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X-change: Cars

The end of the ICE age

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In partnership with:

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What is the X-change?

The X-change is a series of reports analysing the impact of exponential change (the X in X-change) on the energy system. It contrasts with the orthodox view of linear change. The baseline scenario for the future of energy should assume continued exponential growth of renewable energy in the period to 2030.

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About RMI

RMI

RMI is an independent non-profit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all.

We work in the world's most critical geographies and engage businesses, policymakers, communities, and non-governmental organizations (NGOs) to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030.

RMI has offices in: Basalt and Boulder, Colo.; New York City; Oakland, Calif.; Washington, D.C.; and Beijing.

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1. Summary

- **The rapid growth of EV[1] means that global oil demand for cars has already peaked and will be in freefall by 2030. The end of the internal combustion engine (ICE)[2] age has begun.**
- **EV are growing on S-curves.** There is a clear exponential growth pattern for electric vehicle (EV) sales, established by the leaders such as Northern Europe and China, and driven by policy. In broad terms, it is taking around six years for EVs to get from 1% to 10% market share of new car sales, and in leading countries another six years to get to 80%.[3]
- **Economics is the new driver**. Because battery costs enjoy learning curves, total cost of ownership price parity has been reached, and sticker price parity will be reached in every major car market and segment by the end of the decade.[4] That will enable the revolution to widen across the Global South and deepen into other transport sectors.
- **The race to the top**. The race for leadership of the transport technologies of the future adds support to the transition. Companies are already building enough battery and car factories for EV to dominate car sales by 2030.[5]
- **Challenges have solutions**. We need to upgrade electricity infrastructure, deploy more charging networks, recycle batteries, and solve a range of complex challenges.[6] Success in China implies that in most places solutions will be found, but hard work is still vital.
- **Feedback loops speed up change**. As ICE demand declines and EV dominate growth, so companies and countries are redeploying talent and capital toward the future.
- **EV will dominate sales by 2030**. If we continue to solve the challenges and sales continue up the S-curves, then EVs will make up between 62% and 86% of sales by 2030, with China enjoying an EV market share of at least 90%. Meanwhile, consensus EV sales estimates are lagging and get upgraded every year.
- **Peak ICE demand**. Demand for new ICE vehicles peaked in 2017 and has been falling at 5% a year since. Rising scrappage and falling sales mean that the ICE fleet is about to peak and will be falling rapidly by 2030.
- **Peak oil demand for cars**. Global oil demand to fuel cars reached a peak in 2019 and is currently on a typical plateau, squeezed between efficiency gains and the growth of EVs. By 2030 oil demand for cars will be falling at over 1 million barrels per day (mbpd) every year and the endgame for one quarter of global oil demand will be in sight.
- **Cars catalyze change in the transport sector.** Rapid growth in batteries for cars is sparking the lower costs and higher energy density needed to drive change across the rest of the transport sector, from two-wheelers in the Global South to trucking in China and the US. That puts half of global oil demand at risk.
- **There is always room to go faster.** We are on the path to net zero by 2050 but we are not on the path to limit warming to 1.5°C. Each death induced from fossil fuel air pollution matters, each dollar spent on importing expensive fossil fuels has an opportunity cost, and each fraction of a degree is a threat multiplier.

2. Exponential change so far

In this note we look at the exponential growth in the sales of passenger car electric vehicles (EV), why it is likely that exponential change will continue and what this continuity implies for the future of car sales and oil demand. In the Appendix we outline different ways to forecast the future of EV sales and examine in more detail the various challenges to growth.

Much of the debate about the future of EV is still taking place without reference to the very rapid change that has already taken place. Rising policy pressure, falling battery costs and rapid technological innovation have already created EV price parity, changing consumer attitudes, and exponential growth in a clear S-shaped pattern. China has established a dominant position, and car companies have been forced to change strategy. As a result, oil demand for cars peaked in 2019 and we are now bouncing along the plateau at the top.

2.1.1 Policy pressure rose

A rising number of countries have put in place measures to support the growth of EV sales. These included price subsidies for EV, ICE bans, preferential tax treatment, and parking and driving privileges. In 2015 no major countries had set a date to phase out ICE sales. By 2022, 21 countries,[7] accounting for over half of global car demand, had set a date to phase out ICE sales.

There are now policy targets to ban the sale of ICE cars by 2035 in the largest and third largest car markets in the world: China and Europe.[8] The Biden administration has set a target of 2030 for 50% of US sales to be EV[9] and many US states have adhered to the California zero-emission vehicle program.[10]

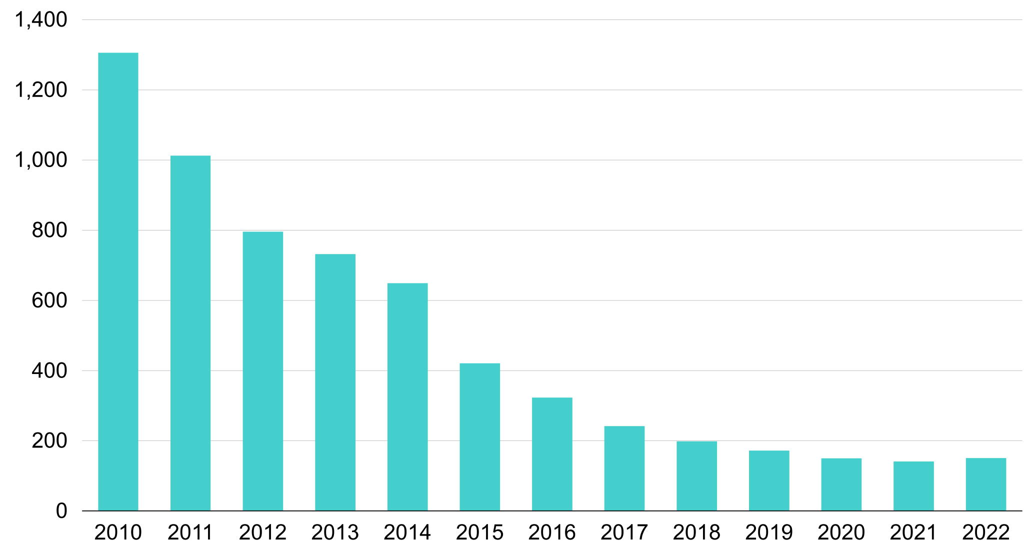
Meanwhile, EV penetration has been running ahead of targets in a number of markets, most notably in China. For example, Beijing's EV share target for 2025 was 25%,[11] but it already reached 29% in 2022.

2.1.2 Battery deployment rose and costs fell

The battery capacity deployed in the transport sector increased from 0.5 GWh in 2010 to 1,500 GWh in 2022,[12] which is nearly 12 doublings and a CAGR of 97%.

Battery costs have fallen by 88% since 2010, at a learning rate of around 17% for every doubling in deployment.[13] The average global price in 2022 was $151 per kWh, and $131 in China. Meanwhile, the energy density of batteries increased by around 6% per annum.[14]

Figure 1: Lithium-ion battery pack prices ($/kWh 2022 real)



Source: BNEF Electric Vehicle Outlook 2023

2.1.3 Price parity was reached

The combination of falling battery costs and policy support enabled price parity to be reached in leading markets. The total cost of ownership (TCO) price parity between ICE and EV was reached in leading markets outside the US in the early 2020s. Drivers of this include cheaper energy (electricity is cheaper than oil), lower running costs, and EV subsidy.[15] RMI calculates that the impact of the US Inflation Reduction Act (IRA) has been to bring TCO price parity in the US as well.[16]

In China, sticker price parity (when the retail prices of comparable ICE and EV are the same) has also been achieved.[17] BNEF notes that the best-selling EV in China in 2022 was the SAIC Wuling Hongguang Mini BEV, which costs about $5,000.

2.1.4 Technology solved challenges

The EV transition from the very start faced many challenges, and few thought that they could be solved. To focus on three challenges from a decade ago: battery costs of over $1,000 per kWh meant that EV were very expensive; the lack of charging infrastructure meant that people worried that it would never be built; and we needed thousands of GWh of battery production capacity, far more than was planned or seemed feasible.

And yet solutions were found to each of these challenges. Battery costs have fallen by nearly 90% in a decade; EV charging infrastructure was built out at the same time as EV sales; Elon Musk put up his first Gigafactory in 2016, and there are now 400 Gigafactories in the pipeline.

The process has not been smooth and has enjoyed its share of setbacks.[18] Nevertheless, it has been sufficient to enable EV growth to continue. The best way to demonstrate this is simply to look at the market share of EV sales in leading markets, now up to 90% in Norway and one third in China. Clearly, solutions are being found.

2.1.5 Consumer attitudes changed

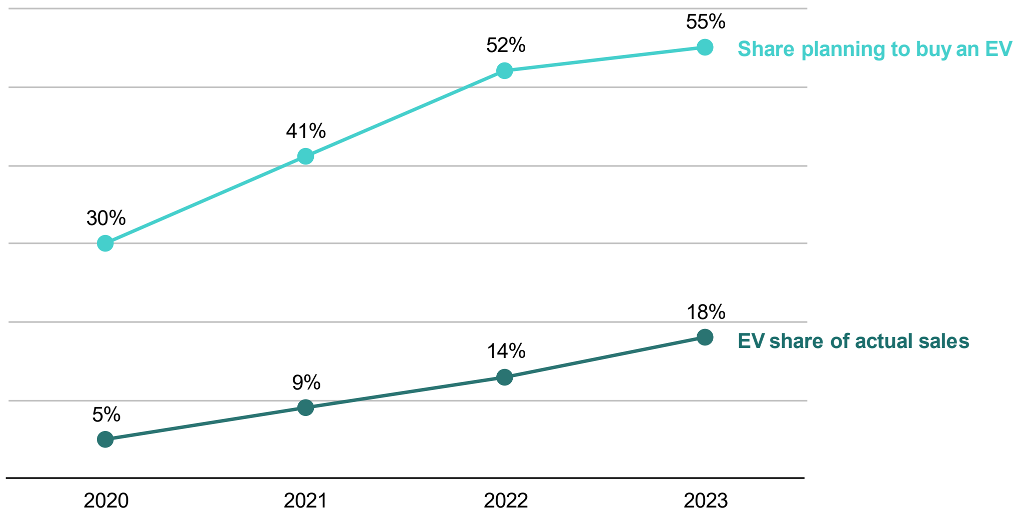
As solutions were found and EV costs fell, so consumer attitudes to EV changed. EV have become a superior value proposition for many consumers. They have faster acceleration than ICE; they are cheaper to drive; they can be charged at home; and they can serve as a backup in case of power failure.

The EY Mobility consumer index[19] notes that in 2023 55% of those planning to buy a car expect to buy an EV. This is almost double the 30% who were planning to buy an EV in 2020.

Moreover, there was a change in the attitudes to EV in the US in 2023 in the wake of the IRA,[20] with the share of those intending to buy an EV rising from 29% in 2022 to 48% in 2023.

It is of course true that today there are many people who are unable to buy an EV, and many who do not want to. Everyone has a story of a friend or relative to provide anecdotal evidence of this. But the data show that this group is now a shrinking minority. Moreover, this group is not yet an impediment to EV sales growth because EV as a share of sales are still well below the ceiling of those who intend to buy them. And as the sales of EV advance up the S-curve, so the prices will continue to fall and the share of those who intend to buy them is likely to continue to rise.

Figure 2: Share of EV sales and share of those planning to buy an EV: Global (%)

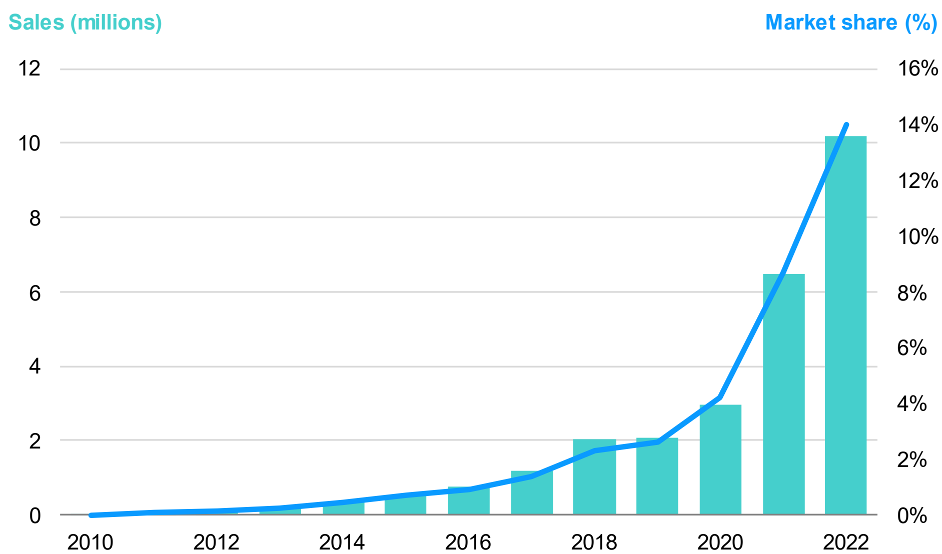


Source: EY Mobility consumer index 2023 (plan), IEA (actual sales), RMI (expected 2023)

2.1.6 Exponential growth took off

EV sales have enjoyed exponential growth on typical S-curves that are characteristic of the growth of other technologies.

