2022
December

SPECIAL REPORT

Are Electric Vehicles Really Green? The Truth About EVs

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Electric vehicles (EVs) are touted as one of the pillars of a net-zero carbon future, along with renewable energy. Unlike internal combustion engines (ICE) that usually run on diesel or petrol (gasoline), they produce zero greenhouse gas emissions or other air pollutants from combustion at the point of use and continue gaining in "cleanliness" each year due to improvements in manufacturing processes and the "greening" of the electricity generation mix.

SPECIAL REPORT

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Yet on a life-cycle basis, EVs are not zero-carbon. They must be charged, with electricity generation that usually still includes a high share of coal, gas, or oil. Manufacturing their motors and batteries requires large quantities of materials, notably lithium, graphite, rare earth elements, copper, cobalt, nickel, and manganese. Mining and processing these minerals produce CO_2 emissions and cause environmental and social damage. EVs are heavier and therefore pose more risk to other road-users and pedestrians, cause more road damage, may emit more particulates from tyre wear, and require more steel and/or aluminium.

So, balancing these considerations - are EVs really green? Can national climate goals to phase-out ICE vehicles by 2035 in lieu of EVs be achieved? What are the challenges and opportunities of shifting to EVs?

Key Takeaways

1. **Even for cars registered today, battery electric vehicles (BEVs) have by far the lowest life cycle GHG emissions compared to all other technologies.**
2. **This is despite the carbon intensity of BEV body manufacturing and battery manufacturing being higher than that of a traditional ICE vehicle.**
3. **BEVs driven on an average grid mix (fossil fuels + renewables) can achieve carbon parity with an ICE vehicle in 2 years or lower.**
4. **BEVs driven on carbon-intensive grids *might* have a higher carbon footprint than their ICE counterpart initially, but as electricity becomes lower-carbon in the coming years, the lifecycle GHG emissions from them will decline further.**
5. **Even the dirtiest batteries emit less CO_2 than using no battery at all. As electricity is decarbonised to meet climate targets, lifecycle emissions will fall for existing EVs, and manufacturing emissions will fall for new EVs.**
6. **Plug-in hybrid electric vehicles (PHEVs) can achieve modest near-term gains, but do not have long-term deep decarbonisation potential compared to BEVs.**
7. **Globally there is more than sufficient resource of each key material required to meet EV targets but will require rapid development of new mines for crucial minerals and metals to keep pace with the rise in EV ambition.**
8. **Still, EVs are only one of multiple solutions to decarbonising the transport sector. Hydrogen fuel cell electric vehicles (HFCEVs) have the potential to offer extremely low GHG passenger vehicle pathways but are not at the scale required to meet crucial near- to medium-term Paris goals.**

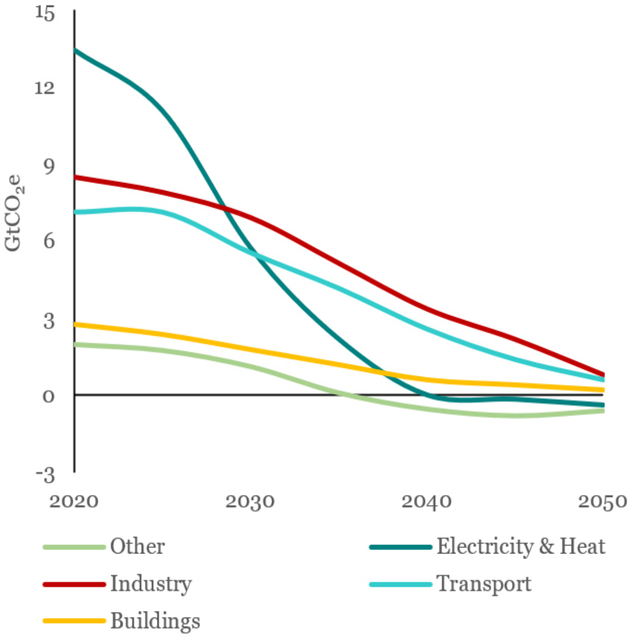
- Electric vehicles (EVs) feature prominently in several leading mitigation pathways that limit warming to well below 2°C or 1.5°C, in line with the Paris Agreement, as well as in ambitious net zero emissions scenarios.
- Compared to 2012, when some 120,000 electric cars were sold worldwide, 2021 saw the same number being sold in a week. Clearly the EV market has made great strides despite the economic uncertainty of the last two years, and not just in sales. Costs have fallen, performance (charging time and range) has improved, and a much greater range of models is available, including two- and three-wheelers, standard and luxury passenger cars, SUVs, buses, and light and heavy trucks.
- A complete lifecycle analysis (LCA) shows that EVs are in fact, not zero-emissions vehicles, although they (chiefly BEVs) have by far the lowest lifecycle GHG emissions compared to other transport technologies.
- However, several studies have concluded that "even the dirtiest batteries emit less CO_2 than using no battery at all", and that as countries decarbonise electricity generation to meet climate targets, lifecycle emissions will fall for existing EVs, and manufacturing emissions will fall for new EVs.
- Manufacturing emissions can be reduced by lowering the carbon intensity of the grid that powers metal processing and battery factories, by improving energy efficiency and reducing waste in the manufacturing process, by recycling EV materials, and by reducing the greenhouse gas footprint of mining by different choices of materials and design, and by greener mining practices.
- Battery manufacture emissions contribute to the GHG emissions of an EV only in the beginning, but the carbon intensity of the grid (depending on the generation mix) used for charging makes the major contribution to its overall cumulative lifetime GHG emissions.
- Manufacturing emissions are higher for EVs in "year zero" of ownership due to the emissions associated with manufacturing their batteries but this (excess carbon debt) will be paid off after a period, depending on the manufacturing process and model, the grid emissions factor, and the pattern of vehicle use.
- Utilising the marginal generation mix to meet EVs' incremental demand would be most appropriate in countries characterised by a higher share of renewables, nuclear or other low-carbon sources in their generation mixes through to 2030. However, because of EVs' higher efficiency, there will still generally be a reduction in emissions, except in the case where most marginal generation is based on coal.
- Charging EVs will require more generation, both in the short and long-term. If the marginal generator on the grid is a fossil-fuelled plant (usually the case today), or if new demand is met by expanding fossil generation (by running existing plants more often or building new plants), the emissions benefit of the EV will be at least partly offset by higher generation emissions.

- Increased penetration of renewables or nuclear into the grid mix to meet this new demand will, therefore, have to be paired with smart solutions to avoid any impacts from EVs' peak charging requirements, and/or potentially reduced carbon savings.
- As EVs are cheaper to run (electricity costs are usually lower than petrol / diesel costs, allowing for EVs' higher efficiency), they will tend to drive further where users have a choice (for example, a family with one ICE and one EV will use the EV for most routine journeys).
- The growth of EVs affects the oil and gas industry in an obvious way. Less use of ICE vehicles means less crude oil refined into gasoline or diesel, but this will be highly heterogeneous among regions.
- Oil and gas producers can invest in EVs internationally or in domestic manufacturing. They could cover various parts of the value chain – the vehicle, battery, critical materials input, software, charging and electricity retail, or related areas such as autonomous vehicles, presenting a potential "hedge" against losing out to EVs.
- Gas exporters may be less exposed in the short- to medium-term, due to increased electricity consumption and the need for flexible generation of EVs.
- In the Middle East, the potential for growing EV adoption makes the case for continuing economic reform and diversification even stronger, while simultaneously meeting crucial climate targets.

It is largely undisputed that EVs will play a critical role in meeting global goals on climate change. They feature prominently in several leading mitigation pathways that limit warming to well below 2°C or 1.5°C, in line with the Paris Agreement, as well as in ambitious net zero emissions scenarios, and are the backbone of contentious pledges signed at or after the UNFCCC COP26 summit in Glasgow that seek to abolish internal combustion engine (ICE) vehicles.

These include the Glasgow Declaration on Zero-Emission Cars and Vans to end the sale of internal combustion engines by 2035 in leading markets and by 2040 worldwide, an MoU to end the sale of fossil-fuel-powered heavy-duty vehicles by 2040, a ban on selling ICE vehicles by 2035 as part of the Fit for 55 EU Green Policy Package, and an increase in transport-specific mitigation measures in countries' updated nationally determined contributions (NDCs) under the Paris Agreement.

Figure 1 Emissions mitigation required by sector to achieve a net zero future under the IEA's NZE 2050 Scenario[i]



Additional updates to these and/or new, potentially legally binding agreements including more stringent targets can also be expected from the ongoing COP27 summit at Sharm El-Sheikh in Egypt.

Figure 2 Number of EVs in the global vehicle parc by scenario, BP[ii]

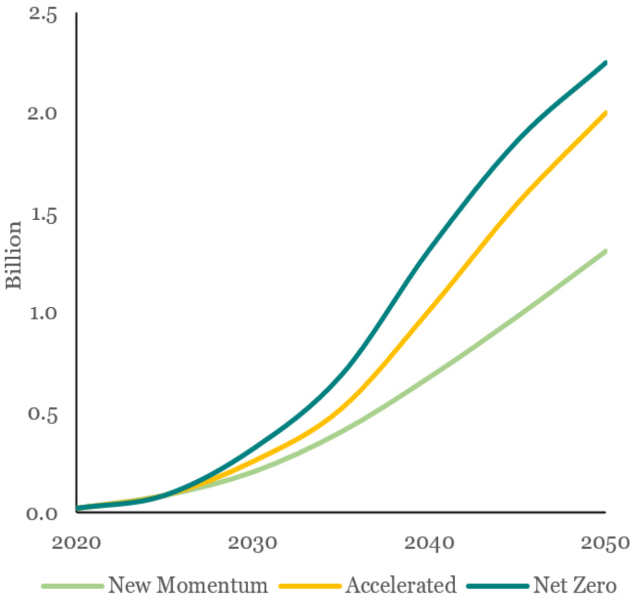


Table 1 What do major net zero scenarios require from the transport sector to remain consistent with a 1.5°C pathway?

