: ChemBAM.com

Absorption-based direct air capture (DAC), in which CO_2 molecules are absorbed into liquid absorbents such as aqueous alkali or alkaline-earth hydroxides, offers lower costs and enables continuous operation but requires high regeneration temperatures (Deutz, 2021). In contrast, adsorption-based DAC utilises a diverse array of solid sorbents (including alkali carbonates, amine-functionalised oxides, and solid organic polymers), in which CO_2 adheres to the material surface, enabling lower-temperature operation and potential scalability (Deutz, 2021). Nevertheless, realising large-scale deployment demands substantial advances in sorbent materials, adsorption kinetics, and energy-efficient regeneration techniques (Zhu et al., 2022).

Figure 11: How direct air capture works

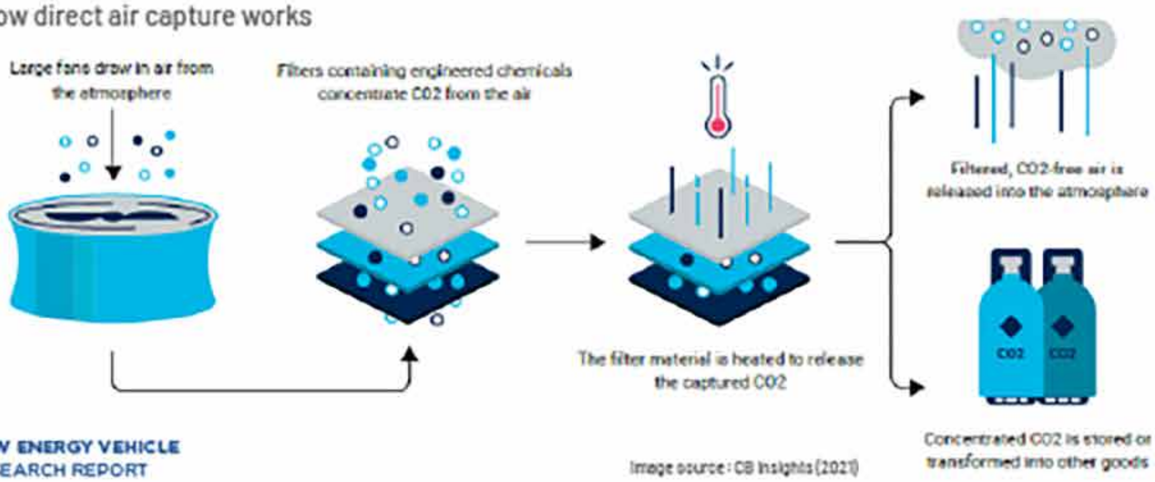


Image source: CB Insights (2021)

The manufacturing process for carbon-based e-fuels is shown in Figure 12 below.

Figure 12: The manufacturing process of carbon-based e-fuels

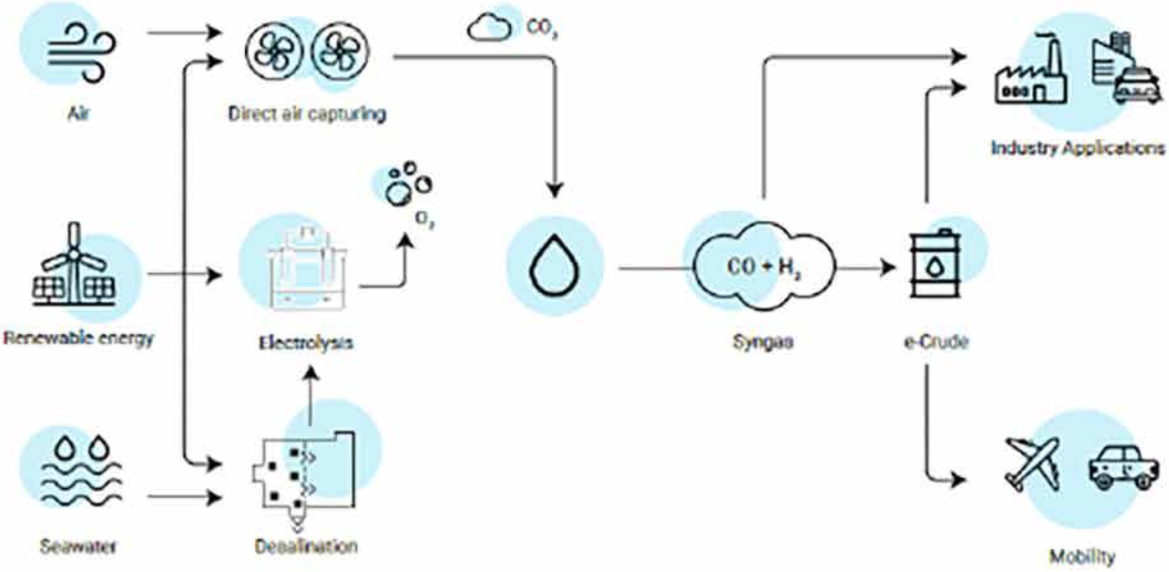


Image source: Adapted from The Royal Society (2019) Synthetic Fuels briefing and from slides shared by Porsche.

Fischer-Tropsch synthesis of methanol to gasoline (MtG)

The Fischer-Tropsch (FT) synthesis process, pioneered by Franz Fischer and Hans Tropsch in 1926 at the Kaiser Wilhelm Institute for Coal Research, constitutes a versatile catalytic method for converting syngas into a spectrum of hydrocarbon molecules. Operating under high-temperature conditions (300-350°C) with an iron catalyst yields approximately 40% wt e-gasoline, along with olefins (alkenes with carbon-carbon double bonds). Conversely, low-temperature regimes (200-250°C) employing iron or cobalt catalysts, coupled with hydrocracking, facilitate the production of diverse diesel-range products (France et al., 2015).

3.2 Carbon e-fuel demand in transport

Fossil fuels, characterised by their high energy density, have underpinned most transport modalities through ICEs. Carbon-based e-fuels, exhibiting comparable physicochemical properties, likewise possess elevated energy densities, rendering them suitable for energy-intensive applications such as long-haul aviation, constrained by both volumetric and gravimetric limitations, and maritime shipping, which demands substantial energy inputs over extended distances. The International Transport Forum (2023) underscores the potential medium- to long-term role of e-fuels in decarbonising these sectors, contingent on technological advancements, scale-up of production, and supportive policy frameworks.

While green hydrogen serves as a foundational precursor for carbon-based e-fuels and is comparatively straightforward to produce, its transport and storage pose significant logistical challenges. Synthesising liquid e-fuels by incorporating captured CO_2 imparts advantages in handling and distribution, avoiding the need for extensive engine retrofits, unlike hydrogen, which necessitates substantial modifications to fossil-fuel-optimised ICEs. These hydrocarbon e-fuels function as "drop-in" substitutes, compatible with existing infrastructure and amenable to blending with conventional fuels to incrementally reduce carbon intensity (Ravi et al., 2023).

Carbon-based e-fuels hold particular appeal for the existing global fleet of 1.4 billion ICE vehicles, which have service lives of approximately 15 years in developed markets but extend by a decade in regions like Africa, which rely on second-hand imports from Europe (UNEP, 2022). Transition timelines will be protracted, propelled primarily by legislative mandates such as Europe's zero-emission vehicle policies, while Asia's burgeoning markets lack analogous regulations, ensuring a persistent ICE presence through 2035-2050. Cost and supply constraints notwithstanding, timely scale-up could carve a viable niche for e-fuels.

Niche demand persists in motorsport, where Formula 1 mandates e-fuels by 2026, unencumbered by volume (190,000 litres per vehicle annually) or cost barriers, and among classic car enthusiasts, who prioritise authenticity over price sensitivity.

Nonetheless, policymakers, academia, and industry converge on the view that e-fuels should be allocated to hard-to-abate sectors, including chemicals, aviation, and maritime transport, rather than to personal mobility.

- Carbon profile

Utilising either carbon capture and storage (CCS) or direct air capture (DAC) as the carbon feedstock, carbon-based e-fuels achieve carbon neutrality upon combustion, as the sequestered CO_2 is re-emitted to the atmosphere, rendering them distinct from zero-carbon emission fuels (Ravi et al., 2023). Given that their combustion chemistry mirrors that of fossil fuels, these e-fuels generate particulate matter emissions comparable to those of fossil fuels; however, synthesis parameters can be modulated to refine their composition and mitigate by-products (Ravi et al., 2023

- Efficiency of production

Production of carbon-based e-fuels involves a multi-stage power-to-liquid (PtL) pathway in which cumulative conversion losses substantially reduce overall system efficiency. First, renewable electricity is used to electrolyse water and generate hydrogen, an energy-intensive step requiring on the order of 50–100 kWh per kilogram of hydrogen, followed by the separate capture of carbon dioxide from either concentrated point sources or the ambient atmosphere, after which hydrogen and CO_2 undergo hydrocarbon synthesis and subsequent upgrading. Given that internal combustion engines convert only around 30% of the fuel's chemical energy into mechanical work, the resultant well-to-wheel energy efficiency for carbon-based e-fuels is approximately 10%, a figure that already assumes what Ueckerdt et al. (2021) characterise as optimistic assumptions regarding the energy requirements of direct air capture.

Table 4 : Conversion of energy : e-fuels for ICE vehicles

Production	Process	Energy source	Energy retained
Hydrolysis	Water to hydrogen	Electricity	0.6
Direct air capture	Carbon dioxide from air : 400 ppm	The majority is through waste heat (overly optimistic)*	1.0
Hydrocarbon production	Combining hydrogen and CO2	Electricit	0.8
Use			
Use in an ICE vehicle	Chemical to mechanical energy	E-fuel	0.3

* This analysis relies on an optimistic estimate of DAC energy demand, assuming a heat requirement of approximately 1,500 kWh per tonne of CO_2, representing around 15–20% of total energy input, which is entirely supplied by waste heat from other processes (Deutz et al., 2021). In contrast, industry stakeholders report substantially higher DAC energy demands of 2,500–3,950 kWh per tonne of CO_2, which pertain solely to the capture process and exclude additional energy needed for CO_2 compression, transport, or storage. Consistent with expectations, the energetic burden of direct air capture is significantly higher than that of carbon capture from high-concentration point sources.

- Efficiency of use

Both e-fuels and fossil fuels exhibit inherently low chemical-to-mechanical energy conversion efficiencies in internal combustion engines, which have incrementally improved from approximately 20% to 35% over recent decades. This contrasts markedly with Formula 1 engines, which currently achieve around 50% efficiency, with projections indicating potential advancements to 55–60%. Translating such innovations from motorsport to road vehicles could elevate standard efficiencies beyond 35%, thereby enhancing fuel economy per litre (Ueckerdt et al., 2021).

3.3 Cost challenges :

The cost of e-fuel production constitutes a formidable barrier to widespread adoption within the sector. Current production technologies operate at suboptimal scales, rendering cost projections heavily reliant on scenario-based modelling incorporating variables such as production volume and temporal horizons. Calculations herein pertain exclusively to production costs, excluding ancillary expenses associated with transportation, distribution, marketing, or profit margins (Homback et al., 2019).

Estimates of e-fuel production costs exhibit substantial variability, predominantly attributable to electrolyser capital expenditures and the price of electricity for hydrogen generation. Homback et al. (2019) projected e-diesel costs at €4.97 per litre at the time of publication, declining to €3.24 per litre by 2030. Similarly, Ueckerdt et al. (2021) conducted a comprehensive analysis acknowledging the inherent uncertainties in forecasting costs for nascent technologies necessitating concurrent advancements in production infrastructure and supportive policy frameworks (such as electrolyser capacity expansion), thereby complicating cross-study comparisons; nonetheless, their 2025 projections approximate €3.20 per litre, aligning closely with Homback et al.'s 2030 benchmark (Ueckerdt et al., 2021).

Table 5: The most important parameters for e-fuel cost estimation and sensitivity analysis

	2020-2025	2023	2050
Annual average electricity price (€MWh-1)	50 ± 10	0 50 ± 10	30 ± 10
Electrolysis CAPEX (€KWh-1, median of AEC/PEMEC literature review)	1,100 ± 389	625 ± 258	334 ± 189
DAC (€ per tCO2 captured)	460 ± 90	150 + 150/-50	50 + 50/-10

Source: Adapted from Ueckerdt et al. (2021)

Cost estimates for carbon-based e-fuel production, derived from industry experts contributing to this research and incorporating real-world data from Climeworks, a direct air capture firm engaged in carbon trading, alongside International Energy Agency projections, are disaggregated below. Divergent measurement units across sources, however, impede straightforward inter-study comparisons.

The aggregate production cost of carbon-based e-fuels currently stands at USD 6.85 per litre, covering only direct manufacturing costs and excluding transportation, distribution, taxation, and profit margins. This total derives from the following constituent costs (Odenweller et al., 2022):

- Electricity costs: USD 1.10 /l e-fuel
- DAC costs: USD 1.25 /l e-fuel
- Electrolyser: USD 2 /l e-fuel
- Fischer-Tropsch: USD 2.5 /l e-fuel

These cost estimates are predicated on the following assumptions (Odenweller et al., 2022):

- Electricity costs: USD 0.04 /kWh (for a fully integrated e-fuel production facility, thereby excluding transmission expenses)
- Production of 1 litre e-fuel necessitates 27.3 kWh of electricity, accounting for direct air capture, electrolysis, and Fischer-Tropsch synthesis
- Direct air capture costs (excluding electricity): USD 0.5 /kg CO_2
- Electrolyser costs (excluding electricity): USD 4 /kg H_2
- Fischer-Tropsch costs (excluding electricity): USD 2–3 /l e-fuel

These projected costs may decline as electricity prices fall and economies of scale increase. As noted in the preceding analysis of hydrogen production expenses, such reductions are anticipated, albeit insufficiently, until approximately 2060, when they could reach 40–45% of current levels (Odenweller et al., 2022).

However, the scientific literature indicates that mitigating the costs of electrolysers and direct air capture presents substantially greater challenges (Ueckerdt et al., 2021). Carbon capture and storage (CCS) costs are estimated at USD 10–25 per tonne of CO_2. In contrast, direct air capture costs approximately USD 2,500 per tonne, a 100-fold disparity that underscores the technological hurdles (House et al., 2011). Consequently, extant processes require modification to achieve economic viability.

Porsche, in collaboration with Siemens Energy and Highly Innovative Fuels (HIF), operates a pilot facility in Chile dedicated to producing e-fuel. Their analyses reveal substantial variability in renewable electricity costs across regions, ranging from €0.05/kWh in Germany to €0.015/kWh in Chile, and posit that e-fuel prices could achieve parity with fossil fuels under a carbon pricing regime (Behbahani & Green, 2023).

Cost projections from the fuel sector anticipate lower figures than those delineated above, estimating Fischer-Tropsch diesel (FTD) production costs at €2.42 per litre in 2030 for European facilities, declining to €2.19 per litre by 2050. For FTD manufactured in the Middle East and North Africa (MENA) and imported to Europe, costs are projected at approximately €1.92 per litre by 2050. These estimates presuppose an annual production volume of 1 million tonnes of diesel (equivalent to 1,176 million litres) to amortise upfront capital and fixed operational expenditures (Concawe & Aramco, 2022). Further analysis by Concawe and Aramco (2022) indicates that e-diesel at €2.42 per litre in 2030 contrasts starkly with conventional diesel at €0.30 per litre; assuming proportional price-cost relationships, this represents an eightfold increase relative to prevailing consumer fuel expenditures.

The commercialisation of e-fuels in the personal automobile sector will hinge substantially on their production costs and retail prices per litre, which currently exhibit considerable variability across temporal horizons and underlying assumptions. More cost-competitive alternatives risk obviating e-fuels as a viable solution for passenger vehicles. Ueckerdt et al. (2021) contend that e-fuel costs are unlikely to diminish sufficiently to warrant deployment in this sector, necessitating a carbon abatement cost of €800 per tonne of CO_2 for economic justification. By contrast, the IEA Net Zero Emissions by 2050 strategy (IEA, 2021a) estimates current carbon capture costs at USD 15–70 per barrel, equivalent to a carbon price of USD 250–400 per tonne.

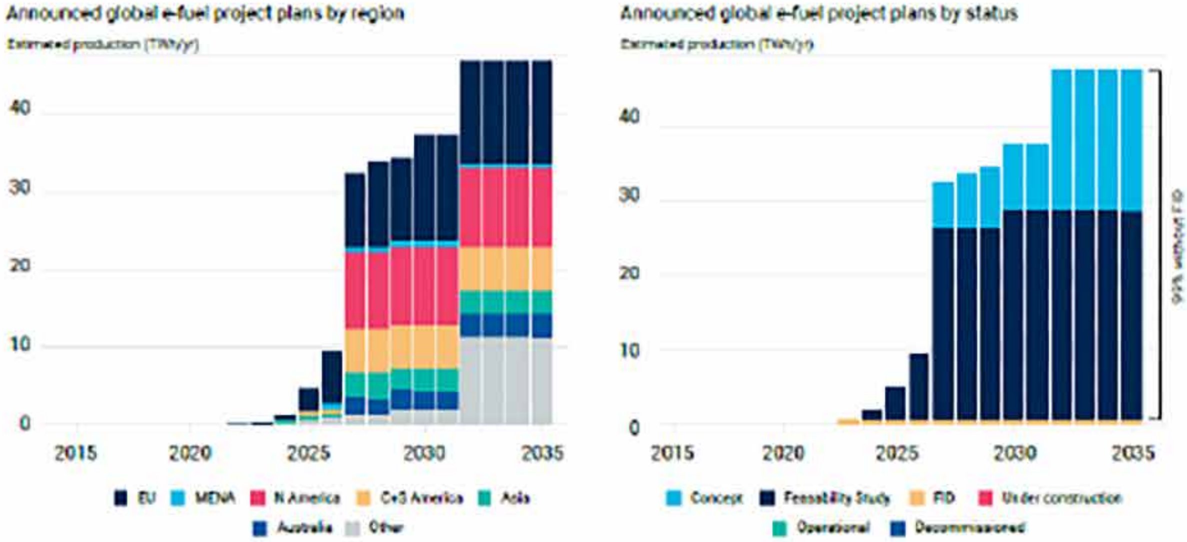
These cost comparisons juxtapose sustainable fuels synthesised from green hydrogen and direct air capture of CO_2 with fossil fuels, in which carbon pricing is excluded from production expenses, rendering the disparity unsurprising and unfavourable to e-fuels. For equitable assessments of alternative propulsion technologies, total cost of ownership metrics are more appropriate, given the divergent cost structures involved (IEA, 2021a). Global daily oil consumption for road transport is approximately 40 million barrels, equivalent to 6,360 million litres, and accounts for approximately 40% of total oil demand, which Exxon estimates at 100 million barrels per day (IEA, 2021a).

Production facilities for hydrocarbon e-fuels are proliferating, though predominantly focused on the synthesis of aviation kerosene. A notable exception is the Haru Oni project in Chile, developed by Porsche, HIF Global, and Siemens Energy, which remains at pilot scale with an annual output of 130,000 litres, anticipated to expand to 55 million litres by 2025 and 550 million litres upon completion of Phase 2. Notwithstanding these advancements, the fully realised HIF Global initiative will satisfy merely 0.02% of daily global road transport fuel demand (IEA, 2021a).

Research by Ueckerdt et al. (2023) indicates that approximately 60 carbon-based e-fuel projects are under consideration through 2035, with 99% lacking final investment decisions. Even assuming full funding across all initiatives, their collective output would satisfy merely 10% of Germany's unavoidable fuel demand for shipping, aviation, and the chemical sector. Projecting scalability akin to the rapid trajectory of photovoltaic technologies (recognised as an exemplar of accelerated industrial growth), these projects would still meet only 50% of Germany's essential requirements, thereby underscoring the formidable scalability challenges confronting e-fuels (Ueckerdt et al., 2023).

3.4 Scale of production:

Figure 13: Carbon-based e-fuels projects



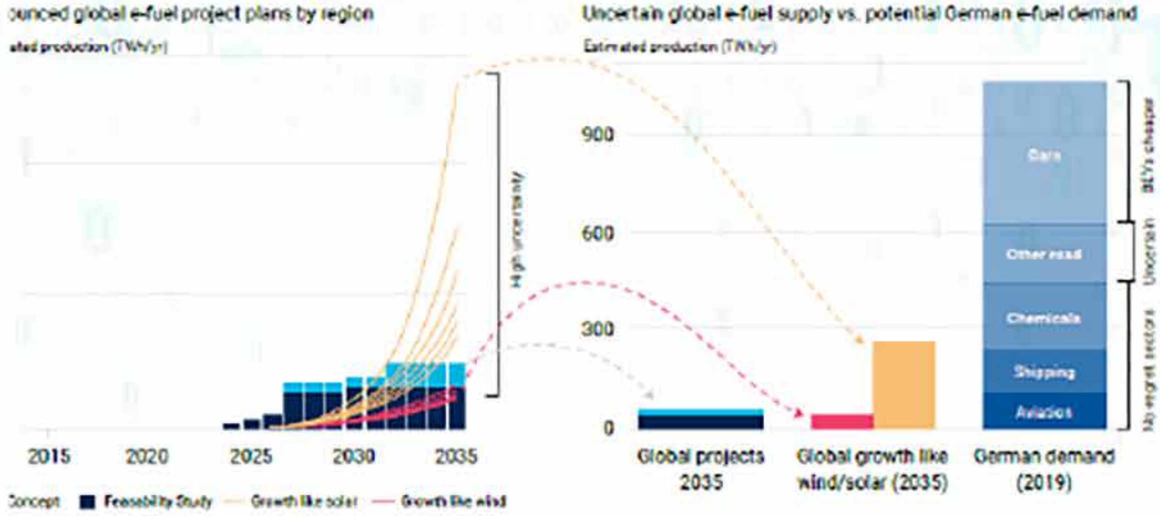


Image source: Ueckerdt et al. (2023)

Other facilities developing carbon-based e-fuels, primarily for aviation and/or maritime applications, include (Ueckerdt et al., 2023):

- Zero Petroleum: 30 litres per day designated for aviation use
- Green Fuels for Denmark: Phase 1 focused on green hydrogen for heavy-duty vehicles; Phase 2 targets carbon-based e-fuels for aviation and maritime sectors
- Norsk e-Fuels: Aviation applications

3.5 Carbon e-fuels policies and strategies:

Policy frameworks governing e-fuels have predominantly targeted 'hard-to-abate' sectors, such as aviation. The European Union has proposed regulations mandating that fuel suppliers incorporate 2% sustainable aviation fuel (SAF) by 2025, escalating to 5% by 2030 and a minimum of 63% by 2050, with a dedicated sub-mandate for e-fuels, as illustrated below. Such mandatory blending requirements would substantially expedite the development and commercialisation of e-fuel (The European Aviation Report, 2022).

Currently, sustainable aviation fuels (SAF) account for only 0.05% of aviation fuel in the European Union. Achieving the aforementioned regulatory targets would necessitate 2.3 million tonnes of e-fuels by 2030 and 28.6 million tonnes by 2050 (The European Aviation Report, 2022).

Scaling up production of carbon-based e-fuels will generate economies of scale, thereby reducing unit costs. Although incorporating the passenger vehicle sector would amplify demand, approximately 50% of fossil fuel consumption occurs beyond automobiles, prioritising expansion to serve 'no-regret' sectors such as aviation and maritime transport (Ueckerdt, 2021).

Government policies and subsidies about personal vehicle transport predominantly advocate electrification as the principal pathway to fulfilling Paris Agreement commitments. Broad-spectrum policy support could foster innovation across diverse technological domains, enabling the emergence of alternative solutions. Energy tax reforms would further engender a level playing field for all propulsion technologies (Ueckerdt, 2021).

Figure 14: Proposed 'Fit for 55' SAF mandate

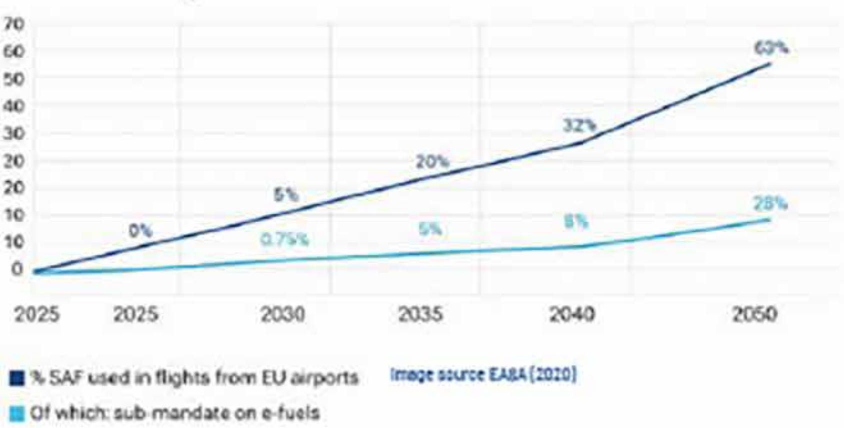


Image source EASA (2020)

Chapter 4: Biofuels As An Alternative Fuel Solution

The ensuing analysis delineates biofuels as an alternative to fossil fuels for vehicular applications, defining them and outlining their attendant advantages and challenges. The initial segment elucidates the historical trajectory of biofuels and their pertinence to decarbonisation imperatives. Subsequent technical considerations address biofuels' carbon profile, typological classifications, sectoral demand in industry and transportation, and attendant costs. Commercialisation facets encompass extant policy frameworks, infrastructural exigencies, and trade dynamics.