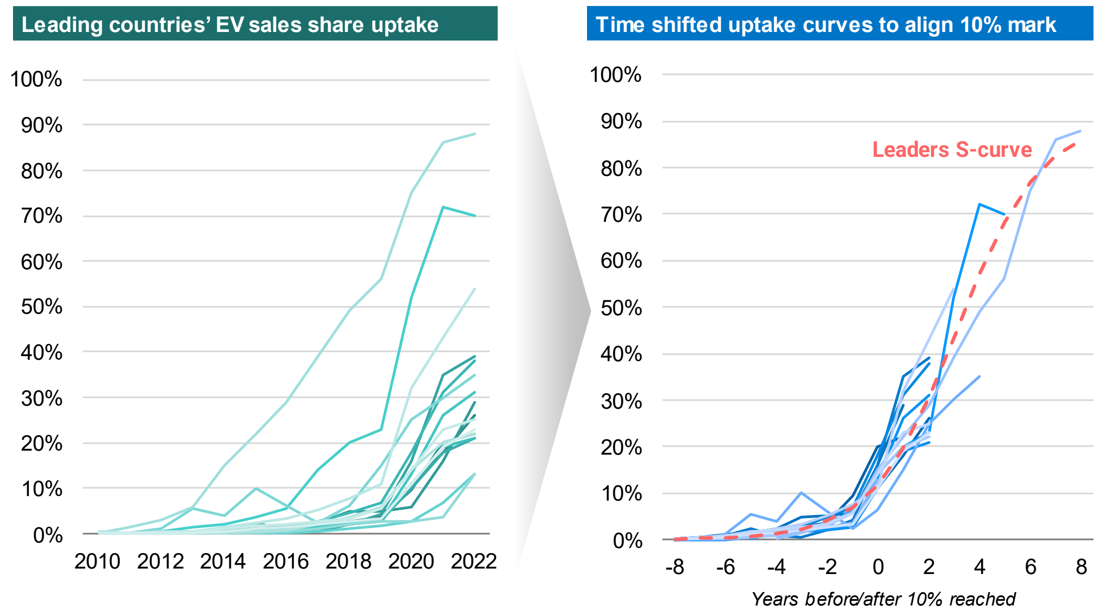
Figure 3: Global EV sales and market share



Source: IEA Global EV Outlook[21]

EV are taking off in different geographies at different times, but they are characterized by the same S-curve of growth. This is seen clearly when you align the leading countries around a given percentage of sales. In Figure 4, we align the leading countries to 10% EV market share and the similarity of the S-curve becomes apparent. In broad terms it takes about six years to get from below 1% to 10% market share and then another six years or so for leading countries to get to 80%.

Figure 4: Countries are following S-curves



Source: Systems Change Lab, IEA, RMI

2.1.7 Car companies changed strategy

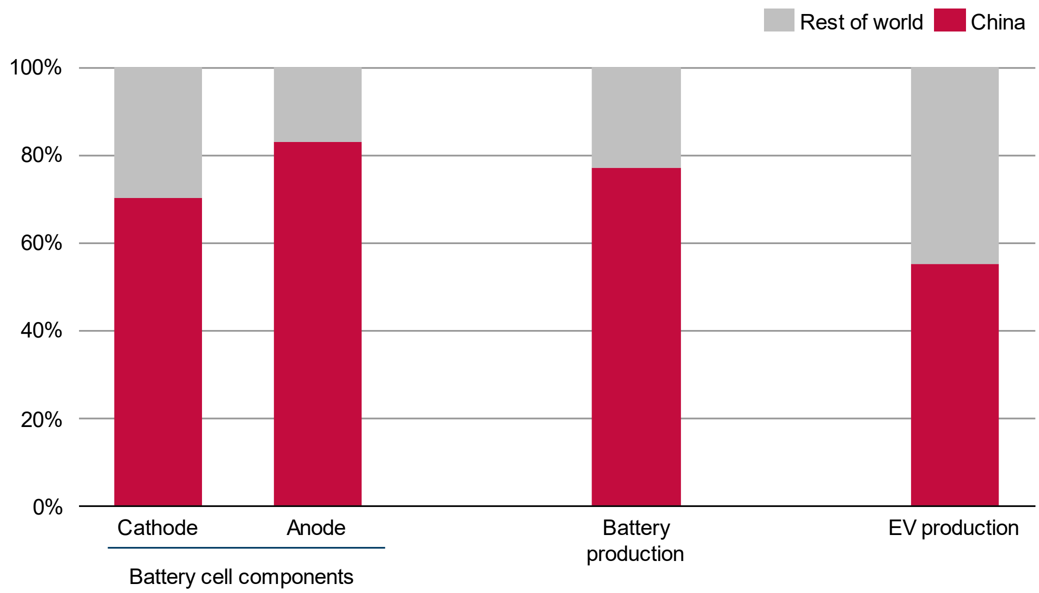
As EV sales took off, so car companies were forced to change strategy. They shifted from ridiculing EV to retooling their strategy to embrace EV. As the IEA details, most major car OEMs are now planning for an EV future, with major carmakers now committing 50%-70% of their capex and R&D budget to EV and digital technologies.[22] OEMs have begun to cease investing in ICE platforms, discontinue some of their ICE ranges,[23] and pull back on plans for hydrogen transport.

This shift to EV has made many more EV models available. In 2015 there were just 50 EV models available; now there are over 500.[24] The considerable capital and talent of the car industry are being brought to bear to drive costs down, performance up and bring the consumer more choice.

2.1.8 China became dominant

China dominates the production of EV and their main components, all the way from batteries to lithium refining. China's success is the result of a combination of pushing the entire value chain at the same time,[25] believing in cost reductions through scale and learning-by-doing, and putting the enabling infrastructure in place.

Figure 5: Share of production of key EV components in 2022 (%)



Source: IEA[26]

In turn this has enabled China to build a large and lucrative export industry in EV, challenging Germany and Japan for global leadership in car exports.[27] As a result EV are emerging as a key nexus of growth within China.[28]

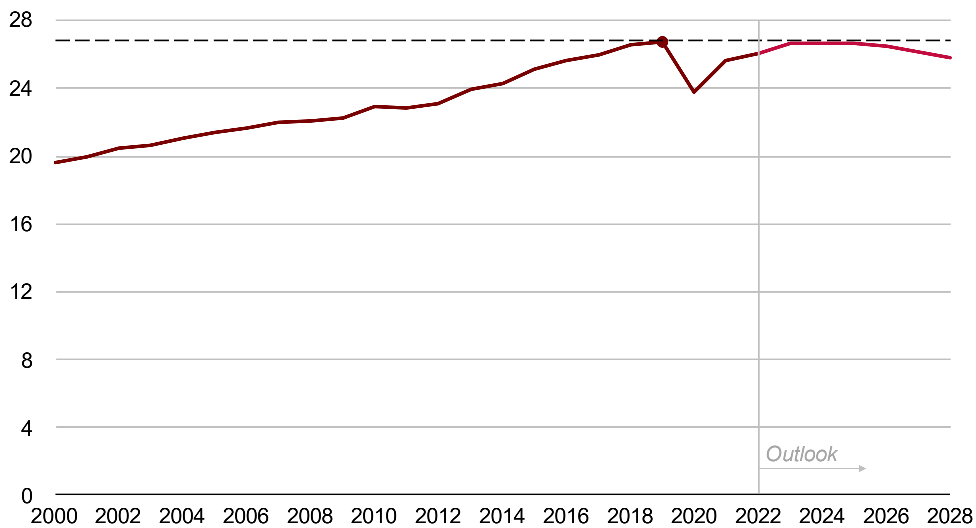
Chinese dominance in turn has sparked a global reaction as other countries seek to catch up. The IRA seeks to increase US domestic manufacturing of EV and batteries,[29] and Europe has also accelerated the development of its own battery industry.[30]

Although Norway is the leader in market share terms, China has emerged as the dominant market for electric vehicles, overtaking Europe as the largest market in 2015. In 2022 China accounted for 58% of all EV sales.

2.1.9 Peak oil for cars

The combination of these factors means that it is likely that oil demand for cars reached a peak[31] in 2019. For example, the IEA notes that demand for gasoline, which we take as a proxy[32] for car demand, reached a peak in 2019. BNEF[33] and Rystad[34] forecast that oil demand for cars will rise slightly above or to its 2019 level, but this is still consistent with our framing that demand is on a plateau with some bumps.

Figure 6: IEA forecast for global gasoline demand (mbpd)



Source: IEA Oil review 2023[35]

Peak oil demand for cars should not come as a surprise to seasoned watchers of the energy transition. A peak, plateau, and decline pattern is a feature of energy transitions, as we have noted before.[36]

Moreover, the peaking process is following the standard playbook whereby OECD demand peaks first, followed by China and then the rest of the world. IEA data indicates that OECD demand for gasoline reached a peak in 2007 at 14.9 mbpd; by 2019 it was down by 4% to 14.4 mbpd. China has been responsible for half the growth in demand for gasoline over 2010-19, but expectations from Sinopec, China's leading refiner, are that gasoline demand is likely to peak in 2023.[37] The OECD and China are more than two thirds of global oil demand for cars, so the rest of the world will be unable to drive demand higher if these two areas are in decline and EV continue to spread out into the Global South.

3. The drivers of change will intensify

The drivers of rapid change are set to intensify. Technological innovation and lower costs will lead to price parity in more markets, emboldening policymakers to push for faster change and encouraging consumers to buy EV.[38] The key driver of change will shift from policy push to economics pull.

3.1 Lower costs

3.1.1 Batteries

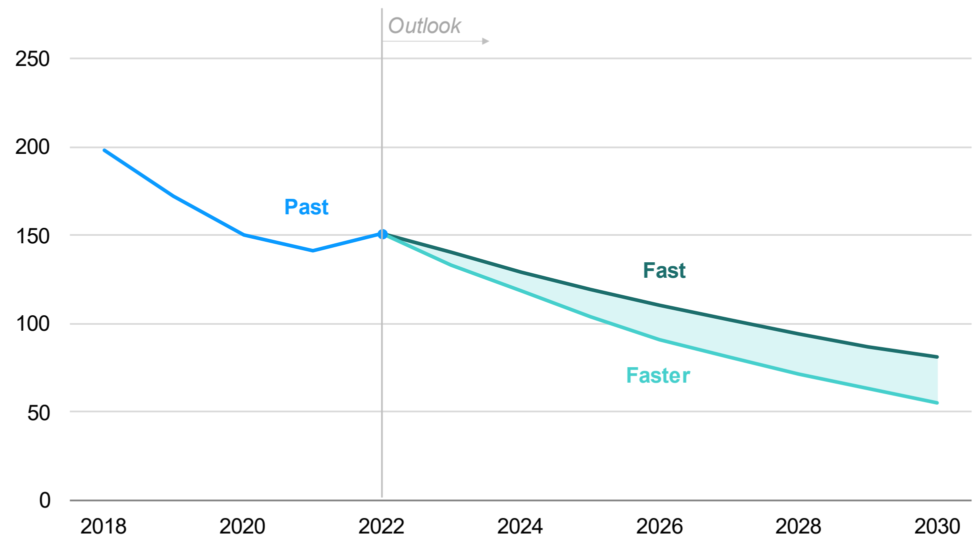
Battery costs are likely to continue to fall. Reports by RMI,[39] the Economist[40] and the IEA[41] illustrate how much innovation is going on in the battery sector, as manufacturers shift to lithium iron phosphate (LFP) batteries and experiment with other technologies such as sodium-ion. [42]

Continued innovation is likely because of the amount of capital and talent being deployed to this area, which can be illustrated by battery production capacity. In 2013, lithium-ion battery sales for transport were 14 GWh p.a., according to BNEF. In 2022, sales were 600 GWh, and companies are planning to put in place battery capacity of 10,000 GWh pa by 2030.[43]

As with most sectors, battery costs rose in 2023 as a result of the Russian invasion of Ukraine and inflationary pressures. However, it is likely that the long-term downward cost trend will resume. BNEF, for example, expects battery costs to resume falling in 2024. As Doyne Farmer has pointed out,[44] learning curves are sticky and prevalent in manufactured technologies of small modular goods such as batteries. INET Oxford has calculated the long-term learning rate for Li-ion batteries as 21%[45] and BNEF calculates a lower learning rate of 17% using a shorter time span.

If we assume continued learning curves of 15% (fast) to 20% (faster) and global growth rates for batteries for all purposes in line with Rystad forecasts[46] (40%-50% pa to 2030), then costs will fall by 2030 to $60-$90 per kWh. That is around half the 2022 average of $151 per kWh.

Figure 7: Likely cost range of lithium-ion battery packs ($/kWh 2022 real)



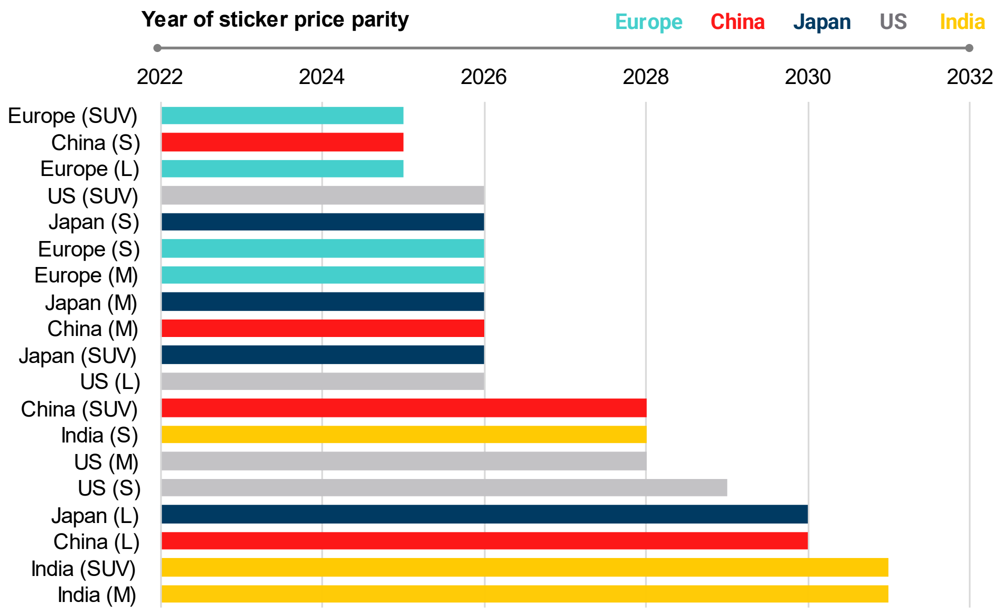
Source: BNEF (past), RMI

BNEF forecasts battery energy density to rise by 4% per annum. And there may of course be major breakthroughs. For example, CATL, the world's largest battery manufacturer, announced in April 2023 that it was planning to commercialize a battery with an energy density of 500 Wh per kg, more than twice the global average.[47] According to CATL, such densities could be used in aircraft, and higher densities make battery technology available for a rising number of uses, as noted by DNV.[48]

3.1.2 EV price parity in more markets

As battery costs fall, sticker price parity will be reached in every major category and market by 2031 according to BNEF calculations.[49] We show data for five key markets below, which make up three quarters[50] of global car sales.

Figure 8: Date of sticker price parity in key markets



Source: BNEF. Note: S = small, M = medium, L = large, SUV = sports utility vehicle

The BNEF calculations are, in fact, rather conservative because they assume standard run sizes and profit margins. In reality, manufacturers may be prepared to make lower margins to gain market share in the new technology. Moreover, companies such as Tesla, CATL and BYD have larger run sizes and will therefore have lower price points. The IEA[51] for example argues that sticker price parity has already been reached in the Chinese car market, some two to three years before the BNEF data would imply. We believe it is therefore reasonable to assume that every major category of demand will cross the sticker price tipping point this decade.

