THE FUTURE OF ELECTRIC VEHICLES AND MATERIAL RESOURCES

A FORESIGHT BRIEF

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BACKGROUND

Limiting global warming to 1.5°C will require a rapid reduction of emissions from the transport sector, which is responsible for almost a quarter of direct greenhouse gas emissions.[1] Electrifying transport systems will be a crucial step in the process, in which electric vehicles (EVs) will play an important role.[2] Recent technological advancements offer an opportunity to replace fossil fuels by electric systems in all transport sectors – including air transport. The electrification of road transport has already begun, which has been led by the continual development of electric cars. Electric buses and trucks – as well as other EVs, such as two-and three-wheelers – are following. After years of doubt and uncertainty, EVs have begun competing commercially with internal combustion engine vehicles (ICEVs).

Besides the potential for replacing fossil fuels, the optimism around EVs is also increasing because of the benefits they offer in terms of increased energy efficiency and reduction in local pollution. Nonetheless, there are genuine concerns about meeting the future energy demand for charging EV batteries, which would ideally come from renewable sources. More importantly, the issue of long-term sustainability of EVs is underscored by the supply risks of critical material resources used in EV batteries and the emissions linked to the extraction of these resources.[3]

To this end, it is worth understanding the likely future scenario regarding the use of material resources in EVs. Governments worldwide are adopting policies, notably in the form of economic incentives, to favour the adoption of EVs and investments in charging infrastructure. However, most policies are not equally focused on addressing the resource sustainability issue.

Based on recent trends, this brief identifies opportunities and challenges involved with the adoption of EVs. It also addresses concerns regarding material resources used in EVs and their batteries with a focus on their end-of-life management. Building on this awareness, the brief investigates environmental and economic aspects of ensuring a green and sustainable transport sector. Finally, it offers recommendations for policy makers on promoting EVs as well as ensuring optimal resource recovery through reuse and recycling of used EV batteries.

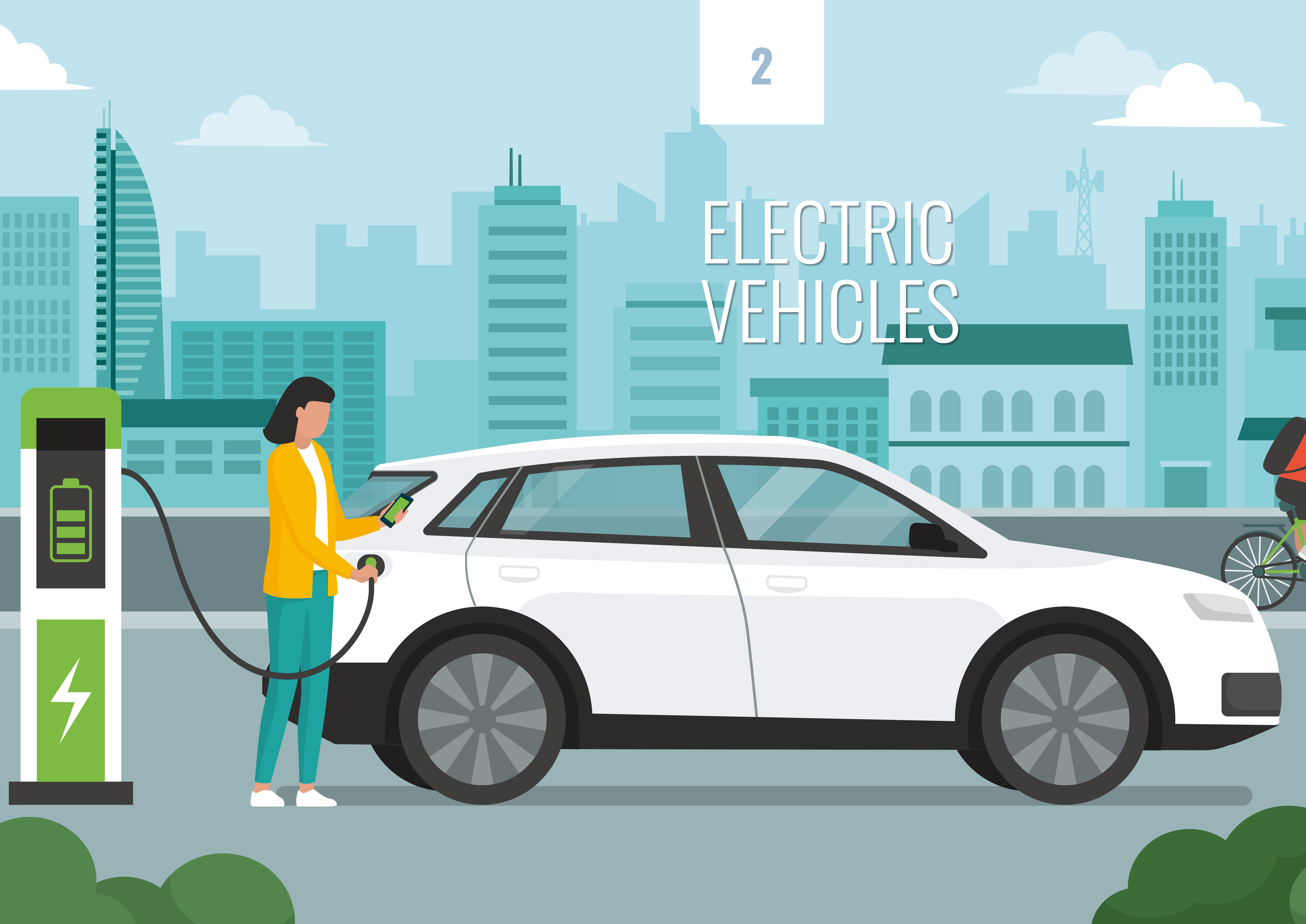
The main goals of this foresight brief are to:

- highlight major opportunities and challenges in the mainstreaming of EVs,
- examine the sustainability case of EVs by focusing on material resources, and
- offer policy recommendations for ensuring the long-term resource sustainability of EVs.

The scope of this work is limited to battery-powered EVs because of the fact that the presence of vehicles using electric motors fuelled by other power sources (including fuel cells) is, for now, essentially negligible in comparison to battery-powered EVs. Furthermore, this report focuses on electric cars. Though the use of other EVs – including buses, trucks, bikes, and scooters – is also increasing rapidly, passenger electric cars represent both the trend and challenges in the electrification of the transport sector. Moreover, this work focuses on the issues linked to material resources used in batteries, which are common across various types of EVs.

2

ELECTRIC VEHICLES

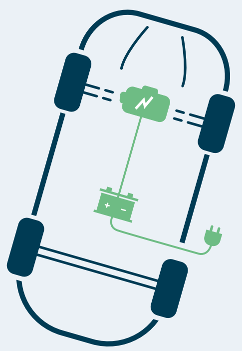


Despite being seemingly a relatively new phenomenon, the origin of EVs dates back to the 1830s. The first battery-powered EV was built in 1834, more than 50 years before the first petrol-powered internal combustion engine vehicle.

By the beginning of the 20th century, EVs became more popular with the availability of rechargeable batteries. More than one-third of automobiles in the United States were electric by 1912.[4]

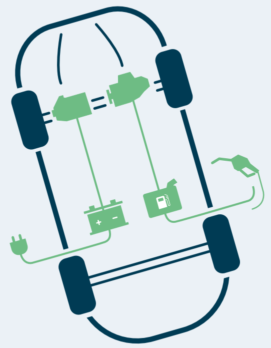
Nonetheless, EVs were succeeded soon thereafter by ICEVs. EVs could not keep up with mass-produced ICEVs, which were cheaper and faster, and which could run longer. Not until the 1990s did EVs return to life again – due to the development of energy-dense and lightweight lithium-ion batteries. Lead-acid batteries have been the primary choice for energy storage for more than a century, but their heavy weight in relation to their low-energy storage capacity did not fit the needs of EVs for running at higher speeds and over longer distances. Lithium-ion technology has proven to be a game-changing solution, offering higher energy density.[5]

BOX 1: TYPES OF EVs



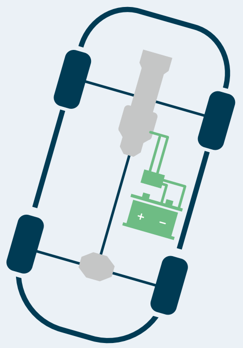
BATTERY ELECTRIC VEHICLES

Battery electric vehicles (BEVs) are powered entirely by electric motor and use rechargeable batteries for the energy storage. The main components of the electric drive system include battery pack, gearbox, inverter, and induction motor. Batteries can be charged externally by connecting BEVs to grid electricity. Additionally, the regenerative braking mechanism converts mechanical energy into electric charge, which is also supplied to the battery.



