WORLD ENERGY COUNCIL
AUSTRIA YOUNG ENERGY PROFESSIONALS

World Energy Council Austria

Young Energy Professionals (YEP), 5. Zyklus

Final Report

Group: Transport & Mobility

Title: "*The Future of CO2-free Mobility and Transportation: Challenges, Policies, and Emerging Technologies*"

ÜBER YOUNG ENERGY PROFESSIONALS

Die Young Energy Professionals (**YEP**) bilden das interdisziplinäre Netzwerk junger Berufstätiger im WEC Austria. Gegründet „von jungen Menschen für junge Menschen“ auf dem Weltenergiekongress 2007 in Rom, sind die Ziele der Young Energy Professionals:

- **faktenbasiert Wissen** zu energiewirtschaftlichen Themen zu vermitteln,
- ein fachlich übergreifendes **Netzwerk** aufzubauen,
- **junge Entscheidungsträger und Meinungsbildner** sowie den energie-wirtschaftlichen Nachwuchs anzusprechen,
- **Erfahrungs- und Wissensaustausch** innerhalb des WEC-Netzwerks zu ermöglichen sowie
- die internationalen Aktivitäten der **Future Energy Leaders** Community von WEC zu unterstützen.

Der WEC Austria beschloss im Jahr **2015** eine **nationale YEP-Gruppe** zu etablieren. Zum einen werden auf nationaler Ebene Lösungsvorschläge zu verschiedenen energiewirtschaftlichen Fragestellungen erarbeitet. Hierbei deckt ein interdisziplinärer Pool an jungen Berufstätigen der Energiewirtschaft vielfältige Themenbereiche ab. Zum anderen unterstützen die YEP von WEC Austria die Arbeiten der internationalen Nachwuchsorganisation des World Energy Council. Ein Board aus Mentoren unterstützt und begleitet die YEP.

Der YEP-Zyklus dauerte in dieser Kohorte ein Jahr. Im Anschluss werden die YEP-Programmteilnehmer in die YEP-Alumni-Community aufgenommen.

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GROUP

Transport & Mobility

TITLE

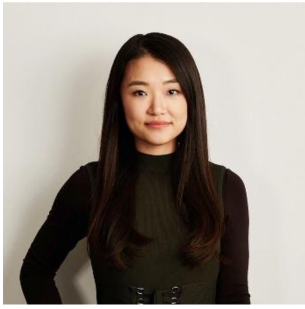
The Future of CO2-free Mobility and Transportation: Challenges, Policies, and Emerging Technologies

AUTHORS

Teresa Oberascher
Wanyu Sheng-Kara
Liesa Zhou
Jelisaveta Pavlovic
Maximilian Klein

About the Authors

Teresa Oberascher *is a renewable energy and climate finance professional with more than eight years of international experience. She is Senior Manager at Renewable Energy and Energy Efficiency Partnership (REEEP), where she leads programmes supporting renewable energy market development and private-sector investment in emerging economies. Her work focuses on climate finance, energy access, programme design, stakeholder engagement, and gender-lens investing, with extensive experience across Sub-Saharan Africa. She currently manages the PURE Growth Programme focusing on Productive Use of Renewable Energy in agri-food value chains in Tanzania. She holds an MSc in Socio-Ecological Economics and Policy from the Vienna University of Economics and Business and a BSc in Environmental and Bioresources Management from the University of Natural Resources and Life Sciences as well as a BA in Transcultural Communication from the University of Vienna.*



Wanyu Sheng-Kara *leads an international product innovation and management team in OMV Retail, that drives the development of premium fuels and supports driving the expansion of electro-mobility solutions across Central Eastern Europe. She is an energy professional with broad cross-sector experience spanning gas, and international commercial fuels business. Throughout her career, she has worked at the intersection of energy systems, customer needs, and decarbonization technologies, developing a holistic perspective on the challenges and opportunities of the energy transition. She began her career in the gas division, where she shaped the product portfolio by advancing carbon-offset solutions and integration of biomethane guarantees of origin. Her work provided practical pathways for customers to reduce emissions while strengthening the company's sustainability offerings. She later played a key role in developing innovative fuel solutions for road transport, marine, aviation, and heating markets. Among her notable achievements is the application of a SAF sustainability-verification solution that enabled major corporate clients to reduce their carbon footprint independently of physical fuel supply.*

Liesa Zhou *is a Product Manager at Huawei in the Renewable Energy sector, specializing in energy storage systems and photovoltaic solutions. She leads go-to-market activities for renewable energy products, including product positioning, certification, and compliance, and works at the intersection of product innovation, customer engagement, and market strategy. Her responsibilities include product portfolio optimization, market analysis, and close collaboration with R&D teams to align technological development with evolving market needs. Throughout her career, she has gained extensive experience in customer-oriented solution development, conducting technical workshops and supporting clients in the implementation of sustainable energy technologies. She has also supported the technical deployment of various grid-supporting BESS solutions across Austria. Her work focuses on bridging technical expertise with commercial strategy, enabling the large-scale deployment and integration of advanced PV and BESS solutions in evolving energy markets.*

***Jelisaveta Pavlovic** is a Senior Energy Expert at OMV with 7+ years of experience spanning the full energy value chain — from crude oil and refinery economics to sustainable fuels and renewable power. She began her career coordinating crude oil supply and optimizing crude oil selection for OMV's two refineries, building a strong foundation in complex commercial and technical decision-making. She later moved into renewable fuels, where she developed business models and investment cases for major CAPEX projects in sustainable aviation fuels, evaluating feedstock economic, process related emissions, and financial viability while translating market and regulatory changes. Most recently, in an upstream role, she has been shaping OMV's renewable power strategy, leading PPA valuations, and supporting renewable power asset development. Holding a Master's in Renewable Energy Systems from Vienna University of Technology and a Master's in Business Administration from the University of Vienna, she combines both technical understanding and commercial perspective in her work across B2B energy markets.*

Maximilian Klein *has been an associate at Schoenherr since 2024 and advises clients on regulatory, especially energy law, matters. Previously, he was an associate in an international law firm in Vienna, in the dispute resolution, regulatory practice group. From 2022 to 2024, he served as a member of the scientific staff at the Austrian Constitutional Court. He began his professional career in 2020 as a research and teaching associate at the Institute for Administrative Law and Administrative Theory, Department of Technology Law, at the Johannes Kepler University Linz, a role he held until 2022.Maximilian holds a PhD in Law from the Johannes Kepler University Linz. His PhD thesis, titled "New market participants in energy law: prosumers and energy communities. A comparative analysis of their legal characteristics" was awarded the Environmental and Technology Law Award in 2023. Prior to this, he completed his law degree at Paris Lodron University Salzburg, where he wrote his thesis on "The procedural duration of environmental impact assessments under the UVP-G 2000".*

Acknowledgements

We would like to express our sincere gratitude to the World Energy Council Austria for providing the opportunity to address the forward-looking and societally as well as technologically highly relevant topic The Future of CO_2-free Mobility and Transportation: Challenges, Policies, and Emerging Technologies within the framework of the Young Energy Professionals Program. The program offered a valuable platform to critically reflect on current challenges, policy frameworks, and emerging technological solutions shaping the transition towards climate-neutral mobility and transportation systems, while fostering interdisciplinary exchange among young professionals.

Our special thanks go to our content supervisor, **Stephan Unger**, **Associate Professor in the Department of Economics and Business at Saint Anselm College**, whose expertise, analytical guidance, and constructive feedback substantially contributed to the quality and coherence of this work. We would also like to thank **Eva Lugstein**, **Program Director**, for her dedicated organizational support and strategic oversight throughout the program. Furthermore, we express our sincere appreciation to **Gerhard Gamperl**, **Managing Director of the World Energy Council Austria**, for his continued support of the Young Energy Professionals Program and for enabling meaningful dialogue and networking within the energy and mobility community.

Acronyms and Abbreviations

ACEA – Association des Constructeurs Européens d'Automobiles - European Automobile Manufacturer's Association

AEL – Alkaline Electrolyser

AEM – Anion Exchange Membrane

AFIR – Alternative Fuels Infrastructure Regulation (Regulation (EU) 2023/1804)

BEÖ – Bundesverband Elektromobilität Österreich (Austrian e-mobility association)

BEV – Battery Electric Vehicle

Bio-ETBE – Bio-Ethyl Tert-Butyl Ether

Bio-MTBE – Bio-Methyl Tert-Butyl Ether

BtL-FT – Biomass-to-Liquid Fischer-Tropsch

BYD – Build your dreams

CAFE – CO_2 and Fuel Efficiency Regulation (Regulation (EU) 2019/631)

CATL – Contemporary Amperex Technology Co Ltd

CGH_2 – Compressed Gaseous Hydrogen

CO_2 – Carbon Dioxide

CRMA – Critical Raw Materials Act

DAC – Direct Air Capture

EEA – European Environment Agency

ESR – Effort Sharing Regulation (Regulation (EU) 2018/842)

ETS – Emissions Trading System

EU – European Union

EVs – Electric Vehicles

FAME – Fatty Acid Methyl Ester

FCB – Fuel Cell Bus

FCEV – Fuel Cell Electric Vehicle

FT – Fischer-Tropsch (Synthesis)

GDP – Gross Domestic Product

GHG – Greenhouse Gas

HDO – Hydrodeoxygenation

HRS – Hydrogen Refueling Station

HTL – Hydrothermal Liquefaction

HVO – Hydrotreated Vegetable Oil

ICE – Internal Combustion Engine

ILUC – Indirect Land Use Change

IRA – Inflation Reduction Act

KSG – Klimaschutzgesetz (Climate Protection Act)

LDVs – Light Duty Vehicles

LH_2 – Liquid Hydrogen

MinStG – Mineralölsteuergesetz 2022 (Petroleum Tax Act 2022)

MPSP – Minimum Product Selling Price

MtG – Methanol-to-Gasoline

NEHG – Nationales Emissionszertifikatehandelsgesetz 2022 (National Emissions Certificate Trading Act 2022)

NEV – New Energy Vehicle

NoVA – Normverbrauchsabgabe

NoVAG – Normverbrauchsabgabegesetz (Standard Consumption Tax Act)

NZIA – Net Zero Industry Act

OEM – Original Equipment Manufacturers

OME – Polyoxymethyl Dimethyl Ether

PEM – Proton Exchange Membrane

PHEVs – Plug-in hybrid electric vehicles

PtG – Power-to-Gas

PtL – Power-to-Liquid

PtX – Power-to-X

RED II – Renewable Energy Directive (Directive (EU) 2018/2001)

RED III – Renewable Energy Directive (Directive (EU) 2023/2413)

RFNBOs – Renewable Fuels of Non-Biological Origin

RWGS – Reverse Water-Gas Shift

SAF – Sustainable Aviation Fuel

TCO – Total Cost of Ownership

TEN-T – Trans-European Transport Network

TRL – Technology Readiness Level

UCO – Used Cooking Oil

UFC – Ultrafast Charging

V2G – Vehicle-to-Grid

VECTO – Vehicle Energy Consumption Calculation Tool

WTW – Well-to-Wheel

Table of Contents

I. Introduction

Reducing emissions is one of the greatest challenges in achieving sustainable transformation globally. In the EU, road transport makes up more than 70% greenhouse gas emissions from the entire transport sector and thus remains one of the most challenging sectors for decarbonization in Europe.

Greenhouse gas emissions from transport in the EU

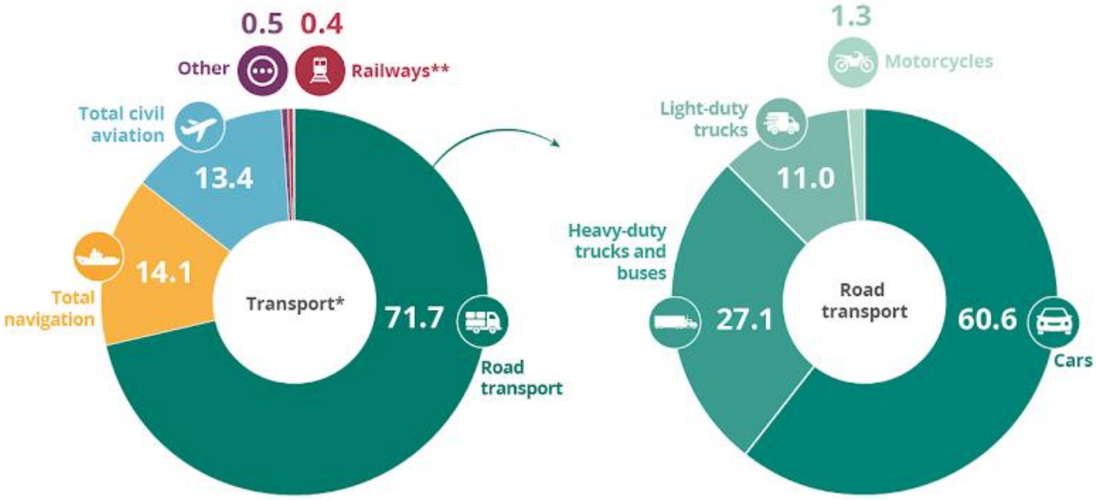


Figure 1: Greenhouse gas emissions from transport in the EU (EEA, 2025)

Over the past decade, renewable fuels and alternative low-carbon propulsion systems, such as electric mobility, have experienced rapid growth and become more efficient, driven by technological advancements, regulatory pressure, and increasing societal awareness of climate change. However, recent years have revealed a notable slowdown in transportation decarbonization, raising important questions about the structural, economic, technological, and political factors shaping the trajectory of transport decarbonization.

This report examines the current state of electric vehicles within a broader system perspective, recognizing that vehicle electrification does not occur in isolation but is deeply embedded in market dynamics, socio-economic conditions, infrastructure availability, and regulatory frameworks. While battery electric vehicles have become the dominant decarbonization pathway for passenger cars, their limitations, particularly regarding cost, charging infrastructure, and applicability to heavy-duty transport have renewed interest in complementary technologies such as hydrogen fuel cells, biofuels, and synthetic e-fuels. The coexistence and competition of these technologies highlight the need for a technology-neutral yet evidence-based assessment of decarbonization options.

Focusing on Europe with a particular emphasis on Austria, this report analyses demand trends, technology maturity and cost structures. across different vehicle segments. It further evaluates the influence of the political landscape (in particular in Europe, Austria, US and China) strategic responses of major automotive original equipment manufacturers (OEMs), socio-economic factors as well as charging infrastructure. s. In parallel, the study investigates the role of the European Union's multi-layered regulatory architecture and national policy instruments in accelerating or constraining the transition.

By combining market analysis, techno-economic comparison, and regulatory assessment, this work seeks to provide a holistic understanding of the drivers and barriers shaping the future of low-carbon road transport. Ultimately, the report contributes to the ongoing debate on how Europe can achieve an efficient, resilient, and socially balanced transport decarbonization pathway under conditions of economic and geopolitical uncertainty providing actionable recommendations for different players.

II. Current State of Electric Vehicles and slowdown in E-Mobility Growth

1 Global Market Dynamics

Global electric vehicle (EV) sales continue to grow, but the pace of expansion has noticeably slowed down in several major markets. According to BloombergNEF's Electric Vehicle Outlook 2025, projections for EV adoption between 2025 and 2030 have been revised downward compared to last year's forecast (BloombergNEF, 2025). This slowdown is especially visible in the United States and Europe, where policy uncertainty, economic pressures, and weaker consumer confidence are affecting market trajectories.

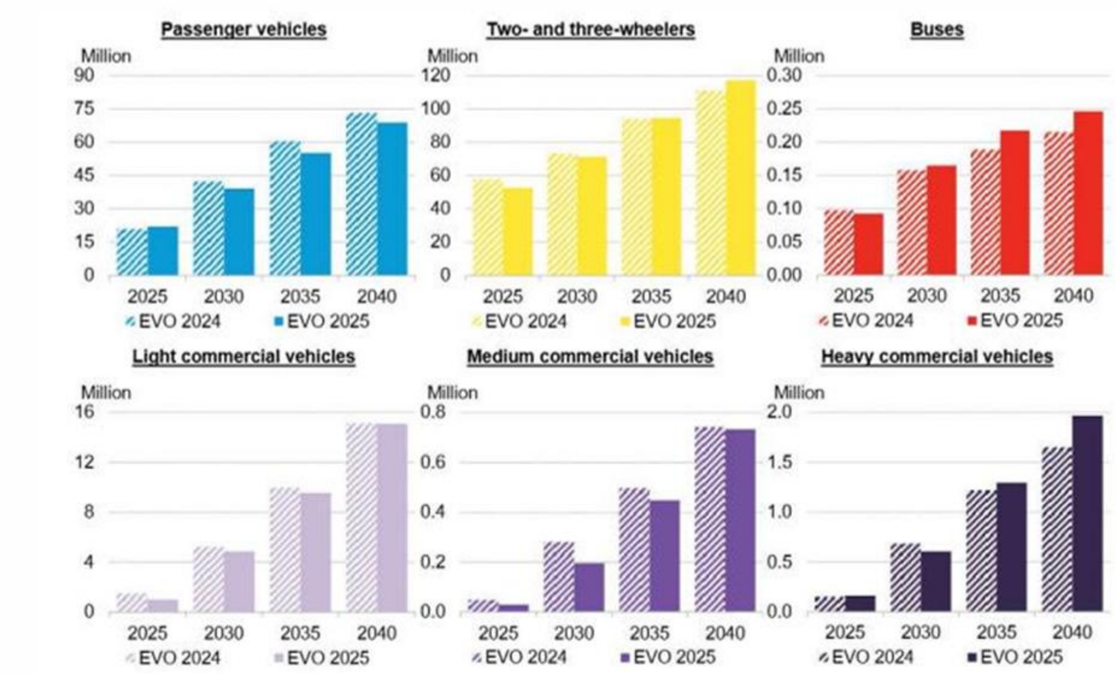


Figure 2: Comparison of electric vehicle sales in outlook 2024 and 2025 (BloombergNEF, 2025a)

China remains the largest and fastest-advancing EV market, representing roughly two thirds of global EV sales in 2024. While growth is expected to continue, China too is approaching a more mature phase, which brings naturally slower expansion. In contrast, the United States now expects EVs to reach only 27% of new passenger vehicle sales by 2030, significantly below previous projections (48%). (Bloomberg NEF, 2025a)

Europe, the world's second largest EV market, experienced stagnation in 2024 due to subsidy cuts, higher interest rates, and delayed automaker model rollouts. EVs in major European countries remain more expensive than internal combustion vehicles, which continues to impact affordability and mainstream adoption.(IEA, 2025a)

2 Demand Overview and current status of e-mobility Europe and Austria

2.1 Global Demand Overview

Despite challenges, global EV sales are still increasing. In 2025, global EV sales are projected to reach nearly 22 million battery electric and plug-in hybrid vehicles, representing a 25% increase from 2024 (BloombergNEF, 2025a). This growth translates to plug-in electric vehicles accounting for one in four vehicles sold globally in 2025 – remarkable expansion from less than 5% just a few years ago (BloombergNEF, 2025b).

EVs represented 22% of global passenger car sales in 2024, and under the current outlook are expected to reach 42% by 2030, though this is also slightly below last year's expectations.(BloombergNEF, 2025b)

As shown in Figure 2, China maintains its dominant position, accounting for nearly two-thirds (approximately 60-65%) of global EV sales in 2025 (BloombergNEF, 2025a). The country achieved its target of a 20% sales share for new energy vehicles (NEVs) by 2025 well ahead of schedule, with electric cars reaching a 29% share of total domestic car sales in 2022, up from 16% in 2021 (IEA, 2025a). Europe follows as the second-largest market, accounting for approximately 17% of global EV sales in 2025 (BloombergNEF, 2025a).

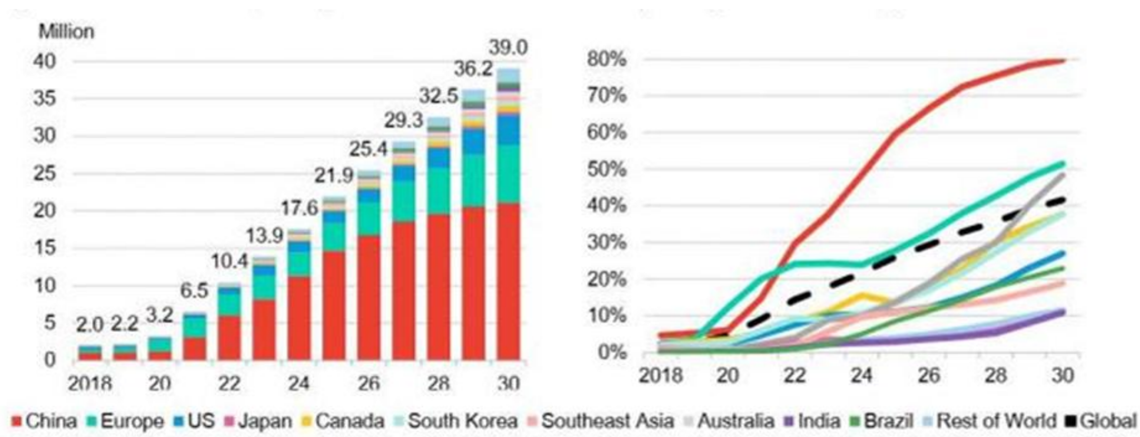


Figure 3: Global near-term passenger EV sales and EV share of new passenger-vehicle sales by market

The United States represents approximately 7% of global EV sales in 2025, marking a significant decline from previous projections (BloombergNEF, June 2025). While passenger EV sales in the US are still projected to rise from 1.6 million in 2025 to 4.1 million in 2030 (which is 27% of total car sales as shown in Figure 3), this revised outlook falls short of previous BloombergNEF projections by 14 million cumulative EV sales over that period (BloombergNEF, June 2025).

