NAVIGATING THE FUTURE: *A REPORT ON THE CURRENT STATE AND FUTURE PATH OF ENERGY TRANSITION IN THE TRANSPORT SECTOR*

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Navigating the Future: A Report on the Current State and Future Path of Energy Transition in the Transport Sector

ABSTRACT

Decarbonisation of road transport was until recently considered the most challenging part of the climate agenda. Still the ascent of electric vehicles is making significant advances possible while, at the same time, opening several new complex conundrums: integration of power and transport systems, establishing supply chains of needed materials and conversion of existing industries to new products.

At the same time, the decarbonisation of heavy road transport, aviation, and maritime transport raises many questions regarding the prevailing fuels and technologies that will secure net zero emissions of greenhouse gases. Different e-fuels like ammonia, methanol, and similar liquid fuels synthesised from green hydrogen look like a possible solution.

This decade is crucial since the whole process, which is essential for achieving the goals of the Paris Agreement, depends on decisions made soon.

CAETS Energy Community
E-Mobility Working Group

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Contents

Executive summary

Decarbonisation of transport was until recently considered the most challenging part of the climate agenda, but the ascent of electric vehicles (EV) is making significant advances possible, while, at the same time, opening several new complex conundrums: integration of power and transport systems, establishing supply chains of needed materials, developing the charging infrastructure for the users, and conversion of existing industries to new products. This decade is crucial since the whole process, which is essential for achieving the goals of the Paris Agreement, depends on the policy being adopted.

This report aims to provide a short overview of the status of the transformation towards new energy technologies within the transport sector and to indicate pointers for future development. The report draws on the extensive experience of members of the various engineering and technical academies forming part of the CAETS organisation.

Key takeaways from each specific chapter of the report are presented in Table 1:

<table>
<tr><td>Key messages</td><td>The ascent of the electric vehicle opened up the possibility of significant advances in establishing environmentally sustainable transport. Sectoral vital messages can be observed as follows:

Joint efforts from industry and research throughout the complete value chain are needed for the innovative and sustainable development of EV batteries
Integrating the power and transport sectors helps to decarbonise both sectors more effectively, which can be done through smart charging and market coupling
The car industry is already being transformed, and newcomers have the opportunity to contribute with additional innovations
Hydrogen-based solutions are still in competition with battery-electric solutions in applications that have functionality as a priority (military, long-distance and heavy freight)
E-fuels have become competitive in maritime and aviation transport, with fuel storage being a cost-competitive option compared to electrified solutions.
Active transport options and sharing travel are cost-effective, while in freight transport, rail and water options provide low-emission solutions but with significant investment costs
In some developing countries, local abundance of mineral sources offers an opportunity to consider holistic and sustainable mining practices and benefit economically, socially and environmentally from the decarbonization industry.
The fire hazard of EVs is not higher than that of ICEVs but is different, and new methodologies are needed to handle them.
</td></tr>
</table>

	Opportunities	Issues to overcome
Battery development for EVs	Technological **innovations** are imperative in a rapidly expanding global battery industry and providing new chemistries The gaining of new knowledge on EV batteries is **excellent** due to the extensive focus of science and industry on this subject around the World	**More joint research efforts** and collaborations between industry and academia are needed Collaboration between all members of **the complete value chain** of resource mining, materials synthesis, cell design, pack design, manufacturing, use, and **recycling** is of paramount importance
Integration of power and transport systems	EVs **can** contribute towards managing the variability in renewable energy production when connected to the electric network through smart chargers (when not in use)	**Smart chargers** should be added to most parking bays to enable the power-transport system coupling Wholesale and retail electricity **markets should be dynamically price coupled** to allow EV use as a demand response
Car Industry transformation	**The car industry is already engaged in a fast and much-needed transformation**. The commercial vehicle sector is next in line, with good progress being achieved regarding electric buses, with China playing a leading role The transformation **provides an opportunity for newcomers to join the industry** with innovative solutions	Transformation of the world fleet of approximately 1.6 billion vehicles to the new technologies will be relatively slow due to the long lifespan of a vehicle and can be expected to take 25 to 35 years
Hydrogen vs. electricity	When **functionality is of larger importance** – for example, with large vehicles, heavy transport, and military applications– **hydrogen solutions are still in competition with battery electric solutions, but so are liquid fuels such as methanol (due to handling issues) and traditional fuels**	For passenger vehicles, battery electric vehicles prevail in terms of efficiency and cost-effectiveness compared to hydrogen/hydrogen-electric vehicles, with the roundtrip efficiency of over 90%, compared to 34% in the case of the fuel cell

		Hydrogen use is hampered by transportation, storage difficulties and safety issues.
E-fuels	**Ammonia is most interesting in the maritime industry** due to the quantity of fuel needed **Carbon-based e-fuels are to be primarily used for aviation** and heavy-duty road transport (depending on electrification rates and direct hydrogen application)	The **regulatory framework** is still in development, and **minimising the cost gap** represents some of the critical non-technical challenges e-fuels face. Safety issues, technology development and standardisation, are needed to support the penetration of e-fuels in the sector
Modal shift	**Active transport options**, such as cycling (including e-bikes and e-scooters) and walking, offer **highly cost-effective options** to achieve decarbonisation **Sharing travel schemes** reduces the greenhouse gas emissions per passenger kilometre of travel, is becoming more popular, and should be promoted Public transport offers significant benefits in terms of the efficiency of the transport system in general and the carbon footprint of the car industry specifically, and should be supported and promoted	Rail and water transport have the lowest emissions per metric ton-kilometre in freight transport. The implications and **cost of transition** to these modes are significant challenges; however, and transition is not always practically possible. Travel time and reliability issues further complicate the matter
E-mobility in developing countries	**Policies for the transition** of the transport sector towards e-mobility **are being promoted by almost all countries in Latin America**, leading to increased EV sales In some countries like Argentina, Bolivia, or Chile, the **local availability of critical**	In Africa, an inadequate regulatory environment and low-income levels, combined with long travel distances and poor infrastructure, pose barriers to e-mobility International support will be needed to facilitate the transition of transport in Africa

	minerals offers an opportunity for an integrated industrial approach to address environmental challenges of possible exploitation. In **South and Southeast Asia and some parts of Latin America, two- and three-wheelers prevail** in road transport, reducing pollution. In addition to this, there is **significant legislative support and industrial development** enhancing transformation (especially in Thailand and Indonesia)	A shortage of charging and other infrastructure and the relatively high cost of EVs impede the transition towards environmentally sustainable technologies in South and Southeast Asia
Fire safety of EVs	**The fire hazard related to EVs is not higher than that of ICEVs,** but it is different regarding battery-specific hazards. Heat release rates from EV and ICEV are similar. Toxic gases emitted from EV and ICEV fires pose health and environmental risks. Different methodologies are required to combat such fires	**Training for emergency response**: EV fires require a unique approach to be applied and given due attention. Emergency response to EV fires is challenging, and more research and training is needed to assist firefighting
Two subjects that are not covered in separate chapters but deserve mentioning are:		
Standardisation	It is crucial to achieve the standardisation of voltages, connectors, chargers, and other elements of the EV grid and to do it right. Too early standardisation may stifle innovation; too late it may impede integration and waste value across world regions. The chaotic world of plugs and sockets is a case in point	
Financing	This issue appears in several chapters in different forms. In some advanced economies, financing has taken the form of economic instruments (incentives and fiscal subsidies); in others, there are various forms of carbon markets or regulations. In emerging markets and developing economies, internationally organised financing is needed. The World Bank should take the lead in parallel with regional multilateral development banks and with advanced economies' financial development agencies	

It is now probable that most short-distance transport will be electrified, but need substantial charging infrastructure that will consume up to 40% more electricity (more details in Chapter 3). Will these changes put pressure on the power system, and/or will they help the integration of variable renewables? The answers to these questions depend on decisions made now. If cars are mainly fast-charged on demand, that will exacerbate the problems. Still if vehicles are mostly charged on smart chargers when parked, they can help integrate variable renewables.

The central part of the new transport system, the battery and the fuel cell, is rapidly improving. New chemistries bring higher energy densities, charging speeds, reduced charging times, and better battery management systems to decrease the degradation of batteries. While batteries will require the build-up of new material supply chains, new battery chemistries will enable additional levels of flexibility. Unavoidable bottlenecks in the supply of certain minerals will result in different market shares of various battery chemistries. Bottlenecks and their resolution will depend on decisions made now or in the next few years. Chapter 1, addresses battery development, car battery chemistries, supply chains and recycling.

Chapter 2, focusing on the integrating power and transport systems, elaborates on the charging infrastructure as a contact point of power and transport systems and stationary batteries needed for support of charging. Issues of charging from the power system perspective, which is based 100% on Renewable Energy Sources (RES), are discussed, as well as concepts like Vehicle-to-Grid (V2G), smart charging, wireless charging and crucial battery issues. The dynamics of charging and demand response provisions are the first critical to tackle as the number of EVs rises in the road transport fleet.

Chapter 3 deals with car industry transformation and addresses supply chain issues related to electric motors and inputs other than batteries. The electric vehicle industry is significantly different from the incumbent automotive sector. The transition will create significant turbulent adjustments, leading to new supply chains and business models, as well as road construction and maintenance financing. These aspects are expected to substantially impact entire countries, especially those heavily dependent on car manufacturing industries and car-based mobility.

While hydrogen and fuel cells will probably play minor roles in short-distance transport, they may have significant roles in long-distance transport. How this will evolve is still unclear. Developing of new hydrogen supply infrastructure will take a long time and depend on early decisions. Furthermore, will hydrogen be supplied as ammonia or some other energy carrier, or will hydrogen be utilised to produce electrofuels used in incumbent engine technologies? Chapters 4 and 5 address hydrogen as a fuel or as a green feedstock for e-fuels to be used in hard-to-abate processes and long-distance transport (maritime or air transport), respectively. More concretely, e-fuels, Power-to-X (PtX), renewable fuels of non-biological origin (RFNBOs) and hydrogen-derived synthetic fuels all represent the production of e-fuels based on electrolytic green hydrogen paired with a carbon or nitrogen source.

Chapter 6, “Modal shift, can it help?” includes active transport, car sharing and similar solutions. It aims to answer whether modal shift helps with the transition in densely populated areas and how freight transport can use different solutions to decarbonise short and medium-distance deliveries. Although it is recognised that public transport has a huge role, this mode of transport is not explicitly addressed in this report.

Chapter 7, on Developing countries and decarbonisation of transport, barriers and opportunities, consists of several subchapters: a subchapter on Latin America, a subchapter on developing countries of Africa, and a subchapter on East and Southeast Asia. These subchapters analyse the evolvement of transition in developing countries given EV’s higher capital expense (CAPEX), spill-off effects of second-hand cars, specific local solutions and other particularities.

Chapter 8, on Fire Safety of Electric Vehicles, brings forward current problems related to fire safety of EVs. The widespread adoption of electric vehicles introduces unique fire safety challenges, especially related to battery hazards and emergency response. Addressing these requires updated regulations, firefighter training, and collaborative safety strategies for a safe transition to sustainable transportation.

Batteries Development for EVs

Lead author: Lian Yubo

- Technological innovations are imperative in a rapidly expanding global battery industry.
- More joint research efforts and collaborations between industry and academia are needed to address scientific and technological barriers.
- Collaboration between all members of the complete value chain of resources mining, materials synthesis, cell design, pack design, manufacturing, use, and recycling is paramount importance.

Abstract

The signing of the Paris Agreement in 2015 drew global attention and marked the beginning of global carbon neutrality efforts. Many governments see it as part of their national development strategy and a vision for net zero greenhouse gas (GHG) emissions. Major global economies, including China, Europe and the United States, have taken the lead in transitioning towards electrified transportation systems, resulting in a rapid uptake in the global electric vehicles (EVs) market. Meanwhile, the battery system is still faced with enormous challenges. For example, further increase of cruising ranges of EVs requires higher energy density[1] of battery materials, high consumer expectations on EV safety require enhanced structural integration of battery pack in vehicles, the dependence of the lifetime[2] of a battery pack on battery cell variations requires an effective battery management system (BMS), the technologies and industry for reusing and recycling of battery towards the end of its life cycle are yet to be mature, the regional concentration of key resources and the imbalance of the production cycle of each link in the supply chain are challenging for the development of a healthy and sustainable industry. Therefore, this chapter intends to address critical technological evolution pathways of EV batteries in terms of materials, pack design, battery management system, reuse and recycling methods, and the supply chain.

Table 2 List of abbreviations in this chapter

Abbreviations	Definitions
EV	Electric vehicle
GHG	Greenhouse gas
LFP	Lithium iron phosphate, $LiFePO_4$
LFMP	Lithium manganese iron phosphate, $LiFe_xMn_{1-x}PO_4$
NMC	Lithium nickel manganese cobalt oxide, $LiNi_xCo_yMn_{1-x-y}O_2$
NCA	Lithium nickel cobalt aluminium oxide, $LiNi_xCo_yAl_{1-x-y}O_2$
LRMO	Lithium-rich manganese-based cathode material
Ni90/Ni92/Ni96	Nickel content in the cathode, 90%/ 92%/ 96%
BMS	Battery Management System
SOC	State of Charge
SOP	State of Power
SOE	State of Energy
SOH	State of health
CMP	Cell-Module-Pack

[1] The energy density of a battery is the amount of electrical energy stored per unit volume or unit mass of the battery.
[2] The lifetime of a battery can generally be defined as the time when the battery can no longer meet the requirements for range, operating time or maximum power capacity under typical usage profiles.