Agency	Scenario	Requires
IEA	Net Zero Emissions by 2050 Scenario[iii]	• An electric car fleet of over 300 M in 2030 • Electric cars to account for 60% of new car sales in 2030 • To get on track with NZE2050, electric cars' sales share to increase by ~6% per year
BP	Net Zero[iv]	• Share of EVs in new vehicle sales to increase from 2% in 2019 to 25-30% in 2030 and around 90% in 2050 • 2 billion or more EVs in the global vehicle parc by 2050 • EVs to account for 65-80% of the vehicle kilometres (VKM) travelled on the road in 2050, compared with <1% in 2020
DNV	Pathway to Net Zero Emissions / ETO / E-mobility Revolution[v]	• Half the global sales of new passenger vehicles to be BEVs by 2032 • 2.8 B EVs on the road by 2050 • 70% of VKM travelled on the road from EVs by 2050 • 7000 TWh of annual EV electricity consumption by 2050
IRENA	1.5°C Pathway / Scenario[vi]	• EVs to account for more than 80% of all road transport activity by 2050 • 1/3rd of all light-duty vehicle sales and 1/5th of truck sales over the current decade to 2030 to be electric • Drastic reduction in transport emissions from 8.2 $GtCO_2e$ in 2018 to 0.4 $GtCO_2e$ in 2050
IPCC	AR6 SSP1-1.9[vii]	• EVs powered by low emissions electricity to decarbonise land-based transport, on a life cycle basis • Advances in battery technologies to facilitate electrification of heavy-duty trucks and complement conventional electric rail systems[viii]

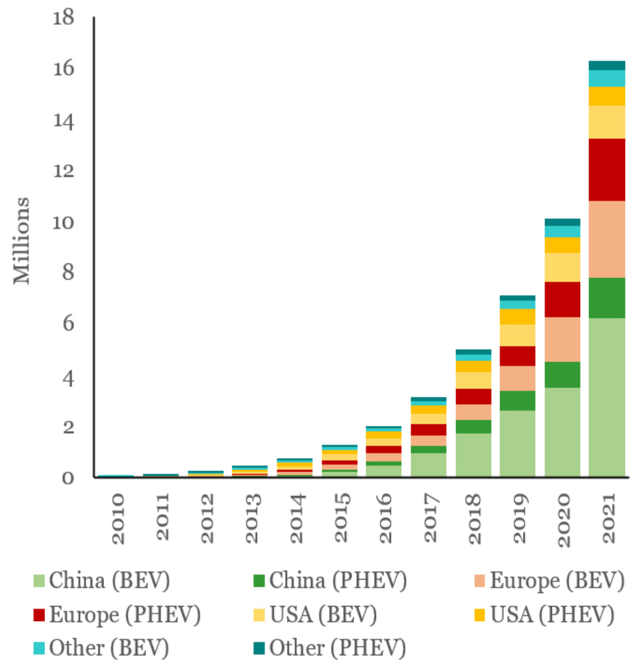
In addition to decarbonising the transport sector, EVs have also been gaining in credibility due to several associated adaptation benefits. These include:

- Substantial human health benefits due to no tailpipe exhaust emissions (zero GHG emissions while driving), resulting in improved air quality (no emissions of particulates, nitrogen oxides, sulphur oxides, unburnt hydrocarbons, carbon monoxide).
- Improved neighbourhood, community and/or societal amenity due to no engine noise or gears, thus being much quieter than conventional ICE vehicles.
- Lower maintenance, reducing life-time material use and lowering the total cost of ownership.
- Better adaptability to automation and self-driving, which would improve road safety and convenience.
- Improved energy security, by eliminating the dependence of transport on volatile commodities like oil

Mention of adaptation priorities around transport has increased in countries' NDCs from just over 20% in 2021 to 32% in 2022[ix], presenting a strong business case to pursue EVs, particularly when considering the avoided costs of petrol and/or diesel (due to higher efficiency and the lower price of electricity per unit versus gasoline or diesel, even when accounting for electricity transmission losses).

Sales of electric cars (chiefly battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)) therefore doubled year-on-year to 6.6 M in 2021 from 2020, bringing the total number of electric cars on the road to >16 million (Figure 3), triple the amount in 2018. As in past years, BEVs account for the most of this increase, at around 70%.

Figure 3 Global electric car stock by region, 2010-2021[x]



Compared to 2012, when some 120,000 electric cars were sold worldwide, 2021 saw the same number being sold in a week. Clearly the EV market has made great strides despite the economic uncertainty of the last two years, and not just in sales.

Original equipment manufacturers (OEMs) have spent nearly US$ 225 B on capital expenditures and R&D for EVs in 2020 alone[xi], while global automakers continue delivering new electrified models. There are around 450 models of EVs currently available on the market, 5 times more than available in 2015[xii].

The "Tesla Effect" has made electric vehicles glamorous. The strong share price performance of Tesla has encouraged a wave of investment into EVs by both traditional manufacturers and other start-ups. Even though Tesla's share price is down significantly since January 2022, its market capitalisation is still more than ten times that of legacy automakers such as GM, Ford, and BMW.

Market consolidation as a result of new partnerships and joint ventures between entry-level and incumbent OEMs has also risen, and established OEMs continue investing in start-ups to take advantage of the capabilities they've built[xiii]. This has resulted in a number of combined multimodal, charging, ride-hailing, parking, and car-sharing services.

For example, UAE start-up-turned-billion-dollar ride-hailing firm Careem now offers Tesla vehicles for the same price as a business service car in partnership with ION, a sustainable commercial transport provider[xiv].

Global automakers and OEMs have also begun undertaking strategic commitments to EVs, with specific production, sales, and electrification targets.

Most of these are borne out of fuel economy and emissions targets imposed by national governments as part of national climate action plans (CAPs), or city access restrictions (zero-/low-emissions zones) on the use of older ICE vehicles by city governments as part of district or county-level CAPs.

Financial incentives continue playing an important role in driving EV sales. Cash subsidies to consumers buying low-emission vehicles, reduced taxes on EVs, and increasing and/or maintaining taxes on ICE vehicles are some of the incentives governments are taking to ensure the transport sector contributes to meeting their NDCs and CAPs.

Fact Box 1 As EVs have only recently overcome the drawbacks of traditional battery technology, their early adoption has been driven mainly by incentives[xv]

Incentives driving early adoption of EVs

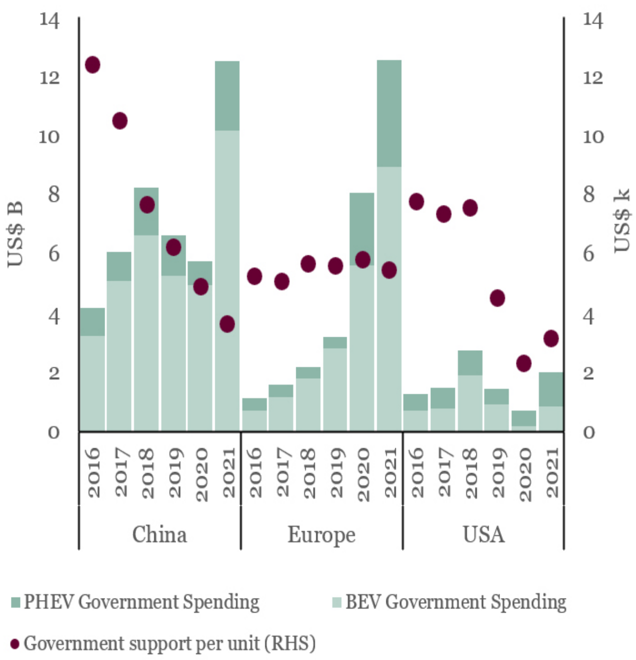
- Tax credits and VAT exemptions on purchase price
- Subsidies on purchase price
- Exemptions from registration tax
- Tax exemptions for corporate vehicles
- Use of high-occupancy lanes
- Free parking and exemption from road and ferry tolls
- Free charging
- Fleet purchases of electric vehicles by government (e.g., city buses)

The economic uncertainty of the last two years has also prompted a range of new incentives to more openly favour EVs. For example, in 2020, Germany temporarily lowered VAT from 19% to 16% on low emission vehicles and doubled existing subsidies to ~US$ 7,000 on EVs costing less than US$ 45,000[xvi]. Other EV incentives are set to be reduced from 2023 however, as the vehicles become "more popular"[xvii].

In France, private consumers who buy electric cars (costing up to US$ 47,000) can receive US$ 6,000 in incentive. Those looking to get rid of their old cars can also receive additional government aid offered by a novel scrappage scheme, which has been designed to get less-efficient models off the road. The country is also planning to subsidise EV leasing that will make all-electric models available for only US$ 100 a month, which is "less than [what] most French drivers currently spend on gasoline alone each month"[xviii].

In the US, the Inflation Reduction Act (IRA) has established a tax credit for electric cars under US$ 55,000 and electric SUVs, vans, and pickup trucks under US$ 80,000 of US$ 7,500 split into two equal halves of US$ 3,750, redeemable for each half if the EV has battery components manufactured or assembled in North America, and; has critical minerals that were extracted or processed in the US, or in countries with which the US has a free trade agreement, or use critical minerals that were recycled in North America[xix].

Figure 4 Government spending on electric cars by region, 2016-2021[xxi]



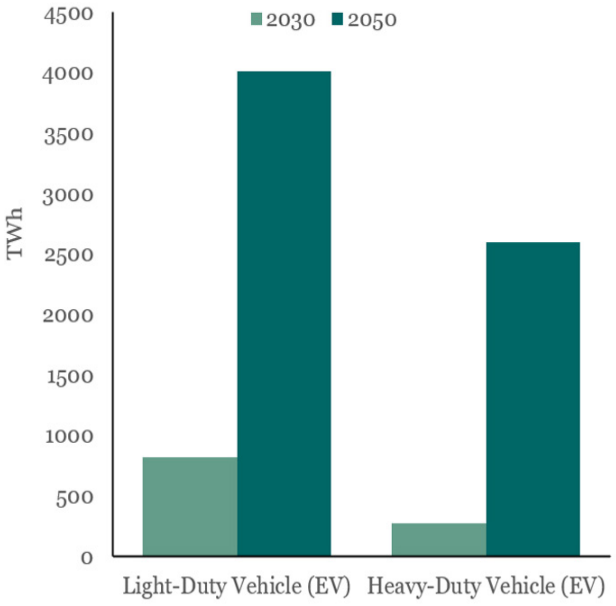
In China, EV subsidies and tax break policies set to expire in 2020 have once again been extended to 2023 (after initially being extended to 2022) to help maintain growth for electric cars, including fully electric as well as PHEVs[xx].

As no GHG emissions are directly emitted from EVs, i.e., when they are driven, they are largely hailed as the "greenest, most environmentally friendly" option in the transport sector today. However, if run on electricity that is still predominantly produced from fossil energy in most countries this alters the lifetime emissions of the vehicle. Considerable energy is also used to manufacture the vehicle, and in particular, the battery of BEVs, further contributing to increasing its lifecycle emissions.

Around half of the emissions from battery production come from the electricity used in manufacturing and assembling the battery[xxii]. Producing batteries in regions with relatively low-carbon electricity or in factories powered by renewable energy (such as Tesla's Gigafactory in Nevada) could substantially reduce emissions from the manufacturing and assembly processes. However, several estimates indicate that renewable energy will have to be scaled up massively to meet the low-carbon power demand of EV battery manufacturing, as well as of EVs' charging requirements.

According to the IEA's Net Zero Emissions by 2050 Scenario, the share of electricity in transport will increase from <2% in 2020 to ~45% by 2050, with demand from EVs (light and heavy-duty) reaching 6,610 TWh. This compares to total generation today of 26,800 TWh, increasing to 45,100 TWh by 2050, i.e., ground transport would account for nearly 15% of all electricity use in 2050, or about 35% of demand growth. This would exert significant pressure on expanding low-carbon power capacity to keep lifetime emissions of EVs low.

Figure 5 Global electricity demand of light- and heavy-duty EVs in the IEA's NZE2050 Scenario[xxiii]



There is also the issue of mining critical materials, including lithium, rare earth elements (REEs) and others, for battery and motor production, which is not a green activity. Producing lithium-ion (Li-ion) batteries for EVs is more material-intensive than producing traditional combustion engines. Currently most lithium is extracted from hard rock mines or above-ground brine reservoirs, and most of the energy used to extract and process it comes from fossil fuels.

Hard rock mining releases 15 tCO_2e of emissions for every tonne of mined lithium[xxiv]. To compare, this is nearly 100x the CO_2 released into the atmosphere from extracting North Sea oil and gas, 21 $kgCO_2e$/bbl of North Sea UK oil produced[xxv], or 0.15 tCO_2e per tonne of North Sea UK oil produced. Per kWh oil produced, emissions are still lower, at 970 gCO_2e, or 11.3 tCO_2e per tonne oil on a lifecycle basis[xxvi]. This logic however ignores the fact that EV batteries can be recharged nearly 2000 times and also recycled, whereas oil can only be used once.

These concerns have led to scepticism around the "green" promise of EVs, although several studies have concluded that "even the dirtiest batteries emit less CO_2 than using no battery at all"[xxvii], and that as countries decarbonise electricity generation to meet climate targets, lifecycle emissions will fall for existing EVs, and manufacturing emissions (including mining for battery raw materials) will fall for new EVs.