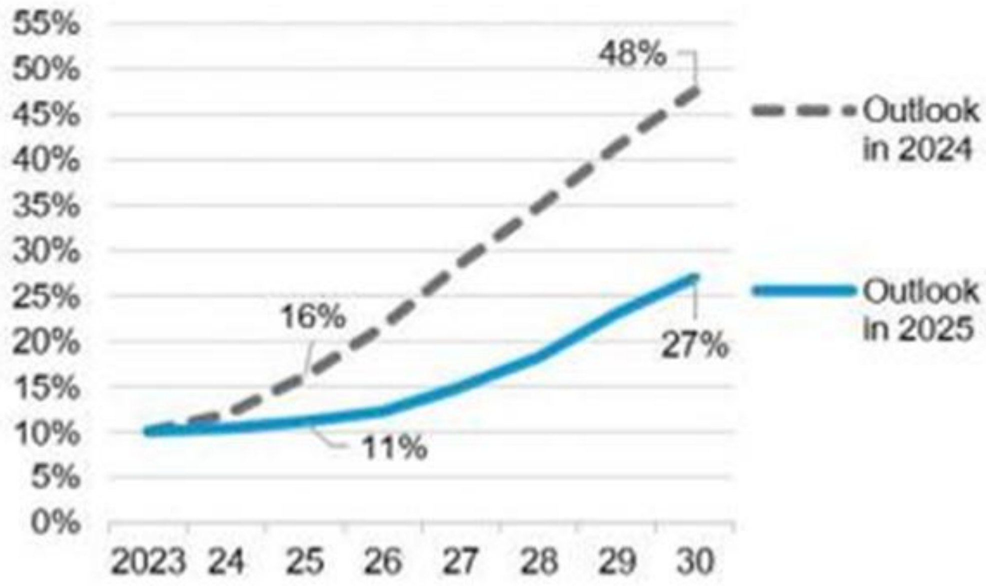


Figure 4: US passenger EV share of total car sales (BloombergNEF, 2025a)

Globally, electric light-duty vehicles (LDVs) remain the greatest consumer of electricity for road transport, though their share of road electricity demand falls by around 5 percentage points from 2024 to slightly above 60% in 2030 in the STEPS (IEA, 2025a). In China, LDVs were responsible for only around 55% of road electricity demand in 2024, remaining the same in 2030 in the STEPS, illustrating China's success in EV adoption across a range of applications (IEA, 2025a). Both China and Europe reached the milestone of 1% of total electricity demand coming from EVs in 2024, with Europe's share exceeding China's by 2030 in the STEPS as electricity demand for other end uses grows faster in China (IEA, 2025a). In the United States, over 90% of electricity demand for road transport came from electric cars in 2024, though this falls to around 75% in 2030 in the STEPS as demand from electric buses and commercial vehicles increases (IEA, 2025a). In Europe, the increasing number of electric heavy-duty trucks means their share of road transport electricity demand increases from less than 5% to more than 20% in 2030 in the STEPS (IEA, 2025a).

2.2 European and Austrian Demand Overview

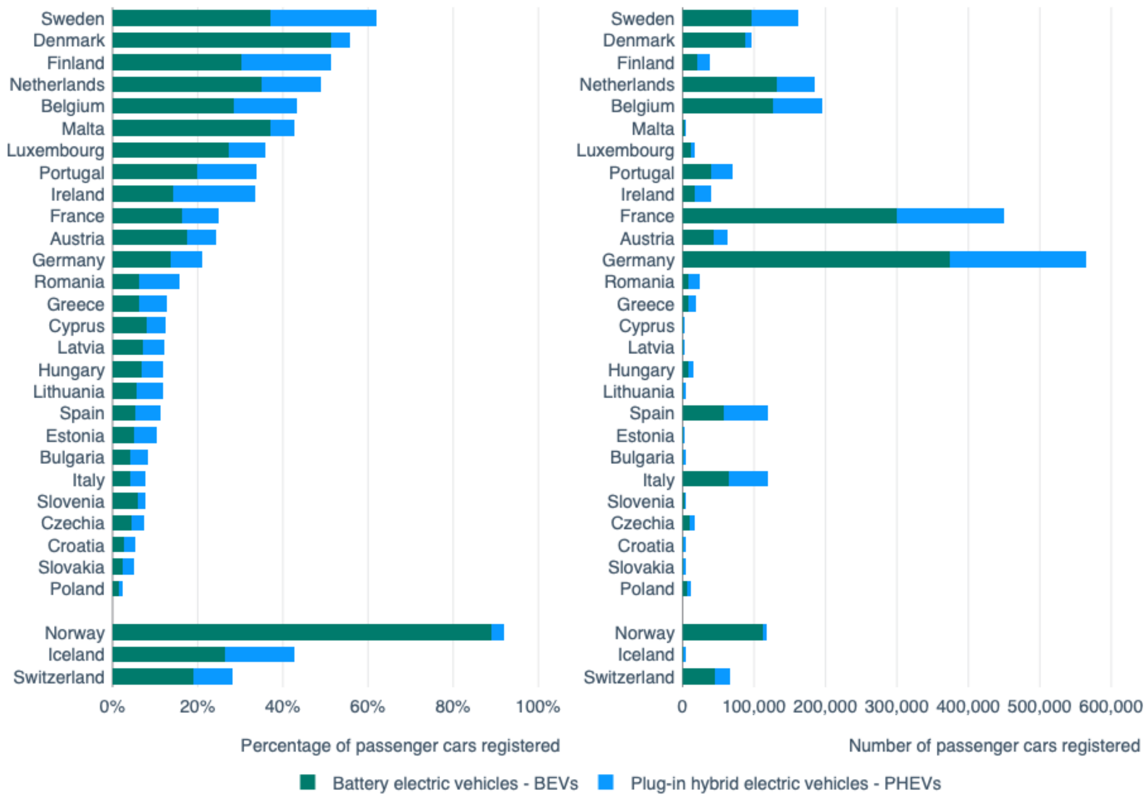


Figure 5: newly registered electric cars by country (EEA, 2025a).

The uptake of electric cars varies strongly between EU countries. As the graph above shows, the Nordic countries take the lead in the EU while in Norway about 90% of newly registered cars are battery electric vehicles or plug-in hybrids (EEA, 2025a).

In Austria, the number of registered battery-electric vehicles (BEVs) was 200,603 by the end of 2024, which marks a substantial increase from 155,490 in 2023. Yet, the pace of growth in registrations slightly declined in 2024 compared to 2023. BEVs registrations accounted for 17.6% of total new passenger car registrations, which means a steady, although not rapid growth of cleaner mobility (European Alternative Fuels Observatory, 2025c).

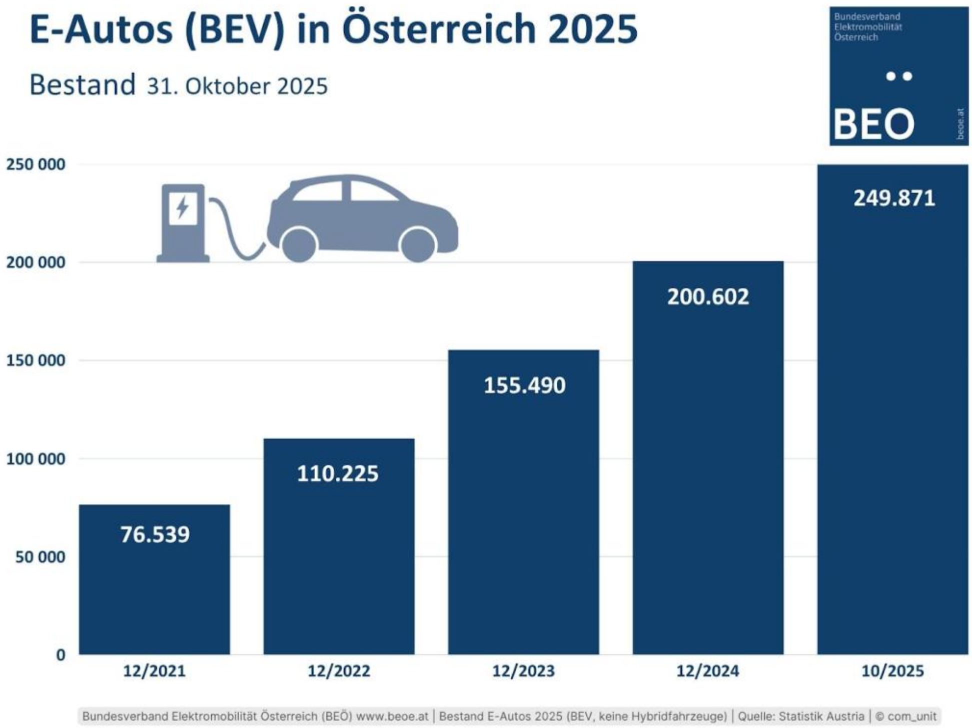


Figure 6: number of BEVs in Austria (BEÖ, 2025).

III. Influencing Factors for E-Mobility Deployment

EV adoption in Europe is not only shaped by market forces (e.g. pricing, competition) or technological readiness, but also heavily influenced by policy frameworks (e.g. through subsidies, tax incentives), strategic decisions, as well as socio-economic factors. This chapter aims to look at these factors in more detail to assess the most crucial factors for an uptake of e-mobility. It must be noted that within the scope of this report, only a few aspects that were identified as having a crucial influence could be highlighted.

1 Political Landscape

First, initiatives on the European level to support the uptake of e-mobility, before looking at the situation in Austria. In particular, the different approaches in the EU member countries as well as the support for e-mobility in Austria will be examined. Subsequently, the analysis will look at influence from international players like the US and China – more specifically, the impact of the Inflation Reduction Act under the Biden administration (2021–2025) as well as tariffs on e-vehicles under the Trump administration (from 2025) and Europe's response. Moreover, China's influence through its early dominance in the battery production and its subsequent competitive advantage with regards to low production costs will be discussed and compared to the current situation in Europe. Finally, the key takeaways from this analysis will be summarized in order to infer recommendations.

1.1 EU level: different approaches in member states and industry influence

At regional and national levels, political priorities and institutional capacities vary. The EU sets overarching regulatory frameworks and climate targets, but member states are responsible for implementation, which often reveals potential gaps between policy design and real-world outcomes.

Member States have implemented a range of national measures in the transport sector aligned with climate targets, generally combining technological, regulatory, and behavioral approaches. This includes for example electrification (e.g. EV subsidies, charging infrastructure), support of model shift (e.g. rail, public transport, cycling), specific regulation (e.g. bans of short-haul domestic flight, low emission zones), as well as economic instruments (e.g. carbon pricing, fuel taxes). These different approaches show different results, especially subsidies can make a big difference in the uptake of EVs: In Denmark, for example, the number of new electric vehicles grew by 9% from 2023 to 2024 compared to conventional vehicles due to incentives such as company tax benefits and electricity tax reimbursements as well as lower registration and ownership taxes (EEA, 2025). Moreover, Denmark had local initiatives such as free parking for BEVs in cities like Copenhagen or Aarhus (European Alternative Fuels Observatory, 2025a). In Germany on the other hand, BEV registrations declined by 27% in 2024 compared to 2023, primarily due to the cancellation of an environmental bonus for BEVs (EEA, 2025). The environmental bonus (*Umweltbonus*) for BEV purchases ended on 17 December 2023 due to budget limitations and a constitutional court decision (European Alternative Fuels Observatory, 2025b). However, it is important to note that, various support schemes for electric vehicles do not have the same impact across EU countries. Ruiz (2023) states that below a certain GPD per capita, subsidies are seemingly not able to trigger market uptake.

On an industry level, the EU started the implementation of the Corporate Average Fuel Emissions (CAFE) regulation (see chapter V) at the beginning of 2025. Some European Countries have attempted to delay the application of the regulation: While France tried to build a coalition against the European Commission to block fines for manufacturers, Italy requested a comprehensive review of the regulation. Romania, which has very few electric vehicles in its range, considered the EU electrification plan as "overly aggressive" (Mobility Portal Europe, 2025a). Germany has been lobbying strongly to overturn the ban on combustion engines due to concerns that the country's manufacturers will come under even bigger pressure with Asian rivals pushing into Europe and US import tariffs causing a big blow to the economy. Germany's Chancellor, Friedrich Merz, is emphasizing the importance of "technological openness". While he sees electric vehicles as crucial in the path to carbon neutrality, he wants the EU to also consider other technologies, such as synthetic fuels. Moreover, he argues that manufacturers need more flexibility as the demand for electric vehicles has not met industry expectations (Blasshofer, T. and Reichert, T., 2025). Ultimately, after pressure from the sector, the EU dropped the ban on new combustion-engine cars from 2035, allowing it to shift to a 90% emissions level compared to 2021 levels instead of zero emissions after 2035. Remaining emissions would need to be offset by using lower-carbon steel or synthetic e-fuels or non-food biofuels, e.g. used cooking oil and agricultural waste. This marks the biggest pullback from the Union's green policies over recent years and removes the stability that companies investing in e-vehicles would need. (Blenkinsop, P., 2025). This shows how economic interests can have a strong influence on the implementation and enforcement of regulations.

The European Automobile Manufacturers' Association (ACEA) has called for clarity to ensure Europe's competitiveness and underlined that achieving stricter CO2 reduction targets will require smooth interaction of several factors. ACEA members have already committed 250 billion euros to transition to electric mobility. Moreover, they would need to stop producing 2.5 million combustion vehicles to avoid penalties from the European Commission (Mobility Portal Europe, 2025a). The EV industry warns that easing the emission targets, would undermine investments in the sector including the charging infrastructure, which makes Europe fall further behind China. As a response, the EU plans to boost EV uptake in corporate fleets - approximately 60% of new car sales in Europe. Moreover, national targets for 2030 and 2035 would be based on GDP per capita with countries being able to decide on how to meet them (Blenkinsop, P., 2025).

1.2 Austria: solid base but need for maintaining momentum

In Austria a mobility master plan to transform the transport system to achieve climate neutrality by 2040 was launched in 2021 by the former Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology. It includes ways to avoid, shift and improve transport and traffic as well as ways to increase the share of eco-friendly mobility in total transport (Federal Ministry of Innovation, Mobility and Infrastructure, n.d.). As part of the 2030 Mobility Master Plan, Austria aims to reduce private car use by 16% by 2040 and increase the share of public transport to 40% (from 27%). For this purpose, the "*Klimaticket*" (Austria Climate Ticket) was introduced, offering almost unlimited use of public transport across the country with a single ticket for a full year. Preliminary results have already shown that the *Klimaticket* has induced behavioral change with about two-thirds of the customers indicating that they are using public transport more frequently (OECD, 2022).

At the same time, several subsidy schemes for e-mobility such as registration tax benefits and VAT benefits were made available in Austria (European Alternative Fuels Observatory, 2025d). In July 2025, the government launched "e-move Austria", a program for the expansion of e-mobility with the aim that 95% of Austrians have access to fast-charging stations within 10 kilometers. They are four pillars of the e-mobility program – covering infrastructure (eCharge), public transport (eBus), freight transport (eTruck), and private mobility (eRide) (Federal Ministry of Innovation, Mobility and Infrastructure, 2025). However, the purchase subsidy scheme, which was first introduced in 2017 and revised several times with the most recent scheme "*E-Mobilität 2024*" ended early in February 2025 due to budget limitations. Moreover, as of April 2025, BEVs are no longer exempt from motor-related insurance tax and are now similarly taxed to internal combustion engine (ICE) vehicles (European Alternative Fuels Observatory, 2025d). At the same time, Austria is spending up to EUR 6 billion on subsidies that are harming the environment such as a tax reduction for fossil fuels as well as support for company cars (Erneuerbare Energie Österreich, 2025). Austria's new administration that was inaugurated in early 2025, announced that they will continue to subsidize charging infrastructure but no longer the purchase of electric vehicles (EVs). The main reason for the cuts being savings to address the budget deficit.

In previous years however, Austria was able to establish a solid base for e-vehicles and charging infrastructure. This has also fostered public confidence in the product – in February 2025, 20.1% of new vehicle registrations in Austria were electric which represents a 31.1% increase in comparison to the previous year (Mobility Portal Europe, 2025b). Although the overall development in Austria can be considered positive, the country faces difficulties in maintaining momentum. The European Commission therefore suggests that addressing policy gaps, strengthening incentives and improving infrastructure will be crucial for Austria to achieve its energy and climate goals in the coming years (European Commission, 2025). According to the Austrian Association for Sustainable Mobility (VCÖ, 2025), Austria's electric-mobility transition is slowed by the absence of a coherent long-term policy framework, creating uncertainty for markets and investors. Moreover, they recommend a stronger taxation of petrol and diesel vehicles – following the Danish model – to speed up the shift to electric mobility. Reforming Austria's preferential tax treatment of diesel would further deliver environmental gains and strengthen public revenues.

1.3 Influence of major players – US: Inflation Reduction Act and Tariffs

The U.S. Inflation Reduction Act (IRA) that was introduced in August 2022, aimed to strengthen the domestic economy, promote future technologies, and reduce greenhouse gas emissions. It includes about USD 433 billion in investments, of which USD 369 billion were dedicated to energy security and climate action. A key element of the IRA is tax credits that act as subsidies for technologies like hydrogen, batteries, heat pumps, and nuclear energy. While the IRA could support transatlantic climate cooperation, it also contains strong protectionist elements that pose challenges for European businesses. For example, a USD 7,500 tax credit for clean vehicles is reduced or unavailable if vehicles or battery components are not produced in North America (World Energy Council, 2023).

The EU launched the Green Deal Industrial Plan to stay competitive with the US and China in attracting industrial investment as a response. This should relax state aid rules so member states can offer tax incentives, partly using leftover COVID-19 recovery funds, and match subsidies offered by non-EU countries (World Energy Council, 2023). Moreover, the European Commission proposed the Net Zero Industry Act (NZIA), which entered into force in June 2024 aiming to reduce bureaucracy for certain "strategic technologies". This includes speeding up permit procedures and improving access to funding. These net-zero technologies are intended to help Europe cut emissions and transition to carbon-free energy production. A key focus is expanding the EU's capacity to produce clean technologies. By 2030, the goal is for the EU to manufacture 40% of the green key technologies it needs each year to meet its climate targets. This is meant to reduce dependence on other countries for these technologies (Federal Ministry for Economy, Energy and Tourism, n.d.).

However, according to the Institute for European Policymaking at the Bocconi University (Gros, 2024), the protectionist subsidies under the IRA create only small disadvantages for European firms, while the main effect is to boost U.S. demand for green technologies. This gives European companies new export and investment opportunities. Gros (2024) sees the bigger risk in Europe overreacting with excessive subsidies, rather than benefiting from the expanded market. Similarly, the Institut Montaigne (2025), suggests that Europe should focus on smarter, targeted investment in clean tech, digitalization, and strategic industries. According to them, the key issue is Europe's longer-term problem of underinvestment in innovation and productivity, which the IRA exposes rather than creates. Therefore, Europe should treat the IRA as a push to strengthen its own competitiveness and coordination and highlight the advantages of a consistent regulatory framework for businesses as they can protect investments from political fluctuations (Institut Montaigne, 2025).

While the new Trump administration has criticized green policies under Biden, President Trump cannot easily dismantle the IRA as it would be a legally complex process, and it would be difficult to revoke tax credits that have already been transferred or claimed. However, the Trump administration could slow down investment in clean tech (Institut Montaigne, 2025). Already on his first day in office, President Trump took aim at state and federal support for Electric Vehicles: He issued an executive order to "eliminate the electric vehicle mandate", although the implications of that are not clear (Isidore, 2025). In March 2025, he announced a 25% tariff on imported automobiles and auto parts as part of a broader push to reshape US trade policy and encourage domestic manufacturing. Trump argues that the policy will bring production back to the US, reduce reliance on foreign supply chains, and generate large federal revenue (estimated around $100 billion annually). He frames the move as necessary to correct what he describes as unfair global trade practices. However, significant concerns have been raised by the auto industry that source components across the world and rely heavily on international suppliers. They warn that the tariffs will raise production costs, increase car prices for consumers, and potentially reduce sales and competitiveness (Boak, 2025).

In response to the U.S. tariffs on steel and aluminum, the EU released a list of products subject to retaliatory duties. Notably, electric vehicles and their components were omitted from the list, likely indicating the EU's hesitation to impede the transition to sustainable mobility and its awareness of the automotive industry's global integration. The US is a key export market for Europe for low emission vehicles (electric, plug-in hybrids and hybrids) and tariffs on this segment could threaten their production by reducing their demand in the US (Serrano, 2025).

In July 2025, a political agreement between President von der Leyen and President Trump was reached and established a tariff rate of 15%. Passenger vehicles and their components are the most affected, while buses and heavy commercial vehicles are likely to see only minimal impact due to their relatively low trade volumes. Given its persistent trade surplus, the EU arguably stands to lose more in a trade conflict with the US (Serrano, 2025). According to the Vienna Institute for International Economic Studies, the negative consequences of tariffs by the US on automotive imports from the EU are not devastating at the overall economy level but will hit EU car manufacturing economies like Germany or Austria during difficult times as these countries are already facing low or even negative growth. Moreover, the automotive industry in Europe is already under pressure due to strong competition from China and the rapid pace of technological change required for e-mobility (Stehrer, 2025).

In conclusion, the U.S. Inflation Reduction Act has strengthened clean technology investment while increasing global competition through protectionist measures. In response, the EU introduced new industrial policies to improve competitiveness and reduce dependence on foreign technologies. Although the IRA creates challenges for European firms, it also offers new market opportunities and highlights Europe's need for stronger innovation and investment. At the same time, rising U.S. tariffs increase pressure on Europe's automotive industry, especially in countries such as Germany and Austria.