CTP	Cell-to-pack
CTC	Cell-to-chassis
CTB	Cell-to-body
OEM	Original equipment manufacturer
AFE	Analog front end
PCB	Printed circuit board
V2G	Vehicle-to-grid
RUL	Remaining useful life
DLE	Direct lithium extraction
DLP	Direct lithium to product
DSO	Direct shipping ore
HPAL	High pressure acid leaching
46800	Cylindrical battery with a diameter of 46 mm and a height of 80 mm
18650	Cylindrical battery with a diameter of 18 mm and a height of 65 mm
21700	Cylindrical battery with a diameter of 21 mm and a height of 70 mm

Materials

The range and safety of electric vehicle batteries are still important factors limiting the rapid spread of electrification in the transport sector. Materials determine the electrochemical performance of batteries and play a dominant role in their energy density and safety [1]. In mass-produced electric vehicles (EVs), lithium-ion batteries, including ternary materials and lithium iron phosphate (LFP) batteries, dominate electric vehicles energy storage medium. Effective ways to increase the energy density of ternary lithium batteries include increasing the nickel content and voltage limit, but the resulting thermal stability and battery safety issues must also be considered. Major suppliers of ternary lithium batteries, including CATL, LG Chem, Panasonic, and Samsung SDI, have either announced or achieved mass production of new battery products with a nickel content of up to 90%. Batteries with LFP cathodes achieve longer lifetimes, improved safety, and lower cost. However, LFP cathodes suffer from low electronic conductivity and slow ion diffusion rate. In the mass production of LFP cathodes, modification techniques, including surface coating, nanocrystallisation, and lithium supplementation, are commonly employed to improve the electrochemical performance of the battery cell [2]. Major suppliers of LFP batteries include BYD and CATL.

Next-generation battery technology focuses primarily on higher energy density and higher safety levels. New electrode materials to improve the energy density include higher nickel content in ternary cathode materials beyond 90%, including Ni90, Ni92, and Ni96 [3]. For LFP materials, competitive next-generation alternatives include lithium manganese iron phosphate (LFMP), cobalt-free lithium nickel manganese oxides, and lithium-rich manganese-based cathode material (LRMO) [4]. For anode materials, natural graphite and artificial graphite are evolving towards silicon-graphite, silicon-oxide, and lithium metal anodes. To improve battery safety performance, solid-state batteries have great potential. However, there are still significant obstacles in technology and the manufacturing process. Solid-state batteries are still in the research and development and pilot production stage. While semi-solid-state batteries are expected to achieve mass production by 2025, it takes another 5-10 years for all-solid-state batteries to reach mass production.

Intensive efforts and investment are still needed in basic research, for example, developing new solid-state electrolytes and electrode materials, gaining an in-depth understanding of the interaction mechanisms between the electrolyte and the electrodes, and optimising the interface structure. Innovations in production technologies, such as process optimisation to improve production efficiency and reduce waste, are also vital to successful mass production.

In addition, new battery technologies that build upon innovations in materials have gained enormous interest, such as lithium-sulphur, lithium-air, and sodium-ion batteries. These new battery chemistries could improve batteries energy density, safety performance, and cost, thereby contributing to more competitive EV products.

Pack Structure

The battery pack of an electric vehicle consists of cells in three form factors: prismatic, cylindrical, and pouch types. All three forms could be integrated into a module considering standardisation and enhancement of structural integrity. One step further, modules can be incorporated into a battery pack. This type of integration, typically called cell-module-pack (CMP), as shown in Fig.1, was common during the early development of electric vehicles. It features low volume utilisation limiting the battery capacity and the travelling range. Further increasing the travelling range would result in heavier packs, negatively impacting the energy efficiency. Technical pathways to increase the volume utilisation of the battery pack include employing higher capacity cells, larger modules and even module-less designs. For example, the use of larger 46800 type cylindrical cells compared to earlier versions of 18650 type and 21700 type cells, as represented by Tesla, resulted in higher volume utilisation and reduced pack complexity due to the reduced number of cells. As represented by BYD, the cell-to-pack (CTP) concept uses a blade battery cell technology, a specialised version of prismatic cells, and a module-less design. These designs reduced structural redundancy to improve volume utilisation.

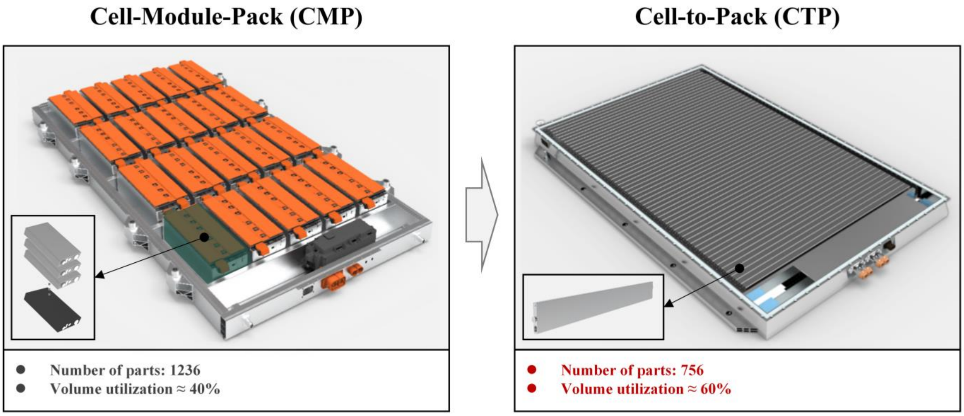

Fig.1 Comparison of two types of battery packs

In the early times of the development of electric vehicles, the battery pack was designed to be protected by the vehicle body structure from intrusions caused by impacts. At present times, the design concept has been transformed such that an integrated vehicle body-battery pack structure enhances the safety of both, as seen in the cell-to-chassis (CTC) concept from OEMs like Tesla and the cell-to-body (CTB) concept from BYD. For example, the CTB concept features a complete integration of the vehicle body and the battery pack by module-less designs, a cold plate that also works as the tray, and shared structural components between the pack and the vehicle body [5]. The design significantly improved the volume utilisation of the battery pack, as well as the strength and stiffness of the body. Moreover, design features that enhance pack safety employ specially designed degassing valves and separate the thermal and electrical systems. In case of a thermal runaway of battery cells, such a design could ensure electrical safety and reduce the risk of high-voltage arcing, thereby improving the safety of the battery pack and the vehicle.

In the future, the pursuing of higher volume utilisation and higher levels of battery pack-vehicle integration will be strengthened by considering the vehicular design and safety targets in the design of battery cells and packs, aiming for longer ranges, higher energy efficiency, and enhanced safety of electric vehicles.

Battery Management Systems

The battery pack generally comprises of a battery module, a thermal management system, a battery management system (BMS), an electrical system and structural components. The battery module consists of multiple battery cells. The BMS is an integral part that connects the battery and the EV, which is responsible for battery status analysis, battery safety protection, energy control and management, battery information management, and vehicle level information exchange, as shown in Fig. 2 and Table 3 [6]. Recent improvements in the BMS include higher levels of hardware integration and intelligent software development.

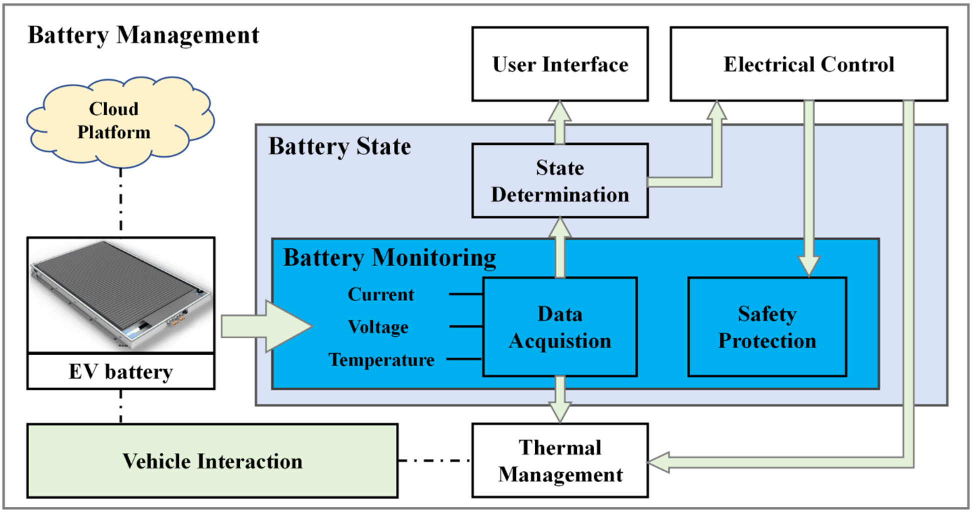

Fig. 2 Battery Management System

Regarding hardware architecture, wired BMS is the mainstream solution. The BMS monitors battery cell status through the analogue front-end (AFE) chip and the high-voltage monitoring chip for control purposes. The complex high/low-voltage wiring scheme results in low levels of integration, and failure of specific printed circuit board (PCB) parts leads to system failure. One of the solutions is the employment of a wireless BMS [7], which reduces the circuit complexity, and improves the reliability and flexibility of the system. However, wireless BMS suffer from poor signal transmission stability in harsh environments and poor electromagnetic compatibility.

Regarding software and control, more complex software and higher levels of software-hardware integration make coordination among software increasingly tricky. The battery monitoring algorithms are mainly calibrated against ternary material and LFP chemistries, and adaptations are needed towards new chemistries and new applications, such as vehicle-to-grid (V2G), where the vehicle battery is used as a resource for energy storage.

With the development of intelligent and connected vehicle technology, the upgrades in vehicular architecture and the demands from more intelligent scenarios, the following trends are expected for the BMS.

Table 3 Main functions of EV battery management system

System	Module	Function
Battery Management System (BMS)	Data Acquisition	Lumped voltage acquisition
		Electric current acquisition
		Temperature acquisition
		Cell voltage acquisition
	State Estimation	SOC estimation
		SOP estimation
		SOE estimation
		SOH estimation
	Energy Management	Charge management
		Balanced management
	Safety Protection	Over-current protection
		Over-voltage protection
		Low-voltage protection
		Over-temperature protection
		Insulation protection
	Information Management	Standard data upload
		Historical information storage
		Vehicle interaction

The development of more advanced sensing technologies, such as electrochemical characterization methods-based online monitoring, can provide more information about the internal state of health of the battery. The BMS integrated with these advanced sensors can more accurately monitor and evaluate the battery's real-time status and long-term health.

Using a cloud-based BMS that leverages fleet battery data to train advanced algorithms online could better monitor battery cell status, including SOH/SOC/SOP. The system could also implement more effective battery management strategies to lengthen battery lifetime and to reduce safety risks [8].

Reuse and Recycling

Global annual battery production capacity is expected to exceed 5 TWh by 2030 [9]. We can also foresee a considerable growth in end-of-life EV battery volumes, with over 100 million vehicle batteries expected to be retired in the next decade [9]. Proper handling and post-processing of these batteries could extend their service life, prevent environmental pollution, and recycle essential materials for a sustainable supply chain.

The two main pathways for retired electric vehicle batteries are reuse and recycling. EV batteries typically retire when they reach 80% capacity or remaining useful life (RUL), although there is a lack of such a standard. The retired batteries can be used for energy storage, backup and other scenarios. Battery reuse or repurposing is still in its early phase of development, which features demonstration projects. Repurposing retired EV batteries into commercial energy storage products and grid energy products is seen by companies such as Brunp Recycling, GEM, Mercedes-Benz, and Nissan. The safety of repurposed energy storage products may also be of concern. Batteries that cannot serve as energy storage resources could be recycled for the raw materials. Recycling EV batteries generally involves two typical processes: physical processes (e.g. crushing, magnetic separation and thermal treatment) and chemical processes (e.g. leaching, chemical/electrochemical precipitation and extraction). Companies such as Brunp Recycling, GEM, Retriev Technologies, and Umicore have carried out small-scale battery recycling. Recycling of batteries is characterised by low recovery levels of critical materials and low efficiency due to the low automation level of the process.

Developing a circular battery value chain requires establishing standards for reusing and recycling retired EV batteries. Key technological developments include cell balancing, rapid sorting and RUL testing. Developments of key processes include more refined and intelligent disassembling and dismantling equipment that improves the recovery of essential materials. A systematic engineering design that includes recycling and repurposing is critical to develop a circular value chain consisting of battery cell manufacturing, battery pack assembling, and recycling.

Battery reuse and recycling are expected to scale up in the long term. For example, an international study [10] projects that recycled materials could meet 60% of China's EV battery demand by 2050. Similar trends are expected globally.

Supply Chain

A rapid increase in the market of electric vehicles poses considerable challenges to the battery supply chain. A highly efficient, healthy, secure, and resilient supply chain is critical to the rapid and sustainable development of the battery industry. The supply chain includes upstream mining, processing and refining suppliers; mid-stream suppliers of battery components, including cathode and anode active materials, solvent, binders, foils, separators, electrolytes and complex production equipment; downstream battery manufacturers, OEMs, and reuse and recycling suppliers.

The supply chain of the battery is spatially concentrated globally. From the supply side, important upstream mining resources are unevenly distributed. For example, over 70% of the global cobalt supply comes from the Democratic Republic of Congo [11]. From the demand side, changes in the market shares of crucial battery chemistry, including LFP cathodes and high-nickel cathodes, pose significant challenges to long-term projections for the need of critical resources and the ensuing investment plans. Innovations in the processing and refining technologies, like direct lithium extraction (DLE), direct lithium to product (DLP), direct shipping ore (DSO), and high-pressure acid leaching (HPAL), expand access to not only previously unusable mining resources but also low-grade mineral resources. Moreover, battery recycling could be essential in building a highly flexible and resilient supply chain.

Mid- and downstream production capacities are also highly concentrated. For example, the top three global battery manufacturers have a market share exceeding 60%. The leading share of the Chinese EV market worldwide is also mirrored in the global battery supply chain. With the continual growth of EV market in Europe and the United States and the need for local production of the EV components, more investments in the local battery supply chain are seen, which will contribute to developing a geographically diversifying supply chain.

The carbon footprint of the whole supply chain may also become a specific constraint. The European Commission has introduced clear regulations for batteries sold in Europe [12]. It sets mandatory minimum levels of recycled contents in batteries with a minimum of 16% for cobalt, 85% for lead, 6%

for lithium and 6% for nickel from August 18th, 2031, and a minimum of 26% for cobalt, 85% for lead, 12% for lithium and 15% for nickel from August 18th, 2036. The necessity for mining products used in the battery to comply with a "sustainable mining" standard is also under discussion.