Major dissidents of EVs unsurprisingly include proponents of the fossil fuel industry and/or sceptics of climate science in general. For example, the Manhattan Institute, a climate-sceptic, conservative American think tank and research group, released figures in a 2020 analysis claiming that 227 tonnes of earth are "dug up to extract the metals for one electric car battery"[xxviii].

Such views have also been echoed by Middle East-based non-resident scholars at the Middle East Institute[xxix], a Washington-based Middle East-focussed think tank, potentially alluding to the "pro-oil and gas" sentiment of many of the countries in the region, seeing as they are major hydrocarbons producers.

The Manhattan Institute's mining figures were swiftly dismissed as a "gross exaggeration" by several climate experts who state that the quantity mined varies depending on the geography and the type of battery. The figures also do not take into account that certain elements that go into making the battery of an EV, such as cobalt, are produced as part of mining another metal, so the ore needed is only mined once[xxx].

Moreover, OEMs are rapidly shifting to more environmentally friendly batteries, including lithium-iron-phosphate (LFP), which are highly recyclable, unlike the fossil energy consumed by ICE vehicles. For example, Tesla has shifted to produce its standard-range vehicles with an LFP cathode, as it is "significantly cheaper and doesn't require any nickel or cobalt… it's also more stable, easily recyclable, and can be charged to 100% without degradation long-term"[xxxi].

Other far-right think tanks have also utilised the US Environmental Protection Agency's (EPA) emissions calculation tool to prove that an electric car charged in St. Louis, Missouri, will produce 247 gCO_2e/mile travelled, which is not much different than the higher efficiency gasoline-powered ICE vehicle segment; for example, the Toyota Corolla Hybrid emits ~200 gCO_2e/mile[xxxii]. However, the subregion relies almost entirely on coal power, and a car charged there will still produce emissions lower than the average of 381 gCO_2e/mile of a typical gasoline vehicle[xxxiii] .

Former British Secretary of State for Environment George Eustice also faced backlash after suggesting that the wear on roads from brake linings and tyres of EVs may be greater than with ICE vehicles, because "of the weight of the battery in electric cars", in turn generating more polluting fine particles, including PM2.5, which is allegedly "the most dangerous", and "contributes to tens of thousands of deaths each year"[xxxiv] .

Leading battery electrochemist Dr. Euan McTurk dismissed his remarks in a report showing that EVs' brakes wear far more slowly than conventional cars, while tyre wear is similar for non-driven wheels and "only slightly worse for driven wheels"[xxxv].

According to McTurk, EVs brakes wear slower because most of the braking is done via regenerative braking where the electric motor works in reverse, converting kinetic energy from the moving vehicle into electricity to charge the battery when slowing down, reducing the use of the mechanical brake discs and pads, and adding more range to the vehicle[xxxvi].

Others to respond to Eustice include Quentin Willson, automotive journalist and electric car ambassador, and his FairCharge Campaign[xxxvii], as well as the Royal Automobile Club, the British automotive services company that is seeking to make the switch to electric "as easy as possible"[xxxviii].

Some automakers like Toyota, however, have been slower moving, and believe EVs will not be adopted "as quickly as policy regulators and competitors think", due to lack of infrastructure, pricing, "how customers' choices vary region to region", and "tremendous shortages" of lithium and battery grade nickel in the next 5-10 years, leading to production and supply chain problems[xxxix].

ZERO TAILPIPE EMISSIONS ARE NOT THE ONLY FACTOR THAT MAKE EVS "GREEN"

Most main-stream analyses of emissions avoided or mitigated from the use of EVs, or electrified transport, have tended to focus on emissions from end-use when comparing them to emissions from ICE vehicles, which causes them to sometimes incorrectly label EVs as "zero-emissions vehicles".

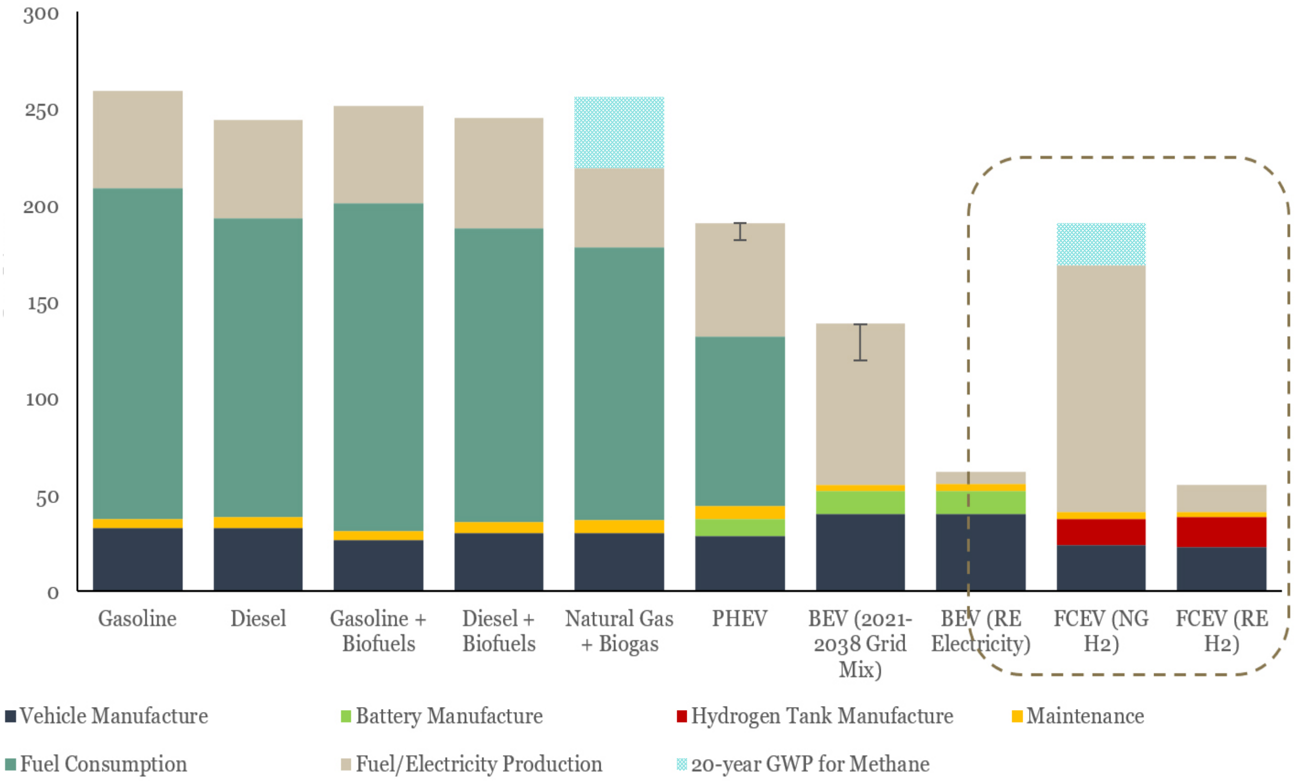
A complete lifecycle analysis (LCA) shows that EVs are in fact, not zero-emissions vehicles, although they (chiefly BEVs) have by far the lowest lifecycle GHG emissions compared to other transport technologies (Figure 6). Moreover, as electricity becomes more lower-carbon in the coming years, the lifecycle emissions of these vehicles will only decline further, making them "gain in cleanliness".

BEVs can potentially be matched in emissions avoided by renewable electricity-based hydrogen fuel cell EVs (FCEVs), but this technology is not yet at the scale of BEVs. For ICE vehicles there is no realistic path to deep decarbonisation within the timeframe of the Paris Agreement goals, and most existing ones will likely be converted to hybrids and/or run on biofuels to achieve near-term gains in meeting global emissions' mitigation targets.

Figure 6 shows the lifecycle GHG emissions of average medium-sized cars registered in 2021 and considers the following parameters.

ICE vehicle technologies fuelled solely on gasoline and diesel have by far the highest lifecycle emissions amongst all vehicle technologies (Figure 7). Gasoline and diesel ICE vehicles fuelled on a fossil/biofuel mix emit approximately 245-253 gCO_2e/km over their lifetime, with the major difference in emissions from pure gasoline/diesel-fuelled ICE vehicles being fuel consumption emissions (or end-use/tailpipe).

Figure 6 Lifecycle GHG emissions for global typical medium-size passenger cars registered in 2021[xl]



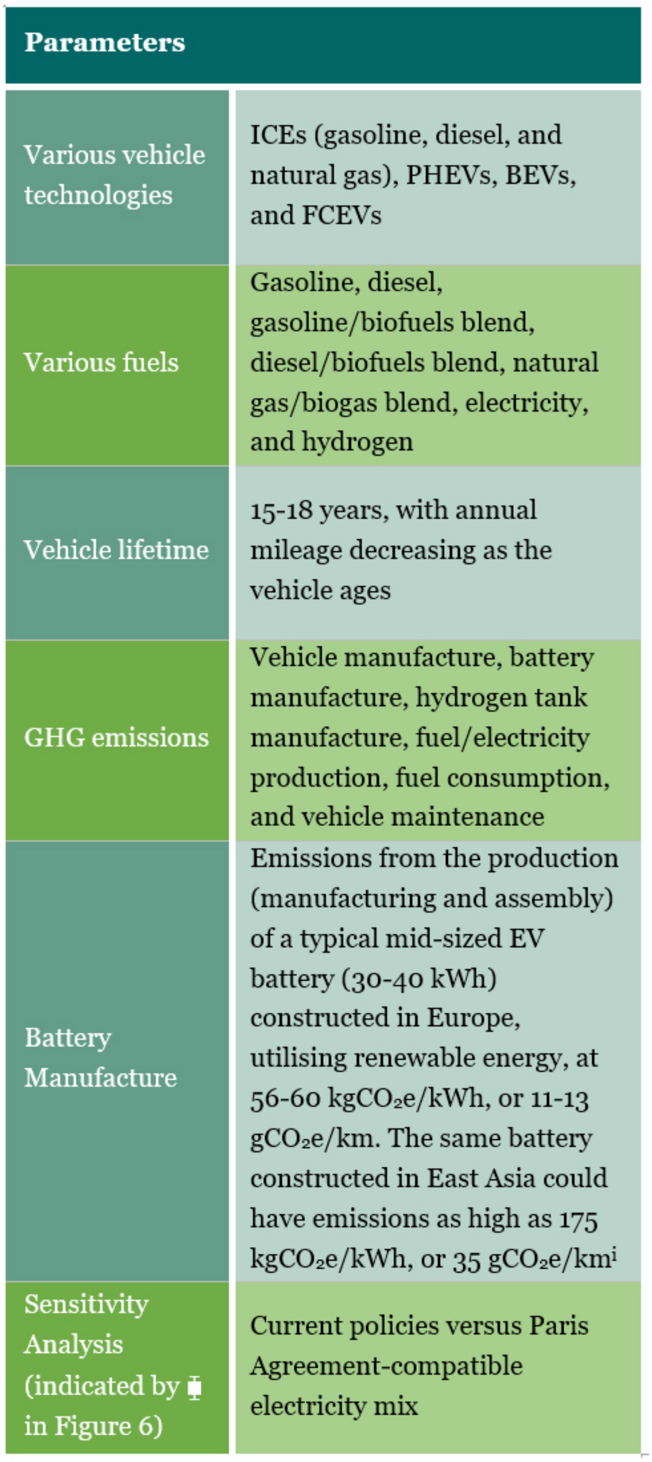
Emissions from hybrids are about 20% lower, at 200 gCO_2e/km, and from natural gas cars at 219 gCO_2e/km. However, emissions cannot be fully accounted for without considering the global warming potential (GWP) of upstream methane emissions. In the high short-term, the 20-year GWP of methane makes the climate impact of natural gas cars just as high as gasoline cars[xlii].

