The Economist INTELLIGENCE UNIT

Cooling: Transporting us to net zero

How efficient, climate-friendly cooling can support the transport sector's transition to net zero emissions

SPONSORED BY KIGALI COOLING EFFICIENCY PROGRAM

Contents

Foreword

Cooling: Transporting us to net zero is an Economist Intelligence Unit (EIU) report that has been commissioned by the Kigali Cooling Efficiency Program (K-CEP). The findings are based on an extensive literature review, an expert interview programme, and economic modelling conducted by The EIU between July and October 2020. The EIU bears sole responsibility for the content of this report. The findings and views expressed do not necessarily reflect the views of K-CEP.

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Jonathan Birdwell – Senior project director
Katherine Stewart – Project director
Diana Hindle Fisher – Project manager
Shivangi Jain – Technical lead
Mrigansh Jain – Economist
Anand Kashyap – Researcher
Audrey Everist – Contributing researcher
Sabika Zehra – Contributing researcher

Interviewees and peer reviewers

Our thanks are due to the following people for their time and insights:

Alasdair King
Drako Motors, Director of Vehicle Engineering

Amandeep Singh
Honda Motors, Chief at Corporate Planning

Brian Van Batavia
Bollinger Motors, Technical Director

Cedric Rouaud
Ricardo, Global Technical Expert, Thermal Systems

Dominik Fries
Evum Motors, Head of Business Development

Darren Palmer
Ford Motor Company, Global Product Development Director, Ford & Lincoln Battery Electric Vehicles

Jeff Bozeman
General Motors, Vehicle Performance Owner

Kristen Taddonio
Institute for Governance & Sustainable Development (IGSD), Senior Climate and Energy Advisor

Peter Fussey
Ricardo, Technical Authority, Propulsion Control

Robert Morgan
University of Brighton, Professor

Shyamasis Das
Electric mobility expert

Stephen Andersen
Institute for Governance & Sustainable Development, Director of Research

Timothy Craig
Melrose Technologies LLC, Owner, Lead Technical Consultant

Toby Peters
University of Birmingham, Professor of Cold Economy

Yulong Ding
University of Birmingham, Director of Birmingham Centre for Cryogenic Energy Storage

For any enquiries about the report please contact:

Diana Hindle Fisher
The Economist Intelligence Unit London, United Kingdom
E: dianahindlefisher@eiu.com

About the Economist Intelligence Unit

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About the Kigali Cooling Efficiency Program (K-CEP)

The Kigali Cooling Efficiency Program (K-CEP) is a philanthropic collaboration launched in 2017 to support the Kigali Amendment to the Montreal Protocol and the transition to efficient, climate-friendly cooling solutions for all. K-CEP works in over 50 countries in support of ambitious action by governments, businesses and civil society. K-CEP's programme office, the Efficiency Cooling Office, is housed at the ClimateWorks Foundation in San Francisco.

Introduction

In 2018, the Intergovernmental Panel on Climate Change (IPCC) announced that to limit global warming to 1.5°C, global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45% from 2010 levels by 2030 and reach "net zero" by around 2050.[1] In practice, meeting this target requires all sectors to shift away from oil, gas and coal while also removing CO_2 from the atmosphere.[2,3,4]

In the transport sector, most of the emissions reductions will fall to on-road passenger transport, which is easier to decarbonise than aircraft and freight ships. If the electricity that charges an electric vehicle (EV) is generated from renewables, driving a fully electric vehicle produces no emissions post-manufacturing.[5] As countries decarbonise electricity, EVs present a net zero solution for getting both people and goods from point A to point B. But concerns over cost, range and charging infrastructure are preventing mass uptake by consumers. At the core of the problem lies the vehicle's battery and its range.

This report focuses on how more efficient cooling can extend EV battery range. Based on an extensive modelling exercise, it quantifies how efficient cooling also reduces costs and emissions. Finally, it outlines priority actions to ensure that the contribution of efficient cooling to increasing EV uptake and speeding up the race to net zero can be realised.

Key findings

- Cooling requirements can cut EV battery range by up to 44%. The range of an EV in the US may be reduced by almost 185 kilometres (km, almost 115 miles) on a single charge when using cooling equipment compared with when there is no cooling.
- It can cost 80% more to recharge an EV battery in warm climates over the course of a year due to the additional electricity required for cooling.
- In trucks with refrigerated units, where cooling accounts for a much lower proportion of the overall electricity requirements than in a car, cooling can reduce the range of the battery by almost 23km for each charge. This translates to an increase in operating costs of almost US$1,500 each year.
- More *efficient* air conditioning (AC) units can extend the range of EV cars and trucks by up to 38% and reduce operating costs by up to 28%.
- Using materials and design that keep EVs cooler naturally can extend the range of EV cars by up to 16% in hot climates and reduce operating costs by up to 14%. Similar measures can improve the range of EV trucks and reduce operating costs by up to 2%.
- Installing better insulation in refrigerated trucks can improve their range and reduce operating costs by up to 5%.
- Lower operating costs from efficient cooling could drive a 7% uptick in EV sales. Furthermore, this is likely to underestimate the sales impact: as consumer anxiety over range falls, it is likely that more people will purchase EVs.
- Efficient cooling reduces EV electricity use and increases uptake, which in turn collectively reduces emissions. In China, efficient cooling in EVs has the potential to cut emissions by 58MTCO$_2$ over the next decade. Of the emissions that could be avoided in China, 72% would have been from coal-fired generation, 22% from oil and 5% from gas, with only 1% from renewable energy.[6]
- While efficient cooling alone cannot meet the transport industry's zero emissions targets, it is certainly a critical component of the path to net zero.