As price parity is reached, a Cambrian explosion of innovation will take place as new companies come to the market and find better ways to deploy EV technology. Many different types of cars are coming to the market, and this competitive pressure will drive more change.

3.2 More policy pressure

There are many reasons for governments to speed up the move to EV. We touch on energy security, manufacturing leadership, pollution, and climate, and conclude that policy pressure will only rise over time.

3.2.1 Energy security

Some 80% of people live in countries that import oil,[52] which is the most expensive form of fossil fuel energy, and a major source of current account deficits for countries such as India. Every new ICE car purchase imposes on an oil importer the burden of importing around 15 tonnes of oil over its lifetime. EV remove that burden.

3.2.2 Manufacturing leadership

Putin's invasion of Ukraine in 2022 alerted the West to the dominance of China in the EV supply chain, and this has sparked some profound changes. The response has been an attempt to replicate the EV supply chain in the West, and this is likely to lead to more innovation and faster change. Anecdotal evidence at the Munich Motor Show in September 2023 suggests that the high quality and low prices of Chinese EV are sparking a rethink by the German auto industry of the necessity to transition. [53]

3.2.3 Pollution

Every major city has problems with air pollution, made worse by vehicles burning oil. The World Health Organisation[54] notes that the combined effects of ambient air pollution and household air pollution are associated with 6.7 million premature deaths annually. Around 90% of these people live in low- and middle-income countries. According to ICCT, nearly 400,000 people a year die from pollution from vehicle tailpipe emissions.[55] The average ICE uses 1 ton of oil a year, which means nearly 3 tonnes of CO_2 per annum, or 40 tonnes over the average lifetime of a car. Assuming a global warming cost of $100 per tonne and a local pollution cost at a similar level implies that each new car being sold imposes a cost upon society of around $8,000. Governments concerned about the health of their citizens are likely over time to encourage people to shift to EV. For example, in China[56] and Colombia[57] governments are specifically acting to clean up the air.

3.2.4 Climate

Transport is one of the main contributors to climate change with road transport representing 19% of energy-related CO_2 emissions.[58] Lower cost EV give governments a ready tool to reduce emissions and reach their commitments under the Paris Agreement.

3.2.5 What do governments do when costs align with other drivers?

As costs fall, so EV will become the cheapest option for personal transport. It follows that for most countries (except perhaps the petrostates and regions ideologically committed to burning stuff) it is highly likely that governments will put in place the enabling conditions for a rapid rollout of EV.

That implies strengthening the grid and electricity distribution infrastructure, putting in place widespread and equitable charging infrastructure, and changing regulatory structures to encourage consumers to buy EV. Over time, and as EV rise to dominance, we expect governments to adopt more stringent measures to reduce ICE sales — and eventually to adopt policies to scrap ICE on the road more rapidly. As ICE sales decline, so the power of the ICE lobby will fall and its ability to resist change will weaken.

The implications are that we will see a sustained increase in policy pressure.[59] The required policy actions to speed up change include a mix of regulation and infrastructure build-outs, carrots and sticks, and are analyzed in more detail by both IEA[60] and BNEF.[61]

3.3 Capacity build-out

New capacity is already being put into place for both cars and batteries, sufficient to meet even optimistic views on EV penetration.

According to Rystad Energy, car companies are planning to build new capacity sufficient to produce 80m EV per annum by 2030.[62] That is more than today's demand for all cars, and almost all of the expected car demand in 2030.

According to the IEA,[63] battery companies are planning factories with enough capacity to produce 10,000 GWh of batteries by 2030. If we assume a maximum of 80m EV car sales and a 60 kWh battery, that implies 4,800 GWh of battery demand from the car sector. So we can assume that battery capacity will be sufficient as well.

3.4 Chinese leadership

China has all the necessary ingredients to continue to roll out EV in the car sector very rapidly. They include:

- A lack of domestic oil supply, meaning that most oil is already imported, and business as usual would see that rise to over 70%.[64]
- Dependency on oil imports using sea lanes not controlled by China.
- The lowest cost EV in the world, and sticker price parity with ICE.

- A relatively weak position in ICE exports but a dominant position in EV exports.
- The opportunity to seize global leadership in a key industry of the future.
- EV as a driver of the economy.[65]
- The opportunity to reduce pollution in cities.
- A government able to plan and execute the necessary changes to grid and distribution infrastructure and build charging infrastructure at speed.
- A successful template for the effective deployment of electric vehicle technology. Market share for electric vehicle sales in two-wheelers and buses is already over 50%.[66]

We would therefore expect to see Chinese sales of EV continue to rise rapidly up S-curves.

3.5 The Global South will also embrace change

EV sales are concentrated in three markets: China, Europe and the US. Some argue that the rest of the world will be unable or unwilling to buy EV.

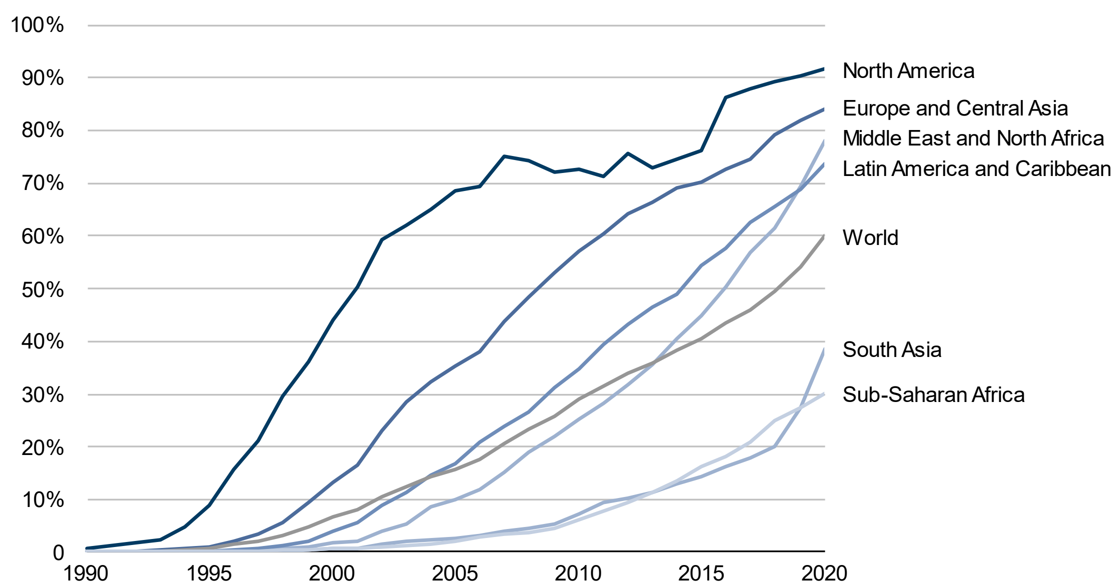
However, this ignores both how transitions work and the fact that most Global South leaders will also want to embrace cheap transport solutions. It is therefore highly likely that the Global South will follow the same pattern as other technology revolutions, and also ride the S-curve of change.

3.5.1 Technologies spread from a core

The three markets that dominate EV sales also dominate all car sales. They are 95% of EV sales but 64% of all car sales. A standard pattern would see EV sales established in the leading markets first and then spread out to the rest of the world as costs fall.

It is common for technologies to develop and get cheaper in wealthier countries and then spread around the world. The classic example of course is the internet. The share of the population using the internet rose very rapidly first in the US and then in Europe. South Asia and Sub-Saharan Africa followed 20 years later, and the world as a whole only reached 50% penetration in 2018. Nevertheless, the technology had huge implications long before the 50% milestone was reached.

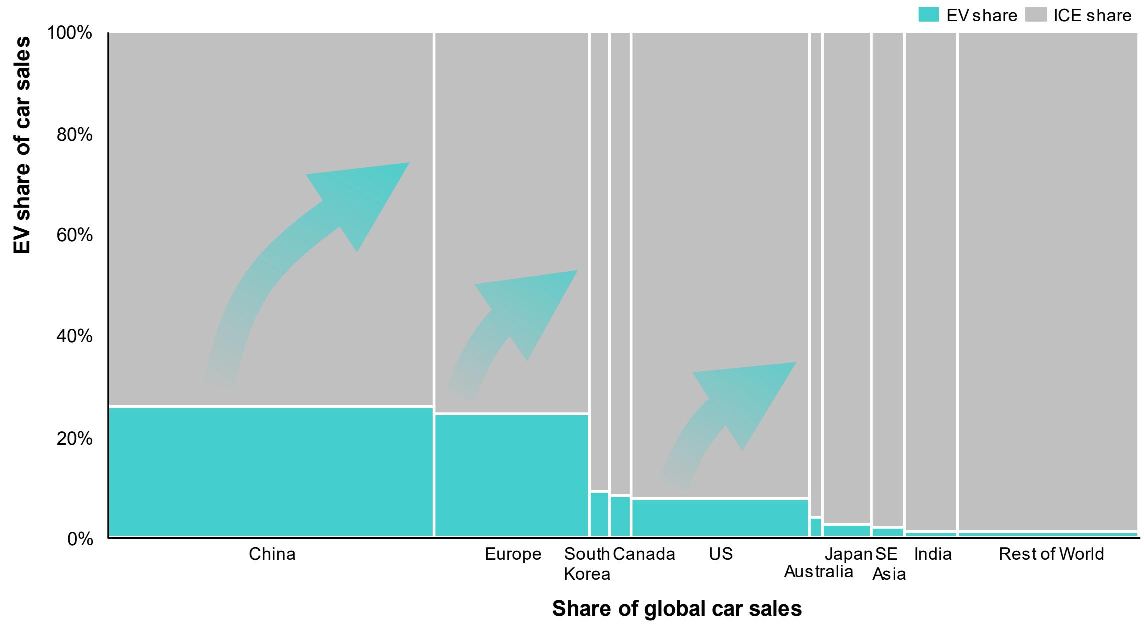
Figure 9: Share of the population using the internet by region (%)



Source: International Telecommunications Union, OWID

In a similar way this energy transition is spreading out from a central core. The difference is that the internet revolution was led by the US, but the EV revolution is being led by China. The graph below shows the share of EV sales today, the relative importance of each market and how change spreads.

Figure 10: EV share of global car sales 2022 (%)



Source: BNEF, RMI

We can also look at the S-curves of change by market. Just like the internet, each country is moving up the S-curve. First China, then Europe, then the US, then oil importers and finally the petrostates. Of course, as with the internet, it is possible for countries to leapfrog and change faster.

3.5.2 The Global South also wants cheap local energy and clean air

Benefits of EV for the Global South include lower oil demand, less pollution and cheaper transport.[67]

- Some 80% of people in the Global South live in oil importing countries.[68]
- Of the 6.7 million people a year dying from pollution linked to air pollution, around 90% live in the Global South.[69]
- The Global South has less fossil fuel infrastructure and can avoid the stranded assets of the fossil fuel era by building out new EV infrastructure.

The key global divide in the energy transition is not between the Global South and the Global North but between the recalcitrant petrostates and the rest of the world. Between those who want to prop up the status quo and those who want a better world.

The implication is that as battery costs fall to enable EV price parity, we are likely to see EV racing up the S-curve in much of the Global South in the same way as we are seeing elsewhere. Because two-wheelers are the preferred transport option in large parts of the Global South, we would expect to see the story play out there first. Two examples illustrate the change that is going on.

- Two-wheeler EV sales in Vietnam[70] have taken off on a very similar trajectory to EV sales globally, and had a market share of 14% in 2022.[71]
- Three-wheeler EV sales in India already have a market share of over 50%. Programs like the Shoonya[72] campaign are speeding up adoption in key areas such as ride hailing and delivery.

3.6 Feedback loops

There are several self-reinforcing feedback loops that will speed up change.

- **The high cost of maintaining a car platform.** Car companies are increasingly being forced to move to EV as their sole manufacturing platform. That will mean that ICE eventually become a niche product only, like horse buggies. And in turn that increases costs and reduces demand.
- **Follow the growth.** ICE demand is indisputably in decline. EV are growing exponentially. Companies tend to prefer to allocate capital and talent to growth and out of decline, which further speeds up change. For example, BNEF calculates that the EV market until 2030 is a $9tn opportunity.
- **Massive excess of ICE vehicle stock**. At the end of 2022, there were over 1,200 million ICE and just 27 million EV.[73] EV are already cheaper to run than ICE, and by the end of the decade they will be cheaper to buy. From our modelling, EV will dominate new car sales by the end of the decade. Second hand car buyers are also likely to want to buy EV, but most of the stock is ICE. If you have more sellers of ICE than buyers, the second-hand value of ICE cars is likely to plummet. That creates a self-reinforcing doom-loop for ICE prices. At the same time this does also create a risk, especially for developing economies, as cars will go on the market for dump prices that may be picked up by low-income communities, locking them into oil offtake for years to come. So this feedback loop will be enhanced provided that governments can avoid ICE "leakage" to poorer communities and instead encourage EV adoption.
- **The race to the top.** China dominates the production and sales of EV. Putin's invasion of Ukraine helped to wake up Western policymakers to the risks of being dependent on one external supplier and encouraged them to see the benefits of leadership in new energy technologies. This has contributed to the IRA, which is now channelling tens of billions of dollars to the US EV supply chain. As well as the REPowerEU policy, which seeks to reduce European dependency on fossil fuels and to increase European battery manufacturing capacity. [74] A race to the top has been started, and this is likely to drive more innovation in the EV sector.
- **Success breeds success**. The more people see and use EV, the more they will be emboldened to buy them. This perhaps accounts for the remarkable similarity between the S-curves of adoption that we see across countries.
- **From EV to ICE range anxiety.** As EV grow and ICE decline, EV range anxiety will be replaced by ICE continuity anxiety. For example, the UK has 400,000 home or workplace chargers as well as 48,000 public EV charging points, 40% higher than a year ago.[75] But the ICE system is in decline and has only 8,400 petrol stations, down by 56% since 2000. As decline sets in, consumers will also question whether or not ICE brands and companies will survive and whether spare parts will be available.