1.4 Influence of major players – China: price advantage and local production

China's success in the EV market lies in a combination of factors: from coordinated government support across the supply chain to a rollout of charging networks that was sponsored by the state, the capability of managing large-scale manufacturing, constant innovation, consumer subsidies as well as a policy mandating automakers to make EVs (You, 2025). Barwick, P., J. et al. from the National Bureau of Economic Research (2025), found that China's domestic content requirements for EV subsidies made local companies like BYD and Contemporary Amperex Technology Co Ltd (CATL) scale up quickly. This resulted in experience that has helped their batteries to get cheaper faster compared to rivals such as Samsung and Panasonic. However, they state that the timing of this policy, namely during a technological catch-up period, was crucial for its success (Barwick, P., J. et al., 2025). Moreover, CATL and BYD often own their suppliers fully or partly and therefore have a vertically integrated business model. This helps to control cost and ensure security as well as reliability of supply chains (You, 2025).

China has always had a big influence on the European EV market as it has been able to localize production of e-vehicles and especially batteries on a big scale, with more than three-quarters of lithium-ion batteries worldwide being produced in the country (You, 2025).Global sales of battery and plug-in hybrid cars hit 17 million in 2024, with China accounting for 11 million. Chinese carmakers are expanding internationally, already making up 10% of EV and plug-in hybrid sales outside China, and this share is expected to rise. According to a report by the Swiss bank UBS, BYD was able to build cars 25% cheaper than its western competitors (Leggett, 2025). According to the European Commission, sales of EVs in the EU that were built in China increased from 3.9% in 2020 to 25% by September 2023, partly due to undercutting of EU industry prices (Cook, 2024).

The sharp increase in China's share of the market has raised concerns within the EU that Chinese vehicles could ultimately undermine Europe's capacity to develop its own green technologies for tackling climate change. Business groups and labor unions worry that this shift could endanger the jobs of 2.5 million workers in the auto industry, along with an additional 10.3 million people whose livelihoods are indirectly tied to electric vehicle production (Cook, 2024). As a response, the European Union has implemented countervailing duties on imports of battery electric vehicles (BEVs) from China through Implementing Regulation (EU) 2024/2754, in force since 30 October 2024 for a period of five years. The tariffs range from 7.8% up to 35% and are different for different suppliers (European Commission, 2024). The move was justified by claims that Chinese EV makers receive significant state subsidies, enabling them to sell at unfairly low prices in Europe. The tariffs should protect EU manufacturers from a surge of cheap imports that could harm the region's industry and disrupt its green transition (Gros, D. et al., 2026).

At the beginning of 2026, the European Commission has agreed with China's Ministry of Commerce to work on arrangements to remove tariffs on some electric vehicles from China, such as limits on the number of EVs they ship from China to Europe and minimum prices for which Chinese producers would sell these cars in exchange for an exception of anti-subsidy tariffs (up to 35%) that were introduced at the end of 2024 (Bradsher, 2026). This agreement was reached to prevent a trade war after China imposed billions of dollars in agricultural sanctions on Canada, the United States, and the European Union, in response to their tariffs on Chinese electric vehicles aimed at protecting domestic car manufacturers. China would only lift farm tariffs if Western governments drop EV duties (Bhattacharya, 2025).

However, European trade officials have been cautious about accepting agreements that permit automakers to set high minimum prices for their electric vehicles, as this could enable them to effectively fix prices and retain profits from restricted sales in Europe rather than paying tariffs – similarly to what has happened to Chinese solar panel manufacturers in 2013 (Bradsher, 2026). This is also highlighted by Gros et al. (2026), who argue that a price floor keeps consumer prices artificially high which would transfer income from the European consumers to Chinese producers while at the same time cancel EUR 2 billion in annual revenues from tariffs.

Moreover, according to Bernhart, W. and Gallus, D., (2025), the lack of a cohesive, EU-wide strategy for the battery industry has resulted in fragmented regulations and ongoing uncertainty in planning. Key initiatives, including the Net Zero Industries Act (NZIA) and the Critical Raw Materials Act (CRMA), fall short in promoting local value creation, as they provide neither strong incentives for local content nor binding requirements. While existing policy tools are relevant, their effectiveness is weakened by slow implementation, non-binding provisions, and challenges in the efficient allocation and accessibility of funding. One particular challenge that Bernhart, W. and

Gallus, D., (2025) state is that a central challenge in Europe is that regulations are not tailored to cell factories – building codes and fire safety are major cost drivers and manufacturers having to deal with a big number of authorities to get the required permits for a single plant (Bernhart, W. and Gallus, D., 2025). Critics however say that the EU's industrial base is much more competitive than political rhetoric suggests. The main challenges are not the immediate threat of Chinese dominance, but rather the EU's slow expansion of charging infrastructure, weak domestic demand for electric vehicles, and the need to scale up battery production (Gros, D. et al., 2026).

According to a study by the consultancy Roland Berger, Europe is expected to become one of the world's biggest markets for lithium-ion batteries. Its demand is projected to reach approximately 1.5 TWh and a market volume of EUR 130–150 billion by 2035, regardless of the slowdown in EV demand expectations. However, the competitiveness and viability of European production is confronted with major challenges: high expansion costs even for experienced players, structural cost disadvantages compared to Chinese imports as well as market uncertainty such as inconsistent political messaging and slower EV demand. These structural issues cause battery cells produced in Europe face a significant cost disadvantage of about EUR 9–11/kWh compared to batteries produced and imported from China and affects both domestic market entrants as well as established Asian players that produce in Europe (Bernhart, W. and Gallus, D., 2025) as the graph below shows.

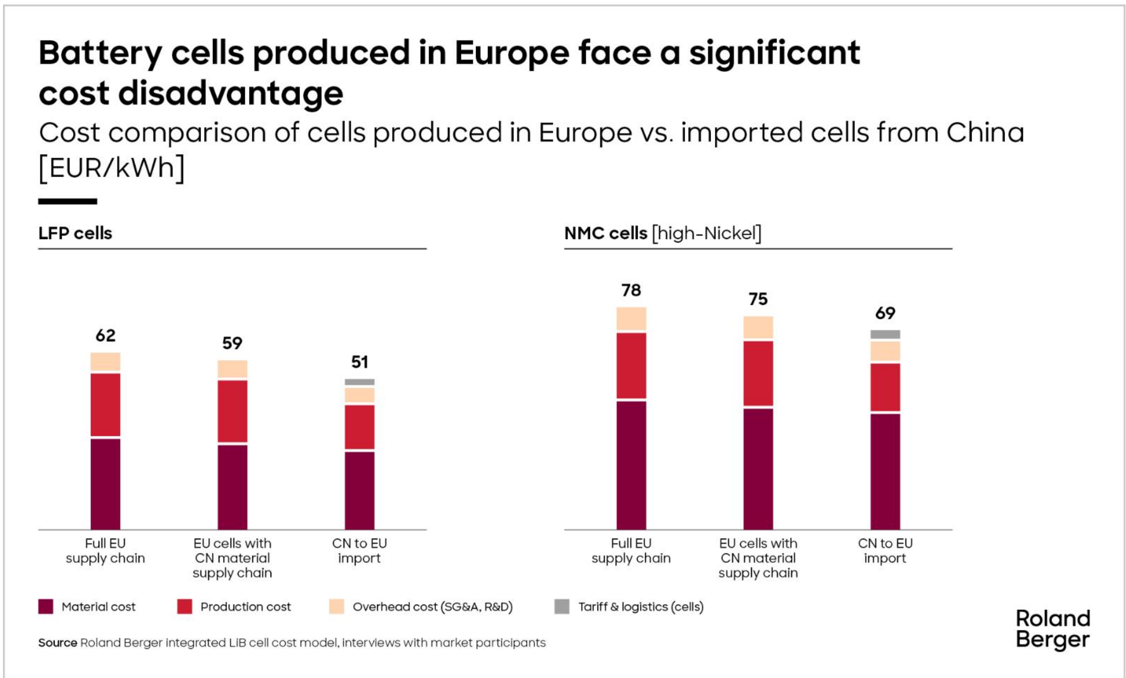


Figure 7: Cost disadvantage of battery cells produced in Europe

To conclude, China's dominance in the EV and battery industry is driven by strong state support, vertical integration, and rapid scaling, allowing firms like BYD and CATL to significantly lower costs and outcompete international rivals. This has increased their global market share, particularly in Europe, raising concerns about industrial dependency and prompting EU tariffs and policy responses. However, Europe's competitiveness remains constrained by structural issues such as fragmented regulation and higher production costs, making long-term success dependent on more coordinated industrial policy and faster scaling of domestic capacity.

1.5 Global Hydrogen Strategies and Policy Approaches

Many countries, including Australia, China, Germany, the United Kingdom, Japan, the European Union, the United States, and South Korea, have developed national hydrogen strategies to support the development of a low-carbon energy system and strengthen the hydrogen value chain. These countries are generally well positioned for hydrogen development due to their renewable energy potential, industrial base, and existing infrastructure.

In Europe, hydrogen is a key element of climate and energy policy. The EU aims to scale up renewable hydrogen production by 2030 and integrate it into industry, transport, and heating. Initiatives such as the European Green Deal and the Clean Hydrogen Partnership, alongside substantial funding programmes, support research, infrastructure, and cross-sector deployment. Germany in particular focuses on building a competitive hydrogen market through investment, innovation, and international partnerships.

The United Kingdom promotes hydrogen as part of its net-zero strategy for 2050, with a focus on low-carbon industry and transport applications. Australia aims to become a major hydrogen exporter by leveraging its strong renewable energy resources and developing large-scale production hubs. The United States follows a structured hydrogen roadmap, focusing on cost reduction, increased production, and the creation of regional hydrogen hubs that combine production, storage, and use.

In Asia, Japan, China, and South Korea are leading hydrogen development efforts. Japan envisions a “hydrogen society” and is an early adopter of fuel cell technology, especially in transport. China integrates hydrogen into its long-term carbon neutrality strategy with major investments in infrastructure and innovation. South Korea is rapidly expanding its hydrogen economy through strong policy support and active industrial participation, particularly from large technology and automotive companies.

Overall, hydrogen strategies worldwide show strong political commitment and growing investment, especially for hard-to-abate sectors. However, large-scale adoption still depends on overcoming challenges related to cost, infrastructure development, and technological maturity. (Hussein Togun, 2025)

2 Strategic outlook of major European OEMs

A decisive influencing factor shaping electromobility deployment and road transport decarbonization in Europe beyond technological readiness is the availability of vehicles with renewable and low carbon propulsion systems. This is determined by the strategic directions of major car manufacturers and original equipment manufacturers. This chapter is structured to shed some light on major OEM strategies and what they plan to bring onto the roads in the years to come that factors in both passenger cars and medium- to heavy-duty vehicles.

2.1 Passenger Car OEMs

European passenger car OEMs have undergone a profound strategic shift towards electrification over the last decade, driven primarily by EU fleetwide CO_2 emission standards. In response, most European manufacturers have announced electric first or electric only product roadmaps:

- Volkswagen Group targets over 80% BEV sales in Europe by 2030 and to be the technologically leading volume manufacturer, supported by focusing on low-cost entry-level electric cars. (VW Group, 2025)

- BMW Group targets to have delivered more than 10 million fully electric vehicles to customers, while maintaining a customer-oriented technological diversity approach: BEVs alongside plug in hybrids (PHEVs) and efficient ICEs, with also some development into hydrogen-powered electric fuel cell vehicles. Mini cancelled its 2030 ICE phase out. (BMW, 2025)

- Volvo cars revised in 2024 the strategy to 90–100% electrified sales by 2030 (BEVs + PHEVs), with limited mild hybrids if needed. In comparison to the originally committed to 100% BEVs by 2030, recent adjustments are said to reflect changing market conditions and customer demands. (Volvo cars, 2025)

- Renault Group aims for 100% electrified passenger car sales in Europe and 50% outside Europe by 2030. Their full hybrid E-Tech models act as a bridge not only during the transition, but beyond 2030 on Europe and international markets. (Renault, 2025)

- Stellantis' prior aim for 100% passenger car BEV sales in Europe by 2030 was announced to be no longer pursued considering unachievable carbon emissions targets laid out by the EU, combined with cost reduction strategies to reach price parity. (Wardsauto, 2025)

- Mercedes Benz plans a predominantly electric lineup by the early 2030s "where market conditions allow". The BEV first transition allows also for flexibility after slower EV uptake in parts of the market. (Mercedes, 2025)

Many global automakers have scaled back previously ambitious EV targets:

- Kia reduced its 2030 EV target by 340,000 vehicles. (Fleetnews, 2025)

- Honda eliminated its target for EVs to represent 20% of sales by 2030 (Money US News, 2026)

In several markets, particularly Germany and Japan, EV sales have declined following the removal of subsidies and a lack of new, affordable models. (BloombergNEF, 2025a)

In summary, battery electric passenger cars are prevalent throughout all major OEM strategies with some transitional focus on hybrid vehicles. However, the recent shifts in strategies reflect OEMs' challenges related to regulatory uncertainty, price pressure, global competition particularly from China and slower than expected mass market demand.

2.2 Medium and Heavy Duty Vehicle OEMs

In the truck and bus segment, electrification strategies are more heterogeneous. The EU's revised CO_2 standards for heavy duty vehicles require fleet wide emissions reductions of –43% by 2030, –65% by 2035, and –90% by 2040 compared to 2019 levels. This has pushed European truck OEMs to accelerate zero emission offerings.

- Daimler Truck (Mercedes Benz Trucks, Freightliner, FUSO) pursues a "dualtrack" decarbonization strategy based on battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV), depending on use case. The company also has the ambition to offer only new vehicles that are CO2-neutral in driving operation ("from tank to wheel") in Europe by 2039. (Daimler truck, 2025)

- Traton SE (Scania, MAN, International/Navistar, VW Truck & Bus) follows a battery electric first strategy, explicitly arguing that system efficiency and total cost of ownership favor BEVs for most applications. Biofuels are treated as treated as essential short-term enabler and hydrogen as an observable complementary solution. (Traton SE, 2025)

- Iveco Group (IVECO, IVECO Bus) adopts a multi energy decarbonization strategy, reflecting diverse regional and customer needs. Electrification is central, but biomethane HVO, and hydrogen are actively pursued alongside BEVs. (IVECO, 2025)

- Volvo Group (Volvo Trucks, Renault Trucks, Mack) follows a three-path technology strategy: Battery electric as the main solution, Hydrogen fuel cells for long haul/high utilization and renewable fuels as transitional solutions. (VW Group, 2025)

- Paccar Group (DAF, Kenworth, Peterbilt) applies a technology neutral but customer driven approach, advancing battery electric and fuel cell trucks while continuing aggressive efficiency improvements in diesel platforms: Fully electric for low payloads and driving inner city, hybrid electric for heavy and medium duty trucks driving mostly outside urban areas, lastly diesel ICE for heavy and medium duty trucks driving long distances. (PACCAR, 2025)

All major European manufacturers now offer battery electric trucks for urban, regional, and increasingly long haul operations. At the same time, several OEMs continue to hedge with hydrogen fuel cells and conventional combustion engines, particularly for long distance freight where battery mass, charging time, infrastructure and energy density remain constraints. Biofuels such as HVO are seen as readily approved drop-in fuel for the transition period.

Nevertheless, adoption remains slow due to infrastructure gaps, high upfront costs, and operational uncertainty. Hence, truck OEMs emphasize strategically the total cost of ownership (TCO), i.e. the aggregate cost of acquiring, operating, maintaining, and disposing of a vehicle over its entire service life, including purchase price, energy consumption, maintenance, insurance, taxes, and residual value, and reliability for fleet operators. Furthermore, many collaborate on battery systems R&D as well as co-develop charging infrastructure with major logistics players.

3 Socioeconomic Factors

Although e-mobility offers lower operating costs, their high upfront price remains a key barrier for many households. Socioeconomic factors such as income and housing influence access to EVs, while consumer confidence affects the willingness to make costly purchases during uncertain economic periods. In addition, changes in electricity and fuel prices shape how financially attractive e-mobility is perceived to be. This chapter explores how the mentioned socio-economic factors can influence the uptake of e-vehicles.

3.1 Affordability and housing

Socioeconomic factors strongly influence EV adoption in Europe. Affordability is widely seen as the main barrier to broader BEV adoption. A survey of 3,000 EU consumers conducted in 2025 found that many are unwilling to pay more for a battery electric vehicle than for a comparable internal combustion model. While fewer than 10% of BEV models available on the European market are priced below EUR 30,000, respondents were indicating a median willingness to pay of around EUR 20,000 (IEA, 2026).

Empirical studies, such as a study by Rabobank (Ruiz, 2023), show a positive correlation between GDP per capita and EV market penetration, with wealthier regions adopting earlier and faster. At the same time, the strong correlation between GDP per capita and electric vehicle market uptake suggests that, despite the lower total cost of ownership of electric vehicle, the higher upfront purchase cost may slow market adoption in countries with lower GDP per capita (Ruiz, 2023).

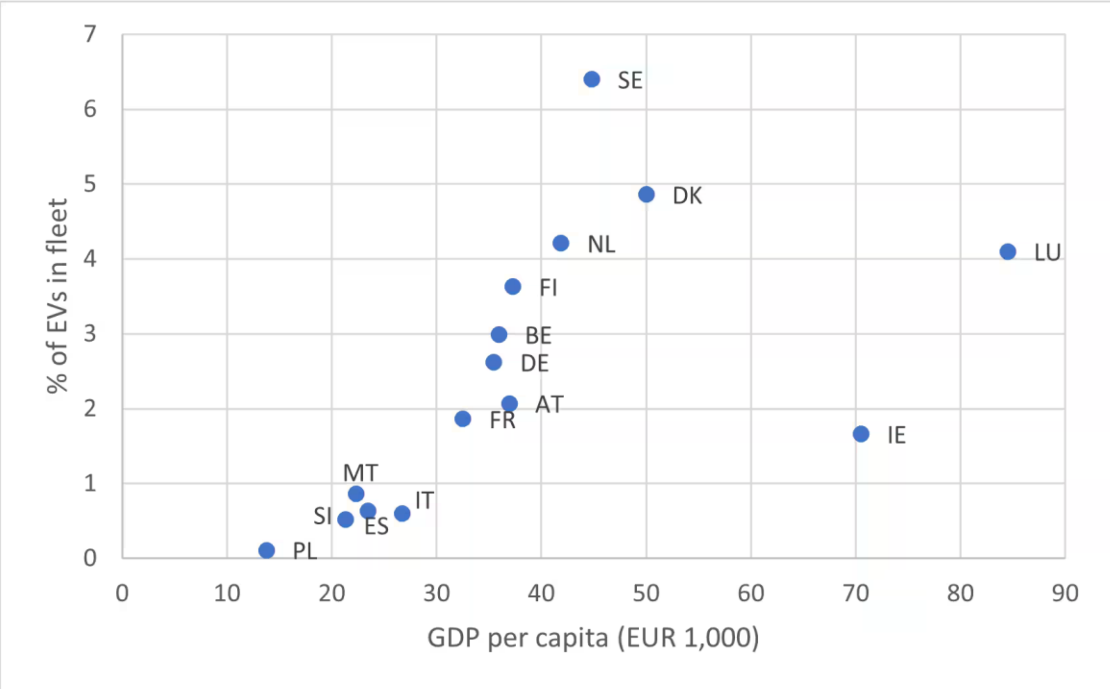


Figure 8: GDP per capita versus EV market penetration in the EU, by country, 2022 (Ruiz, 2023).

The used car market could serve as an important channel for affordability. In recent years, electric vehicles have steadily gained a larger share of the used car market across major regions. In China, five key European markets (France, Germany, Italy, Spain, and the United Kingdom), and the United States, used electric car sales exceeded 3 million in 2025, representing an increase of about 35% compared with 2024. However, resale values for battery electric vehicles in Europe have declined since 2022 as supply and demand have rebalanced, with BEVs experiencing a sharper drop in value retention than the overall used car market. (IEA, 2026). The rapid depreciation of EVs and the ongoing price competition in the new electric vehicle market may keep used EV prices low and discourage buyers from choosing them over combustion engine vehicles (Butts, 2024).

Housing conditions are equally decisive: access to private or workplace charging significantly increases adoption likelihood, disadvantaging lower income and urban populations without off street parking. Pezeshknejad et al. (2026) find that strong evidence that home charging access is instrumental in EV adoption. People living in rental homes and homes with inadequate parking are less likely to adopt a BEV when controlling for other factors including home value and vehicle preferences.

3.2 Energy Prices and Geopolitics

Energy price volatility following recent geopolitical crises has reinforced the strategic value of electrification. By shifting from imported fossil fuels to domestically produced electricity, electromobility improves energy security and trade balances as with the EU transport sector 88% reliant on imported fossil fuels (Rosslowe, 2025).

According to a study by Fraunhofer ISI, battery-electric passenger cars have a clear cost advantage over cars with combustion engines in the long term, even if the costs for purchase and charging infrastructure are much higher. The findings also indicate that energy prices become increasingly important over time; however, their effect on the relative cost advantage of electric vehicles only becomes evident over a longer period, as short-term price differences are relatively small (Fraunhofer ISI, 2023).

3.3 Consumer Confidence

EVs remain significantly more expensive than internal combustion engine (ICE) vehicles in many markets (McKinsey, 2025):

- On average, EVs in Europe and the US cost 36% more than comparable ICE vehicles.
- In contrast, EVs in China are now cheaper than ICE vehicles on average.