To remain competitive in a zero emissions world, the car and truck industry needs to invest in electric vehicles

Cars are critical to many people's lives: by making it possible to move from one place to another, they provide people with autonomy. This is particularly true for those living in rural areas and for marginalised groups (including the elderly and disabled) who have limited access to public transport, and for whom cars may be the only option for independent mobility. The majority of vehicles on the road today use an internal combustion engine (ICE) that burns fuel – typically petrol or diesel – to release energy to power the engine.[7] Today there are approximately 1.1bn cars on the road.[8]

Advancements in electric vehicles (EVs), however, are disrupting the automotive market. Unlike ICE ("conventional vehicles"), EVs use electricity stored in a battery to power an electric motor, which turns the wheels of the car. To power the battery, EVs are plugged into a charging point and take electricity from the grid.[9] There are two basic types of EV: battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEVs).[10] BEVs run purely on electricity, whereas PHEVs combine the use of an ICE with an EV battery. They run for a short distance (approximately 26 miles)[11] on electricity and then switch over to the ICE. [12]

Most vehicles can be electric, including passenger cars; buses; light commercial vehicles that transport goods and passengers for commercial purposes; medium- and heavy-duty trucks;[13] and refrigerated trucks, which include a refrigeration unit on the back.

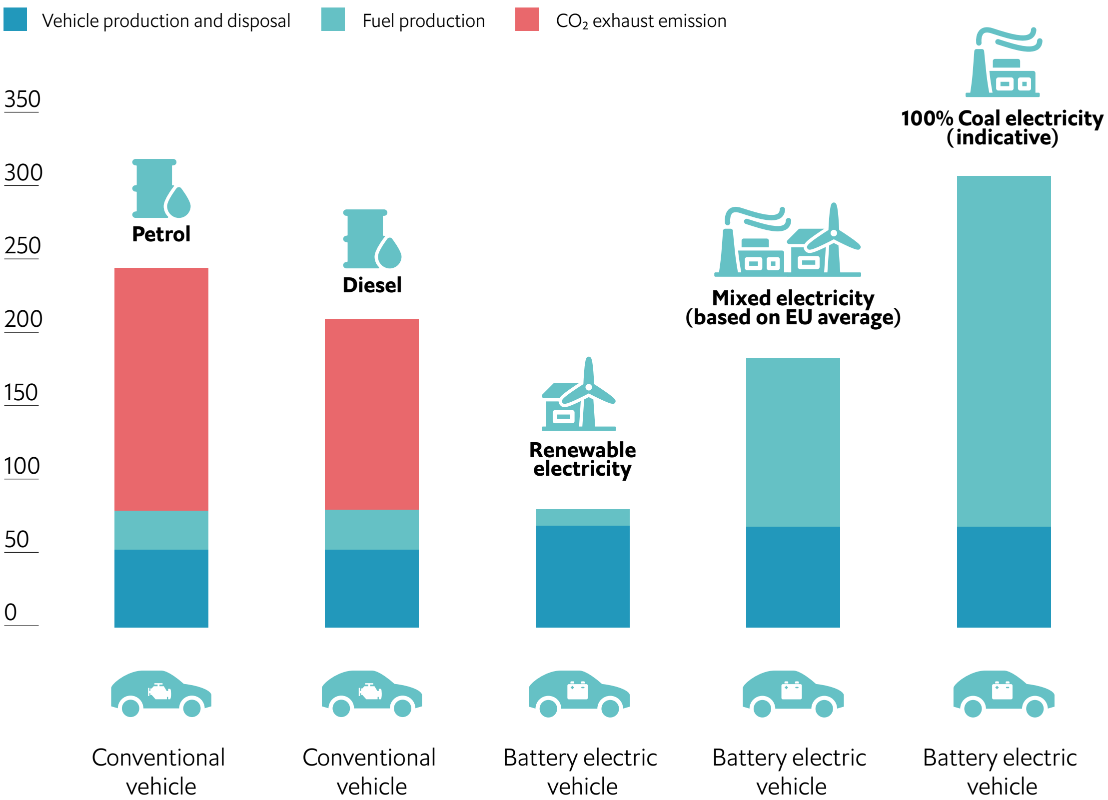
The environmental case for EVs

Driving cars comes at a cost to the environment. Emissions are created not just when the car is driven, but along the whole production process. As with conventional vehicles, the manufacturing of EVs – including the battery – contributes to emissions. If the electricity that charges the battery is generated from fossil fuels – oil, gas or coal – then EVs can contribute to emissions too.[14]

When it comes to actually driving the car though, fully electric vehicles produce no emissions.[15]
In comparison, when you drive a conventional vehicle, the process of burning petrol or diesel creates both air pollutants, which contribute to smog and health problems, and greenhouse gas emissions, which contribute to global warming.[16]
As countries decarbonise electricity to support the commitment to net zero emissions, EVs present a net zero emissions solution for getting both people and goods from one place to another.