4. Implications of continuity

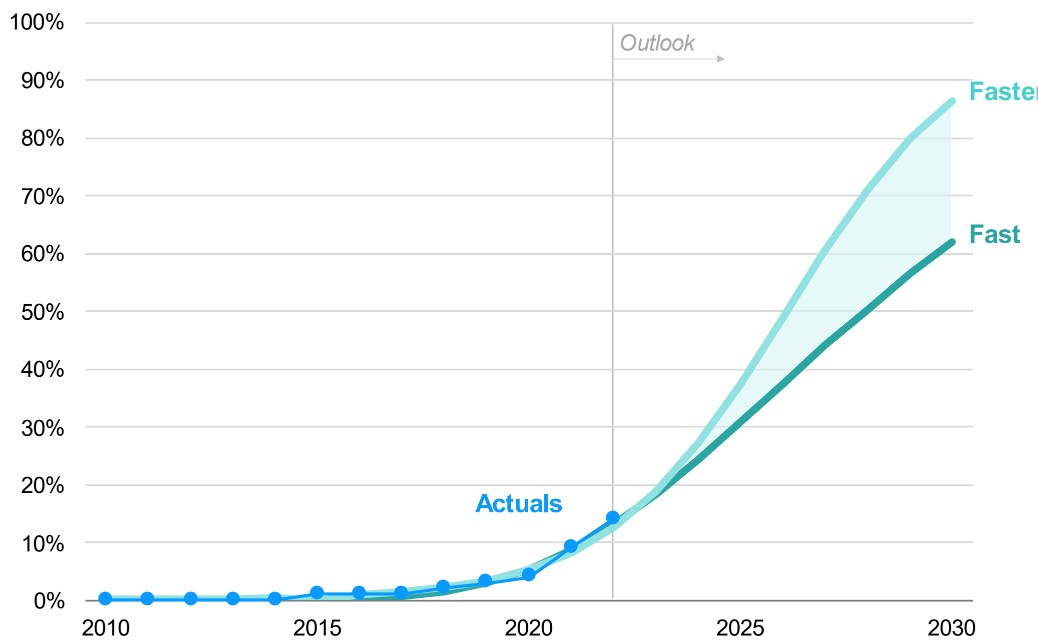
In this section, we look at the implications of the continuity of rapid change. We use S-curves to model two futures – fast and faster change. We first look at EV as a share of car sales and then turn to the wider implications for ICE, oil demand and other areas of transport. In the Appendix, we expand on the various ways to model the future of EV sales. Of course, this framework is not certain, and there are many challenges to overcome, as we detail in the Appendix. It is nevertheless the most likely pathway based on what has already happened in leading markets and how other technology shifts have worked.

4.1 Implications for EV

4.1.1 EV market share

The implication of S-curve continuity is that EV will have a market share of 62%-86% by 2030. This might seem like a wide range, but it is reasonable given that we are relatively early in the S-curve. Moreover, it is also significantly higher than the consensus framing, which is currently at around 40% of sales.

Figure 11: EV market share (%)

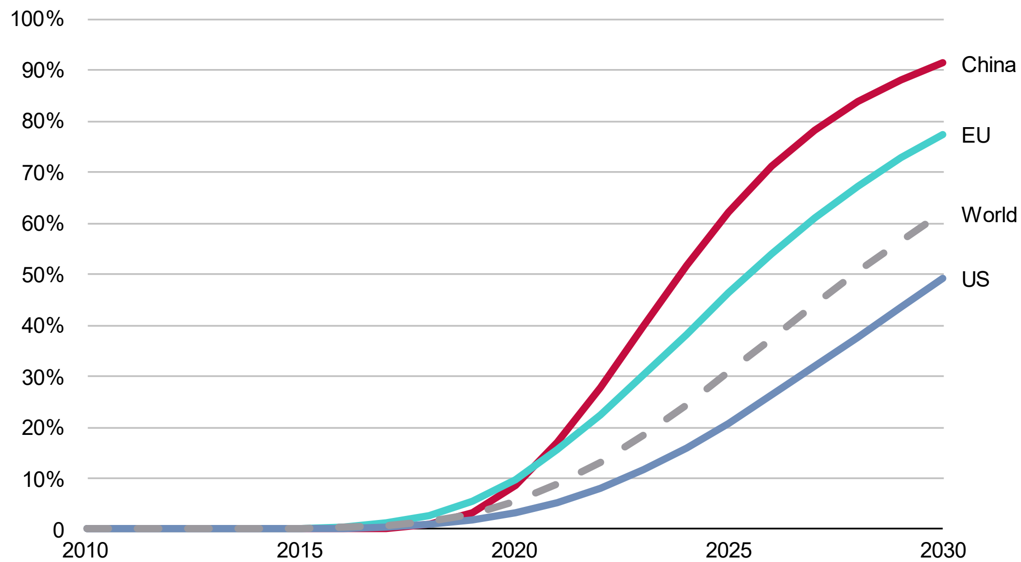


Source: IEA (past), RMI forecasts

4.1.2 Regional market share of EV

To compare regions, we take the lower band of the framing above — fast change up S-curves — as set out in the Appendix. This suggests that China will enjoy over 90% market share of EV sales by 2030 and the EU will be approaching 80%. The US will be a little below 50%. The implication is that the market share of EV targeted by commercial or political leaders in those three regions is very achievable.

Figure 12: Implied EV market share in leading markets: Fast change (%)



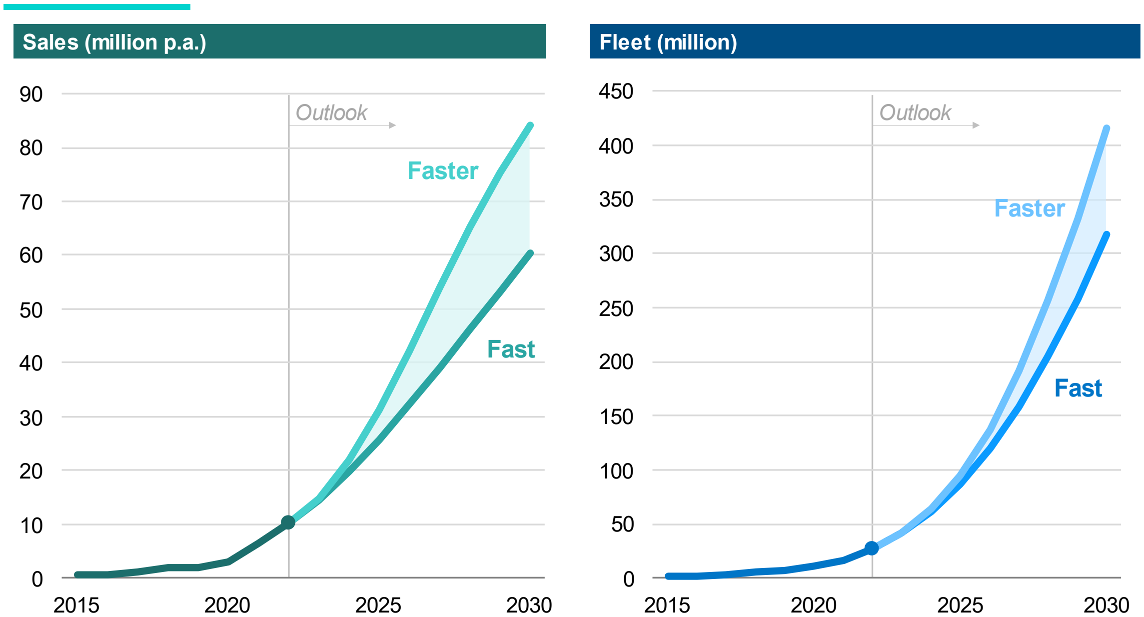
Source: IEA (past), RMI forecasts using a Gompertz S-curve

4.1.3 EV sales and fleet

If we assume 3% growth in car sales to 95 million in 2030, in line with BNEF framing in its EV Outlook, then the numbers of EV sold will be between 60 million and 84 million in 2030. This implies that EV sales in 2030 will be around the same as ICE sales in 2023.

And the stock of EV will increase to between 318 million and 416 million.

Figure 13: EV sales and fleet



Source: Historical data BNEF, RMI forecasts

4.2 Implications for ICE

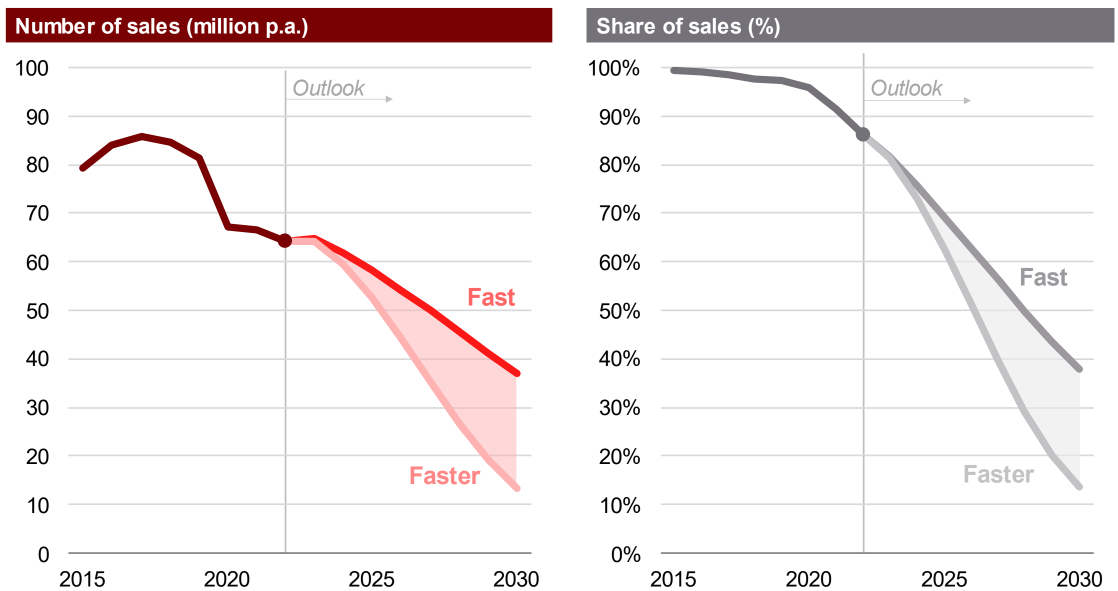
The implications for ICE[76] are largely derived from the EV market share gains, but with an important variable around the expected levels of scrappage. It is highly likely that ICE stocks are about to peak, meaning the end of the ICE age will begin.

4.2.1 Sales

The market share of ICE of course falls with the rise of EV. To a level of 14%-38% of sales by 2030.

ICE sales peaked in 2017, have been falling at 5% a year since then, and are likely to fall rapidly by the end of the decade to between 14 million and 38 million cars a year.

Figure 14: Sales and market share of ICE



Source: Historical data BNEF, RMI forecasts

4.2.2 The ICE car fleet

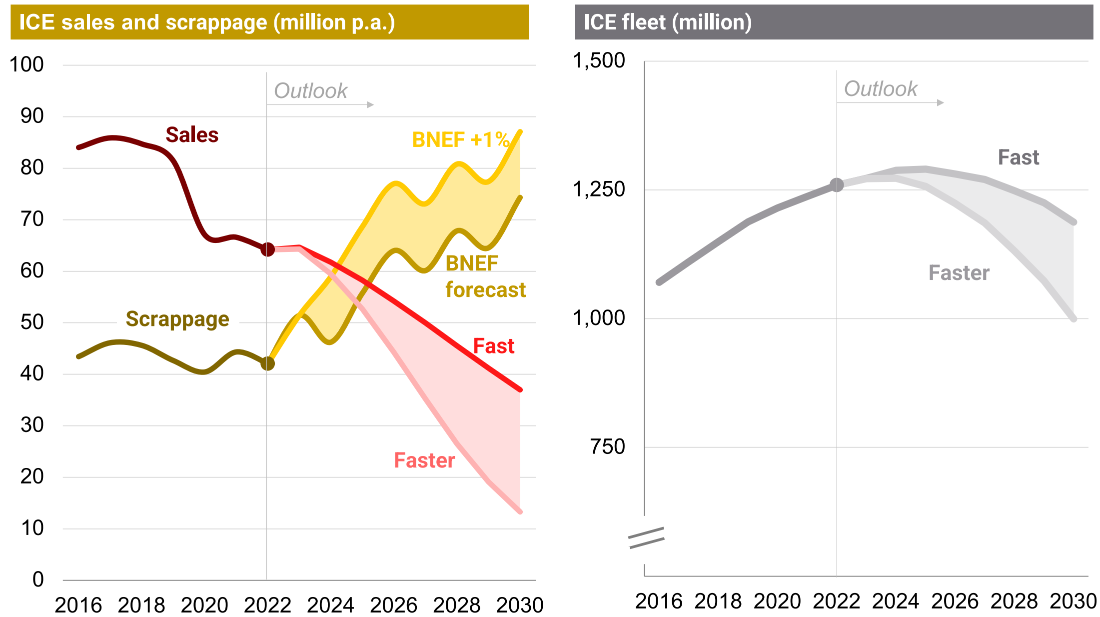
When it comes to the fleet of ICE cars, there is a further variable to consider – the scrappage rate. On average a car lasts about 15 years (more that the average age of the fleet, which is 12 years), but the average number scrapped is clearly not dependent upon today's sales.

Over the past decade, the number of ICE cars scrapped every year has been 40 million to 50 million. However, BNEF estimates that the scrappage rate of ICE cars will increase to between 60 million and 70 million per annum by 2030, which is in line with the increase in sales 15 years ago.

It is also possible that the scrappage rate will increase to levels even higher than this because governments will be anxious to take ICE cars off the roads and consumers are likely to want to upgrade to superior EV more rapidly once they are cheaper. We therefore also examine below the implication of scrappage rates rising by a further percentage point of the fleet per annum (BNEF +1%).

The stock of ICE cars is a function of gross sales and the scrappage of existing cars. In 2022 for example, we saw sales of 64 million ICE cars and scrappage of 42 million. So the net growth was 22 million. As the chart below shows, our two ranges for these variables cross each other very shortly. By the middle of the decade, scrappage will be higher than new sales.

Figure 15: Sales and scrappage of ICE and total ICE fleet



Source: Historical data BNEF, RMI forecasts. BNEF +1% assumes that an extra 1% of the global fleet is retired

The implication is very clear: the ICE fleet is about to peak. And by the end of the decade the size of the ICE fleet is likely to be falling at a rate of 40 million to 70 million per year, or 3%-7%.

4.3 Implications for oil demand

Cars account for around a quarter of global oil demand and made up more than a third of the growth in oil demand in 2010-19. Fleet efficiency[77] increases by around 2% each year and the driver of oil demand growth from cars has been the increase in the size of the fleet by more than the efficiency gains of the fleet.

