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Perspective

Electricity vs hydrogen in the transition towards sustainable mobility

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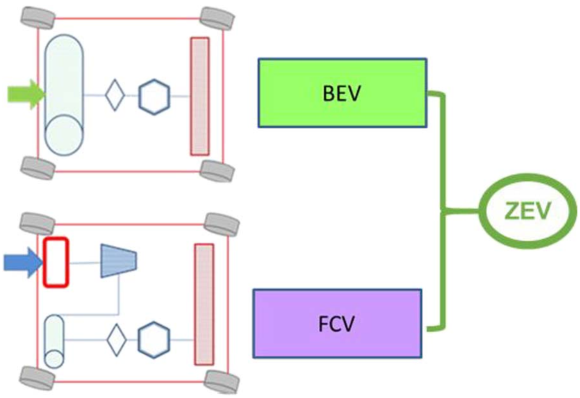
Abstract

Currently, the transport and automotive industry sectors are at a crossroads moving away from fossil fuels to various alternatives increasing the global competition on vehicle markets and for resources. Over the last years, electrification of mobility has emerged as one of the major strategies that, accompanied with supporting measures, has led to rapid increase in the number of electric vehicles. Recently, hydrogen and hydrogen derivates as alternative fuels have also gained more interest and are considered to grow substantially in the near future as their production costs are decreasing. Here, we discuss the electric and hydrogen pathways towards zero-emission vehicles and sustainable mobility focusing on their benefits and challenges in the transition. We conclude that the future relevance of zero-emission vehicles will be heavily dependent on the policy framework, investments, and long-term visions.

Graphical Abstract



Lay summary: The transport sector is presently slowly moving away from fossil fuels towards greener fuels and low-carbon technologies. Currently, electrification of mobility is seen as one of the major strategies for the decarbonization of the transport sector. In addition, hydrogen as an alternative fuel is becoming of interest especially for the decarbonization of the transport modes, which are difficult for electrification. This paper provides discussion on the electric and hydrogen pathways towards zero-emission vehicles and sustainable mobility. We conclude that the future relevance of zero-emission vehicles will be heavily dependent on the policy framework, investments, and long-term visions.

Key words: electric vehicles; hydrogen; fuel cells; batteries; policies

Introduction

The transport sector has the highest dependency on fossil fuels within the sectors of the energy system, accounting for 37% of the global CO_2 emissions from the end-use sectors in 2021 [1]. This reflects the major importance of the transport sector to economic and social development. Although transport does not have a dedicated specific sustainable development goal (SDG), it is an essential enabler of several SDGs, especially SDG13—Climate Change. This goal is extremely challenging for the transport sector. It requires deep transformation of the whole transport system including a broad range of policy measures, as well as improved technologies and innovative approaches, to speed up the decarbonization of mobility.

The transport sector and the automotive industry are presently at a crossroads moving away from a fossil fuel base to various

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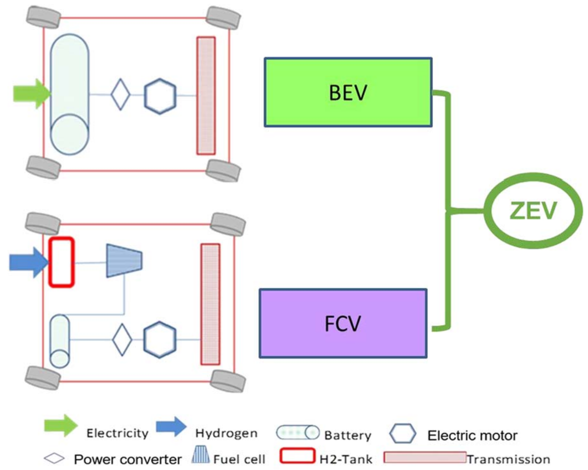

Figure 1. Zero-emission vehicles.

alternatives such as greener fuels and technologies and utilization of digitalization. In addition, the global competition for car markets and resources is increasing [2].

Although electric vehicle (EV) market growth has been supported through a variety of direct and indirect measures in the past, the recent global COVID crisis and the energy crisis in Europe boosted some governments, especially in Europe, to accelerate the electrification of mobility [3]. Accordingly, the global private and public spending on electric cars has significantly increased in the last 3 years [4]. However, the pandemic crisis was also a stress test for the car industry highlighting major challenges and needs regarding the future sustainable development of the transport sector such as complicated supply chains and raw material dependency.