The full picture

CO_2 emissions for different vehicle and fuel types (2015, g/km)



Source: EEA[17]

EV uptake is critical to meeting net zero goals

As of October 2020, a total of 120 countries have now signed up to meet net zero emissions by 2050. Moreover, 452 cities, 22 regions, 1,101 businesses, 45 of the biggest investors, and 549 universities have joined the Race to Zero campaign – an initiative to mobilise actors outside of national governments to commit to net zero emissions.[18]

In 2019, the transport sector accounted for 24% of CO_2 emissions from fuel combustion, and road vehicles accounted for nearly three-quarters of all transport emissions.[19]
A net zero pathway for the transport sector requires a two-thirds reduction in total energy use and a transition of over 50% of transport energy use to hydrogen or zero-emission electric energy by 2050.[20] Most of the emissions reductions in the transport sector will fall to on-road passenger transport, which is easier to decarbonise than aircraft and freight ships. Aircraft and freight ship emissions will need to be offset by other reduction measures.[21] Since many vehicles have long lifespans, on-road transport needs to phase out fossil-fuel-consuming vehicles now.[22]

Net zero policies are driving uptake in EVs

Governments can set targets for the emissions of new vehicles, with the aim of limiting the amount of CO_2 emitted. The Norwegian government has announced that all new passenger cars and light commercial vehicles should be zero-emission vehicles by 2025.[23] In June 2020, California set its first ever emissions-free target for trucks. The Advanced Clean Trucks Regulation mandates that truck manufacturers meet targets on the percentage of sales of zero-emission trucks from 2024.[24,25] As recently as November 2020, the UK introduced a ban on new sales of petrol and diesel cars from 2030.[26]

Alternatively, policymakers can offer financial incentives to consumers who might be unable to afford EVs, which are typically more expensive than conventional vehicles. In May 2020, France announced that buyers can receive up to €1,200 to put towards purchasing an EV.[27] In China, subsidies currently range from approximately US$2,350 to $3,265, depending on the car.[28] In California, the Clean Cars 4 All programme retires lower-income consumers' older, higher-polluting vehicles and upgrades them to a lower-emissions option.[29]

At the local level, authorities can introduce urban emission policies that restrict access of high-emissions vehicles to certain areas. This restriction makes it either more costly or illegal to drive in those areas, and encourages a shift to EVs. In April 2019, London launched the 24-hour Ultra Low Emissions Zone, which sets an emissions standard for vehicles entering into the zone. If vehicles do not meet the standard they incur a daily fee of £12.50.[30,31]

Demand for EVs is rising

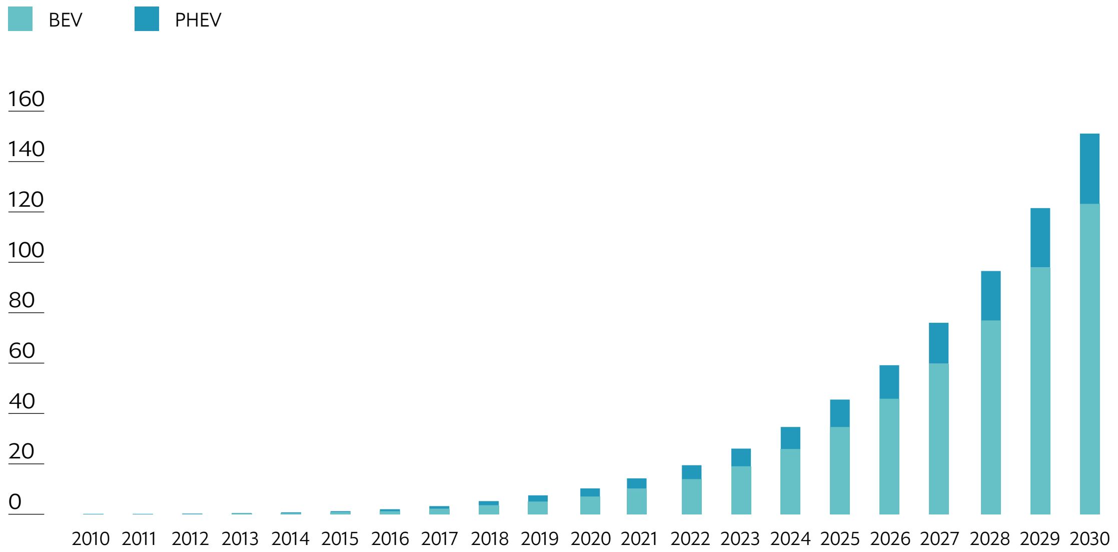
Cars

Globally, the number of light EVs (electric passenger cars and electric light commercial vehicles) on the road has grown at an average rate of 100% each year from just over 10,000 in 2010 to 10.2m in 2020. In 2010, EVs accounted for just 0.01% of sales in the light vehicle market. They now account for 3.7%, a figure expected to grow to over one-third (34.8%) of all sales by 2030.

China has seen the most rapid growth in EV sales: a 104% increase on average each year between 2010 and 2020,[32] driven by policymakers setting EV targets and launching the EV subsidy scheme in 2009. While the annual rate of growth is expected to slow to 25% over the next decade, China is still expected to account for 39% of total global EV sales by 2030.