The battery supply chain is characterised by varying lead times for different components. For example, the lead time could be as short as one year for downstream battery manufacturers or OEMs, whether by retooling existing or building new production facilities. In contrast, lead times for electrode production usually span three to five years, and that for new mining resources, it is between ten and twenty years [13]. Therefore, mining resources might be a key obstacle when developing a battery supply chain for future electric mobility. Closer collaborations across the supply chain and strategic planning for product and technology portfolios are important to building a more resilient supply chain and avoiding over-reliance on certain elements, as exemplified by the current evolving balance between LFP and NMC chemistries.

Summary and Outlook

This chapter provided a comprehensive analysis of the status of the lithium battery industry with a prediction of future trends in battery materials, battery pack structural innovations, battery management systems, battery recycling, and the supply chain. The energy density of mass-produced lithium-ion batteries is approaching the engineering limit, and breakthroughs in new battery materials (i.e. silicon anodes) and new systems (i.e. solid-state batteries) will bring new growth to the battery industry and play a key role in promoting the global adoption of electric vehicles. Therefore, technological innovations are imperative in a rapidly expanding global battery industry. Meanwhile, more research and collaboration between industry and academia are crucial to addressing scientific and technological bottlenecks in terms of material and structure. Agile and close cooperation between supply chain members is also required to upgrade the battery technology along the complete value chain of resources mining, materials synthesis, cell design, pack design, manufacturing, use, and recycling, and creating a more efficient and resilient battery ecosystem.

Integration of power and transport system

Lead author: Neven Duić

- EVs can improve integration of variable renewables if connected when parked to smart chargers
- Smart chargers should be added to each parking spot to enable the power-transport coupling
- Wholesale and retail markets could be dynamically price coupled to allow the use of EVs for demand response

Emerging renewable energy solutions drive the electrification of transport

Wind and solar are becoming the leading new power generation technologies, with 80% of added capacities since 2020 [14] and heading for an even higher share in the coming years. At the COP28 held in Dubai in 2023, a Global Pledge on Renewables and Energy Efficiency together was proclaimed by the EU, with the COP28 Presidency and 118 countries supporting it and announcing the goal to triple the installed capacity of renewable energy and to double the rate of global energy efficiency improvements from roughly 2% to an annual figure of 4%, by 2030. The pace of advancement of variable renewables (VRES) is unequal in different countries, which depends on several factors, including the local potential of wind and solar, local abundance of conventional energy sources and/or policies which may be enabling or creating barriers [15]. In 2023, several North-Eastern Brazilian states, together with several mid-Western US States, Scotland and Denmark, already have more than 50% share of wind in electricity supply, Rio Grande do Norte being the highest, with three times the local energy demand. Solar is a latecomer but is now growing more rapidly than wind, with Tokelau being the first 100% solar nation and several more states, provinces and countries above 10% [16].

Integration of up to 20% wind and 10% solar can usually be done by flexibilisation of the existing power system. Still, more than that means balancing VRES by interconnectors with neighbouring territories, mainly done now, or by using demand response (an immense potential exists in already present electric water heaters, heat pumps, fridges, etc.) and storage [17]. Going above that level of VRES creates an excess of electricity in some hours, which may be traded away, stored, or used in additional demand, which will stem from the electrification of heating, transport and production of green hydrogen needed for decarbonisation of industry and making hydrogen-based fuels and industrial feedstocks [18]. Which way it will go depends on many local factors, like periodicity of VRES (solar in the tropics is periodic, so ideal for storing in batteries), potential for demand response (heating in the Northern hemisphere is 40% of final energy demand and storing hot water is cheap) but mainly from policies and planning. Demand response by sector coupling is more affordable and environmentally friendly than batteries, but batteries need less planning and policy [19]. In contrast, the integrated energy system must be carefully planned for low wind and solar generation. It includes distributed storage and flexibility options, depending on the climate and potential in the observed system [20].

The increasing share of VRES in power systems decreases the marginal price of electricity when an hourly share is high since VRES have zero variable cost (no fuel) [21]. That creates the so-called duck curve (in the case of solar when, during the day, all electricity is supplied by solar). The excess may be traded away, curtailed, stored, or it may create additional demand. When the electricity price falls under 20 EUR/MWh (22 USD/MWh), electricity is cheaper than biomass at the same calorific value. In places where heating, including sanitary hot water, is a significant part of demand and solar insolation is significantly seasonally variable, a power-to-heat demand response may be created if the retail price is coupled with wholesale and there are no regulatory barriers [22]. Governments should remove the barriers to demand response and create flexibility opportunities and markets to minimise the future cost of decarbonisation [23]. While the power-to-heat demand response starts in areas where heating is needed, the power-to-transport demand response will come later.

Energy demand and charging infrastructure

The electrification of transport has started, and plug-in electric vehicle (BEV+PHEV) sales reached 13% of global light vehicle sales. Share of two and three-wheeler sales in China has reached 50% of the worldwide market in 2021 [24]. Commercial vehicles are also starting to electrify; city buses, local delivery trucks, construction, city fleets, and long-distance semi-trucks are beginning to appear on the market. Short distance maritime transport like ferries has started to electrify. Short-distance aviation may also electrify [25]. Medium and long-distance marine and aviation transport will probably need some kind of biogenic or green hydrogen-based fuel, which may be produced in a bio-e-refinery, or it might also be made on demand in ports or airports [26].

Complete electrification of road transport will increase demand for electricity between 20 % [27] and 40 % depending on the share of electrification and the composition of the transport system [28], for example, taking into account only personal and light vehicles or innovations in the long-range transport as well. The production of green hydrogen and hydrogen-based fuels will increase the electricity demand by another 25% [29], which can be further improved depending on energy efficiency, modal shift and electrification in the integrated energy system. Both demands are mostly not time-critical [30], apart from public transport, open road and ferry port chargers [31].

All these will need adequate charging infrastructure and better grids [32]. The three-pronged philosophy can be recommended for planning the development of charging infrastructure and its interplay with the power grid transmission and distribution, based on expert and consultant studies [33]:

- Integrated approach to planning the power grid and the charging grid for EVs.
- The charging process needs to be managed by the system (through smart charging and V2G), with appropriate business models in place, including TSO-DSO cooperation.
- Careful scenario analysis of the bottlenecks and integrated energy systems' operation needs to be employed to plan the grid expansion.

The share of different reasons for taking a drive differs significantly throughout the countries in the European Union [34] and especially in comparison to the United States [35]. Overall, most drives are for commuting or short-distance errands like shopping trips. More than 64 % of the driving is for less than 10 km, while only 2 % is for more than 80 km [35]. Charging quickly when driving long distances is critical, so fast on-demand chargers are the rule. These charging stations must be built to provide for peak transit periods and discharges, which may be many times higher than average [36]. The trend is the increase of charging power of fast chargers, from 50/120 kW to 250/350 kW [37], towards the MW level when electric trucks appear on the highways [38]. For example, a 3.75 MW MCS standard for charging heavy-duty electric vehicles was developed [39] and presented [40]. To aid in flexibility and to minimise the operational and investment costs, the charging providers may implement hybrid systems with stationary batteries that accumulate energy and avoid peak loads [41] or be guided towards regulated and smart charging solutions to limit the influence of >1 MW chargers for heavy-duty trucks[42], which require case-by-case planning, also depending on the telemetry of such vehicles along their operational routes[43]. The build-up of this variety of hybrid systems will be the result of the relation between the CAPEX into batteries and the electrical grid. In the long term, the ratio is expected to be more in favour of expanding the grids.

On the other hand, when used for daily commuting, cars are parked 95 % of the time [44] and drive 60 km daily in the US [45], between 32 and 84 km in the EU [46], [47] 52 in China [48]. How do we charge them? While commercial charging companies may push for high-profit fast charging, consumers will tend to charge at home [49], and charging at work may become a significant employee perk. Since the charging time is not essential, slow charging is acceptable if that means no hassle (like idling fees). Electricity will be costly when wind and solar energy are not abundant (>100 EUR/MWh) and very cheap (<10 EUR/MWh) when they are overabundant [50]. Wholesale price spread is of an order of magnitude, sometimes two. Low prices will be whenever wind or solar is high, 3000-4000 hours per year. If properly coupled with retail markets, drivers will be incentivised to charge when electricity is cheap [51]. That will only be possible if most parking places have smart slow chargers. Thus, excess wind energy, when available, would be used to charge at home and solar at work, helping to valorise the excess VRES and hence helping energy transitions. Smart charging could help double the share of VRES in the power system [20]. A recent study showcasing various countries in the EU concluded that smart charging might effectively smoothen the charging demand profiles of large fleets of EVs, limiting the peak demand increase (that is expected due to transport electrification) to 30%–41%. In the case of Germany, this would mean a reduction in the average daily electricity demand peak of about 6 GW[52].

An alternative to the smart slow-charging business model is the demand (dumb) charging model. In the unlikely case of everyone wanting to charge an empty car at precisely the same time using a 7 kW charger, the needed power would be approximately double the presently installed power. If everyone would prefer a 50 kW charger, 14 times more power is required for 1 hour than is installed. Due to regular driving cycles, this will never happen, but even increasing power needed by 50% in times when no wind and solar are available will be expensive and environmentally wasteful compared to smart charging [53]. Dynamic road EV charging, which is being tested in various countries of the World (Germany, Italy, Korea, Sweden, UAE, and USA) on smaller portions of the highways, would have a significant influence on load shifting and aligning the charging of (in this case even heavy transport) with most abundant periods of the day, for example in collision with the generation from solar PV generators [54]. The flexibility introduced by the electric vehicles fleet has to be considered with the other flexibilities (electric water heaters, heat pumps, fridges, power-to-X...) to reduce the need for new production capacities and to operate as efficiently as possible the electric power system at lowest cost with low emissions [55], [20].

Electric vehicle batteries' role in the power system balancing

Vehicle-to-grid is a possibility to use car batteries to provide electricity when there is a lack of other sources [56], and price is high enough to cover the cost of decreasing the lifetime of car batteries [57]. System-level cost reductions incurred by V2G use primarily result from displacing stationary storage systems, and reducing the capacity of dispatchable generators, as well as altering the mix of renewable energy sources. Compared to traditional demand response programs, even with modest participation rates (5-10%), V2G technology generates savings over three times higher and displaces storage ten times more effectively. V2G's greatest advantage lies in aggressive emission caps, which decrease the need for surplus renewable generation capacity and expensive CCS technologies [58]. Many more technical standards, pilot applications and empirical research findings are needed to substantiate the application of these technologies.

Since the replacement cost of car batteries is higher than that of stationary batteries, the system will prefer stationary batteries for such situations.

Once car batteries fall to 80% of their nameplate capacity, they must be replaced. However, such batteries can have a second life when used as stationary batteries [59]. Also, other chemistries which do not have energy density as their primary design parameter could be used as stationary batteries to provide buffers for charging, fast response, daily storage, or market arbitrage [60]. Flow batteries are currently receiving the most attention globally as the preferred battery technology for large-scale long duration stationary energy storage and vanadium flow batteries, in particular, are already being installed in multi-MWh applications in grid-connected, off-grid and microgrid applications around the world, with China currently leading the world in vanadium flow battery implementation [61]. However, the more widespread implementation of this technology is currently limited by global vanadium supply issues and insufficient manufacturing capacity, which are being addressed with significant investment and government support in recent years. All these stationary batteries may compete with car batteries smart charging and correct mixture will depend on government and company policies and markets.

Car Industry: the challenges of a necessary speedy transformation

Lead author: Patrick Pélata

- The car industry is already engaged in a very fast but much-needed transformation; commercial vehicles are next in line for the transformation, with China already in a dominant position on electric buses.
- The transformation will be much slower in the service and maintenance sector of the 1.6 billion vehicles in operation worldwide today, happening over 25 to 35 years
- The transformation provides an opportunity for innovative newcomers to join the industry, with innovative companies in small countries providing value

Road mobility emits 10.5% of global greenhouse gasses (GHG) [62] and is still growing. So, no plan for a zero-carbon economy can avoid ways to move cars, light commercial vehicles (LCVs), trucks, buses and coaches out of fossil fuels. Because these vehicles stay in operation for more than 10 years on average, and a substantial proportion of them have more than 15 years, demands that an entire move to zero carbon for new vehicles must be achieved by 2035, 2040 or 2045 in countries which want to be net zero carbon in 2050 or 2060. This means this industry has 12 to roughly 25 years to entirely escape its almost exclusive dependence on fossil fuels for road mobility. That is a challenging, speedy transformation.

Furthermore, the global automotive industry is huge, accounting for approximately 5% of the world economy employing approximately 80 million people [63]. Total production output went heavily down from 2020 to 2022 because of COVID and limited semiconductors supply but has started to recover in 2023.

Table 4 Motor vehicles production (in millions)[3]

Countries / Regions		Volume 2019	2022 / 2019
Europe		**21.5**	**- 25 %**
	European Union 27 & UK	18.0	- 23 %
	Turkey	1.5	- 7 %
	Russia, CIS & others	2.1	- 49 %
Americas		**20.2**	**- 12 %**
	US, Canada & Mexico	16.8	- 12 %
	South America	3.3	- 11 %
Asia-Oceania		**49.3**	**+ 1 %**
	China	25.8	+ 5 %
	Japan	9.7	- 19 %
	India	4.5	+ 21 %

[3] OICA 2023

	Korea	4.0	- 5 %
	Others	9.9	+ 10 %
Africa		**1.1**	**- 7 %**
Worldwide		**92.1**	**- 8 %**

So how could such a heavy-weight industry transform itself in such a limited time without significant economic or social disturbances? Which challenges need to be overcome?

A speedy transformation is already on its way

After the Li-ion battery revolution made it possible to have safe electric vehicle that could travel a few hundred kilometres, regulations and financial incentives allowed the mass market to take off in China, Europe and parts of the USA. (See Figure 3).