The various market transformation mechanisms such as incentives, subsidies, and CO_2 standards have had positive effects on zero-emission vehicle (ZEV) targets, also accelerating the desired transformation within the transport sector. ZEV mandates and conventional vehicle bans have already been announced by some countries, e.g. from 2025 onwards, only zero-emission passenger cars will be sold in Norway, and Denmark and Ecuador will only sell zero-emission public buses. Many other countries will follow this example from 2030 [5].

The European Commission has set ambitious targets for reducing the CO_2 emissions of new vehicles. Emissions from cars should be reduced by 55% by 2030 compared to 2021, and new cars should have zero emissions by 2035. In addition, the Commission promotes the use of ZEVs through investment in necessary charging infrastructure, putting a price on pollution, stimulating cleaner fuel use, and investing in clean technologies [6]. However, there is currently only a low number of low-carbon technologies and fuels available for mobility such as EVs, biofuels, renewable electricity, and green hydrogen.

ZEVs do not produce internal combustion engine exhaust fumes or other carbon emissions. However, currently, there are just two types of ZEVs available: battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), see Fig. 1. In contrast to BEVs, which rely only on a larger battery for energy storage, FCVs use a much smaller battery in addition to a fuel cell stack.

Battery electric vehicles

Electrification of mobility is presently one of the key strategies to cope with increasing greenhouses (GHG) emissions from the transport sector and to reduce use of fossil fuels. EVs are highly energy-efficient and reduce local air and noise pollution in addition to reducing GHG emissions (though this depends on the whole supply chain). However, the full environmental benefits of EVs can be achieved only in combination with electricity generated from emission-free sources such as renewable energy sources (RES).

Like every technology, EVs also have some disadvantages compared with conventional vehicles that have to be overcome in the future. The major obstacles to a faster penetration of EVs include: (i) high capital costs, (ii) lack of charging infrastructure, (iii) long charging times, and (iv) a changeable policy framework [7–9]. In addition, recent challenges originating from the rapid demand of EVs relate to the material supply chain (e.g. availability of battery materials Li, Ni, Co) and battery production capacity as well as battery recycling.

In 2022, over 26 million electric cars were in use worldwide, of which more than half were in China, followed by Europe and the USA [10]. China is the largest user and producer of electric cars, and the largest trade partner of Europe for electric cars and EV batteries.

Currently, ∼70% of the total EV stock are BEVs and 30% are plug-in electric vehicles (PHEVs), see Fig. 2. Since PHEVs are using both fossil fuels and electricity, they are mostly considered as a bridging technology and policy support, but anticipated to diminish over time as EVs develop further.

However, despite increasing number of EVs, their total number is still low compared to the total vehicle stock. For example, just ∼1.5% of all cars on EU roads were electrically chargeable in 2021 [12].

EV sales in Europe showed extraordinary growth in 2020 and 2021 due to very generous supporting measures, such as purchase incentives provided in the EU, as well as due to the increasing pressure on the car manufactures to achieve the car emissions standards set for 2021. These measures helped to mitigate the effects of the COVID crisis on the EV market in Europe contrary to conventional internal combustion vehicles (ICE). As a matter of fact, the sales of EVs in Europe increased by ∼130% in 2020 [3]. The COVID crisis also revealed some weaknesses in the European auto industry, as well as the complexity and sensitivity of the different supply chains. An additional challenge for EVs in 2022 was the increasing energy price, including both electricity and fossil fuels, leading to higher operating costs and higher manufacturing costs of vehicles.

Currently, Europe is the world's second largest market for EVs with a 30% share of the global EV stock [10], but the differences within the EU in EV sales and charging infrastructure are huge. Although EVs accounted for 21.6% of new cars registered in the EU in 2022, their market share was <9% in more than half of the Member States, notably in Central, Eastern and Southern European countries, such as Greece, Italy, Poland and Croatia, characterized by lower annual net income (ca €13 000 per employer [13]). A market share >30% was found in just five EU countries: Germany (31.4%), Netherlands (34.5%), Denmark (38.6%), Sweden (56.1%), and Finland (37.6%), with net annual income exceeding €32 000 [13]. The relation between income and EV sales is very clear. The affordability correlation also affects the investments in charging infrastructure. Currently, ∼50% of all charging points in the EU are located in just two countries—the Netherlands and Germany [14]. Most of the EV charging points in Europe are slow chargers. European countries with the most fast chargers are Germany, France, and Norway.