Accelerating demand

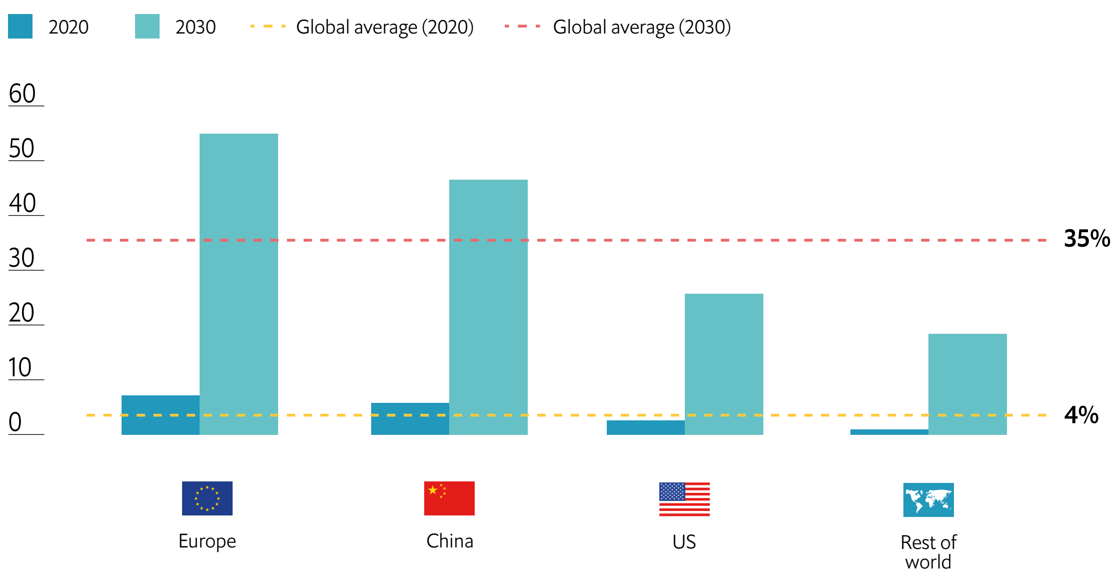
Global BEV and PHEV light vehicles stock (2010-2030, EV car stock millions)



Source: EV Volumes, EIU analysis

Taking the market by storm

Market share of EVs in total light vehicle sales by country (2020 and 2030, %)



Source: EV Volumes, EIU analysis

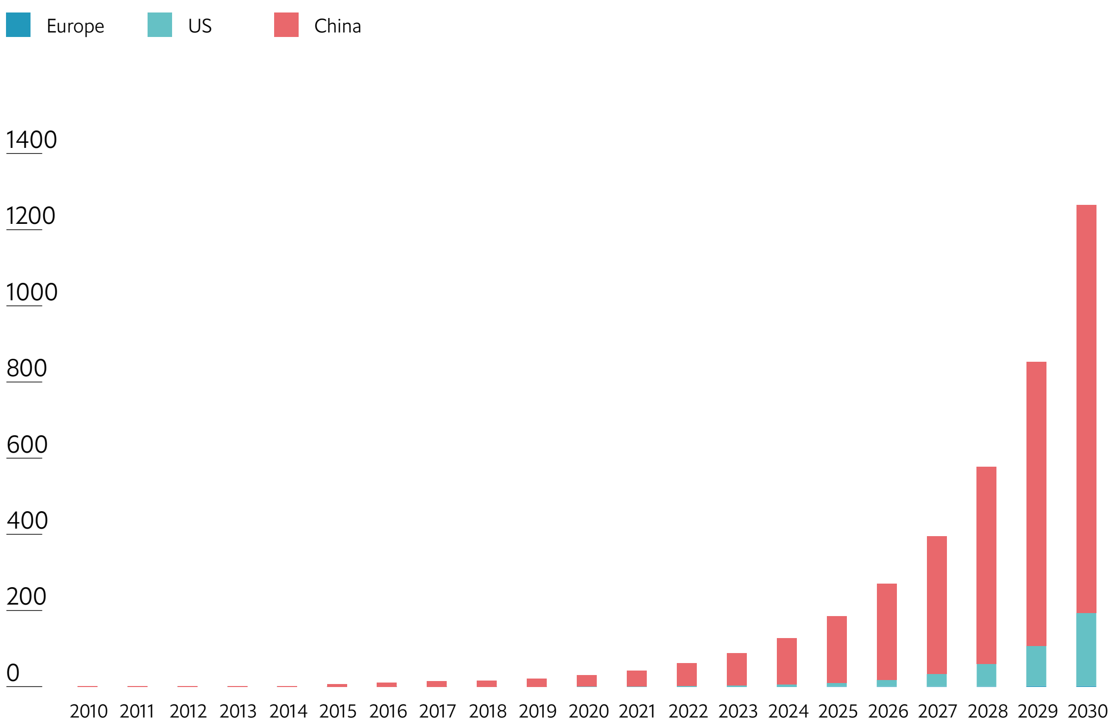
Trucks

In the trucks market (5% of which are refrigerated), EVs still account for only a tiny share of the market: 0.2% of the total stock of trucks in China and 0.01% in the US.[33]

Sales of medium- and heavy-duty trucks are expected to see rapid annual growth (44% in China, 80.5% in the US and 18.5% globally) out to 2030.[34] However, by 2030, electric trucks will still account for only 5.5% of the total truck stock in China and 2.5% in the US.

Slow and steady

Medium- and heavy-duty electric truck stock* by country (2010-2030, Electric truck stock 000s)



* Note: Includes trucks with and without refrigeration units.

