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Electric vehicles and electricity

1. Introduction[1]

There is a broad consensus that penetration of electric vehicles (EVs) will rise throughout the world, but great uncertainty as to the timing and extent. There is also a growing recognition that automated, shared and electric vehicles (SAEVs) will be an important part of the coming revolution in sustainable mobility. Particularly in combination, shared mobility, automation and electric powertrains can result in major reductions in greenhouse gas (GHG) emissions from transportation, as well as significantly less air pollution and greater social equality. This article adopts these views as a starting point.

The central questions addressed here are: what will determine the speed and nature of EV deployment; what barriers could slow the process; and, more specifically, could the electricity system and its regulatory regime be barriers to EV penetration, or rather assist that penetration. The focus is mainly on Europe and on passenger light-duty vehicles[2], including battery EVs (BEVs) and plug-in hybrid EV's (PHEVs) in cities.

The central message is that, while electricity is obviously necessary for EV penetration, it is very unlikely to constitute a barrier to penetration, unless policy and regulation are badly designed or implemented.

The Insight has four sections, in addition to this introduction. Section 2 analyses the global prospects for EVs. It summarizes the forecasts for EV penetration and considers key factors that explain why the range is so wide. While adequate electricity generation capacity and charging infrastructure are obvious requirements for the penetration of EVs, other factors are more important determinants. Some of them – notably public policy support for EVs, falling battery costs, sharing and automation, and bans on fossil-fuel vehicles – improve the prospects for EVs to escape the technology "lock-in" of Internal Combustion Engine Vehicles (ICEVs). Others could reduce the number and type of EVs on the road, for instance: increased investment in public transport, congestion management, competition from other energy sources (like hydrogen or natural gas), the expanded use of fleets, mobility sharing, as well as changing consumer habits. Some of these factors (in particular sharing and automation) are likely to increase the distance travelled by EVs and increase total electricity demand, even if they reduce the number of EVs. There will also be competition among business models (for instance, car sharing versus ride-hailing

[1] The author would like to thank those who have commented on earlier drafts of this Insight and Dr Tim Schwanen of the University of Oxford for drawing attention to the importance of SAEVs. As always, any remaining errors are the author's.

[2] These include passenger cars and passenger light trucks but exclude two-wheelers, three-wheelers and low-speed, low-power four-wheeled vehicles. The paper does not analyse other alternative energy vehicles (hydrogen and natural gas), nor other modes of urban transport (buses, trams, undergrounds), long-distance freight transport, maritime or air transport, except in recognising that these transport modes and many other factors will have an important influence the future demand for EVs.

David Robinson

with buses) that will influence the number of EVs, the distance travelled and electricity demand. In short, many factors are more important than electricity in explaining the wide range of EV forecasts.

Section 3 focuses on the link between EVs and investment in electricity infrastructure to cope with anticipated EV growth, especially in Europe. It argues that this investment is very unlikely to be a barrier to EV penetration; historic investment trends have been higher and in some countries very little additional investment would be required. There is, however, concern about the chicken and egg problem: without EV penetration, investors are reluctant to invest in new infrastructure; and without that infrastructure, consumers are reluctant to buy EVs. Experience suggests that in these cases, governments may need to provide guidance to investors to limit the risk of stranded assets; otherwise, the infrastructure investment may not occur. However, if governments take a position on the preferred technology (e.g. BEVs, PHEVs, hydrogen) or the staged introduction of different technologies, this could establish a new technology lock-in.

Section 4 argues that current public policies for electricity in some European countries are barriers to EV penetration and should be eliminated as a matter of good regulatory practice. These barriers include: fiscal policies that favour fossil fuels over electricity; electricity tariff regulations that do not provide efficient incentives for consumers to charge their vehicles in off-peak periods; and electricity market designs that discourage participation of distributed energy resources (such as EV batteries) in wholesale and retail markets. The section also identifies other public policy choices that would support EV penetration, distinguishing between supply-side and demand-side support.

Section 5 summarises the arguments and offers some concluding comments on global prospects for EVs. Although this Insight does not look in detail at prospects for EVs outside of Europe due to the very wide range of circumstances, past experience in large developing countries (such as India) suggests that what happens in OECD Europe is important. This is due to the 'demonstration effect' which, for instance, led power sector reform to spread from OECD to non-OECD countries – primarily through the vehicle of multilateral financial lending. European, North American and Japanese experience is also relevant to the extent that penetration there drives down the costs of EVs and creates new business models, such as those built on SAEVs. We should also recognize that China is already the largest market for EVs and is likely to remain so at least until 2040.

Finally, the conclusion argues that public policy and cost competitiveness will be critical to EV penetration everywhere. In particular, public policy should be designed to foster low carbon innovation and encourage competition on a level playing field, at least by lowering and preferably eliminating regulatory, fiscal and other policy barriers to low carbon transport and other sustainable mobility options. However, governments may also need to provide guidance to investors about the nature of the charging infrastructure in order to ensure that investment is forthcoming.

2. Prospects for EVs

This section summarises the wide range of forecasts for EVs. To help explain that range, it introduces the concept of "path dependence" and the challenge of technology "lock-in" of ICEVs. It identifies a number of reasons why EVs are increasingly likely to escape ICEV lock-in – hence the high forecasts. It then analyses reasons why changes in technology, public policy and consumer preferences could limit the number of EVs – hence the lower forecasts.

a. Forecasts

The penetration of EVs is still very low but rising quickly[3]. The global electric car stock surpassed 2 million vehicles in 2016[4], which is about 0.2% of the approximately 1 billion passenger light-duty

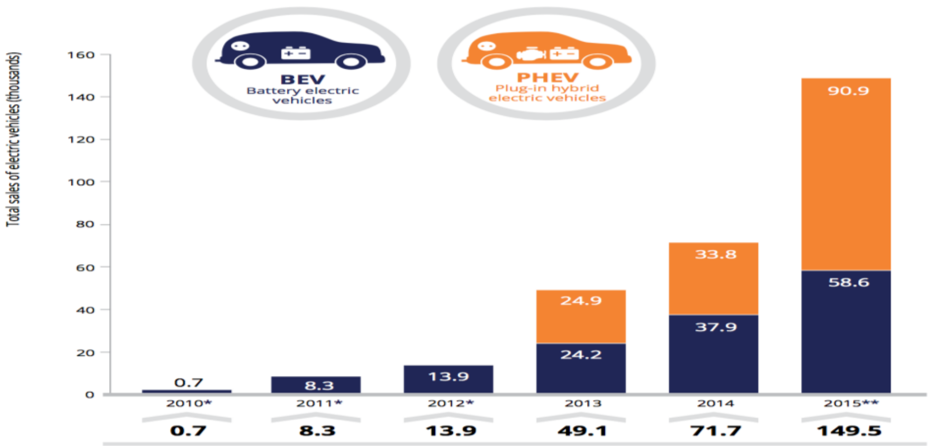
[3] IEA (2017).