Rising costs of public fast charging – often exceeding the per kilometer cost of gasoline – further discourage adoption in Europe and the US. (BloombergNef, 2025a)

Early adopters have largely already transitioned to EVs. Remaining segments of the population display:

- Range anxiety
- Concerns about charging convenience
- Hesitancy toward new technologies
- Cultural attachment to ICE vehicles (BloombergNef, 2025a)

3.3.1 Passenger Car Consumers

Consumer acceptance has evolved rapidly but unevenly. According to the European Alternative Fuels Observatory Consumer Monitor 2025, nearly 80% of EU consumers now hold positive or neutral views on electric cars, and a growing share considers an EV for their next purchase. Major perceived benefits include lower operating costs, environmental performance, and driving comfort (European Alternative Fuels Observatory, 2025e).

However, persistent barriers remain:

- High purchase prices, especially after subsidy rollbacks in countries such as Germany,

- Range anxiety and charging availability, particularly for apartment dwellers,
- Residual value uncertainty in the used car market (McKinsey, 2024).

3.3.2 Fleet Operators and Heavy-Duty Users

For commercial fleets, decisions are primarily driven by economic viability and operational risk, rather than individual attitudes. While pilot projects show that electric trucks can outperform diesel on energy efficiency and maintenance costs, high upfront vehicle prices and uncertain resale values remain critical concerns. (Shell, 2026)

Fleet operators also depend heavily on:

- Guaranteed infrastructure availability,
- Stable electricity prices,
- Policy certainty over vehicle taxation, tolling, and incentives.

Where these conditions are met, such as in urban logistics or captive fleets, adoption is accelerating. Elsewhere, hesitation persists.

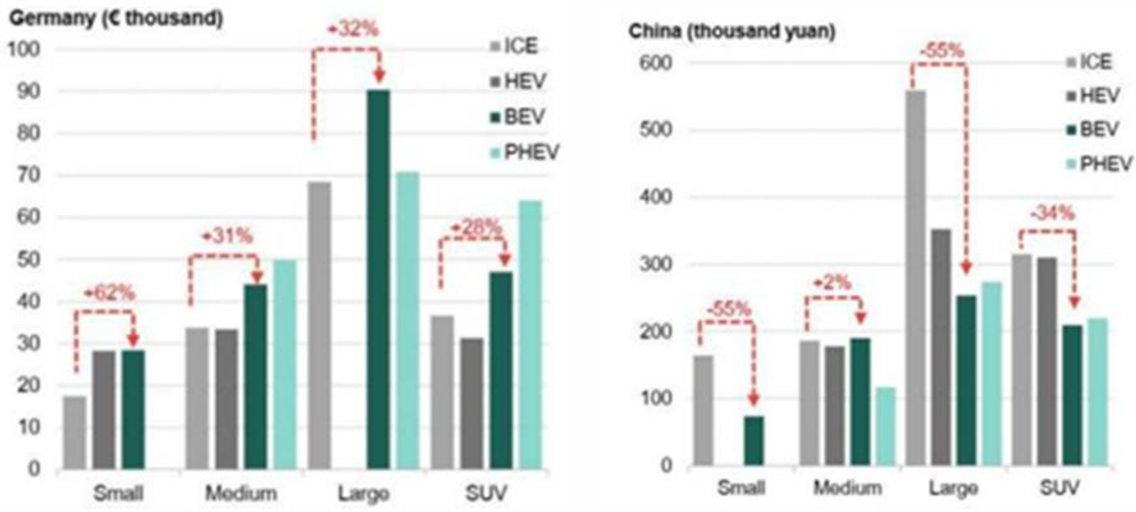


Figure 9: Sales weighted passenger vehicle prices in 2024 (BloombergNEF, 2025a)

4 *Charging Infrastructure (Readiness) and Grid Capacity*

Europe's public charging infrastructure for electric vehicles is expanding, but current growth remains far below future requirements. By the end of 2023, Europe had approximately 632,000 public charging points. The European Commission estimates that 3.5 million charging points will be needed by 2030 to support the EU's climate targets, while the European Automobile Manufacturers' Association argues that the actual demand will be significantly higher, reaching around 8.8 million charging points by 2030 and almost 19 million by 2035.

To meet even the Commission's lower target, Europe would need to install nearly 2.9 million additional charging points by 2030, equal to roughly 410,000 new chargers per year. However, only around 153,000 charging points were added in 2023. If the current pace continues, Europe would reach only about 1.6 million public charging points by 2030.

Another major issue is that charging infrastructure growth is not keeping pace with electric vehicle adoption. Between 2017 and 2023, BEV sales increased more than eighteenfold, while the number of public charging points grew only sixfold. In 2023, BEVs already represented 14.6% of all new car sales in the EU, and their market share is expected to exceed 70% by 2030.

The distribution of charging infrastructure across Europe is also highly uneven. Around 61% of all public charging points are concentrated in only three countries: the Netherlands, Germany, and France. Many Eastern and Southern European countries still have comparatively limited charging networks.

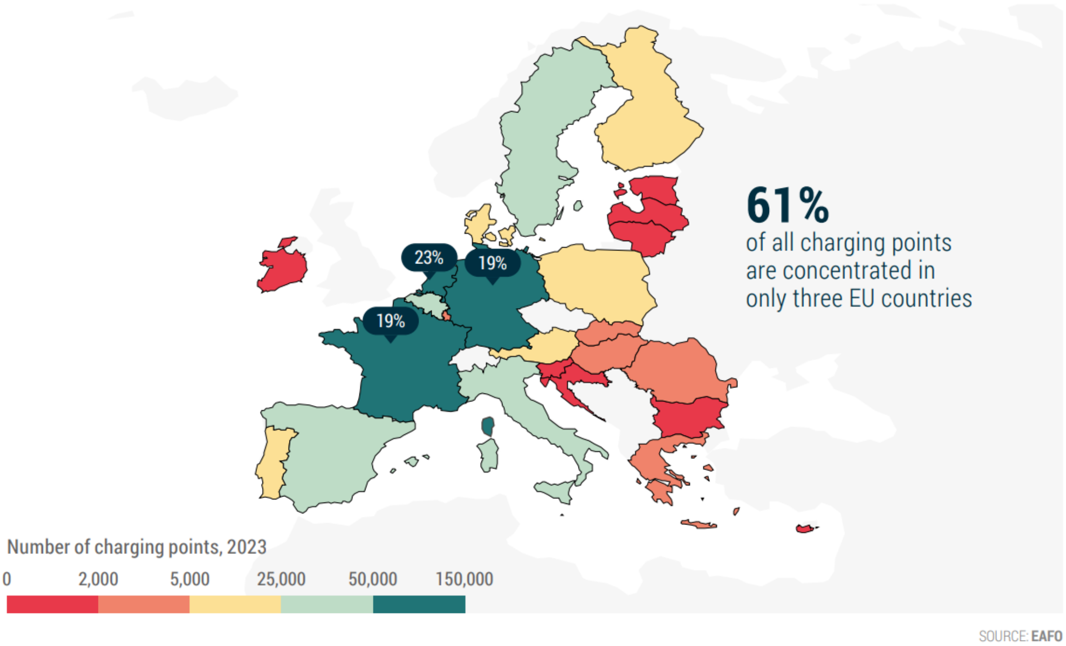


Figure 10: Distribution of electric car charging points across the EU

Compared to Europe, both China and the United States have expanded EV charging infrastructure more rapidly, but with different approaches.

China has by far the largest public charging network in the world, accounting for almost two-thirds globally. Its expansion is strongly driven by central government planning, large-scale investment, and close coordination with industry. The network is designed mainly for smaller, lower-cost EVs with shorter ranges, so many chargers have lower power output but are very densely distributed. This widespread availability has helped strongly accelerate EV adoption by reducing charging anxiety.

The United States relies more on financial incentives and market-based deployment. Through programs like the Inflation Reduction Act, the government supports both EV purchases and charging infrastructure via tax credits and subsidies, alongside requirements to boost domestic manufacturing. While the US network is currently smaller than China's, these policies are intended to significantly speed up expansion.

In contrast, Europe's charging rollout is more fragmented across countries and less strongly funded at a central level, which leads to slower and uneven infrastructure growth compared to both China and the US.

To accelerate infrastructure deployment, experts emphasize the need for faster implementation of EU regulations, greater financial incentives, grid modernization, technological innovation, simplified payment systems, and reduced bureaucratic barriers. Overall, while the current charging network may still support today's EV fleet, Europe must significantly accelerate infrastructure expansion to meet future demand and ensure the continued growth of electric mobility. (ACEA, 2024)

Another key challenge for the continued development and large-scale market penetration of electric vehicles is the limited capacity of existing electricity distribution networks. While EV adoption is increasing rapidly worldwide, most current grid infrastructures were not originally designed to accommodate large-scale, simultaneous charging demand from a high number of vehicles. As a result, the growing electrification of transport introduces significant additional stress on low-voltage and distribution-level networks, particularly in residential areas where many vehicles tend to charge during similar time periods, such as in the evening peak hours.

This simultaneous charging behavior can lead to several technical issues within the power system. These include voltage deviations beyond acceptable operational limits, thermal overloading of transformers, and congestion in distribution feeders and lines. Such effects reduce the overall "hosting capacity" of the grid, which describes the maximum level of electric vehicle integration that can be supported without requiring substantial infrastructure reinforcement or causing operational violations. Consequently, grid capacity becomes a critical limiting factor for the scalability of electric mobility.

The problem is further exacerbated by uncoordinated charging behavior, where vehicles begin charging independently of grid conditions or system load. Without smart charging strategies, demand-side management, or load-shifting mechanisms, peak loads can increase significantly, raising the risk of local grid instability. Therefore, recent research emphasizes that EV expansion cannot rely solely on the deployment of charging infrastructure but must also include corresponding upgrades and modernization of distribution networks, combined with intelligent control strategies such as smart charging and optimized load management. (Hussain et al., 2025)

5 Summary of the Key Factors Shaping Electric Mobility in Europe

The implementation of policies both on an EU level as well as on a national level underscores a key tension between climate objectives and economic interests: while industry actors have made substantial investments in electrification, they require regulatory stability and supportive infrastructure. At the same time, easing targets risks undermining these investments and slowing the EU's progress relative to global competitors such as China. In Austria, initiatives such as EV subsidies or the *Klimaticket* show that policy measures can effectively drive behavioral change and increase electric vehicle adoption. However, recent cuts to incentives and new EV taxes highlight that unstable, short-term policy shifts can slow progress of a transition to emission free mobility. Overall, this shows that achieving EU climate goals in mobility depends not only on policy ambition but also on consistent implementation, market incentives, and alignment between political and industrial priorities.

Examples from the US and China highlight the significant influence of political leadership on climate and mobility policy – which can result in substantial regulatory volatility (as seen in the Biden and Trump administration) or strong consistent support of national priorities (as seen in the case of China). This is also an important learning for Europe where policy inconsistency has important implications: it creates uncertainty for investors and manufacturers, potentially slowing the transition to electric mobility and undermining long-term industry planning. Overall, this underscores that achieving sustained progress in transport decarbonization depends not only on policy ambition, but on the continuity and stability of regulatory frameworks across political cycles. While there are rising concerns about global competition, the EU has a strong industrial base but needs to address internal issues around sluggish demand for electric vehicles, and limited battery production capacity. Addressing these internal challenges will be crucial for sustaining competitiveness and ensuring the long-term success of the EU's electric vehicle industry.

With regards to other influential factors, most OEMs continue to expand battery electric vehicle offerings, many have adjusted earlier targets due to weaker demand, cost pressures, and regulatory uncertainty. In heavy-duty transport, manufacturers are pursuing more diverse strategies, e.g. combining battery-electric and hydrogen. At the same time, adoption is strongly influenced by affordability and infrastructure. High upfront costs, uneven charging access, and consumer uncertainty continue to limit uptake, particularly among lower-income households and commercial fleet operators. Overall, the success of electric mobility will depend on how well vehicle supply, policy support, and infrastructure development align across different markets.

IV. Different Technologies

The transition toward sustainable transportation has accelerated significantly in recent years as governments, industries, and researchers seek alternatives to fossil-fuel-based mobility. Rising concerns about climate change, greenhouse gas emissions, air pollution, and energy security have driven the development of new propulsion technologies and alternative fuels for the transport sector. Among the most important solutions are electric vehicles, hydrogen fuel cell vehicles, biofuels, and synthetic e-fuels, each offering different technological approaches to reducing the environmental impact of transportation.

Electric mobility has become a central pillar of global decarbonization strategies, particularly in passenger transport and urban mobility. The performance, efficiency, infrastructure requirements, and economic feasibility vary considerably depending on the energy source and propulsion system used for vehicles. At the same time, major advances in charging technologies, ultrafast charging systems, wireless charging, battery swapping, and hydrogen refueling infrastructure are reshaping the practical usability of low-emission vehicles.

Beyond electrification, alternative liquid fuels such as biofuels and synthetic e-fuels are increasingly being explored as complementary solutions, particularly for sectors where direct electrification remains difficult. Biofuels derived from biomass and synthetic fuels produced using renewable electricity and captured carbon dioxide can reduce emissions while remaining compatible with existing combustion engines and fuel distribution systems. However, these technologies also face important challenges related to sustainability, production costs, efficiency, and large-scale deployment.

This section therefore examines the main types of electric and hydrogen-powered vehicles, the development of charging and refueling infrastructure, and emerging technological trends in sustainable transportation. In addition, it analyzes the production pathways, economic viability, environmental performance, and future role of hydrogen, biofuels, and e-fuels within the broader transition toward low-carbon mobility systems.

1 Types of EVs

Electric vehicles (EVs) can be classified based on their energy sources and propulsion systems into the following main categories: battery electric vehicles, hybrid electric vehicles, fuel cell electric vehicles.

1.1 Battery Electric Vehicles (BEVs)

BEVs do not use an internal combustion engine as conventional vehicles do. Instead, they rely entirely on an electric motor for propulsion. The required traction energy is supplied by electrical energy stored in rechargeable battery packs.

The core component of a BEV is a high-capacity lithium-ion battery system, which serves as the primary energy storage unit. BEVs are characterized by high drivetrain efficiency, since electric motors typically achieve significantly higher energy conversion efficiencies than combustion engines. Additionally, most BEVs are equipped with regenerative braking systems, which recover kinetic energy during deceleration and convert it back into electrical energy to recharge the battery. Because no combustion process occurs during vehicle operation, BEVs produce zero exhaust emissions. (Yusuf Fedai, 2025).

1.2 Hybrid Electric Vehicles (HEVs)

In HEVs, the internal combustion engine and the electric motor work together to provide propulsion. The electric motor is typically used for low-speed driving and vehicle stop and start moments. The energy for the electric motor is primarily supplied through regenerative breaking or by the internal combustion engine. Another possibility is the use of a high-capacity battery, which can be charged via an external charging station. For short trips, the vehicle can operate in pure electric mode, while the internal combustion engine is engaged during longer trips to extend the driving range (Yusuf Fedai, 2025)

1.3 Fuel Cell Electric Vehicles (FCEVs)

In Fuel Cell Electric Vehicles (FCEVs), electrical energy is generated through an electrochemical reaction between hydrogen and oxygen. The electric motor serves as the primary propulsion system, while the battery acts as a secondary energy storage unit. The key components of an FCEV include a high-pressure hydrogen storage tank, a fuel cell stack, an electric motor, and a small battery (Yusuf Fedai, 2025)

2 EV Charging Infrastructure

With the growing significance of EVs, the availability, reliability, and accessibility of charging infrastructure also become increasingly important. A well-developed charging network mitigates drivers' concerns about limited range and plays a key role in integrating electric vehicles into everyday transportation. To support different power requirements and usage situations, a variety of charging technologies have been designed and put into use. (Ugur Fesli, 2024)

Charging modes describe how the vehicle connects to the power source:

- Mode 1 (slow charging) uses a standard household outlet without advanced safety or communication features. Because of limited protection, it is restricted or prohibited in several countries.

- Mode 2 (semi-fast charging) adds in-cable safety devices such as residual current protection and temperature monitoring. It is typically used with portable chargers and supports single- or three-phase connections.

- Mode 3 (fast charging) requires a dedicated charging station or wall box. It enables communication between vehicles and charging equipment, provides integrated safety systems, and is commonly used for public AC charging.

- Mode 4 (ultra-fast charging) uses external converters to supply DC power directly to the battery. These stations are larger and can deliver very high-power levels, making them suitable for rapid charging. (Ugur Fesli, 2024)

2.1 Advancements and Emerging Trends in Electric Vehicle Charging Technologies

2.1.1 <u>Ultrafast Charging & Charging Station Designs</u>

The main difference between combustion engine vehicles and electric vehicles often lies in the charging experience. While residential and slow public charging options are generally sufficient for everyday use, they become inadequate in more demanding scenarios such as long-distance travel, commercial transport, or high-density urban mobility. To address this, ultrafast charging (UFC) technologies have been developed, delivering power levels above 350 kW with the goal of recharging EVs in under 10 minutes, thereby significantly reducing downtime.

UFC refers to high-power EV charging, typically above 150 kW and up to 350 kW or more, enabling batteries to charge to 50–80% within 5–20 minutes. Charging performance depends on charger size and battery constraints, with typical DC output voltages between 200–900 V. Higher charging power places significant demands on battery design: lower-voltage systems require higher currents, leading to greater losses, larger components, and more complex thermal and battery management, whereas higher-voltage systems reduce current and improve efficiency but introduce safety and design challenges. This tradeoff is driving a shift toward higher-voltage platforms, especially in heavy-duty EVs. While most current chargers operate on low-voltage AC input, emerging solutions aim at much higher power levels, such as the Tesla V4 Supercharger and BYD Super e-Platform, which target charging capacities up to 500 kW to 1 MW and beyond. (Pasquale Franzese et al., 2025)

Feature	Description
Power range	150–350+ kW
Voltage levels	Up to 800–1,000 Vdc (required for high power at manageable currents)
Current handling	Up to 500 A; requires liquid-cooled cables to manage heat
Charging time	~5–10 min for 0%–50% ~10–20 min for 0%–80%, depending on battery and station
Connector type	Primarily Combined Charging System Combo 2 (Europe), Tesla Supercharger, CHAdeMO (Japan)
Cooling system	Active liquid cooling in both charger and cable

Figure 10: Key characteristics of UFCSs (Pasquale Franzese et al., 2025)

UFC infrastructures are being developed in different architectural forms that differ not only in power levels and connector setups but also in how their power conversion and distribution systems are structured. The main difference is the topology, meaning where conversion and control components are placed relative to the grid and charging points. Based on this, three main infrastructure types can be identified depending on how power conversion is arranged and how dispensers are connected.

1. Stand-alone charging stations: Each charging unit is an autonomous and self-contained system.

2. Distributed satellite architecture: AC-DC conversion is centralized, and DC-DC conversion is located with each dispenser.

3. Concentrated satellite architecture: All power conversion is centralized and shared across multiple dispensers.

When comparing the three architectures based on scalability, power sharing, and efficiency, the following outcomes can be observed:

The stand-alone system is simple and reliable but limited in scalability and efficiency, making it suitable mainly for small-scale deployments. The distributed satellite model provides a middle-ground solution for medium-sized stations by combining centralized power conversion with decentralized control. The concentrated satellite architecture is identified as the most promising, offering centralized conversion, dynamic load management, and high modularity, which leads to superior charging speed and resource utilization. Overall, stand-alone and distributed systems are less effective for high-demand fast charging due to structural limitations. (Pasquale Franzese et al., 2025)

Feature	Stand Alone	Distributed Satellite	Concentrated Satellite
Charging power per charging point	Limited by conversion units	Limited by conversion units	Limited by dispenser and POD
Charging time	Long	Long	Shorter for some EVs
Power sharing	Not possible	Partial (ac–dc only)	Full (ac–dc + dc–dc)
Efficiency under load	High	Moderate	Moderate
Charger avail-ability	Fixed per unit	Limited by local dc–dc	Dynamic and optimized

Figure 11: Overview of performance of the three proposed UFCS arrangements (Pasquale Franzese et al., 2025)

Although UFCS currently offers the best charging experience, its deployment is complex and resource intensive. It puts significant pressure on electrical grids, often requiring medium-voltage connections, dedicated substations, and sometimes local energy storage or renewables to handle peak demand and ensure stability. The technology also relies on advanced power electronics and strong thermal management to safely handle high power levels and prevent battery degradation. Furthermore, different system architectures—centralized, distributed, and satellite-based—must balance scalability, cost, and grid integration. Practical challenges such as space limitations, permitting, and vehicle compatibility further complicate large-scale deployment. (Pasquale Franzese et al., 2025)

2.1.2 Highway Charging

In this system, transmitter coils are embedded in the roadway and connected to the power grid. As a vehicle moves over these coils, electrical energy is transferred wirelessly, typically via magnetic inductive coupling, sto a receiver coil mounted underneath the vehicle. The received high-frequency AC power is then rectified and used to charge the vehicle's battery in real time.

The main objectives of dynamic charging are to extend driving range, reduce required battery capacity, and minimize stationary charging times. This approach is particularly relevant for long-distance and highway applications, where continuous energy supply can improve overall system efficiency and vehicle usability. (Sihan Chen et al., 2024)

Wireless EV charging still faces several key challenges. Its efficiency is lower than wired charging due to energy losses during electromagnetic transfer, and the charging distance is very limited, which makes stable energy supply difficult, especially for moving vehicles on highways.

A major problem is the lack of global standards, leading to compatibility issues between systems. Safety concerns such as electromagnetic exposure and overheating must also be carefully managed. In addition, the technology is currently more expensive than conventional charging because of high infrastructure and installation costs.

Despite these limitations, improvements in materials, coil design, and power electronics are expected to increase efficiency and reduce costs. Future progress will depend on standardization, pilot projects, and large-scale infrastructure development. (Sihan Chen et al., 2024)

2.1.3 Battery Swapping

BSS works similarly to a traditional gas station. Instead of recharging the battery within the vehicle, a depleted battery is exchanged for a fully charged unit at a dedicated swapping facility. This process significantly reduces service time and eliminates extended charging delays. Under this model, vehicle owners typically pay a subscription or leasing fee for batteries managed by the BSS operator, thereby lowering the upfront purchase cost of the electric vehicle.