4.1 Background and history

Biofuels are increasingly regarded as a viable renewable energy source, capable of mitigating greenhouse gas emissions and curtailing reliance on fossil fuels. Biomass-derived fuels, such as charcoal and firewood, have been utilised since prehistoric eras, and among the earliest applications in transportation occurred during the 1890s, when Rudolf Diesel developed an engine compatible with diverse feedstocks, including vegetable oils. The twentieth century witnessed the ascendancy of abundant, inexpensive petroleum, relegating biofuel alternatives to secondary status. Contemporary interest burgeoned amid the 1970s oil crisis, prompting numerous nations to explore vegetable oils as petroleum substitutes; research endeavours culminated in the transesterification of oils into more efficient variants, yielding the term 'biodiesel' by the early 1980s. In 1985, an Austrian agricultural institution inaugurated a biodiesel production facility, and commercial-scale manufacturing proliferated across Europe and the United States by the mid-1990s (Farm Energy, 2019). Since the 1990s, biofuel production and consumption have shown consistent annual growth, driven by government policies aimed at displacing fossil fuels in transport sectors.

4.2 Technical considerations

- Definition

Biofuels, predominantly utilised in transportation, comprise liquid fuels derived from renewable biomass feedstocks. Most are deployed as blends with refined petroleum products such as gasoline and diesel, whereas 'drop-in' variants require no such admixture (EIA, 2022). Biodiesel and bioethanol constitute the predominant biofuel types for vehicular applications. Advanced biofuel production entails a multi-stage process, as depicted in Figure 15: initial deconstruction of recalcitrant plant cell walls via thermochemical (high-temperature) or biological (low-temperature) methods yields intermediates such as sugars or chemical precursors, which undergo upgrading through microbial fermentation, employing yeasts or bacteria, to generate marketable fuel blendstocks and chemicals (U.S. Department of Energy).

Figure 15: Comparison between biofuels and crude oil production

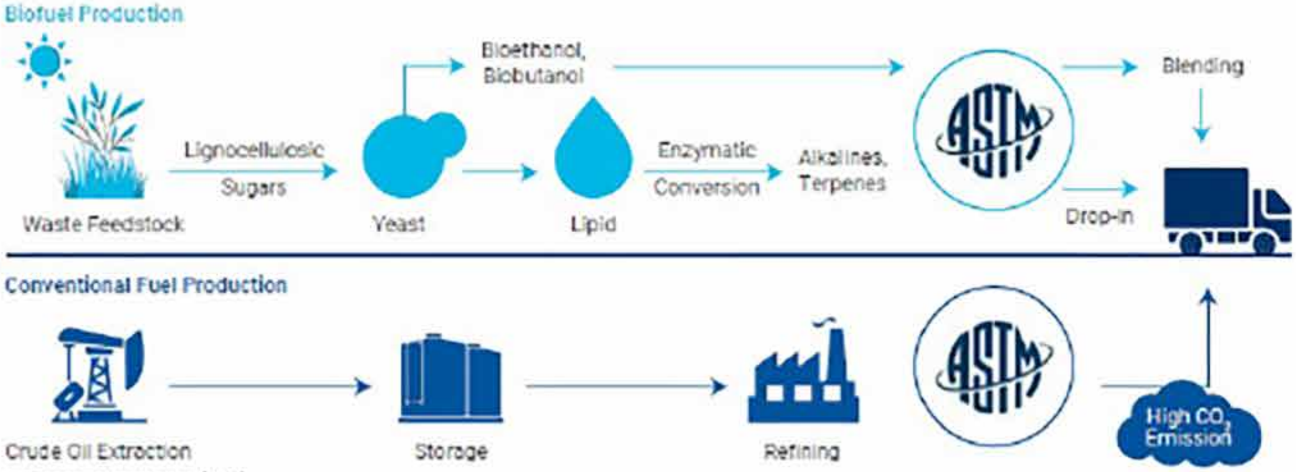


Image source: Malode et al. (2021)

• Carbon profile

In addition to evaluating an energy source's carbon footprint (defined as greenhouse gas emissions across its supply chain), land and water footprints must be considered, denoting the direct and indirect appropriation of these resources. The water footprint comprises green (rainwater consumption), blue (surface- and groundwater use), and grey (pollutant dilution) components. Holmatov and Hoekstra (2020) compared these footprints per kilometre driven in midsize vehicles across energy sources (Table 6), revealing that biofuel-powered vehicles, particularly biodiesel blends, exhibit the most adverse carbon, land, and water impacts, with bioethanol blends ranking second-worst; solar-powered battery electric vehicles demonstrated the lowest environmental burdens. Conventional gasoline displayed the second-highest carbon footprint but the minimal land footprint and second-lowest water footprint per kilometre. A critical limitation of biofuels is the inadequate accounting for land- and water-use change effects, which are paramount. Puricelli et al. (2021) conclude that biofuels generally perform comparably or inferior to fossil fuels across non-GHG impact categories, except for fossil resource depletion and ozone formation.

Table 6: Comparison of carbon, land and water footprints of vehicles with various fuel types

	Gasoline	Biofuel blend		Electricity	Hydrogen	
		B20	Bio	Bio	Solar (PVC)	
Carbon footprint (g CO2eq/km)	165	185	80.2	7.3	0	0
Land footprint (m2/km)	0	0.37	0.21	0.028	0.00091	0.0023
Water footprint (L/km)	0.25	170	163	40	0.12	0.39
Carbon footprint (kg CO2eq/driver/year)	3579	4010	1739	158	0	0
Land footprint (m/driver/year)	0	7977	4463	611	20	50
Water footprint (m/driver/year)	5	3685	3534	859	3	8

Notes:
Biofuel blend B20: 20% biodiesel from rapeseed and 80% conventional diesel - assuming circular production (using bioenergy to produce bioenergy)
Biofuel blend Bio: 85% bioethanol from sugar beet and 15% conventional gasoline - assuming circular production (using bioenergy to produce bioenergy)
Electricity Bio: from sugarcanes' biomass - assuming circular production (using bioenergy to produce bioenergy)

Hydrogen Solar (PVC): assuming circular production (using solar PV panels to make solar PV panels). Fuel efficiencies refer to: 2019 Kia Forte FE or 2019 Toyota Camry for conventional gasoline; 2019 Chevrolet Cruze Hatchback for B20; 2018 Mercedes-Benz E350 for E 85; 2019 Honda Clarity EV or Nissan Leaf (40kWh battery pack) for electric; and 2019 Honda Clarity for hydrogen. We assume here the average annual travel distance as in the US (FHWA, 2018), which is 21687 km.

Carbon footprint (g CO2eq/km) Electricity Bio: the CF of biofuels originates from nitrogen fertiliser production and soil management, while the CF of bioelectricity also includes nitrous oxide and methane emissions during combustion. Land footprint (m/driver/year): 85% bioethanol from sugar beet and 15% conventional gasoline
Water footprint (m/driver/year): from sugarcanes' biomass
Source: Holmatov and Hoekstra (2020)

• Classification of biofuels

Biofuels are categorised into four generations predicated on their production feedstocks, encompassing first-, second-, third-, and fourth-generation variants (Jord, n.d.). Distinctive production methodologies across these generations yield diverse biofuel types, several of which are enumerated in Table 7.

Table 7: Classification and types of biofuels

Classification / Generation	Feedstocks	Production	Biofuel types produced	Advantage	Disadvantage
First Generation	Corn Oil Crops Sugar beet Sugar cane Wheat	Transesterification Fermentation	Bioethanol Biodiesel	Simplest and most common production method end products reduce vehicular Exhaust pollution	Large arable agricultural land needed Land needed is in competition with land for food production
Second Generation	Grass Straw Waste Wood	Fischer-Tropsch Gasification Hydrogenation Hydrolysis Pyrolysis	Bioethanol Biomethanol Biobutanol Biopropanol Jet fuels Hydro-treated vegetable oils Mixed alcohols	Plants used are not edible therefore not in direct competition with food production The goal is to have a product for which the net carbon ratio between produced and consumed CO2 is negative.	Commercial production is not profitable as it requires costly and sophisticated technologies
Third Generation	Macroalgae Microalgae	Heterotrophic cultivation	Methane Biodiesel Biohydrogen	Most sustainable, environment-friendly economically feasible fuels Production does not require arable agricultural land and is photosynthetic, reducing CO2 from the atmosphere	Not yet a sustainable form of production due to the tedious cultivation, harvesting and extraction of microalgal strains, requiring expertise and high costs.
Fourth Generation	Genetically modified organisms	Pyrolysis Solar to fuel	Ethanol Butanol Isobutanol Modified fatty acids	Synthesised from inexhaustible raw materials which are inexpensive and easily available worldwide Unused agricultural lands and water bodies can be used as producing sites without destruction of biomass	Related regulations are diverse and complex Health, environmental and technical safety risks exist

Source: Jord (n.d.)

- **Demand and use**

According to the IEA (2023d), nearly two-thirds of biofuel demand growth preceding 2024 will materialise in emerging markets, principally Brazil, India, and Indonesia, as illustrated in Figure 16. These economies benefit from abundant domestic feedstocks, excess production capacity, competitive manufacturing costs, and multifaceted policy frameworks bolstering demand.

Figure 16: Biofuel demand growth by fuel and region (2022-2024)

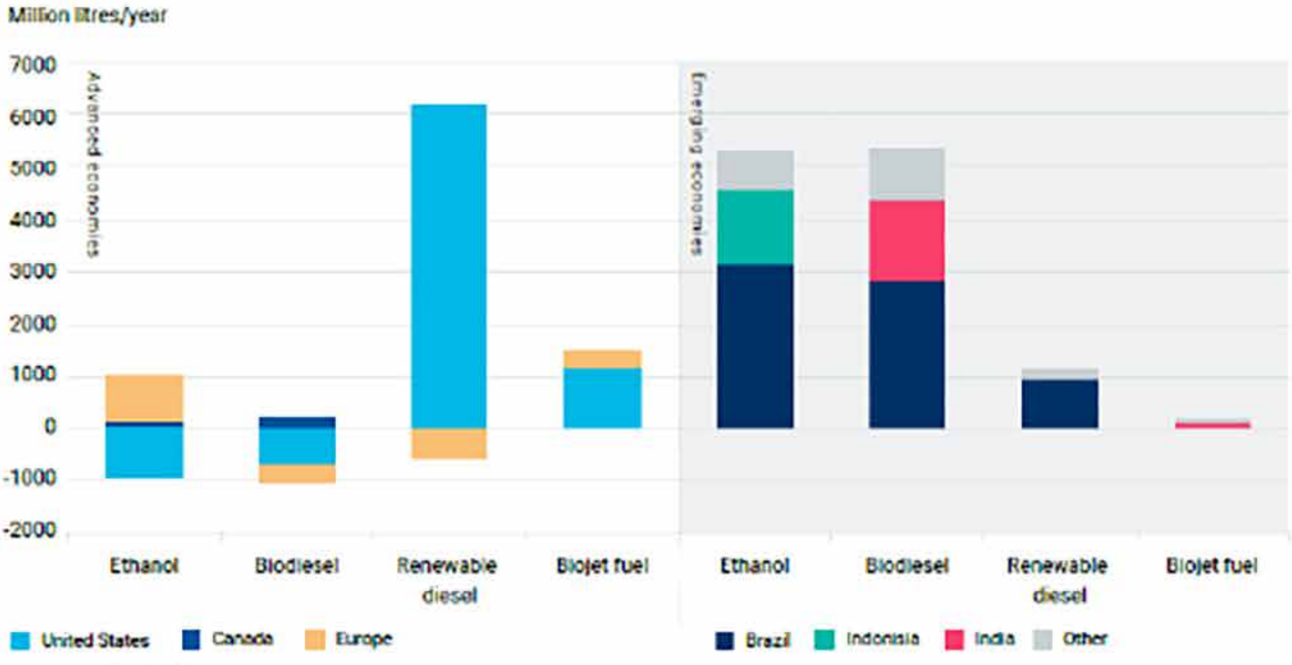


Image source: IEA (2023d)

Biofuels play a pivotal role in transportation decarbonisation, as they are compatible with existing infrastructure and engines that require minimal modifications. While vehicles optimised exclusively for biofuels remain commercially scarce, these fuels are predominantly blended with conventional petrol and diesel to attenuate CO_2 emissions. The ensuing discussion delineates three prevalent biofuels in personal vehicles: renewable diesel, biodiesel, and bioethanol (IEA, 2023d).

Table 8: Biofuel types and their advantages and disadvantages

Biofuel type	Advantages	Disadvantages
Renewable diesel	• Chemically indistinguishable from petroleum-based diesel and therefore can be used as a drop-in replacement for petroleum. • Compatible with existing diesel engine infrastructure without needing to be blended. • Cleaner alternative to fossil fuels. • Does not freeze at lower temperatures like biodiesel tends to.	• Newer technology than biodiesel, and therefore not yet as widely produced or readily available to power passenger vehicles
	Manufacturers that have approved HVO100 Renewable Diesel (Hydrotreated Vegetable Oil made from 100% renewable items and free from fossil fuels) for their diesel vehicles:	
	Volkswagen, Audi, Skoda, SEAT, Renault, Mercedes-Benz, Citroen, Peugeot, Volvo	
Biodiesel	• Almost all engines running on diesel can run on biodiesel, as it is a drop-in fuel and commonly comprises anywhere from 5% - 20% of a blend with petroleum. • Compatible with a variety of passenger road vehicles. In Europe, diesel contains 7%-10% biodiesel and is labelled 'B7' or 'B10'. • In the UK, diesel contains up to 7% biodiesel and is labelled 'B7'	• Can freeze at very low temperatures.
	Vehicles that run on biodiesel include:	
	Chevrolet Silverado, GMC Sierra 250 or 3500 HD, Ford Super Duty F250, 350, and 450, Ram 2400, 3500, 4500, and 5500, Chevrolet Colorado, GMC Terrain, Range Rover Vela, Ford Transit, Jaguar XE 20D	
	• All petrol vehicles manufactured after 2011 can use E10, the standard 95-octane petrol that contains up to 10% bioethanol. • Flexible fuel engines can run on fuel blends of up to 85% bioethanol (E85), but these require some level of engine modification for ordinary vehicles. E85 is available at several European service stations. • Bioethanol-unleaded petrol blends are popular in Brazil, where 80% of light vehicles have flexible fuel engines.	• Flexible fuel vehicles require engine modifications for a larger percentage of bioethanol in the blend.
	Manufacturers that produce flexible fuel vehicles:	
	Audi, Citroen, Dacia, Ford, GM, Chrysler, Fiat, Holden, Honda, Hyundai, Kia Motors, Mercedes-Benz, Mitsubishi, Nissan, Peugeot, Renault, Saab, SEAT, Skoda Auto, Toyota, Volvo, Volkswagen	

Sources: Car Pro Solutions (2022), Biofuel Express and Energyfactor Exxonmobil (2022)

- Cost and financing challenges

The principal impediment to biofuels (such as biodiesel, bioethanol, and biomethane) is their higher production costs relative to subsidised fossil alternatives, such as diesel and petrol. Wholesale prices for bioethanol and biodiesel range from USD 14–32/GJ and USD 22–28/GJ, respectively, contrasting with USD 9–16/GJ for conventional diesel or petrol (IRENA, 2022c). An additional constraint entails procuring financing for nascent biofuel technologies tailored to transportation, which necessitate extensive pilot-scale demonstrations; attendant market uncertainties and technological risks exacerbate funding challenges vis-à-vis projects exempt from such large-scale validation (IRENA, 2022c).

4.3 Biofuels commercialisation

4.3.1 Biofuels policy and infrastructure challenges

Policy frameworks: In 2022, energy security re-emerged as a paramount driver of biofuel policy expansion amid the energy crisis and disruptions to petroleum supply chains. The EIA (2023) projects an 11% augmentation in global biofuel demand by 2024, underpinned by policies prioritising energy security objectives. Notwithstanding this trajectory, few jurisdictions are vigorously accelerating biofuel deployment, constrained by elevated prices, feedstock scarcities, and technical limitations. Regarding feedstocks, Puricelli et al. (2021) advocate transitioning to non-edible variants, wastes, and by-products to mitigate land-use change risks, a direction reinforced by European legislation via Directive 2018/2001 and Regulation 2019/807. Table 9 delineates policy typologies across select countries and regions.

Table 9: Policies and their barriers

Barriers	Policies	Examples of countries and regions with policies and programmes
Policy uncertainty	Long-term strategy and targets	European Union, Thailand, United States
High cost	Blending mandates	Angola, Brazil, Canada, Ethiopia, Kenya, Malawi, South Africa, United States, Zimbabwe
	Renewable fuel standards	United Kingdom, United States, California
	Financial and fiscal incentives	Brazil, Philippines, Sweden, Thailand, United States
Low technical readiness level	Loan guarantees to RD&D	United States
Sustainability concerns	Sustainability governance	European Union

Source: IRENA (2022c)

Infrastructure

Novel biofuel technologies exhibit low technology readiness levels, attributable to the intricacy of processes such as gasification, pyrolysis, and hydrothermal liquefaction, compounded by constraints on sustainable feedstock availability. Moreover, scaling biofuel deployment for transportation necessitates substantial capital investment in ancillary infrastructure for storage, transportation, and distribution. Even drop-in fuels like HVO100 renewable diesel demand supplementary infrastructure, while the paucity of E85 fuelling stations further impedes bioethanol adoption (IRENA, 2022c).

4.5 Biofuels trade and international collaboration

Amid the 2022 energy crisis, biofuel production expanded in jurisdictions possessing abundant, cost-competitive feedstocks, surplus manufacturing capacity, and adaptable policy mechanisms. Nations including Argentina, India, and Indonesia accelerated biofuel adoption that year, thereby curtailing fossil fuel imports. Conversely, biofuel prices escalated more rapidly than those of petrol and diesel in numerous countries, exacerbating transportation costs; in response, Brazil, Finland, and Sweden deferred scheduled augmentations to biofuel blending mandates. To expedite biofuel deployment notwithstanding elevated comparative pricing, international collaboration, encompassing best-practice dissemination, coordinated research endeavours, and harmonised standards, proves indispensable. Select initiatives are examined below (IEA, 2023d).

The Biofuture Platform Initiative, inaugurated under the Clean Energy Ministerial framework in 2021, engages over 20 countries in cultivating consensus on biomass sustainability, disseminating best practices, facilitating financing mechanisms, and advancing international cooperation.

IEA Bioenergy: A Technology Collaboration Programme delivering pioneering analyses on bioenergy technology advancement, demonstration projects, market deployment strategies, sustainability considerations, and policy frameworks.

Global Bioenergy Partnership: An initiative designed to bolster national and regional policymaking alongside sustainable practices within emerging economies.

Infrastructure: Novel biofuel technologies exhibit low technology readiness levels, attributable to the intricacy of processes such as gasification, pyrolysis, and hydrothermal liquefaction, compounded by constraints on sustainable feedstock availability. Moreover, scaling biofuel deployment for transportation necessitates substantial capital investment in ancillary infrastructure for storage, transportation, and distribution. Even drop-in fuels like HVO100 renewable diesel demand supplementary infrastructure, while the paucity of E85 fuelling stations further impedes bioethanol adoption (IRENA, 2022c).

Chapter 5: Electricity As An Alternative Fuel Solution

This section explores vehicle electrification, encompassing its historical development, principal typologies, and contributions to decarbonization efforts. First, the advancements in battery technologies integral to EVs will be examined. Secondly, the escalating demand for electrical energy storage across transportation and industrial sectors will be addressed. Finally, commercial dimensions, including pertinent policies, infrastructure imperatives, and global trade dynamics associated with EVs, will be explored.

5.1 Background and history

EVs emerged in the aftermath of the Industrial Revolution, with a developmental history spanning more than a century. Unlike the dominant steam and gasoline engines of the period, EVs offered distinct advantages, including silent operation, ease of handling, and zero tailpipe emissions (Rajashekara, 1994). The first viable EV, developed by Thomas Parker in 1884, exemplifies early innovation in electric propulsion (Guarnieri, 2012). Similarly, Ferdinand Porsche's prototype, constructed in Germany in 1899, highlights pioneering advancements in electric mobility (Guarnieri, 2012). EVs achieved notable market penetration in the 1920s, accounting for approximately 28% of U.S. vehicle production before Henry Ford's mass production of the Model T (Sun et al., 2019). Nevertheless, their progress was curtailed by prohibitive manufacturing costs, limitations in battery performance, and concurrent advances in internal combustion engine technologies (Guarnieri, 2012).

5.2 Energy crisis and climate awareness

The energy crises of the 1970s revitalised interest in EVs as a strategy to mitigate reliance on fossil fuels (Coyle et al., 2014). The subsequent resurgence in EV adoption gained significant traction, propelled by heightened environmental awareness, breakthroughs in battery technology, imperatives to curtail fossil fuel consumption, and supportive government policies that foster sustainable transportation (Coyle et al., 2014). The trajectory of EV development thus extends beyond the technical dimensions of battery chemistry and electric drivetrains to encompass a profound societal shift toward cleaner, more efficient, and sustainable mobility paradigms.

Figure 17: Timeline of the key milestones in the history of EVs

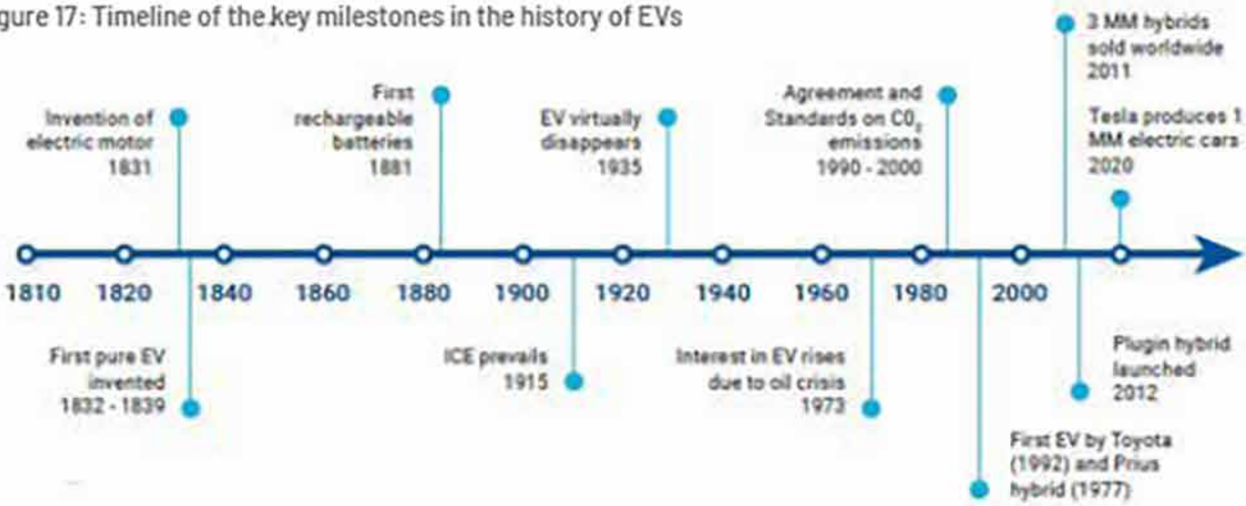


Image source: Malode et al. (2021)

5.3 Types of EVs

This section delineates the principal typologies of EVs currently produced and marketed by leading automotive manufacturers. For comparative analysis in subsequent sections of this report, emphasis is placed on BEVs, given their capacity to achieve near-zero tailpipe emissions.

5.3.1 Battery Electric Vehicles (BEVs)

BEVs are fully electric platforms that rely on an onboard battery pack to store electrical energy, which powers the vehicle's electric motor. These batteries are recharged by connecting the vehicle to an external electricity source. The provenance of electricity used for charging remains a salient concern, as non-renewable generation continues to cause air pollution and greenhouse gas (GHG) emissions. Nonetheless, BEVs are classified as zero-emission vehicles owing to their absence of direct tailpipe or exhaust emissions (EERE, 2023).