[4] The number of EV vehicles on the road is the easiest and most common way to measure penetration. A better but more difficult measure is in terms of the distance driven by EVs. For instance, since they are used intensively throughout the day, fleets for

vehicles in circulation. Annual EV sales are growing quickly, although the rate of growth has fallen from 85% in 2014 to less than 50% in 2016, which is consistent with a growing stock.

In 2016, 1.2 million cars were BEV and 800,000 were PHEVs. The largest EV stocks were in China and the US, with 32 percent and 28 percent, respectively. China has a very high share of BEVs. Excluding China, the global growth rate of PHEV stock has been higher than for BEVs since 2009, with the exception of 2014. There is evidence that some governments (such as Sweden) have recently been reducing subsidies to PHEVs and increasing support to BEVs. Nevertheless, it is noticeable in Figure 1 that PHEVs have been gaining market share in the EU.

Figure 1: Total sales of EVs in EU-28, 2010-2015



Source: EEA (2017), page 48

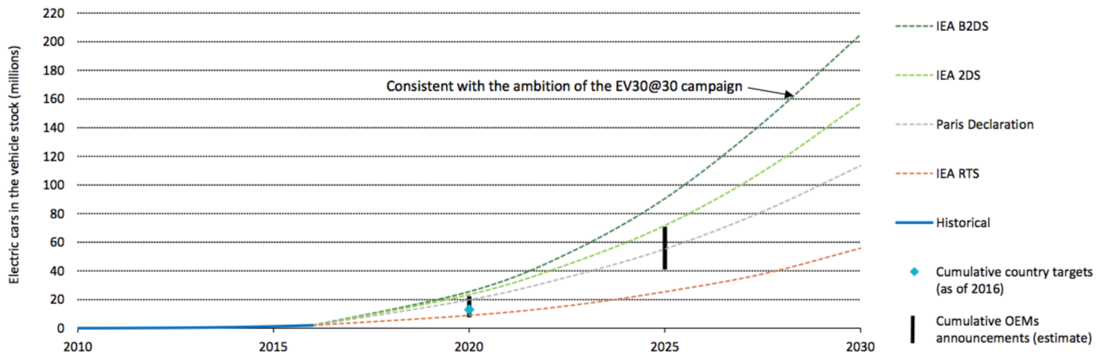
There is considerable uncertainty about future EV penetration in the next 10 to 15 years. For instance, the IEA's main scenarios (IEA 2DS and IEA RTS)[5] forecast global EV deployment of between 40 million and 70 million by 2025, and between about 120 million and 160 million by 2030. The IEA also has a Scenario (B2DS)[6] that reaches over 200 million EVs in 2030.

shared mobility and autonomous EVs significantly increase the average distance driven by EVs, compared to privately-owned vehicles. This is a subject to which the article returns later in this section.

[5] The IEA Reference Technology Scenario (RTS) incorporates technology improvements that support policies announced or under consideration. The 2DS scenario is consistent with a 50% probability of limiting expected global temperature increases to 2ºC this century. (IEA, 2017, page 6.)

[6] The IEA B2DS scenario is consistent with a 50% chance of limiting average future temperatures increases to 1.75°C compared to the pre-industrial era. (IEA, 2017, page 6).

Figure 2: Deployment scenarios for the stock of electric cars to 2030



Source: IEA (2017), page 6.

Not too surprisingly, there is a much wider range of longer-term forecasts. Near the top end are forecasts by merchant banks; for instance, Morgan Stanley's base case is over 1 billion EVs by 2050[7]. According to press reports, a number of oil companies forecast a stock of at least 100 million EVs globally between 2030 and 2035, while Bloomberg NEF (BNEF) expects 559 million EVs to be sold by 2040. While the range of forecasts is very wide, most forecasters (for instance OPEC, IEA, Bloomberg) have increased their EV projections substantially over the last few years.[8]

To look at one set of forecasts in a bit more detail, BNEF[9] expects 55 percent of new car sales and 33 percent of the global car fleet to be electric by 2040, with China, Europe and the US making up over 60 percent of the global EV market. They forecast EV sales to reach 11 million in 2025 and 30 million in 2030, as EVs become cheaper to make than equivalent ICEVs. In their projections, China will account for almost 50 percent of global EV sales in 2025, 39 percent in 2030 and still be the largest EV market in 2040. They expect EV buses to grow faster than passenger EVs and that EVs (passenger and buses) will displace 7.3 million barrels per day of transport fuels in 2040. The two challenges they see on the horizon are a risk of a cobalt shortage (increasing the cost of batteries in the early 2020s) and the charging infrastructure.

b. Escaping ICEV lock-in

Path dependence refers to the importance of history in determining outcomes[10]. Where we go depends not only on where we are now, but also on where we have been. Some of the economics literature on path dependence argues that inferior technology can dominate and persist because it gets 'locked in' as a result of economies of scale, learning and networks, as well as public policy, anti-competitive behaviour and other factors. According to this literature, markets are not working the way traditional economics say they do – in other words, market failures lead to the adoption of sub-optimal technologies. The Qwerty keyboard is the standard example, with others including Betamx v VHS and Microsoft v Apple. Supposedly, the technically inferior product gets locked in. However, some academics have argued that the winning technology (even Qwerty keyboards) is usually the superior one when measured empirically against the alternatives, in terms of economic efficiency rather than technical efficiency. Although these are contrasting views, there is presumably a consensus that when a technology does become dominant, path dependence makes it very hard, but not impossible, for new technologies to replace the previously dominant one. A key challenge facing EVs is escaping the lock-in of ICEVs.

[7] Morgan Stanley (2017), page 3.
[8] https://www.greentechmedia.com/articles/read/everyone-is-revising-electric-vehicle-forecasts-upward#gs.9odKkbU
[9] BNEF (2018) and BNEF (2017) pp 2-3.
[10] See Liebowitz and Margolis (1995).

Twenty years ago, a review by Cowan and Hultén[11] examined six conditions that might allow EV's to escape this lock-in: crisis in the existing technology, regulation, technological/cost breakthrough for EVs, changes in taste, suitable niche markets and scientific results. Notice that there was no reference to the availability of electricity. Their conclusion was that EVs could not escape the ICEV lock-in.

A fresh look at these same issues below makes it clear that conditions have changed. ***Is there a crisis of existing ICEV technology?*** There has been significant improvement in the efficiency of ICEVs, largely in response to more stringent performance standards. However, in view of the policies to address climate change and improve air quality, ICEV technology faces a crisis related to its emissions of CO2, NO2 and particulates. As governments at all levels increase the stringency of emission standards, this will require further investment, raising the costs of manufacturing ICEVs. Meanwhile, rising taxes on fossil fuels and high world oil prices will raise the cost of driving ICEVs. The crisis facing ICEVs is becoming more acute because many governments have decided to penalize them or ban their entry into urban areas. The reputational damage from the Diesel-gate scandal[12] involving Volkswagen has made the crisis even more serious for diesel manufacturers, especially in Germany. Although companies will continue to invest in improving the efficiency and performance of ICEVs, financial markets and the main car manufacturers are now betting heavily on EVs.