PHEVs partly fuelled by fossil/biofuel electricity emit emissions some 30% lower than gasoline cars, at 184-191 gCO_2e/km. FCEVs fuelled by natural gas-based hydrogen emit 169 gCO_2e/km, but when taking into account the 20-year GWP of upstream methane emissions, they emit the same as PHEVs, at 191 gCO_2e/km. FCEVs fuelled by renewable electricity-based hydrogen emit only 55 gCO_2e/km over their lifetime, but this technology is still not as commercial as BEVs.

BEVs fuelled on an average grid electricity mix emit between 105-124 gCO_2e/km, and if fuelled completely on renewable or nuclear electricity emit only 46 gCO_2e/km. Countries like Switzerland, Norway, France, Sweden, and Austria, which are largely powered by nuclear and hydroelectricity, have some of the lowest BEV lifecycle emissions in the world.

However, these numbers can change significantly if the BEV is fuelled from more carbon-intensive grids. For example, BEVs emit significantly more in India and China, where the national grids are characterised by heavy reliance on coal. A BEV fuelled by coal power in China with a battery manufactured in China would emit only 13%[xliii] less than a high-efficiency gasoline ICE vehicle, at ~215 gCO_2e/km.

Table 2 Parameters considered for assessing the lifecycle GHG emissions of average medium-sized cars in Figure 6



Parameters	
Various vehicle technologies	ICEs (gasoline, diesel, and natural gas), PHEVs, BEVs, and FCEVs
Various fuels	Gasoline, diesel, gasoline/biofuels blend, diesel/biofuels blend, natural gas/biogas blend, electricity, and hydrogen
Vehicle lifetime	15-18 years, with annual mileage decreasing as the vehicle ages
GHG emissions	Vehicle manufacture, battery manufacture, hydrogen tank manufacture, fuel/electricity production, fuel consumption, and vehicle maintenance
Battery Manufacture	Emissions from the production (manufacturing and assembly) of a typical mid-sized EV battery (30-40 kWh) constructed in Europe, utilising renewable energy, at 56-60 $kgCO_2e/kWh$, or 11-13 gCO_2e/km. The same battery constructed in East Asia could have emissions as high as 175 $kgCO_2e/kWh$, or 35 gCO_2e/km[i]
Sensitivity Analysis (indicated by ⌶ in Figure 6)	Current policies versus Paris Agreement-compatible electricity mix

In Poland, where 72% of the generation mix is also characterised by coal, a BEV with a battery manufactured in Europe would emit 194 gCO_2e/km[xliv] (Figure 7), limiting the amount of emissions avoided or mitigated by switching to an electric car.

A major consideration is the assumed emissions from battery manufacture for an EV, because the methodology used for its LCA can greatly influence the conclusions drawn about the carbon intensity of EVs overall. Numerous studies have extensively examined the emissions associated with battery production for EVs, and have yielded a wide range of values, indicating a high degree of uncertainty and lack of a common methodological and data framework to build assumptions and test results.

Although estimates have continuously been refined from their early days in 2010-11, most analyses still rely on only a few primary sources for emissions inventories and typically consider only one major type of battery chemistry (i.e., Li-ion, with an NMC cathode). The type of battery chemistry analysed does make a difference to the lifecycle emissions, as some chemistries have higher or lower concentrations of energy-intensive metals.

These studies also typically do not include battery recycling in their calculations, as there is significant uncertainty about how recycled materials could affect carbon footprints. Additionally, the Li-ion battery industry is rapidly changing, and larger, more efficient factories typically have lower emissions per kWh of battery produced.

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[i] -Qamar Energy Research, based on calculations from Mia Romare & Lisbeth Dahllöf, The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, IVL Swedish Environmental Research Institute, 2017

Figure 7 Lifecycle GHG emissions for typical medium-sized cars by country[xlv]

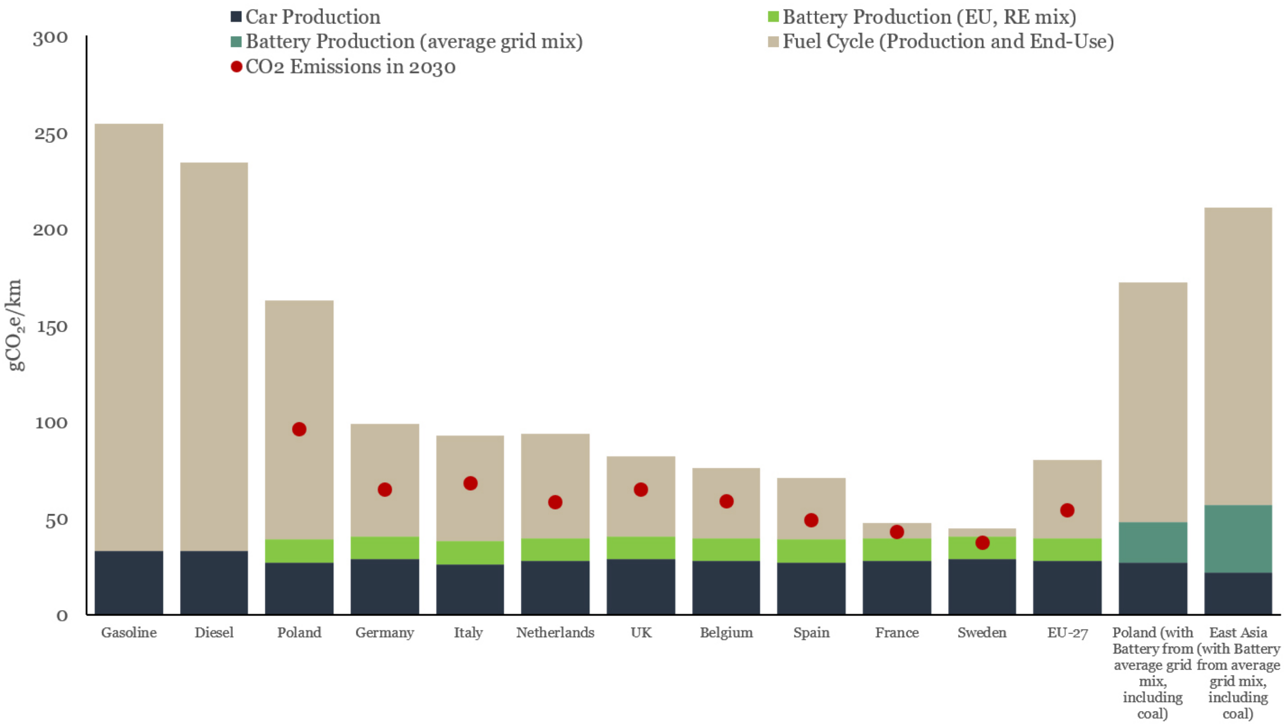
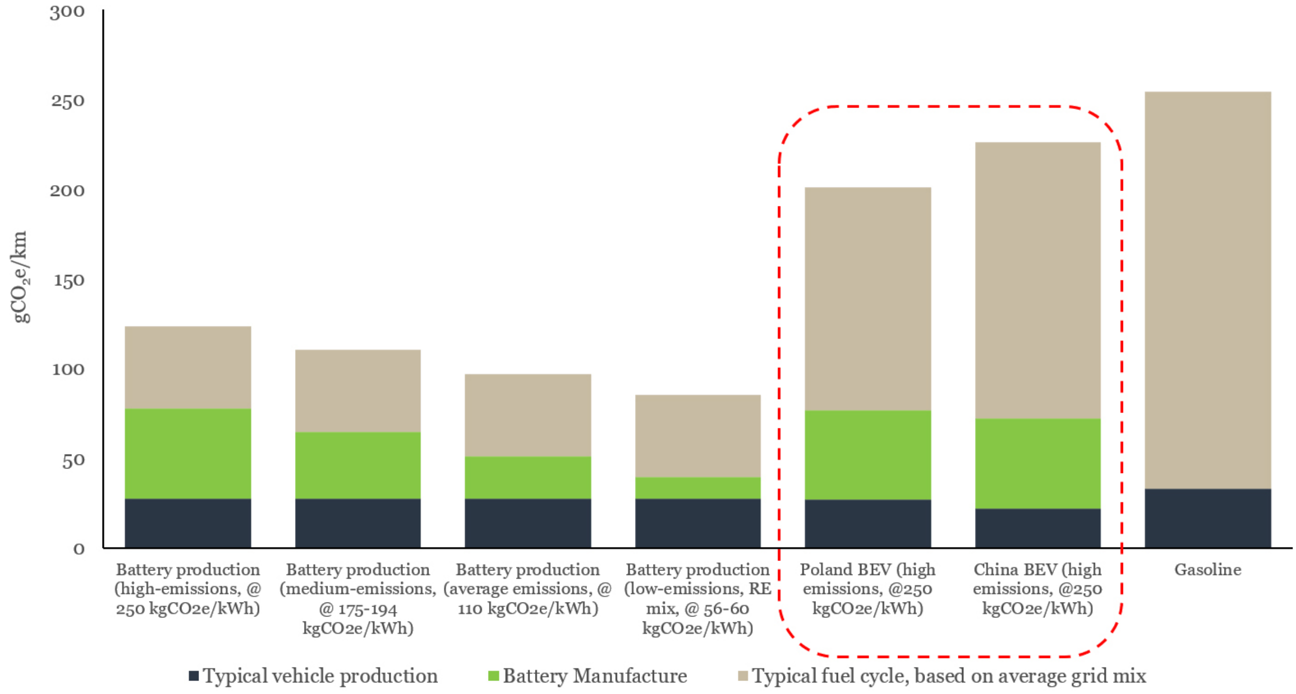


Figure 8 Even the EV with the "dirtiest battery" emits lower than a gasoline ICE vehicle; lifecycle GHG emissions of typical EV with 30 kWh battery produced with different battery production emissions scenarios due to differences in grid mix



Estimates can also vary using either a bottom-up or top-down approach. For example, a bottom-up approach incorporates the activity data for each stage of each component of a battery and aggregates these different components. In contrast, a top-down analysis first determines the total emissions from a factory, and then attributes these emissions to different processes.