Figure 18: Components of an all-electric vehicle (BEV)

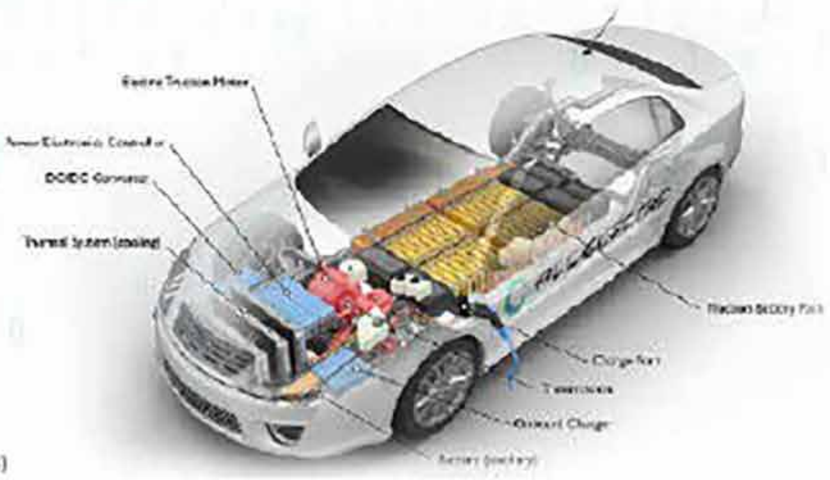
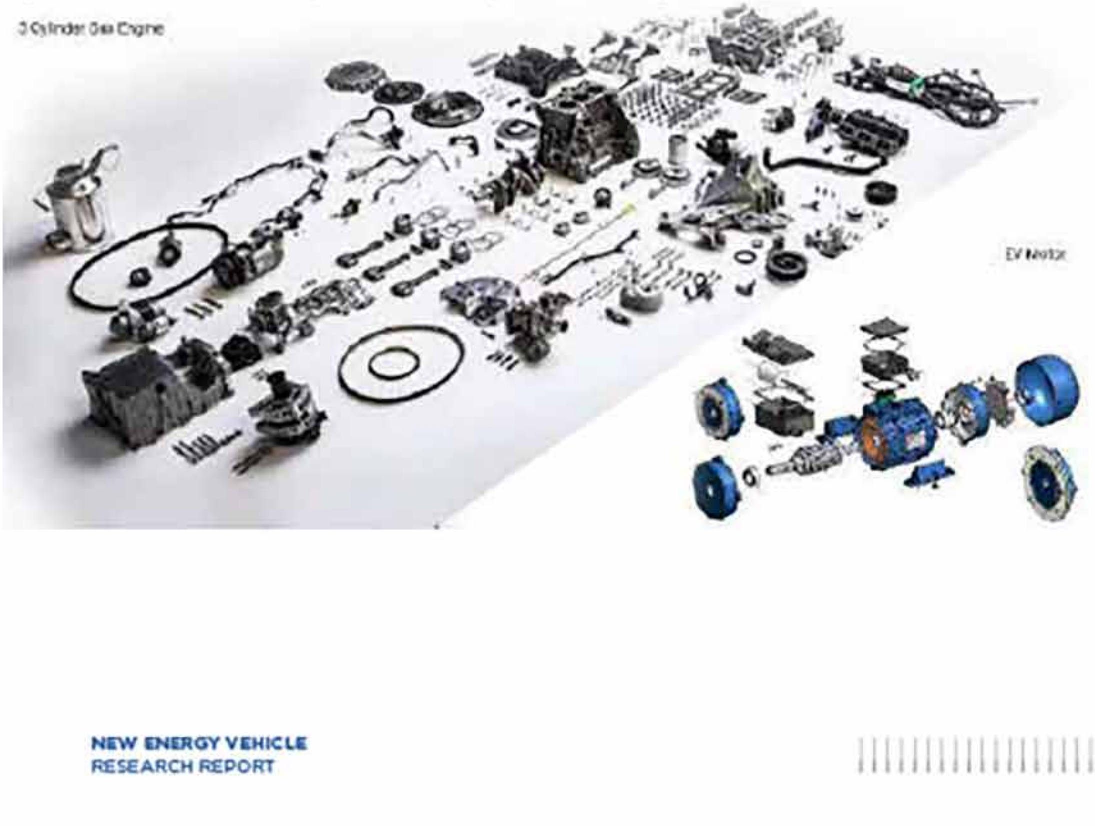


Image source: EERE (2023)

Component	Description
Battery (all-electric auxiliary)	Provides electricity to power vehicle accessories.
Charge port	Connects to an external power supply to charge the traction battery pack.
DC/DC converter	Converts higher-voltage DC power from the traction battery pack to lower-voltage to run vehicle accessories and recharge the auxiliary battery.
Electric traction motor	Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.
Onboard charger	Takes incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery. It also communicates with the charging equipment and monitors battery characteristics such as voltage, current, temperature, and state of charge while charging the pack.
Power electronics controller	Manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.
Thermal system (cooling)	Maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.
Transmission (electric)	Transfers mechanical power from the electric traction motor to drive the wheels.

Source: EERE, 2023)

Figure 19: EV motor in comparison to a 3-cylinder fuel engine



5.3.2 *Hybrid Electric Vehicles (HEVs)*

HEVs integrate an ICE, a battery pack, and at least one electric motor to propel the vehicle. The ICE serves as the primary power source, with the electric motor augmenting it to optimise performance. This synergistic architecture yields reduced CO_2 emissions and enhanced fuel efficiency without compromising drivability. Batteries are recharged via regenerative braking, though HEVs lack plug-in capability (EERE, 2023).

Table 11: Key components of a Hybrid Electric Vehicle (HEV):

Component	Description
Exhaust system	The exhaust system channels the exhaust gases from the engine out through the tailpipe. A three-way catalyst is designed to reduce engine-out emissions within the exhaust system.
Fuel filler	A nozzle from a fuel dispenser attaches to the receptacle on the vehicle to fill the tank.
Fuel tank (gasoline)	This tank stores gasoline on board the vehicle until it's needed by the engine.
ICE (spark-ignited)	In this configuration, fuel is injected into either the intake manifold or the combustion chamber, where it is combined with air, and the air/fuel mixture is ignited by the spark from a spark plug.
Power electronics controller	This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.
Thermal system (cooling)	This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.
Traction battery pack	Stores electricity for use by the electric traction motor.
Transmission	The transmission transfers mechanical power from the engine and/or electric traction motor to drive the wheels.

Source: (EERE, 2023)

5.3.3 *Plug-in Hybrid Electric Vehicles (PHEVs)*

PHEVs employ a dual-propulsion architecture that integrates BEV and ICE technologies. Propulsion derives from an ICE fueled by conventional hydrocarbons and an electric motor powered by an onboard battery pack. Batteries are recharged via external wall outlets or dedicated charging infrastructure, the ICE itself, or regenerative braking. The operation prioritises electric propulsion until battery depletion, at which point the system seamlessly transitions to ICE dominance. This configuration enhances fuel economy, elevates performance, and extends overall range (EERE, 2023).

PHEVs typically operate across at least two propulsion modes (Agnew Group, n.d.):

- **Hybrid Mode:** The vehicle draws power concurrently from both electricity and liquid fuel (petrol or diesel).
- **All-Electric Mode:** Propulsion relies exclusively on the electric motor and battery pack.

PHEVs generally operate in hybrid mode, with the driver manually selecting all-electric mode.

Table 12: Key additional components of a Plug-in Hybrid Electric Vehicle (PHEV)

Component	Description
Charge port	The charge port allows the vehicle to connect to an external power supply in order to charge the traction battery pack.

Source: (EERE, 2023)

5.3.4 *Battery technology and EVs*

The rechargeable battery pack constitutes the cornerstone of electric propulsion systems (Shen et al., 2014). Advancements in core performance indicators, including energy, power, lifespan, safety, and cost, command substantial interest from both industry stakeholders and consumers (Wang et al., 2016a). These metrics are subdivided into specific energy (〖Wh kg〗 ^(-1)), energy density (〖Wh L〗 ^(-1)), specific power (〖W kg〗 ^(-1)), power density (〖W L〗 ^(-1)), and charge acceptance (notably fast-charging capability). Critical supplementary factors include cycle and calendar life, alongside mechanical, electrical, and thermal safety, and cost per unit energy content (Liu et al., 2022). The industrial value chain for rechargeable batteries in EV mobility, as illustrated below, encompasses six sequential stages: raw material processing and component fabrication, cell manufacturing, module assembly, pack integration, vehicle incorporation, and subsequent recycling or second-life applications.

Figure 20: Industrial value chain and circulation of rechargeable batteries for EV mobility

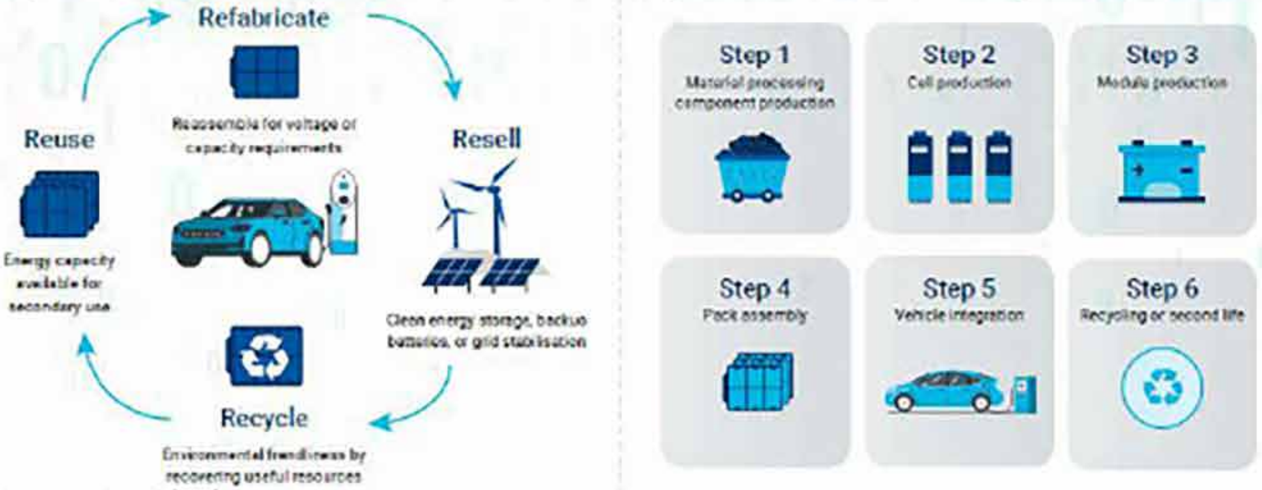


Image source: Liu et al., (2022)

5.4 Types of electrochemical energy storage

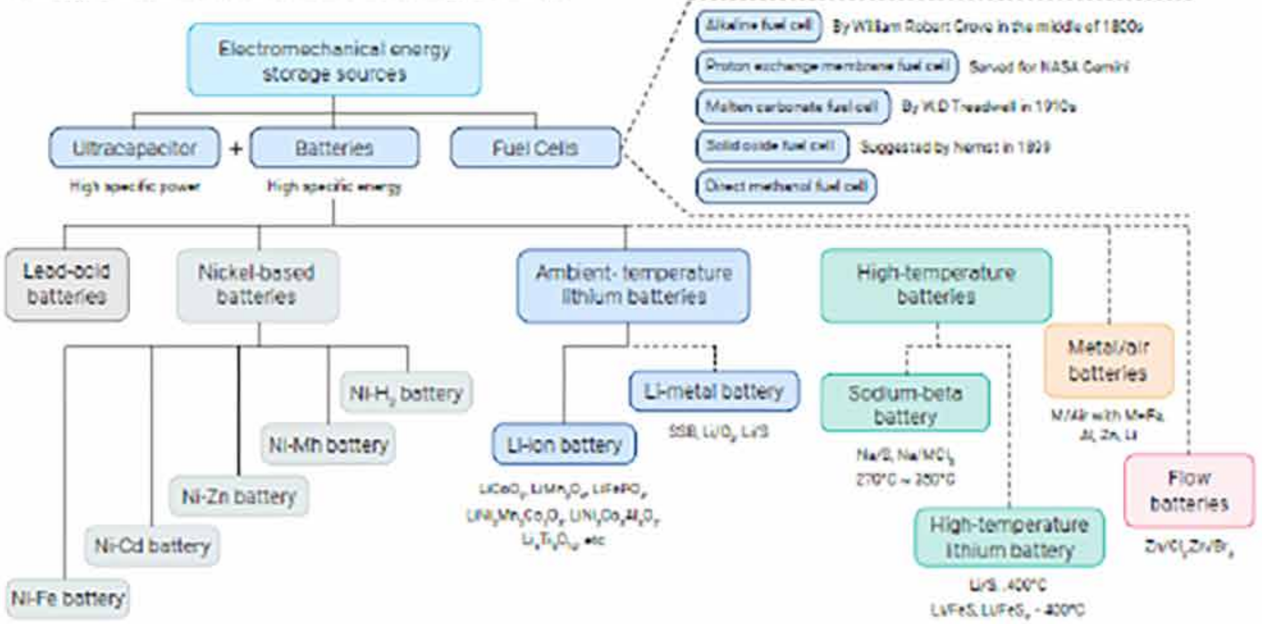


Image source: Liu et al., (2022)

The figure above delineates the principal battery technologies in EV evolution, namely, nickel-based batteries, lead-acid batteries, and lithium-ion batteries (LIBs), each fulfilling distinct roles across developmental phases (Hannan et al., 2018). While nickel-based batteries have been mainly supplanted, lead-acid variants persist in niche applications such as vehicle ignition and lighting. Nevertheless, their specific energy and energy density remain modest (up to 40"" 〔"Wh kg"〕 ^(-1) and 90"" 〔"Wh L"〕 ^(-1)), in stark contrast to LIBs (260"" 〔"Wh kg"〕 ^(-1) and 700"" 〔"Wh L"〕 ^(-1) at the cell level) (Schmuch et al., 2018).

Lithium-ion batteries (LIBs) represent a pivotal advancement in battery technology, distinguished by their superior energy density, enhanced safety profiles, and extended cycle life (Schmuch et al., 2018; Gong et al., 2015; Winter et al., 2018). High-temperature batteries, operable at 270–400 °C, show substantial promise with elevated specific power and specific energy metrics (Liu et al., 2022).

5.6 Dominance of lithium-ion batteries

Lithium-ion batteries (LIBs) have achieved hegemony in portable electronics and secured pervasive adoption across burgeoning electric vehicle and stationary energy storage markets (Duffner et al., 2021; Lukic et al., 2008; Whittingham, 2012). This dominance stems from the inherent limitations of antecedent technologies (such as lead-acid and nickel-based batteries) and the suboptimal performance of post-lithium alternatives, including sodium-ion batteries (SIBs), which exhibit markedly lower energy density and specific energy than state-of-the-art LIBs (Karabelli et al., 2020). SIBs, however, constitute a notable exception among emerging metal-ion technologies (e.g., Mg-, Zn-, Al-ion), demonstrating superior maturation and poised for imminent market entry (Konarov et al., 2018; MIT Review, 2023).

Lithium demand for batteries is forecast to expand tenfold between 2020 and 2030, driven primarily by accelerating electric vehicle (EV) adoption. EVs constituted 34% of global lithium demand in 2020 but are projected to comprise 75% by 2030 (IRENA, 2022b).

5.7 Importance of battery management systems

Effective battery management systems (BMS) are essential for ensuring the reliable and secure operation of EV batteries. Throughout charge-discharge cycles, BMS optimises peak performance while prolonging operational lifespan. Every EV integrates a dedicated BMS (Xiong et al., 2018), which coordinates an array of critical functions encompassing:

1. Battery state estimation: Accurately gauging the current state of the battery to optimise its usage (Ouyang et al., 2019).
2. Battery cell balancing: Ensuring uniform performance across battery cells for enhanced efficiency (Ouyang et al., 2019).
3. Pack charging/discharging control: Regulating the charging and discharging processes of the battery pack (How et al., 2020).
4. Thermal management: Maintaining optimal battery temperature to prevent overheating (Zhang et al., 2018).
5. Fault prognosis and health diagnosis: Predicting faults and diagnosing the health of the battery (Li et al., 2021).
6. Correspondence: Coordinating various functions within the BMS.

From a software standpoint, the evolving paradigm of information, communication, and computing technologies offers transformative opportunities for advancing battery management systems (BMS) (Ng et al., 2020). These encompass the assimilation of nascent paradigms, including artificial intelligence (AI), cloud computing (CC), and blockchain. As the automotive sector assimilates these innovations, the BMS emerges as a catalyst for safer, more efficient, and technologically advanced electric mobility (Liu et al., 2022).

5.8 Growth and demand of the global battery industry

The figure below shows the exponential growth of the global battery industry, with capacity forecast to exceed 2500 GWh within the next decade. Subfigures (b) and (c) delineate trajectories of battery demand across diverse applications and geographic regions (Liu et al., 2022). Electric mobility is the primary catalyst for this surge, driven by escalating demand for advanced battery systems. While China anticipates a contracting market share (Zhao et al., 2021), other regions project proportional expansion. This evolution aligns with government mandates promoting electric and new energy vehicles, concomitant advancements in battery materials and vehicular computing, and the broader transition toward intelligent, green mobility paradigms.

Figure 22: The expansion of the global battery industry

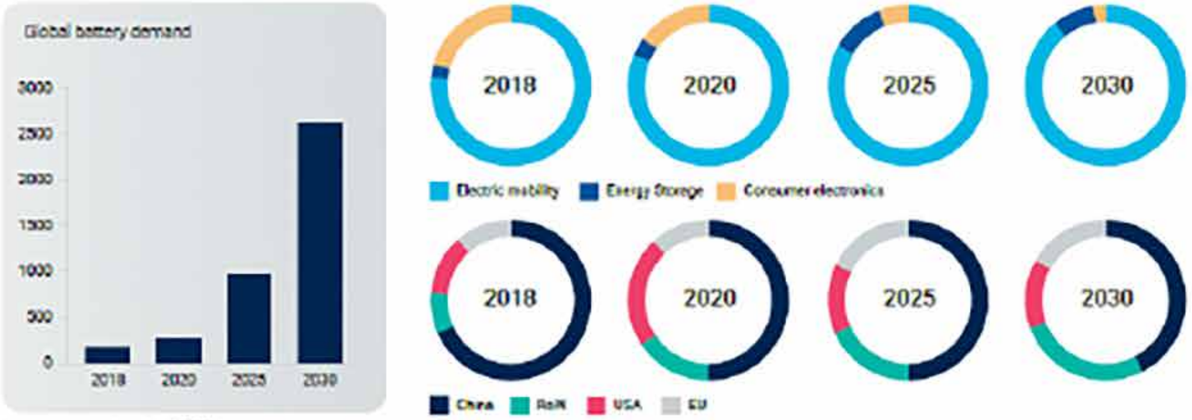


Image source: Liu et al., (2022)

Table 7: Classification and types of biofuels

Classification / Generation	Feedstocks	Production	Biofuel types produced	Advantage	Disadvantage
First Generation	Corn Oil Crops Sugar beet Sugar cane Wheat	Transesterification Fermentation	Bioethanol Biodiesel	Simplest and most common production method end products reduce vehicular Exhaust pollution	Large arable agricultural land needed Land needed is in competition with land for food production
Second Generation	Grass Straw Waste Wood	Fischer-Tropsch Gasification Hydrogenation Hydrolysis Pyrolysis	Bioethanol Biomethanol Biobutanol Biopropanol Jet fuels Hydro-treated vegetable oils Mixed alcohols	Plants used are not edible therefore not in direct competition with food production The goal is to have a product for which the net carbon ratio between produced and consumed CO2 is negative.	Commercial production is not profitable as it requires costly and sophisticated technologies
Third Generation	Macroalgae Microalgae	Heterotrophic cultivation	Methane Biodiesel Biohydrogen	Most sustainable, environment-friendly economically feasible fuels Production does not require arable agricultural land and is photosynthetic, reducing CO2 from the atmosphere	Not yet a sustainable form of production due to the tedious cultivation, harvesting and extraction of microalgal strains, requiring expertise and high costs.
Fourth Generation	Genetically modified organisms	Pyrolysis Solar to fuel	Ethanol Butanol Isobutanol Modified fatty acids	Synthesised from inexhaustible raw materials which are inexpensive and easily available worldwide Unused agricultural lands and water bodies can be used as producing sites without destruction of biomass	Related regulations are diverse and complex Health, environmental and technical safety risks exist

Source: Jord (n.d.)

Tesla

Tesla takes a prominent lead in the BEV sector, with production of over 1.3 million units in 2022 (Pontes, 2023) representing 18.2% of the global BEV sales, though it signifies a slight decline of an estimated 5% from the preceding year.

18.2% of the global BEV sales

BYD

BYD substantially bolstered its BEV sales during 2022, reaching 913 052 units and capturing a 12.6% share within the BEV market (Pontes, 2023).

12.6% share within the BEV market

SAIC

SAIC, with a 9.3 % share (671 725 units sold) is partially enabled by the SAIC-GM-Wuling joint venture and its microcars (Pontes, 2023).

9.3% Market share

Volkswagen Group

The Volkswagen Group had a 7.9% share (571 067 units sold) in 2022 and is expected to increase to a 10% share, that it held in 2021 (Pontes, 2023).

7.9% Market share

Geely-Volvo

Subsequently, the fifth-largest contributor to the BEV market is the Geely-Volvo partnership, with a 5.3% (383 936 units sold) market share.

5.3% Market share

The top five BEV manufacturers collectively account for 53.3% of the market, or 3,854,110 units sold. The residual market share, comprising approximately 3.38 million units, is attributable to other producers, including several major ICE OEMs that currently hold modest positions in the EV segment. In aggregate, the global BEV market thus totals roughly 7.23 million units (Pontes, 2023).

Figure 24: Top 10 EV Battery Manufacturers in 2022:

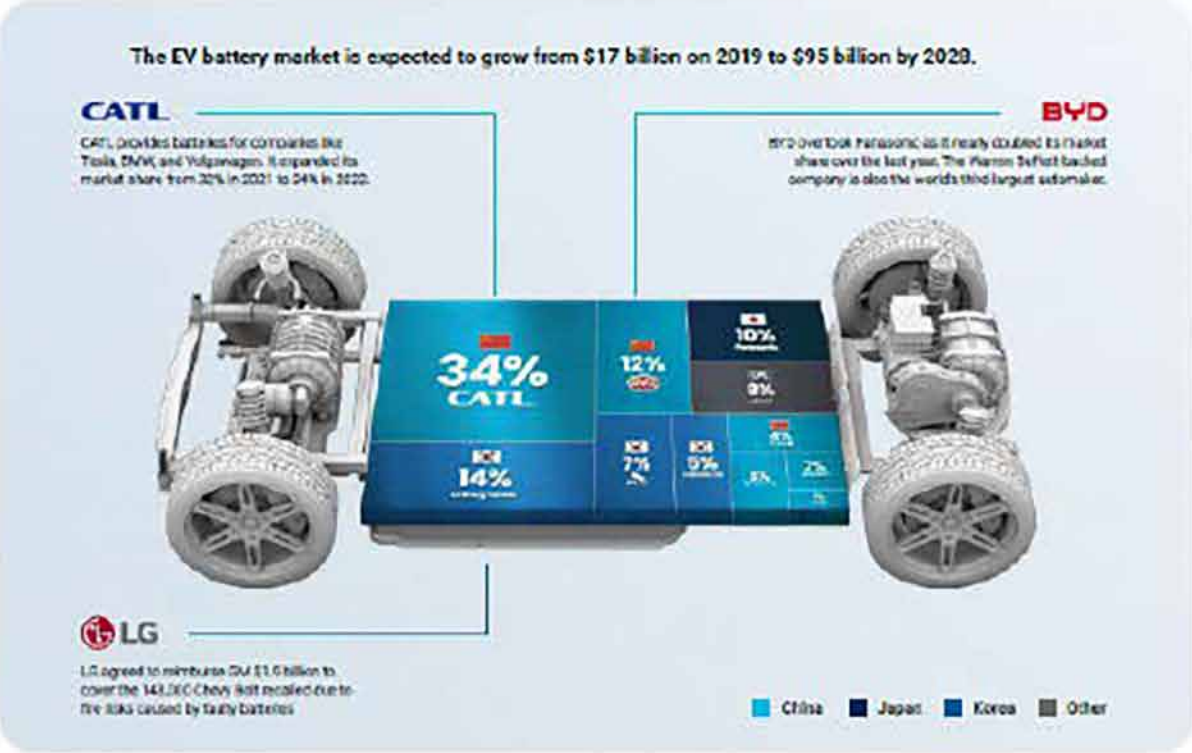


Image source: Venditti (2022)

The figure above shows the top 10 EV battery manufacturers in 2022. Notably, production among these top manufacturers remains geographically concentrated in Asia. CATL, in particular, expanded its dominance in battery manufacturing, capturing one-third of the global EV battery supply in 2022 (Venditti, 2022). The company serves as a key lithium-ion battery supplier to prominent OEMs, including Tesla, Peugeot, Hyundai, Honda, BMW, Toyota, Volkswagen, and Volvo.

5.11 Battery production costs

In 2022, the estimated average battery cost stood at approximately USD 150 per kWh (IEA, 2023c). Pack manufacturing expenses accounted for roughly 20% of total battery costs, a significant decline from over 30% a decade prior. In contrast, cell production costs rose in 2022 relative to 2021 levels, reverting to those observed in 2019. This increase stems partly from surging raw material prices, which account for a significant share of cell costs, and from elevated electricity costs, which further burden manufacturing.

The variability in the availability and pricing of battery-critical minerals profoundly influences production costs and shapes the development and manufacture of specific battery chemistries. For example, lithium carbonate prices have risen steadily over the past two years. As illustrated in Figure 24 below, 2021 witnessed a dramatic surge, with prices escalating four- to five-fold relative to prior years (IEA, 2023c). In 2023, lithium prices peaked at levels six times higher than their 2015-2020 average, though they have since begun to decline. By contrast, manganese prices remained relatively stable over this period.