Will regulations have an impact on the car industry? Obviously, the answer today is yes. IEA (2017) details the significance of public policy support for EV penetration. Many governments (such as the UK and France) have adopted targets for EV penetration or policies to promote them. Policy support typically includes either demand-side subsidies or supply-side obligations (for example zero emission vehicles, or ZEV, mandates), or some combination. Norway, for instance, has provided substantial fiscal and other incentives for consumers to buy EVs. California, on the other hand, has introduced ZEV mandates, which embed a system of tradable credits, for automakers to sell a set proportion of zero-emission vehicles. In most countries, we also see tightening emission standards (CO2, NO2 and particulates), and in a growing number, national or local governments are introducing low-emissions zones, diesel bans and full phasing out of ICE vehicles.

In its 2011 EU Transport White Paper[13], the European Commission outlined a road map that halves the use of conventionally fuelled cars in urban transport by 2030 and phases them out entirely by 2050. In 2017, the Commission proposed a Clean Mobility Package whose new emission standards that will accelerate the transition away from ICEVs.[14] The justification for European public policy support for EVs is primarily related to the environment, although reduced dependence on imported oil is also relevant.[15]

- First, EVs help to meet EU and global climate change targets. While greenhouse gases (GHG) from all other major economic sectors in the EU have fallen in recent decades, road transport's emissions have risen and in 2014 were about 17 percent above 1990 levels. Furthermore, the contribution of road transport to total EU GHG emissions increased from 13 percent in 1990 to 20 percent in 2014. In 2015, the IEA argued that EVs (battery and plug-in hybrids) were already a lower-carbon option than ICEVs and hydrogen vehicles in the US, Japan and Europe as a whole (considering GHG emission intensity per kWh of the average European electricity generating mix). By contrast, according to the IEA, the high carbon intensity of electricity in China in 2015 meant that battery EVs were still more carbon intensive than hydrogen vehicles and diesel cars. [16]
- Second, EVs help to reduce local air pollution, especially NO2 and particulates. Most large cities today are concerned about the impact of local pollution on the health of their citizens. The EU's

[11] See Cowan and Hultén (1996).
[12] http://www.bbc.com/news/business-34324772
[13] EC (2011), page 9.
[14] EC (2017)
[15] EEA (2016), page 8-9.
[16] IEA (2017), page 26.

annual limit for NO2 was widely exceeded across 19 Member States in 2013, mainly at roadside locations. Furthermore, a number of Member States report particulate matter (PM) levels that are higher than EU air quality standards allow, resulting in a significant number of premature deaths. As a consequence, the European Commission has brought infringement proceedings against a number of Member States, and many cities have introduced restrictions on diesel and gasoline vehicles.

- Third, road traffic noise harms human health and well-being. According to the European Environmental Agency, in 2012 almost 90 million people living in cities were exposed to long-term average noise levels that exceed EU thresholds.

These and other justifications for policy support have been questioned. First, key reports argue that transport policy reform must address traffic congestion, not just environmental pollution[17]. Second, the potential for EVs to reduce GHG emissions is limited, especially where electricity remains carbon intensive[18]. Third, even though subsidies are justified when fossil fuel externalities are not internalised, at some point subsidies may be financially unsustainable. Furthermore, as the cost of EVs falls, they may not require policy support. Fourth, many people are employed in the transport business (for instance the self-employed who have bought their own minivan) and will resist strongly the restrictions on diesel and gasoline vehicles as well as the move to autonomous vehicles; governments are concerned about the potential for unemployment as well as disruptive protests. Fifth, EVs favour those who can afford to buy them, often as a second or third car. Finally, privately-owned EVs are not the only form of zero carbon mobility; governments may choose to support many other forms.

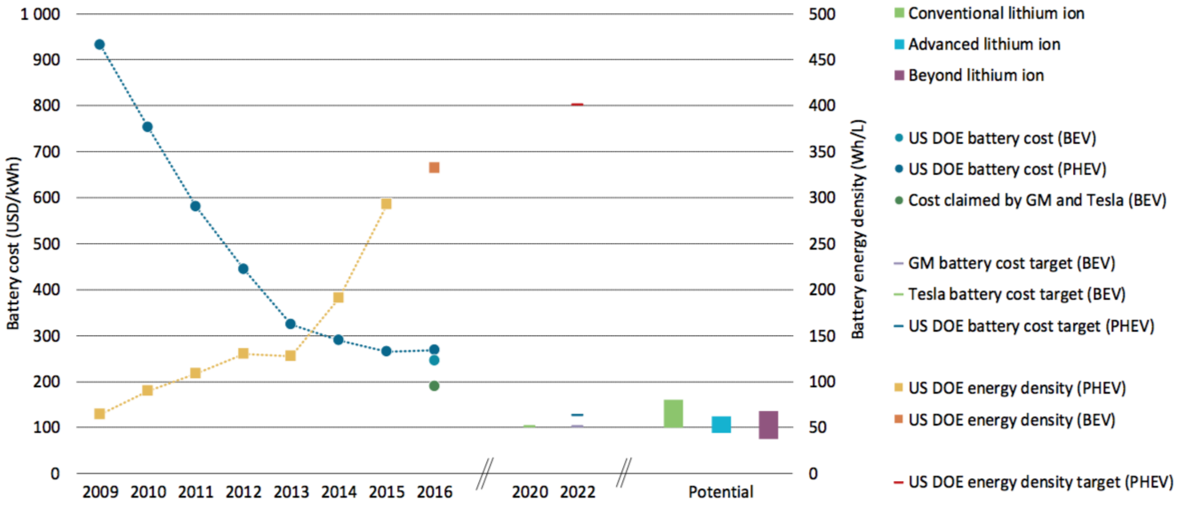
These and other qualifications do not vitiate the public policy case to support EVs, and they can all be challenged. But they could condition the speed and the nature of EV penetration. For instance, concerns over congestion could lead to policy support for measures other than electrification of personal vehicles. These measures could include improved public transport, bicycle lanes, pedestrian areas and urban planning that limits access to private vehicles. It could also lead to policy support for SAEVs because they favour poorer citizens (who cannot afford a personal EV), while reducing congestion, emissions and the cost of EVs.

Has a technological or cost break-through occurred in the EV industry? Again, the answer is yes. In future, the central reasons for rapid penetration of EVs are likely to be the falling cost of EVs and batteries and the increased range of EVs.

The decline in the cost of EVs is largely related to declining battery costs, which are inversely proportionate to battery density, as reflected in Figure 3. IEA (2017, page 14) argues that the cost of batteries in the R&D phase is below those now being sold and, hence, future costs of EV batteries will continue to fall. Bank of America Merrill Lynch (BoAML, page 14) forecasts that battery cell and pack costs will fall by 6.1 percent annually between 2016 and 2030. There is debate about whether and at what pace battery costs will fall, with concern expressed about potential shortages of lithium or cobalt[19]. However, the consensus appears to be quite strong that the cost of batteries will fall significantly, even if there are periods when the prices of these materials spike.