Source: IEA, P&S Intelligence, Mordor Intelligence, EIU analysis

Low running costs and sleek design are also driving EV uptake

EVs are appealing not just to policymakers; their popularity is increasing among consumers. According to a global survey by AlixPartners in 2019, "consumers' interest in electric vehicles is high, with half saying they're interested in owning one, and more than a quarter saying they would purchase one as their next vehicle."[35]

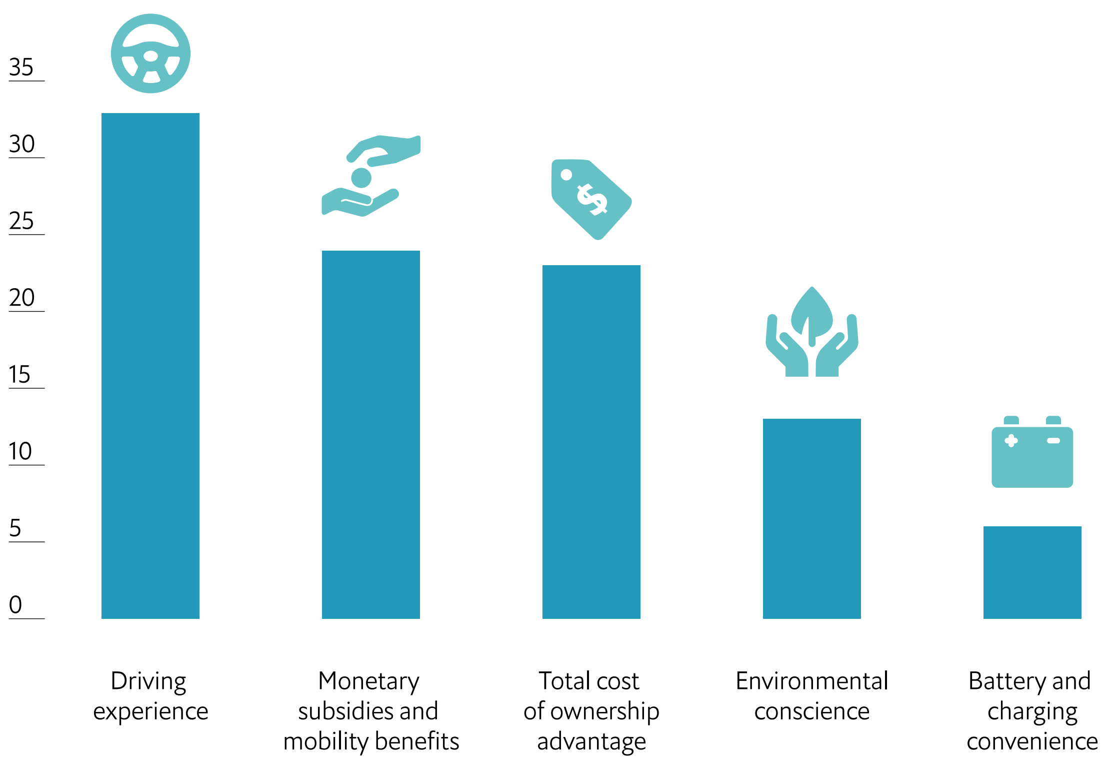
Interest from consumers stems from more than a desire to be more environmentally friendly. A 2020 SSMT survey found that, in the UK, drivers are most attracted to the lower running costs (41%).[36] In the UK, on average, an EV costs about £2 to drive 100 miles, compared with £11.60 for a conventional car.[37]

Over time these savings can add up: a US Department of Energy National Renewable Energy Laboratory (NREL) and Idaho National Laboratory study estimated that over the 15-year lifespan of a vehicle, cost savings from an EV could add up to as much as $14,480 in the state of Washington.[38] There are also maintenance savings. EVs have fewer moving parts; they do not require oil changes and the brakes require less upkeep due to the braking system putting less pressure on the brake pads.[39]

EVs also offer an improved driving experience. A 2020 survey by NewMotion noted that 58% of respondents cited the driving experience and technology of EVs as a reason for switching from an ICE.[40] EVs give improved acceleration, and the distribution of the batteries and low centre of gravity enable greater comfort and safety.[41] Darren Palmer, Global Product Development Director at Ford, explains that "the number of people buying an EV because of the environmental benefits has hit its natural level in some parts of the world. The next group of people to target are people who appreciate the driving experience – the space inside, the speed and the digital technology and connectivity."

Consumer preferences

Benefits perceived by consumers who considered EVs in their last purchase (2019, % of respondents)



Source: McKinsey EV Consumer Survey 2019[42]

The car and truck industry needs to invest in EVs to remain competitive

EVs are disrupting the auto industry from design to dealership. They require less, and different, maintenance, and manufacturers are not able to capitalise on an existing supply chain advantage.[43] Tesla was founded in 2003 and designed its first car from the ground up – launching it by 2008.[44] Its share price has since far exceeded that of all other carmakers and is more commonly compared against the likes of Netflix, Amazon and Apple.[45] Tesla wants to make 20m EVs a year by 2030 – over 50 times what it produced in 2019.[46] Traditional auto giants, such as Volkswagen Group, General Motors (GM) and Ford, are having to rethink their business models or face being forced out of the market, just as Kodak was with digital cameras and Blockbuster was with online film platforms.