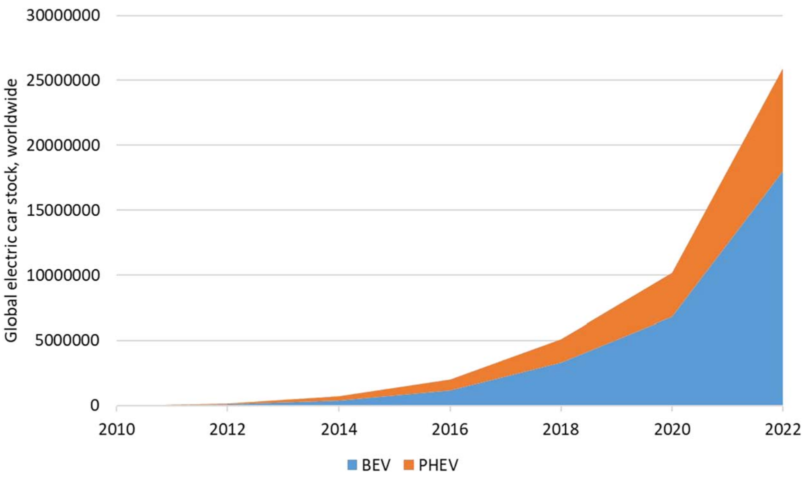

Figure 2. Global electric car stock, 2010–22 [11].

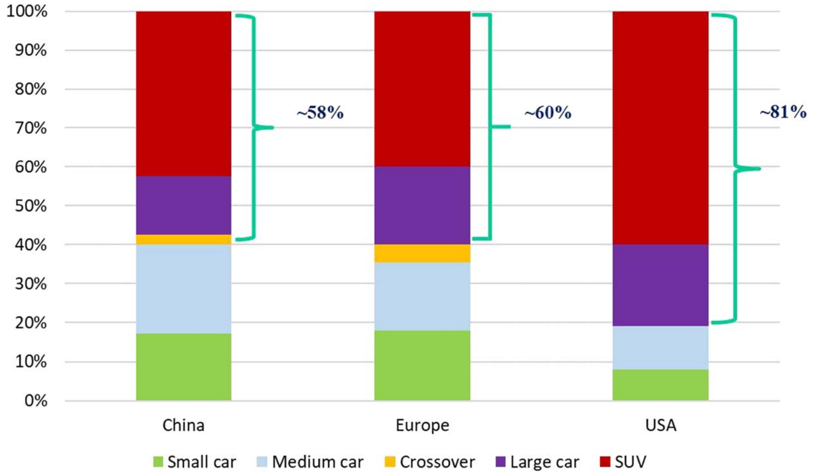

Figure 3. Battery electric car model availability by segment in 2022 [10].

Another challenging issue is the high share of large EVs such as SUVs, which require large batteries and have higher specific electricity consumption. Figure 3 shows that over half of the 500 BEV models available on the market in 2022 were large cars. The largest number of BEV models is found in China, or nearly 300 models, ~150 models are available in Europe, and <100 in the USA [10]. The focus on large BEVs also raises concerns on the affordability and sustainability of EVs as most of the available models are mainly in the reach of consumers with high income. The large battery size required (ca 70–90 kWh) will cause concerns with higher demand of critical raw materials needed in the batteries, such as lithium, cobalt, nickel, among others.

Currently, due to their high energy and power density, lithium-ion batteries are the dominant battery technology used in EVs [15, 16]. There are different battery chemistries in which lithium is used in combination with other materials such as nickel, cobalt, aluminum, and manganese [17, 18]. Lithium nickel cobalt aluminum oxide (NCA), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP) batteries are the most used lithium-ion batteries in EVs [19, 20]. With the increasing electrification of mobility, demand for all these materials is rapidly rising.

Global proven lithium reserves in 2022 were ~23 million metric tons, of which 41% are found in Chile, 27% in Australia, 12% in Argentina, 9% in China, 9% in North America, and 2% in other countries and regions [21]. Lithium mining requires considerable amounts of energy if lithium has to be extracted from rock, or huge amounts of water (ca 2 million l of water per 1 ton of lithium [22]) if lithium is extracted from brine [23]. Consequently, intensive lithium mining in South America has resulted in groundwater depletion, soil contamination, and other forms of environmental degradation [22, 24].

The largest reserves of the critical mineral cobalt are found in the Democratic Republic of the Congo and Australia, whereas the main nickel reserves are located in Indonesia, Argentina, and Brazil [20]. The mining operations in Congo are very concerning as ca 40 000 children work in cobalt mines under extremely dangerous and unhealthy conditions [25].