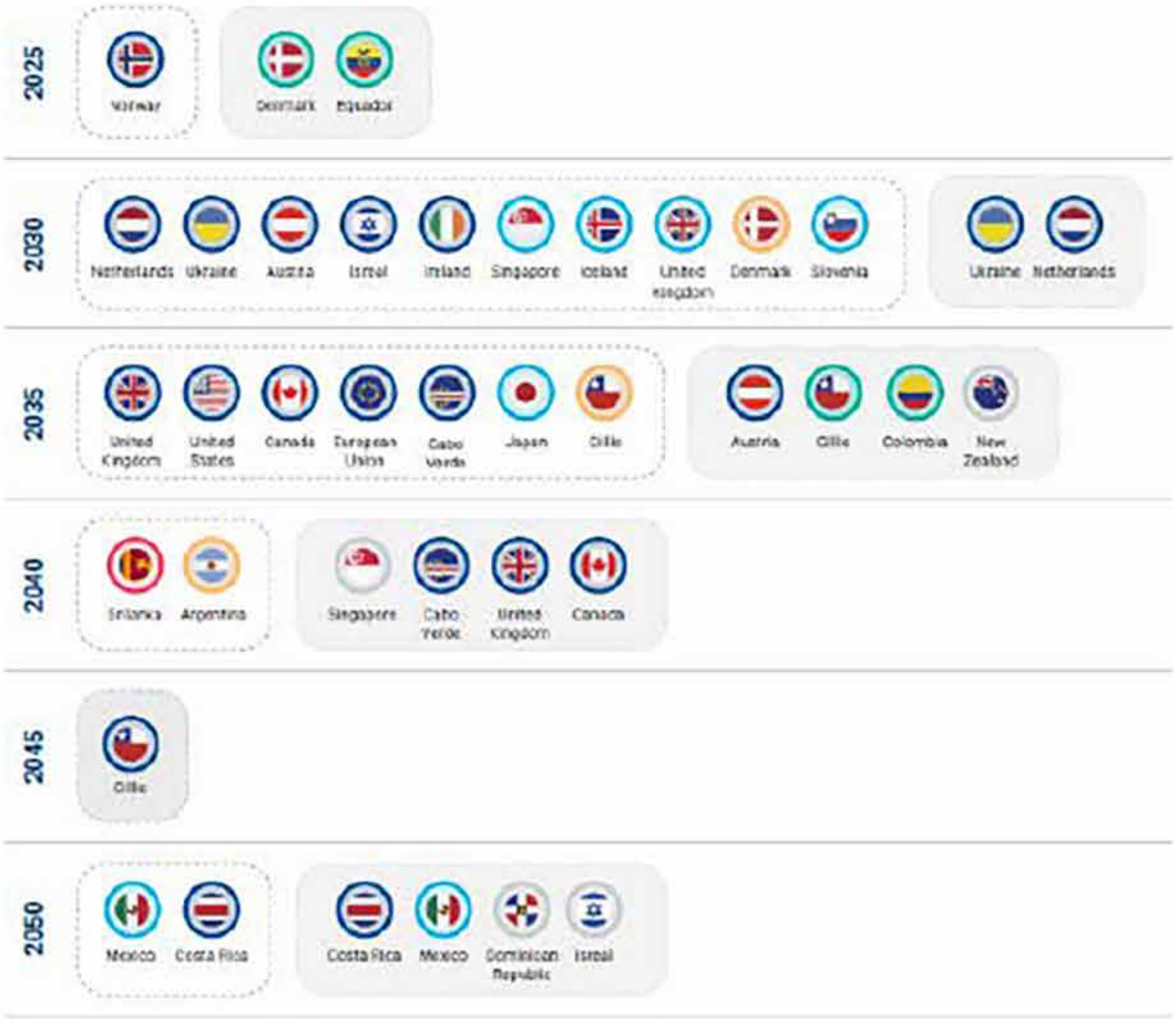
Figure 25: Price of selected battery materials and lithium-ion batteries (2015-2023)

Notes: Data until March 2023. Lithium-ion battery prices (including the pack and cell) represent the global volume-weighted average across all sectors. Nickel prices are based on the London Metal Exchange, used here as a proxy for global pricing, although most nickel trade takes place through direct contracts between producers and consumers. The 2023 battery price value is based on cost estimates for NMC 622.

From 2021 to the end of 2022, the prices of critical materials such as lithium, cobalt, and nickel increased dramatically, putting pressure on the historical trend of Li-ion battery price decreases.
Image source: IEA (2023c)

5.12 *Electrification policies and strategies:*

Figure 26: Global zero-emission vehicle mandates and ICE bans



* Refers to the share of passenger light-duty vehicle sales accounted for by Advanced Clean Cars II (ACC II) signatories or proposed signatories. Notes: ICE = internal combustion engine; ZEV = zero-emission vehicle; "electrified" includes HEVs in addition to EVs and fuel cell electric vehicles. European Union countries with LDV targets earlier than the EU 2035 target are included separately. Only countries that have legislated or proposed an ICE ban or 100% electrification target have been included. The proposed EU heavy-duty vehicle CO2 standards include a 100% emission-reduction target only for urban buses and are thus not included in the chart. The Global Memorandum of Understanding (MoU) on Zero-Emission Medium- and Heavy-Duty Vehicles is a pledge and is therefore also not included. Zero-emission vehicle targets are now in place in an increasing number of countries, including in emerging markets and developing economies. Image source: IEA (2023c)

Global EV markets exhibit considerable heterogeneity today, influenced by varying degrees of policy support, corporate strategies, consumer preferences and awareness, driving habits, and cultural factors. Policy interventions have played a particularly pivotal role in directing corporate strategies toward electrification and facilitating consumer adoption (IEA, 2023c). In key markets such as China, Europe, and the United States, targeted policies have been implemented to promote EV manufacturing, deployment, procurement, and component production (IEA, 2023c).

Many regions are witnessing the maturation of EV markets, particularly in the passenger vehicle segment, where market share is expanding rapidly. In more advanced markets such as China and several European countries, incentive schemes for EVs are being progressively reduced or phased out, with policy attention shifting to segments such as heavy-duty transport and charging infrastructure (IEA, 2023c). Concurrently, some governments have raised their EV adoption targets and are addressing broader supply chain issues through measures that support vehicle and battery manufacturing and critical mineral sourcing. Nations beyond the primary markets have likewise begun introducing supportive policies in recent years. Collectively, global expenditures by governments and consumers on EVs have surged markedly, surpassing USD 400 billion in 2022 (IEA, 2023c).

For OEMs, policy mandates served as a critical driver for electrification during the nascent stages of EV adoption. However, amid the exponential surge in EV sales, major incumbent OEMs have increasingly prioritised EV offerings to secure market share and sustain competitive advantage. Intensifying competition, fuelled by the proliferation of new entrants, particularly from China and other emerging markets and developing economies, has propelled the industry toward accelerated decarbonization (IEA, 2023c). Between 2022 and 2023, OEMs issued a series of pivotal announcements, encompassing commitments to fully electric fleets, more affordable models, expanded investments, and deeper integration across battery production and critical mineral supply chains.

The subsequent section delineates key policies, categorised as follows:

- Manufacturing incentives: Aimed at accelerating innovation and production scaling.
- Net zero emissions incentives: Designed to advance net zero emissions objectives.

5.1.3 Manufacturing incentives

In China, initiatives in Chongqing and Jilin have systematically incentivised and collaborated with EV manufacturers, thereby fostering domestic production across the supply chain. These decade-long endeavours encompass both supply- and demand-side incentives, alongside partnerships with global OEMs, particularly at the local level, that have propelled EV adoption and cultivated leading domestic EV enterprises. Ambitious manufacturing targets, such as Chongqing's mandate for a 10% NEV contribution and Jilin's goal of 1 million NEVs in annual capacity by 2025, exemplify China's commitment to bolstering its EV manufacturing ecosystem (Wang et al., 2017).

In the United States, the Inflation Reduction Act (IRA) of 2022 establishes tax incentives and funding mechanisms to advance a cleaner energy economy, with a strong emphasis on EV adoption through stringent vehicle eligibility criteria. Effective from 2023, qualifying EVs must be assembled in North America, incorporate batteries with a capacity exceeding 7 kWh, and meet specified price thresholds, while income restrictions cap the per-vehicle tax credit at USD 7,500. Restrictions on foreign-sourced critical minerals take effect in 2025. Additionally, the IRA offers Advanced Manufacturing Production Tax Credits for domestic battery production, which could offset nearly one-third of battery costs. These measures, alongside strategic partnerships and supply chain initiatives, underscore the United States' commitment to EV development (WH, 2023).

In the European Union, the Green Deal Industrial Plan, unveiled in February 2023, rests on four pillars: expedited permitting, financial support, skills development, and open trade, with a central focus on net zero initiatives. It incorporates the Critical Raw Materials Act to address supply security, extraction, and recycling. The Net Zero Industry Act streamlines planning approvals for facilities such as battery production plants. Financial measures aim to accelerate access to subsidies, bolster liquidity, and offset elevated energy costs. The plan further emphasises workforce reskilling through Net Zero Industry Academies, alongside efforts to strengthen supply chain resilience, foster open trade partnerships, and attract private investment (European Commission, 2023).

In India, the Production Linked Incentive (PLI) scheme, launched in 2021 with a budget of INR 181 billion, aims to strengthen domestic battery manufacturing. It targets 50 GWh of capacity within five years, contingent on meeting sales and value-added benchmarks. Despite nascent local battery cell production, the initiative garnered 10 bids totalling 128 GWh of capacity; funding was ultimately awarded to 3 companies for 30 GWh, with further allocations anticipated. Complementing this, the Automotive PLI scheme, encompassing the Champion OEM and Component Champion segments, provides incentives for the sale of advanced vehicles and components, backed by an INR 260 billion budget. It has secured INR 677 billion in investments across 95 approved applicants, while mandating a minimum 50% domestic value addition (PIB Delhi, 2021).

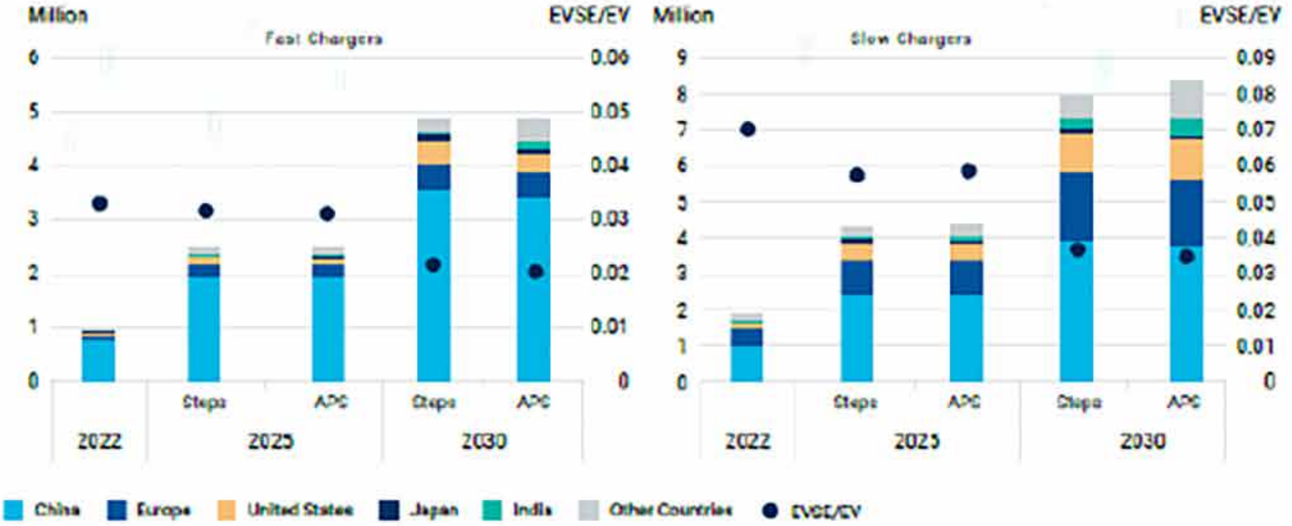
5.14 Net-zero emissions incentives

- **China:** Eighteen Chinese provinces have established explicit EV targets within their carbon peaking frameworks, aspiring to a 40% EV sales share by 2030 (IEA, 2023c).
- **USA:** California's Advanced Clean Cars II (ACC II) rule mandates progressively increasing EV sales shares for light-duty vehicles (LDVs), culminating in 100% by 2035. States such as Vermont, Washington, Oregon, and New York have adopted ACC II, collectively representing approximately 20% of US LDV sales. Massachusetts, Delaware, and Colorado are contemplating adoption, potentially expanding coverage to nearly 25% (CARB, 2023).
- **EU:** The Fit for 55 package sets EU-wide targets to reduce CO_2 emissions by 55% for cars and 50% for vans from new vehicle sales by 2030 (European Council, 2023).
- **United Kingdom:** A ban on advanced ICE vehicles is slated for 2030, targeting a complete transition to zero-emission EVs by 2035 (UK Department of Transport, 2021), although this policy is presently under review.
- **Greece:** Enhanced policies mandate zero-emission LDV sales from 2030 onward (MEE, 2021).
- **Switzerland:** Surpassing its 2018 target of 15% EV sales share, achieving 25% in 2022, the country has set a new goal of 50% by 2025 (SFOE, 2023).
- **Italy:** A renewed subsidy scheme emphasises the scrappage of older polluting ICE vehicles (MBMI, 2022).
- **Spain:** Policies prioritise vehicle scrappage and support for lower-income households (IEA, 2023c).
- **Denmark:** Tax reforms enhance the attractiveness of EV company vehicles (SKM, 2022).
- **Finland:** Reductions in import and annual taxes for EVs (TRAFICOM, 2023).
- **Austria:** Renewed EV subsidies maintain parity with prior-year rates (KPC, 2023).
- **Croatia and Cyprus:** Introduced EV purchase subsidies in 2022 (IEA, 2023c).
- **Canada:** Targets zero-emission vehicle sales shares of 20% by 2026, 60% by 2030, and 100% by 2035. British Columbia aims for 90% by 2030 (Transport Canada, 2022).
- **Australia:** Launched competitive grants for EV purchases as part of the AUD 500 million Future Fuels Fund (MDISR, 2022).
- **New Zealand:** Seeks 30% zero-emission vehicles (ZEVs) in the light-duty vehicle (LDV) stock by 2035, with subsidies implemented in mid-2021 (ME, 2022).
- **Japan:** The Green Growth Strategy targets full LDV electrification by 2035, aligned with the Act on Rational Use of Energy (METI, 2021).
- **Indonesia:** Mandated electrification of government vehicles since 2022, alongside EV subsidies from 2023 (Times Indonesia, 2022).
- **Seychelles:** Aims for 30% EVs in new vehicle sales by 2030 and 100% electric buses by 2050 (MTRS, 2023).
- **Panama:** Targets 40% EVs in selected public vehicles by 2030 (SNE, 2023).
- **Vietnam:** Plans net zero emissions for transport by 2050 and a fossil fuel vehicle ban by 2040 (IEA, 2023c).
- **Ghana:** Sets new EV sales targets of 4% by 2025, 16% by 2030, and 32% by 2050 (UNEP, 2022).
- **Other countries:** Proposed EV policies, encompassing tax exemptions, mandates, and adoption targets, in Angola, Brazil, Ecuador, Pakistan, Trinidad and Tobago, Tunisia, Uzbekistan, and Vietnam (IEA, 2023c).

5.16 *EV charging infrastructure*

The cornerstone of EV infrastructure resides in charging technologies. The expansion of charging stations, ranging from residential units to fast chargers, encompassing Level 1 (AC), Level 2 (AC), and Level 3 (DC fast charging), proves indispensable (IEA, 2023c). The European Union's ambition to deploy one million charging points by 2025 exemplifies such proactive targets. Nevertheless, challenges persist, including interoperability of charging infrastructure, protocol standardisation, and the imperative to reinforce the grid.

Figure 27: Number of public light-duty vehicle chargers by region (2022-2023)



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; evse = Electric Vehicle Supply Equipment. Regional projected EVSE stock data can be interactively explored via the Global EV Data Explorer. The number of publicly accessible light-duty vehicle chargers increases from about 3 million on 2022 to around 13 million in 2030 in the Announced Pledges Scenario. Image source: IEA (2023c)

Public charging points are increasingly essential to facilitate broader EV adoption, even as the majority of current charging demand is met by residential charging. Publicly accessible chargers are vital for delivering equivalent levels of convenience and accessibility to those offered by refuelling conventional vehicles. This need is particularly acute in densely populated urban areas, where access to home charging remains constrained, rendering public infrastructure a critical enabler of EV uptake. By the end of 2022, the global stock of public charging points reached 2.7 million, with over 900,000 units installed that year, reflecting a 55% increase over 2021 levels and approximating the pre-pandemic growth rate of 50% observed between 2015 and 2019 (IEA, 2023c).

5.17 *Slow chargers*

Globally, over 600,000 public slow charging points were installed in 2022, with 360,000 of these in China, elevating the country's slow charger stock to exceed 1 million units (IEA, 2023c). Europe ranked second, with 460,000 slow chargers in 2022, a 50% year-on-year increase (IEA, 2023c). Within Europe, the Netherlands led with 117,000 units, followed by approximately 74,000 in France and 64,000 in Germany (IEA, 2023c). The United States recorded the slowest growth among major markets, with slow charger stock rising by just 9% in 2022. In South Korea, the number of slow-charging infrastructure points doubled year-on-year, reaching 184,000 (IEA, 2023c).

Slow chargers are defined as those with power ratings of 22 kW or less. Fast chargers, by contrast, exhibit power ratings exceeding 22 kW and extending up to 350 kW. The terms "charging points" and "chargers" are used interchangeably to denote individual charging sockets that determine the number of electric vehicles (EVs) that can charge simultaneously. "Charging stations," meanwhile, may encompass multiple charging points (IEA, 2023c).

5.18 *Fast chargers*

Publicly accessible fast chargers, particularly those situated along motorways, facilitate extended journeys and mitigate range anxiety, a key impediment to EV adoption. Similar to slow chargers, public fast chargers provide essential charging options for consumers without reliable access to private charging, thereby broadening EV accessibility across diverse demographics. Globally, fast charger installations surged by 330,000 units in 2022, with nearly 90% of this growth attributable to China (IEA, 2023c). Such rapid deployment compensates for limited home charging availability in densely populated urban centres and aligns with China's ambitions for accelerated EV proliferation. China now hosts 760,000 fast chargers, over 70% of which are concentrated in just ten provinces (IEA, 2023c).

In Europe, the total stock of fast chargers exceeded 70,000 by the end of 2022, reflecting an approximate 55% increase from 2021 levels (IEA, 2023c). The leading countries by fast charger deployment were Germany (over 12,000 units), France (9,700 units), and Norway (9,000 units) (IEA, 2023c). Across the European Union, there exists a pronounced commitment to expanding public charging infrastructure, evidenced by the provisional agreement on the Alternative Fuels Infrastructure Regulation (AFIR). This regulation will impose electric charging coverage mandates along the trans-European transport network (TEN-T). Furthermore, an accord between the European Investment Bank and the European Commission will allocate over EUR 1.5 billion by the end of 2023 to support alternative fuel infrastructure, including electric fast charging (IEA, 2023c).

In the United States, 6,300 fast chargers were installed in 2022, with approximately three-quarters comprising Tesla Superchargers (IEA, 2023c). The total stock of fast chargers reached 28,000 units by the end of 2022. Deployment is anticipated to accelerate in subsequent years following governmental approval of the National Electric Vehicle Infrastructure (NEVI) Formula Program (IEA, 2023c). All US states, Washington, DC, and Puerto Rico participate in the program, which allocated USD 885 million in 2023 to support charger deployment along 122,000 km of highways (IEA, 2023c). The US Federal Highway Administration has established new national standards for federally funded EV chargers to ensure uniformity, reliability, accessibility, and interoperability. Consequently, Tesla has committed to opening portions of its US Supercharger and Destination Charger networks (representing 60% of the nation's fast-charger stock) to non-Tesla EVs (IEA, 2023c).

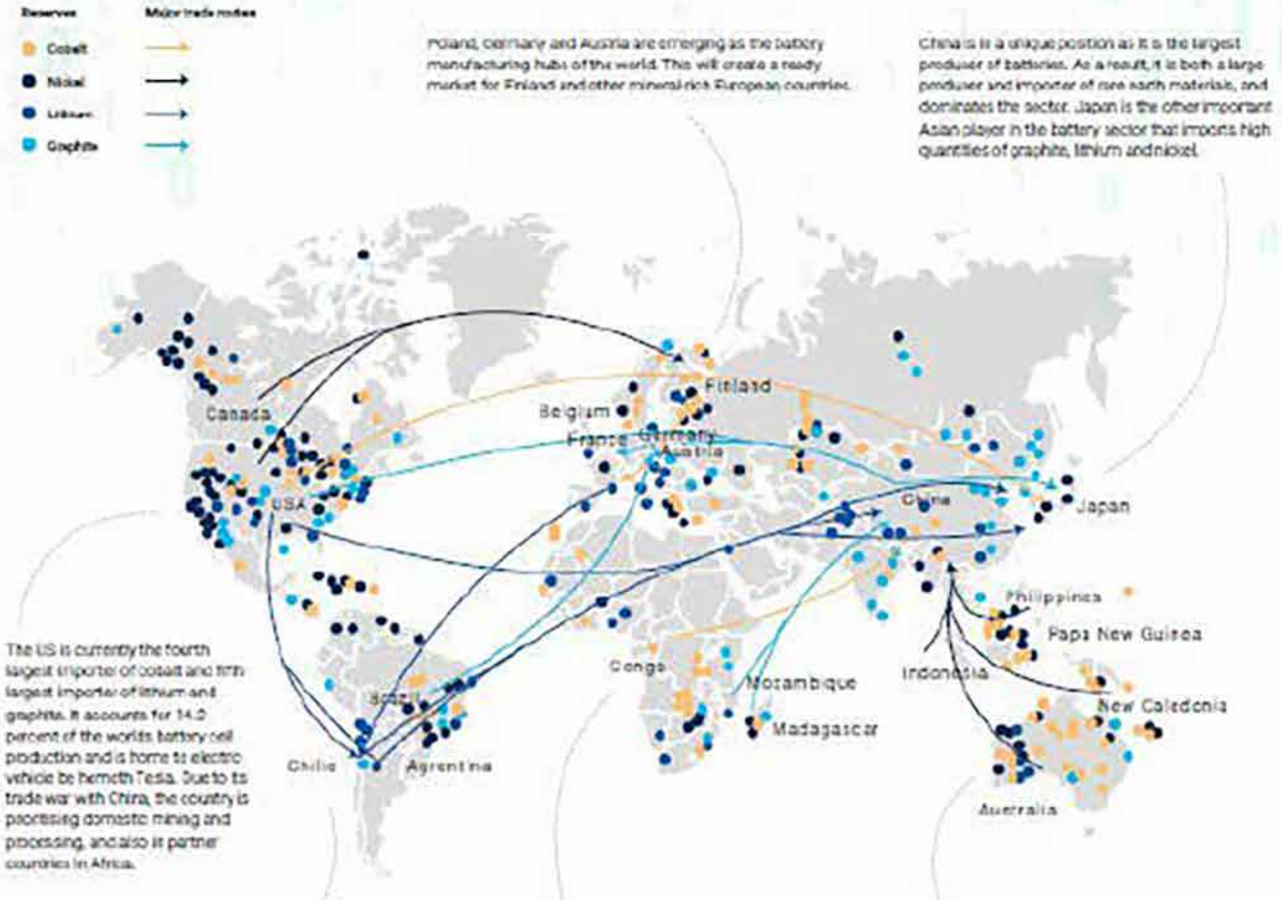
Moreover, seamless integration of EVs into the electricity grid necessitates grid stability (Tavakoli et al., 2023). This requires consideration of EV charging impacts on grid demand, peak load management, and vehicle-to-grid (V2G) interactions. Smart charging algorithms, bidirectional energy flows, and demand response programs play a pivotal role in optimising schedules and alleviating grid strain.

5.18 EV trade and supply chains

At the heart of every EV resides the battery, which relies on critical materials such as lithium, cobalt, and nickel. The sourcing of these materials raises profound ethical concerns, particularly regarding responsible extraction practices and labour conditions (Carreon, 2023).

Collaboration among industry stakeholders is essential for bolstering supply chain resilience. OEMs, battery producers, and technology suppliers partner to enhance production efficiency, avert disruptions, and refine distribution networks. Such alliances cultivate adaptability amid unforeseen challenges. The complexities of EV trade and supply chains reflect the intricate interplay of global trade dynamics, technological advancements, geopolitical tensions, and sustainability imperatives (Capri, 2021). As the EV market continues to expand, addressing these supply chain intricacies is critical to cultivating a robust and resilient ecosystem.

Figure 28: Emerging electro world



Poland, Germany and Austria are emerging as the battery manufacturing hubs of the world. This will create a ready market for Finland and other mineral-rich European countries.

China is in a unique position as it is the largest producer of batteries. As a result, it is both a large producer and importer of rare earth materials, and dominates the sector. Japan is the other important Asian player in the battery sector that imports high quantities of graphite, lithium and nickel.

The US is currently the fourth largest importer of cobalt and fifth largest importer of lithium and graphite. It accounts for 14.2 percent of the worlds battery cell production and is home to electric vehicle behemoth Tesla. Due to its trade war with China, the country is prioritising domestic mining and processing, and also in partner countries in Africa.

Chile and Argentina are the major exporters of lithium globally (70 percent). Brazil is the fourth largest graphite exporter.

Congo alone meets 87 percent of global cobalt needs. Mozambique is the second largest exporter of graphite. Zimbabwe, South Africa and Madagascar have healthy reserves of lithium and cobalt.

Australia started exploiting its huge reserves of lithium, cobalt and nickel recently in 2012. Its currently a major exporter of nickel alone but can challenge China's rare earth dominance because of its healthy reserves.

Image source: OEC (2021)

While electricity offers a versatile and efficient alternative fuel source for transportation, achieving 87-91% efficiency in electric motors and reducing reliance on fossil fuels (IEA, 2025), its practical implementation hinges on the evolution of NEVs. The subsequent chapter explores the global NEV landscape, highlighting leading markets such as the Republic of China, the United States of America and Europe. Moreover, the current NEV landscape in South Africa is explored, as well as performance, maintenance, reliability and risks of mechanical failure in NEVs.