PLUG-IN HYBRID ELECTRIC VEHICLES

Plug-in hybrid electric vehicles (PHEVs) utilise both an internal combustion engine and an electric motor. PHEVs can be operated in different driving modes: as an ICEV, BEV, or both. Like BEVs, the battery can be charged by external power sources. While running, the internal combustion engine powers the electric motor as needed and can recharge the battery.



HYBRID ELECTRIC VEHICLES

Hybrid electric vehicles (HEVs) also have both internal combustion engine and smaller-capacity electric motor/battery combinations. The battery is charged from regenerative braking or by the internal combustion engine, but external charging of the battery is not possible. HEVs currently have more sales share than other EV types. HEVs cannot be considered as 'electrified' transport modes, though, because they cannot be charged using an external electricity source. HEVs are not included, for example, in the definition of 'alternatively powered vehicles' by the European Union.

EVs operate by converting electrical energy to kinetic energy via an induction motor for propulsion. They are equipped with an energy storage battery unit on board. The power needed to charge EV batteries and run the EV's motor could be supplied from different arrangements of energy sources, which also define the type of an EV. Currently available EVs can be grouped into three categories: battery electric vehicles (BEV), plug-in hybrids (PHEV), and hybrid electric vehicles (HEV).[6] See Box 1.

LITHIUM-ION BATTERIES

Batteries are an important part of EVs, regardless of their type. The lack of reliable, small, and light-weight batteries has long been an issue, but lithium-ion batteries (LIBs) offer both economic and technological solutions to the problem. LIBs offer a less toxic and higher-energy storage potential than lead-acid batteries do, and they can be designed with various chemical combinations. Their importance is reflected in the 2019 Nobel Prize in Chemistry, which was awarded to scientists who contributed to the development of LIBs.[7]

Each battery cell in LIBs consists of four components: cathode, anode, electrolyte, and separator. The characteristics of the battery cell vary depending on the cathode's chemical composition. The common cathode chemistries used in EV batteries include: lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA), and lithium iron phosphate (LFP).[8]

The lithium-ion battery technology has evolved significantly in recent years and continues to advance rapidly, offering increased efficiency at lower and lower prices. Over the past decade, the price of LIBs has decreased from more than USD 1,100/kWh to about USD 150/kWh and is projected to cost roughly USD 100/kWh by 2030.[9] Total ownership cost (including fuel and maintenance) is already lower for electric cars, and with the price of the battery being at or below USD 100/kWh, electric cars are expected to reach vehicle price parity with ICEVs for personal use.[10]

More recently developed 'extreme fast charging' technology promises to decrease the charging time for a 320-kilometre drive to as little as 10 minutes.[11] Such developments are set to solve the so-called 'range-anxiety' issue, prompting an accelerated adoption of electric cars. Battery cell chemistry also continues to mature, and technologies such as solid-state batteries hold promising prospects for future development in terms of battery performance. Nonetheless, the EV sector currently relies on the lithium-ion formula, and LIBs are expected to be the leading battery technology, at least in the near future.

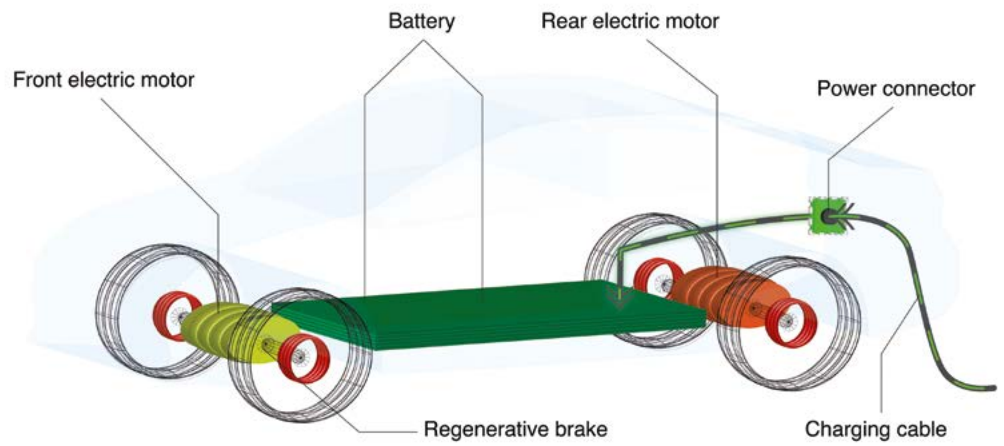


FIGURE 1: SCHEMATIC DIAGRAM OF A BATTERY ELECTRIC CAR
Source: Ian Furst / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)

3

OPPORTUNITIES AND CHALLENGES

OPPORTUNITIES

TECHNOLOGY

EVs offer numerous technological and performance-related advantages over conventional ICEVs. In terms of engineering, induction motors are superior because of their higher energy efficiency. Compared to a maximum of 30% tank-to-wheel energy efficiency[a] of ICEVs, EVs offer more than 77% of wall-to-wheel efficiency. Induction motors are also more reliable than internal combustion engines because they use fewer components, which means less chance of failure and lower maintenance costs of EVs than for ICEVs. The regenerative braking system in EVs can convert a part of the kinetic energy lost during deceleration into electric energy for recharging the battery. The lower centre of gravity in EVs gives them more stability and better control[b], which, along with better braking systems, makes them more reliable and safer. EVs allow for the possibility of software to replace mechanical solutions to several problems of EV driving, which further enhances vehicle performance in several respects.

POLLUTION

The absence of an internal combustion engine in EVs equates to significantly less noise pollution. Since no exhaust gases are released during their use, EVs are free of tailpipe emissions, contributing virtually zero air pollution to the local environment. Moreover, given that there is no need to keep the engine running, unlike with combustion engines, EVs perform more efficiently in heavy traffic and congestions. As such, the overall pollution from EVs comes largely from the production of energy for recharging the battery, which depends on the local energy mix. Nonetheless, direct emissions (including air pollutants resulting from the combustion process) are invariably lower in EV use, when operated correctly, than in ICEV use. Even when the energy is produced from the combustion of fossil fuels, the air pollution can be more efficiently reduced at the power plant level than at the individual vehicle level.