The geographical concentration of most of the critical materials needed in mainstream Li-batteries poses a risk for supply security [26], which together with the increasing mining volumes accompanied with social and environmental concerns could potentially also affect the electrification goals of transport [7]. The sufficiency of the material base will be a concern with increasing electric mobility as the EV batteries already now represent ~60% of all lithium, 30% of all cobalt, and 10% of all nickel demand worldwide [10].

Therefore, the R&D efforts on batteries to diversify the technology base (e.g. new battery chemistries) will be of outmost importance to the future of BEVs [18, 24]. Recycling of batteries needs

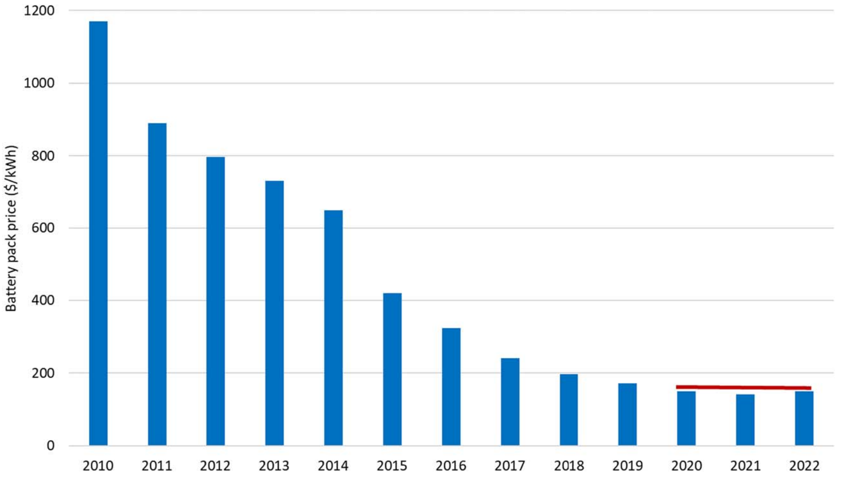

Figure 4. Development of the battery pack prices [30, 31].

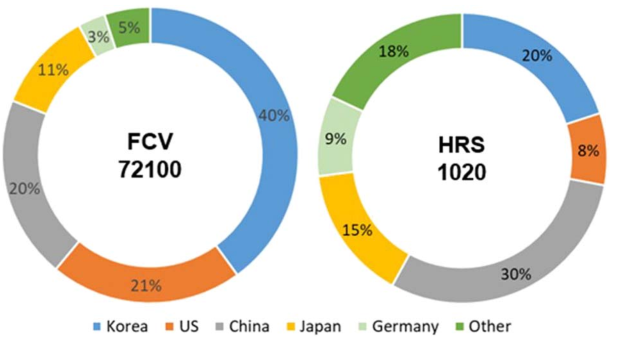

Figure 5. Global share of FCVs and hydrogen refueling stations (HRS) in 2022 (data source [10]).

to be intensified to extend the resource base and to minimize adverse environmental impacts, though still hampered by the high up-front costs compared to mined resources [24, 27–29].

The increased demand of battery materials has also increased their price, which has seized the price decrease of Li-ion batteries (Fig. 4) in spite of decreasing battery pack manufacturing cost.

Hydrogen fuel cell vehicles

Zero-emission mobility can also be reached through hydrogen and FCVs. Hydrogen is like electricity, a secondary energy carrier, which can be produced from a broad range of primary energy sources, which also affects the specific emissions of the produced H_2 [32]. Though the idea of using H_2 in the transport sector is old, the high costs of H_2 and fuel cells, huge investments needed for the necessary infrastructure, and also some technical barriers, such as reliability and durability of fuel cells, have hampered the penetration of this technology [7, 33–35].

Currently, the market share of FCVs is negligible. In 2022, the global stock of FCVs was ca 72 000 (Fig. 5). About 80% of all FCVs were passenger cars, 10% were trucks, and almost 10% buses [10]. The fuel cell truck segment grew fastest in 2022.

The FCV market is currently concentrated in just a few countries: South Korea, USA, China, Japan, and Germany. Half of the whole FCV stock is in Korea, explained by the strong public support both to production and sales of FCVs. Actually, the Korean car manufacturer Hyundai Ltd. is the global leader in FCV production.

The USA and China also have a notable share of the FCVs. Contrary to the USA, where most of the FCVs are cars, in China, heavy-duty FCVs are dominating [10]. In 2022, there we just 1020 hydrogen refueling stations worldwide, most of them in China.