Between 2016 and 2023, most carmakers could start production and selling EVs, with a few = in "automotive volumes", i.e., those above 100,000/year. However, well-established carmakers have been joined by newcomers, Tesla and BYD notably, the two-volume leaders of this new field in 2022. Interestingly, if we look at carmakers' market capitalisation [62] in mid-2023, Tesla (#1) and BYD (#4) are now ahead of Mercedes, BMW, Honda, GM, Stellantis, VW and Ford, close to Toyota (#2) and Porsche (#3).

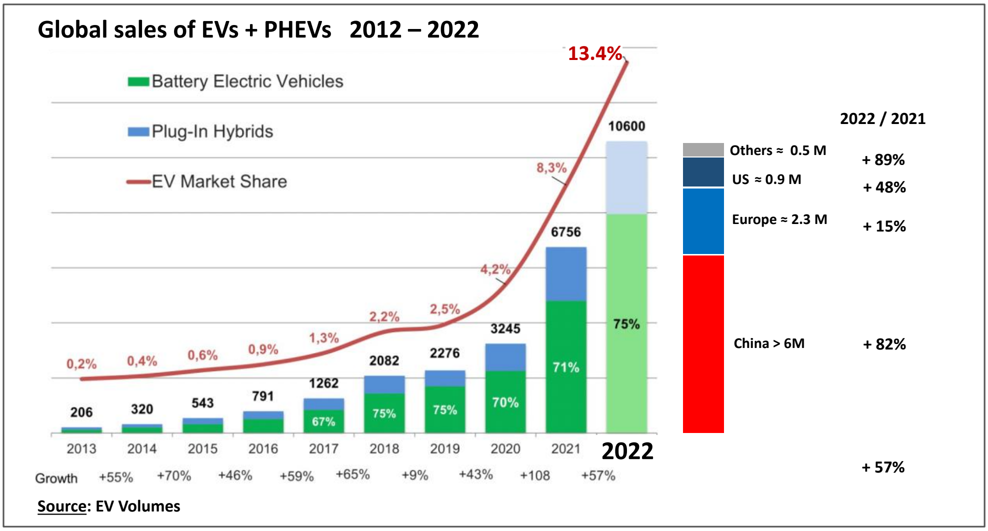

Fig. 3. Global Electric Vehicles Sales, distribution by region in 2022 and growth 2022 / 2021 [64]

A strong push from Public Authorities

The industry is transforming, partially on its own, partially with newcomers shaking up the traditional companies. The move has also been driven by public authorities' incentives and regulations for this latter. This is especially true in the European Community, where a stringent regulation of CO_2 emissions has been imposed, for the first time, heavy penalties for carmakers not reaching their target in 2020 and 2021. The decrease in diesel engine share following the VW diesel scandal 2015 made the target impossible to reach[4] without a 10 to 15% share of electric vehicles[5].

The European Commission, in July 2022, seeing that the European automotive industry had somewhat been able to start such a transformation in the years 2017-2022, decided to raise the bar in terms of CO_2 emissions targets for cars, LCVs and trucks in 2030 (-55%, -50% and -45% respectively) and even forbidding selling cars with thermal fossil fuels engines in 2035. The United States is on a similar trend but with a policy much more focused on supporting financial the production of EVs and batteries made in the US-Mexico-Canada through the Inflation Reduction Act of the President Biden administration.

In China, the *Energy-Saving and New Energy Vehicle Industry Plan (2012-2020)*, specifically, *Notice on printing and issuing the development plan for the energy-saving and new energy automobile industry (2012-2020)* [65], focused on Technology Development for New Energy Vehicles (NEVs)[6] and related components, Lithium-ion batteries etc. It also set the objective of a 5 million NEVs cumulative total production and sales by 2020 [65], which was almost met. The *New Energy Vehicle Industry Development Plan (2021-2025)* targets a 20% share of NEVs at the end of 2025 in the whole China fleet of passenger cars in operation, in addition to many other more technical objectives on batteries, car efficiency, etc.[66].

Changes from Internal Combustion Engine vehicles to Electric vehicles (ICE to EV)

Whereas the interior and exterior body parts do not change much, many car components will disappear when new ones are needed.

Table 5 Components evolution from ICE car to BEV

Disappearing	**No or limited change**	**New**
IC Engine	Interior equipment	Battery pack & Management System
Transmission (only 1 gear in an EV)	Electronics, ADAS, low voltage wiring	Electric Motors
Exhaust system	Axles & Suspension, Tires & Wheels	Power electronics, incl. Invertor
Tank and fuel distribution	Braking system	Heat pump (battery & interior cabin)
Engine Cooling & Air Cond. (current solutions)	Car assembly	High Voltage wiring

[4] A diesel engine is emitting 10 to 15% less CO_2 than a gasoline engine for the same car.
[5] Up to 2017, the European average CO_2g/km was decreasing in direction of the 95gCO_2/km to be reached in 2021. From 2018 this global average of new cars sold over Europe went up with the double effect of less diesel engines and more SUVs. Not reaching the 2021 target would have led OEMs to pay very important fines above a B€ for the biggest OEMs. Therefore, the only solution was to launch EV and PHEV programs before 2021. Given the way Europe calculates the score on gCO_2/km of each company, 10 to 15% of EVs & PHEVs was necessary not to pay these big fines.
[6] In the Chinese context, new energy vehicles (NEVs) are battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs; extended-range electric vehicles included), and fuel cell electric vehicles (FCVs).

Impact in terms of cost/ value		
22-24% of a traditional ICE car cost. More in hybrid and plug-in hybrid cars	Very limited cost difference: The body is white and the chassis + because of weight increase, but car assembly – thanks to fewer components to assemble	Motor, power electronics & high voltage wiring become ≈ half the cost of ICE and auxiliary. The battery pack is the main added cost: 8,000$ in 2020, 4,000$ in 2030 (for a 50kWh battery) [67]

For engine and transmission, as material cost is limited, we can estimate that 20 to 25% of the current auto industry added value will disappear over time while battery, power electronics and electric motor industries, mandatory for EVs & PHEVs, will develop at the speed imposed by European regulation. For battery gigafactories, for example, and only for 2030 Europe needs, it is estimated that 70 B€ (77B$) of investments will be required with an additional 70B€ for their upstream supply chain[7].

So, while 1/5 to ¼ of the current automotive industry will substantially decrease over the next 12 to 25 years[8], the new one will need R&D and production engineers, technicians and operators with very different skill sets. Training and adaptation of technical education are paramount, aside from easy access to financing for such big investments.

Newcomers versus traditional players, China versus traditional automotive industry strongholds

Newcomers' only focus is EV tech, manufacturing and sales, and they have innovated in these three fields. A few even took over innovative charging networks. Legacy auto powerhouses were much slower to move, and they also had to continue to focus on current ICE R&D, manufacturing and sales. The most profitable companies have deep enough pockets to finance a late surge of an EV line-up. Still, they have difficulties adapting their culture and transforming their R&D or company organisation, supply chain, plants and legacy distribution networks.

But one country, China, anticipated this transformation, and its leadership understood that the move to electricity was the opportunity of a shortcut to become an automotive world leader. A direction was given from the top, but a tough, Darwinian competition among the 100+ carmakers from the years 2010 finally gave birth to excellent companies along the whole EV new value chain, from Nickel and Lithium mining to refining these metals, manufacturing the cathode and anode active materials, building battery gigafactories and finally delivering modern, innovative EVs, impressing the whole global industry leaders in the 2023 Shanghai motor show and again in Beijing motor show in 2024[9]. A steady increase in Chinese EV exports is now following. The challenge to legacy carmakers and suppliers from the US, Europe, Japan and Korea is clear: innovative competition from newcomers and the Chinese auto industry.

[7] Investment for gigafactories range from 700M€ to 1B€ for a 10GWh/year capacity and forecasts for Europe range from 800 GWh to 1000 GWH/year.

[8] 12 years in Europe with the zero thermal engines in 2035. 20 to 25 years for the countries having a zero carbon target for 2060. As the carpark last 10 to 15 years or more, new car sales have to be 100% zero carbon in 2045 or 2050 at the latest. Some exemptions may be decided in some limited countries, but volumes would be significantly lower than what they are today.

[9] All automotive and general media

Conclusion

The car industry is already undergoing a fast but much-needed transformation, challenging legacy players and a more than century-old ecosystem. Commercial vehicles are following. With electric buses, the Chinese industry has already gained a dominant position. However, the transformation will be much slower in the service and maintenance of the 1.6 billion vehicles in operation worldwide, happening over 25 to 35 years.

Electricity or hydrogen for sustainable road vehicles?

Lead author: Bob Evans

- For passenger vehicles, battery-electric vehicles prevail in terms of efficiency and cost-effectiveness compared to hydrogen/hydrogen-electric vehicles
- When functionality is of larger importance – large vehicles, heavy transport, and military – hydrogen-based solutions are still in competition with the battery electric solutions

Both electricity and hydrogen have been proposed as alternative energy carriers for sustainable road vehicles to reduce greenhouse gas emissions. When considering these two approaches, comparing both carriers' overall energy "in-out" efficiency is instructive. Today, most commercial hydrogen is produced by reforming methane CH_4, in which case all the carbon becomes CO_2. To eliminate the use of fossil fuels, it would be necessary to use electricity generated from renewable energy sources, such as wind and solar power or from nuclear power plants. There are two potential ways to use this low-emission electricity to power road vehicles. The first case: batteries are now widely using lithium-ion or other high-efficiency batteries. In the second case, hydrogen, produced by electrolysis of water, is used as an intermediate energy carrier, with a fuel cell then used to convert the stored hydrogen back into electricity. Both cases are summarised in Figure 4.

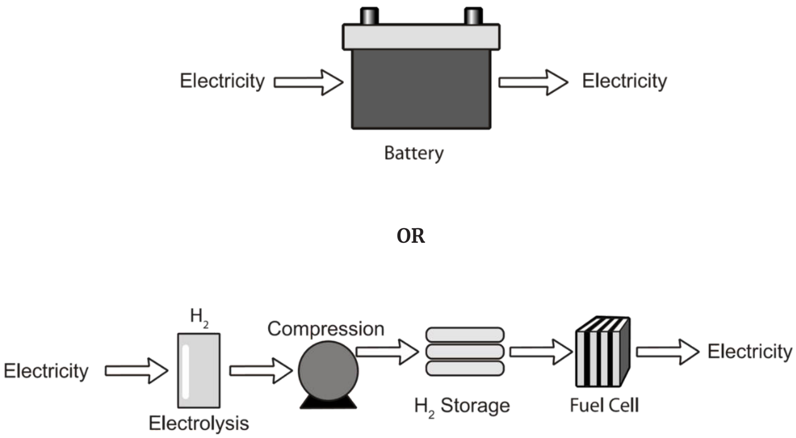

Fig. 4. Alternative Electrical Energy Storage Concepts

Although not all the process steps shown in Figure 4 are energy conversion processes, there is a loss of available energy associated with each step in the chain. To account for these energy losses, we may assign an "in-out" efficiency value to each step in the conversion chain. There is only one step for the battery between the input to the energy storage and output to the vehicle. Since about 10% of this energy is typically lost as heat during the battery charging, we can assign an "in-out efficiency" of 90% to the battery. For the hydrogen storage case, it takes about 8% of the total energy content of the hydrogen to compress it to the pressure used in the storage cylinders. For every 100 kilojoules of hydrogen energy produced by electrolysis, the net energy content of the stored hydrogen is around 92 kilojoules. In more detail, other products are addressed in the E-fuels chapter. The in-out efficiency for each of the steps in the two, equivalent energy "storage" processes of Figure 4 is shown in Table 6 for comparison. The efficiencies of each step are then multiplied together to get the final "overall efficiency" of the complete process, going from electricity "in" from the primary source to electricity "out" to the traction motor. With an assumed fuel cell energy conversion efficiency of 50%, the overall "in-out efficiency" for the hydrogen storage energy conversion chain is approximately 34%, compared to 90% for the conventional battery.

Table 6 Electrical "In-Out" Efficiencies

"In-Out" Efficiency Comparison			
Fuel Cell		**Battery**	
Electrolysis	75%	Battery	90%
Compression	92%	–	–
Fuel Cell	50%	–	–
Overall Efficiency	***34%***	Overall Efficiency	***90%***

This simple analysis indicates that with batteries with sufficient energy storage capacity to provide a reasonable vehicle range, the battery electric vehicle would be a much more attractive alternative to a fuel-cell-powered vehicle.

Suppose the electricity used to charge the battery is generated primarily by sustainable primary energy sources, such as renewable or nuclear power. Road transportation would no longer significantly contribute to greenhouse gas production. Of course, once significant numbers of these vehicles enter the market, shifting much of the transportation energy requirements from petroleum to electricity, there would need to be a substantial expansion of low-emission electrical generation capacity. An added benefit to utilities of such a shift would be an improved load factor by spreading the electrical load more evenly during the day. With many commuters plugging their cars in for recharging overnight, the increased electrical load, which is usually low at these times, would ensure that electrical generation capacity is better utilised. This "load-levelling" could significantly improve utility load factors, reducing electricity generation costs. However, in countries with a high proportion of solar generation, generation capacity will be low at night, so that daytime charging would be desirable. Passenger transport is moving towards the battery electric vehicles due to cost and efficiency. However, heavy transport of goods is still the field where hydrogen-based solutions can have fruitful ground. Hydrogen use is also needed in other sectors, such as industry (especially high-temperature processes with the need for a longer duration of more significant energy intensity compared to the electric arch technologies) and the buildings sector. Therefore, its abundance and availability for the transport sector depend on the scale and the process of its utilisation in other sectors.

Other important issues that need to be addressed are: storage and functionality. The question of effective storage remains (as current solutions include compression in cylinders or hydrogen liquefaction). There is space for solutions in terms of novel storage applications. However, the issue has been on the table for 20 years, but so far, solutions involving methane have shown better results. The global warming potential (GWP100) of hydrogen is around 20 times that of CO_2 in the worst case [68], while recent studies estimate it to be 11.4 (+/- 2.8) [69]. However, potential hydrogen leakage into the atmosphere during electrolysis, storage and transportation needs to be considered to ensure that the impact of hydrogen on global warming does not exceed current CO_2 emissions.