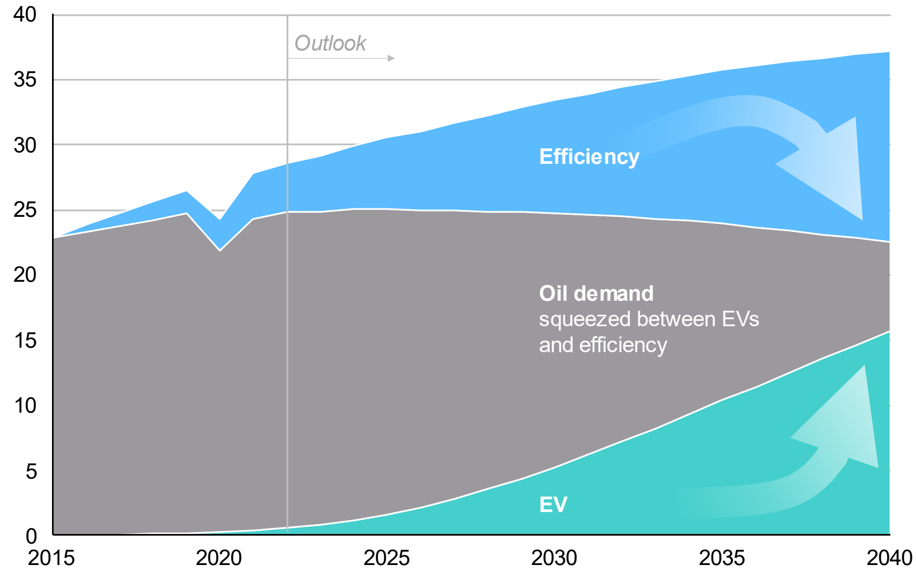
There are two key drivers of change. The longstanding efficiency driver is being joined by the rise of the EV.

As Amory Lovins pointed out over 40 years ago,[78] efficiency gains have long been the main factor reducing the growth of oil demand in the car sector. Government targets, better engines, superior design of cars, public transport availability and a host of other factors have combined to mean that each year the efficiency gains of the fleet are around 2%. We expect that these drivers are likely to continue and may even increase as a result of the added pressure coming from EV competition and rising policy pressure. Nevertheless, we assume continued fleet efficiency gains of 2% a year.

The new driver is of course the rise of the EV, meaning that the fleet of ICE cars will start to shrink.

When we combine these two factors, oil demand for cars will be caught between efficiency gains and EV growth.

Figure 16: Oil demand for cars, efficiency and EV (mbpd)

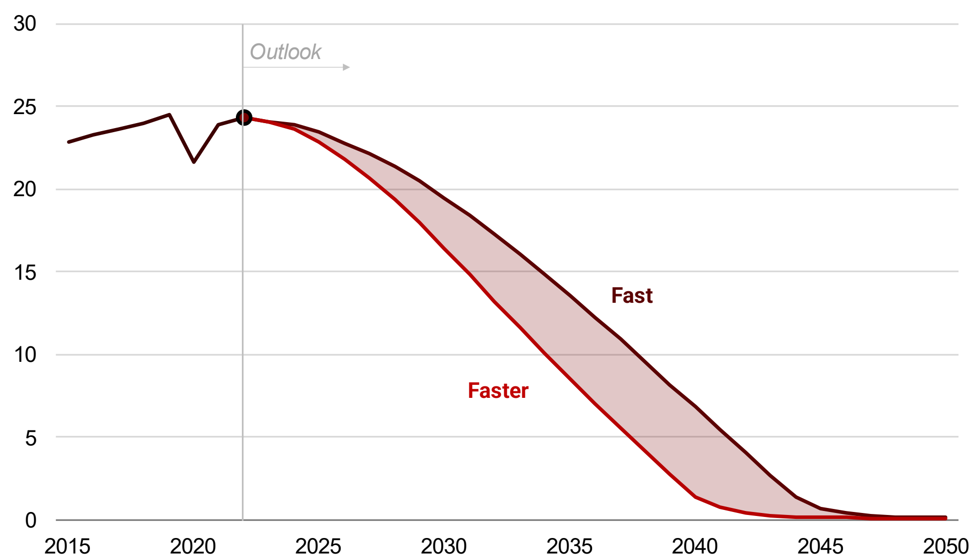


Source: BNEF, RMI assuming fast change

Oil demand will therefore bounce along a plateau for a few years and be in clear decline by 2030. That implies an annual fall in oil demand from cars in 2030 of 5%-9% pa. Or a reduction in oil demand of 1-1.5 mbpd every single year.

By the 2040s, oil demand from the car sector in this framing will fall to zero.

Figure 17: Oil demand from cars (mbpd)



Source: Historical data from BNEF, RMI forecasts assuming continued fleet efficiency gains of 2% pa

By 2030 it will be obvious that in the car sector, the largest sector of oil demand, oil demand is in terminal decline. Even the slowest analyst in 2030 will be able to put into their spreadsheets the clear S-curves of EV supply and years of life of ICEs, and work out how quickly demand for oil will fall to zero.

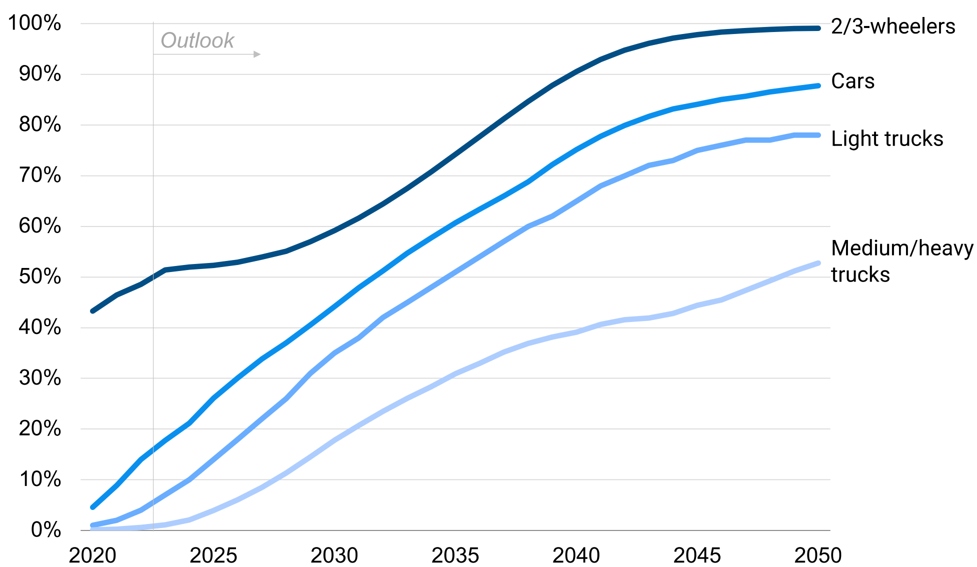
As soon as ICE cars stop being produced in large volumes, we are only the lifetime of the last cohort of ICE cars away from minimal car demand for oil. Most cars last around 15 years, and even if some last longer, the implications for demand will be clear.

And once markets can see the prospect of falling demand in the largest sector of oil demand, they are likely to restrict the flow of growth capital to the oil sector.

4.4 Other areas of transport

The electrification of road transport is following a clear path, largely dependent upon weight. Electrification is moving from two-wheelers to cars to light trucks to heavy trucks. Within road transport, cars are the largest sector, making up over half of road transport demand; commercial vehicles are a little under 40%, and two/three-wheelers are 5%. BNEF models the process below. Although we expect change to happen faster than this, it is a good framing for the order and nature of the change that is taking place.

Figure 18: Share of electric vehicle sales by transport sector (%)



Source: BNEF (ETS)

The success of EV in the car sector drives down battery prices, increases expertise and emboldens vehicle manufacturers to replicate the success of batteries elsewhere. Lower battery prices in China therefore are driving the two-wheeler EV revolution across Southeast Asia.

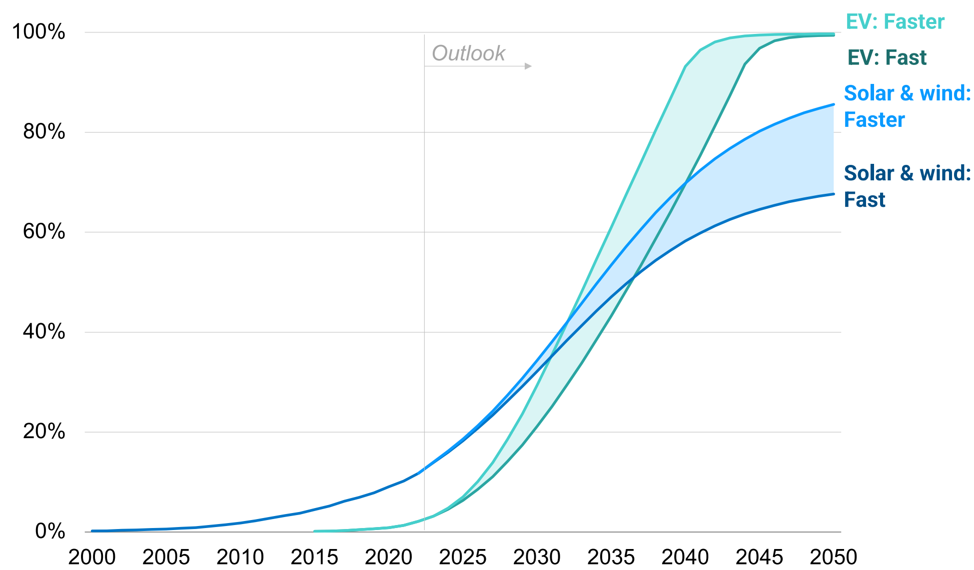
RMI analysts note that the trucking sector could change even faster.[79] Truck turnaround rates are eight years instead of 15 years for cars — so even if 100% EV sales for trucks is achieved seven years later than car EV, they may still hit 100% EV uptake at the same time.

4.5 Change will be faster than in the electricity sector

Solar and wind got to price parity with fossil fuels for electricity generation in the late 2010s. In the car sector the price tipping point has happened later, but the change is likely to be faster because EV sales are growing faster and the EV fleet turns over around three times as fast as the power fleet.

In Figure 19, we compare solar and wind electricity generation as a share of all electricity as set out in our recent report, X-Change Electricity,[80] with EV as a share of the total fleet. We project forward using the framing of fast or faster to create two ranges.

Figure 19: Solar and wind share of generation versus EV share of the fleet (%)



Source: RMI

The implication of this is that the share of EV in the car fleet will overtake the share of solar and wind in electricity generation in the 2030s. The disruption we are already seeing in the electricity sector will therefore happen faster in the car sector. Meanwhile, the car sector can add to the flexibility of the electricity grid, enabling higher solar and wind penetration.

5. Appendix 1: How to model EV sales

We examine the various ways of modelling the future of EV demand, and conclude with a likely range for the share of EV sales based on S-curves. This implies that EV will be between 62% and 86% of sales by 2030. This range is higher than the top of current forecasts, but we argue that it is the most reasonable starting point for thinking about the future of EV sales.

5.1.1 What are the options

In X-Change Electricity,[81] we modelled solar and wind supply based on total electricity demand, which is a stock. However, this does not work so well for EV sales because the stock of EV is still so small and the process of change is so early. Moreover, EV have the inherent advantage that we can model based on market share of sales because we have an end point of a maximum of 100%. Therefore, we model the sales of EV, which are a flow.

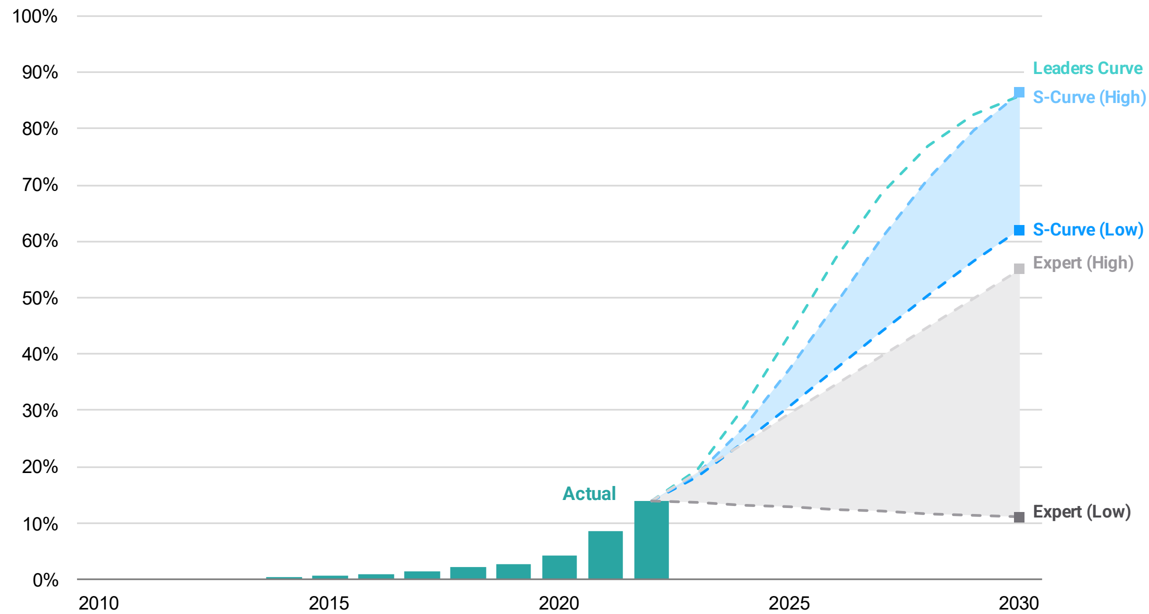
There are four main ways in which to model the future of EV sales: expert forecasts; exponential growth; the experience of the leading markets; and S-curves.

- Expert forecasts have a poor track record and in recent years have been regularly upgraded. Moreover, they have a very wide range even for 2030 market share, from just 11% of sales in the OPEC forecast[82] up to the Rystad forecast of 55% of sales.[83]
- Simple exponential growth forecasts are difficult to use because the growth rate is so high. For example, the average annual growth rate of EV sales for the last decade has been nearly 60%. But at 60% growth rates, we are only five years away from EV making up all sales. So, it becomes necessary to assume a lower growth rate over time.
- The sales curve we have seen from markets that have embraced EV enables us to produce a Leaders curve. It implies 86% of sales will be EV by 2030.
- The S-curve is clearly the best way to handle a fast-growing technology like EV. There are then three main variants of S-curve to consider: the standard logistics curve; the Gompertz S-curve, which works best in early-stage markets; and the Richards curve, which is more complex. We argue that a credible range lies between the Gompertz curve (fast) and the logistics curve (faster).