Due to higher costs associated with the use of hydrogen and fuel cells in the transport sector, the public support and policy framework will have a major impact on the deployment of FCVs. Currently, FCVs are still expensive mainly due to the low production volumes and high manufacturing costs [36]. Also, precious and costly materials such as platinum are used in fuel cells, and though their share of the total manufacturing cost is just 20% [36–38], the goal is still to significantly cut the platinum content in FCVs. This should also reduce some of the negative environmental impacts associated with platinum extraction, e.g. sulphur oxide emissions [36].

Although there are still several barriers in front of faster deployment of FCVs, the recent progress with green hydrogen production has also increased the interest in FCVs as part of the strategies to reach the net-zero carbon emission goals by 2050 [39]. With the increasing use of variable renewable sources such as solar and wind power, and increasing full-load hours of electrolysis, the production costs of green hydrogen could become significantly lower in the future [16, 32]. Also, increasing carbon tax improves the competitiveness of green hydrogen. However, most of the car manufactures are focusing on BEVs and only a few of them, such as Toyota, Hyundai, and General Motors, also have a strong focus on FCVs. With limited industrial interest, lacking infrastructure, and high costs associated, a broad deployment of FCVs is unlikely and a focus on niche markets, such as long-haul trucks, may be necessary to increase the deployment.

The role of hydrogen, however, goes beyond just FCVs, and it can be used in a broad range of applications, e.g. as an energy storage for the surplus electricity from RES [40]. This new role of hydrogen may drive the cost down and accelerate the buildup of infrastructure making hydrogen use in FCVs more attractive.

Comparison of electricity vs hydrogen for mobility

Electricity and hydrogen are complementary energy carriers, both of which could contribute to the transformation and decarbonization of the transport sector. While both have some advantages, they also have some challenges to overcome in the future.

The major advantage of both electricity and H_2 is that they, in combination with BEVs and FCVs, can contribute to the

Table 1. Major advantages/challenges for BEVs and FCVs [2, 7, 44]

Major advantages of BEVs	Major challenges for BEVs
- High energy efficiency - Charging infrastructure is expanding rapidly due to major policy support - Relatively low operating costs, but could be impacted by increasing energy prices - Using electricity from RES, could significantly contribute to GHG emission reduction - Contribution to the energy supply security and reduction of fossil fuel import dependency - Improvement of air quality at the point of - Reduction of noise level	- Cost reduction - Low battery energy density - Slow charging process - Limited driving range and range anxiety - Battery weight - Dependency on critical materials, and limited availability of these - Battery supply chain bottleneck risks - Environmental and social material mining concerns - 'Thermal runaway' safety concerns - Development of charging infrastructure, especially fast chargers - Reduction of the overall life cycle emissions - Battery recycling
Major advantages of FCVs	**Major challenges for FCVs**
- Relatively short refueling time, 5–10 min - Application to sectors where electrification is too expensive or impossible, e.g. long-haul trucking, ships, airplanes - Higher energy density of hydrogen - Using green hydrogen, FCVs could significantly contribute to GHG emission reduction - Contribution to the energy supply security and reduction of fossil fuel import dependency - Improvement of air quality - Reduction of noise level	- High mobility costs - Fuel cell stack complexity - High fuel cell technology costs - Infrastructure costs - Less efficient than BEVs - Relatively low support from car industries - Durability, reliability, and robustness of fuel cells - Handling hydrogen safely requires proper training, procedures, and equipment

improvement of air quality and reduction of noise, as well as to better life quality in urban areas. Moreover, since they can be produced from a broad range of primary energy sources, they could reduce energy import dependency and contribute to energy supply security. Currently, both BEVs and FCVs benefit from policies aimed at emission reduction and promotion of clean and sustainable mobility.

Comparing the two technologies, BEVs are clearly ahead FCVs in commercialization and infrastructure. Also, the overall efficiency of BEVs from electricity to mileage is much better than that of FCVs. However, FCVs have some advantages over BEVs, such as a quick refueling time, high energy density, and a longer driving range.

In order to improve the energy efficiency of BEVs, regenerative brake systems can be used. In principle, when the vehicle is braking, kinetic energy is converted into electric energy, which is stored in the battery. This energy recuperation process helps to reduce the energy consumption and to extend the driving range of the vehicle [41].