EMISSIONS

The higher energy efficiency of EVs equates to lower engine and driveline losses, which, in turn, equates to better economic and environmental performance than ICEVs offer. EVs provide environmental savings in terms of reduced emission during their use, depending on the energy mix, as well as over their whole lifecycle. On average, for 2018, a medium-size electric car emits about 60% less CO2-equivalent emissions per kilometre than does its ICE counterpart.[9] When charged using 80% renewable energy, EVs can reduce GHG emissions by 85%, SO2 and NOx by 75%, and particulate matter (PM) emissions by 40%.[12] With the growing share of renewables in the energy mix, these savings can be expected to be even higher in the future.

a https://www.fueleconomy.gov/feg/evtech.shtml
b https://afdc.energy.gov/vehicles/electric_maintenance.html

ECONOMY

EVs also offer an opportunity for many countries with no fossil reserves to be independent of foreign oil and to develop flexible infrastructure based on renewable sources of energy. Countries such as India, which are less industrialised but have significant potential for economic growth, are also trying to capitalise on the economic opportunities that EVs provide through local manufacturing of EVs and batteries. These initiatives can help capture potential economic benefits and create local jobs, along with other technological and environmental benefits that EVs offer.[10]

GROWTH OUTLOOK

Recent developments, especially relating to electric cars, show an optimistic trend for the EV industry. With major car manufacturers joining the race, a rapid growth in production and sales of electric cars is expected in the coming years. The global electric car fleet reached 7.2 million in 2019, with 2.1 million units having been added that year.[9] Despite the slowdown caused by the COVID-19 pandemic in 2020, annual EV sales is expected to grow to approximately 9 million units by 2025 and nearly 26 million by 2030, after which the fleet of petrol and gasoline cars will begin declining. Electric passenger cars are forecasted to take over internal combustion engine cars in global annual sales before 2040.[9,13]

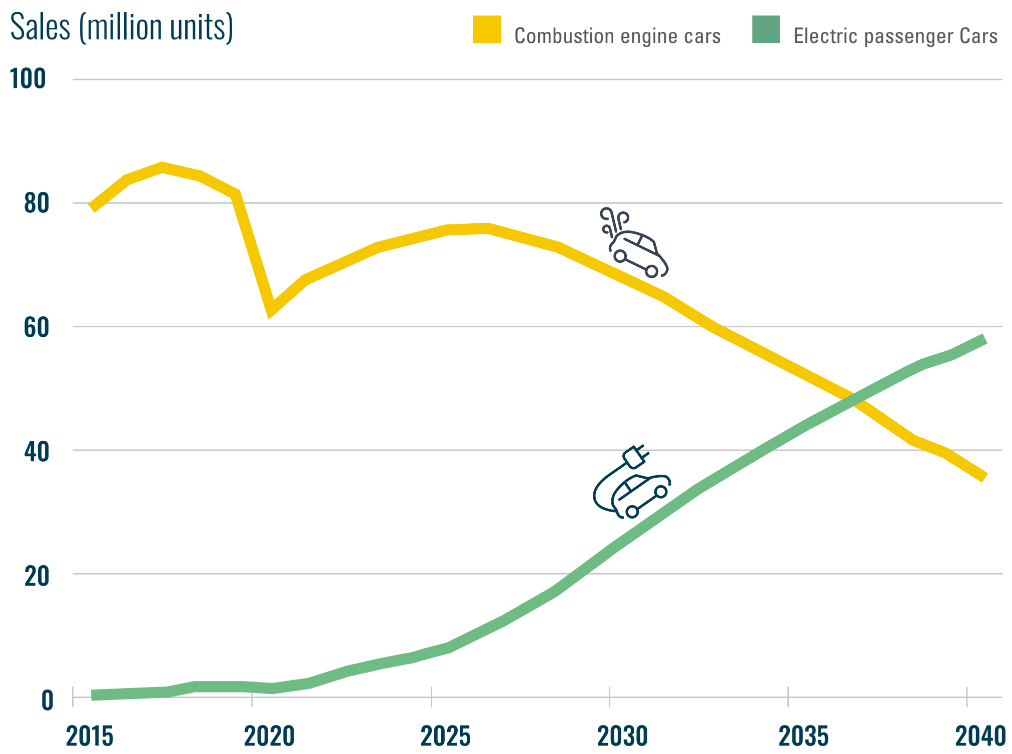


FIGURE 2: SALES OF ELECTRIC CARS ARE EXPECTED TO INCREASE RAPIDLY OVER THE NEXT 20 YEARS

Source: Reproduced from BloombergNEF's Electric Vehicle Outlook 2019 (https://about.bnef.com/electric-vehicle-outlook/)

CHALLENGES

The growth of EVs is expected to follow the S-curve trend, which is a typical pattern for new technology adoption.[14] Like other technological advancements, it can be inferred that battery technology will evolve rapidly, and as the price of EV batteries continues to decrease, the adoption of EVs will grow substantially. Besides financial and technological factors, the growth will also depend on transport and energy policies, as well as consumer preferences and infrastructure for supporting the rapid adoption of EVs. The role of private sector players, including vehicle manufacturers and charging infrastructure operators, will also be equally important in the expansion of electric mobility.[15]

Despite numerous benefits and an optimistic growth outlook, EVs face some crucial challenges. Higher purchase price, lack of supportive infrastructure and clean energy, and the need for a sustainable supply of material resources are some of the key challenges that need addressing in order for EVs to become a steadfast replacement for ICEVs.

AFFORDABILITY

Market uptake and consumer acceptance depend primarily on costs. Electric cars are more expensive than their fossil-fuelled counterparts. So, it is not surprising that the majority of electric cars are sold in countries with high GDP. Apart from China, most EV sales are reported in OECD countries. Even within the EU, 85% of sales are in only six Western European countries.[6] The widespread adoption of passenger electric cars is only possible when the purchase price and ownership cost for electric cars are similar to those of conventional diesel and petrol cars.

CHARGING INFRASTRUCTURE

On the technical side, EVs are still evolving toward offering the same performance and convenience that ICEVs offer. The combination of short-range capacity and unavailability of charging facilities is a barrier for EV adoption, especially in the case of personal cars. With most electric car batteries being in the 50-70 kWh range, the battery capacity of EVs continues to increase.[9] However, most electric car users are using private charging facilities at home or at work. Along with improvements in battery technology, sufficient charging infrastructure across road networks is necessary to prompt public adoption of EVs.

CLEAN ENERGY

The increase in EV sales also means a directly proportionate increased demand for electric energy. EVs will not be 'zero emission' unless the electricity for charging them is as well. The use of fossil-based electricity for running EVs means sending the emissions upstream to the energy production stage. Energy production has to be free of fossil fuels for EVs to run truly emission-free. The share of renewable energy is expected to increase significantly in the decades to come, with solar and wind power having up to 80% share by 2050.[16] However, with fossil fuels (coal, oil, and natural gas) being the major source (64%) of the total electricity produced globally, significant progress is needed in the decarbonisation of the power sector.[17] For countries heavily reliant on non-renewable sources, 'greening' of their energy production is an equally important challenge, parallel to the public adoption of EVs.

MATERIAL RESOURCES

Though EVs are free of tailpipe pollution and can run on green energy, their production accounts for a significant share of their total lifecycle environmental impacts. This is mainly due to the material resources used in EV batteries, which require more effort to extract. Material extraction and manufacturing of EVs is the most significant stage in terms of energy use and other impacts linked to the primary production of critical and important metals, such as cobalt and nickel. Moreover, some of these material resources on which the EV system relies end up bearing supply risks due more to geopolitical issues than to their limited availability.[18]

Until recently, the main demand for LIBs came from the consumer electronics sector, but that is anticipated to change with the growing EV market. By 2030, approximately 85% of LIB demand (in terms of their capacity) is estimated to come from EVs, with the rest being used in consumer electronics and for stationary energy storage.[13]

Lithium is the base element in LIBs and is expected to remain so for battery technologies of the near future, which implies that the demand for lithium will increase alongside the growing demand for LIBs. By 2030, LIBs will likely make up 80%[c] of the 160,000 metric tons of the global lithium demand each year.[3] Other metals that are used in current battery chemistries – including cobalt, copper, and nickel – will also see an increase in demand.