5.1.2 How they compare

At first sight there is quite a wide range between the options.

Figure 20: EV as share of sales in 2030 (%)



Source: RMI estimates

However, if we take our preferred three options, the range is much tighter. The logistics S-curve (S-curve faster) is also very close to the experience of the leaders – the Leader curve. Therefore we set a range between the two S-curves for the sake of simplicity.

5.2 Expert forecasts

We set out the three types of expert forecast and note that experts have been obliged to upgrade their forecasts in light of reality over the course of the past five years. Our conclusions are:

- Some of the expert forecasts are simply the wish list of the oil industry and their paid consultants for slow change.
- Exponential modelling of S-curves in line with other technology transitions has so far been a superior forecasting tool than the most complex expert models.
- Expert forecasts can be excellent in the short term (e.g. the number of EV sales in Colorado next quarter), but they are less effective when seeking to forecast the long-term future of the EV sector on a global level.
- For the past six years, the IEA has upgraded its 2030 EV sales share forecast by 5 percentage points a year while BNEF has upgraded its equivalent estimate by 3 percentage points a year. If they stay on this trajectory of annual upgrades, then by 2030 they will be forecasting a 65%-70% share of EV in sales.
- Many commentators are still rehashing the debates of the past decade. They focus on range anxiety, cost, the supposedly high carbon footprints of EV, weight and so on. But most of these issues have solutions, expertly explained by analysts such as Auke Hoekstra.[84]

5.2.1 What are the options

For the sake of comparison, we do not focus on normative models, which seek to get to net zero regardless of what is likely. While these are very helpful, the risk is that they are rejected because they seek to tell us what we should do, not what we will do. Expert forecasts then fall into three main groups.

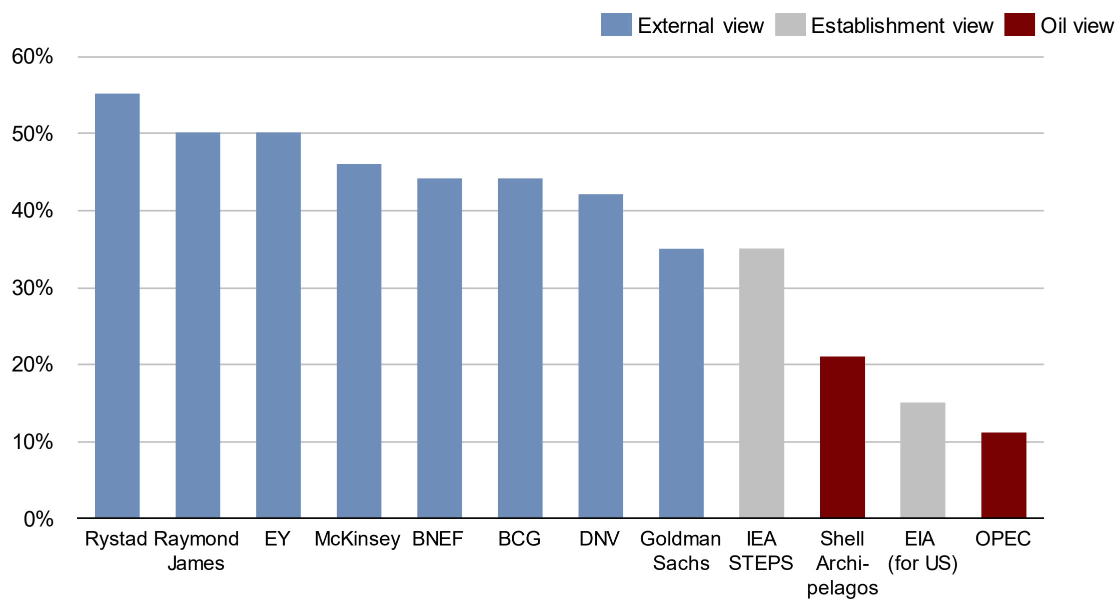
The oil view. The desire of the fossil fuel sector for slow change, given form in an Excel spreadsheet. While we can and should largely dismiss these forecasts, they are given far too much credence by many people. It is reasonable to be skeptical about oil sector forecasts for EV sales.[85]

Establishment view. The view of incumbent organisations such as the IEA or the EIA. These forecasts can be dragged down by the inherent conservatism of organisations seeking to pull together the views of oil producers and users.

External expert view. The view of external experts such as BNEF or the investment banks. These are superior, but as we show below they have also been forced to upgrade in light of the facts.

We set out below the forecast share of EV sales in 2030 from a range of organizations. They range from OPEC at 11% to Rystad at 55%.

Figure 21: EV sales market share forecasts for 2030 (%)



Source: Rystad,[86] Raymond James,[87] EY,[88] McKinsey,[89] BNEF,[90] BCG,[91] DNV,[92] Goldman Sachs,[93] IEA,[94] Shell,[95] EIA,[96] OPEC,[97] RMI assumptions in order to standardise around a 2030 benchmark for BEV and PHEV vehicles

5.2.2 The oil view

Some oil companies profess great theoretical enthusiasm for EV but then provide a long litany of concerns that, regrettably, will hold back growth. They worry about mineral availability, price, the Global South, charging infrastructure, and so on. And by worrying, they manage to persuade themselves that EV will not grow very fast. Which is very reassuring, because their business model is dependent upon their ability to hold back the growth of EV for as long as possible.

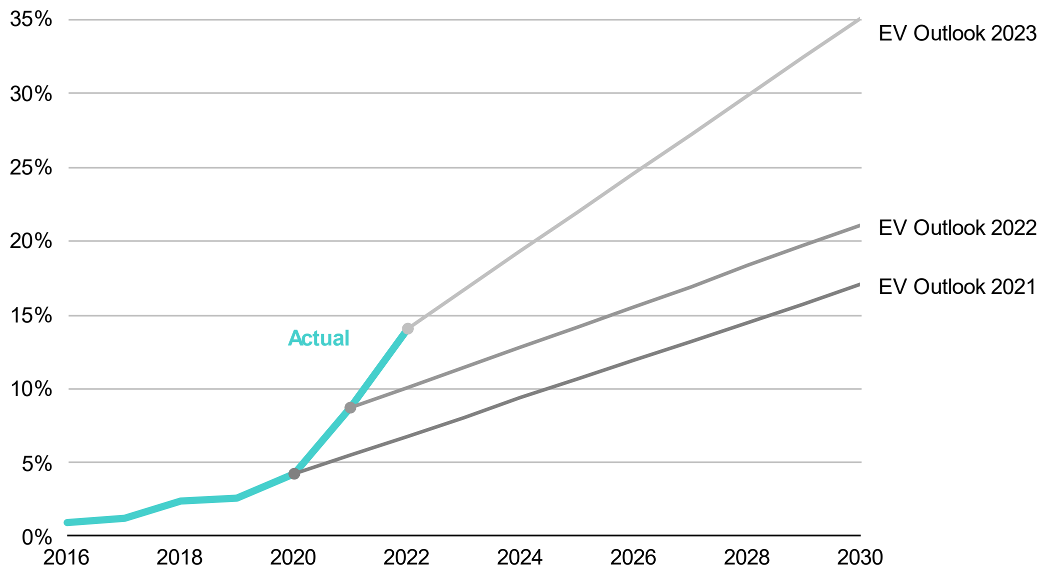
Some organisations are deeply linked to their high-paying clients in the oil sector, and we leave to the reader to judge whether those close relationships imperil the ability of these organisations to think objectively about change.

5.2.3 The establishment view

The classic establishment view is that of the IEA. Until 2021, the IEA's view were closer to those of the oil sector, but since then it has changed very considerably in light of the exponential change in clean technology deployment. If we standardise on the IEA's stated policy (STEPS) scenario, the IEA has consistently upgraded its forecast for the share of EV sales in 2030, from 15% in 2019 to 35% in 2023, or an average of 5 percentage points every year. Another seven years of upgrades at the same rate, and it would be forecasting a 70% EV market share in 2030.

Meanwhile, the US EIA retains a highly conservative outlook, expecting just 15% of sales in the US to be EV in 2030 and 18% in 2050.[98]

Figure 22: IEA forecasts for EV as a share of sales (%)

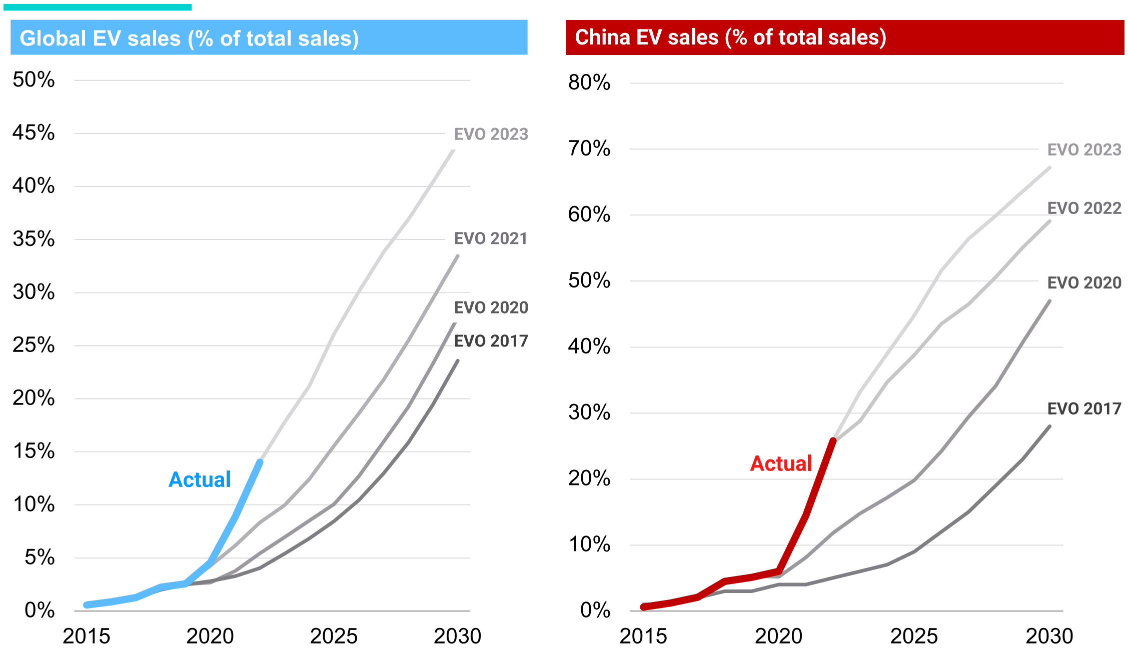


Source: Hannah Ritchie,[99] Stated Policies scenarios (STEPS) from IEA's Global EV Outlooks

5.2.4 The external expert view

The best-known analyst of the future of the EV sector is probably BNEF. And BNEF forecasts[100] have also been rising over time.

Figure 23: Projected EV market share of sales globally and in China by BNEF



Source: BNEF EVO

EV as a share of expected 2030 global sales has increased from 24% to 44% in seven years, so by 3 percentage points a year. Another seven years of that trajectory, and BNEF would be forecasting 65% EV sales in 2030.

Meanwhile, EV as a share of expected China sales has increased from 28% in the 2017 forecast to 67% in the 2023 forecast, so 6 percentage points a year.

We make this point not as a criticism of the excellent BNEF, but simply to illustrate the point that a bottom-up detailed approach has not had a good track record in forecasting the future of EV sales.

5.2.5 Inherent problems with current modelling structures

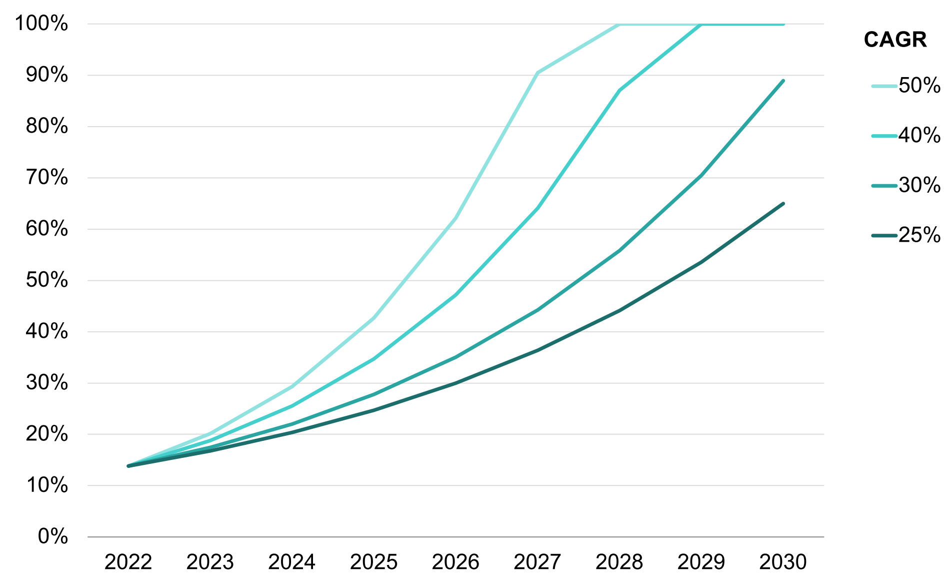
There are some inherent problems within many of these models. The result is that many of them simply model today's challenges into the future without regard to future solutions. They include:

- Excess complexity. Sometimes less is more.
- Lack of learning curves for battery costs.
- Assumption of limited policy action. Just because you cannot forecast policy in detail, you should not assume the trajectory of change will be stagnant.
- Assumption of fixed consumer attitudes to EV. As we have seen, attitudes change over time as costs fall.
- Limited efficiency gains.
- Limited change in the Global South.
- Assumption of fixed barriers. As we explore below, the existence of barriers inspires solutions. When analysts calculated we would run out of cobalt, battery makers developed batteries without cobalt.

5.1 Exponential growth

Growth rates of EV sales have enjoyed a CAGR of nearly 60% over the past seven years but have fluctuated very considerably. At any growth rate of much more than 30% they would make up all car sales by 2030, so it will be necessary to assume a falling growth rate. The complexity of this is such that it would simply be easier to use an S-curve.