When functionality is more important than cost and efficiency, hydrogen applications can also come out on top. However, due to handling issues, methanol and similar liquid fuels might come on top as a solution. Examples of such uses include military uses. Hydrogen solutions find space between batteries and e-fuels.

E-fuels other than hydrogen

Lead author: Iva Ridjan Skov

- The integration of fluctuating renewable energy requires storage solutions to achieve a robust system that can meet the demand, with fuel storage being one form of storage that serves the integration of e-fuels.
- Ammonia is the most promising alternative fuel in the maritime industry due to the fuel needed and CO_2 availability limitations.
- Carbon-based e-fuels are to be primarily used for aviation with limited heavy-duty road transport applications, highly dependent on battery development and direct hydrogen application.

The concept of e-fuels has gained increasing interest as systems thinking has become the new norm for integration of renewable energy sources into the entire energy system. Redesigning energy systems from a linear approach, where different demands are met by directly using fossil fuels, toward smart energy systems, which introduce a cross-sector approach, is vital in reaching the 100% renewable energy goals [70].

Conversion of the transport sector is challenging due to the vast types of transport modes, needs and number of transportation units. Finding a solution for the hard-to-abate parts such as heavy-duty road, shipping and aviation, which cannot be easily electrified, resulted in a decades-long focus on utilising conventional biofuels as a direct replacement for oil products [71], [72]. However, as biomass represents a desired fuel for all sectors and is a limited resource, its implementation must be restricted to parts of the energy system where other alternatives are not feasible [73]. Diversification of feedstocks for fuel supply therefore becomes an integral part of ensuring the security of supply.

The integration of fluctuating renewable energy requires storage solutions to achieve a robust system that can meet the demand, with fuel storage being the cheapest form of energy storage [19]. The transport sectors uses large amounts of complex hydrocarbons, and introducing an alternative means of combining carbon and hydrogen allows for integrating variable energy sources into the grid and expanding renewable capacity and balancing. The transport sector's role thus changes from a primarily demand-driven industry to a system flexibility agent.

E-fuels, electro fuels, Power-to-X (PtX), Renewable fuels of non-biological origin (RFNBOs) and hydrogen-derived synthetic fuels all, to a certain extent represent the production of e-fuels based on electrolytic hydrogen paired with a carbon or nitrogen source [74] (Fig 5). Carbon sources can be either fossil (industrial point sources) or biogenic, which are sourced from either biogenic point sources or directly from biomass through biogas or biomass gasification. To meet the fuel demand for carbon-based fuels, Carbon Capture and Utilisation (CCU) technologies are needed to provide the needed carbon. Mikulčić et al. (2019) [75] provide an overview of different carbon capture technologies that can be applied. Using carbon capture technologies such as oxyfuel combustion in combination with electrolysis is beneficial for closing the material balance, as oxygen as a by-product of electrolysis can be utilised for the combustion process. It is still debated whether carbon capture from fossil carbon sources should be used for e-fuel production, as EU legislation does not necessarily recognise this as a green fuel.

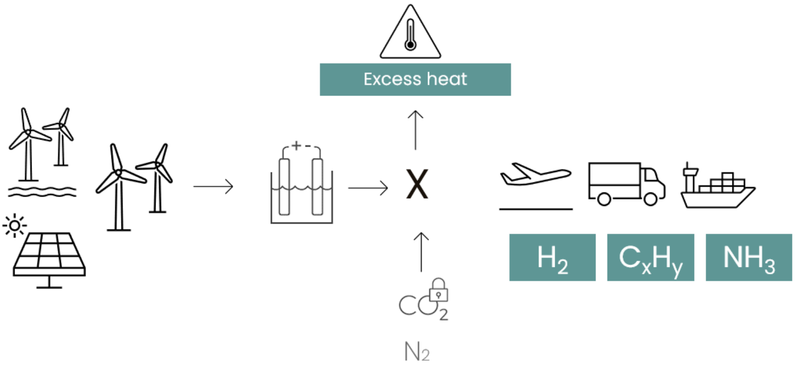

Fig. 5 e-fuel production pathways

Nitrogen, sourced by air separation units, produces ammonia (NH_3). Ammonia eliminates the dependence on carbon sources, which will, in the future, become limited, apart from capturing carbon from the air with direct air capture (DAC) technology. DAC is a promising technology as it can tackle even accumulated atmospheric emissions. However, it is relatively energy intensive, with high costs [75].

Efficiency is not a strong asset of e-fuels, as it is highly dependent on the low efficiency of electrolysis requiring large amounts of renewable energy and high water quality, further coupled with fuel synthesis of different kinds ([76], [77], [78], [79], [80], [81]). Further application of e-fuels in ICE engines lowers the overall efficiency due to the limitations of the Carnot cycle. In addition, the regulatory framework is still in development, and minimising the cost gap represents some of the critical non-technical challenges e-fuels face. However, e-fuels represent lower land and water demands than biofuels [82]. E-fuels have also gained vast interest from industrial actors as the needed length and complexity of e-fuel value chains allow for the involvement of a greater variety of players in the field compared to conventional fuels.

Production of e-fuels also allows for the integration of excess heat flows from electrolysis and fuel production into district heating grids if available [80]. Establishing industrial symbiosis is also possible, especially in cases where there is a potential for excess heat integration and utilisation of oxygen generated during hydrogen production. Vast oxygen production can be used for various applications, for example, in water treatment plants [83] or for oxyfuel combustion and carbon capture [84], as well as in the medical sector, aquaculture and metal production. The end fuels discussed across the sectors have been limited to methanol and ammonia for marine applications, e-jet fuels for aviation, and partly methanol for heavy-duty road transport [85], [86], [87].

Ammonia is most interesting in the maritime industry as a promising alternative fuel due to the quantity of fuel needed. Forty-five percent of the new orders for ships in the shipping sector are for vessels powered by alternative fuels. Among these, 23% are dual-fuel methanol vessels; four vessels are designed to run on ammonia. International and domestic shipping uses approximately 300 million tonnes of fossil fuels annually, making non-carbon-based fuel a more exciting alternative [88]. However, e-ammonia can also be used as a green fertilizer, which could create a competitive market for ammonia. The future ammonia price is expected to be lower than for hydrocarbon e-fuels [89]. Even though ammonia is widely used as a fertiliser and a commodity chemical, it has yet to be tested as a fuel for shipping. There are many developments in applying ammonia as a marine fuel from prominent actors such as DNV, MAN Energy Solution, NCL, Yara, and Mitsubishi Heavy Industries. Bunkering ammonia can increase the risks, therefore, developing on board safety and risk avoidance regimes is needed [90], [91]. E-ammonia offers an option to eliminate CO_2 emissions from the shipping sector, which has set a target to be carbon neutral in 2050 [92]. However, there is still some development to accommodate the ammonia-related emissions, NH_3 slip, N_2O and NO_x that current emission management technologies cannot provide [93]. On the other hand, E-methanol enables a 95% CO_2 emissions reduction on well-to-wake [94] and is seen as a valid alternative and potentially a transition fuel for parts of the sector, including ferries and fisheries and parts of shipping.

Carbon-based e-fuels are primarily used for aviation but have limited application for heavy-duty road transport, depending on battery development. The transition of aviation based on alternative propulsion technologies will play a relatively small role. At the same time, the continued use of jet fuel requires the development of alternative production pathways, such as e-fuels. Aviation e-fuels can be produced via Power-to-liquid (PtL) routes using Fisher-Tropsch processes or via Methanol-to-jet routes. According to [95], the current TRLs of PtL routes range between 5-8, indicating maturation from technology development and demo stages towards deployment. For example, Exxon Mobile and Haldor Topsøe work with methanol-to-jet routes [96]. Future perspectives from IATA indicate that PtL pathways will play a significant role in meeting the aviation demand.

The application of methanol in combustion engines has been researched for many years, indicating nearly soot-free combustion with extremely low NOx emissions and reductions in CO and PM emissions ([97], [98], [99]). Geely, a Chinese truck producer, launched a methanol truck in 2019 [100], and 100 trucks have been on the road in China since 2022 [101]. In Denmark, Geely's first EU methanol truck is being tested [102]. However, several truck manufacturers focus on electrification and hydrogen-powered trucks (IVECO, MAN and Volvo); therefore, methanol is not necessarily expected to have large-scale applications in the future haulage sector.

Modal shift: can it help?

Lead authors: Vaughan Beck and Chris Hendrickson

- Active transport options like cycling (including e-bikes and e-scooters) and walking can offer highly cost-effective options to contribute to decarbonisation in the transport sector.
- Sharing travel in a single vehicle can readily reduce the greenhouse gas emissions per passenger kilometre of travel and is becoming more popular.
- In freight transport, rail and water transport have the lowest emissions per metric ton-kilometre, with heavy-duty trucks having significantly larger emissions than rail and medium-duty trucks somewhat higher yet. Still, the transition cost, travel time, and reliability are a primary concern. Air travel has relatively high energy costs and emissions.

Introduction

Vehicle electrification with clean energy and low-carbon alternative fuels are common strategies for achieving transportation decarbonisation, but shifting travel to modes with low or minimal emissions can also be effective [103], [104]. Reducing travel altogether through options telework or virtual meetings can also reduce transport emissions, although telework may divert commuters from transit or induce other travel [105]. This chapter is intended to consider the potential of these alternatives to vehicle modifications, beginning with active transport followed by shared ride passenger transport and freight modal shifts.

Modal shifts in travel are evident over long periods. Railroads only became available in the 19th century, while motor cars and aeroplanes came in the 20th century. Light-duty vehicles have become prominent in passenger travel share over time. Figure 4 shows the growth in light-duty vehicle modal share in the United Kingdom from less than 30% of passenger kilometres in 1952 to over 80% in recent years [106]. During this period, travel increased from 218 to 645 billion passenger kilometres. Other countries also exhibit a shift to greater reliance on motor vehicles over time. Not included in Figure 6 are walking trips undertaken daily for short-distance travel.

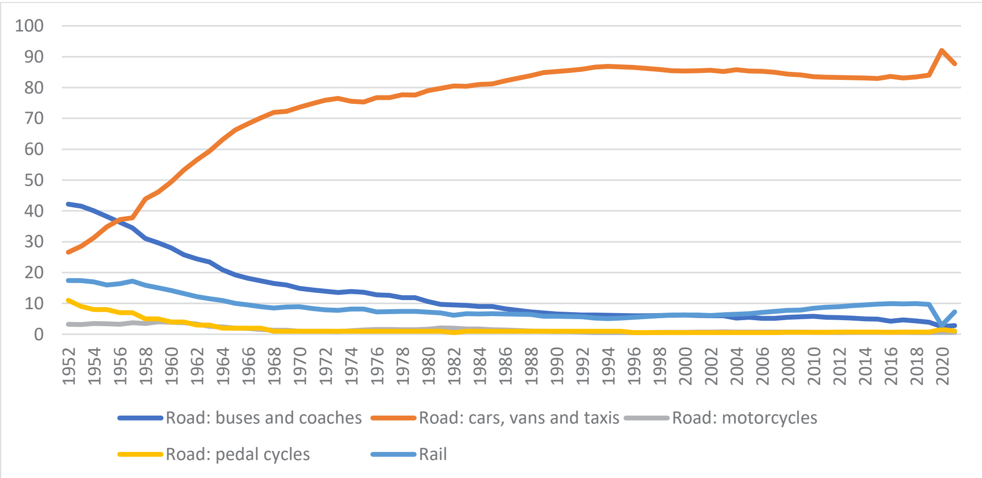

Fig. 6 United Kingdom Passenger Modal shares as a Percentage 1952-2021. Attribution: Authors. Source of Data: UK Department for Transport table code: TSGB0101 [%], [106]

Even with a predominance of light-duty vehicle travel overall, modal shares have considerable variability within and across countries. Urban areas have higher proportions of public transportation. Higher-income countries have higher levels of motor vehicle use. While modal choices are challenging to change significantly, public policies and individual decisions can influence travel modes, energy use and greenhouse gas emissions.

Active transport

Active transport (AT) modes, namely cycling (including e-bikes and e-scooters) and walking, can offer highly cost-effective options to contribute to decarbonisation in the transport sector. AT can also deliver significant co-benefits such as improved human health, and reduced traffic congestion, air pollution and noise. Furthermore, there is considerable complementarity between AT and public transport (refer to section 3). In the USA, e-bikes are outselling electric vehicles (in Europe, this outselling has occurred in recent years) [107]. Accordingly, policy interest in active transport (AT) has been renewed. In this section, consideration is given to the potential scale AT can contribute to decarbonisation, the associated health benefits and the identification of actions that can help achieve some possible benefits.

It was noted in a recent publication [108] that a shift from car to active travel is possible for trips up to 16 km in length, and those trips are responsible for 40% of carbon emissions from all car trips (in medium-size cities). The share of cycling varies significantly between cities. Many factors influence these outcomes, including the provision of cycling infrastructure. One study found a non-linear association between cycling network length and cycling mode share in 167 European cities and where the asymptotic maximum cycling mode share was 25 per cent [109]. Global GHG emissions from light vehicles were about 3.3 Gt CO_{2e} in 2020 [110]. Given the high percentage of short trips made by car, the potential for AT to decrease GHG emissions is considerable. There is widespread recognition that the dependence on personal motor vehicles for transport has substantial and wide-reaching negative health impacts. Mode shifting from personal motor vehicles to AT can lead to substantial reductions [108] in overall mortality, cardiovascular diseases, cardiorespiratory morbidity, cancer, and type 2 diabetes.