[17] See for instance EC (2011), page 5.
[18] Obviously, the lower the carbon intensity, the less the avoided emissions, but already today there is a ¨no regrets” argument for EVs in these regions. See IEA (2017), page 26, and Transport & Environment (2017).
[19] See Moores (2018) for information on the potential supply chain risks and opportunities related to energy storage technologies.

Figure 3: Evolution and battery energy density and cost



Source: IEA (2017), page 14.

When the total cost of ownership (TCO)[20] of EVs is equivalent to that of ICVEs, the economic benefits of EVs will be more evident. These benefits derive from the superior energy efficiency of EVs (3-4 times more efficient than ICEs)[21] and related savings in fuel costs, and due to the lower maintenance costs and remaining subsidies. Already, in some countries, the TCO is close to or below that of ICEVs, especially when fuel savings and subsidies are included; this is even more likely for fleets. Excluding fuel savings and subsidies, most forecasts suggest that the inflection point (at which the acquisition cost of ICEVs and EVs is equivalent) will be reached well before 2030. For example, BoAML (2017, page 7) argue that the inflection point could be 2024 (Europe-diesel), 2027 (US), 2028 (Europe-petrol) and post-2030 (China); and even earlier by including fuel savings.

The other key technological breakthrough increasing the appeal of EVs is the longer driving range. According to BoAML (2017), these are expected to rise from 200 km today to about 400 km by 2030. The Tesla's Model 3 has a range of 310 miles on the more expensive variant. Perhaps in response to Tesla, OEM's are announcing plans for EVs with similar ranges to be available well before 2030.

Will changes in taste propel the EV industry into self-sustained growth? For many years, consumers have indicated an increasing interest in the environment; this and the "cool effect" of EVs help to explain public policies favouring EVs. However, consumers have developed habits that are related to their ICEVs, including driving long distances without range concerns, quick and convenient fill-ups, and being able to choose from a very wide selection of manufacturers and models, some of which are very inexpensive or meet special requirements (such as small diesel delivery vans, or sports cars with loud engines). The economics have also favoured the ICEVs, especially in countries that do not internalise the cost of environmental and other externalities in gasoline and diesel prices. EVs are making headway through increased range, lower costs and a wider variety of models (more than 30 models are currently available in Europe). However, convincing the majority of consumers to adopt EVs will be an uphill struggle until EVs can meet and beat ICEVs on cost and on many of the other factors that favour ICEVs.[22]

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[20] The TCO sometimes refers to the cost of acquisition ("sticker price"), but can be defined to include the avoided costs related to fuel savings as well as other benefits, such as subsidies or tax advantages.
[21] See https://insideevs.com/efficiency-compared-battery-electric-73-hydrogen-22-ice-13/
[22] Walker (2018).

Are there sufficiently attractive niche markets? Early adopters of a new technology can provide a foundation from which to learn and build scale. For EVs, most early adopters were concerned primarily for the environment, or at least for being seen by others as being environmentally responsible. The question is whether these early adopters provoke suppliers to also improve performance in other ways, including driving range, styling, number of models and ease of charging. There is evidence that this is happening. Table 1 lists OEMs that, by April 2017, had publicly announced their willingness to create or significantly widen their electric model offer over the next five to 10 years. Since then, several OEMs have announced electric car production capacity scale-up plans, new models and new business strategies[23]. For instance, GM has been claiming over the past year that "electric is the future" and they recently unveiled two new EVs at the Beijing Auto Show.[24] They have also announced that they are partnering with Honda to build the next generation of batteries[25]. Meanwhile, Volvo expects to generate half of all sales annually from fully electric cars by the middle of the next decade, with one third of all cars to be autonomous. Volvo also sees an opportunity to build direct consumer relationships and to develop new recurring revenue sources from connected and other services for customers.[26]

Table 1: OEM announcements on electric car ambitions, as of April 2017

OEM	Announcement
BMW	0.1 million electric car sales in 2017 and 15-25% of the BMW group's sales by 2025
Chevrolet (GM)	30 thousand annual electric car sales by 2017
Chinese OEMs	4.52 million annual electric car sales by 2020
Daimler	0.1 million annual electric car sales by 2020
Ford	13 new EV models by 2020
Honda	Two-thirds of the 2030 sales to be electrified vehicles (including hybrids, PHEVs, BEVs and FCEVs)
Renault-Nissan	1.5 million cumulative sales of electric cars by 2020
Tesla	0.5 million annual electric car sales by 2018 1 million annual electric car sales by 2020
Volkswagen	2-3 million annual electric car sales by 2025
Volvo	1 million cumulative electric car sales by 2025

Source: IEA (2017), page 24. This s an incomplete copy of Table 2 in that report.

Can scientific results help the EV industry? The EV industry is clearly benefiting from scientific evidence of the irreparable damage that ICEVs are doing to the global and local environment. The scientific case for EVs is more powerful when the electricity is generated by zero-carbon or low-carbon energy. However, in most OECD countries, even with a relatively high average carbon intensity of generation, we saw earlier that the IEA (2017, page 26) concluded that EVs have lower emissions than ICEVs.

c. Other factors affecting EV penetration

There are many factors, apart from ICEV lock-in, that could condition or limit EV penetration. The first is the combination of urban planning and policies to address concern over traffic congestion. This could

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[23] For example, see "Electric Vehicles: OEM plans for China xEVs revealed at Beijing Motor Show", posted 30 April 2018, https://roskill.com/news/electric-vehicles-oem-plans-for-china-xevs-revealed-at-beijing-motor-show/

[24] "Here are 2 Glimpes of General Motors´Battery-Electric Future", The Motley Fool, 24 April 2018. https://www.fool.com/investing/2018/04/24/here-are-2-glimpses-of-general-motors-electric-fut.aspx

[25] "GM and Honda are partnering to build nextt-gen batteries for electric vehicles", Electrek, June 7 2018. https://electrek.co/2018/06/07/gm-honda-partner-next-gen-batteries-electric-vehicles/

[26] "Volvo Cars announces new business ambitions", Automotive World, June 7 2018, https://www.automotiveworld.com/news-releases/volvo-cars-announces-new-business-ambitions/

lead to restrictions on the use of private vehicles in city centres, as well as congestion fees and other forms of taxing road use, vehicle ownership or access to city centres. As mentioned earlier, concerns over congestion, the local environment and health could also lead to the promotion of public transport, including more buses, trams, undergrounds and trains running on electricity. For instance, in Shanghai and Beijing, governments have vastly increased the number of underground lines in order to reduce pollution and congestion related to the use of private vehicles. Furthermore, although electric buses still have a very low market share worldwide, the economics increasingly favour them over diesel buses, and performance (e.g. speed and climbing hills) of the best electric buses appears no longer to be an issue. In addition, policy makers could promote other forms of sustainable mobility, including bicycle lanes and pedestrian areas.