Table 3 Lifecycle GHG emissions from battery manufacture by component and manufacturing stage, with upper and lower estimates[xlvii]

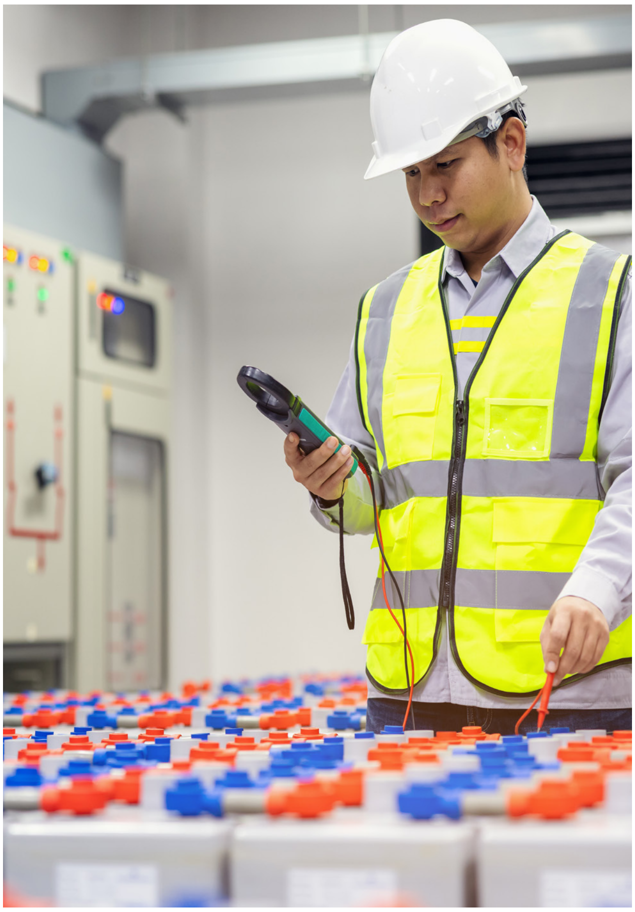
Component	**kgCO_2e/kWh Battery**					
	Raw Material Mining & Refining (Lower)	**Raw Material Mining & Refining (Upper)**	**Battery grade material production (Lower)**	**Battery grade material production (Upper)**	**Manufacturing (component and cell + battery assembly) (Lower)**	**Manufacturing (component and cell + battery assembly) (Upper)**
Anode	2	11	7	25		
Cathode	7	18	13	20		
Electrolyte	4	0	4	13		
Separator	0	5	1	1		
Cell Case	0	1	1	1		
Battery Case	4	13	10	25		
Cooling	0	3	2	6		
BMS	1	0	4	30		
Total	**18**	**51**	**42**	**121**	**20**	**110**

Breakdown of lifecycle GHG emissions from battery manufacture	**Unit**	**Lower**	**Upper**
Battery Grade Material Production, including Mining & Refining (most likely value)	kgCO_2e/kWh	56	60
Final Manufacturing including Assembly (most likely value)	kgCO_2e/kWh	60	106
Battery Grade Material Production, including Mining & Refining (most likely value)	gCO_2e/km	11.2	12
Final Manufacturing including Assembly (most likely value)	gCO_2e/km	12	21.2
Total average GHG emissions from battery manufacture	**gCO_2e/km**	**23.2**	**33.2**

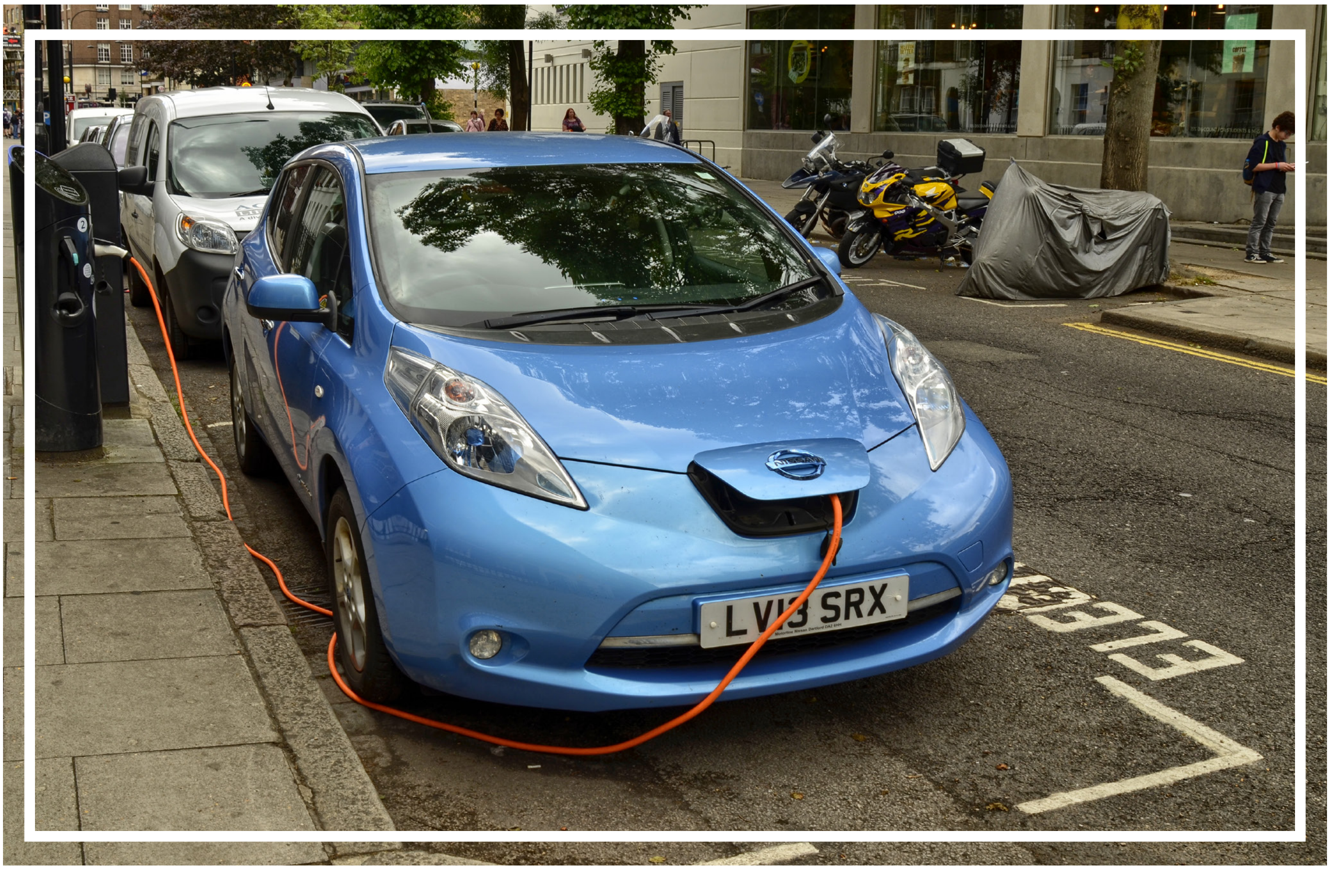
Top-down inventories typically include more auxiliary energy uses but may double-count certain processes and emissions. Therefore top-down inventories typically find higher emissions, often by a factor of 2 or more[xlvi].

Battery production emissions also vary depending on the representative manufacturing grid. High emission estimates usually assume manufacturing grids representative of a high fossil fuel mix, including fuel oil/diesel, coal, and natural gas.

Table 3 summarises the lifecycle GHG emissions from battery manufacture for an EV by component and manufacturing stage, with a sensitivity analysis (upper/lower values) to account for the differences in estimates from various studies.



GRIDS CONTRIBUTE TO OVERALL LIFECYCLE GHG EMISSIONS MORE THAN BATTERY PRODUCTION



Battery manufacture emissions contribute to the GHG emissions of an EV only in the beginning, but the carbon intensity of the grid (depending on the generation mix) used for charging makes the major contribution to its overall cumulative lifetime GHG emissions (although battery second life and recycling could result in a modest net reduction).

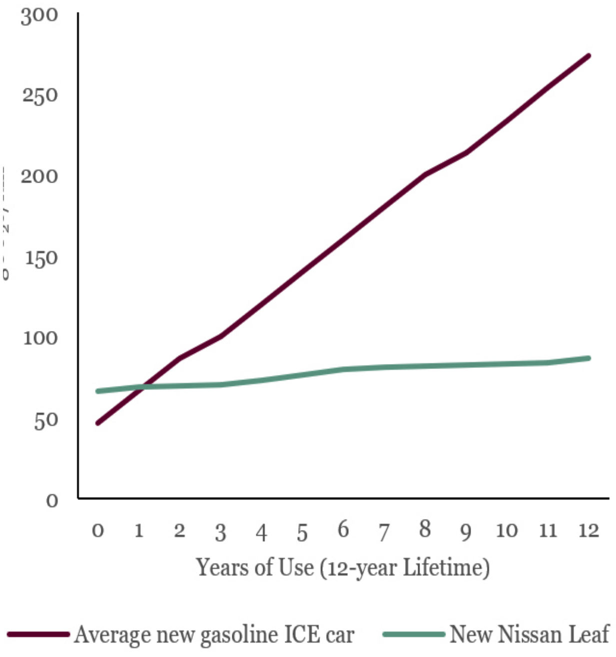
Manufacturing emissions are higher for EVs in "year zero" of owning one due to the emissions associated with manufacturing their batteries (Figures 6-8), but this (excess carbon debt) can be paid off depending on where the break-even point for the EV occurs during its lifetime.

Estimates as to how big the carbon gap is between a typical ICE vehicle and an EV, and where the break-even point comes for it, can be accurately assessed by taking into account the model, lifetime, battery type, range, size, cathode material of the vehicle, and the power/grid input (charging) and grid carbon intensity (based on geography). However not all methodologies are consistent in their assumptions.

A simple illustration of the carbon debt break-even of an EV compared to a conventional ICE vehicle can be presented by considering a Nissan Leaf EV in the UK, one of the highest-efficiency EVs available on the market today, emitting 76 gCO_2e/km[xlviii], some 3x lower than the lifetime emissions of an average conventional car.

While the production of the battery would result in a carbon debt in "year zero" of owning the Nissan Leaf, if charged with the UK's average electricity carbon intensity over the last two years of ~223 gCO_2e/kWh[xlix] for year zero and gradual improvement towards a 2030 target of 100 gCO_2e/kWh[l], this would be paid back after less than two years of driving.. This period would be even shorter in countries with much lower grid carbon intensities, like Austria (grid carbon intensity of 81 gCO_2e/kWh in 2021), where a Nissan Leaf would reach its carbon debt break-even within 6-7 months of driving.

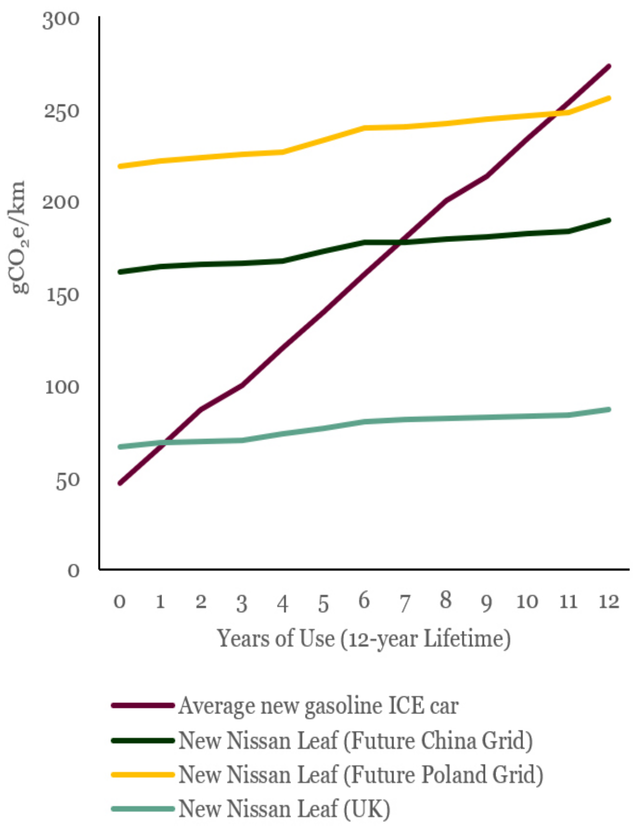
Figure 9 Cumulative lifetime GHG emissions for an average new conventional car versus a new Nissan Leaf in the UK, assuming 150,000 km driven over a 12-year lifetime[li]



However, in countries with much higher grid carbon intensities, the payback period is much later. For example, in China, which had an average grid carbon intensity of 541 gCO_2e/kWh in 2021, a Nissan Leaf would pay back its excess carbon debt in 7 years, assuming a future grid carbon intensity scenario of 215 gCO_2e/kWh, a 60% reduction from current grid carbon intensity (based on a post-COP21 target of reducing GHG emissions from the power sector by 60% in 5 years[lii]), although the lack of clarity around China's emissions reduction targets in its updated NDC and vaguely-defined net zero by 2060 pledge makes this hard to accurately assess.