The batteries are usually charged slowly at the station, which can help extend their lifespan. Battery swapping stations can also be connected to renewable energy sources like solar or wind power.

A notable advantage of BSS infrastructure is its capability to enable large-scale bidirectional power flow with the grid. As part of a vehicle-to-grid (V2G) framework, fully charged batteries stored at the station can supply electricity to the grid during peak demand periods and recharge during off-peak hours, supporting grid stability and energy management.

However, several limitations must be considered:

- The system requires substantial initial capital investment, including land, infrastructure, and a significant inventory of high-cost battery units. Balancing battery stock is critical, as insufficient inventory leads to service delays, whereas excessive inventory increases capital costs.
- Additionally, subscription fees may result in higher long-term expenses for EV users.
- Limited interoperability between different vehicle battery standards and station specifications remains a significant technical and regulatory challenge. (Ugur Fesli et al., 2024)

3 Hydrogen fuel cell vehicles HFCV

Hydrogen fuel cell vehicles generate electricity by reacting hydrogen with oxygen, producing only water and heat as byproducts, which makes them zero-emission vehicles. Compared with battery electric vehicles, they are particularly attractive for commercial transport because they offer longer driving ranges, lower battery weight, and much faster refueling times. This makes HFCVs especially suitable for long-distance logistics and heavy-duty applications.

However, the widespread adoption of HFCVs is still limited by high hydrogen production costs, scarce hydrogen refueling infrastructure, and the environmental impact of hydrogen produced from fossil fuels. Despite these challenges, governments are increasingly supporting hydrogen technologies through funding programs and national hydrogen strategies, which could strengthen the future role of HFCVs in sustainable commercial transportation. (Ömer Faruk Günaydin, 2025)

3.1 Hydrogen production

Hydrogen is classified by colors according to its production method, which reflects its environmental impact. Brown and grey hydrogen are produced from coal and natural gas and are associated with high greenhouse gas emissions. Blue and turquoise hydrogen offer lower emissions through carbon capture or methane pyrolysis, but they still depend on fossil resources or immature technologies. Green hydrogen, produced by water electrolysis using renewable electricity, is considered the most sustainable option and the most relevant for decarbonization.

A wide range of hydrogen production technologies exists, each with specific benefits and limitations. Conventional fossil-based methods such as steam methane reforming remain the most established and cost-efficient but generate considerable CO_2 emissions. Among all methods, electrolysis has gained the most attention as a clean hydrogen pathway because it can produce hydrogen without direct carbon emissions when powered by renewable energy. Different electrolyzer systems, such as PEM, alkaline, AEM, and solid oxide technologies, vary in efficiency, cost, and technical maturity, but all aim to improve large-scale green hydrogen production.

Current research therefore focuses on reducing electrolysis costs and increasing efficiency through improved catalysts, advanced membranes, hybrid renewable systems, and emerging alternatives such as photoelectrochemical and thermochemical water splitting. These developments are essential for making sustainable hydrogen production economically viable in the future. (Ömer Faruk Günaydin, 2025)

3.2 Operating Principle of Hydrogen Fuel Cell Vehicles

A hydrogen fuel cell vehicle consists of five main subsystems: the electrical air compressor, hydrogen storage system, fuel cell stack, electric drivetrain, and fuel cell control unit, all of which work together to ensure efficient vehicle operation.

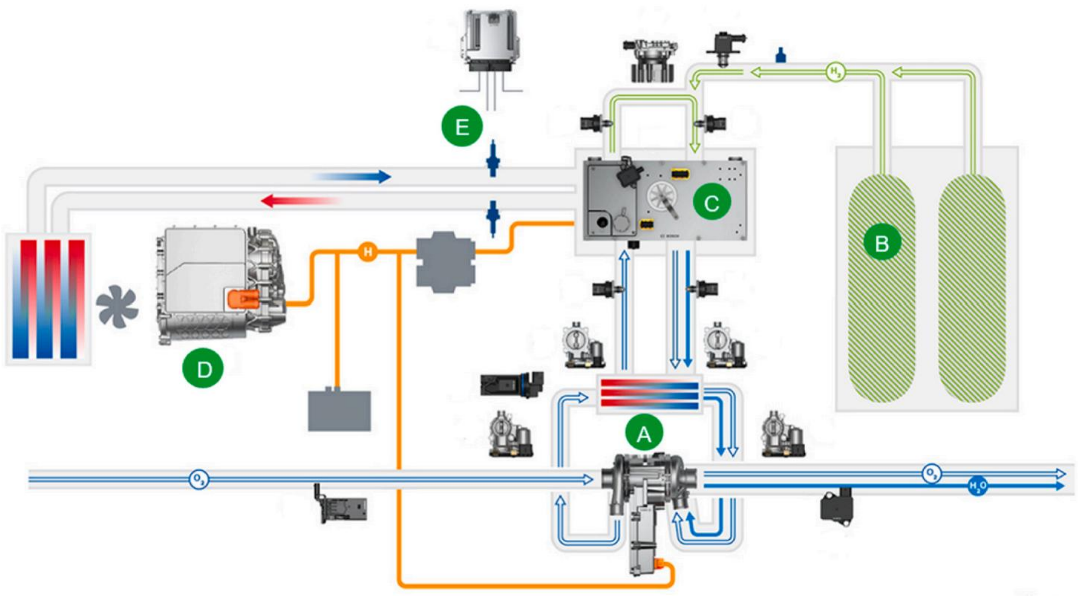


Figure 12: System overview of a fuel cell electric drive (Ömer Faruk Günaydin, 2025)

The electrical air compressor supplies pressurized oxygen to the fuel cell stack, which is necessary for the electrochemical reaction that generates electricity. Although this improves system performance, it also consumes part of the energy produced. The hydrogen storage system safely stores hydrogen and delivers it to the fuel cell at the required pressure. Since hydrogen has low volumetric density, storage remains a major challenge, and solutions such as compressed gas, liquid hydrogen, or material-based storage each involve compromises between safety, cost, weight, and driving range. (Ömer Faruk Günaydin, 2025)

At the center of the vehicle is the fuel cell stack, where hydrogen and oxygen are converted into electrical energy, with water and heat as byproducts. This electricity is then transferred to the electric drivetrain, which converts it into mechanical power for propulsion and manages energy distribution between the fuel cell, battery, and motor to ensure smooth and efficient driving.

The overall system is monitored by the fuel cell control unit. It regulates parameters such as hydrogen flow, air supply, temperature, and humidity, ensuring optimal performance, safe operation, and early detection of technical faults. Together, these subsystems make HFCVs a reliable zero-emission technology for future transportation. (Ömer Faruk Günaydin, 2025)

3.3 Hydrogen Refueling Stations (HRSs)

Hydrogen refueling stations are essential for the development of hydrogen energy and fuel cell vehicle (HFCV) adoption. Their planning is similar to electric vehicle charging networks, as it depends on factors such as demand, driving distance, and accessibility. However, building HRSs is much more expensive than conventional fuel stations, with costs ranging from about 1 to 24 million USD due to complex equipment for production, storage, compression, cooling, and safety systems.

Hydrogen can be supplied in two main ways: offsite production, where hydrogen is generated in large central plants and transported to stations, or onsite production, where hydrogen is produced directly at the station using processes such as electrolysis or steam methane reforming. Onsite systems reduce transport needs but are more limited in capacity. Most stations include key components such as production or supply units, purification systems, compressors, storage tanks, cooling systems (down to around −40 °C), safety mechanisms, and dispensers for refueling vehicles.

The refueling process typically includes compression, storage, pre-cooling, and fast dispensing under very high pressure (up to around 90–95 MPa). Hydrogen purity is critical, as impurities can damage fuel cells. Stations are also categorized by storage type: gaseous hydrogen (CGH_2) or liquid hydrogen (LH_2). Gaseous systems use compressed hydrogen delivered via pipelines or tube trailers, while liquid hydrogen systems rely on cryogenic storage, which offers higher density but requires energy-intensive cooling and careful handling due to boil-off losses.

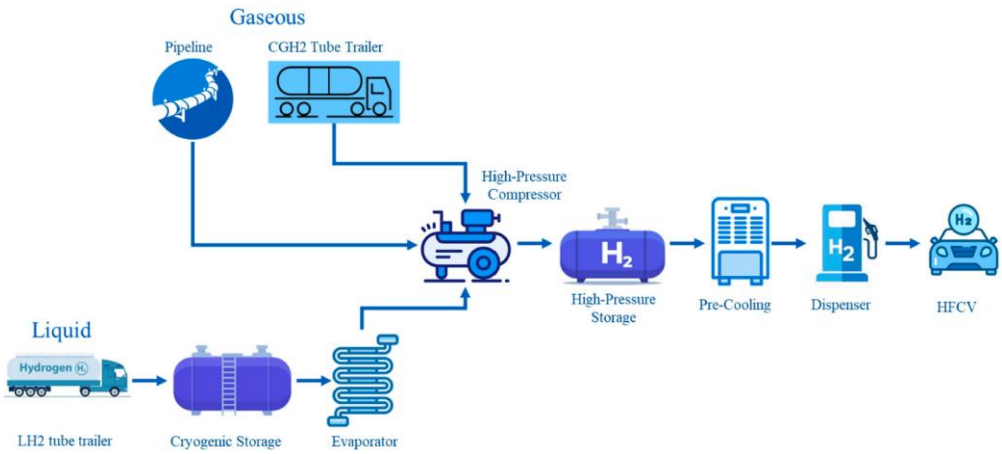


Figure 13: Overview of gaseous and liquid hydrogen storage (Ömer Faruk Günaydin, 2025)

Transportation and storage methods strongly influence hydrogen costs. Compressed hydrogen is suitable for short distances, liquid hydrogen is more efficient for medium-range transport, and pipelines are most cost-effective for large-scale, long-distance distribution, although they require high initial investment.

Global HRS infrastructure is currently expanding but still limited. Growth is expected to accelerate significantly in the coming years, supported by government policies and investment programs. Most existing stations still have relatively low capacity, but there is a clear trend toward larger, high-capacity stations to support future demand. Regulations in regions such as the EU are also pushing for wider deployment. (Ömer Faruk Günaydin, 2025)

4 *Cost Comparison of EV and Hydrogen Fuel Cell Vehicles*

4.1 Fuel Price Comparison

The economic comparison between battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) is strongly influenced by regional differences in energy prices. Across most countries, electricity is consistently the cheapest energy carrier, which provides BEVs with a clear operational cost advantage due to their high drivetrain efficiency and low energy consumption per kilometer. Hydrogen, in contrast, is generally more expensive than electricity in almost all regions when evaluated on a comparable driving-distance basis, which increases the running costs of FCEVs and limits their economic competitiveness.

However, significant regional variation exists. In South Korea and China, hydrogen prices are comparatively low due to strong governmental support, large-scale hydrogen infrastructure development, economies of scale, and the integration of renewable energy into hydrogen production. These conditions improve the cost competitiveness of FCEVs, particularly in passenger transport applications. Japan shows a more balanced cost structure with moderate hydrogen and electricity prices, allowing both BEVs and FCEVs to remain viable. In contrast, the United States faces relatively high hydrogen costs due to limited infrastructure, higher production expenses, and a smaller hydrogen vehicle market, which restricts FCEV adoption. Overall, BEVs benefit from globally lower and more stable electricity prices, whereas FCEV competitiveness is highly dependent on regional hydrogen infrastructure and policy support. (Ömer Faruk Günaydin, 2025)

Fuel consumption prices ($/62miles)

	USA	South Korea	Japan	China (Changsha)	China (Other regions)	Germany
	Passenger cars					
Hydrogen ($/62miles)	32.04	6.21	9.49	4.32	9.28	16.1
Battery ($/62miles)	7.88	4.03	3.94	2.8		9.98
Gasoline ($/62miles)	5.32	7.45	7.57	5.53		12.18
	Commercial vehicles					
Hydrogen ($/62miles)	288	55.7	85.2	38.8	83.2	144.8
Battery ($/62miles)	57.15	29.21	28.58	20.32		72.39
Diesel ($/62miles)	27.28	33.73	29.27	28.68		49.04

Figure 14: Economic values for passenger cars and commercial vehicles in different countries worldwide (Ömer Faruk Günaydin, 2025)

4.2 Manufacturing, Operation, and Economic Viability between BEVs and FCEVs

From a broader economic perspective, BEVs and FCEVs differ significantly in manufacturing cost, operating efficiency, maintenance requirements, and long-term scalability. At present, BEVs are generally more cost-effective to manufacture because battery production is already highly industrialized and benefits from established large-scale supply chains. FCEVs, on the other hand, remain more expensive due to complex fuel cell stacks, high-pressure hydrogen storage systems, and additional system integration requirements. This results in higher upfront purchase prices for FCEVs compared to BEVs.

In terms of operational costs, BEVs currently hold a clear advantage due to lower electricity prices and higher energy efficiency. This makes them particularly suitable for short- and medium-distance transport. FCEVs, however, offer potential advantages in long-distance and high-utilization applications, as they enable rapid refueling and reduced downtime, which is especially relevant for commercial transport and logistics. Although BEVs are more efficient in energy conversion, ongoing reductions in hydrogen production costs and improvements in infrastructure may enhance the long-term competitiveness of FCEVs. (Hussein Togun, 2025)

Maintenance considerations also differ between the two technologies. BEVs benefit from mechanically simpler drivetrains, but battery degradation over time and sensitivity to charging conditions can result in significant long-term replacement costs. FCEVs may experience lower mechanical wear and potentially longer system lifetimes, although fuel cell durability and system reliability remain critical cost factors. Advances in component design and energy management strategies are expected to reduce maintenance costs for both technologies.

4.3 Comparison of BEVs and HFCVs in Future Transportation Systems

BEVs currently dominate the passenger vehicle market due to their high energy efficiency, relatively mature charging infrastructure, and lower operating costs. They convert electrical energy into motion much more efficiently than hydrogen-based systems, achieving well-to-wheel (WTW) efficiencies of approximately 60–75%. In addition, BEVs produce no direct CO_2 emissions and are particularly suitable for urban transportation and short- to medium-distance travel. Advances in battery technology and the expansion of fast-charging networks have further improved their practicality for everyday use. Modern BEVs can achieve driving ranges between 350 and 400 miles, while fast charging can recharge batteries from 10% to 80% within approximately 30–40 minutes.

Despite these advantages, BEVs also face limitations, especially in heavy-duty and long-distance transportation. Large battery systems increase vehicle weight, reduce payload capacity, and require long charging times compared to conventional refueling. These challenges become more significant in sectors such as freight transport, aviation, and maritime shipping, where operational efficiency and minimal downtime are essential.

In these sectors, HFCVs are increasingly viewed as a promising alternative. Hydrogen fuel cell technology offers longer driving ranges, fast refueling times comparable to conventional vehicles, and zero tailpipe emissions. Passenger HFCVs such as the Toyota Mirai and Hyundai Nexo already achieve ranges of approximately 400–470 miles while requiring only a few minutes for refueling. Although hydrogen fuel remains more expensive than electricity, HFCVs are particularly attractive for applications where vehicles operate continuously and downtime must be minimized.

Public transportation represents one of the most important future applications for HFCVs. Fuel cell buses (FCBs) have the potential to significantly reduce greenhouse gas emissions, noise pollution, and local air pollutants, especially when powered by green hydrogen. While battery electric buses are currently considered more practical for urban areas in the short and medium term, fuel cell buses may become more suitable in the long term because of their extended range and faster refueling capabilities. Cost reductions through technological progress and economies of scale are expected to improve the competitiveness of hydrogen-powered buses in the future.

Hydrogen fuel cell technology also shows strong potential in aviation. The aviation sector faces growing pressure to reduce emissions, particularly as global passenger and cargo traffic continues to increase. Fuel cells are being explored as power sources for short-haul and regional aircraft due to their low noise levels, reliability, and environmental benefits. However, for larger long-haul aircraft, hydrogen combustion may currently be more practical than fuel cell systems.

The maritime sector is another area where hydrogen technologies could play a major role. Shipping currently relies heavily on fossil fuels and contributes significantly to global greenhouse gas emissions. Hydrogen fuel cells offer a promising solution for decarbonizing maritime transport, particularly as international climate targets become stricter. Pilot projects have already demonstrated the feasibility of hydrogen-powered ships.

Overall, the future transportation sector will likely see a division of roles between BEVs and HFCVs. BEVs are expected to dominate urban mobility, passenger cars, and short-distance transportation because of their high efficiency and well-established charging infrastructure. HFCVs, on the other hand, are more likely to become important in long-distance, heavy-duty, and commercial applications where fast refueling, long range, and reduced vehicle weight are critical. Rather than competing directly, both technologies are expected to complement each other in supporting the global transition toward low-emission and sustainable transportation systems.

Overall, BEVs are currently the more economically mature and cost-efficient technology due to lower energy and production costs, while FCEVs remain less competitive in the short term. Nevertheless, FCEVs are projected to become increasingly viable in the long term, particularly in heavy-duty and long-range transport sectors where operational flexibility and fast refueling provide clear economic advantages. (Hussein Togun, 2025)

5 Biofuels

Biofuels are liquid transport fuels produced from biomass – organic material from plants, agricultural residues, waste fats, and other biological sources. They can serve as direct substitutes or blending components for fossil petrol and diesel in the existing vehicle fleet (IEA, 2025b)

The global biofuel market is dominated by two main products: bioethanol (produced from sugars and starches, primarily used as a petrol blending component) and biodiesel/renewable diesel (produced from vegetable oils and animal fats, used in diesel vehicles). By 2022, approximately 60% of global renewable ethanol was produced from maize, 23% from sugarcane, and the remainder from other grains and molasses. Around 70% of biodiesel and HVO/HEFA originated from vegetable oils (rapeseed 14%, soybean 23%, palm oil 29%), while the remaining 25–30% came from used cooking oil (UCO) and animal fats. (Mercado-Cordova, 2025)

5.1 Indirect Land Use Change (ILUC) – The Core Sustainability Challenge

The sustainability profile of first-generation biofuels is fundamentally complicated by the problem of indirect land use change (ILUC). ILUC occurs when additional demand for biofuel feedstock displaces food and feed crop production to new land areas, which may cause the conversion of carbon-rich natural ecosystems -- forests, peatlands, grasslands -- into agricultural land, releasing stored carbon into the atmosphere. (European Commission, 2026)

The range of published ILUC estimates is very wide and methodologically contested. For corn ethanol, estimates range from 13 to 104 g CO_2eq per MJ of fuel depending on the model and assumptions. For cellulosic biofuels, estimates range from 5.8 to 111 g CO_2eq/MJ. This uncertainty makes ILUC a highly debated topic in both scientific and regulatory communities (Khanna et al, 2017).

A key empirical finding across multiple studies is that the extent of deforestation driven by biofuel demand is largely independent of which specific vegetable oil feedstock is used, because all vegetable oils are close substitutes in global food markets. This challenges the logic of assigning differentiated ILUC scores by feedstock and suggests that a cap on total vegetable oil volumes in biofuel may be a more effective safeguard.

5.1.1 Hydrotreatment: HVO (Renewable Diesel)

Hydrotreated Vegetable Oil (HVO), also called renewable diesel, is produced by reacting biological fats and oils with hydrogen at high temperatures (300-400 degrees C) and pressures over a solid catalyst bed. The two key reactions are hydrodeoxygenation (HDO) -- removing oxygen from the triglyceride structure to produce long-chain alkanes and water -- followed by isomerization and hydrocracking to optimize cold-flow properties. (Gerveni et al, 2023) Unlike FAME biodiesel, HVO is a pure hydrocarbon fuel (predominantly C15-C18 paraffins) chemically identical to fossil diesel. This makes HVO 100% drop-in compatible with all diesel engines, storage systems, and distribution infrastructure at any blend ratio -- including as a full B100 replacement -- without any vehicle modifications. HVO demonstrates a significant reduction in carbon dioxide emissions ranging from 60% to 95% compared to conventional diesel throughout its entire lifecycle, depending on the feedstock. Utilizing 100% UCO as feedstock can achieve GHG savings of up to 93%, while a newbuild facility using exclusively UCO can increase GHG emission savings to this level. (Kourkoumpas et al, 2024) HVO production is at TRL 9 and is the most commercially advanced biofuel beyond conventional 1G ethanol and FAME biodiesel.

5.2 Biofuel Costs and Learning Curves

5.2.1 Current Production Costs

Current biofuel production costs vary significantly by feedstock and technology. First-generation ethanol (from sugarcane or corn) is the most cost-competitive, with production costs broadly in the range of EUR 0.30-0.50 per liter ethanol equivalent in leading producing countries. FAME biodiesel and HVO production costs are more closely tied to feedstock prices – vegetable oils and waste fats – which represent 60-80% of total production cost. (IEA, 2020)

The feedstock share in MPSP varies among the different biofuel conversion pathways from 66% to 16%. Hydrothermal liquefaction had the lowest average minimum product selling price at approximately 4 USD per gasoline gallon equivalent, while gasification had the highest capital expenditure share in minimum product selling price. (Karimi et al, 2025)

HVO production has faced structural cost pressure as demand for waste feedstocks (UCO, tallow) has grown faster than supply. UCO and animal fat feedstocks remain constrained, with allegations of origin fraud periodically roiling European markets, and RED III's tougher traceability rules raise the compliance burden. Biofuels are not expected to become cheaper than fossil fuels over the timeframe studied in most current analyses, and any changes in future average fuel blends are expected to continue to be determined by policy rather than market pricing alone.

Learning curves – which describe the relationship between cumulative production volume and unit cost – have played a major role in reducing biofuel costs over recent decades. As technology is deployed at larger scale, producers learn through experience, optimize processes, and benefit from economies of scale.