Moreover, the BEV charging industry is working continuously on innovations and developments that should improve the BEV charging experience while meeting the needs of drivers as well as helping in load balancing and system reliability [42]. There are already some technology innovations in BEV charging that are market-ready or close to launching. Smart energy management solutions should reduce demand charges and lower operational costs, increase energy resilience, and maximize use of renewable energy. With new battery chemistry solutions, the goal is to have greater range, shorter charging time, and improved safety. In addition, with international standards, the communication between EV charging stations and a central management system should enable smart charging functionalities and more suitable payment options.

In addition, bidirectional charging, which is also known as vehicle-to-grid (V2G) capability, can contribute to the optimization of power demand, shaping the load variations and sustainability of smart grids.

However, there are still some important challenges on the way such as the lack of a concrete V2G business model, lack of stakeholders and government incentives, the excessive burden on EV batteries during V2G, and the deficiency of bidirectional battery chargers [43].

Depending on future technology and price developments, preferences for BEVs and FCVs may change over time.

Table 1 summarizes the comparison between BEV and FCV technologies.

Discussion and outlook

Although BEVs and FCVs still face many challenges, such as affordability and a lack of infrastructure, they can markedly contribute to the achievement of the global and European climate policy goals and decarbonization of the transport sector.

However, several issues need still to be solved to ensure future success. A very important issue is related to the environmental benefits in the well-to-wheel chain, which depend on the type of primary energy source used. Worldwide, the carbon intensity of the electricity mix varies by country g from 25 gCO_2/kWh (Paraguay) up to 795 gCO_2/kWh (Botswana) [45]. There are also significant differences in carbon intensity of electricity in Europe, which range from 26 to 635 gCO_2/kWh [45]. Only if electricity and hydrogen are produced from clean sources such as renewable energy, significant environmental benefits can be achieved. However, for the assessment of the full environmental benefits of ZEVs, the total emissions over the whole supply chain, from the mining of the materials needed in car production to the disposal and recycling of vehicles, have to be considered. With the acceleration of the transport transformation, it is becoming increasingly important to ensure fairness

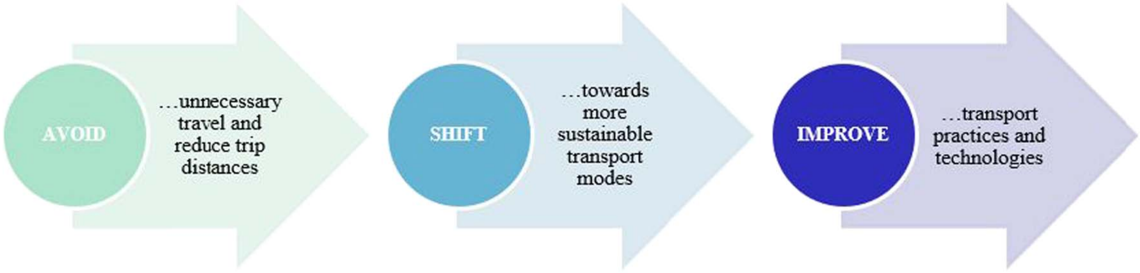

Figure 6. Avoid-shift-improve strategy (adapted from [3]).

and environmental sustainability through the whole mobility supply chain.

The future of ZEVs will strongly depend on the policy framework, investments, and long-term goals. Currently, ZEVs are generously supported through different monetary measures (e.g. purchase incentives, subsidies, tax exemptions, and reductions) and non-monetary measures (e.g. free parking spaces, use of the bus lanes, permission to enter zero-emission zones) [10, 46]. However, it is clear that such measures can be offered only as long as the number of ZEVs is very low. Taxes on fossil fuels are a significant source of income for governments, and to some extent, they are also used for investment in and maintenance of the transport infrastructure. With an increasing number of ZEVs, these tax revenues are expected to decline, which could have a negative impact in Europe due to the highest taxes on gasoline and diesel globally. In the future, new policy design will be needed to encourage the use of ZEVs, but should also be more considering the full CO_2 emission reduction benefits over the whole vehicle life cycle. Some of the measures discussed currently, such as the higher taxes on fossil fuels, distance-based charges, and weight-based taxes, are politically unpopular.

Moreover, with the ongoing urbanization and increasing car ownership level all over the world, it is clear that the problems in the transport sector cannot be solved just through new technologies. Especially in urban areas, it is important to provide affordable, reliable, comfortable, and convenient public transport, so that the dependency on private car ownership can significantly be reduced. The current supporting measures for BEVs or FCVs are often beneficial just for a small group of high-income people. Whereas in the lower income segment, these can seldom be afforded. Moreover, use of public charging points is becoming more inconvenient with the increasing number of users. For these reasons, it is very important to support electrification and improvement of the public transport as well, which provides benefits more broadly to society.