In Poland, which had the world's highest grid carbon intensity at 731 gCO_2e/kWh in 2021, the payback would occur in nearly 11 years, assuming an aggressive reduction in grid carbon intensity of 7% annually, derived from a scenario where the country's grid carbon intensity reaches well below 300 gCO_2e/kWh by 2030, based on the EU Taxonomy's provision of limiting financing to CHP projects fulfilling emissions criteria of 270 gCO_2e/kWh[liii].

Figure 10 Cumulative lifetime GHG emissions for an average new conventional car versus a new Nissan Leaf in different geographies [liv]



The longer payback period in countries with high grid carbon intensities has often been used as a criticism against EVs, as actual cost savings from avoided fuel use show up almost at the end of the EV's lifetime.

This can be further compounded by considering the marginal grid or average grid mix when assessing the lifetime GHG emissions of the vehicle, particularly in countries that have a varied generation mix.

Renewables-based and other low-carbon power plants (nuclear, hydro, wind, solar) are typically fully utilised, and are not able to easily change their generation output to meet the incremental growth in power demand from a new EV. The power output from fossil fuel-based power plants like coal and natural gas, however, can increase in the short-term to respond to this new load.

This is the "consequential grid mix", or the marginal generation mix, which typically has higher emissions than the average generation mix (which takes into account all the sources of generation), as it reflects the emissions from the power plants "turned on" to meet the new demand from EV charging.

Higher emissions from a marginal generation mix can contribute to an increase in the emissions impact of an EV, but only in the short-term due to the flexibility of fossil fuel-based power plants to respond to the new incremental demand.

However, as the demand from more and more EVs is added to the grid medium- to longer-term, additional lower-carbon generation sources will come online, reversing this trend, with EVs charging mainly from a low-carbon or ideally, zero-carbon mix.

For example, in our illustrative assessment of a Nissan Leaf's carbon debt break-even in the UK, the vehicle's emissions in the first year of ownership (when powered by the marginal grid) are ~33%[lv] higher than in year 7, due to the increase in fossil fuel-based power to meet the new incremental demand.

The emissions from the vehicle at the end of its lifetime, however, are nearly 65% lower[lvi] than the emissions in its first year of ownership, because by then the UK's mix has added more low-carbon and renewables-based generation to meet the higher electricity demand.

Table 4 “Break-even” point of a typical EV to become cleaner than an equivalent gasoline car in terms of lifetime carbon footprint, based on the Argonne National Laboratory model[lvii]

Mid-size Saloon		**Lifetime VKM**	**Fuel Economy (Gasoline, km/L)**	**Curb Weight (Kg)**	**EV Battery Range (km)**	**EV Battery Type**	**EV Battery Size (kWh)**	**Cathode**
Model EV	Tesla Model 3	278,660		1,625	483	Li-ion	54	NCA
Model ICE	Toyota Corolla (year unspecified)		14	1,340				

Scenarios					
Power Scenario 1	100% Hydroelectric	Power Scenario 2	US Average Generation Mix	Power Scenario 3	100% Coal-fired
Break-even (Km)	13,518	Break-even (Km)	21,726	Break-even (Km)	126,655
Break-even (Years)	6 months	Break-even (Years)	1 year	Break-even (Years)	6 years, 3 months

Mid-size SUV		**Lifetime VKM**	**Fuel Economy (Gasoline, km/L)**	**Curb Weight (Kg)**	**EV Battery Range (km)**	**EV Battery Type**	**EV Battery Size (kWh)**	**Cathode**
Model EV	Tesla Model Y	295,094		2,003	483	Li-ion	60	NCA
Model ICE	Honda CR-V (year unspecified)		13	1,514				

Scenarios					
Power Scenario 1	100% Hydroelectric	Power Scenario 2	US Average Generation Mix	Power Scenario 3	100% Coal-fired
Break-even (Km)	14,806	Break-even (Km)	23,818	Break-even (Km)	143,232
Break-even (Years)	6 months	Break-even (Years)	1 year, 1 month	Break-even (Years)	6-7 years

It should be noted that such a scenario would require effective management of potential constraints for EVs on renewables' deployment for decarbonising grids elsewhere. For example, if the UK buys more and more wind turbines to meet EV charging, this might cause a shortage for other countries like Egypt, who can't get sufficient turbines to decarbonise its grid. Table 4 summarises data generated by an Argonne National Laboratory model to determine at what point a typical EV (in this case, a Tesla) becomes cleaner than an equivalent gasoline car (Toyota Corolla and a Honda CR-V) in terms of its lifetime carbon footprint.

The break-even for both Tesla 3 and Y models would come in less than a year if driven on 100% renewable energy (hydropower), such as in Norway, and in just over a year if being driven on a US average generation mix (23% coal, other fossil fuels, and a larger share of renewables). However, if driven on 100% coal-fired generation, both EVs would take at least 6 years to reach carbon parity with an equivalent gasoline ICE vehicle. Nevertheless, even on the most pessimistic assumptions that marginal generation is entirely met by coal, the EVs still have a lower carbon footprint than the ICE vehicle well within their service lifetime, and long before the 2050 net-zero target.

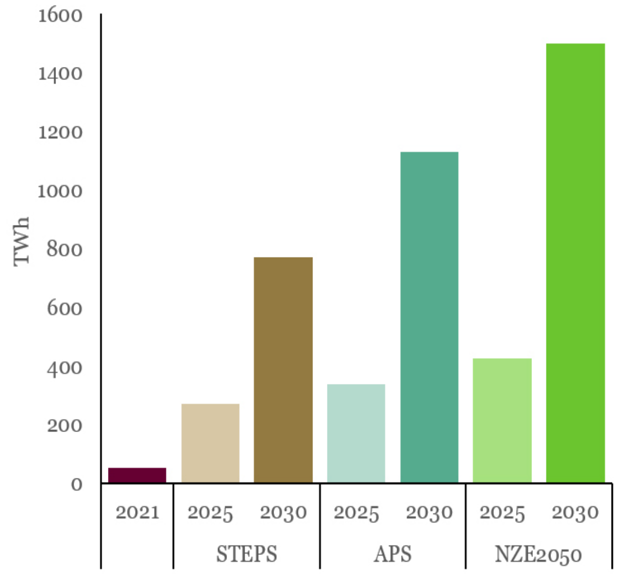
Note that these figures assume no change in the generation mix down the line, i.e., under all three scenarios, the power input remains the same and is not subject to decarbonisation, which would bring forward the break-even point considerably.

PEAK CHARGING REQUIREMENTS CAN HAVE A SIGNIFICANT IMPACT ON GRID CAPACITY

While incremental demand from a modest rise in EVs could be met by temporarily overfiring hydrocarbons-based generation units, a concerted growth in EVs will demand additional generation capacity, low- or zero-carbon, if the sector is to remain aligned with a Paris-compatible pathway.

The global EV fleet in 2021 consumed 55 TWh of electricity, which is less than 0.5% of current global total final energy consumption (TFEC)[lviii]. According to the IEA's Announced Pledges Scenario (APS), electricity demand from EVs globally in 2030 would be equivalent to twice of Brazil's current electricity use, at 1,100 TWh[lix]. Demand under the Net Zero Emissions by 2050 Scenario would be slightly higher, at ~1,500 TWh in 2030[lx], making EVs account for some 4% of global electricity demand in 2030, which is not large enough to warrant dedicated renewables-based grid capacity expansions solely for meeting EVs' demand.

Figure 11 Electricity demand from the global EV fleet by scenario, 2021-2030[lxi]



Utilising the marginal generation mix to meet EVs' incremental demand would therefore make most sense in countries characterised by a higher share of fossil fuels in their generation mixes through to 2030.

Table 5 Share of electricity consumption attributable to EVs relative to final electricity demand by region and scenario, 2021 and 2030[lxii]

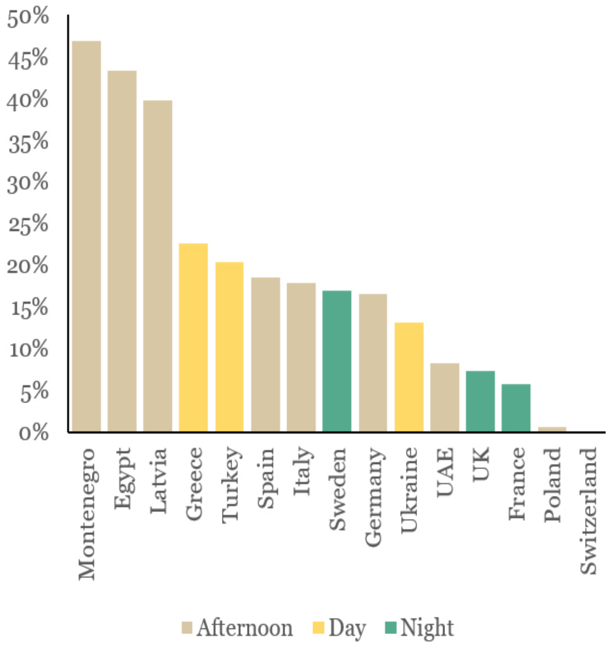
Country /Region	2021	STEPS 2030	APS 2030	NZE2050 2030
China	0.5%	3.3%	3.6%	4.8%
Europe	0.3%	5.5%	6.5%	8.7%
India	0.0%	1.9%	3.9%	5.2%
Japan	0.0%	1.3%	2.6%	3.5%
US	0.2%	3.0%	5.7%	7.6%
Global	0.2%	2.7%	3.9%	5.2%

However, this will most likely change as the electricity demand from EVs (excluding electrified shipping and aviation) crosses 6,600 TWh in 2050 under a Paris-aligned global climate pathway (Figure 5). Decarbonising power grids will become essential to not only reduce the sector's own carbon intensity but electrify end-use sectors like heavy industry (which will see a rise in demand of >11,000 TWh between 2020 and 2050) and light industry to help reduce their emissions.

Increased penetration of renewables into the grid mix to meet this new demand will, therefore, have to be paired with smart solutions to avoid any impacts from EVs' peak charging requirements, and/or potentially reduced carbon savings.

For example, in countries with large investments in solar and wind capacity, a lack of renewable energy storage means that the amount of carbon saved by driving an EV depends heavily on the time of day it is recharged. In Germany or Spain, charging in the afternoon, when the sun and wind are more prevalent and when some renewable energy may be shed if not used, results in saving 16-18% more carbon than at night, when grids are more likely to be fuelled by gas or coal[lxiii].

Figure 12 Variation in carbon emissions depending on time of day for charging an EV in different countries[lxiv]



Typical levels of battery grid storage even in highly renewable-based systems may only amount to a few hours, which means that even countries that source significant amounts of solar and wind power during the day will struggle to keep it on tap for night-time charging, which is when most EV users prefer to charge their vehicles at home.

A study by the Swiss Federal Institute of Technology shows the impacts of overnight home charging by EV drivers on the western US power grid, which is slated to handle the demand of an estimated 50% of drivers using EVs by 2035. Charging EVs mainly at home during the night could lead to a 25% surge in peak net electricity demand (i.e. the highest electric power demand minus power provided by solar and wind) when most of the 11 western US states reach 50% EV ownership, and possibly surpass grid capacity at even higher levels of ownership.