The geological availability of these metals will not be an issue for meeting the demand. However, extraction of these resources will result in increased environmental impacts, such as GHG emissions, water and soil pollutions, and stress on water resources.[15,19] The continuous supply of some of these resources is subject to geopolitical challenges. Social and ethical issues, such as child labour and poor working conditions, are also of concern for the extraction of some metals.[20]

c https://www.forbes.com/sites/woodmackenzie/2019/07/24/can-metals-supply-keep-up-with-electric-vehicle-demand/

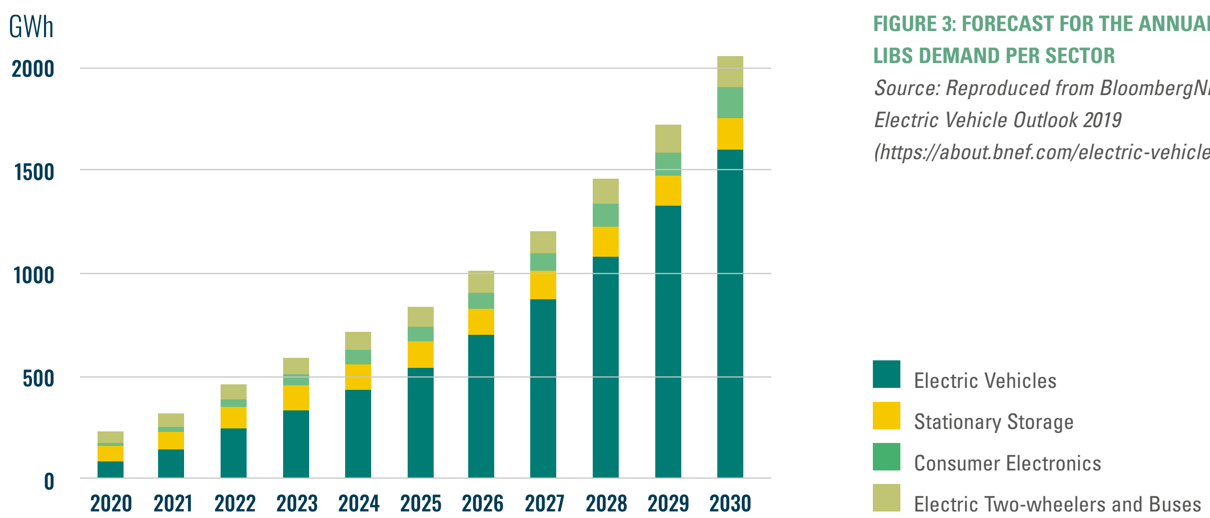


FIGURE 3: FORECAST FOR THE ANNUAL LIBS DEMAND PER SECTOR
Source: Reproduced from BloombergNEF's Electric Vehicle Outlook 2019 (https://about.bnef.com/electric-vehicle-outlook/)

4

END-OF-LIFE BATTERIES

Ensuring a sustainable supply of material resources to meet the growing demand for LIBs will require exploiting both primary and secondary sources of the materials. By 2030, roughly 2.5 million metric tons of LIBs each year will be reaching their end-of-life (EoL), with a sizable fraction coming from EVs.[21] The production of LIBs carries a substantial share of the total lifecycle GHG emission of an EV, which varies depending on the battery chemistry, EV type, and available energy mix.

For example, LIBs of a midsize passenger electric car (78 kWh size, 400 km range) account for about 22% of the vehicle's total lifecycle GHG emissions based on 2018 global average power mix with carbon intensity 518 g CO2-eq/kWh.[15]

This share of emissions from battery manufacturing will increase if the vehicle runs using a more renewable energy mix. The total lifecycle GHG emissions of an EV can be reduced by about 20% through material recycling.[22]

These emissions can presumably be reduced even further via reuse of EV batteries before recycling. Proper management of EoL EVs is thus crucial for facilitating their reuse and recycling, which will bring significant economic and environmental savings.

BOX 2: REUSE – EXAMPLES, BENEFITS AND CHALLENGES

EXAMPLES

- Powervault, a UK company, works with car manufacturers Nissan and Renault to repurpose EoL EV batteries into power banks as a way of providing a 'cheaper and greener' alternative to its customers[d].
- The world's largest mobile phone tower operator, China Tower, is replacing lead-acid batteries with repurposed EV batteries and reducing significant operational costs in the process[e]. China Tower is also working with Huawei to test the use of LIBs for high-power demands of 5G base stations[f].
- EV manufacturers are also introducing similar services. The Nissan Energy Storage program has joined forces with other partners in Asia, Europe, and South America to offer energy storage solutions while giving a second life to EoL batteries[g].

BENEFITS

- Repurposing EoL batteries is relatively straightforward and significantly cheaper than the cost of new batteries.
- The environmental performance of EV batteries improves with their reuse, as it circumvents the need to manufacture new batteries.
- The higher reuse potential and monetary value of used EV batteries (as compared to other LIBs, such as those used in electronic products) offer an incentive for implementing more circular business models.

CHALLENGES

- Proper collection of used batteries is required to facilitate reuse, which will not be possible without an efficient EoL management system that is currently lacking.
- With improved chemistries and decreasing prices of new batteries, repurposed batteries will have to compete increasingly with newer, cheaper, and more efficient batteries.
- Variation in battery types and designs, as well as their usage, hinders utilisation of the full potential of EoL batteries' reuse.

d https://www.powervault.co.uk/powervault-to-store-your-solar-energy/
e https://www.chinadaily.com.cn/a/201905/06/WS5ccf756da3104842260b9eb5_2.html
f https://www.huawei.com/en/press-events/news/2019/4/chinatower-huawei-test-5g-energy-solutions
g https://global.nissannews.com/en/releases/nissan-to-create-electric-vehicle-ecosystem

REUSE

With use over time, EV batteries lose their storage capacity, output power, and the ability to rapidly charge and discharge, which are essential functions needed for an EV's purpose. These batteries come to their EoL as to their use in an EV, but they are not completely exhausted, and the remaining potential can be utilised elsewhere. EoL EV batteries carry up to 80% of their initial capacity, which can be used for less demanding purposes in other applications, and during which they can last for several more years. They can be converted into stationary power supply units for homes, commercial buildings, streetlights, and sport arenas, as well as for enterprise purposes, such as being used in service vehicles in mining and construction work, electric forklifts, etc.