Chapter 6: The Impact Of NEVs On Road Safety, Sustainability & Socio-Economic Conditions In South Africa

6.1 Global Overview of NEVs and Road Safety

The current global landscape of NEVs reveals a complex integration of market growth and road safety performance (Rhibusbar, 2025a; DEKRA, 2025). NEVs exhibit safety enhancements, such as advanced driver-assistance systems (ADAS) and diminished fire risks due to the absence of combustible fuels, complemented by specialised battery protection technologies (DEKRA, 2025; Xu et al., 2025). These attributes have coincided with a 1.3% decline in road fatalities in the European Union (19,800 deaths in 2024) amid increasing electrification (DEKRA, 2025).

Nevertheless, regulations in the United Kingdom mandated acoustic vehicle alerting systems (AVAS) for all new BEVs and HEVs at low speeds (<19.31 kmph) from July 2019, addressing safety concerns for pedestrians about the quiet operation of BEVs and the potential for collisions with pedestrians. Post-regulation casualty rates fell significantly: BEVs from 137.2 per billion miles between 2014 and 2018 to 57.8 per billion miles between 2019 and 2023, and HEVs from 201.6 to 120.1 per billion miles, exceeding ICE vehicle declines (73.6 to 58.9 per billion miles). This suggests AVAS contributed to improved pedestrian safety amid rising NEV adoption (Nature, 2025). Battery mass further extends braking distances by 10-20% in heterogeneous traffic environments, while studies indicate NEV drivers face 4% higher at-fault insurance claim rates linked to instant torque and regenerative braking (McDonnell et al., 2024; PubMed, 2025). These findings underscore the potential need for standardised global metrics to fully assess NEVs' safety profiles within sustainable mobility transitions (ERTRAC, 2023).

6.2 The impact of NEVs on road safety in South Africa

6.2.1 Autonomy in NEVs

As mentioned in sections above, 2024 recorded 12,172 fatalities from 10,339 crashes (a 2.4% year-on-year increase from 2023). These fatalities were predominantly attributable to human error (88.3%), and these incidents disproportionately affect pedestrians (45.1%), including hit-and-runs, jaywalking, fatigue, loss of control, and speeding (RTMC, 2025).

The Various levels of autonomy in NEVs potentially automates critical driving tasks to directly address human error by handling acceleration, braking, and lane-keeping. These systems reduce the risks posed by human behaviour and/or error (Creecy, 2025). SAE J3016 standards define the progression of vehicle automation from Level 0 (no automation) to Level 5 (full automation) (SAE International, 2021).

Table 13: Levels of vehicle automation:

Level	Type of automation	Type of automation
Level 0	No Automation	Driver performs all driving tasks; no automated support available.
Level 1	Driver Assistance	Assists with either steering or acceleration/braking (e.g., adaptive cruise control), but the driver remains fully responsible.
Level 2	Partial Automation	When steering and accelerating/braking are combined (e.g., Tesla Autopilot), the driver must constantly monitor the environment.
Level 3	Conditional Automation	Vehicle handles all driving tasks under specific conditions; the driver must be ready to intervene when requested.
Level 4	High Automation	Performs all tasks within limited operational domains (e.g., highways) without driver intervention; no steering wheel needed in some cases.
Level 5	Full Automation	Complete automation in all conditions and environments; no human input required ever.

Source: SAE International (2021)

6.2.2 How Autonomy Reduces Human Error

Autonomy replaces manual inputs with sensors, cameras, and artificial intelligence (AI). Level 0-2 automation systems show lower injury crash rates than human drivers globally (NHTSA, 2024). This is also true locally, where human behaviour has been identified as the leading cause of fatal crashes (Creecy, 2025; RTMC, 2025).

6.2.3 Limitations of autonomy

Higher autonomy levels (3-5) face challenges in South Africa due to the current road infrastructure, including potholes, unmarked roads and load shedding. These challenges pose risks of sensor failures, and drivers should remain vigilant and cannot entirely rely on vehicle automation, as current road infrastructure may require human intervention (Climate Scorecard, 2025; MotorHappy, 2025). NEVs with higher levels of autonomy require robust, well-maintained infrastructure, which is absent locally, potentially exacerbating the risk of road crashes (RTMC, 2025; RTMC, 2024a).

6.3 Advantages and disadvantages of NEVs on road safety in South Africa

Reducing road fatalities in South Africa is a complex challenge. Human behaviour, such as jaywalking, speeding, disregard for rules of the road, impaired driving, and intoxicated pedestrians, is a leading contributing factor to road fatalities (RTMC, 2025). Thus, the impact of NEVs on human behaviour and the potential advantages and disadvantages are explored below:

6.3.1 Advantages of NEVs in terms of road safety in South Africa

1. BEVs, HEVs and PHEVs benefit from a lower centre of gravity due to underfloor batteries, enhancing vehicle stability and reducing the risk of rollover, thereby providing mass occupant protection (RoSPA, 2023).

2. The integration of advanced driver assistance systems (ADAS) in the majority of NEVs, such as lane-keep assist, forward collision warning and autonomous emergency braking, supports improved collision avoidance (Brightmile, 2020).

3. Regenerative braking in HEVs enhances control and reduces brake wear, contributing to smoother handling (Autel Energy, 2024). Their hybrid design supports advanced stability features without full BEV battery weight extremes (RoSPA, 2023).

4. The dual powertrains of PHEVs provide flexibility, reducing range anxiety and enabling engine noise at higher speeds to alert pedestrians (NHTSA, n.d.).

5. The low hydrogen density in FCEVs causes leaks to dissipate upward quickly, reducing the risk of fire spread compared to gasoline. Tanks are also designed to withstand extreme impacts (Knauf Automotive, 2024). FCEVs produce only water vapour emissions, eliminating tailpipe fire hazards, and their electric drivetrains enable instant torque for responsive handling (Kelley Blue Book, 2024). Crash tests show robust protection, with fuel cells often surviving severe impacts without rupture (RoSPA, 2023).

6.3.2 Disadvantages of NEVs in terms of road safety in South Africa

1. The added weight of batteries in BEVs, HEVs and PHEVs increases the kinetic energy during crashes, potentially increasing injury severity for occupants of lighter vehicles (RoSPA, 2023).

2. The quiet, low-speed operation of BEVs, HEVs (when in electric mode), and PHEVs poses safety risks to pedestrians and cyclists because they cannot hear approaching vehicles. Due to their quiet operation, higher rates of pedestrian-NEV incidents have been reported compared with pedestrian-ICE incidents (RoSPA, 2023).

3. The batteries of BEVs, HEVs and PHEVs pose fire risks post-crash, including thermal runaway risks (RoSPA, 2023). However, the smaller battery packs of HEVs limit these risks.

4. Charging PHEVs introduces electrocution or fire risks if damaged, and post-crash exposure of batteries to water heightens corrosion and ignition risks (NHTSA, n.d.).

5. The added complexity of dual powertrains in HEVs can elevate repair risks if not properly managed (Autel Energy, 2024), while the complexity of PHEV plug-in systems may complicate emergency response (RoSPA, 2023).

6. High-pressure hydrogen tanks (up to 700 bar) in FCEVs pose an explosion risk if punctured, though multi-layer composites help mitigate this (TWI Global, n.d.). Hydrogen's wide flammability range (4-75%) raises ignition concerns during refuelling or in the event of leaks, despite its rapid burn-off (TechEtch, 2022). Limited infrastructure increases the risk of stranding in remote areas, such as more rural parts of South Africa (Cartrack, 2025).

6.4 Performance, maintenance reliability & risk of mechanical failure of various types of NEVs:

6.4.1 Performance

BEVs deliver instant torque for acceleration superior to ICE equivalents, with energy conversion efficiencies of 87-91%, exceeding ICE vehicles' 16-25%, yielding up to 60% lower operating costs (IEA, 2025).

PHEVs in South Africa offer strong performance by combining instant electric torque with petrol range extension. The electric motor's immediate power delivery provides superior acceleration compared to ICE equivalents, similar to BEVs (IEA, 2025). In electric-only mode, PHEVs achieve energy conversion efficiencies of 85-91%, compared with 20-30% for ICE vehicles, resulting in significantly lower energy consumption and running costs when charged regularly (U.S. Environmental Protection Agency, 2025).

Regenerative braking further enhances efficiency and reduces brake wear. The dual powertrain provides seamless transitions, reducing range anxiety (GreenCape, 2025).

HEVs in South Africa deliver robust performance through the integration of petrol engines and electric motors, providing instant low-end torque for responsive acceleration without the need for external charging, as energy is recaptured through regenerative braking (EV24 Africa, 2025).

FCEVs offer fast refuelling and long driving range, which makes them well-suited for long-distance and heavy-duty transport (IEA, 2024). Their performance is strong, with smooth power delivery and zero tailpipe emissions. However, their overall well-to-wheel energy efficiency is lower than that of BEVs because hydrogen production and conversion introduce energy losses (ICCT, 2024).

6.4.2 Maintenance reliability

BEVs exhibit superior maintenance reliability compared to ICE vehicles, owing to their simpler drivetrains with fewer moving parts, eliminating the need for oil changes, spark plugs, and exhaust servicing, resulting in 50-60% lower maintenance costs (EV24 Africa, 2025).

This reliability is bolstered by regenerative braking, which extends brake life and battery warranties up to 8 years (EV24 Africa, 2025). However, challenges include specialised high-voltage technician training (Department of Trade, Industry and Competition, 2020) and heat impacts on lithium-ion batteries in local climates, necessitating proactive diagnostics and software updates (Department of Trade, Industry and Competition, 2020).

PHEVs in South Africa offer reliable maintenance profiles due to the electric motor's durability and reduced engine strain, resulting in fewer reported breakdowns than ICE vehicles (IEA, 2025).

HEVs in South Africa demonstrate high maintenance reliability, with overall costs 20-40% lower than those of conventional ICE vehicles due to fewer moving parts in the electric system and regenerative braking, which extends brake pad life by up to 50% (EV24 Africa, 2025). Challenges include the need for specialised technicians to handle high-voltage systems, which can lead to longer wait times in rural areas (IEA, 2025).

FCEVs generally require less routine maintenance than ICE vehicles because they do not need components such as oil, spark plugs or exhaust systems, and their electric drivetrains contain fewer moving parts (National Renewable Energy Laboratory, 2025). Most scheduled maintenance, therefore, focuses on the fuel cell stack cooling system and on standard items such as brakes, tyres and suspension (GreenCars, 2025).

However, long-term reliability is still influenced by fuel cell stack durability. Real-world fleet data from the National Renewable Energy Laboratory shows that early fuel cell stacks often reached 2,000-5,600 operating hours, indicating that durability improvements are still required to meet typical automotive lifetime expectations (National Renewable Energy Laboratory, 2019).

Recent technical reviews also highlight that factors such as membrane degradation and thermal cycling can reduce the long-term reliability of the fuel cell stack (Hu, Sheng, & Xu, 2025). As a result, although FCEVs offer a simplified, lower-maintenance drivetrain, their overall maintenance reliability still depends on advances in fuel cell durability and hydrogen system robustness.

6.4.3 Risk of mechanical failure

As discussed, BEVs in South Africa generally present a lower risk of mechanical failure than ICE vehicles, mainly because of their simplified drivetrains that lack complex components such as multi-speed transmissions and exhaust systems (EV24 Africa, 2025). This design significantly reduces typical breakdown causes associated with wear and tear in traditional ICE vehicles (MyBroadband, 2025). Battery packs, the most critical component, exhibit low failure rates globally, with annual degradation typically below 2% when adequately maintained (IEA, 2025).

South Africa's hot climate can accelerate lithium-ion battery wear if charging and thermal management are not optimised, yet modern BEVs incorporate advanced cooling systems to mitigate this risk (EV24 Africa, 2025). Potential failure points remain in high-voltage electrical systems, software-related issues, and regenerative braking components, which may require specialised diagnostic tools and technicians (a challenge heightened by inconsistent grid power during load shedding) (GreenCape, 2025). Despite these concerns, automotive reliability surveys consistently rank BEVs among the least fault-prone vehicle types, with local examples of high-mileage models demonstrating exceptional durability on minimal major repairs (TopAuto, 2025).

PHEVs in South Africa carry a moderately elevated risk of mechanical failure compared to BEVs due to their dual powertrain complexity, with global surveys indicating 80% more reported issues than ICE vehicles, primarily from battery degradation, charging system faults, and powertrain integration glitches (Consumer Reports, 2023). Annual battery failure rates remain low, under 1.5%, with proper thermal management. However, South Africa's hot climate and dust can accelerate the degradation of PHEV cooling systems and electrical connections, potentially leading to overheating or corrosion if not regularly maintained (EV24 Africa, 2025). The internal combustion component shares risks, such as engine and brake failures, common to ICE vehicles, though regenerative braking can reduce brake wear by up to 50% (J.D. Power, 2025).

HEVs in South Africa exhibit a low risk of mechanical failure, outperforming ICE vehicles by 26% on average, due to their established technology, regenerative braking that reduces brake wear by up to 50%, and lower engine strain from electric assist (Consumer Reports, 2024). Battery failure rates are minimal, at under 1% annually, though South Africa's high temperatures may slightly accelerate hybrid battery degradation if cooling systems are not maintained, similar to PHEVs (EV24 Africa, 2025). The dual powertrain introduces minor complexity risks, such as inverter or transmission faults. However, overall dependability remains high in local surveys, with models demonstrating over 300,000 km on original components amid dusty roads and load shedding (GreenCape, 2025).

FCEVs have fewer mechanical components than ICE vehicles, which reduces the number of conventional mechanical failure points. However, they still face specific reliability risks linked to fuel cell and hydrogen system technology. The National Renewable Energy Laboratory reports that the most significant sources of mechanical failure risk are degradation of the fuel cell stacks, including membrane wear, catalyst loss, and contamination, all of which can reduce output and eventually lead to fuel cell stack failure (National Renewable Energy Laboratory, 2019). The hydrogen storage system also requires careful management, as high-pressure tanks and valves must maintain integrity under repeated cycling to minimise the risk of leaks or component fatigue (IEA, 2024). Reviews of fuel cell technology identify additional risks such as failures in humidifiers, compressors and thermal management systems, which must operate continuously to maintain stable fuel cell performance (Hu, Sheng, & Xu, 2025). As a result, while FCEVs avoid many traditional mechanical failures, their reliability depends heavily on the durability of specialised hydrogen and fuel cell subsystems.

The above indicates that different electric and hydrogen vehicle technologies are suited to different needs in South Africa. BEVs are efficient and cost-effective for urban commuters with short daily trips (IEA, 2025), while PHEVs and HEVs offer extended range and fuel savings, making them suitable for drivers who require flexibility or travel longer distances (GreenCape, 2025). FCEVs offer long-range capability and fast refuelling but rely on further improvements in fuel cell durability and hydrogen infrastructure (IEA, 2024). A diversified fleet that combines the strengths of BEVs, PHEVs, HEVs, and FCEVs could support a more resilient and sustainable transport system in South Africa while addressing the country's varied driving needs and environmental challenges (EV24 Africa, 2025).

6.5 The impact of NEVs on sustainability in South Africa:

A diversified approach that strategically uses BEVs for urban travel, PHEVs and HEVs for mixed-distance use, and FCEVs for long-haul transport offers the most effective route to reducing greenhouse gas emissions and air pollution. When combined with renewable energy expansion and supportive policies, this combination can lower South Africa's transport sector carbon footprint, reduce local air pollutants, and build resilience against fuel price volatility and concerns regarding electric grid reliability (IEA, 2025).

6.6 Suggested renewable energy expansions and supportive policies:

6.6.1 Promote BEVs for Urban and Short-Distance Travel

BEVs offer the highest energy conversion efficiency among the NEV types, converting over 85% of stored electricity into motion compared with 16–25% for ICE vehicles (IEA, 2025). Their zero tailpipe emissions make them particularly effective at reducing urban air pollution, which is a critical environmental concern in South

African cities such as Johannesburg and Pretoria. Even when accounting for electricity from a coal-heavy grid, BEVs can have lower lifecycle greenhouse gas emissions than traditional ICE vehicles (International Council on Clean Transportation, 2024).

6.6.2 Integrate PHEVs for Flexibility and Range Extension

PHEVs offer the flexibility of electric-only operation for short urban trips while retaining petrol range for longer journeys, helping mitigate range anxiety and encouraging broader adoption (U.S. Environmental Protection Agency, 2025). In electric mode, PHEVs achieve high energy conversion efficiency (85-91%) and significantly reduce fuel consumption and CO_2 emissions compared with traditional ICE vehicles (IEA, 2025). For South Africa, where public charging infrastructure is still developing, PHEVs offer an interim solution to reduce overall emissions without requiring immediate full electrification.

6.6.3 Use HEVs for Continuous Fuel Efficiency Gains

HEVs combine ICEs with electric motors to enhance fuel efficiency without requiring external charging, achieving 3.8-5.2 L/100 km in urban and highway driving (EV24 Africa, 2025). They are particularly suited for regions with limited charging infrastructure, reducing fuel consumption and CO_2 emissions while maintaining operational reliability in high-temperature and load-shedding conditions (GreenCape, 2025).

6.6.4 Deploy FCEVs for Long-Distance and Heavy-Duty Transport

FCEVs are ideal for long-distance travel and heavy-duty transport because of their fast refuelling and long range (IEA, 2024). When the hydrogen is produced from low-carbon sources, FCEVs can provide significant lifecycle emission reductions (Fédération Internationale de l'Automobile, 2022). While current hydrogen production in South Africa is mainly fossil-based, scaling green hydrogen infrastructure could make FCEVs a key component in decarbonising freight and regional passenger transport.

6.6.5 Complement Vehicle Technology with Renewable Energy Integration

The environmental benefits of BEVs, PHEVs, and FCEVs are maximised when coupled with low-carbon electricity or hydrogen production. Expanding renewable energy capacity, such as solar and wind, can lower lifecycle emissions for BEVs and PHEVs (IEA, 2025). Green hydrogen produced via electrolysis using renewable electricity can further reduce emissions from FCEVs (FIA, 2022).

6.6.6 Policy and Incentives to Encourage Adoption and Fleet Transition

Policies that incentivise the adoption of low-emission vehicles, enforce emissions standards, and gradually phase out high-polluting ICE vehicles can accelerate environmental benefits. Fleet-level interventions, such as electrifying public transport and commercial vehicles, can reduce emissions in high-use sectors (GreenCape, 2025).

6.7 The impact of NEVs on socioeconomic conditions in South Africa

A diversified strategy that combines BEVs for urban commuting, PHEVs and HEVs for mixed-distance travel, and FCEVs for heavy-duty and commercial transport can address multiple socio-economic challenges. Households save on fuel and maintenance costs, reducing economic pressure (EV24 Africa, 2025), while the industrial and transport sectors benefit from local manufacturing, maintenance employment, and reduced fuel costs (Department of Trade, Industry and Competition, 2020). Coupled with renewable energy development and supportive policies, this combination can improve transport affordability, create employment opportunities, and reduce economic inequalities associated with vehicle ownership and operation (IEA, 2025).

6.7.1 Suggested renewable energy development and supportive policies

Promote BEVs in Urban Areas with Supporting Incentives

BEVs can reduce household fuel expenses by lowering operating costs, which are 40-60% more affordable per kilometre than those of ICE vehicles (EV24 Africa, 2025). Urban commuters may benefit most, as BEVs cover approximately 400-420 km on a single charge, which is sufficient for nearly all daily urban travel (IEA, 2025). Subsidies, tax rebates, or financing programs targeted at middle- and low-income households can enhance access to BEVs and reduce transportation expenditure, which is a significant portion of household budgets in South Africa (IEA, 2025).

Encourage PHEVs and HEVs for Flexibility

PHEVs and HEVs can reduce fuel consumption by 20-30% compared with traditional ICE vehicles (GreenCape, 2025). PHEVs allow electric-only driving for daily urban travel while retaining petrol range for extended travel, minimising range anxiety. HEVs provide continuous fuel efficiency without requiring charging infrastructure, making them accessible for semi-urban or rural communities with limited electricity access (EV24 Africa, 2025).

Develop Local Manufacturing and Maintenance Ecosystems

Supporting local assembly and maintenance of BEVs, HEVs, and FCEVs can create employment opportunities and upskill the workforce. Training programs for high-voltage vehicle systems and fuel-cell maintenance create employment opportunities and technical capacity (Department of Trade, Industry and Competition, 2020). Expanding local manufacturing of batteries and components can also reduce vehicle costs over time, making low-emission vehicles more affordable.

Introduce FCEVs for Heavy-Duty Transport

FCEVs are well-suited for long-distance freight and buses (IEA, 2024). Deploying FCEVs in commercial fleets can reduce operational fuel costs and dependence on imported diesel while promoting the adoption of green technology. Investments in green hydrogen infrastructure could generate industrial employment and support regional economic development (IEA, 2024).

Combine Vehicle Transition with Energy and Transport Policies

Socio-economic gains are maximised when vehicle adoption is paired with renewable energy development, public transport electrification, and incentives that lower upfront purchasing costs for low-income households (GreenCape, 2025). Targeted policies ensuring equitable access to low-emission vehicles can reduce transport inequality while supporting national economic goals (IEA, 2025).

A mixed approach that strategically deploys BEVs for urban commuting, PHEVs and HEVs for mixed-distance travel, and FCEVs for long-haul and commercial use offers the most effective pathway for South Africa. When coupled with renewable energy expansion, rigorous maintenance programs, and supportive socio-economic policies, this combination can reduce road fatalities, lower emissions, improve transport affordability, and generate employment opportunities, making it a potential holistic solution for the country's road safety, sustainability and socio-economic challenges (EV24 Africa, 2025).

6.7.2 Suggested renewable energy expansion, maintenance programs and supportive socio-economic policies

Promoting safer vehicle technologies and infrastructure in high-risk areas through policymaking

A clearer understanding of South Africa's evolving vehicle-energy landscape can help policymakers prioritise investments and regulations that maximise safety, environmental benefits, and socio-economic equity. Data from GreenCape indicates that, although NEVs still account for a small portion of the national fleet, their growth, particularly in centralised, high-usage fleets such as taxis, buses, and commercial vehicles, presents opportunities to improve road safety and reduce emissions in areas of highest risk (GreenCape, 2023). Insights from Naamsa and the IEA highlight that combining electrification strategies with localisation and industrial incentives can make safer, modern vehicles more accessible while supporting domestic industry (IEA, 2025).

By targeting high-risk urban zones and fleet-dense corridors with BEV and HEV deployments, policymakers can reduce mechanical-failure-related accidents and lower fatality rates (EV24 Africa, 2025). Infrastructure investments, such as public charging stations and electricity grid upgrades, should be prioritised in areas with frequent road crashes and where vehicle electrification is feasible, rather than applied uniformly (GreenCape, 2025). Furthermore, integrating real-world vehicle performance and energy-use data into regulations can guide standards for vehicle safety, battery and fuel-cell reliability, and charging infrastructure safety, ensuring that new technologies contribute effectively to both road safety and reducing carbon-based emissions (Naamsa, 2023).

Improved mapping of NEV types by region and transport sector can also guide where carbon-based e-fuels and other alternative fuels should be piloted to complement electrification in a safety-focused manner (ITF, 2023; IEA, 2024). Data shows that specific long-distance freight and intercity bus routes have high crash densities, ageing diesel fleets, and weak prospects for short-term electrification. Regulators could prioritise those routes for targeted trials of e-fuels or biofuels alongside stricter roadworthiness enforcement and driver-behaviour interventions (RTMC, 2024; Brynolf et al., 2022). Decisions to switch to alternative fuels become an integrated component of a safe-system strategy rather than a purely environmental measure, ensuring the most effective reduction of both emissions and serious crashes (iRAP, 2024; ITF, 2023).

Chapter 7: Challenges & Barriers To The Adoption Of NEVs In South Africa

NEVs (BEVs, PHEVs, HEVs, and FCEVs) accounted for 3% of South Africa's new vehicle sales (15,611 units) in 2024, with HEVs accounting for 87.1% of NEV sales, BEVs accounting for 8.1%, and PHEVs accounting for the remaining 4.7%. FCEVs remain unavailable due to infrastructure constraints (Naamsa, 2025).

7.1 Socioeconomic challenges

Socioeconomic factors, including high costs, inequality, limited infrastructure, and insufficient support services, are significant barriers to NEV adoption in South Africa. Without targeted interventions, NEVs risk being accessible only to wealthier households, limiting their environmental and social benefits (Moeletsi, 2021).

7.1.1 High upfront cost and affordability constraints

Many South African households find the purchase price of NEVs unaffordable. High battery and vehicle costs make NEVs less accessible than conventional vehicles, limiting adoption among low- and middle-income consumers (EV24 Africa, 2025).

7.1.2 Economic inequality and vehicle-ownership patterns

The market is dominated by older, second-hand ICE vehicles because they are more affordable to acquire and maintain. South African households under financial pressure often avoid high-cost NEVs due to perceived risks of battery replacement and limitations in charging infrastructure (Moeletsi, 2021).

7.1.3 Lack of charging and electricity infrastructure

Widespread NEV adoption depends on reliable electricity and charging infrastructure, both of which are unevenly distributed across South Africa. Many semi-urban and rural areas lack public charging stations, and frequent load shedding increases range anxiety and reduces the practicality of NEVs for South Africans (EV24 Africa, 2025).

7.1.4 Limited model availability and after-sales support

NEV models in South Africa are limited, and import duties and taxes inflate their prices. In addition, the scarcity of a qualified workforce to service NEVs and perform required maintenance in conjunction with the scarcity of spare parts discourages potential buyers, particularly in lower-income communities (Moeletsi, 2021).

7.1.5 Perceived mismatch with user needs

Many households rely on a single vehicle for multiple purposes, including commuting and informal business. Unreliable electricity supply and concerns over battery life make NEVs appear impractical for daily needs, further limiting adoption (EV24 Africa, 2025).