Given the potential environmental and health benefits associated with AT, numerous studies have been conducted to quantify these benefits. Results from a recent study [111] show that a mix of policies maximises the net economic benefits (using benefit cost ratios), and these include bike-sharing, cycle parking, training and education, low-traffic neighbourhoods, e-bike grants, a workplace parking levy and increased use of a 'cycle-to-work' scheme. Additional measures that can help promote safe cycling and walking include the following [108]:

- Redesign urban spaces that meet daily needs related to accessing facilities and amenities within distances that can be reached safely by active mobility.
- Provide appropriate infrastructure for safe walking and cycling.
- Provide trip-end facilities, such as changing rooms at workplaces and secure parking for bikes.
- Provide green spaces, parks and trails, and forms of urban revitalisation.
- Reduce car dependency through better land use, urban planning, efficient public transport and disincentivising driving.

A related study [112] recommends reallocating space for cycling and walking, improving active mobility infrastructure, and increasing cyclist and pedestrian safety to reduce fatalities. Such recommendations include the development of national cycling strategies, policies and regulations, providing sustainable funding to construct user-friendly and safe infrastructure and integrating cycling into health policies and urban and transport planning. AT solutions cannot be considered in isolation. To achieve a greater uptake of AT, it is essential to integrate and deploy a range of strategies supported by strong policy and regulatory frameworks [113].

Many barriers exist to moving away from car-based transport and towards bike riding. In a recent peer-reviewed review paper [114], it was found that some of the leading barriers to adults riding a bike for transport in OECD countries were safety (perceived injury risk and riding on roads with high traffic density), infrastructure (poor condition of dedicated bike lanes and roads); environmental factors (weather); and, personal and attitudinal factors. Recognition of these factors will permit more informed decision-making regarding cycling infrastructure, the development of promotion campaigns and policy reform.

To advance active transport, robust policy-relevant evidence is needed to understand how to change behaviour and support decision-making by policymakers and practitioners. A global-first priority-setting exercise for active transport was undertaken [115]; this study also identified new policy-relevant areas of research, funding, policy-making and practice for active transport in Australia.

Shared Ride Passenger Transport

Sharing travel in a single vehicle can reduce greenhouse gas emissions per passenger kilometre. While extra weight from additional passengers can reduce energy efficiency per kilometre, this reduction is very small compared to the energy required for multiple single-occupancy vehicle trips [116]. Shared rides can occur in private vehicles, for-hire vehicles, urban mass transit and inter-city transport modes.

As illustrated in Figure 6, shared ride modes such as bus and rail have been declined over time for passenger kilometres of travel share in the UK. Similar trends exist elsewhere. A fundamental difficulty for shared rides is to match origins and destinations. Occasionally, this matching is straightforward, such as when a family travels together. However, urban mass transit and shared-for-hire services often involve extra travel time and distance. In addition, travellers usually prefer the privacy of a single occupancy vehicle, especially with fears of disease or security.

For urban mass transit, adequate travel demand is a critical [117]. Buses and trains require considerably more energy and have higher emissions per kilometre of travel than light-duty vehicles. If vehicle loads are sufficiently high, this extra energy use and emissions per kilometre of vehicle travel can be allocated to many passenger kilometres. However, vehicle load factors can be low during off-peak periods or in low population density areas, resulting in high costs, energy use and emissions per passenger. Similarly, shared ride-for-hire services require adequate demand to make up for lower fares for travellers. In the EU, air travel requires 160 gCO_{2e}/passenger-km, cars 143 gCO_{2e}/passenger-km, bus 80 gCO_{2e}/passenger-km, maritime 61 gCO_{2e}/passenger-km and trains 33 gCO_{2e}/passenger-km [118].

A variety of policy levers exist to encourage ride-sharing. Examples include information dissemination, subsidies for urban mass transit, land use restrictions to increase population density, special lanes for high occupancy vehicles to avoid congestions and tolls on private vehicle use [104]. Many of these policy levers have been implemented. However, the average private vehicle occupancy has generally not been increasing, nor has the share of trips in urban mass transit.

With the introduction of electric vehicles powered by clean energy and low-carbon liquid fuels, the ride-sharing emissions are correspondingly reduced. As a result, the long-term emissions reductions from ride-sharing encouragement policies are relatively modest if vehicle electrification with clean power generation goals is achieved.

Freight Modal Shifts

The emissions of current freight movements vary considerably over space and time, especially with different vehicle capacities [119]. Moreover, estimates of efficiencies and emissions are uncertain. Rail and water transport have the lowest emissions per metric ton-kilometre, with heavy-duty trucks having significantly larger emissions than rail and medium-duty trucks, which are somewhat higher yet. In the EU, the emissions are 1036 gCO_{2e}/tonne-kilometre for air, 137 for trucks, 33 for inland waterways, 24 for rail and 7 for maritime shipping [118].

World carbon dioxide emissions from freight transportation were 7.6 Gt in 2022 [120]. While there was a decline in emissions during the COVID-19 pandemic, the trend of freight emissions has otherwise been steady growth, with 5.8 Gt of emissions in 2000. Roadway transport was the largest share (5.9 Gt), followed by shipping (0.8 Gt), aviation (0.7 Gt), pipeline (0.2 Gt) and rail (0.1 Gt).

While there have been improvements in vehicle efficiency, the primary reason for the growth in freight transport emissions has been the growth in the underlying quantity of freight shipments [121].

The modal share of freight movements also varies among regions and countries. For most countries, trucking is the primary mode of freight movements an exception is Russia, where rail transport dominates. Rail freight modal share is relatively low in China and the EU but higher in North America and India. The availability of rivers for water transport influences the modal share significantly.

As with passenger travel, various strategies can be used to reduce emissions from freight movements [119]. Electric vehicles and low-carbon fuels are of widespread interest, although rail, ship, and long-distance trucking are challenging to rely on batteries due to significant energy requirements. As a result, fuel cells and low-carbon liquid fuels are of considerable interest. Efficiency improvements in routing and material handling can be beneficial in both reducing emissions and costs. Reducing the amount of freight moved can also help with approaches such as local procurement or distributed manufacturing. In addition, shifting freight to different modes is a possible strategy.

Shippers make decisions about modes to use based on the expected level of service. Cost is a significant concern, but also travel time and reliability. Investments in transport infrastructure can influence the predicted shipping level of service. A considerable shift to rail and water freight movements could reduce transportation emissions, but the investments needed to accomplish such a shift can be immense.

Last-mile freight delivery has different characteristics and opportunities than line-haul freight shipping. Delivery services must balance the economies of consolidation of packages with the speedy service customer’s desire. Again, routing and inventory efficiencies can be helpful for last-mile services. Modal shifts, such as electric drones or pedal delivery vehicles can also play a role.

E-mobility in developing countries

- Policies for the transition of the transport sector towards e-mobility are being promoted by almost all countries in Latin America (LA), leading to an increase in sales of EVs.
- Local abundance of critical minerals can allow some LA countries to facilitate integrated industrial approaches.
- In Africa, insufficient regulatory mechanisms and low incomes, long travelling distances, and lack of infrastructure pose barriers to e-mobility.
- International support will be needed to facilitate the transport transition in Africa.
- In South and Southeast Asia, two and three-wheelers are used in road transport, which helps in reduce pollution. Still, there is also significant legislative support and industrial development (especially in Thailand and Indonesia).
- Lack of infrastructure and currently still relatively high cost of EVs impedes the transition in South and Southeast Asia.

E-mobility in Latin America

Lead author: Jaime Domínguez

Introduction

Virtually all Latin American countries are taking steps to reduce greenhouse gases and environmental pollution from cities. Although it is not an exact norm, in countries with lower incomes or with cheaper fossil fuels, the measures are more limited or have been taken later. In other countries, usually those with greater economic capacity, the development of public policies has been greater. Those who are more advanced in the development of e-mobility, as is the case of Costa Rica, Colombia, and Chile, have been promoting its growth for years both in the public transport sector and in private vehicles. Brazil and Mexico, with the largest population in Latin America, are a little behind in promoting EVs, but their population makes the increase larger than in any other country.

Other countries, such as Honduras and Guatemala, have been starting in the last two years. In any case, practically all countries are promoting policies for developing electric urban transport to reduce pollution in large cities as soon as possible. Brazil and Mexico, with the largest population in Latin America, are a little behind in promoting EVs, but their population makes the increase larger than in any other country.

Some features

Among the most outstanding features of the development of electric mobility in Latin America are the following:

- Compared to Europe or North America, the proportion of pollution due to traffic is higher in Latin America: more than 20% in Europe and the USA and more than 30% in Latin America.
- The electric vehicle market has grown fast in recent years. While the absolute numbers are still relatively low compared to other more developed markets, the trend is upward, with annual sales growth levels in many cases exceeding 100%. Growth is expected to continue in the coming years as awareness of sustainable mobility increases and more supportive policies are implemented.
- There are significant differences between some countries and others in the number of electric vehicles circulating, which is highly influenced by the country's population and market share.

- Although the absolute numbers are still relatively low compared to other more developed markets, in the case of public urban transport vehicles, such as buses and taxis, their development in some countries is higher than in European or North American countries. The case of Colombia and Chile is worth mentioning, with more than 1000 electric urban transport buses each and a significant fleet of taxis.
- Most countries have implemented and are implementing policies to promote the adoption of electric vehicles, some for more than 5 years and others have started in the last year. These policies include tax incentives, tax exemptions, purchase subsidies, and incentive programs for the installation of charging infrastructure. These government measures are intended to encourage the adoption of electric vehicles and reduce economic barriers for consumers. However, the scope of the measures and their impact on the promotion of electric vehicles is very different in some countries and others.
- Some countries, like Argentina or Chile, have developed plans to ban the sale of fossil fuel vehicles between 2035 and 2050; others, like Costa Rica or Paraguay, have strategic plans but do not consider banning the sale of fossil fuel vehicles yet and others have not yet developed any structured decarbonisation programme of this type.
- One of the critical challenges for adopting electric vehicles in Latin America is charging infrastructure. Although significant advances are being made in installing charging stations in urban areas and on major roads, there is still a need to expand and improve the charging network to increase the comfort and confidence of electric vehicle drivers.
- Automotive multinationals have not yet started to produce electric vehicles in the area, but they have begun to set up factories there. However, several automakers are already introducing electric vehicles to the Latin American market.
- Some local manufacturers have begun to develop electric vehicles in the region, such as Coradir, Sero Electric or Volt in the case of cars in Argentina, or Reborn Electric Motors, which has begun manufacturing passenger buses in Chile. This increased share of the local automotive industry is driving the advancement of electric vehicles in the Latin American market.
- In addition to charging infrastructure, there are other challenges to the widespread adoption of electric vehicles in Latin America. These include the high upfront cost of electric vehicles compared to internal combustion vehicles, a lack of awareness and education about the benefits of electric vehicles, and the limited availability of electric vehicle models and options at affordable prices compared to other markets.
- The incipient development of electric mobility means that statistics are sometimes not sufficiently detailed, combining fully electric vehicles (BEV), hybrids (HEV) and plug-in hybrids (PHEV) without distinction between them or HEV and PHEV without distinction, which makes it challenging to analyse the evolution of their development.
- The typical characteristics of the vehicle fleet in Latin America, with a percentage of motorcycles and mopeds as high or higher than cars in some countries, means that this proportion in the growth of these vehicles also extends to electric vehicles. At the same time, electric micro-mobility has also developed highly in many of the countries analysed here.

Evolution of the electric vehicle sales

Below are some graphs that present the sales of electric vehicles in countries with significant development within Latin America. Those countries in which the development of electric mobility is still embryonic, such as Venezuela, Honduras or Nicaragua, among others, have been excluded.

Figure 7 shows the number of fully electric vehicles sold in 2022 in different countries (author's data).

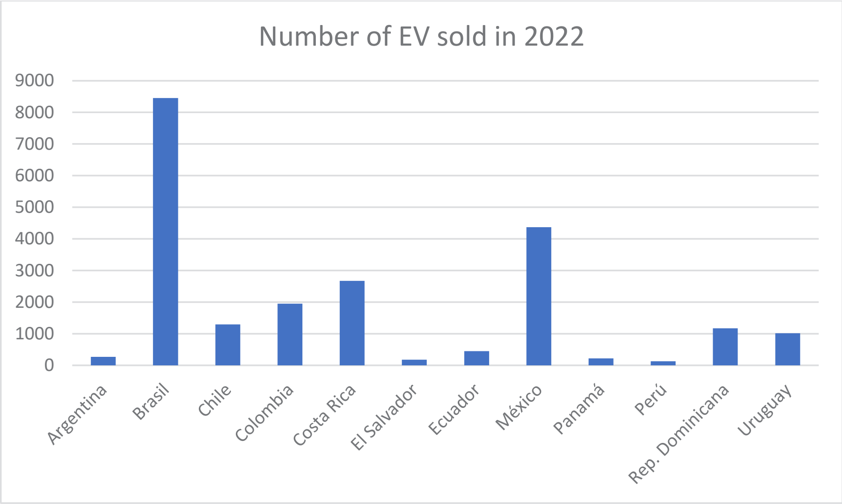

Fig. 7 Fully electric vehicles sold in 2022

It can be seen that Brazil and Mexico are the countries with the highest number of vehicles sold in the last year, mainly due to the more significant population and fleet of vehicles. However, the situation changes if sales data are analysed concerning the total number of cars sold, as shown in Figure 8. In that case, Costa Rica stands out at levels similar to Europeans and the Dominican Republic.

With the speed of growth of the electric vehicle fleet, figure 9 shows that in most countries, sales are growing at a rate of more than 100%. In this case, Mexico stands out, which has begun to have high growth in recent years, and Argentina and Peru, which have so far had lower growth in the last years, but now are starting to grow. So, in these previous two cases, getting a very high number of sales is unnecessary to achieve a higher percentage of growth.

According to these data, it can be said that the development of electric mobility has begun to develop in an orderly manner at an uneven pace except for Costa Rica, which is more advanced, and the countries that are still in incipient development, the rest develops a growth rate similar to that existing in Europe about 5 to 7 years ago.