Figure 24: EV share of sales at different CAGR (%)



Source: RMI

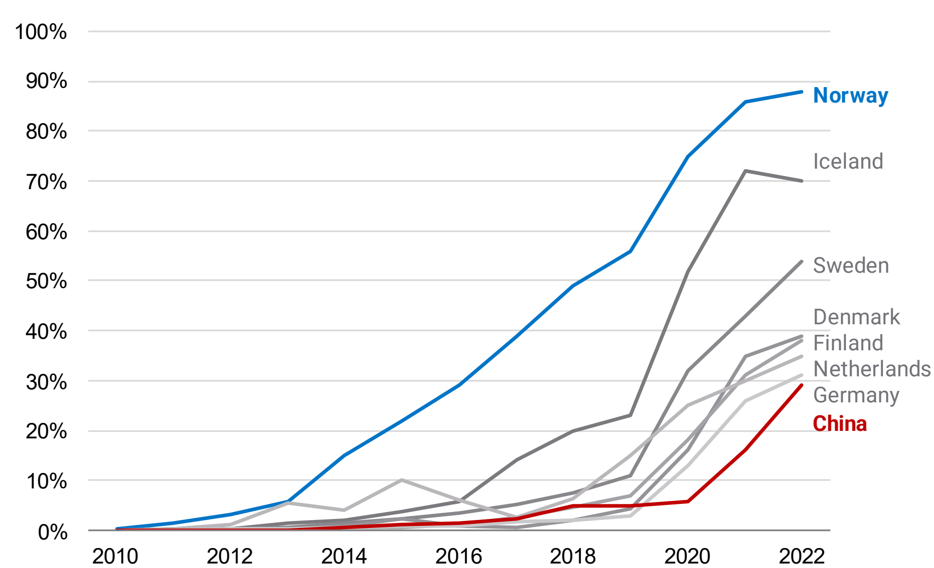
5.2 Experience of the leading markets

We show the experience of the leading markets. So far they have followed a remarkably similar growth curve, and that enables us to derive a standard curve of EV market share.

5.2.1 EV as a share of sales

Norway was the first market up the S-curve and has been followed by many in Northern Europe and in China.

Figure 25: EV share of sales in leading markets (%)

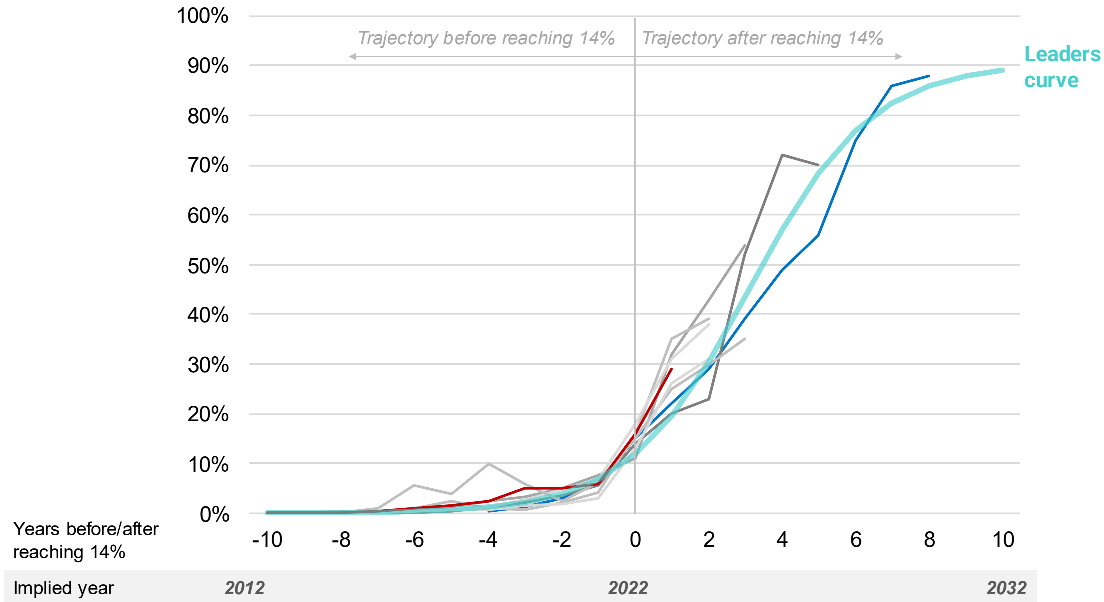


Source: IEA Global EV Outlook 2023

5.2.2 EV as a share of sales normalized to a common starting point

If we normalize these curves around a central point of 14% (the EV global market share in 2022), the similarity becomes even more clear. We can then take the experience of the leading markets and turn it into a leading country curve, or Leaders curve. As it happens, this Leaders curve is very similar to a logistics curve built using only the global data up to a 14% market share in 2022.

Figure 26: EV share of sales around a central point and the implied Leader curve (%)



Source: RMI, ChatGPT

5.2.3 Can we take this Leaders curve as a global standard?

The question is whether we can take this Leaders curve as a global standard? There are arguments on both sides and we conclude that on balance this curve can best be seen as a high-end forecast for the global story. While the experience of the leaders was indeed driven by policy and subsidy, it is highly likely that EV will be cheaper than ICE in most markets over the course of this decade. Countries lacking the ability to subsidise EV sales can nevertheless take successful policy tools and deploy them to scale the sector.

Reasons not to take the experience of the leaders

- Many of the leaders are wealthy and committed to change. They subsidised EV. That makes them unusual.
- Some countries and regions outside the leaders are actively opposed to EV.

Reasons to use the experience of the leaders

- The driver was policy but is now increasingly economics. As soon as we get to price parity there is no more need for subsidy.
- The leaders of the transition have been China and Europe. Combined these are nearly half the global car market.
- Most countries are fossil fuel importers. That gives them a reason to want to embrace EV. The 10% of the world living in petrostates is too small to prevent change.
- Everywhere has people who do not want to buy EV. They make little difference to the overall story. 'Twas ever thus: certain groups of people once refused to use railroads, electricity or the internet, and some still do. Change happened regardless. The US for example is 17% of global car sales, so even if a third of the country is opposed to buying EV, that is less than 6% of global car sales.

- The leaders have shown how the various barriers to change can be resolved.
- There is an inherent logic in the way technologies are adopted, as shown by the Roger's diffusion of innovation curve. A study of the leaders makes this apparent.

5.3 S-curves

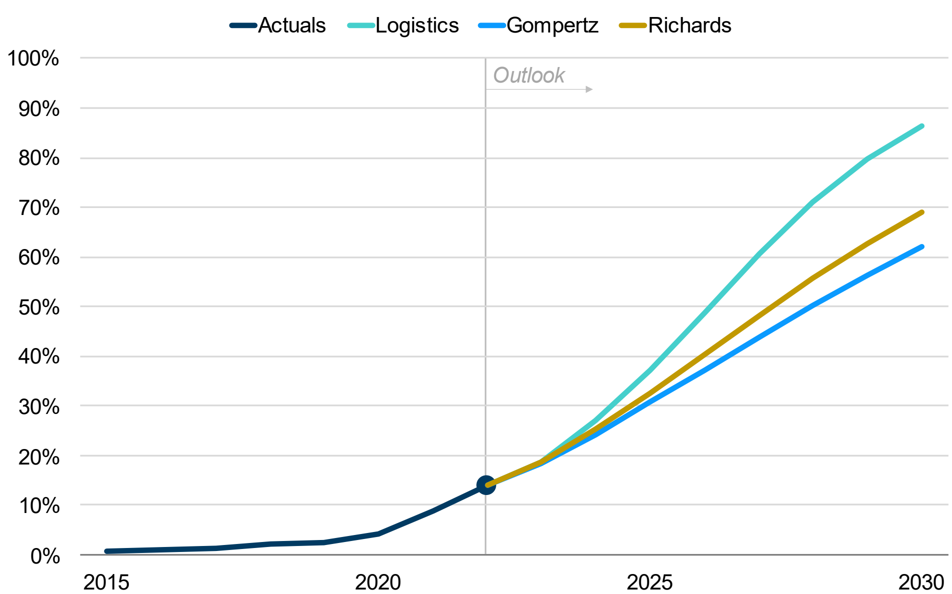
We look at the options, consider their forecasting power with regard to the leading market of Norway, and conclude that the Gompertz S-curve provides a useful low-end range (fast change) and the logistics S-curve is a sensible top-end range (faster change). It is important not to get too distracted by arguing about the different types of S-curves: while they do lead to different conclusions, they all imply a very different perspective on the future from the consensus.

5.3.1 What are the options

Just like most other new technologies, the growth of EV is likely to follow some kind of an S-curve. There are three classic S-curves that are often used to forecast the future:

- The logistics function. The type of S-curve that is most appropriate for fast growing technologies according to Doyne Farmer at Oxford.
- The Gompertz curve. A modified S-curve that is skewed to grow more slowly in the early stages and is often more useful at the early stage of change.
- The Richards curve. An S-curve that uses historic data to determine skew and comes up with a pathway between the two. While this is attractive, it is often accused of overfitting the data.

Figure 27 S-curve options for EV share of sales (%)



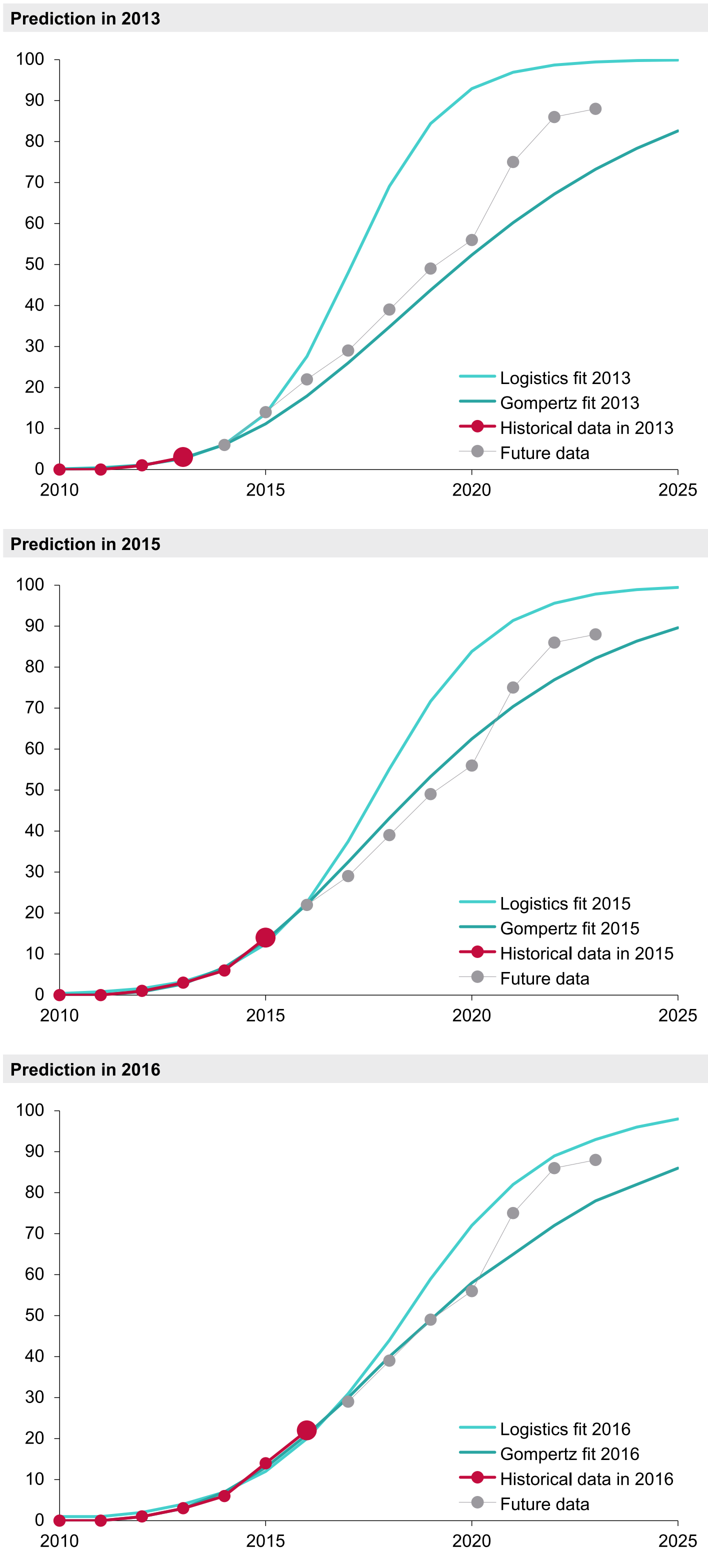
Source: IEA, RMI estimates

5.3.2 How good were S-curves at forecasting Norwegian growth

S-curve models take historic data and an end point and use the past to estimate a mid-point and growth rate in the future. In the early stages of growth, S-curves can be too aggressive and small changes in numbers can have a major impact. As you get more and more data points, the forecasting ability of S-curves increases.

If we look at the experience of Norway, then S-curves in the initial stages were too aggressive. A Gompertz curve had better predictive power. By the time you get to higher penetration levels (29% in this case) the logistics S-curve had higher predictive powers.