Traditional car manufacturers are waking up to the fact that they need to produce EVs to remain competitive. Volkswagen has invested more than US$40bn in a goal to sell 28m EVs by 2028.[47] GM is investing $27bn in electric and autonomous technologies, building a US-based battery plant, and is working on the development of a battery with a range of 450 miles.[48] Ford is due to release an all-electric version of the popular Mustang model in 2021.[49]

COVID-19 and EV cars

As lockdown measures ground daily commuting, travel and general mobility to a halt, the automotive industry took a particularly big hit and car dealerships were forced to close.[50,51] The IEA forecasts overall sales in 2020 to be at least 15% lower than the previous year.[52]

While the wider car market has struggled, the EV car market has been better able to withstand the impacts of the pandemic. EVs could achieve a record share of market sales of 3% in 2020.[53]

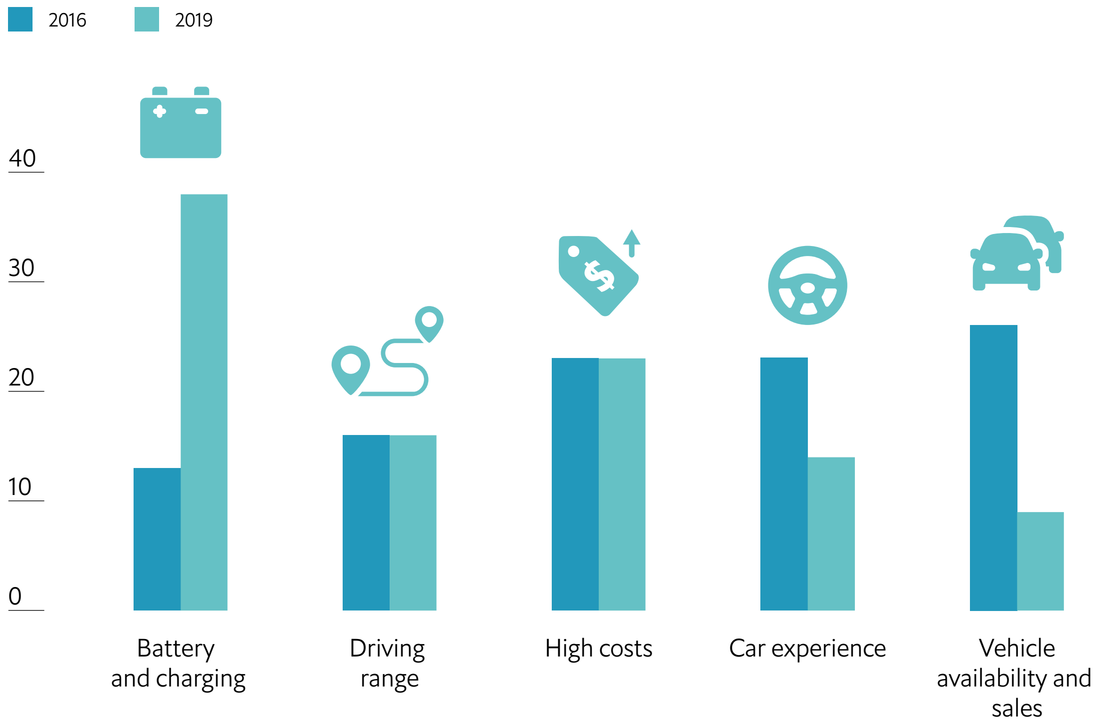
In Europe, EV sales between January and April were almost 90% higher than in 2019.[54] The continued growth has been supported by emissions standards, the availability of purchase subsidies, and the tendency for EV consumers to be wealthier than many drivers of conventional cars and, for the most part, less affected by the economic effects of the pandemic.

Concerns over cost, battery range and charging infrastructure are holding consumers back

Despite the benefits and growth predictions, EV uptake is not increasing as fast as it could. Consumers are put off by upfront cost, battery range and charging infrastructure.

Changing perceptions

Concerns perceived by consumers who considered EVs in their last purchase (2016 and 2019, % of respondents)



Source: McKinsey EV Consumer Survey 2016 and 2019[55]