Addressing socioeconomic barriers is essential to ensure that NEVs benefit a broad segment of South African society. Policies and interventions that reduce upfront costs, expand charging infrastructure, increase model availability, and provide reliable after-sales support can make NEVs more accessible to low- and middle-income households. Without such measures, adoption will remain limited to wealthier consumers, constraining the environmental and social potential of cleaner-energy transport (Moeletsi, 2021).

7.2 Government intervention

South Africa is expected to pursue a phased transition to NEVs, starting with the development of domestic manufacturing facilities (Naamsa, 2023). Governmental incentives remain indispensable to incentivise consumer adoption of NEVs. Given the nation's pronounced socioeconomic disparities, elevated unemployment, and widespread poverty, a comprehensive fleet replacement is projected to span 15 to 20 years (Naamsa, 2023).

7.2.1 The automotive industry has put forward several practical steps for the government to adopt to aid the widespread introduction of NEVs

- Set clear targets to cut CO_2 emissions across the entire automotive value chain, from manufacturing to recycling (Naamsa, 2023).
- Protect and strengthen local vehicle and component manufacturing, since stricter European emission rules from mid-2025 and the planned ICE bans across Europe by 2035 could eradicate more than half of South

- Offer purchase subsidies for NEVs (Naamsa, 2023).
- Lower the import tariff on NEVs from the EU and UK from 25% to 18% under the existing trade agreements, and ease restrictions of origin for exports (Naamsa, 2023).
- Offer a 50% rebate on tax for imported NEV components (Naamsa, 2023).
- Raise the Automotive Investment Scheme allowance for NEV projects from 30–35% to 50% and extend it to lower-tier suppliers and companies that process raw materials locally (Naamsa, 2023).

A pressing concern is the current 60% local content requirement for duty-free exports of NEVs to the EU and UK. Given South Africa's protracted timeline for establishing large-scale battery manufacturing capacity, this requirement warrants relaxation during forthcoming trade agreement negotiations. Without this change, domestic manufacturers will be precluded from duty-free NEV exports, thereby jeopardising the broader transition to sustainable mobility (Naamsa, 2023). Moreover, any aspirational targets, such as attaining 60% NEV sales penetration by 2035 as envisaged in the South African Automotive Masterplan, ought to be conditional upon governmental support mechanisms (Naamsa, 2023).

7.3 Infrastructure

To facilitate the adoption of NEVs in South Africa, collaboration among government entities, municipalities, Eskom, private sector stakeholders, and property developers is essential. These entities should leverage incentives, grants, rebates, and direct investments to establish a robust network of charging infrastructure and hydrogen refuelling stations across three primary domains: residential areas (particularly apartment complexes and high-density suburbs), workplace facilities, and public locations along highways or in underserved public transport sectors (Naamsa, 2023).

South Africa will, in all likelihood, adopt a distinctive pathway for NEV integration, shaped by persistent electricity supply constraints affecting many households and by the prevalence of apartment dwellings, informal settlements, and rural areas lacking off-street parking. Commuters in the region often contend with extended daily travel distances, necessitating a robust emphasis on fast-charging infrastructure along principal roadways and in public spaces (Naamsa, 2023).

No universally optimal strategy exists for NEV deployment across all contexts. South Africa must tailor its approach to its unique energy landscape, fiscal constraints, and societal requirements. Regardless of the selected pathway, establishing an effective charging and hydrogen refuelling infrastructure demands substantial, meticulously coordinated investments from both public and private sectors (Naamsa, 2023)

7.4 Lack of knowledge and education

Adoption of NEVs in South Africa is influenced not only by cost and infrastructure but also by public awareness and understanding. Many potential consumers are unfamiliar with how NEVs operate, uncertain about charging infrastructure, and unsure of long-term maintenance or financial benefits. This lack of knowledge contributes to misconceptions, "range anxiety," and hesitancy to adopt cleaner-energy transport, particularly among lower- and middle-income households. Addressing these informational barriers is critical for ensuring that NEV adoption is equitable, practical, and environmentally effective (Moeletsi, 2021).

7.5 Misconceptions about NEV performance, costs, and reliability

Many South Africans remain uncertain about the actual costs and benefits of NEVs. Concerns over battery costs, maintenance, and availability of service infrastructure significantly reduce willingness to adopt NEVs, even among those aware of their environmental benefits (Moeletsi, 2021).

7.6 Low personal exposure to NEVs

The adoption of NEVs in South Africa remains low, resulting in limited direct exposure to NEVs among the population. A Gauteng-based survey indicated that approximately 88% of respondents lacked personal acquaintance with NEV owners, thereby constraining social familiarity and undermining the perceived viability of NEVs as conventional transport options (Moeletsi, 2021).

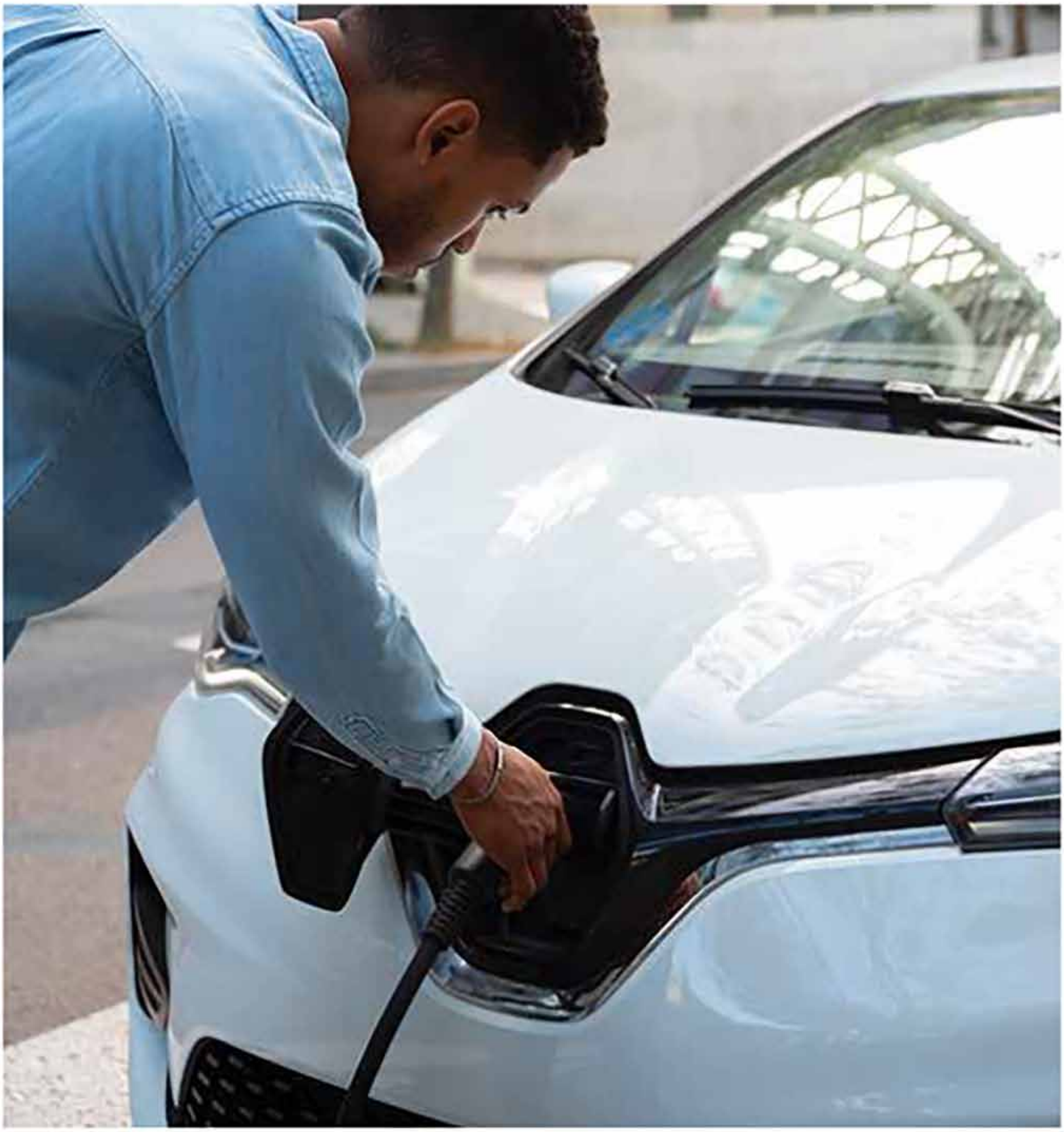
7.8 Limited information on long-term costs and benefits

Due to NEVs being relatively new in South Africa, there is limited accessible data on maintenance costs, battery lifespan, resale value, insurance, and real-world performance under local conditions. This uncertainty deters risk-averse consumers, particularly those with limited disposable income (Moeletsi, 2021).

7.9 Insufficient formal and informal education or outreach

There is a lack of structured public-education programmes, community outreach, and demonstration projects to increase familiarity with NEVs, particularly in low-income communities. Consumer educational programmes have been identified as a key intervention to overcome adoption barriers (Moeletsi, 2021).

Lack of public knowledge and education is a significant barrier to NEV adoption in South Africa. Misconceptions about costs, limited exposure to NEVs, uncertainty about charging and maintenance, and insufficient outreach all hinder uptake. Addressing these gaps through targeted education, demonstration projects, and transparent information sharing can increase trust, awareness, and equitable adoption of NEVs across different socioeconomic groups within South Africa (Moeletsi, 2021).

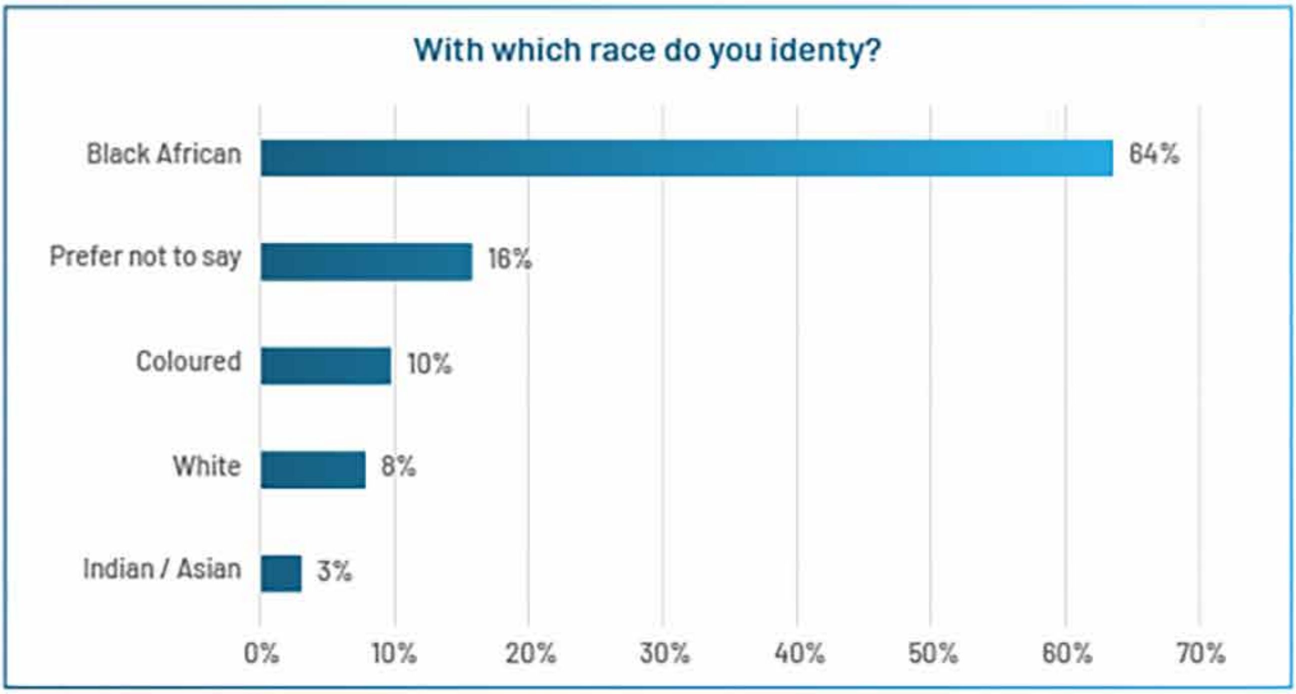


Chapter 7: Survey Results

An online survey was conducted with 3547 respondents to assess public perceptions, awareness levels, and behavioural tendencies regarding NEVs in South Africa. The survey explored how South Africans view vehicle safety, efficiency, and associated risks of NEVs. The results show substantial variation in familiarity with NEV technologies, perceived safety benefits, and the types of hazards respondents associate with different vehicle energy systems. Additionally, respondents highlighted concerns ranging from mechanical reliability to human behavioural factors. Together, these findings present a comprehensive picture of the evolving NEV landscape in South Africa and the factors shaping public attitudes toward emerging mobility technologies.

- Demographics

Figure 29: Demographic breakdown by race.



(Sample size : 3547)

Figure 30: Demographical breakdown by age.

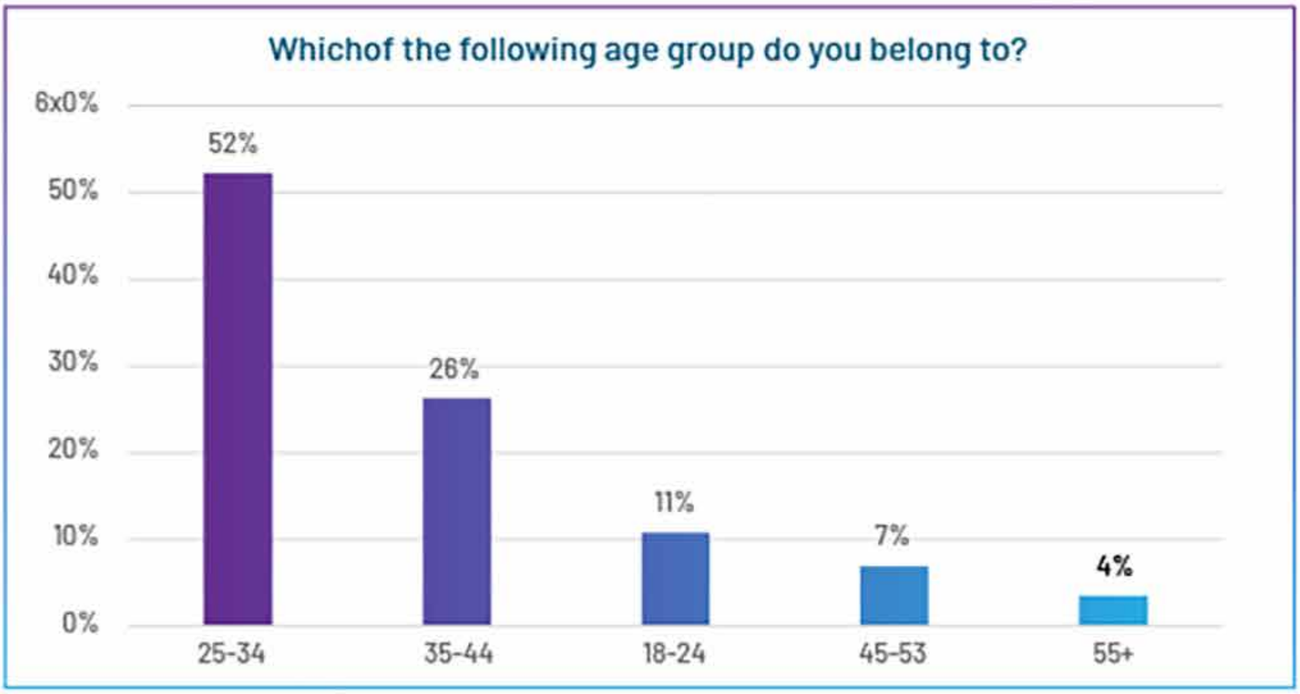
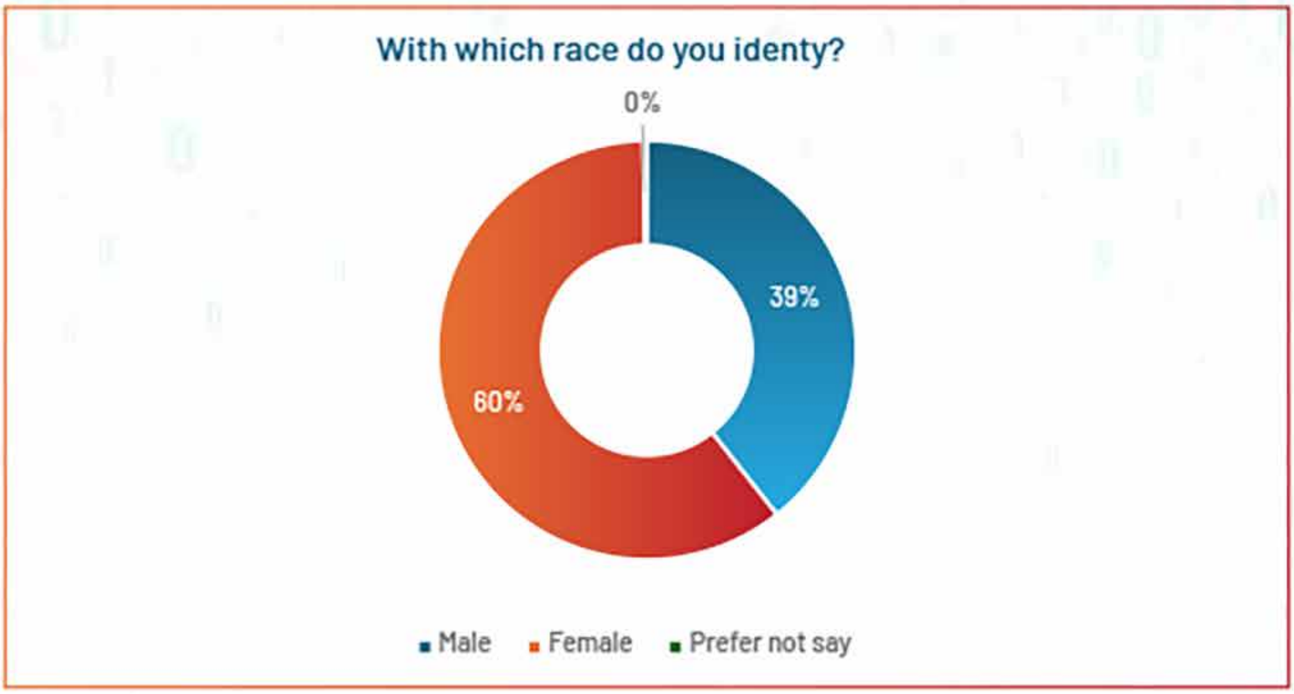


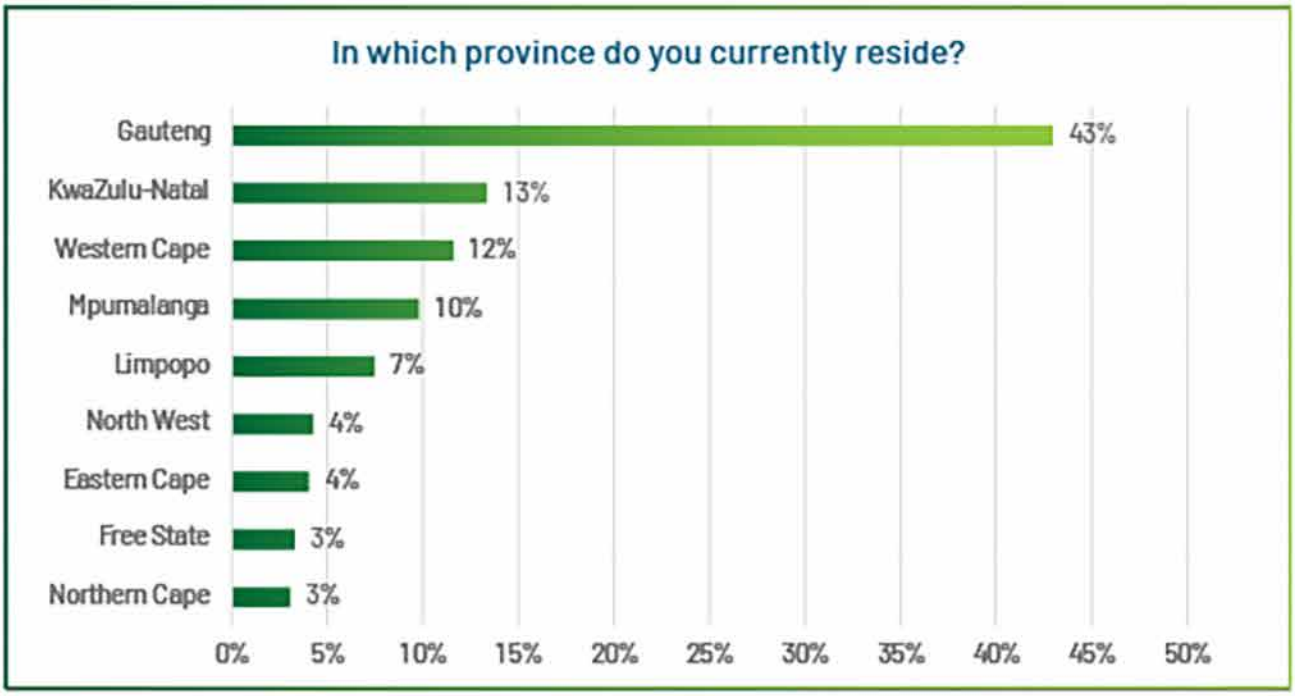
Figure 30: Demographical breakdown by age.

Figure 31: Demographical breakdown by gender.



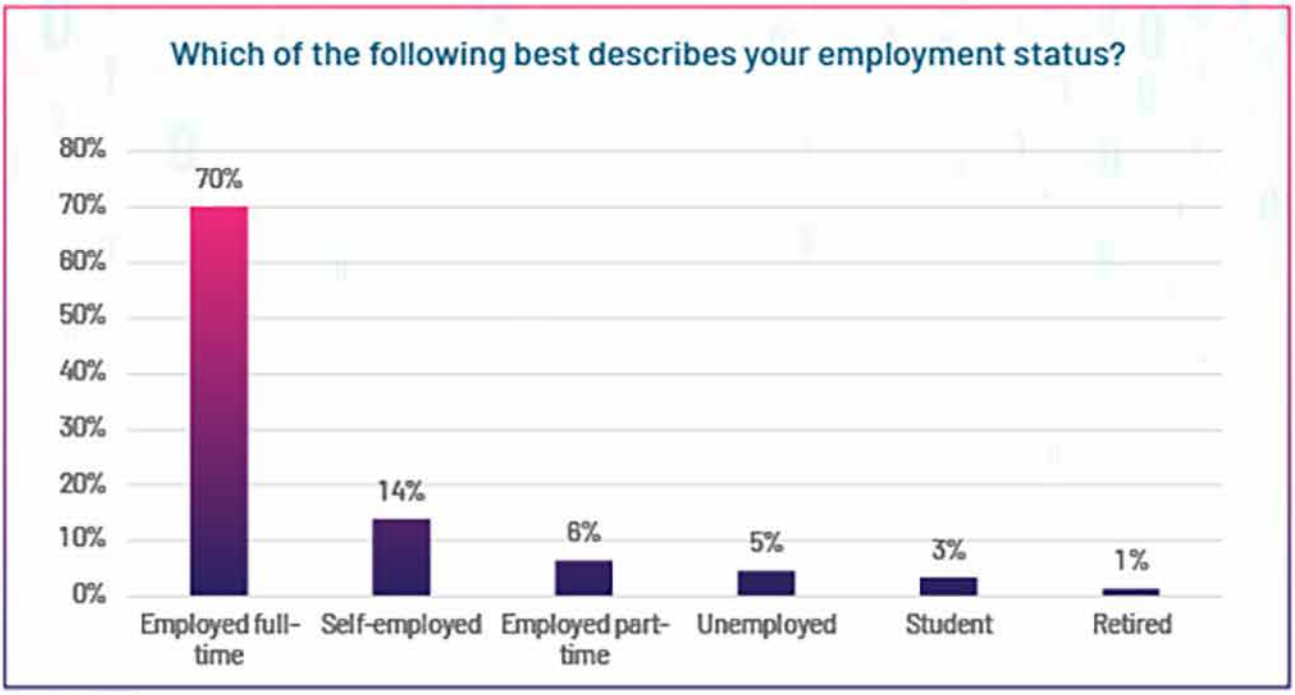
(Sample size: 3547)

Figure 32: Demographical Breakdown by province.