6 Synthetic (E-)Fuels

E-fuels – also referred to as electrofuels, synthetic fuels, or power-to-liquid (PtL) fuels – are synthetic hydrocarbon fuels produced from water, renewable electricity, and captured carbon dioxide through a multi-step chemical conversion chain. They function as drop-in substitutes compatible with current internal combustion engines (ICEs) and existing transport infrastructure. (IEA, 2024) E-fuels are also described in the literature as power-to-X (PtX), power-to-gas (PtG), and power-to-liquids (PtL). The principal types of liquid e-fuels relevant to road transport include e-diesel (Fischer-Tropsch diesel), e-petrol/e-gasoline (via methanol synthesis and methanol-to-gasoline conversion), e-methane (Sabatier reaction), and e-methanol. (Concawe, 2019) Unlike first-generation biofuels, e-fuels do not compete for agricultural land and can be scaled in parallel with the expansion of renewable energy systems. Their production is also independent of seasonal biomass availability, which gives e-fuel supply chains greater geographic flexibility. (Colelli, 2026)

6.1 E-Fuel Efficiencies

The energy efficiency of e-fuel production – defined as the ratio between the energy contained in the final fuel and the total energy used to produce it – decreases as fuel molecules become more complex. E-hydrogen has the highest energy efficiency at 75%, driven primarily by electrolysis efficiency (alkaline electrolyser). E-methane, the simplest carbon-containing e-fuel molecule, has an energy efficiency of 52% when produced from air-captured CO_2. E-diesel and e-kerosene via Fischer-Tropsch drop further to approximately 42% energy efficiency when using DAC-sourced CO_2. (Concawe, 2024) When CO_2 is sourced from a concentrated industrial source rather than DAC, the Fischer-Tropsch diesel and kerosene pathways improve to an energy efficiency of up to 51%. For polyoxymethyl dimethyl ethers (OME3-5, a clean-burning synthetic diesel alternative), efficiency is 34% with DAC and 28% with concentrated CO_2 source, reflecting the high processing requirements for complex molecules. (Concawe, 2024) The Fischer-Tropsch fuel synthesis process efficiency – from syngas to fuel – is approximately 58%, with only 45% of the carbon in the CO_2 feed ultimately fixed in the FT fuel product. When starting from green hydrogen, 1 MJ of FT e-diesel requires 2.4 times the energy needed to produce 1 MJ of e-hydrogen, and 1 MJ of e-OME3-5 requires 3.6 times the e-hydrogen energy equivalent. (Colelli et al, 2026)

6.2 E-Fuel GHG Performance

The GHG performance of e-fuels is not fixed – it is entirely dependent on the carbon intensity of the electricity used to produce them. Using nuclear or solar/wind electricity and DAC-sourced CO_2, FT fuel production can reduce well-to-wheel (WTW) GHG emissions by 90-108% relative to petroleum fuels. (Zang et al, 2021)

Taking northern Europe as an example, the net GHG emissions of different e-fuel pathways on a cradle-to-grave basis are around 4.3-6 g CO_2eq per MJ (except for e-OME3-5), and around 0.5 g CO_2eq/MJ if only operational and maintenance emissions are counted. Well-to-wheel emissions are almost zero when using 100% renewable electricity and DAC. (Concawe, 2024)

A key finding from 2025 research is that using the projected EU electricity mix for 2030, synthetic fuels show no clear advantage over fossil fuels in terms of GHG emissions. Only with a fully clean (renewable) electricity mix expected by 2050 does their emission factor become significantly lower than fossil equivalents. (Lukacs et al, 2025)

6.3 E-Fuel Costs and Learning Trajectories

E-fuel production is currently expensive. Concawe/EUCAR report that e-fuel costs can reach up to approximately EUR 7,500 per ton in some early-stage configurations but are expected to decrease to roughly EUR 1,050–3,200 per ton by 2050 as scale, learning effects, and declining renewable electricity prices materialize. (Concawe, 2019)

A detailed levelized cost analysis of FT e-diesel production using solar PV, direct air capture, electrolysis, and Fischer-Tropsch synthesis finds a baseline production cost of approximately EUR 3,300 per ton, with 84% of modelled scenarios falling between EUR 3,000 and EUR 3,750 per ton. (Concawe, 2019)

7 Cost Comparison with BEVs and applicability across transport segments

Fossil diesel trades at approximately EUR 700–900 per ton in European markets today. Current commercial HVO market prices stand at approximately USD 1600–2650 per ton depending on feedstock class and mandate value. E-fuel production costs at EUR 3000–4400 per ton represent a 3.5-6x premium over fossil diesel – a gap that policy support, carbon pricing, or technology learning must close for e-fuels to play a meaningful role in mainstream road transport.

In conclusion, for road transport, direct electrification via BEVs offers the most energy-efficient and – at scale – most cost-competitive decarbonization pathway per kilometer travelled. Biofuels, particularly HVO from waste feedstocks, are the near-term liquid fuel alternative for segments where electrification is not yet feasible. E-fuels for road transport are a longer-term option for hard-to-abate niche segments but are unlikely to be economically competitive with BEVs for mainstream road transport within the foreseeable future.

Direct electrification of road transport is not feasible or cost-effective for all vehicle segments. For passenger cars and light commercial vehicles in urban and short-range applications, BEVs are the most energy-efficient and increasingly cost-competitive option. However, liquid fuel alternatives retain genuine advantages in specific segments:

Long-haul heavy-duty freight: Battery weight and charging time constraints limit BEV applicability. Biofuels (HVO) and e-fuels can be used in existing engine architectures with immediate fleet compatibility.

Existing fleet decarbonization: The average EU passenger car fleet age exceeds 11 years. Drop-in biofuels and e-fuels can reduce emissions from vehicles already on the road without requiring vehicle replacement – a capability BEVs cannot match.

Rural and remote transport: Sparse charging infrastructure makes BEVs less practical. HVO and biofuel blends can be distributed through existing fuel networks without infrastructure investment.

Cost-effective grid use: E-fuel production can utilize surplus renewable electricity (curtailed wind and solar) that would otherwise be wasted, potentially improving the overall economics of the renewable energy system – though this benefit is contested and location-dependent.

V. Analysis of EU and Austrian Regulatory Framework

1 The Legal Architecture of Decarbonization: Introduction

The decarbonization of transport is, at its structural core, a legally constituted governance project. Technologies do not scale in a regulatory vacuum: market uptake, investment decisions, and competitive positioning of decarbonization pathways are fundamentally shaped by the legal instruments that mandate, incentivize, prohibit, or tolerate technological choices. A dedicated regulatory analysis is warranted because the binding legal architecture – from the Paris Agreement (Art 4 Para 2 and 3) through the European Climate Law (Art 2 Para 1 Regulation (EU) 2021/1119) – imposes commitments that cannot plausibly be achieved through market dynamics alone; because transport decarbonization is governed by a dense, interlocking ensemble of EU and national instruments whose coherence, gaps, and tensions must be mapped; and because formally technology-open frameworks may, through specific regulatory instruments, produce *de facto* technological preferences – a question that constitutes one of the central analytical contributions of this chapter.

Rather than offering a comprehensive doctrinal survey, this analysis examines each instrument for its functional effect on the competitive positioning of decarbonization technologies – identifying whether it operates as a regulatory accelerator or a regulatory brake. The selection of instruments is guided by functional relevance, normative significance, and direct bearing on technology adoption dynamics. Whether battery-electric vehicles (BEV) or hydrogen-powered alternatives come to dominate specific transport applications will depend critically on which technologies the law mandates, enables, incentivizes, or – through inaction or ambiguity – effectively deters. It is to that analysis that the following sections are devoted.

2 EU Regulatory Framework – Top-Down Governance

2.1 Overarching Climate Framework: European Climate Law – Regulation (EU) 2021/1119

The European Climate Law establishes the binding target framework at the apex of the Union's decarbonization architecture. It sets a legally enforceable objective of climate neutrality by 2050 at the latest – requiring that Union-wide greenhouse gas (GHG) emissions and removals be balanced and that negative emissions be achieved thereafter (Art 2 Para 1 Regulation (EU) 2021/1119). The binding 2030 interim target requires a net domestic reduction of GHG emissions of at least 55% compared to 1990 levels (Art 4 Para 1 Regulation (EU) 2021/1119). Both EU institutions and Member States are expressly obligated to take the necessary measures to enable collective achievement of these objectives (Art 2 Para 2 Regulation (EU) 2021/1119), generating regulatory pressure across all emitting sectors, including transport.

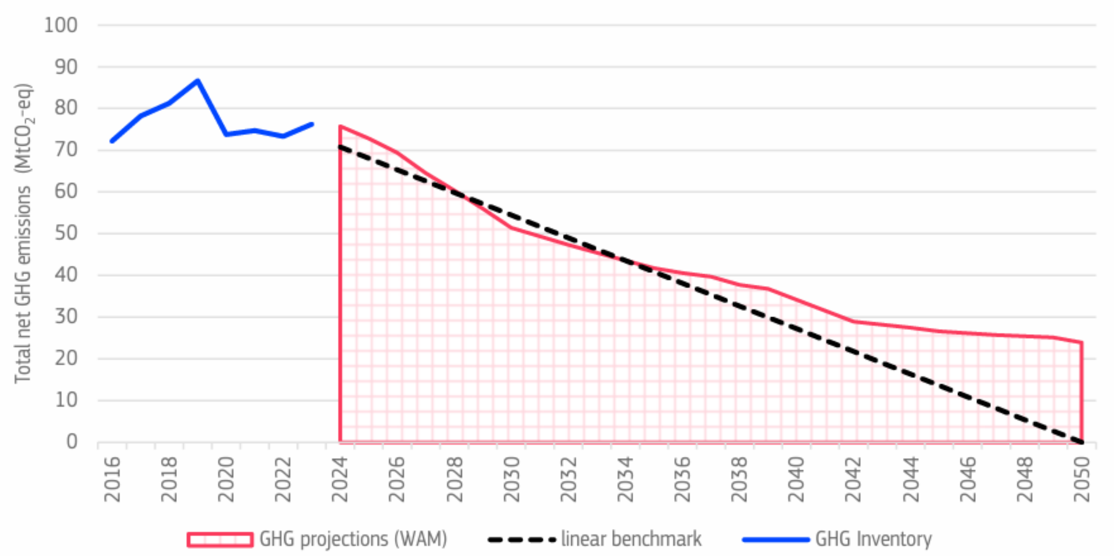


Figure 15: Projected cumulative net GHG emissions vs cumulative emissions of a linear trajectory to climate neutrality between 2023 and 2050 (European Commission, Climate Action Progress Report 2025 – Austria Country profile)

Importantly, the European Climate Law is formulated in a technology-neutral manner. When taking relevant measures, Member States and EU institutions shall consider, inter alia, cost-effectiveness and technological neutrality in achieving GHG emission reductions and removals and increasing resilience (Recital 34 Regulation (EU) 2021/1119). The Regulation prescribes outcomes but does not prescribe the technological means by which those outcomes are to be achieved. The choice between BEVs, hydrogen-powered alternatives, sustainable fuels, or other decarbonization vectors is consequently left to the sector specific regulatory instruments that implement the European Climate Law's binding target framework – and it is the design of those instruments that determines, in practice, which technologies the law favors or inhibits. The analysis of those instruments follows in the subsequent sections.

2.2 Road Transport (Passenger Cars & Light Commercial Vehicles): CAFE Regulation – Regulation (EU) 2019/631

Regulation (EU) 2019/631 (CAFE Regulation) establishes CO_2 emission performance requirements for new passenger cars and new light commercial vehicles with the objective of contributing to the Union's GHG emission reduction targets under the Effort Sharing Regulation and to the goals of the Paris Agreement and ensuring the smooth functioning of the internal market (Art 1 Para 1 CAFE Regulation). On 16 December 2025, the Commission published a proposal for a regulation amending CAFE Regulation (COM(2025) 995 final), which – if adopted – would introduce significant modifications to the CO_2 reduction trajectory, additional compliance flexibilities, and new provisions on vehicle labelling. The following analysis sets out the currently applicable legal framework and, where relevant, identifies the changes envisaged by the Commission's proposal.

Each manufacturer must ensure that its average specific CO_2 emissions do not exceed its individually assigned specific emissions target (Art 4 Para 1 CAFE Regulation). The system of progressively tightening fleet-wide targets functions as the primary regulatory accelerator of zero-emission vehicle deployment: 15% reduction from 2025 (Art 1

Para 4), 55% for passenger cars and 50% for light commercial vehicles from 2030 (Art 1 Para 5), and 100% from 2035 under currently applicable law – equivalent to zero grams of CO_2 per kilometer for all newly registered vehicles (Art 1 Para 5a CAFE Regulation). This *de facto* phase-out of new combustion engine vehicles from 2035 constitutes the most significant regulatory acceleration of zero-emission powertrain adoption in the Union's legislative history. However, the Commission's December 2025 proposal (COM(2025) 995 final) envisages a material softening: the 2030 target for light commercial vehicles would be lowered from 50% to 40%, and the 2035 target for both categories would be reduced from 100% to 90%, thereby abandoning the complete phase-out of internal combustion engine vehicles.

Where a manufacturer's average specific CO_2 emissions exceed its specific emissions target in a given calendar year, the Commission imposes an excess emissions premium, calculated as the amount of exceedance in grams per kilometer multiplied by EUR 95, further multiplied by the number of newly registered vehicles (Art 8 Para 1 and 2 CAFE Regulation). This financial penalty mechanism creates a powerful investment incentive compelling manufacturers to deploy zero-emission vehicles at scale.

The fleet targets are formulated in a formally technology-neutral manner: the Regulation prescribes quantitative CO_2 outcomes but does not mandate any particular powertrain technology. Zero-emission and low-emission vehicles are defined as vehicles with tailpipe emissions of zero to 50 g CO_2/km (Art 3 Para 1 lit m CAFE Regulation), encompassing battery-electric, fuel-cell electric, and hydrogen-powered vehicles alike. A zero- and low-emission vehicle benchmark of 25% for passenger cars and 17% for light commercial vehicles applies from 2025 to 2029 (Art 1 Para 6 CAFE Regulation). The Commission's proposal would strengthen technology neutrality by introducing two new credit mechanisms from 2035: fuel credits for sustainable renewable fuels – comprising RFNBOs and Annex IX biofuels under Directive (EU) 2018/2001 (RED II) – capped at 3% of the 2021 EU fleet-wide target (proposed Art 5a), and credits for low-carbon steel produced in the EU, capped at 7% (proposed Art 5b). These mechanisms would, if adopted, create regulatory space for non-zero-emission technologies to remain viable beyond 2035, materially altering the investment calculus for competing powertrain technologies.

An important qualification arises from the political commitment recorded at the time of adoption of Regulation (EU) 2023/851 to allow vehicles running exclusively on CO_2-neutral fuels to be registered after 2035. The Commission has now acted on this commitment – not through a separate e-fuel exemption, but by proposing to reduce the 2035 target from 100% to 90% and to introduce the credit mechanisms described above. The proposal further requires the Commission to assess the Regulation's effectiveness in 2035 and every five years thereafter, with the mandate to adjust fleet targets to maintain alignment with the climate-neutrality objective under Regulation (EU) 2021/1119 (proposed Art 15 Para 1). It must be emphasized that the proposal remains subject to the ordinary legislative procedure and has not yet been adopted. Nevertheless, it already generates significant regulatory uncertainty as to the definitive scope of the 2035 combustion engine phase-out, with direct implications for investment decisions across competing zero-emission technology pathways.

In summary, the CAFE Regulation constitutes the most powerful regulatory accelerator for zero-emission vehicle deployment in the passenger car and light commercial vehicle segments through progressively tightening fleet-wide CO_2 targets culminating in a near-complete phase-out of combustion engines from 2035.

2.3 Freight and Heavy-Duty Transport: CO_2 Standards for Heavy-Duty Vehicles – Regulation (EU) 2019/1242

Regulation (EU) 2019/1242 sets CO_2 emission performance standards for new heavy-duty vehicles, contributing to the Union's climate-neutrality objective and its intermediate climate targets, Member States' GHG emission reduction obligations, and the goals of the Paris Agreement (Art 1 Para 1 Regulation (EU) 2019/1242). The Regulation applies to new vehicles type-approved or individually approved under Regulation (EU) 2018/858 (Art 2 Para 1 Regulation (EU) 2019/1242).

Art 3a Para 1 Regulation (EU) 2019/1242 establishes a trajectory of progressively tightening EU fleet-wide CO_2 reduction targets for new heavy-duty motor vehicles compared to the average CO_2 emissions of the reporting period of the year 2019: a 15% reduction applies for the principal long-haul and regional delivery subgroups for the reporting periods of the years 2025 to 2029; a 45% reduction applies to all subgroups other than vocational vehicles for the reporting periods of the years 2030 to 2034; a 65% reduction applies to all subgroups for the reporting periods of the years 2035 to 2039; and a 90% reduction applies to all subgroups from the reporting period of 2040 onwards. Where a manufacturer is found to have excess CO_2 emissions in a given reporting period from 2025 onwards, the Commission imposes an excess CO_2 emissions premium (Art 8 Para 1 Regulation (EU) 2019/1242). This penalty mechanism creates a structural investment incentive compelling manufacturers to accelerate the deployment of zero-emission heavy-duty vehicles.

The Regulation is technology-open in its approach to zero-emission powertrains. Art 3 No 11 Regulation (EU) 2019/1242 defines a zero-emission heavy-duty vehicle as any heavy-duty motor vehicle without an internal combustion engine, or with an internal combustion engine that emits not more than 3 g CO_2/(tkm) or 1 g CO_2/(pkm), or alternatively, not more than 1 g CO_2/kWh or 1 g CO_2/km where no Vehicle Energy Consumption Calculation Tool (VECTO) values are available. Both battery-electric trucks and hydrogen fuel-cell electric vehicles (FCEV)are therefore legally equivalent compliance pathways under the Regulation.

In contrast to the passenger car sector, the regulatory trajectory for heavy-duty freight vehicles is more gradual, reflecting the greater technical and operational heterogeneity of the sector. Art 15 Para 2 Regulation (EU) 2019/1242 required the Commission to assess the role of sustainable renewable fuels in the transition towards climate neutrality, and – separately from the general review – to present by 31 December 2025 a report to the European Parliament and to the Council with a comprehensive analysis of the need to further incentivize the uptake of advanced biofuels, biogas, and renewable fuels of non-biological origin (RFNBO) in the heavy-duty vehicle sector, together with an appropriate framework of measures including financial incentives. The Regulation thus combines binding quantitative reduction targets for new vehicles with formal technology neutrality as between BEV and H_2-FCEVs powertrains and simultaneously addresses the decarbonization of the existing fleet through a parallel policy strand on sustainable renewable fuels – indicating a more gradual and pluralistic technological transition than in the passenger car sector.

In brief, the heavy-duty vehicle CO_2 standards establish a more gradual reduction trajectory than the passenger car regime – reaching 90% by 2040 – while maintaining formal technology neutrality between BEV and FCEV powertrains and simultaneously addressing the decarbonization of the existing fleet through a parallel policy strand on sustainable renewable fuels.

2.4 Infrastructure: AFIR – Regulation (EU) 2023/1804

Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR) constitutes the central EU infrastructure regulation in this field, establishing binding national targets leading to the build-up of a sufficient alternative fuels infrastructure for road vehicles, trains, vessels, and stationary aircraft throughout the Union (Art 1 Para 1 AFIR). It repeals and replaces the former Directive (EU) 2014/94, upgrading the legal instrument from a directive to a directly applicable regulation – a structural choice that reduces implementation discretion at Member State level and thereby functions as a regulatory accelerator for infrastructure roll-out.

From a technology adoption perspective, AFIR's primary significance lies in the asymmetric intensity with which it supports different powertrain technologies. The Regulation operates most forcefully as an accelerator for BEVs: Member States must ensure the deployment of publicly accessible recharging stations commensurate with the uptake of battery-electric and plug-in hybrid vehicles, providing at least 1.3 kW of total output power per registered battery-electric light vehicle (Art 3 Para 1 lit a AFIR). For the core Trans-European Transport Road Network, publicly accessible charging pools must be deployed at maximum 60 km intervals in each direction, providing at least 400 kW by 31 December 2025 and at least 600 kW – with at least two 150 kW charging points – by 31 December 2027 (Art 3 Para 4 lit a AFIR). For heavy-duty electric vehicles, by 31 December 2030, publicly accessible charging pools must be deployed along the Trans-European Transport Network (TEN-T) core road network at maximum 60 km intervals, each providing at least 3,600 kW with at least two charging points of at least 350 kW individual output (Art 4 Para 1 lit c AFIR). The density, specificity, and short-term binding nature of these obligations makes the electric charging infrastructure framework a strong regulatory accelerator for battery electric vehicle (BEV) adoption across both light and heavy road transport.

The regulatory support for hydrogen is comparatively more cautious. Member States must ensure that by 31 December 2030, publicly accessible hydrogen refueling stations with a minimum capacity of 1 t/day and at least one 700-bar dispenser are deployed at maximum 200 km intervals along the TEN-T Core Network, with at least one station at each urban node (Art 6 Para 1 AFIR). While binding, the longer lead time and lower spatial density compared to electric vehicle charging reflect a policy bet on BEV dominance in road transport. In functional terms, AFIR's principal contribution is to resolve the classic chicken-and-egg problem between vehicle deployment and infrastructure availability – decisively for BEVs, and to a more limited extent for hydrogen FCEVs. By mandating minimum coverage and capacity thresholds, it de-risks vehicle purchasing decisions and reduces the infrastructure uncertainty premium. Its modal asymmetries are themselves regulatory signals about which technologies the Union expects to prevail.