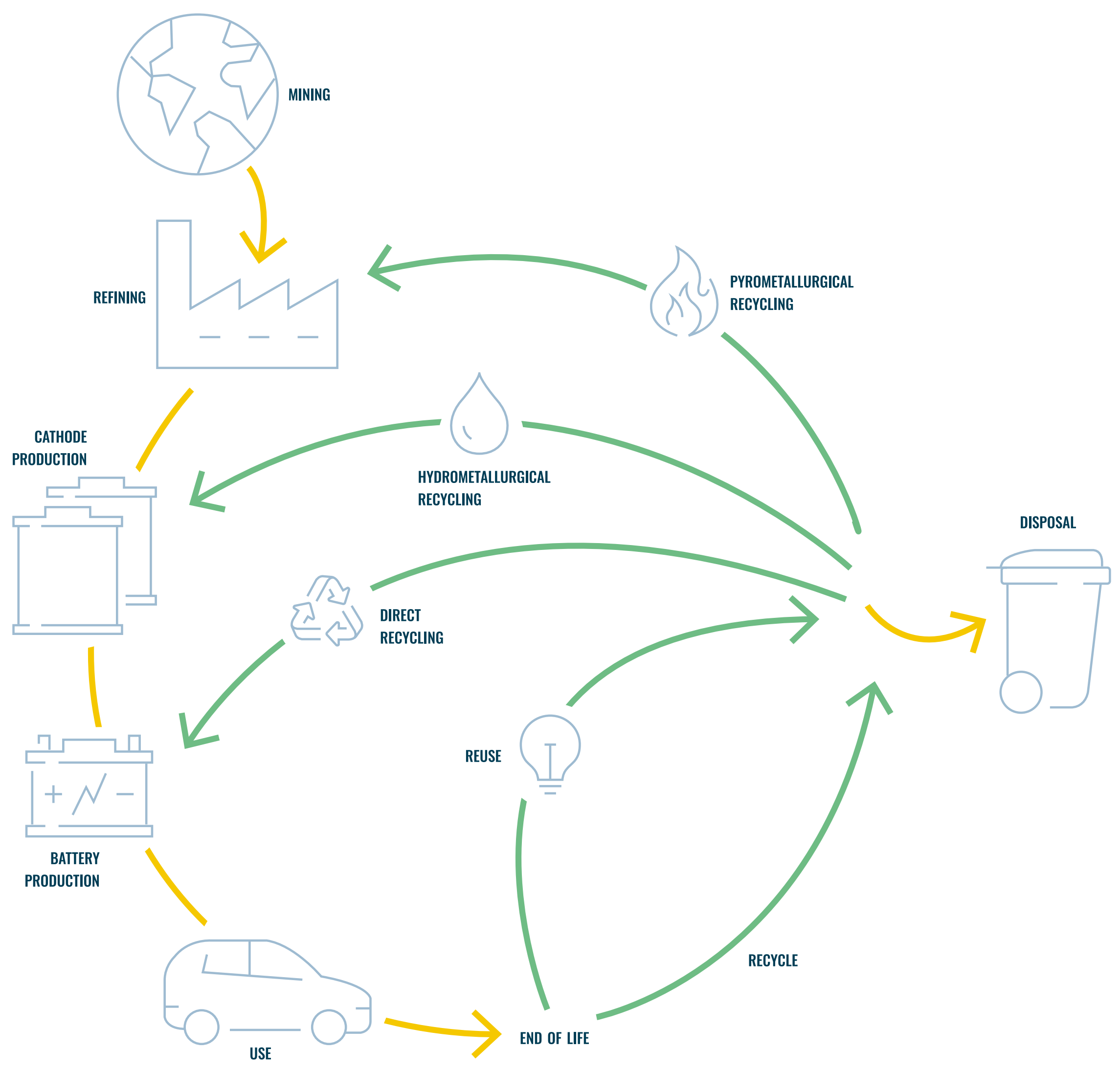


FIGURE 4: CIRCULAR SYSTEMS FOR EOL REUSE AND RECYCLING OF EV BATTERIES
Source: Reproduced from ReCell Center's illustration (https://recellcenter.org/research/)

RECYCLING

With increased adoption of EVs comes an increased demand for material resources for making new batteries. Ensuring a sustainable supply of materials to meet the ever-increasing demand will require optimised material recycling from EoL batteries. In terms of technology, lithium-ion battery recycling mainly uses three methods.

Direct recycling is a physical process for recovering materials with minimum damage to their crystal structure. The two other methods are based on metallurgical approaches (hydrometallurgical and pyrometallurgical) for extracting valuable resources from the cathode.

Hydrometallurgy uses multi-step chemical treatment processes, including solvent extraction, leaching, and chemical precipitation.

Pyrometallurgy involves smelting of EoL batteries at temperatures in excess of 1,000°C. The pyrometallurgical process is less efficient in terms of material recovery rate, but it is more commonly used in the recycling industry than hydrometallurgy because of its simpler and more productive process in terms of throughput.

These three recycling methods can be used in combination, depending on the type of battery chemistries and the target materials being recycled.[23, 24]

BOX 3: RECYCLING: EXAMPLES, BENEFITS AND CHALLENGES

EXAMPLES

- Umicore, a leading metal recycler based in Belgium, has installed a dedicated dismantling and recycling process with a capacity of 7,000 metric tons[h] of LIBs per year. The process combines hydrometallurgical and pyrometallurgical steps to produce refined metals that can be used to make new LIBs.
- New companies have emerged with business models focusing on LIB recycling. For example, the Canadian company Li-Cycle[i] claims to have developed a technology (combining mechanical and hydrometallurgical processes) that can recover up to 100% of all materials from LIBs.
- American carmaker Tesla[j] has been collaborating with local recyclers in different countries for their EoL battery recycling. Recently, it has started developing its own recycling system for both manufacturing scrap and recycling EoL batteries.

BENEFITS

- Batteries are one of the most expensive components of EVs. Thus, the recycling of EoL batteries, especially the direct recycling of cathodes, has considerable business potential.[25]
- Recovery of material resources from recycling EoL EVs can significantly reduce their lifecycle GHG emissions.[26]
- Recycling can address geopolitical supply risks of certain materials by creating local and secure sources of material supply for countries and regions with no material reserves.

CHALLENGES

- Shapes and sizes of lithium-ion cells, as well as their material composition, vary across LIBs, which adds to the difficulties of battery recycling.[27]
- Policy gaps, lack of organised EoL collection systems, and processing costs serve as the major hurdles in recycling LIBs.[28]
- There is a need for advanced recycling technologies, including the automated dismantling and processing of EoL batteries.

h https://csm.umicore.com/en/recycling/battery-recycling/our-recycling-process
i https://li-cycle.com/li-cycle-technology/
j https://www.tesla.com/ns_videos/tesla-impact-report-2019.pdf

5

POLICY EXAMPLES

Policies will play a crucial role in setting the overall course of development for the EV sector. Direct and indirect policy measures can contribute to the growth of EVs for personal and public use purposes. Such measures may include incentives for investment in the electric vehicle and battery industries, fuel economy standards, public procurement requirements, etc. Other more direct measures – often at the country level – may lie in the form of economic incentives for the importation, purchase, and use of EVs.

Policy measures promoting EVs will not succeed without addressing the associated increase in electricity demand and related infrastructure, such as charging stations. Besides uptake, future policies will be equally important in defining the long-term sustainability of EVs. In particular, effective EoL management systems for EVs will be crucial in order to allow for the recovery of value and resources from used batteries.[15] The next two pages offer examples of policy interventions in Europe, the U.S., China, and India – the major, growing markets and primary producers of EVs.

PROMOTION OF EVs

Significant progress in terms of policies to promote EVs, especially that of passenger cars, can be observed globally. Financial incentives to compensate for the higher price of EVs are the most common policy intervention, which include subsidies and rebates for vehicle purchase, tax deduction provisions, and reduced road taxes and parking fees.

EUROPE

Norway has led the way in promoting EVs with a series of early and generous policy measures, such as a waiver of value-added tax and registration fees, as well as driving privileges and free parking.[29] The Netherlands, an EV-friendly EU Member State, has adopted aggressive policies for banning ICEVs by 2030. Other European countries – including Germany, France, and the UK – have announced plans to end sales, as well as an eventual banning, of ICEVs within next 10–20 years.[10] Recently, Germany increased purchase subsidies for passenger EVs by 50% and announced an ambition to build one million charging stations by 2030.[30]

USA

Financial incentives for purchasing EVs in the form of tax credits and purchasing rebates are popular in several states as well as at the federal level in the U.S. The federal tax credit for new EVs purchased (in and after 2010) varies between USD 2,500 and USD 7,500, depending on the vehicle's size and battery capacity.[31] At the state level, for example, the Clean Vehicle Rebate Project in California offers a rebate of up to USD 7,000 for purchasing or leasing new EVs. This California initiative gets credit for the increased adoption of electric cars in the U.S.