An average EV passenger car costs between US$35,000 and $103,000

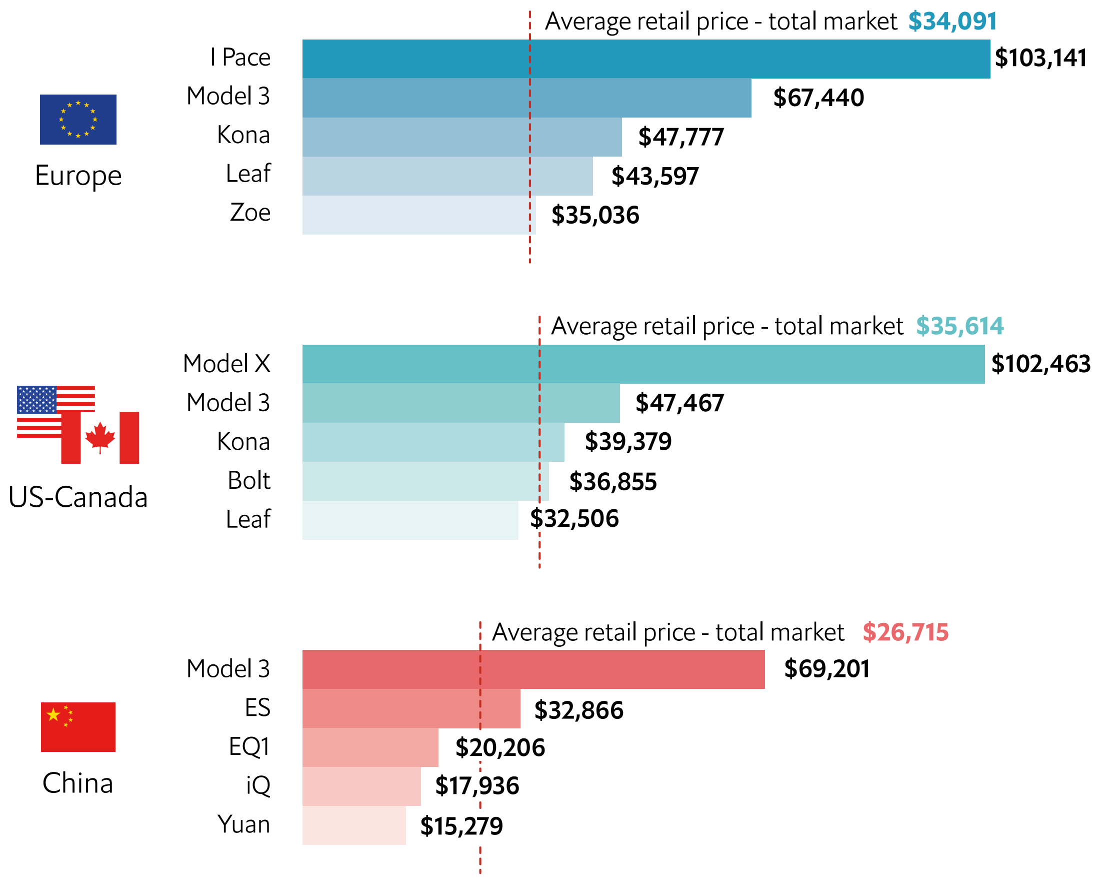
Outside of China and Norway, where EVs have been heavily subsidised, the additional cost of purchasing an EV has been a major concern for consumers. In one study, more than two-thirds of respondents claimed that they would purchase an EV if the cost was the same as that of a conventional car.[56] In 2019, the average price of all new cars sold in Europe was $34,091 per unit,[57] whereas the price of the most popular BEV models varied from $35,000 and $103,000.[58]

Shyamasis Das, an electric mobility expert based in India, explains that, "Despite lower operating costs, the general public is more used to the notion of price tag, they give less weight to savings in fuel costs in their purchase decision-making; they think about upfront cost and if they see a bigger price tag, they will be less interested."

The main cost differential between an EV and a conventional car is the cost of the battery. Despite decreasing (by 87% in real terms from 2010 to 2019[59]), the battery cost is still a major driver of the cost of EVs.

Price comparisons

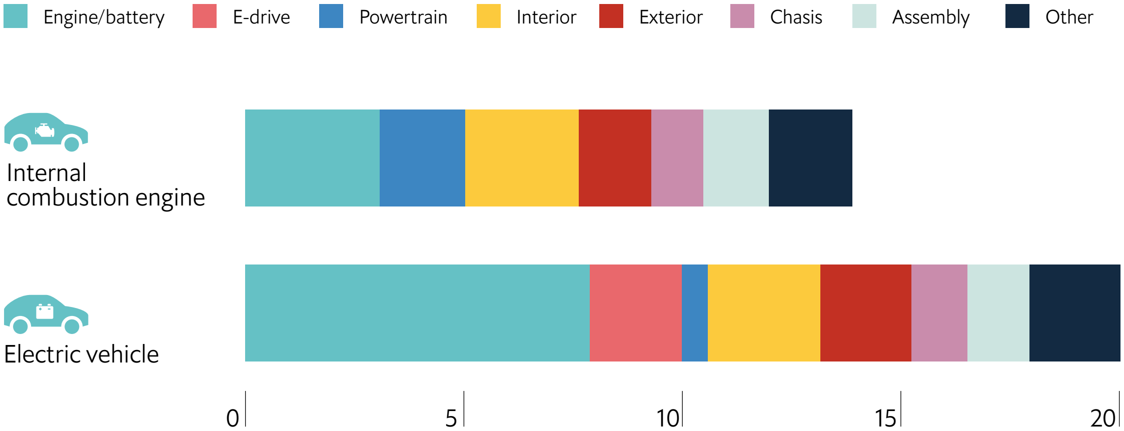
Average price of a conventional car compared with an EV (2019)



Source: JATO[60]

Production costs

Cost to produce an EV versus a conventional car in Europe (2020, estimated costs €000s)



Source: FT[61]

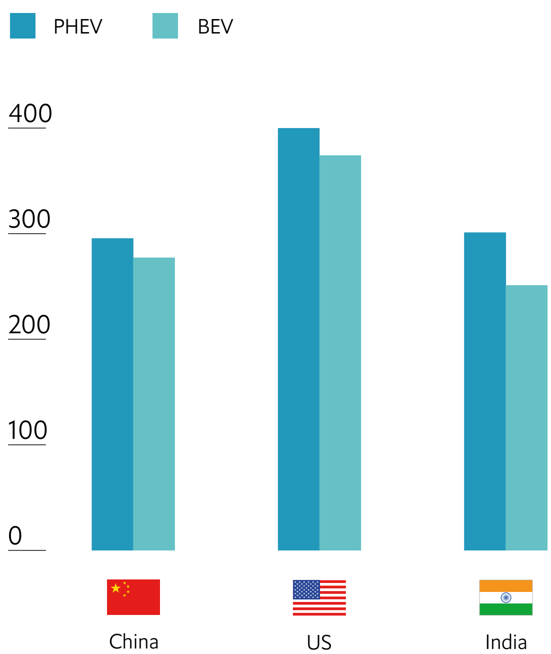
The average EV in the US runs 374km before recharging

In an EV, the battery determines how far the vehicle can travel on a single charge. This is called the range. In a conventional vehicle, battery range is not a concern. A tank full of petrol or diesel can keep a car going for up to 1,000km.[62] In comparison, our analysis of EV battery capacity and electricity use shows that EVs can travel, on average, 374km before needing to recharge.[63,64] Driving a Tesla is a different story, however – the model S, for example, advertises a battery range of 650km.[65] But even a Tesla cannot achieve the distance of an ICE.