Finally, when heading towards more sustainable mobility, the most important is to apply the 'avoid-shift-improve' strategy illustrated in Fig. 6. This strategy focuses on (i) reducing transport activity, (ii) a shift towards more sustainable modes of transport including better conditions for the use of public and non-motorized transport, and (iii) support the use of more efficient and environmentally friendly vehicles and transport practices. Importantly, the success of such a strategy will rely on political support and on the policy-framework provided. The major cornerstones of such a policy framework are the balanced use of monetary and non-monetary supporting measures, improvement of infrastructure for environmentally friendly transport modes, as well as proper combination of standards, taxes and subsidies.

Conflict of interest

No conflict of interest is reported.

Authors' contributions

The manuscript was solely prepared by the author.

Data Availability Statement

All data and figures are based on open sources available online.

References

1. IEA, *Global Energy Review: CO2 Emissions in 2021*. Paris: International Energy Agency, March 2022, https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2
2. Brown D, Flickenschild M, Mazzi C, Gasparotti A, Panagiotidou Z, Dingemanse J, Bratzel S. The future of the EU automotive sector, https://www.europarl.europa.eu/RegData/etudes/STUD/2021/695457/IPOL_STU(2021)695457_EN.pdf
3. Ajanovic A. The impact of COVID-19 on the market prospects of electric passenger cars, WIREs. *Energy and Environment* 2022;**11**:e451
4. STATISTA: *Electric Car Spending Worldwide Between 2017 and 2022, by Consumers and Government*. https://www.statista.com/statistics/1312334/global-spending-on-electric-cars-by-spender/, 2023
5. IEA. *Policy Developments*. https://www.iea.org/reports/global-ev-outlook-2023/policy-developments, Paris: International Energy Agency, 2023
6. European Commission, *European Green Deal – Delivering on Our Targets*, European Union, 2021, file:///C:/Users/ajanovic/Downloads/EGD_brochure_EN.pdf-1.pdf
7. Ajanovic A, Haas R. Heading towards low-carbon passenger car mobility: electricity vs hydrogen. *Renew Sust Energy* 2023;**1**:0002
8. IEA, Global EV outlook 2021. Paris: International Energy Agency. Available: https://www.iea.org/reports/global-ev-outlook-2021.
9. EV100, Climate Group EV100. Progress and insight report. *The EV revolution is here* 2021. Paris: International Energy Agency. Available:. https://www.theclimategroup.org/ev100-annual-report-2021
10. IEA. Global EV outlook. 2023, 2023;
11. IEA, *Global EV Data Explorer*. Paris: International Energy Agency. https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer
12. ACEA, *Share of Alternatively-Powered Vehicles in the EU Fleet, per Segment*. https://www.acea.auto/figure/share-of-alternatively-