Ultimately, AFIR resolves the infrastructure chicken-and-egg problem decisively for BEVs – through dense, short-term binding charging mandates along the TEN-T network – and more cautiously for hydrogen FCEVs, whose refueling stations are mandated at wider intervals and with longer lead times, thereby signaling a structural regulatory preference for direct electrification in road transport.

2.5 Renewable Fuels & RFNBOs: Renewable Energy Directive – Directive (EU) 2018/2001

RED II, as substantially amended by Directive (EU) 2023/2413 (RED III), establishes the Union's binding framework for the promotion of energy from renewable sources, including a detailed set of transport-specific targets, accounting rules, and incentive mechanisms with direct implications for the competitive positioning of decarbonization technologies.

At the macro level, Member States must collectively ensure that the share of energy from renewable sources in the Union's gross final consumption of energy reaches at least 42.5% by 2030, with a collective endeavor target of 45% (Art 3 Para 1 RED II). For transport specifically, Member States must impose an obligation on fuel suppliers requiring that the renewable energy share in transport final energy consumption reaches at least 29% by 2030, or alternatively that the GHG intensity of energy supplied to transport is reduced by at least 14.5% compared to the applicable baseline (Art 25 Para 1 RED II). Within this obligation, a combined sub-target applies: the share of advanced biofuels and biogas and RFNBOs in the energy supplied to transport must reach at least 5.5% by 2030, of which at least 1 percentage point must be accounted for by RFNBOs (Art 25 Para 1 lit b RED II).

The Directive's most significant feature for technology adoption is its system of multipliers. Renewable electricity supplied to road vehicles is counted as four times its energy content for compliance with the transport obligation (Art 27 Para 2 lit d RED II). This 4x multiplier constitutes a powerful regulatory accelerator for BEVs: it enables fuel suppliers to satisfy a disproportionately large share of their compliance obligation through renewable electricity, generating a structural commercial incentive to expand electric vehicle charging infrastructure.

By contrast, biofuels and biogas produced from Annex IX feedstocks and RFNBOs are counted as twice their energy content (Art 27 Para 2 lit c RED II). This 2x multiplier constitutes a meaningful regulatory accelerator for both advanced biofuels and renewable hydrogen across transport modes.

The Directive simultaneously functions as a regulatory quality threshold for renewable fuel of non-biological origin investments. Energy from RFNBOs may only be counted towards Member States' renewable energy shares and the relevant transport targets if it achieves GHG emissions savings of at least 70% compared to the applicable fossil fuel reference value (Art 29a Para 1 RED II). This threshold operates as a gatekeeper mechanism: it excludes low-quality renewable fuel of non-biological origin production from regulatory credit, thereby guiding investment towards genuinely low-carbon hydrogen and synthetic fuel supply chains, but it also raises the bar for market entry and may constrain the pace of renewable fuel of non-biological origin scale-up in the near term – functioning in this respect as a conditional brake on hydrogen adoption where production processes do not yet meet the savings threshold.

In sum, the Directive operates as a strong regulatory accelerator for BEVs through the 4x multiplier, as a meaningful accelerator for advanced biofuels, biogas, and RFNBOs through the 2x multiplier and dedicated sub-targets, and simultaneously as a quality-based constraint on RFNBO deployment where the 70% GHG savings threshold is not met.

2.6 Carbon Pricing: Directive 2003/87/EC – EU ETS Revision by Directive (EU) 2023/959

Directive 2003/87/EC establishes the EU Emissions Trading System (ETS) as the Union's primary market-based instrument for reducing GHG emissions cost-effectively, and – as comprehensively revised by Directive (EU) 2023/959 – explicitly aligns the ETS with the climate-neutrality objective and the Union's interim climate targets (Art 1 Directive 2003/87/EC). Its fundamental mechanism is a cap-and-trade architecture: regulated entities must surrender allowances equal to their verified annual GHG emissions, with the aggregate cap declining over time, thereby generating a carbon price signal that raises the relative cost of fossil-intensive activities (Art 12 Para 3 Directive 2003/87/EC).

For transport, the 2023 revision pursues two structurally distinct strategies. First, it extends and tightens carbon pricing within ETS1 for aviation and maritime transport. Shipping companies are subject to surrender obligations covering 100% of emissions from intra-EU voyages and 50% from extra-EU voyages, phased in from 40% in 2024 to 100% from 2026 (Art 3ga Para 1, Art 3gb Directive 2003/87/EC). For aviation, free allocation is progressively replaced by full auctioning from 2026, and up to 20 million allowances are reserved for 2024–2030 to support the uptake of eligible aviation fuels – including renewable hydrogen and RFNBOs – by covering differentiated shares of the residual price differential with fossil kerosene (Art 3c Para 6 Directive 2003/87/EC). These provisions function as targeted regulatory accelerators for sustainable fuel adoption in hard-to-electrify transport modes.

Second, and most significantly for road transport, Directive (EU) 2023/959 introduces an entirely new emissions trading system – ETS2 – under Chapter IVa of Directive 2003/87/EC. ETS2 applies to the release for consumption of fuels used for combustion in road transport (and buildings), placing the compliance obligation on upstream regulated entities such as fuel suppliers (Art 30a in conjunction with Annex III Directive 2003/87/EC). These entities must hold a GHG emissions permit from 1 January 2025 (Art 30b Para 1 Directive 2003/87/EC) and surrender allowances corresponding to their covered emissions, with the operative surrender obligation commencing from 1 January 2028 (Art 30e Para 2 Directive 2003/87/EC). The ETS2 cap declines steeply, with linear reduction factors of 5.10% from 2027 and 5.38% from 2028 (Art 30c Para 1 and 2 Directive 2003/87/EC). Member States must use ETS2 auction revenues for climate purposes, expressly including measures to accelerate the uptake of zero-emission vehicles and the deployment of recharging and refueling infrastructure (Art 30d Para 6 lit b Directive 2003/87/EC). ETS2 thus operates as a structural regulatory accelerator for zero-emission mobility by monetizing the carbon content of road transport fuels at the supply chain level, increasing the relative cost of fossil-fueled vehicles across the entire fleet.

A notable brake mechanism, however, is embedded within ETS2 itself: where exceptionally high energy prices prevail – assessed by reference to Title Transfer Facility gas and Brent crude benchmarks – the commencement of ETS2 auctioning may be postponed from 2027 to 2028, and the initial surrender deadline deferred to 31 May 2029 for emissions of the year 2028 (Art 30k Directive 2003/87/EC). This postponement clause introduces regulatory uncertainty regarding the timing of the carbon price signal in road transport and may dampen near-term investment incentives for zero-emission vehicle adoption precisely in periods of elevated energy prices – when the relative cost advantage of BEVs and FCEV is otherwise greatest.

In conclusion, the revised ETS framework introduces a powerful carbon pricing signal for road transport through ETS2, structurally increasing the relative cost of fossil-fueled mobility from 2028 onwards. However, the embedded postponement clause for periods of elevated energy prices introduces regulatory uncertainty that may dampen near-term investment incentives for zero-emission vehicle adoption.

2.7 Effort Sharing: Effort-Sharing-Regulation – Regulation (EU) 2018/842

Regulation (EU) 2018/842 (ESR) governs the Member States' obligations with respect to their minimum contributions to achieving the Union's target of reducing its GHG emissions by 40% compared to 2005 levels in those sectors not covered by the EU ETS

– principally road transport, buildings, agriculture, and waste. It thereby complements the ETS architecture by establishing a binding quantitative framework for the sectors that account for a substantial share of total Union GHG emissions but fall outside the cap-and-trade system (Art 1 ESR).

Each Member State must ensure that its GHG emissions do not exceed the annual emission allocations determined by a linear reduction trajectory towards its 2030 target (Art 4 Para 1 and 2 ESR). Non-compliance triggers mandatory remedial action plans (Art 8 Para 1 ESR) and a penalty factor of 1.08 applied to excess emissions carried forward to the following year (Art 9 Para 1 lit a ESR).

Austria's 2030 target under ESR is a reduction of 48% compared to 2005 levels (Annex I Column 2 ESR), placing Austria among the Member States with the most stringent national obligations in the Union. Since road transport constitutes one of the largest emitting ESR sectors in Austria, this target generates direct and substantial regulatory pressure to accelerate the decarbonization of the domestic vehicle fleet – functioning as a powerful top-down regulatory accelerator for the adoption of zero-emission powertrains. ESR thus reinforces the technology-specific incentives created by the CAFE Regulation and the Regulation (EU) 2023/1804 (AFIR) at the national level, by making continued reliance on fossil-fueled road transport legally and financially costly for Austria as a Member State.

Considering the above, the ESR imposes on Austria one of the most stringent national reduction obligations in the Union – 48% by 2030 – generating direct top-down regulatory pressure to decarbonize road transport and reinforcing the technology-specific incentives created by the CAFE Regulation and AFIR at the national level.

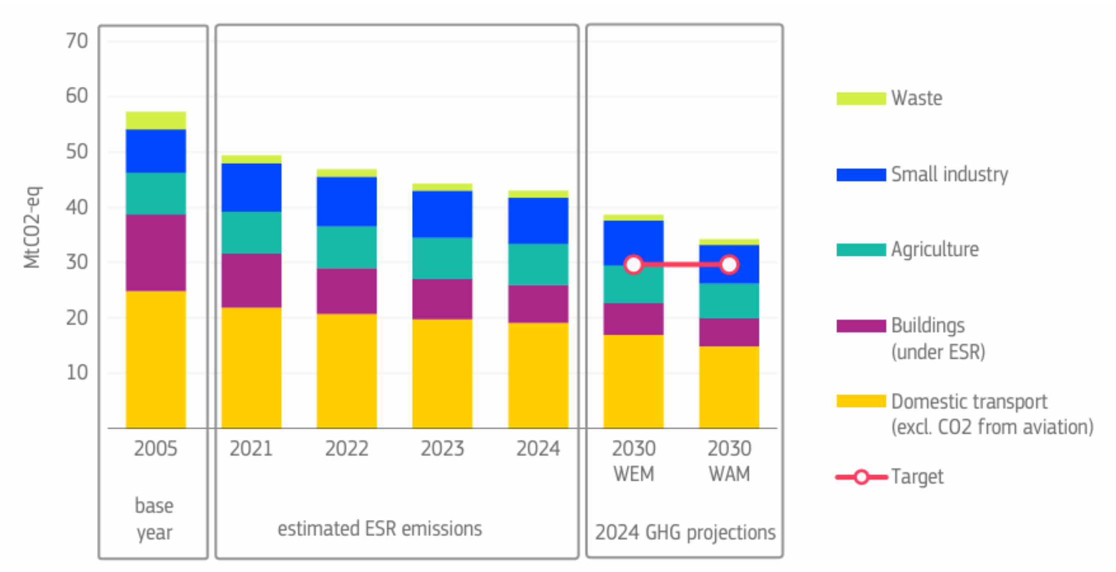


Figure 16: ESR emissions by sector (2005–2030) (European Commission, Climate Action Progress Report 2025 – Austria Country profile)

3 *National Regulatory Framework – the Austrian Case*

3.1 Climate Policy: Climate Protection Act (*Klimaschutzgesetz*)

Austria's primary national instrument for climate governance is the Federal Act on the Compliance with Maximum Quantities of GHG Emissions and on the Development of Effective Climate Protection Measures (*Bundesgesetz zur Einhaltung von*

Höchstmengen von Treibhausgasemissionen und zur Erarbeitung von wirksamen Maßnahmen zum Klimaschutz, KSG). The Act pursues the overarching objective of enabling a coordinated implementation of effective climate protection measures (Sec 1 KSG).

At its structural core, the KSG establishes a sectoral allocation mechanism for GHG emission ceilings. Pursuant to Sec 3 Para 1 KSG, maximum quantities of GHG emissions applicable to Austria under international or EU law are fixed in the Act's Annexes and disaggregated by sector – including transport as a distinct regulated sector. For the commitment periods 2008–2012 and 2013–2020, the transport sector was allocated declining emission ceilings (Annex 1 and Annex 2 KSG), but notably, the KSG does not contain sectoral emission ceilings extending beyond the 2013-2020 period.

This legislative gap does not render the Act defunct: the KSG remains formally in force, and its procedural and institutional framework continues to apply. The coordination and reporting obligations persist – including the obligation to conclude renewed negotiations on strengthening measures within six months where emission ceilings are exceeded (Sec 3 Para 2 KSG), the annual progress reporting to the National Council (Sec 6 KSG), and the advisory role of the National Climate Protection Committee (Sec 4 KSG). In the absence of domestically legislated sectoral targets for the post-2020 period, the KSG's normative pull on the transport sector derives not from binding quantitative ceilings but from this procedural framework, with the principal quantitative pressure shifting to Austria's binding annual emission allocations under ESR.

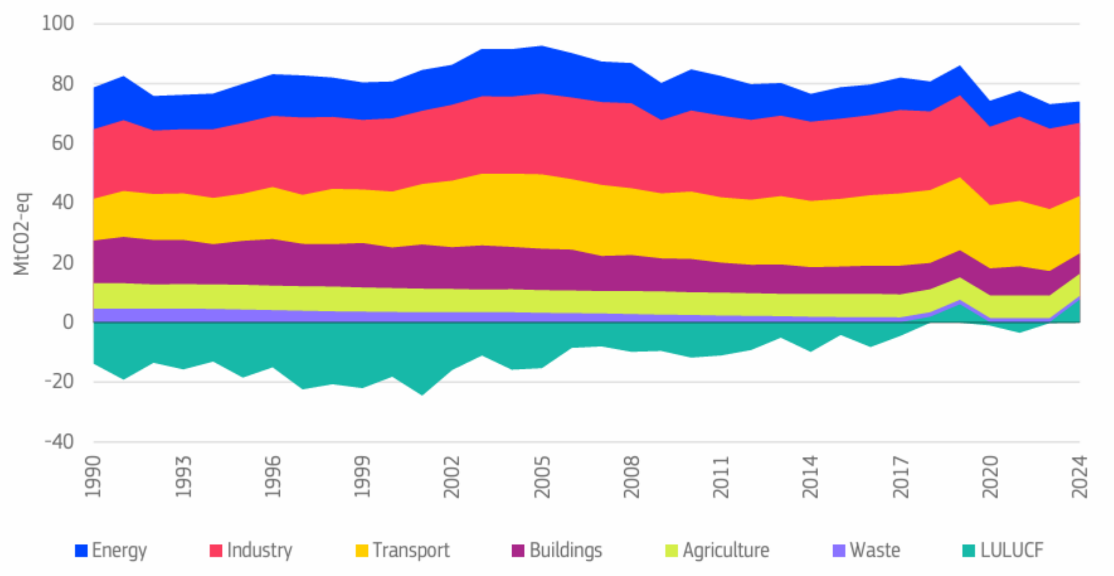


Figure 17: GHG emissions by sector (Source: European Commission, Climate Action Progress Report 2025 – Austria Country profile)

From the analytical perspective of this paper, the KSG thus functions as a regulatory pressure instrument for the transport sector: while its quantitative ceiling architecture has not been updated beyond 2020, its institutional and procedural architecture sustains ongoing normative pressure for emission reductions – generating a continuing structural demand for low- and zero-emission technologies, including BEVs and hydrogen-powered alternatives.

To summarize, the KSG's quantitative ceiling architecture has not been updated beyond 2020, but its procedural and institutional framework sustains ongoing normative pressure for transport emission reductions – with the principal quantitative steering function now exercised by Austria's binding ESR obligations.

3.2 Taxation and fiscal Incentives

3.2.1 Standard Consumption Tax Act (*Normverbrauchsabgabegesetz*)

The Austrian Standard Consumption Tax Act (*Normverbrauchsabgabegesetz, NoVAG*) imposes a one-time standard consumption tax on motor vehicles upon their first domestic supply, intra-Community acquisition, or first registration in Austria. The taxable events encompass the domestic supply of vehicles not previously registered in Austria by a taxable entrepreneur, their intra-Community acquisition, and their first registration for domestic use (Art 1 NoVAG). In functional terms, the NoVAG operates as a direct financial incentive at the point of vehicle acquisition, making it a primary cost-side determinant of consumer demand and, consequently, a significant accelerator or brake on technology adoption dynamics.

Of relevance to the decarbonization of road transport is the full exemption accorded to zero-emission vehicles. Pursuant to Art 3 Para 1 No 1 NoVAG, transactions relating to motor vehicles that exhibit a CO_2 emission value of 0 g/km on account of their drive system – expressly including electric and hydrogen propulsion – are entirely exempt from the standard consumption tax. This provision constitutes a direct financial adoption incentive: by eliminating the NoVAG burden at the moment of acquisition, it reduces the effective purchase price of zero-emission vehicles relative to conventionally powered alternatives, thereby improving their competitive positioning in the retail market.

Critically, the exemption is framed in a technology-neutral manner. The statutory criterion is exclusively the verified CO_2 emission value of 0 g/km, with electric and hydrogen drive systems mentioned only as non-exhaustive examples (*insbesondere*). This drafting technique ensures equal treatment of BEVs and FCEVs, precluding any regulatory bias in favor of one zero-emission technology over the other and leaving the competitive outcome to market and technological forces.

The NoVAG's role as a regulatory accelerator is, however, contingent on legislative stability. For vehicles subject to the tax, the rate is calculated progressively based on CO_2 emissions – with deduction thresholds, maximum rates, and malus surcharges that structurally penalize higher-emission vehicles (Art 6 Para 1 and 2 NoVAG). These thresholds are subject to periodic downward adjustment. The CO_2 deduction amount is reduced on a scheduled basis, and the malus surcharge is increased (Art 6 Para 7 NoVAG), reinforcing the incentive gradient in favor of zero-emission vehicles. Should the exemption under Art 3 Para 1 No 1 NoVAG be curtailed or repealed by future legislative action, the fiscal advantage currently enjoyed by BEVs and FCEVs would be eliminated, and the NoVAG would immediately transition from a regulatory accelerator to a regulatory brake on zero-emission vehicle adoption.

3.2.2 Petroleum Tax Act (*Mineralölsteuergesetz*)

The Austrian Petroleum Tax Act 2022 (*Mineralölsteuergesetz 2022, MinStG*) constitutes a central fiscal instrument of the national regulatory framework governing the competitive positioning of transport fuels. The Act imposes an excise duty – the Petroleum Tax (*Mineralölsteuer*) – on mineral oils, fuels, and heating materials manufactured within or brought into the Austrian tax territory, thereby functioning as a primary cost determinant for conventional fossil-fuel-based propulsion.

From the perspective of technology adoption dynamics, the Act operates primarily as a differentiated regulatory accelerator for biogenic alternatives, whilst maintaining a structural cost burden on fossil incumbents. The tax rates for both petrol and gas oil are reduced where the fuel contains a minimum share of biogenic substances and meets Sulphur content limits – for petrol, from EUR 515 to EUR 482 per 1,000 liters (minimum 46 liters biogenic content), and for gas oil, from EUR 425 to EUR 397 (minimum 66 liters biogenic content). Qualifying biogenic substances include bioethanol, fatty acid methyl esters, biogas, biomethanol, biodimethylether, Bio-ETBE, Bio-MTBE, synthetic biofuels, renewable hydrogen, and pure vegetable oil.

The Act explicitly recognizes renewable hydrogen as a qualifying biogenic blending component within the rate-reduction regime. Renewable hydrogen is statutorily defined as hydrogen produced exclusively from renewable energy sources (Sec 2 Para 4 No 9 MinStG), signaling a legislative intent to incentivize hydrogen integration, albeit in a blending context rather than as a standalone fuel. By contrast, BEVs consume no taxable fuel and thus fall entirely outside the scope of this Act; the fiscal incentive structure of the MinStG is accordingly irrelevant to the competitive positioning of BEV technology and constitutes neither an accelerator nor a brake in that context.

A further relevant mechanism is the full tax exemption for mineral oil consisting exclusively of biogenic substances – subject only to trace additives for improvement or denaturization purposes – which is entirely exempt from petroleum tax (Sec 4 Para 1 No 7 MinStG). Liquefied natural gas and liquefied biogas satisfying the sustainability criteria of the Fuel Ordinance (*Kraftstoffverordnung*) or other instruments transposing RED II are equally exempt from the excise duty (Sec 4 Para 1 No 10 MinStG).

In functional terms, the MinStG acts as a partial regulatory accelerator for biofuels, synthetic biofuels, and renewable hydrogen in blended applications, whilst remaining structurally neutral with respect to battery-electric mobility. The rate-differentiation mechanism rewards higher biogenic content but stops short of mandating decarbonization, leaving the pace of technology adoption substantially contingent on market price dynamics.

Taken together, Austria's fiscal framework operates through two complementary channels: the NoVAG exemption reduces the acquisition cost of zero-emission vehicles in a technology-neutral manner, while the MinStG rate differentiation incentivizes biogenic fuel blending without directly affecting BEV competitiveness. Both instruments function as regulatory accelerators, though their continued effectiveness depends on legislative stability and market price dynamics.

3.3 Alternative Fuels – Biofuels & RFNBOs: Fuel Ordinance (*Kraftstoffverordnung*)

The Ordinance of the Federal Minister for Agriculture, Forestry, Environment and Water Management on the quality of fuels and the sustainable use of biofuels (*Kraftstoffverordnung*) constitutes the central national transposition instrument governing biofuel blending quotas and the accounting of RFNBOs in the Austrian road transport sector. The Ordinance transposes, *inter alia*, RED II (Sec 24 No 7 Kraftstoffverordnung).