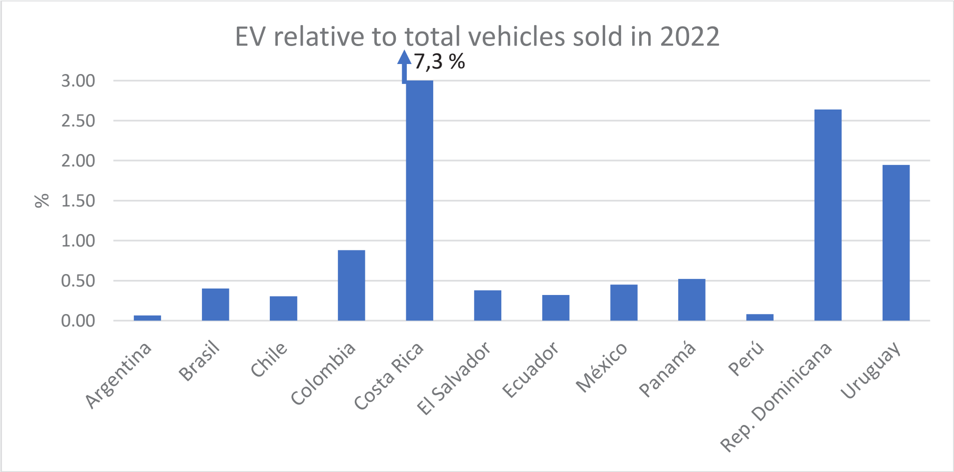

Fig. 8 EV sales relative to total vehicle sales

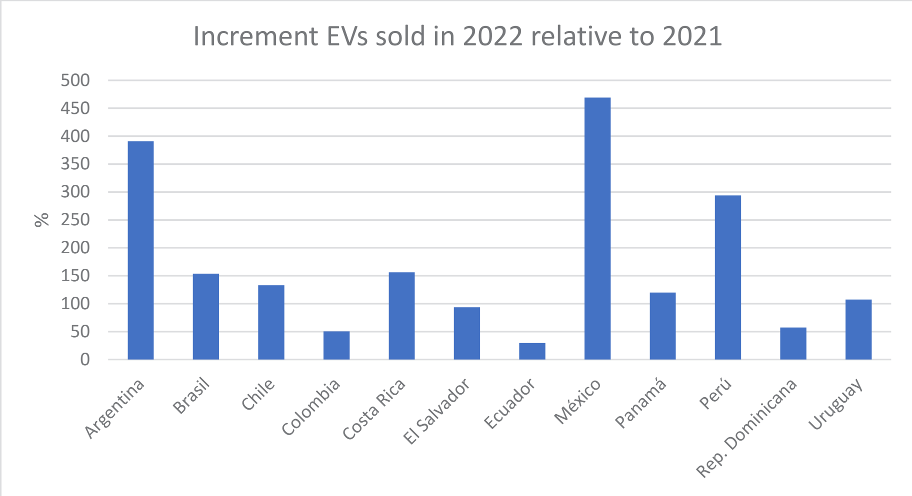

Fig. 9 Increment EVs sold in 2022 relative to 2021

Charging stations

Governments are taking measures to promote the installation of charging stations on public roads and in private garages. They are being installed and dispersed to cover the entire territory as much as possible. On the other hand, in different countries, the busiest roads have been selected, and corridors have been established in which charging stations have been installed at distances between 70 and 100 km. The current situation can be seen in Figure 10, which shows the number of charging stations currently existing in each country, standardised, in the absence of the total number of existing electric vehicles in each country, with the number of vehicles sold in the last year, which is generally between a third and a fifth of the total existing electric vehicles.

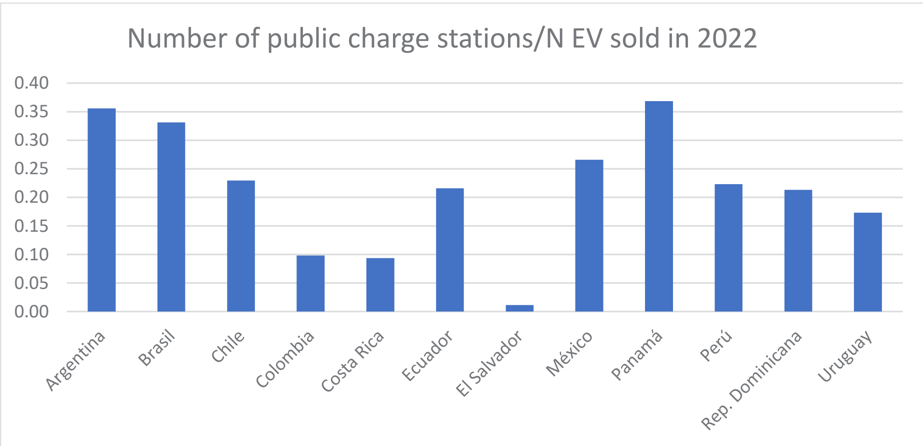

Fig. 10 Public charging stations relative to the number of EVs sold in 2022

Considering that there is also a high number of private charging stations, it can be said that, with limitations, the demand for installed public stations is currently satisfied. In any case, practically all countries are currently developing programs for the installation new charging stations, which will at least double the number of existing ones in the coming years.

Regulations on electro-mobility

All the countries analysed have laws that promote the use of electric and hybrid vehicles, usually through tax incentives, regulations for the development of charging station networks on public roads and other provisions. Some have achieved more significant effects than others, depending on the incentives established and their relationship with the country's socio-economic conditions. But, for the development of electro-mobility, it is important to have not only tax incentives for the acquisition and use of electric vehicles or standards for the development of the installation of chargers but also a comprehensive plan in which electro-mobility is contemplated as a whole, including analysis of the situation, medium and long-term objectives, expected effects on the environment, manufacturing possibilities of vehicles and components, necessary raw materials, recycling and reuse, etc.

Some countries that have developed national e-mobility plans after establishing different measures to promote electric mobility in the last few years. In addition, others are in the process of approval, although the date these plans will be established is not yet defined. Table 7 shows the list of countries and a column indicating the date of adoption of the comprehensive plan. There are some countries where, although there is not yet a plan, a draft plan is already under discussion and is expected to be adopted shortly. In such cases, the expected date has been indicated with a question mark to show that it has not yet been approved. The column has been marked in grey in countries that do not yet have a comprehensive plan.

Table 7 Adoption of comprehensive clean transportation plans

Country	Year	Country	Year
Argentina	2023?	El Salvador	
Brazil		México	2023?
Chile	2021	Panamá	2022
Colombia	2019	Perú	2023?
Costa Rica	2019	República Dominicana	2020
Ecuador		Uruguay	

Analysing the table and previous graphs of sales, it is worth highlighting the high relationship between the existence of a comprehensive electric mobility plan with several years of operation and the market share of electric vehicles relative to the total number of vehicles sold in 2022.

Other considerations

With the need for electric power generation to meet the future charging needs of vehicles, it does not seem that there will be problems. Most countries currently have sufficient production capacity, and are largely renewable, and the expected growth rate of the electric vehicle fleet will not generate urgent needs to expand production capacity.

Practically all plans for electric mobility contemplate electrification level goals, with goals of eliminating the sale of internal combustion vehicles between 2035 and 2050 and somewhat earlier than that of public transport vehicles. They also set targets for reducing emissions from the transport sector by 30% between 2030 and 2040 and higher levels in 2050.

On the other hand, the plans set objectives for the manufacture of electric vehicles in different countries and exploitation and increase in the efficiency of mines of the materials necessary for the production of batteries, such as copper or lithium, in countries that have these raw materials such as Argentina, Bolivia and Chile in the case of lithium.

E-mobility in Africa

Lead author: Pine Pienaar

Introduction

The Comprehensive Africa Climate Change Initiative (CACCI) was launched at the 26th United Nations Conference of the Parties (COP26) in November 2021 in Glasgow, Scotland. The CACCI is a partnership formed with the African Union Commission (AUC), aimed at addressing the Paris Agreement goals of reducing carbon emissions and implementing long-term plans to adapt to climate change in Africa. With this event, all fifty-four African countries ratified the Paris Agreement and committed to its objectives ([122]).

There are apparent differences between developed and developing countries regarding their ability to decarbonise and adopt e-mobility technologies. The main characteristics of developing countries include [123]:

- Inadequate regulatory mechanisms to promote decarbonisation
- Low household income levels
- A shortage of infrastructure, not only in terms of basic infrastructure like roads but also charging facilities
- Longer travel distances, which impact on battery charging needs and patterns
- Inadequate financing and ability to service debt.

Opportunities

Opportunities available to developing countries regarding decarbonisation and moving toward e-mobility are discussed below:

Without vested interests and consumer resistance, new technologies are often easily adopted in the developing world. In the e-mobility sphere, for example, [124] refers to renewable energy mini-grids in rural electrification in Africa. Electricity can be provided to rural communities as grid extensions, standalone solar systems and mini-grids (independent, decentralised electricity networks functioning separately from a national grid). Regarding e-mobility, electric vehicles could be charged from such a network, especially scooters and three-wheelers, which are becoming popular in many parts of Africa [125].

Regarding economic development opportunities in mining and manufacturing, essential lithium-ion battery (LIB) minerals are available in various African countries, for example:

- South Africa (manganese, nickel and platinum)
- Democratic Republic of Congo (DRC) (cobalt)
- Zimbabwe (lithium)
- Mozambique (graphite)
- Zambia (copper).

While mining these minerals contributes toward economic development and employment creation, there are also significant opportunities for value addition in smelting, refining, cell assembly and EV production, which could be developed on the African continent. The first step in the value chain consists of beneficiation, the treatment of raw material to improve its physical or chemical properties, especially in preparation for smelting [125].

Financing is available directly or through dedicated climate change funds from various first-world countries and agencies to fund decarbonising and climate change projects in African countries, specifically Sub-Saharan Africa (SSA). African states can benefit from such funding. A recent study [126] distinguishes amongst the following sources of financing for climate action:

- Concessional financing, mainly through climate funds
- Debt instruments that are linked to climate change
- International carbon credit schemes
- Climate-related insurance schemes.

According to [127], electric vehicles will dominate passenger transport systems worldwide. The opportunity for developing countries is to establish or upgrade public transport fleets to electric vehicles, hopefully with subsidised funding, which will benefit commuters and the economy in general.

Conzade [123] points out that two-wheeler vehicles constitute up to 50 percent of the total vehicle population in most sub-Saharan African (SSA) countries (apart from South Africa). There is considerable potential to improve short-distance mobility by transforming this industry to electric vehicles.

Challenges

Conzade et al. [123] identified several challenges Sub-Saharan Africa is facing in terms of its electric mobility transition, one being unreliable electricity supply. Although many African countries progressed well in terms of access to electricity, a survey done in 2019 across 34 African countries found that fewer than half of users connected to the grid enjoy reliable electricity supply. Without sufficient electricity supply, the introduction of electric vehicles will remain problematic.

A second challenge in terms of electric vehicles is affordability [123]. Low household income, the low availability of asset finance at affordable rates, and the purchase price of electric vehicles tend to be higher than that of the equivalent internal combustion engine vehicle all contribute towards this challenge.

A third challenge is the dominance of used vehicles on much of the continent, caused by affordability challenges and weak regulation [123]. Countries allow the importation of older vehicles that do not meet modern-day emissions standards. A 2020 United Nations Environment Programme (UNEP) report found that used-vehicle regulations are inadequate in many sub-Saharan African countries [128]. Under these circumstances, it is difficult for new electric vehicles to compete price-wise with older, low-cost internal combustion engine (ICE) vehicles.

The International Energy Agency [129] refers to national policies and incentives in developed countries which enhance electric vehicle sales and utilisation. These initiatives include vehicle purchase incentives, direct incentives to car manufacturers, policy support to vehicle and battery manufacturers, as well as to critical mineral supply chains, subsidies, and bans in ICE-only vehicles. Policy support for electric vehicle supply equipment (EVSE) (charging equipment) is also increasing. This type of support is generally not available in SSA countries.

Some African countries are energy-wise dependent on coal and fossil fuels, which is a challenge to replace in the short to medium term. The reasons for this include the abundant availability of these energy sources, the relatively low cost, and inadequate funding and institutional strength to provide sufficient alternative energy sources.

The way forward

It is essential for stakeholders worldwide, from different countries and sectors of the economy, to continue to take hands in the transition to climate-friendly technologies. Undoubtedly, international support has played a vital role in the successes achieved to date in Africa and will continue to do so.

E-mobility in South and Southeast Asia

Lead author: Neven Duić

Introduction

The South and Southeast Asia region constituted more than 30% of the global population. Addressing the surge in emissions and achieving socio-economic progress are top priorities for this region. Transport holds significant importance for these countries, not only in connecting people and markets and facilitating economic growth and social development but also due to its impact on oil demand and contribution to emissions. Over the past few years, South and Southeast Asia countries have been intensifying their efforts and commitments to combat climate change [130].

The transportation sector in Southeast Asia has long been known for its significant carbon-intensive energy consumption. According to the 6th ASEAN Energy Outlook (AEO6), the transportation sector ranks as the second-largest energy-consuming sector after industry, accounting for approximately 30% of the region's total final energy consumption (TFEC). However, the region's transition to electric mobility offers hope for a more sustainable and eco-friendly transportation system if renewable energy sources are used for charging. In South Asia, the transportation sector contributes to GHG emissions in different SAARC countries, with percentages ranging from 6% to 27% of the total emissions. As the world embraces sustainable transportation, adopting EVs is a crucial mission. To achieve this transformative shift, collective efforts from the automotive industries in the nations become essential. By embracing the potential of EVs and aligning strategies towards clean and green mobility, the regions can pave the way towards a brighter and more sustainable future.

Some Features

A notable feature of the transportation landscape in Southeast Asia is the prevalence of two and three-wheelers, constituting about 80% of vehicles in the region [131]. This characteristic sets it apart from other areas like China, Europe, and the United States, where the growth of electric vehicles (EVs) is primarily focused on cars. The adoption of two-wheeled EVs has outpaced that of electric cars, with market leader Vietnam witnessing around 8% of all vehicle sales being attributed to two-wheeled EVs in 2020. However, the transition to EVs faces challenges due to the higher cost of purchasing an electric passenger car than traditional ICE vehicles, deterring many drivers from making the switch.