A second group of factors is the introduction of sharing, automated electric vehicles (SAEV), for passengers or for commercial and industrial use. The SAEV model supports higher usage of the vehicles and potentially fewer vehicles, even though it is likely to increase electricity use.[27] The economics increasingly favour SAEVs because the fixed costs of the vehicles can be recovered quickly (through energy cost savings), and because SAEVs facilitate an efficient approach to charging and avoid the need to share revenue with the drivers. Consequently, the SAEV model leads to a faster turnover of vehicles. It is also attractive for political reasons; it helps to reduce congestion and allows people with less income to take advantage of EV transportation. The SAEV model is likely to favour larger over smaller EVs. It is interesting, for instance, to note that the UK National Grid's (NG's) Consumer Power Scenario involves fewer EVs but significantly higher electricity consumption than their Two Degree Scenario.[28]

A third factor is changing consumer habits. For instance, younger people are less inclined to own a car and more inclined to use public transport, participate in car sharing, cycle or walk. Younger people also rely heavily on communication technologies to access integrated services which support the uptake of shared EV (and other sustainable) mobility-based business models.

Although the SAEV model seems the most likely and desirable direction for EVs, it is difficult to know the combined effect of all these factors on future mobility. For instance, if autonomous vehicles become so cheap that they remove the cost incentives for sharing, people may not want to ride-share anymore. Furthermore, if the cost of ride-hailing with small private buses is very low, this would lower the demand for single-user rides with Uber and Lyft. And if public transport is particularly good and cheap, this will reduce the demand for many competing mobility services, but increase demand for services that provide the last-mile mobility between the public transport and the origin or final destination.[29] In spite of the difficulty in determining the combined effect of these factors, SAEVs, public transport and changing consumer habits will likely be key determinants of EV penetration. They may reduce that penetration in terms of EVs on the road at any time, while at the same time speeding up vehicle turnover, increasing distance driven (and electricity consumed) by EVs and other transport modes that use electricity.

Finally, policies could condition the path-dependent process by which a technology achieves lock-in. Most forecasts assume quite reasonably that BEV technology is the way to go due to lower life-cycle costs and greater emission reductions than for ICEVs, PHEVs, hydrogen vehicles or natural gas vehicles. Although it seems unlikely that PHEVs or hydrogen vehicles will become the new dominant technology, one cannot completely rule this out. In particular, PHEVs have been gaining market share in some regions, notably the EU. Even the relatively bullish long-term forecasts by BNEF assume that PHEVs will continue to be important until 2025. Furthermore, if governments postpone, or take, decisions on charging infrastructure that effectively support PHEVs, this further reduces the potential

[27] See Kamargianni (2018) for more on Mobility-as-a-Service.
[28] National Grid (2017), page 42. The NG is discussed in Section 3 of this Insight.
[29] See Fulton and Compostella (2018) for more on factors affecting urban passenger travel.

penetration of BEVs or other technologies that require a different infrastructure. Supporting PHEVs might be politically expedient for some governments because these vehicles do not require a major change from the driver experience with ICEVs and could be justified as a transition arrangement. Governments could also argue that PHEVs will be required to operate in EV mode when in cities, thereby reducing local pollution. The longer these arrangements last, the more likely is technology lock-in in favour of PHEVs, or at least a postponement of BEV penetration.

d. Conclusion

Although most forecasts anticipate fast growth of EVs, these forecasts are open to significant uncertainty. There is a strong presumption today that EVs will escape the lock-in of ICEVs in the next 10-20 years. However, the timing is uncertain and it is important to recognise that even if EVs do replace ICEVs, changing government policies, technologies, business models, costs and consumer preferences could condition the number of EVs and influence what becomes the dominant EV technology.

3. Modest investment in generation and the charging infrastructure should enable EV penetration

Electricity charging networks and sufficient generation capacity are obvious preconditions for the successful penetration of EVs. The cost of electricity, the approach to charging, and the potential to sell vehicle to grid (V2G) services are also relevant. However, the electricity system is generally reacting to the penetration of EVs – which is mainly being determined by the factors addressed in the last section.

People often ask whether electricity networks and generation will be able to cope with the increased penetration of EVs. In Europe, the electricity system should not be a barrier because the investment requirements are well within historic norms, as explained below, and in some cases will not require much investment. Furthermore, penetration of EVs will provide flexibility to the electricity system, facilitating the integration of intermittent renewables, so governments have reasons to want to support this investment. However, there is uncertainty about what the investment costs will be, primarily related to the choice of the charging infrastructure and the extent of existing network capacity. Furthermore, in the absence of government guidance, there is a risk that investment in electricity will not occur due to concerns over stranded assets.

a. Charging infrastructure options

There are many possible charging infrastructure models and each has different implications for investment.

- *Home charging*. This produces relatively few electricity problems as it can be done overnight and in a flexible way. But this depends on the specific city, both its physical layout and its regulations. For instance, in the UK, National Grid (NG) argues that home charging is only really suitable for a minority of homes - those with private drives. Flats raise further complications - in some cases there will be access to collective parking but for many there will not be.
- *Roadside charging points.* A substantial EV fleet requires a significant charging network. This raises public policy problems, such as whether non-EVs be allowed to park at charging points. If so, this limits their availability for EVs and wastes an expensive asset; on the other hand, denying owners of ICE vehicles most of the available parking space would be difficult. The problem is essentially one of congestion (although less for SAEVs). Furthermore, it is not possible to generalise about the electrical implications.
- *Fleets.* Central overnight charging is probably the most efficient model for charging fleet vehicles (autonomous or not) in sharing business models like Uber's. But to what extent will this sharing model apply to private transport? To assess this, one would need to address questions such as how far consumers are prepared to forego the optionality of a private vehicle and rely on hiring as needed, and how public policy makers will view the issues related to sharing.

- *Fast charging at gas stations and highways.* This is certainly going to be needed. However, the implications for electricity are very different from the previous options; there could be significant additional local capacity and generation needs. But those in turn depend on how fast the charging will need to be. In any case, as illustrated below for the UK, the investment requirements do not seem to pose a serious problem. Indeed, a UK start-up called Pivot plans to build the world´s largest network of grid-scale batteries and rapid charging stations to provide electricity charging capability on UK highways, posing a direct challenge to the countries' existing motorway refueling stations[30].
- *Battery replacement.* This would allow flexible recharging and, in terms of the customer experience, is probably closest to the current model of a quick in-and-out to the garage. However, it is difficult to see a business model without strong public policy support (for example on standardising battery and vehicle design) and it could be expensive - presumably you would need to have a lot more batteries than cars.