powered-vehicles-in-the-eu-fleet-per-segment/, September 2023
13. ACEA, *Affordability of Electric Cars: Correlation Between Market Uptake and Annual Net Income*, https://www.acea.auto/figure/interactive-map-affordability-of-electric-cars-correlation-between-market-uptake-and-annual-net-income/
14. ACEA, *Electric Cars: Half of All Chargers in EU Concentrated in Just Two Countries*, https://www.acea.auto/press-release/electric-cars-half-of-all-chargers-in-eu-concentrated-in-just-two-countries/
15. IEA, *Key World Energy Statistics*. Paris: International Energy Agency, 2021. Available: https://www.iea.org/reports/key-world-energy-statistics-2021
16. Ajanovic A, Haas R. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *Int J Hydrog Energy* 2021;**46**:10049–58
17. Xu C, Dai Q, Gaines L *et al.* Future material demand for automotive lithium-based batteries. *Commun Mater* 2020;**1**:1–10
18. Deng J, Bae C, Denlinger A *et al.* Electric vehicles batteries: requirements and challenges. *Joule* 2020;**4**:511–5
19. GVR. *Lithium-Ion Battery Market Size & Share Report, 2030*. https://www.grandviewresearch.com/industry-analysis/lithiumion-battery-market (2021)
20. Zhang C, Zhao X, Sacchi R *et al.* Trade-off between critical metal requirement and transportation decarbonization in automotive electrification. *Nat Commun* 2023;**14**:1616
21. STATISTA, *Reserves of Lithium Worldwide as of 2022 by Country*, https://www.statista.com/statistics/268790/countries-with-the-largest-lithium-reserves-worldwide/
22. UNCTAD. *Developing Countries Pay Environmental Cost of Electric Car Batteries*, 2020. Available: https://unctad.org/news/developing-countries-pay-environmental-cost-electric-car-batteries
23. Castelvecchi D. Electric cars and batteries: how will the world produce enough? *Nature* 2021;**596**:336–9
24. Whiteaker J. *Opinion: Let's be Honest, Batteries Are Bad for the Environment*, 2021. Available: https://www.investmentmonitor.ai/insights/batteries-are-bad-for-the-environment
25. DW. 2017. *Child Labor Still Rife in DR Congo*, https://www.dw.com/en/child-labor-still-rife-in-democratic-republic-of-congo/a-39194724
26. The World Bank. 2022. Worldwide governance indicators. https://databank.worldbank.org/source/worldwide-governanceindicators
27. Costa CM, Barbosa JC, Gonçalves R *et al.* Recycling and environmental issues of lithium-ion batteries: advances, challenges and opportunities. *Energy Storage Mater* 2021;**37**:433–65
28. Chagnes A, Pospiech B. A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries. *J Chem Technol Biotechnol* 2013;**88**:1191–9
29. Dunn JB, Gaines L, Sullivan J *et al.* Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. *Environ Sci Technol* 2012;**2012**:12704–10
30. Bloomberg NEF. *EV Battery Prices Risk Reversing Downward Trend as Metals Surge*. 2021. Available: https://www.bloomberg.com/news/newsletters/2021-09-14/ev-battery-prices-risk-reversing-downward-trend-as-metals-surge, 2022
31. Bloomberg NEF. *Lithium-Ion Battery Pack Prices Rise for First Time to an Average of $151/kWh*, https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/ , 2022
32. Ajanovic A, Sayer M, Haas R. The economics and the environmental benignity of different colors of hydrogen. *Int J Hydrog Energy* 2022;**47**:24136–54
33. Trencher G, Edianto A. Drivers and barriers to the adoption of fuel cell passenger vehicles and buses in Germany. *Energies* 2021;**14**:833
34. Hardman S, Shiu E, Steinberger-Wilckens R *et al.* Barriers to the adoption of fuel cell vehicles: a qualitative investigation into early adopters attitudes. *Transp Res Part A Policy Pract* 2017;**95**:166–82
35. Wang J, Wang H, Fan Y. Techno-economic challenges of fuel cell commercialization. *Engineering* 2018;**4**:352–60
36. Deloitte. *Fueling the Future of Mobility Hydrogen and Fuel Cell Solutions for Transportation. Deloitte China*. 2020. Available: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf
37. Hyundai. *Hydrogen Society - Safe and Cost-Efficient FCEV*. 2020. Available: https://tech.hyundaimotorgroup.com/article/hydrogen-society-safe-and-cost-efficient-fcev/
38. Pollet BG, Kocha SS, Staffel I. Current status of automotive fuel cells for sustainable transport. *Curr Opin Electrochem* 2019;**16**:90–5
39. International Energy Agency. *The Future of Hydrogen: Seizing Today's Opportunities*. Paris: International Energy Agency, 2019. Available online: https://www.iea.org/reports/the-future-of-hydrogen.
40. Hiesl A, Ajanovic A, Haas R. On current and future economics of electricity storage. *Greenhouse Gases* 2020;**10**:1176–92
41. my-cardictionary.com. *Recuperation and Regenerative Brake Systems*. https://www.my-cardictionary.com/electric/brake/recuperation-and-regenerative-brake-systems-bev.html, September 2023
42. Driivz Team. *Six Technology Innovations in Electric Vehicle Charging*. https://driivz.com/blog/ev-charging-technology-innovations/ , 2023
43. Mojumder RH, Antara FA, Hasanuzzaman M *et al.* Electric vehicle-to-grid (V2G) technologies: impact on the power grid and battery. *Sustainability* 2022;**14**:13856
44. Albatayneh A, Juaidi A, Jaradat M *et al.* Future of electric and hydrogen cars and trucks: an overview. *Energies* 2023;**16**:3230
45. Our World in Data, Carbon intensity of electricity, 2022, https://ourworldindata.org/grapher/carbon-intensity-electricity
46. Siebenhofer M, Ajanovic A, Haas R. How policies affect the dissemination of electric passenger cars worldwide. *Energies* 2021;**14**:2093