The substantive core of the instrument lies in its substitution obligations. The category of obligated party (*Substitutionsverpflichteter*) encompasses any person who, as the relevant excise-tax debtor under the Austrian Petroleum Tax Act 2022 (*Mineralölsteuergesetz*), first places petrol or diesel into free circulation for excise purposes within Austrian territory, or who imports or uses such fuels therein (Sec 2 No 25 Kraftstoffverordnung). Parties placing petrol (*Ottokraftstoff*) into free circulation are required to ensure that, calculated on an energy-content basis, biofuels account for at least 3.4% of the total volume of fossil or non-sustainably produced petrol they bring to market annually (Sec 5 Para 1 Kraftstoffverordnung). An equivalent obligation applies to diesel (*Dieselkraftstoff*): the mandated minimum share of biofuels is 6.3% per year, likewise measured by energy content relative to the total volume of fossil or non-sustainably produced diesel placed into free circulation (Art 5 Para 2 Kraftstoffverordnung).

Of functional significance for the technology-neutrality of the framework is the treatment of RFNBOs. RFNBOs are defined as liquid or gaseous fuels used in the transport sector – excluding biofuels or biomethane – whose energy content derives from renewable sources other than biomass (Sec 2 No 17 Kraftstoffverordnung). Such fuels may be counted toward compliance with the substitution obligations under Sec 5 and the GHG intensity reduction obligation under Sec 7 Kraftstoffverordnung, both when deployed directly as fuels and when used as intermediates in the production of conventional fuels (Sec 8 Para 8 Kraftstoffverordnung). For this purpose, a minimum lifecycle GHG emission reduction of 70% relative to the fossil comparator is required; upon positive verification by the *Umweltbundesamt GmbH*, RFNBOs may be credited at four times their energy content toward the Sec 7 target (Art 8 Para 8 No 1 and No 3 Kraftstoffverordnung).

Assessed through the analytical lens of this paper, the Ordinance functions as a regulatory accelerator for biofuels broadly construed and – through the RFNBO crediting mechanism – creates a structurally favorable accounting environment for green hydrogen and its derivatives, potentially incentivizing their deployment in road transport where direct electrification faces technological or commercial constraints.

In brief, the Kraftstoffverordnung establishes binding biofuel substitution quotas and creates a structurally favorable accounting environment for RFNBOs – including green hydrogen – through a 4x crediting mechanism, thereby incentivizing their deployment in road transport segments where direct electrification faces technological or commercial constraints.

3.4 Carbon Pricing: National Emissions Certificate Trading Act 2022 (*Nationales Emmissionszertifikatehandelsgesetz 2022*)

The Austrian National Emissions Certificate Trading Act 2022 (*Nationales Emmissionszertifikatehandelsgesetz 2022, NEHG*) establishes a national certificate trading system for GHG emissions not covered by the EU ETS1, with the explicit statutory objective of contributing to the achievement of the long-term targets of the Paris Agreement and the applicable Union-law reduction targets for non-ETS sectors. The system is designed as a phased instrument and is to be transferred into the European ETS2 framework as of 2027 (Sec 1 NEHG). In the transport context, the Act operates as a carbon pricing mechanism targeting the supply side of fossil fuels: it applies to fossil mineral oils, motor and heating fuels, natural gas, and coal placed on the market within Austrian territory, with the relevant point of taxation anchored in the mineral oil tax liability (Sec 2 Para 1 and 2 in conjunction with Sec 3 Para 1 No 1 NEHG).

From the perspective of technology adoption dynamics, the NEHG functions as a regulatory accelerator for zero-emission drivetrains. By prescribing a fixed, annually escalating certificate price – rising from EUR 30 per ton of CO_2 in 2022 to EUR 55 per ton in 2025 – (Sec 10 Para 1 NEHG) the Act structurally increases the operating costs of fossil-fuel-powered vehicles. This cost escalation improves the relative price competitiveness of BEVs and FCEVs, which are not subject to certificate obligations.

However, the law's steering effect is subject to a significant structural limitation. Sec 10 Para 2 NEHG establishes a price stability mechanism (*Preisstabilitätsmechanismus*): Where the annualized change in the fossil energy price index for private households exceeds 12.5%, the planned increment in the certificate price for the following calendar year is reduced by 50%. The Austrian Energy Agency (*Österreichische Energieagentur*) is tasked with providing the relevant annualized data to the Federal Minister of Finance by 30 November of each year, who must then determine the applicability of the mechanism and publish the result in the Federal Law Gazette by 15 December (Sec 10 Para 3 NEHG).

Operationally, this mechanism introduces a counter-cyclical dampener: In periods of elevated energy prices – precisely the market conditions under which the relative cost advantage of zero-emission alternatives is greatest – the incremental carbon price signal is softened. The result is a paradox of diminished regulatory steering capacity at the moment of potentially highest behavioral responsiveness, thereby attenuating the instrument's transformative effect on technology adoption in the road transport sector.

Ultimately, the NEHG functions as a regulatory accelerator for zero-emission drivetrains by imposing an escalating carbon price on fossil transport fuels, but its steering effect is structurally limited by a price stability mechanism that softens the carbon price signal precisely in periods of elevated energy prices – when the relative cost advantage of BEVs and FCEVs would otherwise be greatest.

4 Accelerators, Barriers, and Regulatory Gaps: Assessment

The preceding analysis reveals that the regulatory framework governing the decarbonization of transport operates through a dense, multi-level architecture of binding targets, fiscal instruments, infrastructure mandates, and carbon pricing mechanisms – confirming that the legal order is not peripheral but constitutive of technology adoption outcomes. While the framework is formally technology-neutral, its cumulative effect produces a pronounced *de facto* regulatory preference for direct electrification via BEVs, with alternative pathways – hydrogen FCEVs, biofuels, and e-fuels – occupying structurally subordinate positions. Three principal findings emerge.

First, the regulatory framework generates a powerful ensemble of accelerators structurally favoring BEV adoption. The progressively tightening CO_2 fleet-wide targets under the CAFE Regulation – culminating in a 100% reduction from 2035 under currently applicable law – the binding AFIR infrastructure mandates with 60 km-interval charging pools along the TEN-T core network (Art 3 Para 4 Regulation (EU) 2023/1804), the 4x multiplier for renewable electricity under the Renewable Energy Directive (Art 27 Para 2 lit d RED II), the ETS2 carbon pricing signal (Art 30e Directive 2003/87/EC), and the full NoVAG exemption at national level (Sec 3 Para 1 No 1 NoVAG) collectively constitute a regulatory ecosystem that decisively privileges direct electrification in road transport. The cumulative force of these instruments is such that, from a regulatory perspective, no alternative technology pathway offers a comparable degree of institutional support for mainstream road transport applications. Hydrogen FCEVs benefit from formal legal equivalence as zero-emission vehicles but face structurally weaker infrastructure support – with refueling stations mandated only at 200 km intervals by 2030 (Art 6 Para 1 AFIR) – and a lower accounting multiplier under RED II, positioning hydrogen as a conditional rather than primary compliance pathway in road transport. Biofuels – including HVO from waste feedstocks – benefit from the 2x multiplier under RED II (Art 27 Para 2 lit c) and from the Kraftstoffverordnung's substitution quotas, but their regulatory function is confined to incremental decarbonization of the existing fleet and to segments where direct electrification is not yet feasible; they do not constitute a regulatory pathway toward full fleet decarbonization. E-fuels, whilst formally eligible for crediting under the proposed CAFE amendment (proposed Art 5a), remain subject to the 70% GHG savings threshold under RED II (Art 29a Para 1), face production costs several multiples above fossil equivalents, and lack a dedicated infrastructure mandate – rendering them a niche regulatory option rather than a systemic alternative to electrification. For heavy-duty vehicles, the trajectory is more gradual but directionally equivalent, with a 90% CO_2 reduction target from 2040 under Regulation (EU) 2019/1242, and a parallel policy strand on sustainable renewable fuels that acknowledges the greater technological heterogeneity of the sector without displacing the primacy of zero-emission powertrains.

Second, the analysis identifies regulatory slowdown factors that attenuate the pace of adoption. The Commission's December 2025 proposal to reduce the 2035 target from 100% to 90% and introduce credit mechanisms (COM(2025) 995 final) generates significant regulatory uncertainty regarding the combustion engine phase-out. The ETS2 postponement clause (Art 30k Directive 2003/87/EC) and the analogous Austrian NEHG price stability mechanism (Sec 10 Para 2 NEHG) introduce counter-cyclical dampeners that soften the carbon price signal precisely when the relative cost advantage of zero-emission alternatives is greatest. At the national level, the absence of updated KSG sectoral emission ceilings beyond 2020 leaves Austria's domestic steering capacity procedurally intact but substantively weakened.

Third, the formally technology-neutral architecture – as mandated by the European Climate Law (Recital 34 Regulation (EU) 2021/1119) – coexists with pronounced structural asymmetries in the enabling regulatory infrastructure. BEVs benefit from denser infrastructure mandates, stronger accounting multipliers, and more immediate fiscal incentives, while hydrogen and RFNBOs occupy a complementary but subordinate regulatory position, supported primarily in hard-to-electrify segments such as heavy-duty freight, aviation, and maritime transport. Biofuels serve a transitional function for the existing fleet but are constrained by feedstock availability and sustainability criteria that preclude indefinite scaling. E-fuels remain at an early stage of regulatory integration, with no binding deployment mandate and production economics that currently preclude competitiveness with either fossil fuels or direct electrification. The net effect of this architecture is that, notwithstanding formal technology openness, the regulatory framework as currently constituted offers no pathway of comparable institutional depth and coherence to that supporting BEV adoption in mainstream road transport – rendering direct electrification the de facto regulatory default for the decarbonization of passenger cars and light commercial vehicles.

VI. Conclusion

This report has examined the current state and future trajectory of CO_2-free mobility and transportation, analyzing demand trends, technology maturity, cost structures, infrastructure readiness, the regulatory architecture at EU and Austrian level, the strategic responses of major OEMs, socio-economic adoption dynamics, and the influence of the broader political and competitive landscape. The findings across all dimensions converge on a central conclusion: while BEVs represent the most energy-efficient decarbonization pathway for new passenger cars and light commercial vehicles, no single technology can deliver the pace and breadth of emission reductions required across the entire transport system. Hydrogen FCEVs and sustainable renewable fuels are the principal decarbonization vectors for heavy-duty, aviation, and maritime transport. Critically, with the average EU passenger car fleet age exceeding 11 years, relying solely on BEV sales for new registrations leaves hundreds of millions of combustion vehicles emitting carbon for decades – making clean-burning ICE pathways utilizing biofuels and e-fuels the only mechanism capable of achieving immediate carbon reductions across this legacy fleet without requiring total vehicle replacement. A technology-open regulatory framework that enables all viable pathways to contribute is therefore not a concession to incumbents, but a precondition for achieving system-wide decarbonization at the required pace. The window for decisive action is narrowing – and the policy, investment, and industrial choices made in the next five years will determine whether Europe achieves a technologically resilient and economically sustainable transition to zero-emission mobility.

From a techno-economic perspective, the verdict is clear: direct electrification via BEVs offers the most energy-efficient and, at scale, most cost-competitive decarbonization pathway per kilometer travelled – benefiting from lower electricity prices, higher drivetrain efficiency, and increasingly industrialized battery production. FCEVs remain more expensive in both manufacturing and operation, but retain decisive advantages in long-distance and high-utilization heavy-duty applications where rapid refueling and reduced downtime are operationally critical. Biofuels – particularly HVO from waste feedstocks – represent the most commercially advanced near-term liquid fuel alternative but face structural cost pressure from constrained feedstock supply and are not expected to become cheaper than fossil fuels within the foreseeable future. E-fuel production costs of approximately EUR 3,000–4,400 per ton – a 3.5 to 6 times premium over fossil diesel – constitute a gap that policy support, carbon pricing, or technology learning must close before e-fuels can play a meaningful role in mainstream road transport.

The regulatory framework, whilst formally technology-neutral, produces a pronounced *de facto* preference for direct electrification through the cumulative effect of the CAFE Regulation's fleet-wide CO_2 targets, AFIR's binding charging infrastructure mandates, RED II's 4x multiplier for renewable electricity, the ETS2 carbon pricing signal from 2028, and the full NoVAG exemption at the Austrian national level. Hydrogen FCEVs benefit from formal legal equivalence as zero-emission vehicles but face structurally weaker infrastructure support and a lower 2x accounting multiplier. Biofuels serve a transitional function constrained by feedstock availability, while e-fuels lack a dedicated infrastructure mandate and face production economics that currently preclude competitiveness. At the Austrian level, the absence of updated KSG sectoral emission ceilings beyond 2020 and the NEHG price stability mechanism – which softens the carbon price signal in periods of elevated energy prices – represent structural limitations that slow the pace of the transition.

However, a fundamental insight emerges from this analysis: regulation should not be – and cannot be – the primary driver of technological innovation. Rather, the function of the regulatory framework is to provide a stable, predictable environment in which any technology capable of delivering verifiable emission reductions can develop and compete on its merits. The rapid pace of market and technological change – exemplified by the Commission's December 2025 proposal to reduce the 2035 target from 100% to 90% and introduce credit mechanisms for sustainable renewable fuels (COM(2025) 995 final) – demonstrates that regulatory frameworks premised on the dominance of a single technology pathway are inherently vulnerable to revision. What is required is not regulatory prescription of technological outcomes, but the creation of legal and economic conditions that allow the emergence and scaling of new technologies across the full spectrum of decarbonization solutions.

The political and market landscape introduces both opportunities and significant risks. At the EU level, the recent softening of the 2035 combustion engine phase-out generates regulatory uncertainty that may undermine the EUR 250 billion already committed by European automobile manufacturers to the electric transition. At the national level, Austria's discontinuation of BEV purchase subsidies and the removal of the motor-related insurance tax exemption for BEVs in 2025 illustrate how short-term fiscal consolidation can erode the incentive structures necessary for sustained technology adoption. Externally, China's structural competitive advantage – with manufacturers producing vehicles at approximately 25% lower cost – cannot be offset by tariff measures alone. The volatility of US trade and climate policy further underscores that sustained progress depends on the continuity and stability of regulatory frameworks across political cycles. Beyond the regulatory dimension, practical barriers further constrain the pace of the transition. Socio-economic factors – including the higher upfront acquisition cost of BEVs relative to comparable ICE vehicles, range anxiety, and the uneven distribution of charging infrastructure across income groups and geographic regions – create adoption barriers that disproportionately affect lower-income households and peripheral regions. Insufficient charging infrastructure density, particularly for heavy-duty vehicles and in rural areas, remains a critical bottleneck, as detailed in the infrastructure recommendations below.

Against this backdrop, this report identifies the following actionable recommendations for policymakers, industry, and investors:

- For policymakers: Regulatory stability and technology openness must be the overriding priorities. Frequent revisions of emission targets and subsidy frameworks – as witnessed with the 2035 phase-out reversal and Austria's abrupt subsidy termination – create uncertainty that deters investment across the value chain. Emission reduction trajectories, once legislated, should be maintained with maximum predictability. Critically, the regulatory framework should establish stable, outcome-oriented conditions under which any technology capable of delivering verifiable emission reductions can develop and compete – rather than prescribing specific technological pathways whose viability may be overtaken by market developments or subsequent regulatory revisions.

- Equally critical is the accelerated deployment of charging and refueling infrastructure. The current shortfall in publicly accessible charging points – particularly high-power charging for heavy-duty vehicles along the TEN-T network and in rural and underserved areas – constitutes one of the most significant practical barriers to fleet electrification. Without a charging network that matches the density, reliability, and geographic coverage of existing fuel distribution systems, fleet electrification targets cannot be met and consumer adoption will remain constrained by range anxiety and access limitations. Policymakers should prioritize streamlined permitting, grid connection procedures, and targeted public investment to close infrastructure gaps, particularly in segments and regions where private investment alone is insufficient. In parallel, the phase-out of environmentally harmful subsidies – such as Austria's estimated EUR 6 billion in fossil fuel-related tax reductions – would generate both fiscal space and stronger price signals in favor of zero-emission alternatives.

- For industry: A technology-differentiated strategy is essential – and must extend beyond exclusive reliance on full electrification. BEVs remain the primary investment pathway for new passenger cars and light commercial vehicles, whilst hydrogen FCEVs and sustainable renewable fuels require dedicated and strengthened commercial frameworks for heavy-duty, long-haul, and hard-to-electrify transport segments. However, continued investment in efficient internal combustion engine architectures – including plug-in hybrids and vehicles compatible with biofuels and e-fuels – constitutes a necessary investment hedge against ongoing regulatory rollbacks and the inherent uncertainty of the transition timeline. With the average EU passenger car fleet age exceeding 11 years, clean-burning ICE pathways represent the only mechanism capable of delivering immediate emission reductions across the hundreds of millions of combustion vehicles already on the road. The market-driven strategic recalibrations undertaken by major OEMs – shifting from exclusive BEV commitments toward customer-oriented technological diversity encompassing hybrids and efficient combustion engines – confirm that a technology-diverse approach offers the most resilient industrial strategy for the transition period. European manufacturers must simultaneously address the structural cost disadvantage in battery production – currently EUR 9–11/kWh compared to Chinese imports – through vertical integration, streamlined permitting, and strategic investment in domestic supply chains.

- For investors: The regulatory and market signals point toward electrification as the dominant pathway for new mainstream road vehicles, but the investment landscape is more nuanced than a singular technology bet would suggest. Investment in BEV charging infrastructure, battery manufacturing capacity, and grid integration offers a robust risk-return profile under the current regulatory architecture. However, the ongoing regulatory recalibrations – including the Commission's proposed reduction of the 2035 target from 100% to 90% and the introduction of credit mechanisms for sustainable renewable fuels – together with OEM strategy shifts toward technological diversity, indicate that efficient ICE, hybrid, and sustainable fuel technologies retain material investment relevance as hedges against regulatory volatility and as the only near-term pathway for decarbonizing the existing fleet. Hydrogen and e-fuel investments carry higher regulatory and cost risk but offer significant upside in heavy-duty and aviation segments where dedicated policy support is emerging. The principal investment risk across all pathways remains regulatory volatility – making jurisdictions with stable, long-term, and technology-open policy frameworks the most attractive deployment environments.

In summary, Europe's competitive position in the global race to zero-emission mobility will be determined not by the ambition of its targets but by the consistency of their implementation and the openness of its regulatory framework to technological diversity. Direct electrification via BEVs remains the most efficient and cost-competitive pathway for new passenger cars and light commercial vehicles – but system-wide decarbonization, encompassing the legacy fleet, heavy-duty transport, and hard-to-electrify segments, requires a broader portfolio of solutions. The regulatory, industrial, and fiscal foundations are largely in place – what is now required is the political resolve to maintain a stable, technology-open framework that enables all viable decarbonization pathways to contribute to the transition at the pace and scale that the climate imperative demands.

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ÜBER DEN WORLD ENERGY COUNCIL AUSTRIA

Der World Energy Council Austria ist das **österreichische Nationalkomitee des World Energy Council** und **Gründungsmitglied** der internationalen Mutterorganisation. Der World Energy Council und damit der World Energy Council Austria feierten im Jahr **2023** ihren **100. Geburtstag**. Der Sitz der Mutteroganisation befindet sich in London, der Sitz der österreichischen Organisation seit Beginn der Aktivitäten an in Wien. Die Tätigkeiten orientieren sich bzw. gliedern sich in die Aktivitäten der Mutterorganisation ein. Dabei gilt jedoch immer ein von den Mitgliedsorganisationen gesetzter individueller und bedarfsorientierter Fokus. Mit einem engagierten Team und einem starken Netzwerk konnte der WEC Austria seine Aktivitäten gerade in den letzten Jahren weiter ausbauen und Sichtbarkeit gewinnen. Eine Besonderheit des WEC Austria ist die durch den Sitz in **Wien** bedingte enge Beziehung zu einer **Vielzahl internationaler Organisationen**, zu denen über den Vienna Energy Club formelle Beziehungen etabliert werden konnten.

In Österreich sind maßgebende Unternehmen, Organisationen und Verbände Mitglied. Die nationale Organisation unterstützt **globale, nationale und regionale Energieinitiativen** durch hochkarätige **Veranstaltungen**, wissenschaftliche Studien und Ausarbeitungen über die aktuelle Energiesituation im Konnex mit den europäischen und globalen Herausforderungen. Dialoge unter den Mitglieds-organisationen und die Förderung von **Young Energy Professionals** (YEP) sind ein wesentlicher Bestandteil.

Der **Nutzen für Mitglieder** liegt vor allem in dem breiten Portfolio von Aktivitäten des World Energy Council Austria:

1. Sicherung des Zuganges zu den Studien, Ausarbeitungen und Veranstaltungen des World Energy Council, der **einzigen weltweiten Nicht-Regierungs-organisation im Bereich Energie**.
2. Bereitstellung des **globalen Netzwerkes** für nationale und internationale energiewirtschaftliche Fragestellungen.
3. Möglichkeit der unmittelbaren **aktiven Teilnahme** an den energie-wirtschaftlichen **Arbeiten des World Energy Council** und damit an der aktiven Mitgestaltung von langfristigen strategischen Zielen der **Energie-transformation**.
4. Behandlung aktueller Fragen der Energiewirtschaft in den eigenen **Gremien**, in öffentlichen **Veranstaltungen** sowie durch **Veröffentlichungen** und damit Verbreitung von Fachwissen sowie Meinungsbildung in energiewirtschaftlichen und energiepolitischen Fragen.
5. **Plattform** für auf Konsens aufgebaute Informations- und Lobbying Arbeit.

Impressum

Eigentümer (Medieninhaber) und Verleger:

World Energy Council Austria (WEC Austria)
A-1040 Wien, Brahmsplatz 3

Tel.: +43-(0)1-5046986
Fax.: +43-(0)1-5047186
Mail: office@wec-austria.at
Webseite: www.wec-austria.at

Druck: Eigenvervielfältigung

WORLD ENERGY COUNCIL | AUSTRIA