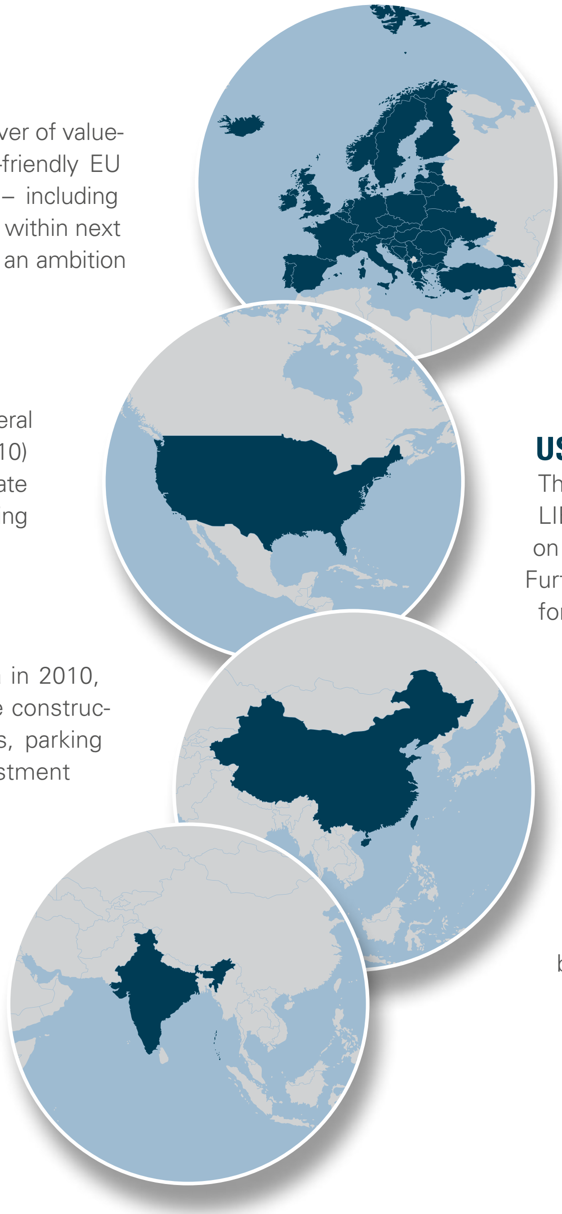
CHINA

The policy intervention to promote the so-called 'energy efficient and new energy' vehicles began in China in 2010, through which the central government subsidised purchase of EVs, and local governments subsidised the construction and maintenance of supporting infrastructure.[32] Subsequent measures (such as traffic restrictions, parking charges, etc.) have been focused on restricting not only the purchase and use of ICEVs, but also the investment in their manufacturing.[15, 33]

INDIA

India is promoting customer adoption of EVs while also focusing on becoming a global player in EV manufacturing. In 2015, the Indian government adopted the Faster Adoption and Manufacturing of Hybrid and EV (FAME) scheme, which was scaled up to FAME II in 2019 with an outlay of USD 1.4 billion for incentivising EV adoption and supporting charging infrastructure. Indian EV policies are also driven by goals of reducing primary oil consumption and creating domestic manufacturing capacity and employment growth. Controlling air pollution in major cities is another important push for EV adoption in India, which is home to 14 of the world's 20 most polluted cities.[34] Financial incentives are marked as an important policy intervention for a price-sensitive Indian market.[35]

Though financial incentives for EV purchase can be effective, they could also carry a downside. Once incentives are phased out, they could adversely impact EV uptake. It is also important to make sure that the incentives (such as subsidies or tax reductions) are available to consumers across different income brackets and that they do not help only those who can already afford EVs – the price of which is still higher than equivalent ICEVs. Moreover, electric vehicles and related policies are still new to many users. Due to the seemingly subtle differences among EV types but a significant difference in their prices, many users carry misconceptions and are reluctant to invest in electric cars. Bridging the consumer knowledge gap, especially by educating consumers on the benefits (such as tax credits and rebates, as well as the financial benefits over the longer use period of electric cars), needs to occur alongside implementation of other policy measures for the promotion of EVs.



SUSTAINABLE MATERIAL CYCLES

While there is a need to promote the use of EVs, ensuring availability of material resources – especially those necessary for producing LIBs – is equally crucial for the long-term viability. Policy measures are also needed to avoid negative impacts on the environment and human health that are related to the handling of used batteries.

EUROPE

In Europe, used batteries have been managed under the EU Batteries Directive 2006, which has set EoL collection and recycling rates.[36] However, the Directive has no such provision for 'automotive' batteries. Following the launch of the industry-led European Battery Alliance (EBA) in 2017, the European Commission adopted a Strategic Action Plan on Batteries in 2018.[37] These initiatives focus on building a competitive and sustainable regional value chain for batteries. The European Commission is in the process of building an EV Batteries regulatory framework for capturing the full potential of secondary material resources and ensuring long-term sustainability of EV batteries.

USA

The U.S. Department of Energy began an R&D initiative called 'ReCell Center' for the recycling of LIBs in early 2019.[38] This collaborative initiative between industry and research institutions is focused on advancing battery recycling technology to match the needs of both current and future batteries. Furthermore, it seeks to establish a competitive battery recycling industry in the U.S. and decrease foreign dependency on the supply of raw materials for battery production.

CHINA

In 2006, the Chinese government proposed a producer responsibility policy for the EoL collection and recycling of EV batteries. The 'Energy-saving and new energy vehicle development plan' of 2012 prioritises the cascaded utilisation and recycling of EoL batteries. The more recent 'Technology policy for the recycling of power battery' plan of 2015 regulates stakeholders, including vehicle and battery manufacturers, as well as businesses dealing with EoL EVs and batteries. The recent policy has also introduced standardisation requirements for the design of EV batteries, along with relevant supervision and management rules, in order to promote better resource recovery from EoL batteries.[39]

6

LESSONS FROM E-WASTE

MANAGEMENT OF EOL BATTERIES

The experience from electronic waste (e-waste) and non-automotive batteries can offer important lessons for the EoL management of EVs and their batteries. Despite policy initiatives such as the Batteries Directive in the EU, the EoL collection and recycling of LIBs that arises from consumer electrical and electronic products has been a challenge. Significant amounts of EoL batteries still end up in undesignated waste bins, which, if not handled properly, can cause hazards, including toxic emissions and fires during transportation and at waste processing facilities. Despite the availability of technologies, battery recycling is hindered, due to the lack of effective collection systems. The mixed chemical composition of different battery types and the lack of economies of scale are also notable challenges for the battery recycling industry.

The relatively large capacity of EV batteries (compared to those used in consumer electronics) and a higher degree of consistency in material composition provide a better business case for the EoL management of EV batteries, including options for reuse and recycling. Unlike batteries for household use, large LIBs are less likely to be randomly discarded in residual waste bins. However, the higher residual value (functional, as well as material) of used EV batteries equates to a larger incentive for their handling, which may lead to the possibility of their unofficial trading. The lack of effective infrastructure for the collection of EoL batteries and ownership for their EoL management can thus result in an unwanted situation of illegal flows to low-income countries, as in the case of e-waste. The responsibility of EoL management therefore needs to be clearly defined and shared among relevant stakeholders. When considered upfront, proper collection and resource recovery systems can also help tackle the challenges of batteries of different chemical composition being mixed together and can help the sufficient throughput of EoL batteries for reuse and recycling.

MANAGEMENT OF ELECTRONIC COMPONENTS

Successful EoL management will also need to ensure the optimal handling of EV components other than LIBs. EVs operate in a more 'electronic' setting than ICEVs do, as EVs have electric power-train components, such as inverters, motors, and controllers. As well, modern EVs are increasingly using a number of consumer electronics for information, communication, and entertainment purposes. This means that more electrical and electronic items will become waste as EVs reach the end of their lives. The material composition of such electronic waste means that, from a material recovery perspective, EVs can perform better in the e-waste recycling path than in the conventional EoL vehicle recycling path.[40] Ensuring the diversion of electronic components from EVs to the e-waste recycling path (and not to the other bulk metal recycling paths) will ensure higher material recovery. This will require easy access to, and dismantling of, electronic components in EVs in order to allow for their separate treatment in the optimal recycling pathway.

DESIGN FOR THE CIRCULAR ECONOMY

At the end of their lives, EVs offer strong potential for the circular economy, not only through recycling, but also via other EoL options, such as reuse of batteries and other electronic and mechanical modules. This possibility needs to be considered early on during the design of EVs and batteries. Product design and business models play crucial roles in facilitating EoL resource recovery. The modular design of LIBs allows easier detection of, and access to, individual cells. The possibility of replacing a single cell in the battery pack means easier repair and reuse, as well as creation of economic opportunities in the process.

Some car manufacturers are already moving toward designing batteries not only to run motors, but also to store energy in their second lives[k] – a trend that will likely become more mainstream in the future. Such due diligence from EV makers' side will enable proper EoL management of EVs and their batteries. Besides batteries, design should also allow easy access to other electronic components in EVs in order to enable their dismantling prior to the recycling process. This will allow better material recovery from electronic items and, where applicable, their reuse. Design standardisation of batteries and other common components across different EV types can play an important role in enabling a circular system in the electric mobility sector.

k https://asia.nikkei.com/Business/Automobiles/Toyota-designs-electric-car-with-batteries-reusable-in-homes

7

CONCLUDING REMARKS

The adoption of EVs is expanding rapidly, which offers several economic and environmental opportunities, as well as new challenges. Many countries are devising policies to support the uptake of passenger electric cars. Besides passenger EVs, electrification of public transport and local fleets (buses and taxis) can also be an effective strategy for many developing cities.