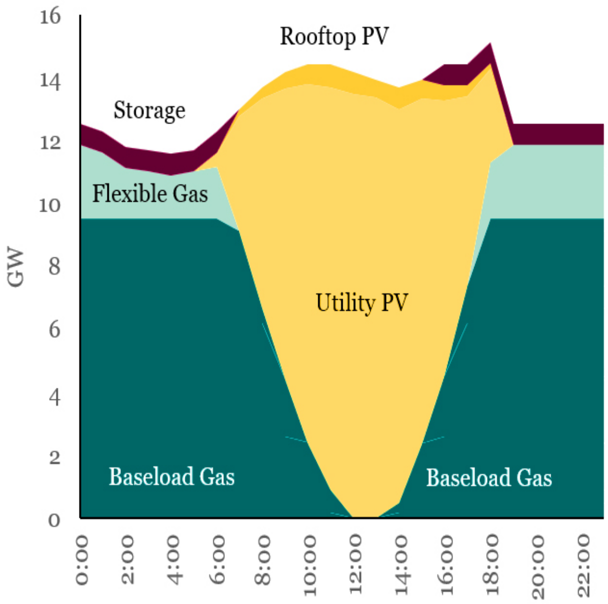
A proposed solution to this is expanding daytime charging, which can help reduce the increase in peak net electricity demand identified in the study to only 7.5% and reduce the costs of expanding grid capacity. It could also help use excess solar power more efficiently as it would enable drivers to tap solar power when it is immediately available, instead of requiring power grid operators to invest in more energy storage to store daytime solar power for night-time charging.

This can be particularly helpful in countries with large solar resources that do not have the requisite energy storage infrastructure in place to support night-time charging. In countries with a hybrid generation mix, daytime charging would eliminate the problem of lower carbon savings from night-time charging, seeing as the grid would likely be fuelled by fossil fuels at that time. The increase in remote working can also help alter consumer behaviour by allowing people to charge their EVs from home during the day, although they could also charge at work if charging points are available.

Figure 13 illustrates how combination storage can help address the intermittency of supply-demand during the day. Peak demand usually occurs in the daylight hours and can include EV charging demand if daytime charging opportunities are appropriately expanded. Solar power is ideally suited to meet this peak but might not be able to in the early evening and/or early morning in a typical MENA/GCC country.

Storage solutions, such as batteries, combined with thermal storage (e.g., CSP with molten salt) can be used for the early evening period to support EVs charging. Other storage solutions, combined with increased energy efficiency to reduce the overall level of load, and in particular to shrink the peak and move it partly into periods with abundant solar generation, can reduce the size, cost, and O&M of storage systems.

Figure 13 Illustration of future MENA country grid that can use solar energy more efficiently by expanding daytime charging opportunities[lxv]



These can also displace significant amounts of gas for power, enabling additional carbon savings from EV charging, as well as improve grid balance and reliability as grids further phase-out fossil fuel sources in favour of renewables.

The reverse option, vehicle-to-grid, is also possible – using car batteries with smart grids to provide electricity at deficit periods and pay EV owners for the service. However, this needs intelligent automated controls to ensure that owners still find their vehicle environmentally friendly when they want it.

MINING CONCERNS AND HIGH METAL PRICES OF CURRENT LI-ION BATTERIES

The increasing requirement of mining precious metals and REEs for battery production of EVs continues to remain a contentious issue due to almost complete reliance on lithium, or the so-called "white gold", as there is no commercially available substitute at scale currently.

Lithium has experienced the fastest demand growth of all battery metals so far, and in practical terms almost 80% of the increase in its demand to 2030 is projected to come from EVs[lxvi], with the remainder from battery storage and consumer electronics. Estimates vary by scenario, but even in a scenario where climate action is moderately pursued, demand increases nearly sixfold to 500 kt in 2030 from 2021 levels, driven by higher EV sales across all modes (LDVs, HDVs, etc.).

In more aggressive climate action-oriented scenarios, lithium demand could increase 42-fold by 2040, or potentially 54-fold under a Paris-aligned, net zero scenario. This translates to a massive ~3.3-4.3 Mt of lithium demand for EVs, which will also require more mines than ever.

Even in a scenario where climate action is only moderately pursued, 50 new lithium mines will be required by 2030, assuming an average annual lithium mine production capacity of 8 kt. Other estimates suggest the number of new mines required to meet more aggressive climate action scenarios could be as high 400 by 2035[lxvii].

These estimates also do not distinguish between demand for lithium hydroxide and lithium carbonate. Most of BEV targets are slated to be met by adoption of higher NCA cathode chemistries, which will drive demand for lithium hydroxide faster than carbonate.

According to Bloomberg New Energy Finance (BNEF), demand for battery-grade lithium hydroxide could be 6x times that of carbonate in 2030. Taking refinery assets currently under development, this could lead to an oversupply in lithium carbonate conversion capacity, but a deficit of battery-grade lithium hydroxide by 2025, causing producers to substitute hydroxide for carbonate in the production of medium nickel chemistries, such as NMC[lxviii].

Other minerals that go into an EV battery (cobalt, nickel, graphite) will also see demand surge by 20-25 times in an aggressive climate action-oriented scenario, while the expansion of electricity networks (for increased electrification of various sectors, including EV charging requirements) will make copper demand for grid lines more than double over the same period. EVs currently also use four times more copper than a traditional vehicle, due to more wiring, which will also add to overall copper demand.

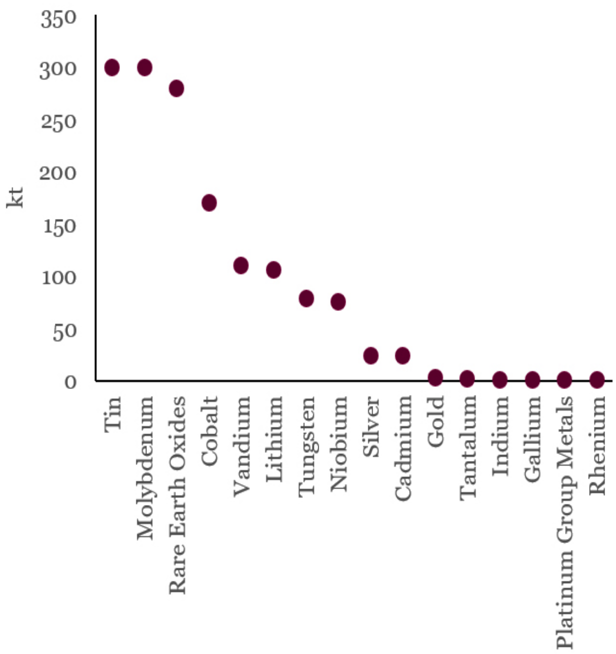
Rare earths in EV motors (such as neodymium, praseodymium, and dysprosium) are slowly being replaced by non-REEs by OEMs like Tesla, Renault, and BMW, although Asian automakers still rely on them.

Globally there is more than sufficient resource of each key material required to meet EV targets, but new mines are not being developed fast enough to keep pace with the rise in EV ambition, particularly for metals like copper.

According to S&P Global Platts' Future of Copper report, refined copper production would have to more than double from the 24.5 Mt produced in 2021 and might still not be enough under its High Ambition Scenario which sees some 27 million EVs sold annually by 2030[lxix]. Ore grades in major copper mines are deteriorating, meaning more waste rock has to be moved and processed, raising costs and carbon footprint.

Community and environmentalist protests in countries including Peru and the US delay the development of new mines or halt operations, sometimes for several years. In response, there will probably be more efforts to substitute copper with aluminium, although its performance is not as good.

Figure 14 Precious metals mined in 2021[lxx]

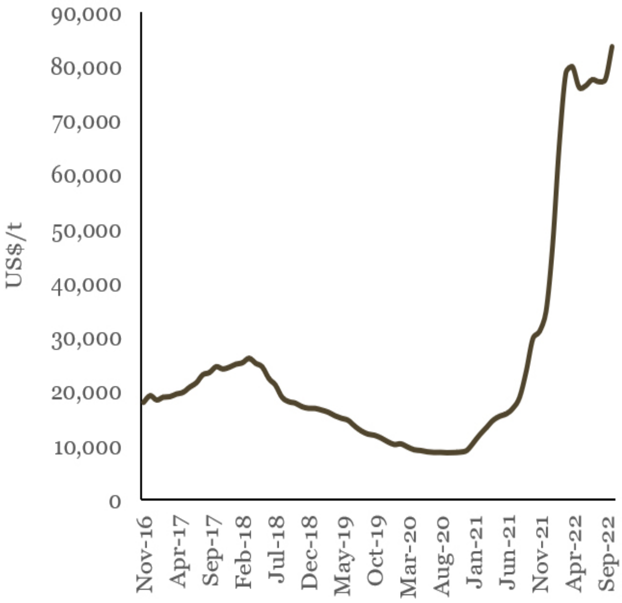


China currently leads the production of Li-ion batteries (nearly 80% of global total), whilst also controlling >60% of global lithium refining for these batteries and processing 100% of natural graphite[lxxi]. 80% of all rare earths currently mined also come from China. This is a cause for concern as it creates a supply-chain dependence and the potential for bottlenecks (causing already-high prices to rise higher), and boycotts. But attempts by Europe and the US to promote domestic mining and processing of REEs, lithium and other critical minerals are limited by environmentalist opposition and high costs.

Chinese-backed "artisanal mining" in the Democratic Republic of Congo, from where 65% of all cobalt is mined, is also a socially and environmentally harmful activity. China has also been accused of labour and human rights violations[lxxii] in the DRC, posing an "ethical dilemma" to proponents of EVs.

There is also criticism surrounding Australia's export of mined lithium to China for refining, which further drives supply chain imbalances. Lithium mining in Chile and Argentina has also come under fire as it comes from salt deserts called salars. Mining from salars is reported to cause droughts in the local areas, threatening local livestock and vegetation farms[lxxiii].

Figure 15 Prices for battery grade lithium hydroxide hit record-highs[lxxiv]



The inelastic nature of lithium supply has contributed to the recent record-highs in prices (as EVs demand grows in Europe and North America), but another reason is the rise in prices of associated battery metals, such as nickel, to which lithium prices can also be exposed.

Russia's invasion of Ukraine has created a lot of pressure, since Russia supplies 20% of global high-purity nickel (most of which is supplied by Norilsk Nickel). Nickel prices reached an unprecedented level of US$ 100,000/t in the aftermath of Russia's invasion of Ukraine (compared to the average price in 2021 of US$ 18,500/t), resulting in the London Metal Exchange temporarily closing nickel trade.

This is problematic for Europe, whose main source of nickel for EV battery development is Russia. Australia and/or Canada as well as Indonesia could fill the supply gap from Russia, , but this will increase overall prices per unit of nickel imported, and Europe will also be competing with North American demand.

Rising battery metal prices have therefore brought to the fore batteries with alternate chemistries. For example, LFP has become more attractive as it contains no cobalt or nickel, instead using low-cost iron and phosphorus. LFP also relies on lithium carbonate rather than hydroxide which is used for nickel-rich chemistries. A shift to LFP is also more environmentally friendly.

However, there is the concern of LFP not being profitable enough to recycle at the end of its lifecycle. Recycling an LFP battery will not be able to recover the value of NMC batteries if conventional recycling methods are used. LFP might require direct recycling to be profitable, an emerging process that does not break down the cathode into elements, but instead retains the material crystal structure and regenerates cathode material.

LFPs also have a lower energy density than high-nickel chemistries. While they do they have cost advantages in a high commodity price market, concerns over performance longer-term might deter consumer appetite. LFP-based EVs are mainly driven in China, but major non-Chinese OEMs like Tesla and Volkswagen have also recently announced moves to LFP batteries.

Other chemistries being considered include the manganese-rich LNMO (lithium nickel manganese oxide) which can deliver results on par with other high-performance lithium-based batteries at a lower cost and without cobalt.