There are three conclusions to this summary on charging infrastructure. First, there are many charging infrastructure options and it is not clear which will dominate; this could well vary by country and region. Second, all options probably require public policy support or facilitation, at least at the outset. Policy guidance is required to address the chicken and egg problem: investment in infrastructure depends on EV penetration and EV penetration requires infrastructure. It may be necessary for governments to give positive guidance on the way forward to avoid or reduce the risk of stranded investment. Third, electricity considerations are unlikely to determine the choice and it is not even obvious which option is best from the electricity point of view. Decisions are going to be made in response to a combination of other factors – such as history, infrastructure needs, consumer preferences and policy considerations – and the different parts of the electricity industry will then need to respond. At that point, the problem is less likely to be whether there will be enough capacity to meet the demand from EVs, but rather, ensuring efficient grid management and limiting demand at peak. It will be especially important to predict charging hotspots and load, and to influence the charging behaviour of consumers through well-designed tariffs and other incentives to charge during off-peak periods.

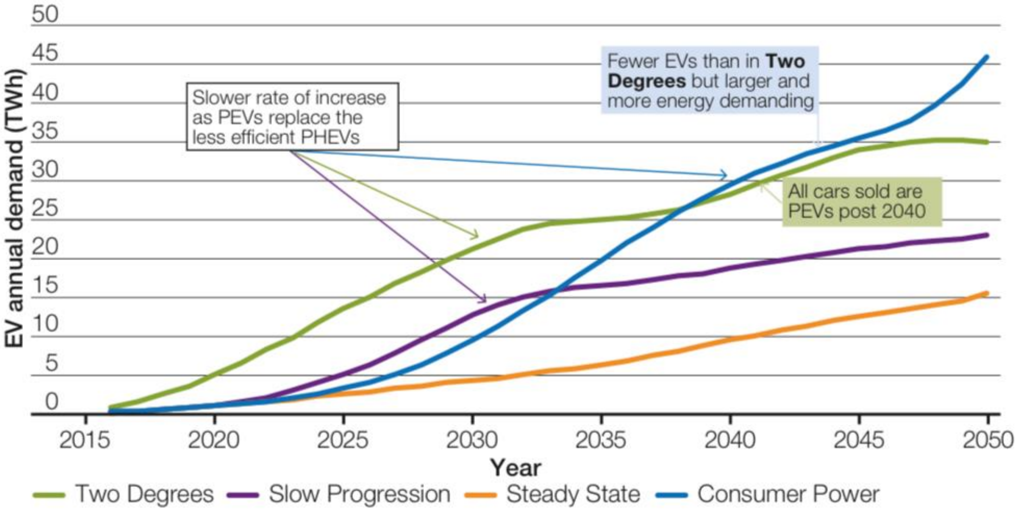
b. Investment in electricity generation and networks – UK example

Investment in the electricity sector could be a barrier to EV penetration if policy was unclear and the investment did not occur. On the other hand, the analysis below for the UK suggests that investment requirements to support high EV penetration are well within historic norms. The analysis should also extend to Europe, since most European countries use similar vehicles and have similar driving patterns. The analysis for North America and the rest of the world may be different, but there is evidence that electricity demand growth related to EVs should be relatively easy to meet, especially if consumers are given incentives to charge off-peak.

Figure 4 compares the annual demand resulting from EV penetration under different scenarios. In its Consumer Power scenario, the UK's NG[31] assumes 90 percent penetration of EVs by 2050 and concludes that this would increase demand by 46TWh, compared to total demand of 308 TWh in 2016. Although this scenario involves fewer EVs than their Two Degrees scenario (in which all cars sold after 2040 are pure EVs), it implies higher electricity consumption because it assumes larger vehicles and vehicles that are driven further, for instance because they are in fleets and sharing schemes. The increase in the Consumer Power scenario is only 12 percent of assumed 2050 consumption (383 TWh). This implies that EVs would increase electricity consumption by only 15 percent over 30 years. Since total UK electricity demand has gone down 11 percent since 2008, there might not even be an overall increase in demand.

[30] S&P Global Platts Power in Europe, Issue 775, June 4, 2018.
[31] National Grid (2017).

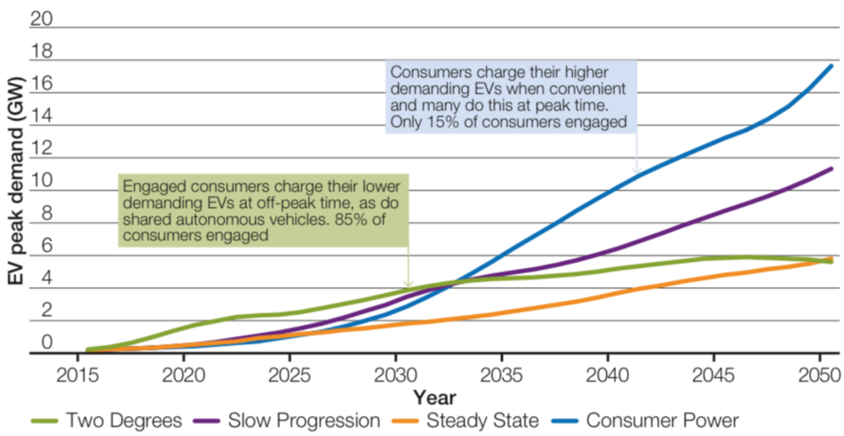
Figure 4: UK Annual demand from EVs, 2015-2050



Source: National Grid (2017), page 42.

The impact on peak demand will depend on the charging scenario. A sensible charging structure would encourage off-peak charging (thereby reducing peak demand and the need for additional capacity).[32] In Figure 5, in the Two Degrees scenario, most consumers charge their vehicles in off-peak periods and the resulting increase in peak demand is only 6 GW. For the Consumer Power scenario, NG estimates an increment of 18GW or about 30 percent of today's peak demand; this reflects a central planner's caution, with many consumers assumed to charge at peak times. Even if we take this worst-case scenario, an increase of 18 GW of peak capacity would require construction of only about 600MW of new capacity a year over the period, well below levels of construction over past decades. For instance, compare the requirement of 18GW over 30 years with the construction of about 30GW of gas-fired generation capacity in the 20 years from 1990.

Figure 5: UK peak electricity demand from EVs



Source: National Grid (2017), page 43.

[32] See Crozier (2018) for more on the impact of EVs.

Some might posit that the electricity system will also have to cope with problems arising from the intermittency of new renewables and that EVs could be the straw that breaks the camel's back, but that argument is unconvincing. First, the intermittency challenge is likely to lead to more flexible market structures, and to more storage and demand response, which is precisely what EVs can offer to the electricity system. Indeed, the rise of EVs would mean a massive increase in flexible storage capacity, so could actually make it easier to balance the system and integrate renewables. Second, in future, it will almost certainly be easier than now to try out some of the new ideas to integrate transport, for instance through vehicle to grid (V2G) sales.