Figure 28: EV market share of sales in Norway: Predictions and reality (%)

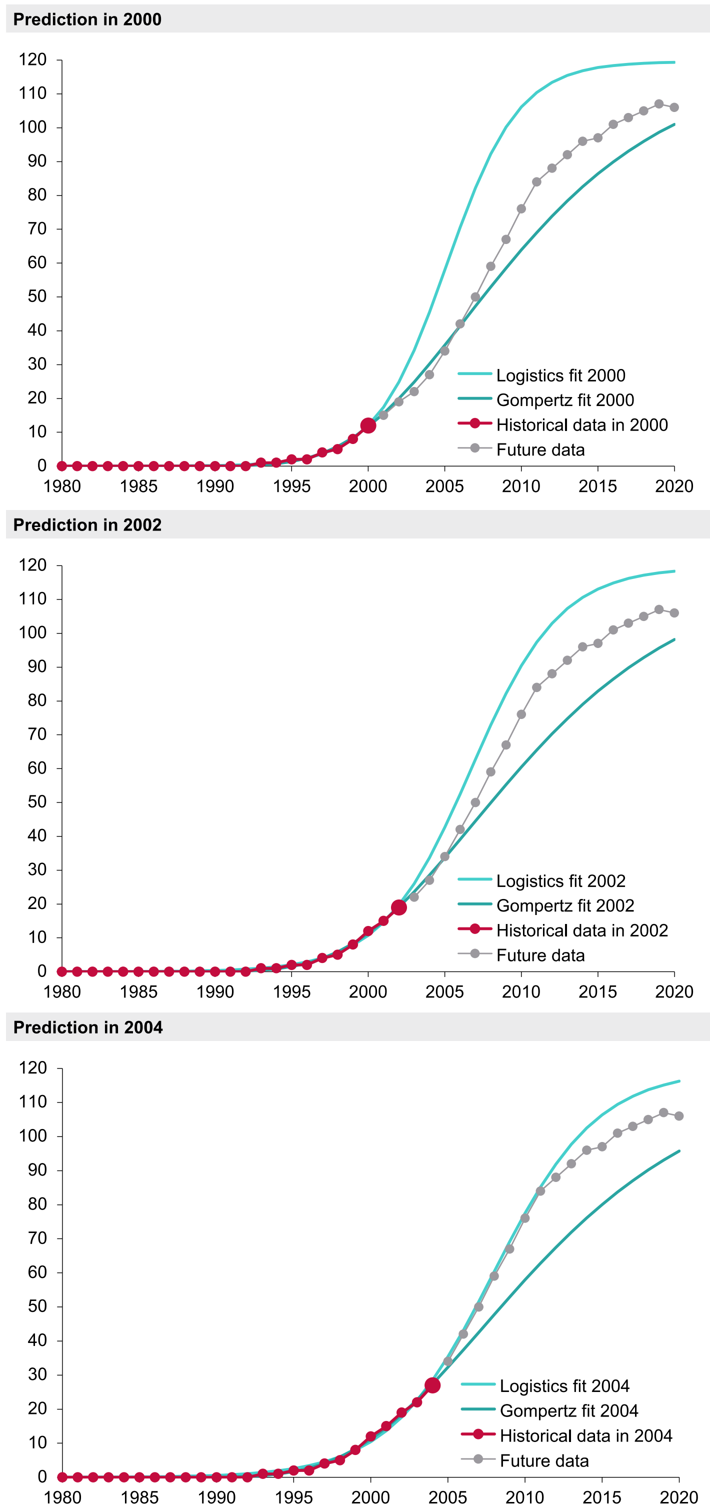


Source: IEA, RMI

5.3.3 Mobile phones

If we back test the Gompertz and logistic curves on the global growth in mobile phones, we see actual deployment lies between the two. Logistics curves forecast too high and Gompertz curves forecast too low.

Figure 29: Global mobile phone penetration: Predictions and reality (subscriptions per 100 people)



Source: Mobile phone data from OWID; RMI analysis

5.3.4 How do S-curves compare against global targets

The IEA net-zero emissions targets require that EV are 60% of global car sales by 2030 to hit its Paris compliant net zero by 2050 target,[101] so our framing would suggest that we are on track to meet this.

BNEF's net zero scenario requires that EV are 70% of global car sales by 2030, which is at the lower end of our framing for what is likely.

Climate Action Tracker (CAT) requires EV (specifically BEV) to be 75-90% of sales to hit its 1.5°C target, so we would struggle to do that.[102]

5.3.5 Agency

The fact that the S-curve is the most likely shape for the future should not distract us from the fact that it requires constant work to get there. Moore's law set a framework for the computer industry, and all players worked to make it happen. In a similar way here, if we take the S-curve as the most likely future, then it provides a target for companies and politicians. Rather than the future sneaking up and surprising us, we can plan for it.

6. Appendix 2: Challenges to EV growth: can they hold back the tide?

There are many challenges to the rapid growth in EV sales. However, there are also many solutions, and the pressure of opportunity, technology and policy adds daily to the solution suite. There is a clearly defined S-curve shaped path to a superior future, and it is within our grasp to continue to follow that path. We frame the challenge, set out the broad grounds for optimism, and then look in more detail at some of the primary challenges.

6.1 Change is hard

As we set out below, change is hard:

- There are many challenges. They range from mineral availability to range anxiety, from charging infrastructure to high costs, from consumer hostility to political blockages.
- Everywhere is different. A solution that works in China may not work in India. A solution that works in Germany may not work in Kenya. Local differences of electricity availability, cultural preferences and taxation structures will all play a role.
- The answer is complex. A strategy note such as this one can only provide a framework for thinking about change and links to papers that examine these issues in more detail.
- Mistakes will be made. But they do not necessarily mean that the entire process of change is without merit. Again, this is very common in the history of technology, and recent examples include diesel cars or BECCS. Moreover, as always in technology transitions, many companies will fail compared to the few that find solutions and break through to success.
- Some places and people will not change. This is completely normal, and even today 40% of people do not use the internet. So the question for the laggards is not whether or not they will embrace EV in the foreseeable future, but are they large enough in number to block change at a global level.
- Some incumbent organisations will always try to block change. The canal owners tried to block the railroads after 1850. The gas companies tried to block the rollout of electricity networks after 1900. And sometimes they succeed. The question again is whether they will be able to block change globally and permanently.

6.2 Grounds for optimism

Before plunging into the detail, it is worth noting that there are some powerful grounds for hope.

6.2.1 Experience of the leaders

As with so much in the energy transition, the challenges are theoretical but the solutions are empirical. In spite of the many challenges, leading countries have found solutions and EV deployment has been growing on clearly defined S-curves. EV are already over 50% of sales in Northern Europe and one third of sales in China, versus 14% globally and 8% in the US. Clearly there are solutions for a host of important challenges such as how to service flat dwellers, how to handle incumbent resistance, how to deploy charging infrastructure, and so on.

6.2.2 Experience of other technology shifts

Other technology shifts indicate that a pattern of leaders and laggards is extremely common. And that technologies have to solve barriers constantly. Moore's law for example needed constant innovation. The rollout of the internet faced massive technical and economic barriers at the start and took place more rapidly in leaders like the US than elsewhere. We should not be surprised either by the existence of challenges or the resistance to change by incumbents. Change is never easy.

6.2.3 Change takes time

Another, perhaps counterintuitive, reason for optimism is that change, even rapid change, does take time. It took Norway a decade to shift from 5% EV sales to 90% EV sales, but even today EV are less than a third of the fleet. It will take another decade or so before they rise to 80% of the fleet and the country has to face the issue of what to do about the last 20% or so of people who want to hold onto their ICE cars.

Many of the concerns about change are about solving the last part of the problem, the endgame. But in fact we are far from the endgame, and by the time we get there we will have many more technological and economic solutions, and the political clout of the oil lobby will be considerably weaker.

When thinking about challenges, we must not try to solve tomorrow's problems with today's solutions.[103] It is clear that we have enough solutions to continue to drive EV up the S-curve for the foreseeable future, and we need to focus on those. As we solve them, so costs will fall on learning curves and so new solutions will materialize. Meaning that we will face tomorrow's problems with tomorrow's solutions.

6.2.4 Technology gets better

Technology gets better over time. Batteries get cheaper and more efficient. Artificial Intelligence and digitization hold out the prospect of integrating transportation into the electricity grid. Technology solutions developed by the leaders are taken up by other countries.

The key costs of the transition are on learning curves. So it is reasonable to assume that many of the economic barriers will be crossed.

6.2.5 Challenges are also opportunities

It should hardly need saying, but challenges for some are also opportunities for others to get rich by solving them. And across the world entrepreneurs and companies are working to do so. Elon Musk became one of the richest people in the world by solving the problem of producing quality EV at scale. CATL and BYD have risen to dominance on the back of their battery and EV expertise. Established companies thought that this could not be done, leaving entrepreneurs to seize the opportunity. Incumbents are now struggling to catch up, but their loss in market share is permanent, and many will not survive the transition, as Christensen's Innovator's Dilemma notes.

6.2.6 We have already solved a lot of the challenges

A decade ago a list of challenges would have the apparent impossibility of building dozens of battery factories on many continents in a short period. Tesla opened its first Gigafactory only in 2016. Today, just seven years later, there are over 400 Gigafactories in the pipeline.[104] By 2030 a large part of the necessary capacity to build out a world of electrified transport will be up and running.

A decade ago, batteries cost over $1,000 per kWh and price parity seemed impossible. Today price parity between EV and ICE has been reached in China and will go global over the course of this decade.

6.2.7 Change gets easier over time

The best proxy for the difficulty of change is arguably the growth rate. High growth rates mean that you need to scale very fast. The past decade has seen really extraordinary growth rates in the EV industry of up to 100% a year. However, now that the market share of EV is nearly 20%, it is inevitable that the growth rate will slow. The implication is that change will become easier.

6.2.8 Bottlenecks are not the same as blockages

Many people point to a bottleneck as if it will never change. But the very existence of a bottleneck attracts capital and innovation and makes it far more likely that it will change. So the very work of McKinsey or the Energy Transitions Commission (ETC) to identify the challenges make those very problems far less likely to be a barrier to change. It is important to distinguish between teething troubles that will pass over time and insoluble challenges. It is our contention that none of the challenges are insoluble, permanent and universal.

6.2.9 Resistance to change is small in number and shrinking

Although they are noisy and have a lot of money to deploy on trying to block change, the beneficiaries of the status quo are small in number. Only 10% of people live in petrostates, and, as Norway has shown us, not all of them are resisting change. Less than 1% of people work in the oil industry. The number of people who do not want to buy an EV falls every year according to EY data.[105]

Moreover, the capital and opportunity are flowing to EV. Over time that will create its own support base. Even in places where the dominant political party does not like EV, the rising tide of battery factories will create a political constituency that favors being able to use them.

These groups are then best seen as islands of resistance in a sea of change. And as the EV tide rises higher, so some will switch, and some islands will disappear beneath the waves. And some will remain alone on their islands, high, dry and irrelevant.

6.3 Key challenges in 2023

We list below some challenges faced in 2023 as well as possible solutions. This is simply a summary of some highly complex questions being worked on in detail by RMI, the ETC, and others every day.

We look at: mineral availability; charging infrastructure; utility infrastructure; and battery circularity.

6.3.1 Do we have enough minerals?

Many argue that we do not have enough minerals to build the machinery for the energy transition. However, this argument is incorrect – there are plenty of mineral resources as has been shown by the ETC,[106] the IEA,[107] IRENA,[108] and in Joule.[109]

Figure 30: Global resources of key minerals

Source: ETC[110]

6.3.2 Can we extract those minerals fast enough?

The argument is then made that we will be unable to extract the minerals fast enough to meet demand at a specific date, say 2030. The debate then centers on the gap between supply and demand in 2030 for lithium, cobalt, nickel, graphite and copper.

It is indeed true that if we make no changes then we will not have enough mineral production in 2030. However, changes are happening, and it is highly likely that we will be able to fill the gap. The broad solutions for batteries were set out in a note by Amory Lovins of RMI in 2022[111] and examined in detail by the ETC in 2023. [112] They include:

- Increase energy density of the batteries.
- Recycle the batteries.
- Enable batteries to last longer.
- New chemistries that require less of the rare minerals in the battery.
- Improve the efficiency of car design.
- Improve system efficiency of transport system.

In addition to this, we are likely to need some new mines, and many are now being built.

The combination of these factors means that we are likely to be able to supply enough minerals. The chart below from Systemiq for the ETC shows how most minerals shift out of the problematic red zone as we deploy efficiency and recycling solutions.

Figure 31: Mineral availability

Source: Systemiq for the ETC

A classic example of this process was cobalt demand. In 2019, BNEF calculated that cobalt demand would increase from 100,000 tonnes a year to 300,000 tonnes by 2030, meaning a shortage was looming. That sparked attempts to find new chemistries to reduce cobalt use, and as they were found, projected cobalt demand in 2030 halved to 150,000 tonnes.

And before cobalt demand we had a panic over rare earths, examined in depth by Amory Lovins.[113] And here we saw a typical story of mineral cyclicality: demand rose rapidly as the result of growth, prices went up, brokers rushed to argue that prices would stay high indefinitely, alternative solutions were found, more supply came to market, and prices came down.

6.3.3 Charging for non-single family homes

The challenge: The low budget EV market will not scale without charging solutions for individuals who do not have home charging access, such as those living in multi-unit dwellings. Now is the time to develop and scale community-based charging solutions for those who do not have the luxury of charging an EV in a dedicated parking space or private garage. This is an equity and climate imperative.

The opportunity: New approaches to infrastructure deployment must be developed, including “right to charge” policies, public-private partnership approaches to infrastructure financing, utility engagement, standard process and procedures for Homeowner Associations, shared mobility business models, and infrastructure siting best practices.

6.3.4 Utility infrastructure investment

The challenge: Utility investment in infrastructure to support large-scale light, medium, and heavy-duty EV deployment happens at pilot scale in most states and is too cautious to achieve ambitious energy and environmental goals. As the regulatory system stands in the US, for a utility to make a sizable grid infrastructure investment, it must receive a service upgrade request from a customer, referred to as "firm demand." But this approach is not conducive to light duty DCFC hubs or medium and heavy-duty (M/HDV) electric truck deployment. By waiting for firm demand from truck charging, public charging investment will be too late, as it takes years to deploy the grid and charging infrastructure needed to satisfy aggregated L/M/HDV charging loads.

The opportunity: The following solutions and approaches must be pursued to overcome the utility infrastructure investment challenge:

- Site specific magnitude of the challenge: Project the effect of future truck charging on specific infrastructure systems (e.g., circuit, substation) to plan for efficient upgrades of utility infrastructure.
- Non-wires alternatives: Estimate potential for deferred or avoided grid investment enabled by on-site distributed energy resources (DERs). Evaluate the costs and business models for the deployment of DERs with truck charging.
- Regulatory enablement: Develop new financing approaches that will enable infrastructure upgrades without adversely affecting ratepayers. Develop regulatory principles that will enable regulators to approve grid infrastructure in advance of truck deployment, while also protecting ratepayers.

6.3.5 Battery circularity

The challenge: As demand for electric mobility increases, the resource-intensive EV value chain will grow proportionally. Much of the raw materials required to support the transition to EV are extracted from, processed in, and assembled in environmentally sensitive and economically marginalized regions of the world.

The opportunity: Coordinated public and private sector action to eliminate adverse impacts of the EV battery value chain, foster a circular battery economy that 1) reduces demand for virgin primary materials and 2) promotes an economically inclusive approach to value chain labor, and workforce development.

7. What is the X-change

The X-change is a series of reports analysing the impact of exponential change (the X in X-change) on the energy system. It contrasts with the orthodox view of linear change. The baseline scenario for the future of energy should assume continued exponential growth of renewable energy in the period to 2030.

Principles of the X-change

- Identify the exponential.
- Model the exponential in a variety of ways to understand the likely future.
- Figure out if there are any insuperable barriers to change.
- Human ingenuity will continue to find ways around impediments in ways that are not foreseen today.
- Focus on the period to 2030. Costs and volumes will be very different by that point.
- Better roughly right than precisely wrong.

Conclusions of the X-change

- Linear change is highly unlikely.
- The most likely future is on an S-curve.
- We are on a path to go fast or faster, but we must keep pushing.

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