Some countries have taken initiatives to evaluate the feasibility of EVs and their lifecycle impacts in the local context. Policy instruments at national and regional levels can benefit from such local evaluations, as spatial variations in economic and environmental impacts of EVs can be expected across varying energy generation systems. Countries powered by renewable energy systems are more suitable and ready for EVs' adoption than countries that rely on fossil fuels for electricity production.[41] For these countries, ensuring the availability of 'green' electricity to match the new demand for EVs is equally important.

Material resources used in EVs – especially those used to make LIBs – are of high economic, environmental, geopolitical, and societal relevance. Sustainable and ethical sourcing of these materials is a key issue at the global level. Addressing this will require a combined effort from stakeholders throughout the lifecycle of EVs, including governments and industry players. A system for increasing transparency and traceability of raw materials in the global supply chain is needed. International agreements can facilitate such a system in order to address the uncertainty in the supply chain of important raw materials, the use of which is expected to grow rapidly with the increased adoption of EVs.

Likewise, an efficient EoL management system supported by future policies and infrastructure is crucial for enabling resource recovery in the form of reuse and recycling of used batteries. EoL management systems should focus on the overall optimisation of resource recovery via reuse and recycling. This will also require a cross-border cooperation that allows the trade of resources in the form of products, components, and materials, while ensuring sound environmental and socioeconomic practices in the EoL management chain. Such cooperation and diligence is especially important for emerging economies that are transitioning toward electric mobility but lack infrastructure and supporting policies for the EoL management of technology products. A new Global E-Mobility Program under the Global Environment Facility (GEF) seeks to promote deployment of EVs in developing countries[I]. Similar programs are also needed to ensure an effective system for the reuse and recycling of valuable material resources from EoL EVs in these countries.

I https://www.thegef.org/news/gef-global-e-mobility-program-help-developing-countries-go-electric

BOX 4: A SUMMARY OF POLICY RECOMMENDATIONS

PROMOTING EV UPTAKE

- Direct economic incentives (purchase subsidies, tax exemptions, etc.)
- Other incentives (driving and parking privileges)
- Investment in charging infrastructure (easy access, fast and cheap charging facilities)
- Public awareness campaigns (on the benefits of EVs and supporting policies)
- Promotion of renewable energy (sufficient and green electricity to charge EV batteries)

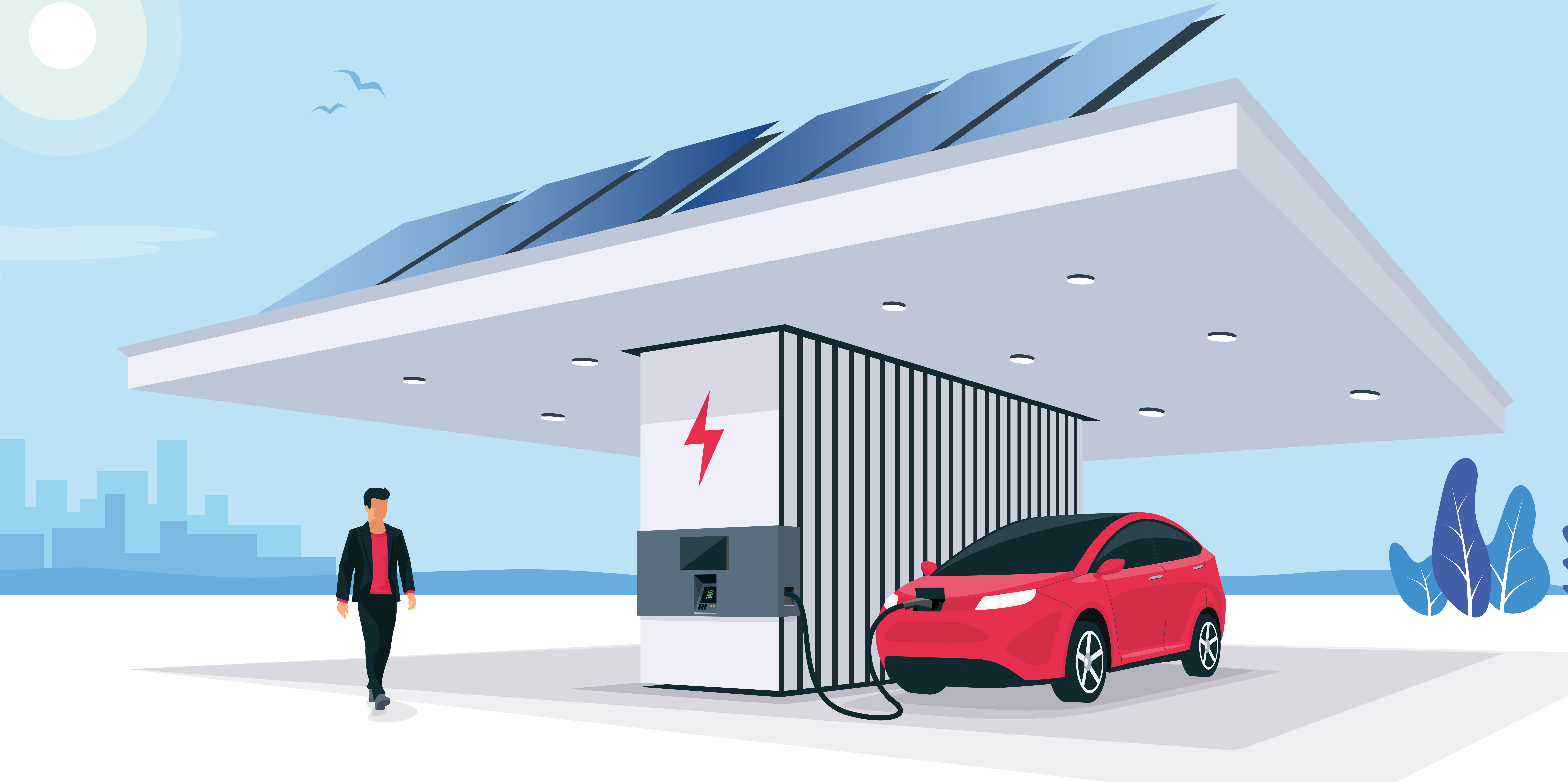
FACILITATING REUSE

- Addressing market needs of used EV batteries for their second life use
- Standardisation of batteries at the cell and module level for commercial and passenger vehicles
- Setting targets and technical standards for the reuse of end-of-life EV batteries
- Regulations and standards for the use and transboundary movement of second-hand batteries

ENSURING RESOURCE SUSTAINABILITY

- Effective EoL collection system for LIBs
- Utilising the full potential of used LIBs for alternative purposes, including reuse, before material recycling
- Establishment of a responsible and transparent supply chain
- Finding alternative solutions for the issue of dependency on one material (such as cobalt) for battery technologies

REFERENCES



1 **International Energy Agency**
CO2 Emissions from Fuel Combustion 2018: Overview (2018).
https://webstore.iea.org/download/direct/1082?fileName=CO2_Emissions_from_Fuel_Combustion_2018_Overview.pdf

2 **Intergovernmental Panel on Climate Change**
IPCC Special Report on Global Warming of 1.5°C (2018).
https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

3 **European Environment Agency**
Electric vehicles from life cycle and circular economy perspectives (2018).
https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle

4 **Chan, C. C.**
The Rise & Fall of Electric Vehicles in 1828–1930: Lessons Learned [Scanning Our Past].
Proceedings of the IEEE 101, 206-212, doi:10.1109/jproc.2012.2228370 (2013).