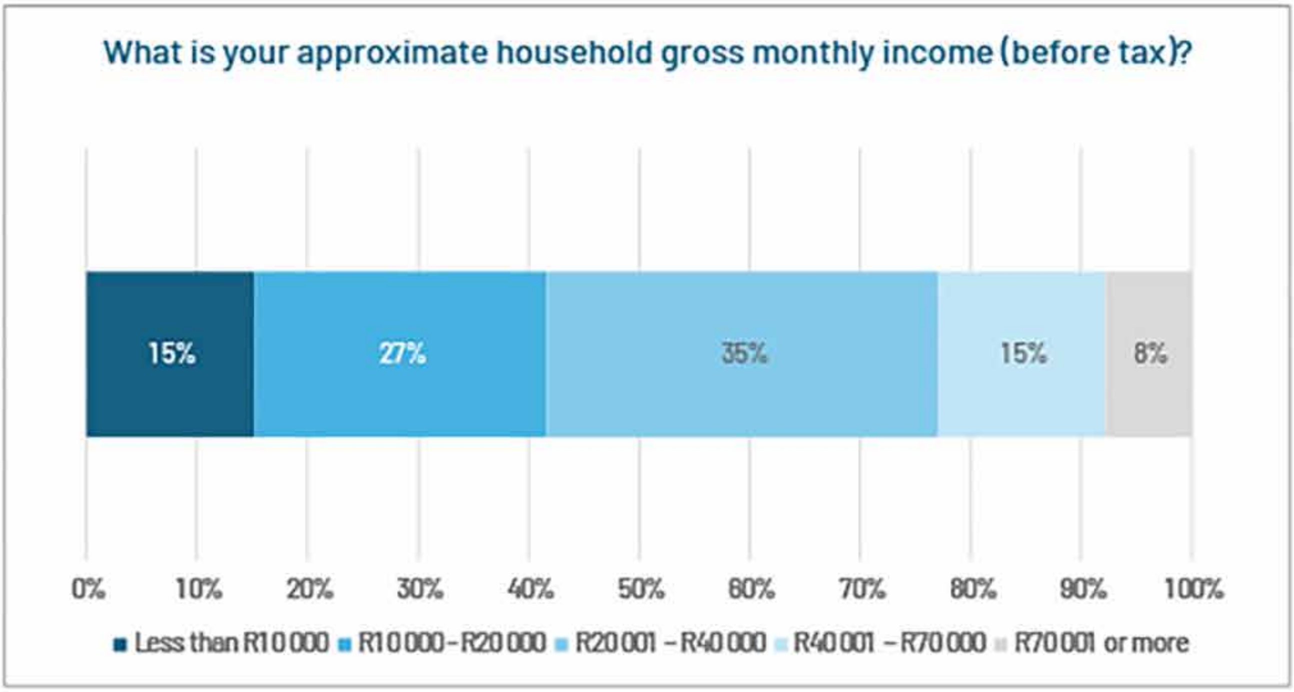
(Sample size: 3547)

Figure 33: Demographical breakdown by employment status



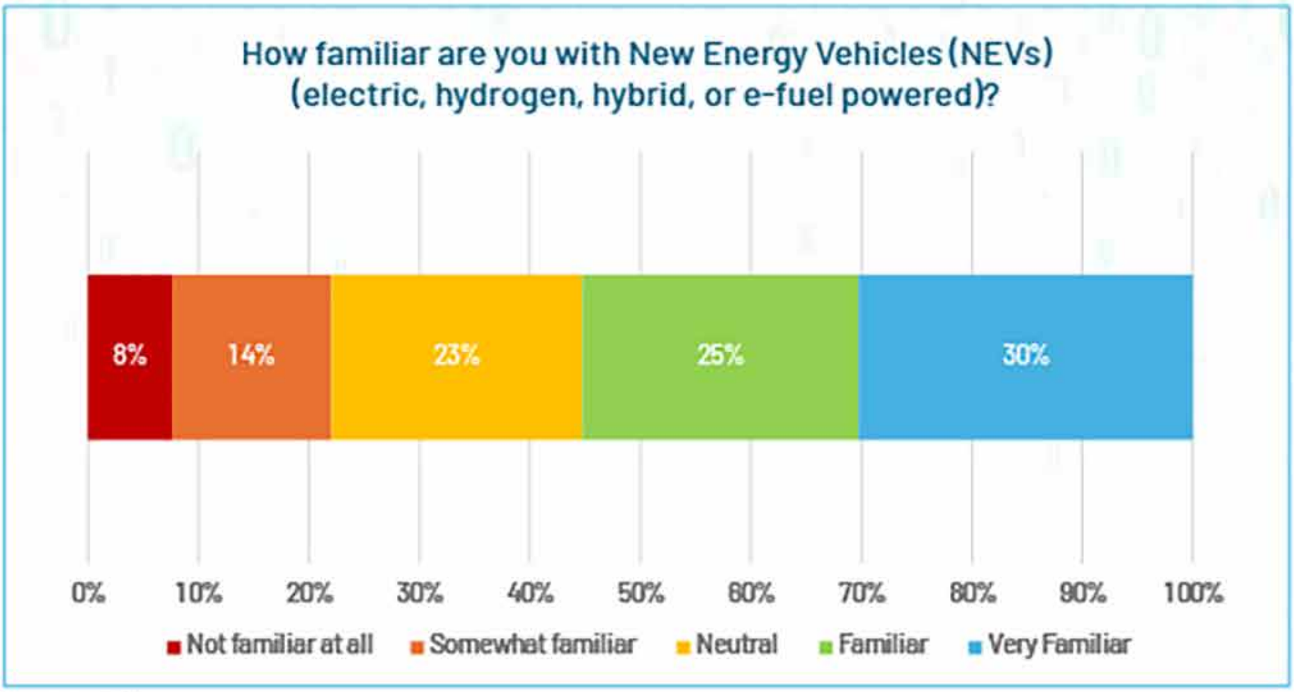
(Sample size: 3547)

Figure 34: Demographical breakdown by income bracket.



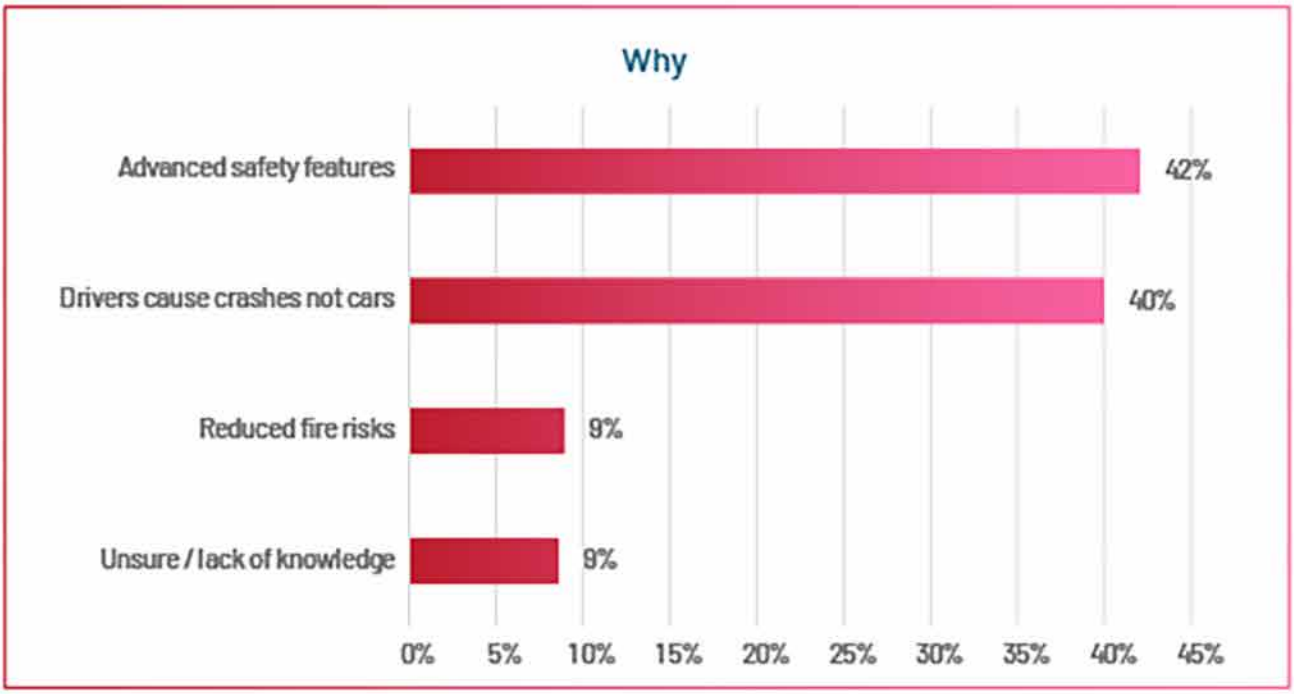
(Sample size: 3547)

Figure 35: Results of familiarity of NEVs



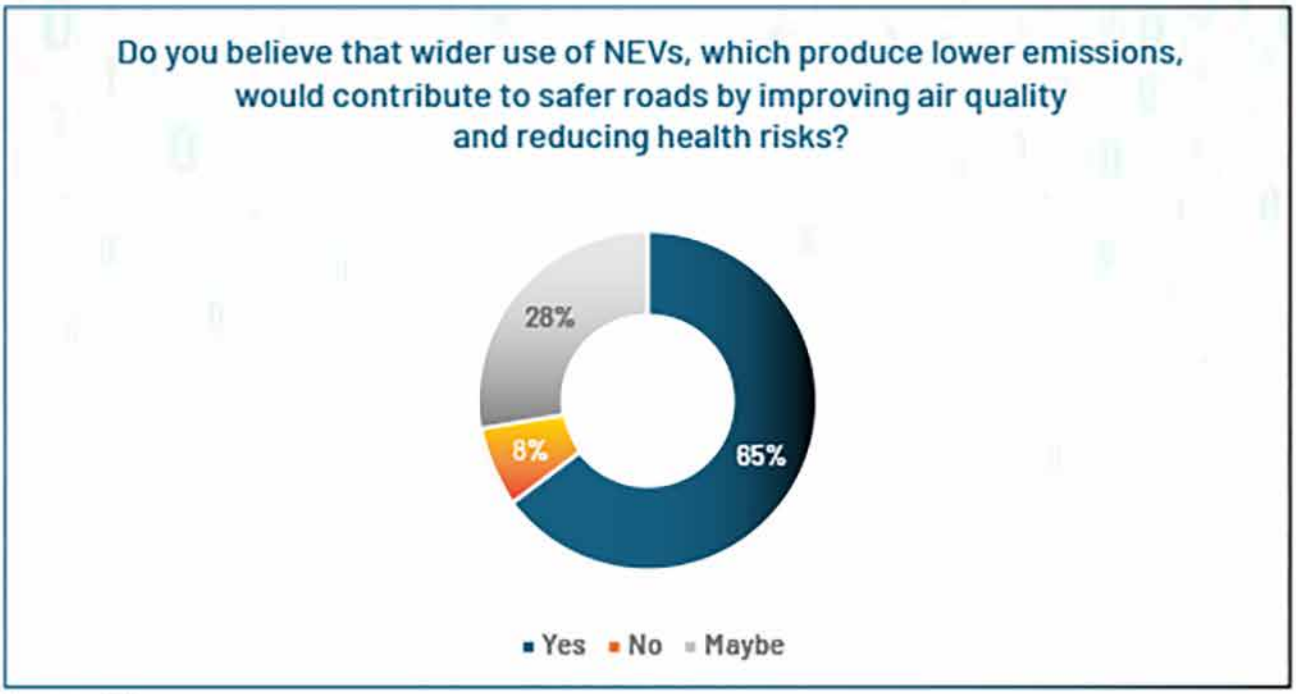
(Sample size: 3547)

Figure 37: Results on why?



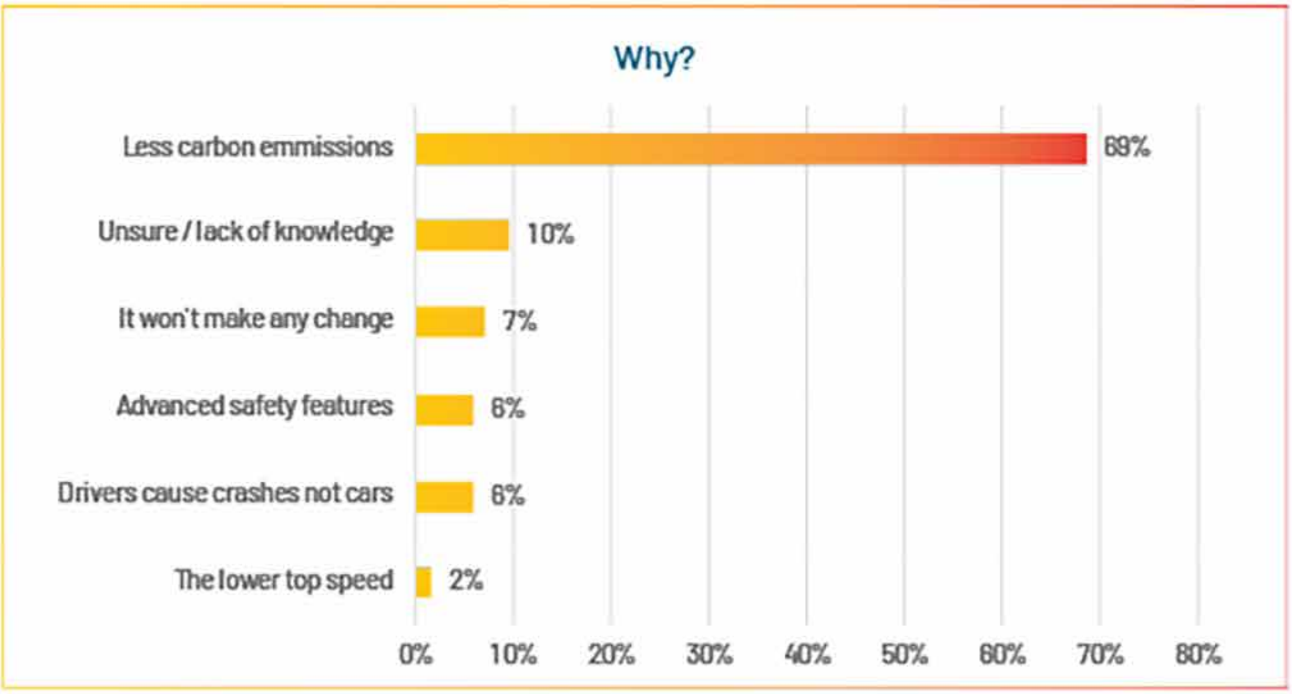
(Sample size: 290)
(Respondents were not required to elaborate on their answers)

Figure 38: Results on if NEVs will contribute to safer roads by reducing health risks



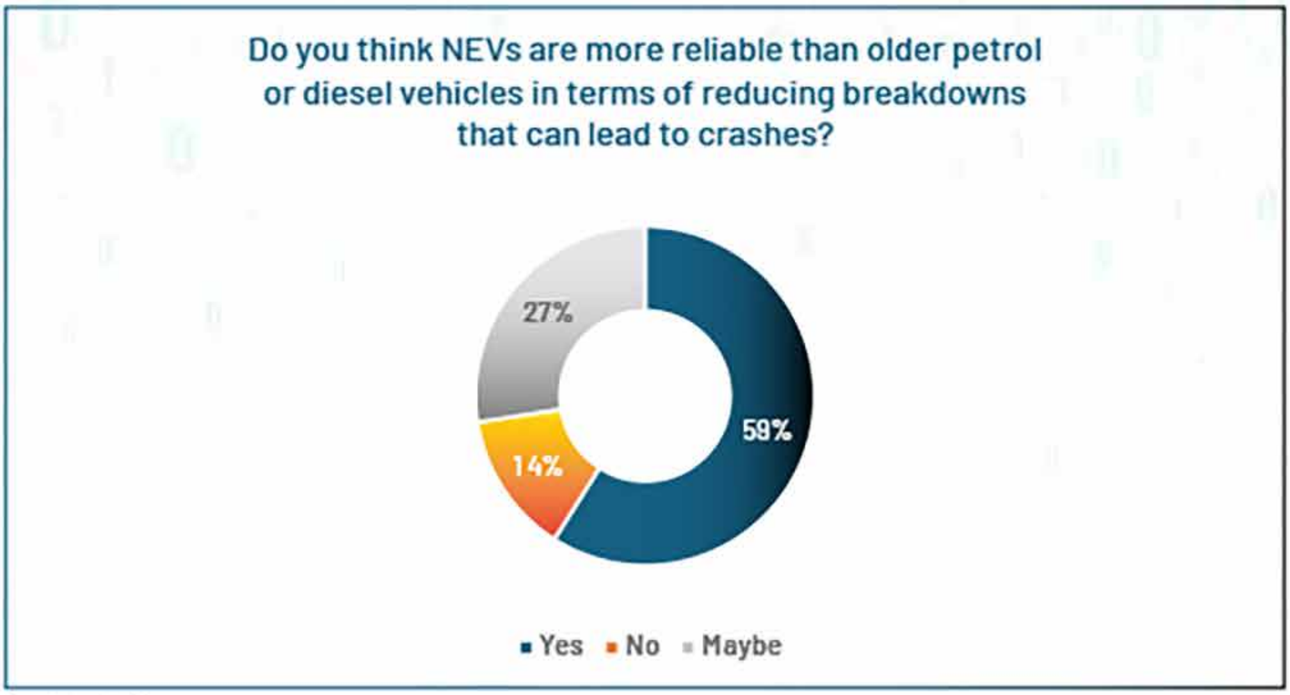
(Sample size: 3380)

Figure 39: Results on why?



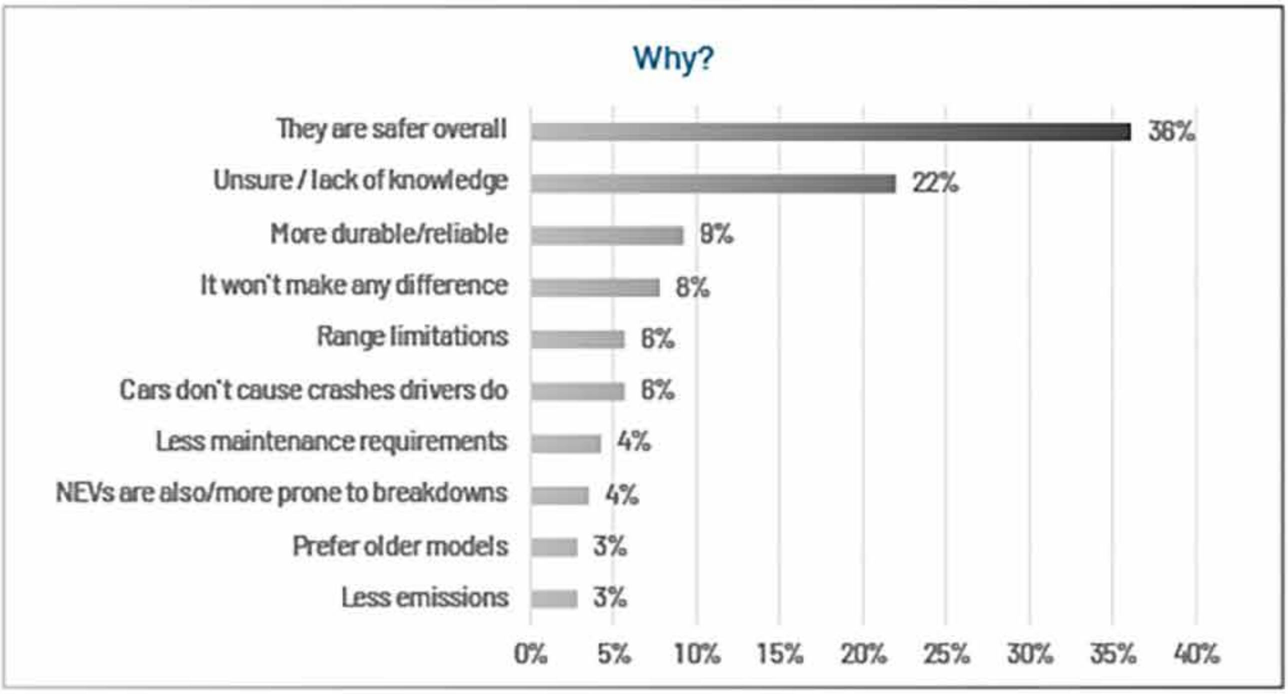
(Sample size: 290)
(Respondents were not required to elaborate on their answers)

Figure 40: Results on reliability of NEVS over ICE vehicles in terms of breakdowns



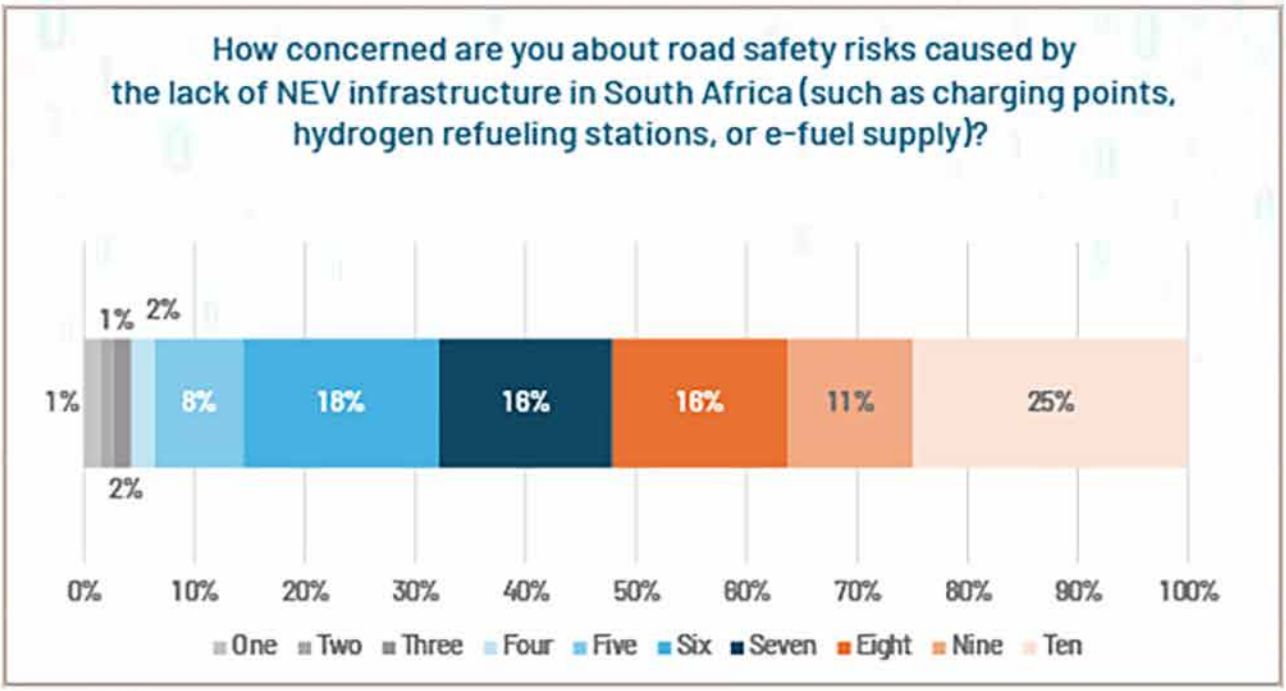
(Sample size: 3318)

Figure 41: Results on why? NEVs preferred reliability over ICE vehicles in terms of breakdowns



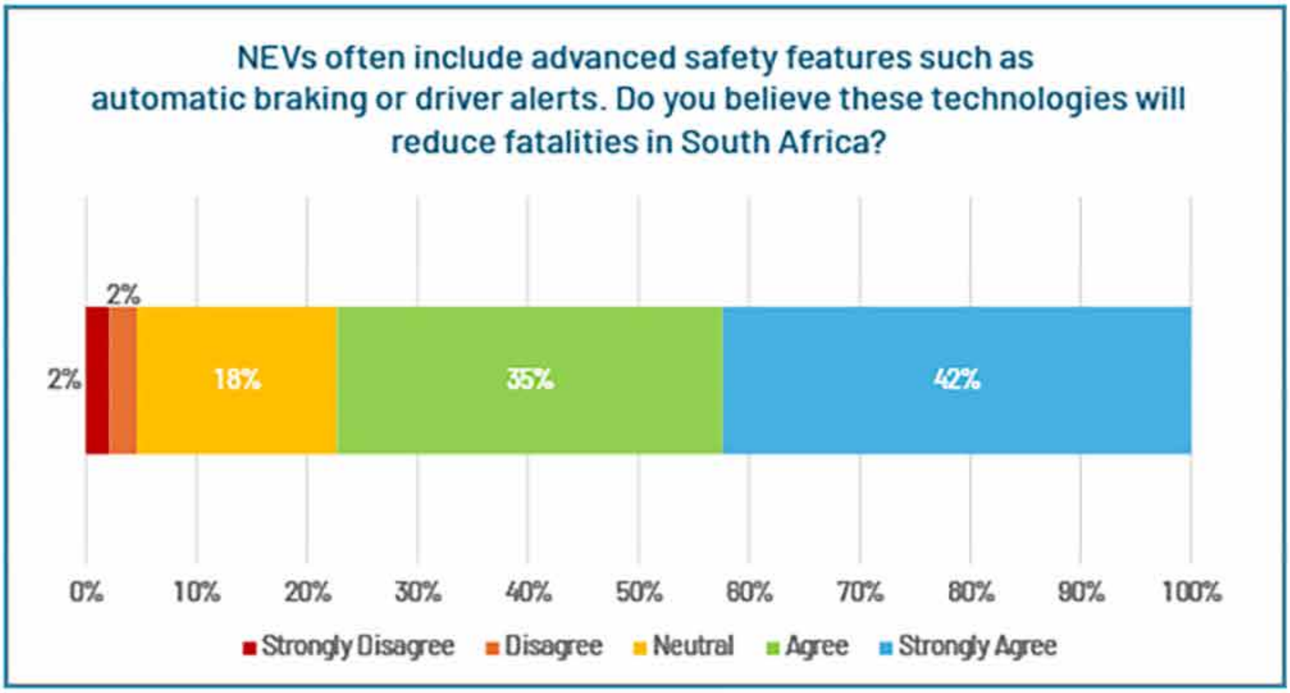
(Sample size: 141)
(Respondents were not required to elaborate on their answers)

Figure 42: Results on concerns for NEV infrastructure in South Africa



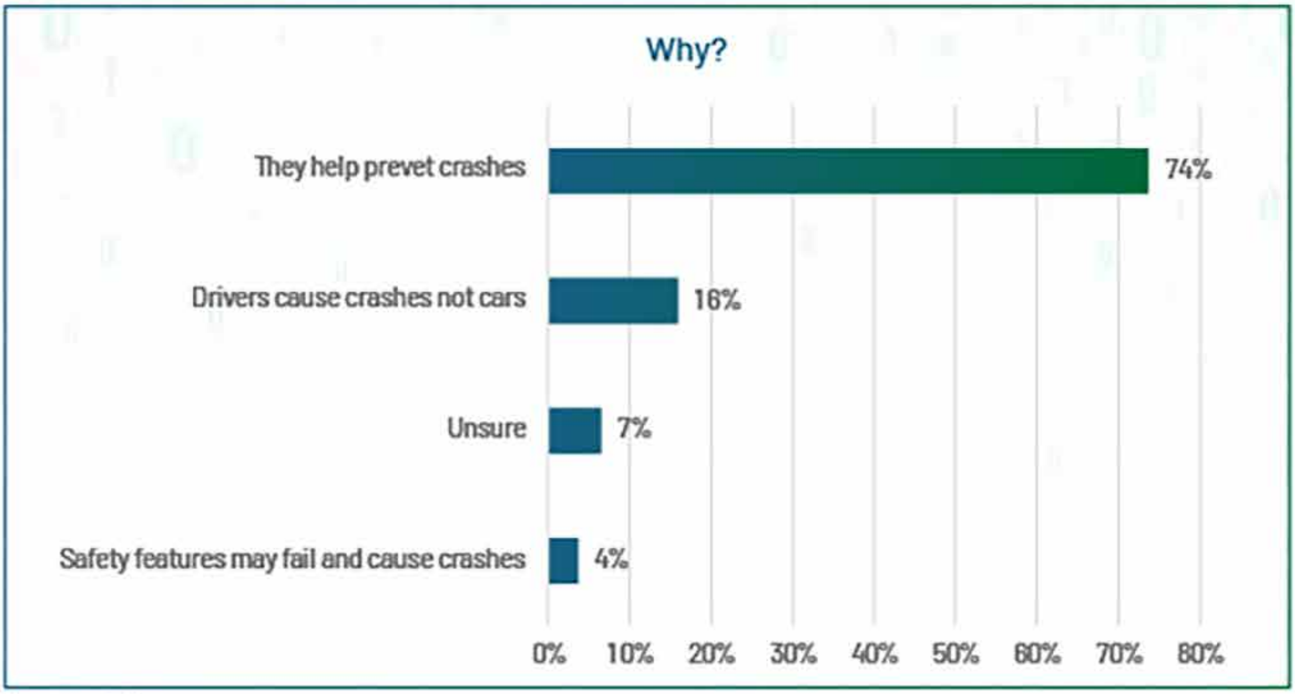
(Sample size: 3547)

Figure 43: Results on ADAS to reduce fatalities in South Africa.