As regards charging infrastructure costs, the UK's Committee on Climate Change published an analysis earlier this year.[33] At least two points deserve attention here. First, the cost is fairly modest. They say about £530 million would be needed by 2030 for the charging network to stay on track for the 2050 target. That is less than £50 million a year, compared with the £8 billion or so a year being spent currently on renewables. Second, over 90 percent of the cost is for roadside charge points. They assess the infrastructure cost of fast charging at filling stations on motorways and major roads as more or less trivial (£30 million over the period). This is consistent with a thought-piece by NG[34] which says it might actually be easier from an electricity point of view to focus on fast charging rather than roadside or home charging because it would mean less extensive strengthening of local distribution systems. However, not everyone takes this view in favour of fast charging, and it could reflect NG's preference for charging directly from its high voltage transmission network.

c. Global impact of EV penetration on electricity demand

A recent study by the Regulatory Assistance Project confirms that electricity infrastructure should not be a serious barrier to EV penetration in Europe. Indeed, it concludes that electricity distribution networks run at well below their full potential, implying that unused network capacity could be utilised for charging EVs with little or no need for additional capacity. It also concludes that smart pricing and smart grid technologies are important to limit investment requirements.[35]

Figure 6 confirms that the UK (and European) studies are broadly consistent with the IEA's view on the global impact of EV penetration. In the IEA 2DS scenario, the additional generation required to meet EV demand amounts to 1.5 percent of total electricity demand in 2030, which is only 6 percent of the expected increase in demand due to new loads from electrification in the industrial, residential and commercial sectors. This scenario is far less ambitious than others with respect to EV penetration by 2030, so it understates the potential electricity demand. Nevertheless, it does confirm that electric car loads are probably manageable in comparison to other sources of additional electricity demand. Further confirmation comes from BNEF's scenario for 2040. They conclude that electricity consumption by EVs will represent just 5 percent of projected global power in 2040, and that limiting the impact on investment will depend critically on providing incentives to charge during off-peak periods.[36]

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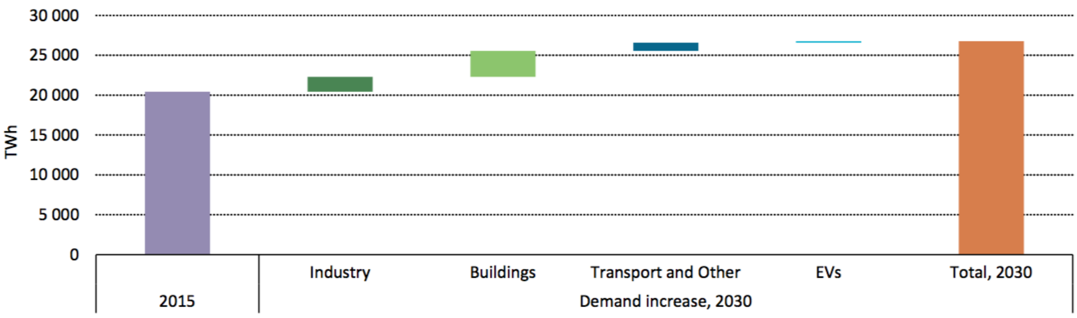
[33] Climate Change Committee (2018). Note that this is a report prepared by consultants for the Committee.
[34] Reported in the Financial Times, "National Grid plans electric car power network", 18 February 2018. https://www.ft.com/content/82859d36-14c1-11e8-9376-4a6390addb44
[35] Hogan et al (2018)
[36] BNEF (2017), page 3.

Figure 6: Impact of electric car deployment on global electricity demand, IEA scenario 2DS for 2030



Source: IEA (2017), page 41.

d. Conclusion

Investment in electricity generation and networks should not be a barrier to penetration of EVs and in some countries very little if any investment will be required. The issues that could limit or condition EV penetration lie elsewhere, particularly in the areas of public policy, the approach to the charging network and consumer preferences.

4. Energy sector policies for EV penetration[37]

In a number of European countries, the current taxation and regulation of energy, as well as market design, form barriers to EV penetration and often do not reflect concerns about congestion. Other policies that need review include those related to the choice of charging infrastructure and the promotion of EVs.

a. Fiscal policy[38]

In many European countries, taxes do not fully internalise the negative environmental externalities of gasoil and gasoline. These externalities include not only carbon dioxide, but also NOx, SO2 and especially particulates. For instance, the European Emissions Trading Scheme requires electricity generators and large industrial facilities to purchase and submit emission allowances for each tonne of CO2 they emit; basically this amounts to paying a tax for those emissions. On the other hand, in most countries, there is no CO2 tax paid for emissions from transport, heating and many industrial uses. In this way, fiscal policy favours fossil fuels over electricity. Furthermore, many governments recover the cost of public policies (notably for renewable energy support) through electricity tariffs, even though these policies aim to meet a wider public good. These fiscal policies make electricity more expensive relative to fossil fuels and discourage a shift towards EVs. Good public policy would tax fully the negative environmental externalities and shift policy costs from electricity to general taxes. Optimal taxation of energy should be technology neutral in the sense that it penalises or favours technologies by reference to emissions, not by reference to the specific end market served or the type of energy used.

Fiscal policy should also reflect congestion externalities. These payments may be introduced through city congestion charges, road taxation or vehicle taxes. The implication is that all private vehicles, including EVs, would face payments for increasing congestion and rebates for reducing it.

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[37] In 2017, the Spanish Government named a Committee of Experts to advise on the energy transition. In its report (Spain 2018), most of the analysis of fiscal, tariff and market reform are in line with the recommendations in Section 4 of this Insight.

[38] For a study of fiscal policy reforms to support decarbonisation in Europe, see Robinson et al. (2017) as well as Spain (2018).

The rising cost of fossil fuels (from higher taxation, tighter emission restrictions and higher fossil fuel prices) will penalise the owners of ICEV cars and small trucks. Governments should consider ways to compensate the most vulnerable, for instance via tax rebates, better public transport or in other ways. Support for the SAEV model will also ensure that EVs are not only for the wealthy.

Finally, the penetration of EVs will eventually lead to a decline in revenues from fossil fuel taxes. These revenues must be recovered elsewhere to pay for road and other infrastructure, most likely through congestion charging and vehicle taxes.

b. Electricity Tariff Structure

Current tariff structures do not adequately reflect the variation in wholesale energy prices nor the impact of demand on network congestion and costs. The result is poor signals for shifting demand to periods when electricity prices are low and networks are underutilised; this lack of appropriate signals raises the cost of charging EVs and increases the costs of the electricity system. It can also increase CO2 emissions if the electricity generated at peak is fossil-fired, whereas off-peak energy is renewable.[39]

Furthermore, fixed costs and public policy costs are often recovered through variable charges. This not only provides inefficient signals (in other words, variable charges which are higher than true variable costs discourage consumption), but also encourages consumers to generate their own electricity when cheaper electricity is available from the system, or to leave the system altogether. Regulators should introduce dynamic prices (or at least hourly retail prices) reflecting marginal system costs[40] and introduce tariffs that recover only fixed system costs through the fixed component. This will encourage EV charging in off-peak periods, when system costs and market prices are lower, and reduce the investment requirements to meet electricity demand peaks.

c. Market design

Current design in most countries discourages the sale of distributed energy resources (DERs) – such as V2G services – in local or wholesale markets. Furthermore, wholesale market cost/price signals are not passed on to most retail customers, because wholesale markets and retail price signals are both distorted. Proposed reforms include allowing DER full access to wholesale markets, creating local markets for DER services, with these markets managed by an independent Distribution System Operator, and considering new market structures where prices reflect the value of flexibility.[41]

d. Beyond barriers

Where governments choose to actively support EV penetration, they adopt policies on the supply or demand-side, or on both sides. The Norwegian experience of demand-side subsidies for EVs was successful in terms of EV penetration, but very expensive and favoured the wealthy. The supply-side approach, such as the ZEV mandates in California, imposes less cost on government budgets and appears to favour competition and innovation by vehicle manufacturers. The advantage of the supply-side approach is greatest where it is technology neutral, in the sense that it encourages innovation without the government necessarily choosing a specific technology. Of course, governments may choose other means of achieving sustainable mobility policy goals, including support for public transport, sharing models, the use of bicycles and low-carbon urban planning.