5 **Zou, C., Zhang, L., Hu, X., Wang, Z., Wik, T. & Pecht, M.**
A review of fractional-order techniques applied to lithium-ion batteries, lead-acid batteries, and supercapacitors.
Journal of Power Sources 390, 286-296, doi:10.1016/j.jpowsour.2018.04.033 (2018).

6 **European Automobile Manufacturers Association**
Making the Transition to Zero-emission Mobility (2018).
https://www.acea.be/uploads/publications/Study_ECV_barriers.pdf

7 **The Royal Swedish Academy of Sciences**
The Nobel Prize in Chemistry 2019 (2019).
https://www.kva.se/en/pressrum/pressmeddelanden/nobelpriset-i-kemi-2019

8 **Zubi, G., Dufo-López, R., Carvalho, M. & Pasaoglu, G.**
The lithium-ion battery: State of the art and future perspectives.
Renewable and Sustainable Energy Reviews 89, 292-308, doi:10.1016/j.rser.2018.03.002 (2018).

9 **International Energy Agency**
Global EV Outlook 2020 - Entering the decade of electric drive? (2020).
www.iea.org/publications/reports/globalevoutlook2019/

10 **Crabtree, G.**
The coming electric vehicle transformation.
Science 366, 422, doi:10.1126/science.aax0704 (2019).

11 **Yang, X.-G., Liu, T., Gao, Y., Ge, S., Leng, Y., Wang, D. & Wang, C.-Y.**
Asymmetric Temperature Modulation for Extreme Fast Charging of Lithium-Ion Batteries.
Joule, doi:https://doi.org/10.1016/j.joule.2019.09.021 (2019).

12 **Huo, H., Cai, H., Zhang, Q., Liu, F. & He, K.**
Life-cycle assessment of greenhouse gas and air emissions of electric vehicles:
A comparison between China and the U.S.
Atmospheric Environment 108, 107-116, doi:10.1016/j.atmosenv.2015.02.073 (2015).

13 **BloombergNEF**
Electric Vehicle Outlook 2020 (2020).
https://about.bnef.com/electric-vehicle-outlook/

14 **Bloomberg**
Here's How Electric Cars Will Cause the Next Oil Crisis (2016).
https://www.bloomberg.com/features/2016-ev-oil-crisis/

15 **International Energy Agency**
Global EV Outlook 2019: Scaling up the transition to electric mobility (2019).
www.iea.org/publications/reports/globalevoutlook2019/.

16 **International Renewable Energy Agency**
Electricity Storage and Renewables:
Costs and Markets to 2030 (2017).
https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets

17 **International Energy Agency**
World gross electricity production, by source (2018).
https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2018

18 **Olivetti, E. A., Ceder, G., Gaustad, G. G. & Fu, X.**
Lithium-Ion Battery Supply Chain Considerations:
Analysis of Potential Bottlenecks in Critical Metals.
Joule 1, 229-243, doi:10.1016/j.joule.2017.08.019 (2017).

19 **Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L. & Anderson, P.**
Recycling lithium-ion batteries from electric vehicles.
Nature 575, 75-86, doi:10.1038/s41586-019-1682-5 (2019).

20 **World Economic Forum & Global Battery Alliance**
A Vision for a Sustainable Battery Value Chain in 2030:
Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation,
World Economic Forum (2019).
http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

21 **Melin, H. E.**
E-Waste World Conference and Expo (2019).

22 **Qiao, Q., Zhao, F., Liu, Z., He, X. & Hao, H.**
Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle.
Energy 177, 222-233, doi:10.1016/j.energy.2019.04.080 (2019).

23 **Chen, M. Zheng, Z., Wang, Q., Zhang, Y., Ma, X., Shen, C., Xu, D., Liu, J., Liu, Y., Gionet, P., O'Connor, I., Pinnell, L., Wang, J., Gratz, E., Arsenault, R. & Wang, Y.**
Closed Loop Recycling of Electric Vehicle Batteries to Enable Ultra-high Quality Cathode Powder.
Sci Rep 9, 1654, doi:10.1038/s41598-018-38238-3 (2019).

24 **Editorial.**
Recycle spent batteries.
Nature Energy 4, 253-253, doi:10.1038/s41560-019-0376-4 (2019).

25 **Ciez, R. E. & Whitacre, J. F.**
Examining different recycling processes for l ithium-ion batteries.
Nature Sustainability 2, 148-156, doi:10.1038/s41893-019-0222-5 (2019).

26 **Hao, H., Qiao, Q., Liu, Z. & Zhao, F.**
Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production:
The China 2025 case.
Resources, Conservation and Recycling 122, 114-125, doi:10.1016/j.resconrec.2017.02.005 (2017).

27 **Huang, B., Pan, Z., Su, X. & An, L.**
Recycling of lithium-ion batteries:
Recent advances and perspectives.
Journal of Power Sources 399, 274-286, doi:10.1016/j.jpowsour.2018.07.116 (2018).

28 **Gaines, L., Richa, K. & Spangenberger, J.**
Key issues for Li-ion battery recycling.
MRS Energy & Sustainability 5, doi:10.1557/mre.2018.13 (2018).

29 **Holtsmark, B. & Skonhoft, A.**
The Norwegian support and subsidy policy of electric cars. Should it be adopted by other countries?
Environmental Science & Policy 42, 160-168, doi:10.1016/j.envsci.2014.06.006 (2014).

30 **Reuters**
Germany to hike electric car subsidies as VW launches car (2019).
https://www.reuters.com/article/us-germany-autos/germany-to-hike-electric-car-subsidies-as-vw-launches-car-idUSKBN1XE1AK

31 **US Department of Energy**
Electric Vehicles: Tax Credits and Other Incentives (2020).
https://www.energy.gov/eere/electricvehicles/electric-vehicles-tax-credits-and-other-incentives

32 **Ministry of Finance and Ministry of Science and Technology**
Notice about the Demonstration Work of Promoting Energy Efficient and Alternative Fuel Vehicles (2009).
http://www.gov.cn/zwgk/2009-02/05/content_1222338.htm

33 **Hao, H., Ou, X., Du, J., Wang, H. & Ouyang, M.**
China's electric vehicle subsidy scheme:
Rationale and impacts.
Energy Policy 73, 722-732, doi:10.1016/j.enpol.2014.05.022 (2014).

34 **NITI Aayog & World Energy Council**
Zero Emission Vehicles (ZEVs):
Towards a Policy Framework, (2018).
https://niti.gov.in/writereaddata/files/document_publication/EV_report.pdf

35 **World Economic Forum**
EV-Ready India Part 1: Value Chain Analysis of State EV Policies (2019).
http://www3.weforum.org/docs/WEF_EV_Ready_India.pdf

36 **European Parliament**
Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, Official Journal of the European Union (2006).
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006L0066&from=EN

37 **European Comission**
Implementation of the Strategic Action Plan on Batteries: Building a Strategic Battery Value Chain in Europe (2019).
https://ec.europa.eu/commission/sites/beta-political/files/report-building-strategic-battery-value-chain-april2019_en.pdf

38 **US Department of Energy**
A surge of lithium-ion batteries is headed for US recyclers (2020).
https://recellcenter.org/

39 **Xu, C. Zhang, W., He, W., Li, G., Huang, J. & Zhu, H.**
Generation and management of waste electric vehicle batteries in China.
Environ Sci Pollut Res Int 24, 20825-20830, doi:10.1007/s11356-017-9890-8 (2017).

40 **Bulach, W. Schüler, D., Sellin, G., Elwert, T., Schmid, D., Goldmann, D., Buchert, M. & Kammer, U.**
Electric vehicle recycling 2020:
Key component power electronics.
Waste management & research, ISWA 36, 311-320, doi:10.1177/0734242X18759191 (2018).

41 **Canals Casals, L., Martinez-Laserna, E., Amante García, B. & Nieto, N.**
Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction.
Journal of Cleaner Production 127, 425-437, doi:10.1016/j.jclepro.2016.03.120 (2016).

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