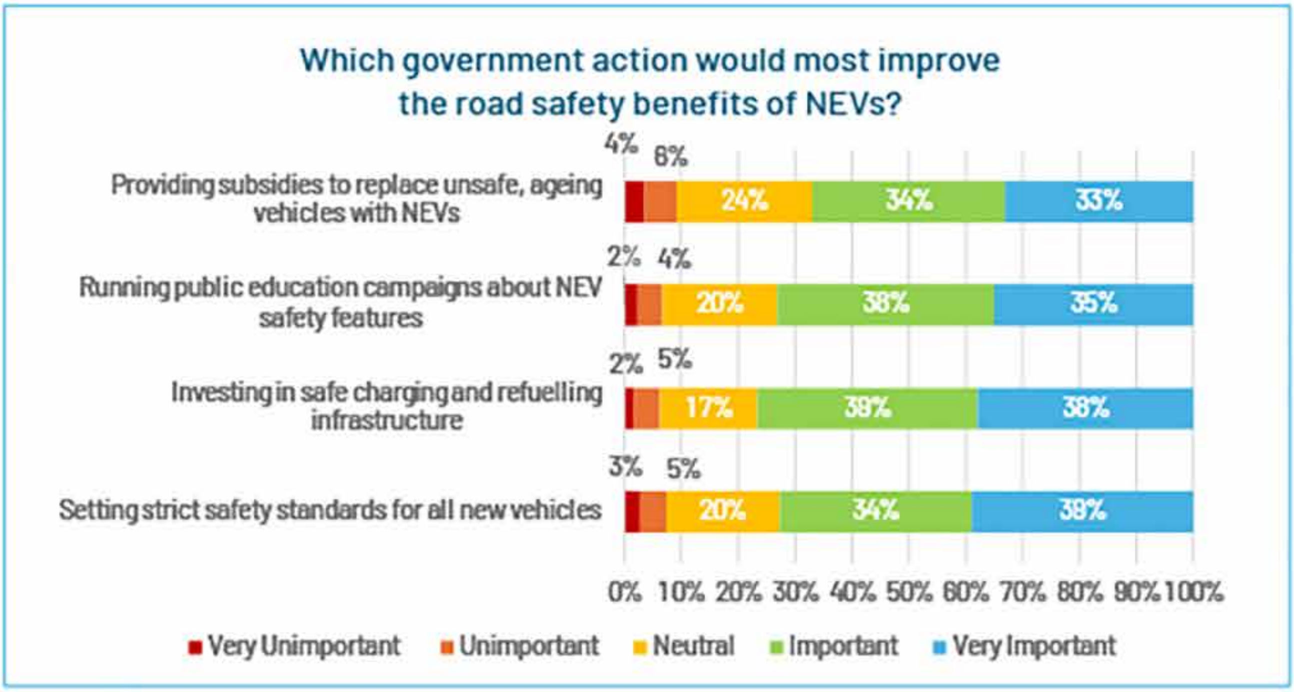
(Sample size: 3547)

Figure 44: Results on why? ADAS to reduce fatalities in South Africa.



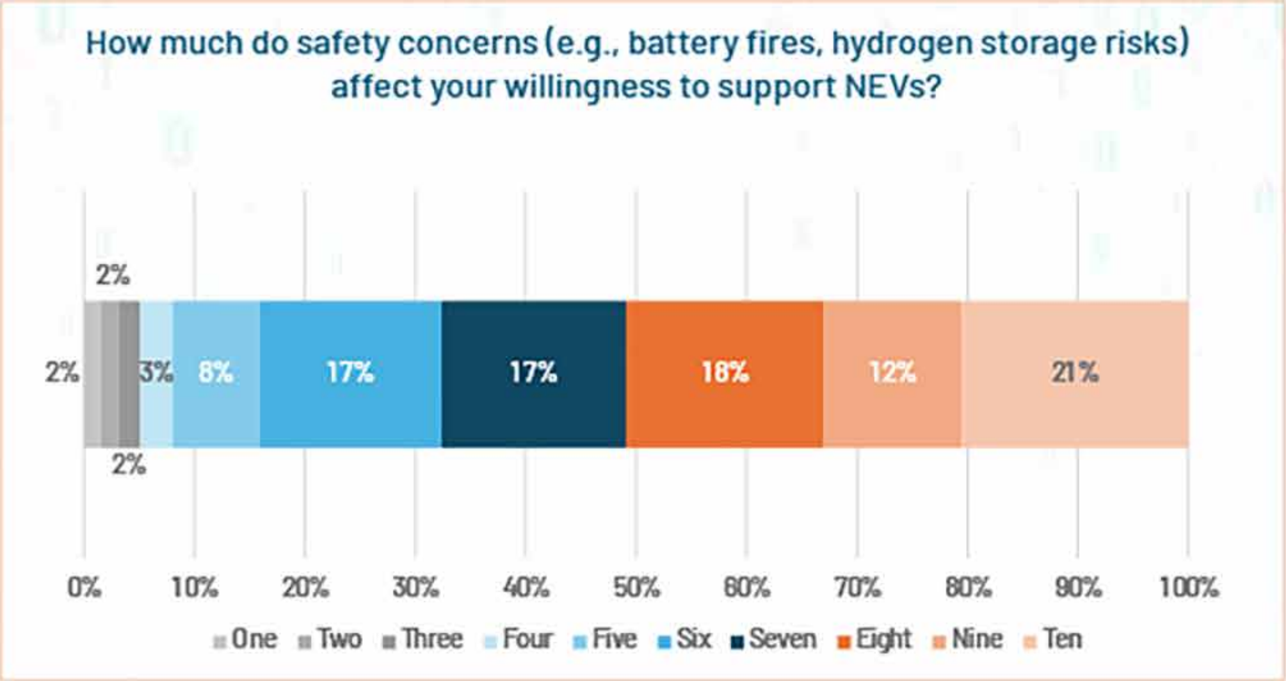
(Sample size: 244)
(Respondents were not required to elaborate on their answers)

Figure 45: Results on government action to improve safety benefits of NEVs.



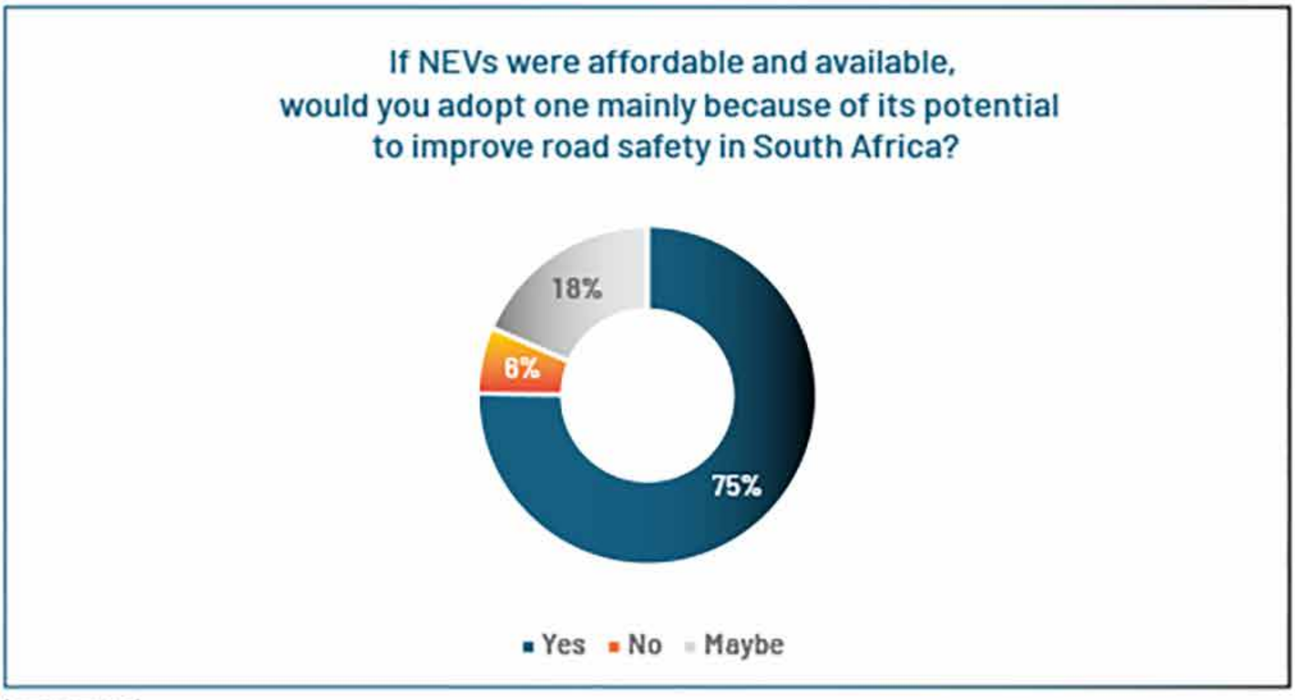
(Sample size: 3047)

Figure 46: Results on safety concerns to affect willingness to support NEVs.



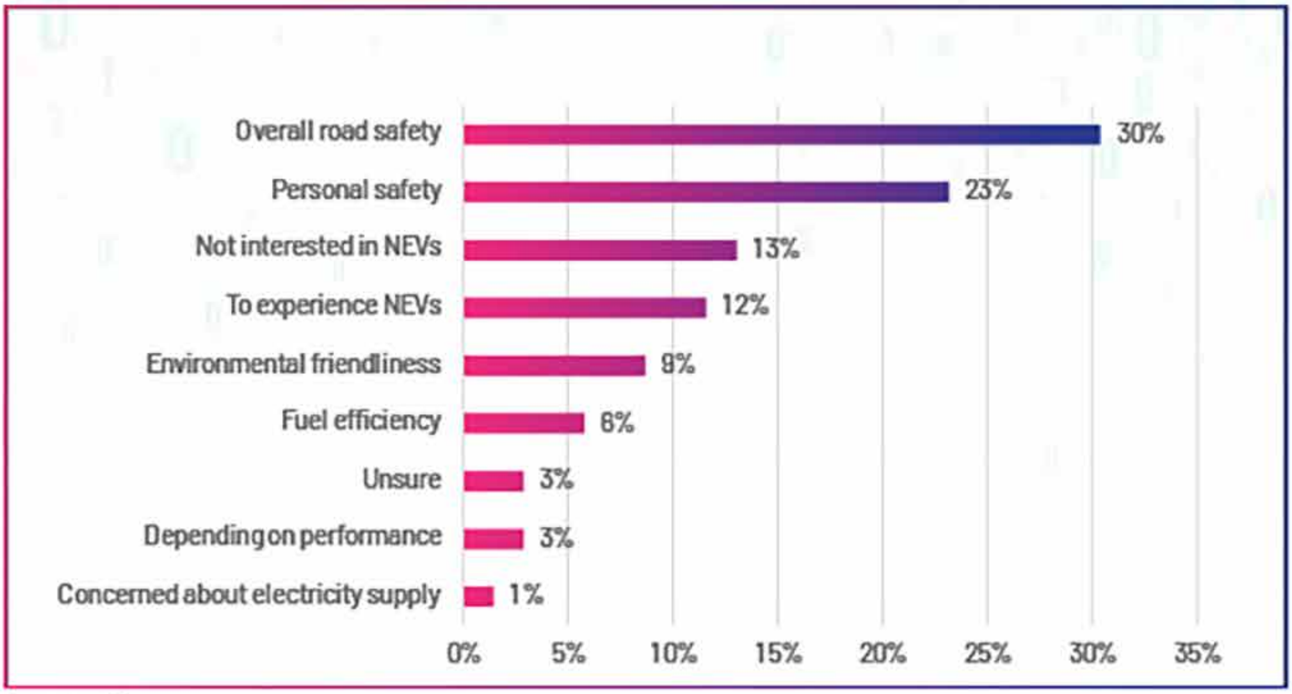
(Sample size: 3547)

Figure 47: Results on NEVs adoption due to improvement of road safety



(Sample size: 3547)

Figure 48: Results on why, NEVs adoption due to improvement of road safety



(Sample size: 69)
(Respondents were not required to elaborate on their answers)

Overall, the results indicate that while there is growing interest in and recognition of the potential benefits of NEVs, public understanding remains uneven, and perceptions are strongly influenced by both real and perceived safety risks. High levels of uncertainty suggest the need for clearer public education, transparent safety communication, and more accessible technical information. Where respondents elaborated, many emphasised human error, infrastructure gaps, and unfamiliarity with new technologies as their main concerns in adopting NEVS, signalling priority areas for policy intervention. The results, therefore, emphasise the importance of aligning technology development, public awareness campaigns, and safety-focused policymaking to ensure the transition to NEVs is both informed and widely supported.

Chapter 8: Discussion & Findings

This study set out to examine whether the transition to NEVs, alongside alternative fuel pathways, can meaningfully improve road safety outcomes in South Africa. The findings demonstrate that, while NEVs and alternative fuels offer significant theoretical and technical safety advantages, their real-world safety impact depends on context-sensitive deployment, supportive infrastructure, and alignment with behavioural and regulatory norms. Crucially, the results indicate that energy transition alone does not automatically translate into crash reduction; instead, safety benefits emerge where cleaner vehicle technologies are deliberately integrated into a broader Safe System-oriented road safety framework (RoSPA, 2023).

The findings indicate that NEVs demonstrate superior mechanical reliability and stability characteristics relative to ageing ICE vehicles prevalent in South Africa. Reduced drivetrain complexity, fewer moving parts, and regenerative braking systems collectively lower the likelihood of mechanical failure, a known contributor to crashes within older vehicle fleets (RoSPA, 2023).

BEVs and HEVs exhibit enhanced vehicle stability due to their low centre of gravity (resulting from battery placement), which improves rollover resistance and braking performance. These attributes align with international evidence linking vehicle stability and braking efficiency to reduced crash severity (RoSPA, 2023). However, the findings also identify emerging safety risks, particularly the near-silent operation, which increases the risk of collisions for pedestrians and cyclists in urban and informal environments with high pedestrian exposure (RoSPA, 2023)

FCEVs offer fast refuelling and long driving range, which makes them well-suited for long-distance and heavy-duty transport (IEA, 2024). Their performance is strong, with smooth power delivery and zero tailpipe emissions. However, their overall well-to-wheel energy efficiency is lower than that of BEVs because hydrogen production and conversion introduce energy losses (ICCT, 2024). However, limited research on FCEVs, especially in South Africa, is available due to a lack of infrastructure.

In this context, where advanced NEV technologies remain constrained by infrastructural readiness, interim fuel solutions that can deliver safety benefits within the existing South African vehicle fleet assume heightened importance.

Carbon-based e-fuels and biofuels offer indirect safety benefits by improving combustion consistency and reducing component wear in older ICE vehicles. Given the average age of the South African vehicle fleet, these alternative fuels offer a pragmatic interim solution to enhance mechanical reliability and reduce roadside breakdowns, an often-overlooked contributor to secondary crashes (IEA, 2025).

Overall, the findings suggest that NEVs reduce mechanical failure risk, but safety benefits vary significantly by vehicle type, operating environment, and infrastructure availability.

Moreover, the results strongly indicate that no single energy pathway is sufficient to meet South Africa's dual objectives of road safety and sustainability. Instead, a portfolio-based approach emerges as the most context-appropriate strategy.

BEVs are best suited to urban environments where shorter trip distances, controlled speeds, and charging access are more feasible (IEA, 2025). However, PHEVs and HEVs offer extended range, fuel savings and flexibility for extended trips. In these contexts, BEVs, HEVs and PHEVs offer both emissions reductions and improved crash survivability through ADAS and vehicle stability enhancements enabled by their low centre of gravity (GreenCape, 2025).

In contrast, rural and freight-dominated areas, characterised by long travel distances, limited grid reliability, and older vehicles, are better served in the medium term by carbon-based e-fuels and biofuel blends, which can be deployed without extensive infrastructure overhaul. These fuels enable incremental safety improvements by enhancing engine reliability and reducing unplanned vehicle stoppages (Ravi et al., 2023).

Hydrogen technologies present long-term safety and decarbonisation potential, particularly for heavy-duty transport. Still, the findings confirm that their contribution in the near future will remain marginal without substantial state-led infrastructure investment (Naamsa, 2023).

Thus, the most effective fatality-reduction strategy involves contextual strategic alignment of new energy technologies with road user risk profiles, geography, and socioeconomic conditions, rather than a uniform national transition model.

The study further found that policymaking in South Africa has historically treated energy transition and road safety as parallel, rather than integrated policy domains. The findings underscore the need for risk-informed spatial prioritisation, whereby NEV incentives, charging infrastructure, and fleet renewal programmes are targeted at high-fatality sectors and vulnerable communities (GreenCape, 2025).

Survey results indicate strong public support for cleaner vehicles but limited awareness of their safety implications. This knowledge gap suggests that policy instruments should explicitly frame NEVs as road-safety interventions rather than solely as environmental interventions. Targeted incentives for safer vehicles equipped with ADAS, particularly in public transport, fleet, and ride-hailing sectors, could yield disproportionate safety benefits.

Moreover, infrastructure planning must be safety-led. Charging and refuelling stations should be integrated into well-lit, secure transport nodes to reduce secondary risks such as pedestrian exposure, roadside stopping, and crime-related vulnerabilities (GreenCape, 2025).

An improved understanding of the NEV landscape, therefore, enables policymakers to sequence investments, prioritise safety-critical technologies, and avoid misalignment between energy policy ambitions and on-the-ground risk realities (GreenCape, 2025).

The findings highlight that technological change alone is insufficient to deliver safety outcomes without complementary behavioural and regulatory interventions. Behavioural adaptation emerges as a critical factor, particularly in pedestrian interactions with quiet NEVs and in driver over-reliance on automation features.

Regulatory reforms are required to mandate pedestrian alert systems, standardise battery and hydrogen safety protocols, and integrate NEVs into roadworthiness testing regimes. Significantly, enforcement frameworks must evolve to account for new vehicle technologies, including autonomous and semi-autonomous features (Nature, 2025).

Infrastructure deficits, especially unreliable electricity supply, limited charging access, and poor road quality, pose a significant barrier to equitable safety gains. Without targeted investment in underserved communities, NEVs risk becoming a safety benefit exclusive to higher-income users (Moeletsi, 2021).

Public education initiatives, informed by behavioural science, are therefore essential to ensure that drivers, pedestrians, and enforcement agencies understand and adapt to the changing vehicle ecosystem. These shifts collectively determine whether NEV adoption translates into systemic crash reduction rather than isolated technological progress (GreenCape, 2025).

In summary, the findings confirm that NEVs and alternative fuels hold substantial promise for improving road safety in South Africa, primarily through enhanced vehicle reliability, reduced mechanical failures, and the integration of advanced safety technologies. However, these benefits are neither automatic nor evenly distributed.

Meaningful safety gains depend on a systems-based approach that aligns energy transition with behavioural adaptation, regulatory reform, and infrastructure investment. Where such alignment is absent, the safety potential of NEVs remains unrealised.

The discussion reinforces the central conclusion of this study: South Africa's readiness for NEVs must be evaluated not only in terms of energy and emissions, but also in its capacity to translate technological change into measurable reductions in fatalities and injuries on its roads.

Chapter 9: Conclusion

This research set out to examine whether South Africa is ready to adopt NEVs that not only advance decarbonisation objectives but also deliver measurable improvements in road safety outcomes. The findings indicate that while NEVs offer significant long-term potential to reduce emissions and modernise the national vehicle fleet, their road safety benefits are not automatic and will only be realised through contextual, deliberate, system-wide policy alignment, infrastructure investment, and behavioural interventions.

South Africa's road safety crisis remains acute, with fatalities driven predominantly by human factors, an ageing vehicle fleet, and infrastructural deficits. The analysis demonstrates that cleaner propulsion technologies alone cannot address these systemic risks. However, when appropriately deployed, NEVs can contribute to improved safety by reducing mechanical failures, enabling advanced driver-assistance systems (ADAS), and accelerating fleet renewal, particularly when integrated into a broader Safe System-aligned mobility strategy (Holmatov & Hoekstra, 2020; ITF, 2023).

From a fuel-pathway perspective, the research indicates that no single energy solution is sufficient for South Africa's heterogeneous transport context. BEVs offer the most direct pathway to zero tailpipe emissions and lower per-kilometre energy costs, yet their safety and sustainability benefits remain constrained by electricity supply instability, limited charging infrastructure, and socioeconomic inequities (IEA, 2023; EERE, 2023). FCEVs present advantages in refuelling time and range, particularly for freight and long-distance travel, but face prohibitive cost and infrastructure barriers in the short to medium term (IRENA, 2022a). Carbon-based e-fuels and select biofuels, while inefficient from a well-to-wheel energy perspective, provide pragmatic transitional options for improving the safety and reliability of the existing ICE vehicle fleet, especially in regions unlikely to electrify rapidly (Ueckerdt et al., 2021; Brynolf et al., 2022).

Critically, the survey findings reinforce that public understanding of NEVs in South Africa remains limited, with safety benefits, maintenance implications, and total cost of ownership poorly understood by consumers. This knowledge gap poses a material risk to both adoption rates and behavioural adaptation, particularly among high-risk road user groups and vulnerable communities. Without targeted education and regulatory clarity, NEVs may replicate existing risk patterns rather than disrupt them (Puricelli et al., 2021; IEA, 2023d).

The study further finds that the most significant road safety dividends from NEV adoption are likely to arise not from propulsion technologies themselves, but from the digitalisation and intelligence embedded within modern vehicles. Advanced braking systems, collision-avoidance technologies, pedestrian detection, and vehicle-to-infrastructure communication offer substantial opportunities to mitigate human error, the current leading contributor to road crashes in South Africa. Ensuring that such technologies are prioritised in vehicle import standards, fleet procurement, and incentive frameworks is therefore essential.

In conclusion, South Africa is partially ready for a transition to new NEVs but is not yet prepared to harness their road-safety potential fully. A successful transition requires a phased, multi-technology approach that balances electrification with transitional fuels, accelerates fleet renewal, and embeds safety as a core performance metric alongside emissions reduction. Policymakers must resist framing NEVs solely as a climate intervention and instead position them as tools for road safety, public health, and socio-economic development.

If supported by coherent policy, targeted incentives, inclusive infrastructure planning, and sustained public education, NEVs can play a meaningful role in reducing road fatalities while advancing South Africa's clean mobility ambitions. Without such alignment, the transition risks entrenching existing inequalities and missing a critical opportunity to address one of the country's most persistent public safety challenges.

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Notes

Notes

Physical Address
Centurion Gate Business Park
Block A to D
146 Akkerboom Street
Zwartkop 0157
Gauteng, South Africa

Email: Info@rtmc.co.za
Tel: (012) 999-5200
Fax: (012) 991-0371

Postal Address
Private Bag X147
Pretoria, 0001

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DECADE OF ACTION FOR
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