The automotive industries in South Asian countries display significant diversity, influenced by varying market demands. India stands out as the prominent leader in automobile manufacturing in the region. India boasts a few domestic automobile manufacturers, and has attracted several foreign automobile companies that have established their manufacturing facilities within the country. In contrast, Pakistan features a limited number of automobile manufacturing facilities, while other South Asian nations have opted for automobile assembling plants. On the other hand, Bangladesh possesses domestic manufacturing factories dedicated to the production of two and three-wheelers. Embracing Electric Vehicle adoption calls for transformative changes in the automotive industries of the respective SAARC nations.

Opportunities

Some ASEAN Member States (AMS) governments have already set national targets for the deploying electric vehicles, including Brunei Darussalam, Indonesia, Singapore, and Thailand [132]. This proactive approach demonstrates the region's willingness to embrace electric mobility. Furthermore, several countries have introduced incentives and subsidies to encourage electric vehicle adoption. For instance, Thailand approved tax cuts and subsidies, while Indonesia is considering reducing value-added tax on electric car sales. These measures aim to make EVs more affordable and attractive to consumers.

The adoption of electric vehicles (EVs) in SAARC nations is driven by many factors, including energy reserve shortages that lead to increased fuel imports. Embracing EVs offers a sustainable solution, reducing reliance on traditional fossil fuels and mitigating energy scarcity challenges. Moreover, countries like Afghanistan, Bhutan, India, and Nepal, rich in natural resources, present a unique opportunity to leverage hydropower for powering EVs, contributing to a greener and more environmentally friendly transportation system [133]. By harnessing their hydropower potential, these countries can significantly enhance the viability and attractiveness of EV adoption, paving the way towards a cleaner and more sustainable future for the entire SAARC region.

Challenges

Despite the progress and opportunities, several challenges impede the widespread adoption of electric vehicles in South and Southeast Asia. One of the main obstacles is the high capital requirement for purchasing EVs, which deters many potential buyers from making the switch. Affordability remains a key concern, and addressing this issue through incentives and financing options is crucial to increasing EV uptake. Furthermore, the lack of supporting infrastructure, especially the availability of charging stations, poses a significant barrier to the seamless integration of electric mobility. A comprehensive and well-connected charging network is essential to alleviate range anxiety and provide EV users with the convenience they need for long-distance travel. Moreover, addressing risk aversion among stakeholders, including consumers and investors, is vital to instil confidence in the reliability and performance of electric vehicles. This requires robust safety standards, transparent information about EV technology, and effective consumer education programs to dispel any misconceptions surrounding electric mobility. To overcome these challenges, concerted efforts from governments, private sector players, and international organisations are essential. Implementing policies and regulations that incentivise EV adoption, investing in charging infrastructure expansion, and promoting research and development in EV technology are all critical steps in advancing the electric mobility agenda in South and Southeast Asia.

Other considerations

Electric vehicle and battery manufacturing

Southeast Asian countries like Thailand and Indonesia aspire to be regional hubs for EV production and are actively building manufacturing facilities for EV batteries. With a strong foothold in the motor vehicle sector, Thailand aims to produce 30% of electric vehicles by the end of the decade [134]. Indonesia, the world's largest nickel producer (a key component in lithium batteries), aims to establish itself as an EV production and export hub in the region. On the other hand, Singapore, a small country with limited natural resources, focuses on battery recycling to extract precious metals from spent batteries for reuse in battery production.

India, the leading country in electric vehicle production in South Asia, has set an ambitious target for its electric vehicles market to reach 17 million units by 2030. However, as of last year, electric vehicle sales have only surpassed the one-million mark (including two and three-wheelers). In response, the Indian government has implemented various initiatives like the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles in India (FAME India) [135]. These measures are aimed at accelerating local production and bolstering the growth of the electric vehicle industry, facilitating the achievement of India's ambitious goal within the specified timeframe. Several companies have also shown keen interest in setting up a production line for two-wheeler EVs in India.

Charging Infrastructure

Accelerating the transition to electric mobility requires establishing adequate charging infrastructure, particularly in urban areas. Governments must play a proactive role in supporting the transformation of mobility and energy systems in cities. For instance, Singapore has proposed laws mandating new buildings with car parks to install EV charging points in at least one percent of their total car and motorcycle parking lots to regulate EV charging. Battery swapping stations offer an efficient charging alternative, particularly for e-motorcycles, e-scooters and other two and three-wheelers. This enables immediate refuelling by swapping discharged batteries with fully charged ones, optimising space and vehicle serviceability [136]. The creation of Electric Vehicle Infrastructure is a crucial prerequisite and a transformative step in shaping the future of transportation in SAARC nations. Recognising the immense potential of electric mobility, several developed countries, alongside some progressive developing nations, have taken proactive measures to invest in and build a comprehensive EV charging infrastructure. Moreover, a well-developed EV charging infrastructure plays a pivotal role in supporting the growth of the electric vehicle market. It not only attracts more consumers to make the switch but also encourages the local manufacturing and production of EV components and technologies, and their recycling.

Overarching observations

- Many developing countries have problems with adequate power supply.
- Do not copy transport modes of advanced economies; prioritise mass transport.
- The less infrastructure there is of gasoline stations and petroleum products storage facilities, the easier it is for a country to promote e-mobility and to leapfrog to all kinds of EVs, mainly two and three/wheelers.
- A long-term lease scheme for batteries makes the cash flow associated with acquiring an EV similar to an ICEV. This option becomes applicable when battery installation designs are suitable for easily exchanging another battery. Battery swapping stations for 2 and 3-wheelers, observed as a feat in SE Asia, apply to all developing economies and, with adequate designs, can be extended to EVs.
- Exports (Imports) of second-hand ICE vehicles should be banned in advanced countries. This is a problem for many developing countries because they go backwards regarding emissions.

Fire Safety of Electric Vehicles

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- The fire hazard of EVs is not higher than ICEVs, but it is different due to the battery-related hazards. Heat release rates in EV and ICEV fires are similar.
- Toxic gases emitted from EV and ICEV fires pose considerable health and environmental risks. Emergency response to EV fires is challenging; more research and training are needed to assist firefighting.

Summary

Global adoption of electric vehicles (EVs) brings new fire safety challenges. EV fires, while rare, pose different risks compared to traditional internal combustion engine vehicle (ICEV) fires. These challenges affect all safety procedures within our built environment and transport infrastructure. Key issues to consider are fire hazards stemming from EV batteries, the toxicity of EV fires, emergency response challenges, impacts on building design, and transportation regulations. EV batteries can go into thermal runaway under various conditions, causing ignition and toxic gas emissions. Firefighters face unique challenges in managing EV fires, and collaboration with original equipment manufacturers (OEMs) is crucial. The transportation of EVs, especially aged or second-life batteries, raises regulatory and logistical concerns. Future developments in battery chemistry can improve EV fire safety, yet transparency from battery producers and rigorous testing of these new chemistries are needed. Comprehensive fire safety strategies encompassing regulation, data sharing, research, and public awareness are essential for a successful transition to sustainable transportation.

Electric vehicle fire statistics

The risk in fire safety is defined as the product of the event frequency and expected consequences of an event [137]. However, given their complexity, estimating this frequency for EVs poses significant challenges. Current statistics indicate a lower frequency of EV fires compared to conventional vehicles. For instance, in Sweden in 2021, there were 23 EV fires, a small number compared to approximately 4000 car fires [138]. In the same year, the Netherlands reported that EVs were involved in 133 accidents, 47 of which resulted in fires, with the battery pack involved in half of these incidents [139]. A global scale, a survey from EV FireSafe [140] since 2010 identified 393 EV fires.

Attempts have been made to collate EV fire statistics in various countries [139], [140], [141], but there remains a lack of comprehensive fire statistics needed to assess risk at the international level [142]. This issue is exacerbated by the novelty of EV technology and the reluctance of insurance companies to share relevant data. Addressing this gap requires a cooperative approach involving automakers, insurers, and fire safety regulators. Legislation may also be needed to mandate the sharing of such information for safety research. Developing an international EV fire incident registry and standardised reporting procedures could significantly improve our understanding of EV fire risks. Notably, current fire safety reporting initiatives focus largely on building fires [143], [144] and do not distinguish between vehicle types [139], underscoring the need for policymakers to expand these initiatives to include all kinds of fires, including those involving EVs.

Electric vehicle fire hazards

While EV battery fire incidents are relatively rare [139], [140], [141], they present unique challenges linked to specific battery characteristics: thermal runaway, jet flames, ejected battery parts, explosion risk in confined spaces and post-extinction risk due to stranded energy. These complexities necessitate tailored response strategies and public awareness, essential to safely adopting sustainable transportation.

EVs and ICEVs contain a significant amount of plastic and other combustible materials [145], resulting in similar heat release rates (HRRs). HRR is defined as the amount of energy released per unit time [kW] during combustion and is a critical metric used by fire safety professionals in the performance-based design of buildings. The differences in HRR progression can be attributed to variations in ignition methods, test set-ups, and the distinct characteristics of their respective drivetrains - the battery in EVs versus the fuel tank in ICEVs. For instance, some comparative studies indicate that the peak HRR for EVs occurs later than for ICEVs, suggesting a longer ignition time for EVs [146]. This points to the critical insight that the fire hazard of EVs isn't higher than that of ICEVs, but it is different in its characteristics.

Due to large-scale EV fire tests' high cost and proprietary nature, our current understanding is primarily based on small-scale tests, leaving some safety issues unresolved. Addressing these requires comprehensive large-scale testing, collaborations between OEMs and academic institutions, publicly funded research, standardised testing protocols, and cross-disciplinary research. Such measures will help translate small-scale data to system-level behaviour, contributing to safer EV technology as their usage expands.

Toxicity of EV fires

All fires, including those in EVs and ICEVs, emit toxic gases that can act as asphyxiants or irritants, posing serious risks to evacuees and first responders. Depending on the levels of exposure, these gases can incapacitate individuals, disrupt evacuation efforts, and potentially lead to long-term health consequences. Toxic gases emitted from EV and ICEV fires pose considerable health and environmental risks. Handling tactics, like letting EV fires burn out, haven't been thoroughly evaluated for their environmental and health implications. Thus, exploring and comparing different fire management tactics, such as direct battery flooding or chassis cooling, is essential [147],[148], [149], [150], [151].

Studies reveal that EV fires produce higher concentrations of toxic substances like hydrogen fluoride (HF) and metals, including nickel, cobalt, lithium, and manganese. While HF can cause irritation and inflammatory reactions, the potential environmental impact of the metals requires further investigation. Water used to suppress EV fires can also become a contamination source, containing high levels of lithium and fluoride compared to water from ICEV fires [148], [150].

Addressing these toxicity issues necessitates establishing regulatory limits for toxic substances in waters, stringent clean-up guidelines for extinguishment water, and further research into the environmental impacts of EV fires. Moreover, promoting best firefighting practices and exploring suppression alternatives would help optimise fire response efficiency and ecological preservation. Such measures should also be relevant for ICEVs and other fire types.

Emergency response challenges

Firefighters face multiple challenges when addressing EV fires in enclosed spaces, such as managing stranded energy, potential explosion hazards, toxic gas exposure, prolonged extinguishing operations, extensive water use, the risk of battery re-ignition, and the handling of the post-fire EV and contaminated water [152]. Due to their cooling effects, water and water-based agents remain the most effective for fighting EV battery fires. While much research concentrates on various suppression methods at smaller scales, these methods may not perform as well at the system level, as batteries installed in systems are well-protected [153].

Despite warnings from OEMs, firefighters are exploring direct methods such as cutting extinguishers and piercing devices, which have shown effectiveness in cooling fires and reducing water usage [154],

[155]. Several post-fire handling techniques have been used, including isolating EVs in containers [156] or letting a fully developed fire burn out to circumvent the stranded energy problem. Collaboration between OEMs and firefighting organisations foster shared learning and creates safety guidelines around EV fire risks. More research is needed to determine which tactic is best from several perspectives: time of operation, risk for fire spread, environmental impact, and handling of stranded energy.

Regulations and knowledge surrounding the fire safety of second-life batteries are lagging. The sale of second-life EV batteries is unregulated, meaning they can be brought into building environments, installed, and reused by the public. Responding to such a fire and the associated potential explosion risk is a current concern for first responders and needs serious attention.

Transportation

Transporting EVs and their batteries, especially in larger quantities or as aged/second-life batteries, poses unique challenges exacerbated by inconsistent regulations across countries. Particularly, regulations for transporting aged and second-life batteries are often insufficient or lacking, leading to market discrepancies and safety concerns [157].

Fire safety considerations for EV transportation by sea aren't fully comprehended or systematically tackled. More research is needed into crew response strategies, fire detection, and suppression methods tailored explicitly for EV transport. Investing more in training on fire safety aspects of EV transportation is crucial, as it would help develop effective crew tactics, enhance detection measures, and optimise fire suppression methods, ultimately increasing safety during EV transportation and reducing potential marine pollution risks.

Future of battery chemistries and implications for fire safety

The safety of Li-ion batteries is intrinsically related to their internal components. Both cathode and anode are continuously being optimised for higher capacity and energy density while mitigating dendrite formation and instability of the solid electrolyte interface. Lithium Iron Phosphate ($LiFePO_4$) is known for its superior thermal stability, yet studies indicate higher HF concentrations in fires [158], [159].

Flammable solvents in current batteries' electrolytes can decompose at low temperatures [160]. Therefore, ongoing research is continuing into stable lithium salts, non-flammable solvents, flame retardants, and overcharge prevention. Non-flammable solvents and new salts have promising safety performance, with potential for aqueous, polymer, and solid-state electrolytes.

However, battery producers often lack transparency about battery chemistry, influencing fire safety and smoke toxicity. Furthermore, critical examination of fire safety in novel solvents and solid-state batteries is lacking [160]. These batteries may not always perform better under short-circuit scenarios, raising safety concerns and emphasising the need for rigorous fire safety testing of new battery chemistries.

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