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[39] A recent study by researchers from Harvard and Tsinghua University found that private EVs can have a positive effect on CO2 reduction provided the cars are charged during off-peak hours, allowing for effective use of wind power. Otherwise, EVs can be counterproductive due to the generation of electricity from coal.
https://www.seas.harvard.edu/news/2018/05/environmental-impact-of-electric-vehicles-in-china-it-depends-on-how-they-are-charged

[40] These system marginal costs include not only the changing marginal costs of generation, but also the changing marginal costs of networks (with those costs rising during periods of greater congestion).

[41] See for instance Keay and Robinson (2017).

5. Summary and conclusions

a. Summary

First, EV penetration will certainly increase, but there is significant uncertainty about the pace of change in different parts of the world and the prospects for different EV technologies. Many conditions now favour EVs escaping the lock-in of ICEVs, in particular: growing stringency of emission controls; policies favouring decarbonisation; rising investment and operation costs facing ICEV technology; policies to protect the local environment and public health; technology/cost breakthroughs for EVs; the increased attractiveness of EVs in terms of range (distance) and the number of models; and the commitment by major manufacturers to expand their EV offering and to adopt new business models to increase post sales revenues from connected customers. These factors help to explain why EV adoption forecasts are becoming more ambitious. On the other hand, different policy concerns (especially on congestion and social equity), competition from other vehicle technologies, and changing consumer preferences could limit the growth in the number of EVs. In this context, the SAEV model should gain public policy support because it reduces congestion, lowers the cost of EVs and supports social equity. This model would likely lower the number of EVs on the road, increase the average distance driven (and electricity consumed) by EVs, and speed up the turnover of EVs.

Second, although electricity is obviously necessary for EV penetration, it is not the key driver. As mentioned above, public policy goals, societal changes, competitive costs of alternatives and technology are more important determinants. Nor is it yet clear precisely how EV penetration will affect the electricity sector, especially because this depends on consumer behaviour and the nature of the charging infrastructure, both of which are still unclear in most countries.

Third, analysis here does suggest that investment in electricity generation and networks should not be a barrier to the penetration of EVs, unless public policy goes badly wrong. On the contrary, EVs offer an important source of flexibility, especially for the integration of growing volumes of intermittent renewable energy. However, there is a risk that investment will not occur due to investor concerns about stranded assets, especially in the charging infrastructure. For that reason, governments should provide some guidance about the nature of the charging infrastructure. Failure to do so could discourage investment and slow the penetration of BEVs.

Fourth, in Europe at least, there is an economic case for eliminating existing fiscal, regulatory and market barriers to the penetration of EVs. Even governments that are not actively trying to promote EVs should eliminate these barriers as a matter of good regulatory practice. They should also begin to introduce taxation or other mechanisms to address environmental externalities and congestion, whether from ICEVs, EVs or other vehicles. For governments that wish to go further in their support for EVs, they can choose between many instruments. Demand-side incentives encourage consumers to buy EVs, but are subject to government budgetary discretion. Supply-side policies, in particular ZEV mandates and tightening emission standards, put less pressure on the public budget, while encouraging competition and innovation.

b. Concluding comments on global prospects for EVs

The analysis has focused on Europe, in particular the UK. The diversity of conditions especially outside Europe makes it difficult and hazardous to draw conclusions for specific countries about the prospects for EV penetration or their relationship with the power sector. Nevertheless, it is worth making some general observations about the US and major emerging countries.

First, the US may take a more evolutionary path than Europe, due to higher private vehicle use, longer distances driven in private vehicles (hence the greater concern about EV range), lower cost of gasoline and lower public policy pressure, at least from the federal government. However, the US has hitherto been where the greatest innovation has occurred and it is likely to be at the forefront of driverless vehicles and other innovation; so developments everywhere will be affected by what occurs in the US. It is also noteworthy that US OEM's, in particular GM, have announced that their future is electric.

Furthermore, if EV costs fall substantially, penetration in the US could rise quickly, especially for fleets for which decisions are based on "spreadsheets".

Second, it is even harder to predict EV penetration in developing countries. There are simply too many unknowns and different circumstances to generalise. However, the role of public policy will be key, as will cost. China currently has the world's largest fleet of BEVs; this reflects significant subsidies, which will decline as EV costs fall.[42] The importance of public policy is even more obvious in India, which announced its intention for all vehicles to be electric by 2030, but then later announced in 2018 that it was seeking a target closer to 30 percent.[43]

Third, it is very likely that China and perhaps other emerging countries will manufacture EVs for their own market and increasingly for export. China already has the largest BEV stock in the world and many Chinese equipment manufacturers have announced ambitious plans to scale up EV production.[44] Furthermore, whereas the traditional OEMs want to protect their ICEV markets and to achieve a slow and smooth transition to EVs, most Chinese OEMs are like Tesla in having nothing to lose by going full steam ahead with BEVs. If EVs follow the model of renewable energy equipment, we can expect a significant reduction in EV costs and accelerated global penetration.

Overall, as global penetration increases, we can expect OEMs and other companies – for instance from the energy sector – to develop new business models aimed at supplying services to connected EV customers. This could well mean that EV penetration has a more disruptive effect than many anticipate; perhaps even akin to the impact of renewable energy, which revolutionized the energy sector. It is true that the rapid penetration of EVs is more complicated than the penetration of renewables because the latter was largely a government decision, whereas EV penetration requires decisions by citizens. Furthermore, as explained in this paper, there are many social, technology and policy concerns that condition or limit EV penetration. Nevertheless, as environmental concerns mount, the relative costs of EVs fall and new business models are developed, we may well reach a tipping point after which EVs quickly replace ICEVs. The traditional OEMs and the oil industry may hope that if this happens, the dominant technology will be PHEVs, but this would probably be wishful thinking.

[42] See Ben Dror and An (2018) for more on EV's in China.
[43] See Sen (2018) for more on EV's in India.
[44] IEA (2017), page 24.

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