However, LNMO batteries lack an electrolyte that can currently handle the stresses of its cathode. The cathode operates at a high voltage that can degrade current electrolytes, rendering the battery useless over time.

Sodium-ion batteries might be the closest, most viable option to Li-ion, and are currently being developed by CATL, one of the world's largest battery makers (who commercially introduced Na-ion in 2021). Na-ion cells have a density even lower than LFP cells, making them more suitable for applications where energy density is not critical, such as grid-scale storage or urban EVs, where research is underway to improve density through new battery pack designs that can integrate both Li-ion and Na-ion cells in one pack.

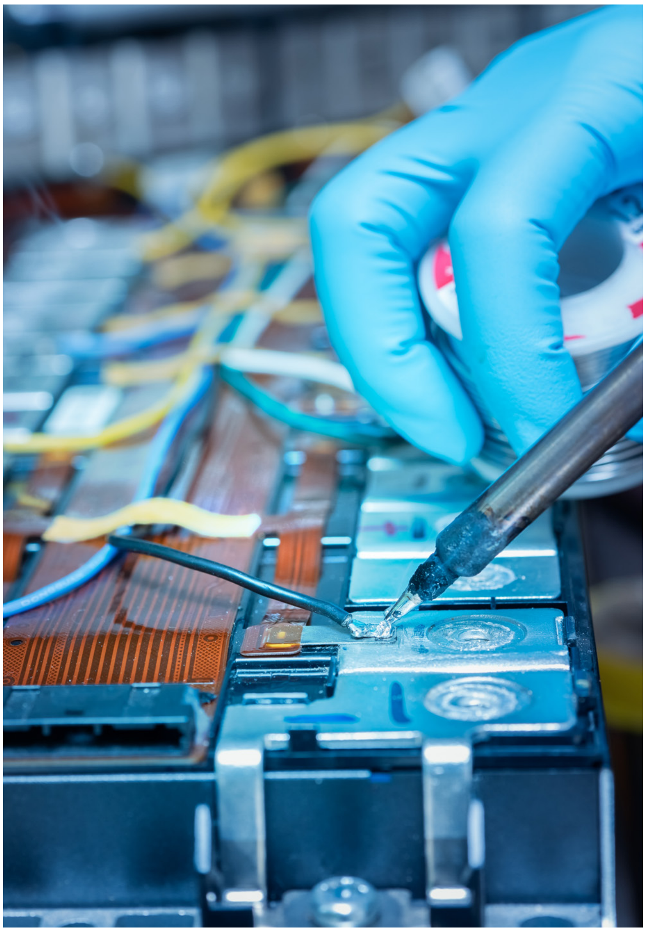
The critical advantage of Na-ion over Li-ion is that it relies on abundant and low-cost materials. Na-ion also cannot use graphite anodes and requires much less copper. While Na-ion has advanced beyond the research stage to demonstration, there are currently no supply chains for its cathode and anode materials due to uncertainties around the scalability of its production process and the time required to develop an industrial-scale supply chain.

Potassium-based batteries (K-ion) have also attracted attention for being abundant and inexpensive, and (in theory) enabling a higher-power battery. However, issues with metal reactivity (making it potentially dangerous to handle) and finding electrode materials to hold the "much heftier" potassium ions has made it difficult to move past its early research stage.

All-solid-state batteries (ASSBs) are being considered as a potential solution that bypasses current high prices and has a battery energy density 70% higher than the current best Li-ion batteries. Utilising a graphite anode, these batteries can dramatically improve driving range capability, opening other applications and eventually driving down costs.

Nissan has opened an ASSB prototype production facility in Japan and is aiming to produce EVs with ASSBs in 2028. Volkswagen, meanwhile, has partnered with Quantumscape in a joint venture that plans a pilot production line in 2024.

Despite the activity around ASSBs, they still need to address major technical challenges. Current high performance relies on impractical pressures, or unscalable, expensive production processes to reach viable performances. As a result, they are not expected to have a significant impact until after 2030.



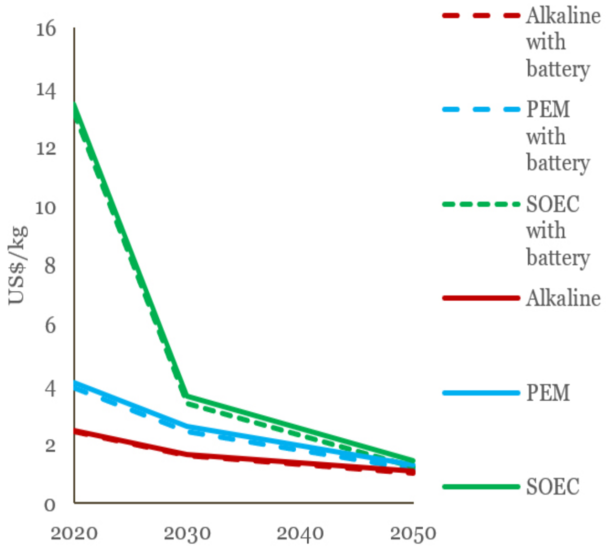
EVs are only one of multiple solutions to decarbonising the transport sector. Recent concerns over ethical mining of battery metals and supply chain bottlenecks resulting in high prices has put the spotlight on competing technologies. These include in the EV segment hydrogen fuel cell electric vehicles (HFCEVs) and autonomous vehicles (especially in public transport), and in the ICE segment synthetic fuels (or e-fuels) and biofuels.

HFCEVs have features that could place them at an advantage to BEVs, such as high energy density, longer driving range (potentially), and the same time as an ICE vehicle for powering or refuelling.

In locations particularly suited to hydrogen production, such as those with ample, low-cost natural gas and/or large low LCOE renewables capacity, and existing, well-connected natural gas infrastructure, they offer an attractive alternative to BEVs. In large gas-producing countries, they also offer a viable route to keeping fossil fuel alive in the longer-term by capturing and storing and/or using the associated CO_2 emissions.

MENA countries have already embarked on ambitious hydrogen production targets, but end-use in transport is still not envisaged as the primary goal, which is exports. Moreover, HFCEVs are complex to build, as they typically function as a small hydrogen-fuelled power station. The fuel is also extremely flammable, which increases its "risk premium" and has to be highly compressed for road use, which can add another layer of complexity, especially if distribution networks are not equipped to handle it adequately.

Figure 16 Renewables-based hydrogen production costs in MENA[lxxv]



Additionally, renewables-based hydrogen production is still expensive due to current high costs of electrolysers, and natural gas-based hydrogen production with a CCUS input is still not anywhere near the level it needs to be to justify mass production and adoption of FCEVs.

While electrolyser costs in the MENA region (Figure 16) could reach parity with natural-gas based hydrogen production by 2030 (mainly alkaline electrolysers, assuming a 100% load factor), the uptake of this "green" hydrogen for the transport sector will depend on the local situation, technological progress, and operational issues such as the ability to ramp up and down easily, and, for solid oxide electrolysers, the potential use of waste heat.

Other competitors to EVs are mainly in the ICE vehicle segment and include synthetic fuels and biofuels. Synthetic fuels are primarily promoted as a climate-neutral option for vehicles with existing ICEs, which can be advantageous, as it does not require the manufacture of a new vehicle.

However, synthetic fuels rely on the availability of (ideally low carbon) hydrogen combined with CO_2 to be produced, and are relatively inefficient when compared to battery technology, not to mention significantly more expensive. They also have similar noise and local air pollution problems to petrol or diesel.

According to the German Energy Agency, vehicles run on e-fuels consume 5x more energy than a BEV and will be ~8x more expensive to run per kilometre[lxxvi]. This makes e-fuels better suited to commercial aircraft and large container ships travelling long distances, two segments where current battery technology is insufficient.

Biofuels, meanwhile, have lower emissions than gasoline, but face significant opposition due to the use of valuable cropland to make ethanol, which contributes to higher food prices. For example, in 100% EVs by 2050 scenario in the US, 551 $MtCO_2e$ could be saved in total out to 2050, and the end of converting maize to ethanol and instead being sold as food would bring down food prices globally[lxxvii].

Biofuels also have higher emissions than EVs (Figure 6). It is likely that limited volumes of biofuels will be reserved for uses such as making sustainable aviation fuels (SAF) for long-distance flights, where there are few viable alternatives.

- The growth of EVs affects the oil and gas industry in an obvious way. Less gasoline for ICE vehicles means less crude oil refined into gasoline or diesel, but this will be highly heterogeneous among regions.
- Some refiners will face tighter economics as they will have to find new, more far-flung markets. In the Middle East, large oil and gas producing countries have embarked on the "internationalisation" of their downstream ventures to secure refining markets in foreign countries, mainly in Asia, which is regarded as the major hub of future near- and medium-term oil demand growth.
- Naphtha as a refined product overlaps with gasoline output and will become particularly important in the "oil to chemicals" segment. New refining capacity additions can take the form of integrated petrochemicals, which will limit production for the light vehicles segment.
- Part of refinery streams going into the gasoline pool can be placed in the petrochemical market. This will cause refinery margins to be increasingly influenced by the petrochemical supply-demand balance and can also allow a greater supply of virgin naphtha coming from increased condensate production from gas fields as oil production declines (due to the drop in demand from road transport).
- Increased EV penetration presents oil companies with a unique opportunity of lending EV users charging points other than at home. They can lend spaces to EV users at their gas stations for a limited time and charge a cost-plus tariff for the electricity used bought from the grid owner/operator.

- The integration of low-carbon technologies into oil and gas operations could allow oil and gas producers in the region to exploit new commercial opportunities, such as hydrogen, which could help develop a commercial case for the uptake of hydrogen in low-carbon transport, particularly shipping and/or in the form of synthetic fuels for aviation.
- While HFCEVs might not gain substantial ground just yet, oil and gas producing countries with large renewable resources can help create a "carbon space" for their exports by decarbonising domestic transport through renewables-based grid charging for EVs, thus freeing up more oil and gas for export.
- Oil and gas producers can also invest in EVs themselves, either internationally, or even in domestic manufacturing. This could cover various parts of the value chain – the vehicle, battery, critical materials input, software, charging and electricity retail, or related areas such as autonomous vehicles, presenting a potential "hedge" against losing out to EVs.
- This is already being witnessed in the EV targets being set in the region, even by traditional climate sceptics like Saudi Arabia, who is seeking to make 30% of all vehicles in Riyadh electric by 2030. The UAE has also established its first EV manufacturing company, indicative of the "dual strategy" approach: decarbonising domestic operations while securing a dominant position in emerging, low-carbon energy sources. Saudi Arabia is expanding copper mining, while all the GCC countries other than Kuwait are important producers of aluminium.
- Smart energy storage solutions, such as batteries, can be combined with thermal storage (e.g. CSP with molten salt) in the MENA region to support EV charging. These can support the integration of higher renewable energy shares, enabling additional carbon savings, as well as improving grid balance and reliability.

CONCLUSIONS

BEVs have by far the lowest lifecycle GHG emissions compared to all other vehicle technologies. As electricity becomes lower carbon in the coming years, their lifecycle GHG emissions will only decline further, making them "gain in cleanliness". There is currently no realistic path to deep decarbonisation of ICE vehicles within the time frame of the Paris targets, making BEVs potentially the only technology with the lowest GHG emissions, today and into the foreseeable future.

Ultimately, whether EVs rise to dominance by 2030 across major geographies, or 2040 and 2050 in others, these dates are still well within the lifespan of current long-lived assets such as oilfields and refineries. In the Middle East, the potential for growing EV adoption makes the case for continuing economic reform and diversification even stronger, while simultaneously meeting crucial climate targets. The electric car transition cannot happen fast enough.

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