Most consumers drive a much shorter distance per day than the total range offered by a fully charged BEV, particularly in cities.[66] But battery range still matters to consumers: people worry about their EV running low on power with no charge point nearby, or so-called "range anxiety".[67] A 2020 McKinsey report states that consumers frequently ask when purchasing an EV: "Will the battery capacity provide the driving range that I need?"[68]

How far can they go?

Average range of EV cars by country (2020, Km per battery charge)



Source: EIU analysis based on multiple sources

A 2019 survey reported that "more than half of all prospective car buyers agree that lower purchase prices and longer driving ranges would be most effective in increasing their interest in getting a Plug-in EV."[69]

The size of the battery pack and the amount of electricity the vehicle requires determine potential range.

The amount of electricity needed depends on vehicle-specific factors – such as the weight and design of the vehicle – and location-specific factors – such as the outside temperature. On average, the larger battery capacity of vehicles sold in the US market allows for a greater driving range compared with that of China and India.

Methodology note

The EIU estimates the average range of EVs across countries based on the average battery capacity of vehicles sold in each market (using data provided by EV-Volumes.com) and estimates of the cooling requirements per kilometre of travel. It is assumed that under normal driving conditions (with an ambient temperature of 10–25°C), an average EV requires approximately 0.2 kWh per km.[70] In the case of trucks, we assume that, on average, an electric truck requires approximately 1.44 kWh per km due to its weight in comparison to light vehicles.[71] With additional electricity requirements for refrigeration, trucks fitted with a transport refrigeration unit (TRU) are assumed to consume 1.57 kWh per km. See the Methodology section of this report for further detail on the methodology and assumptions used in the analysis.

EV charging points are a concern for consumers

In 2019, there were about 7.3m chargers worldwide, of which around 6.5m were private, light-duty vehicle slow chargers in homes and workplaces.[72] This gives rise to concern about access to charging, despite rapidly expanding infrastructure. In a 2019 survey, almost 50% of respondents stated that they would consider an EV if charging stations were as abundant as conventional fuel stations. Nearly as many claimed that they "lack the ability to install a charger at home, which puts a large dent in their interest in buying a battery EV".[73]

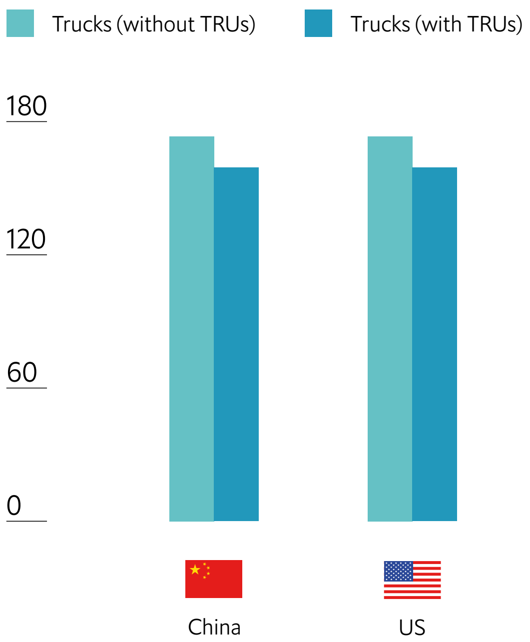
Another survey of US consumers found that, after cost, a lack of charging stations (56%) remained the top concern posing a primary barrier to purchase.[74] Shyamasis Das explained that, "right now people are used to going to a petrol station to refill the tank, and they see refueling stations everywhere. In case of EVs they are just yet to see charging points in the same density."

Trucks bring additional challenges

The challenges that hinder uptake of EV cars – cost, battery range and charging infrastructure – apply to an even greater extent to EV trucks. EV trucks require more power, which results in greater limitations around battery range and purchase cost. They also take longer to charge and require increased flexibility around charging. This is a particular problem for long-haul trucks, which are required to travel long distances but have an average range of less than half that of an EV passenger car.[75]

Short journeys

Average range of EV trucks by country (2020, Km per battery charge)



Source: EIU analysis based on multiple sources[76]

The cost of the required electricity to charge an EV truck is a concern for uptake, particularly as purchasers tend to be companies that want to keep operating costs low. A study by the European Federation for Transport and Environment (T&E) states that "the biggest sensitivity to cost competitiveness [of an EV truck compared with a conventional truck] is the electricity price."[77] Brian Van Batavia, Technical Director at Bollinger Motors, explained that "Commercial truck operators do understand the costs of electricity and costs of fuel. They have other different requirements to cars too – e.g. they need specialised infrastructure to accommodate hundreds of vehicles charging at the same time."

Battery range is tied to all of these concerns

At the root of the challenge with EVs – both cars and trucks – is battery range. If batteries were less expensive, range issues could be solved by adding more battery capacity to the car. But even though battery costs are due to fall – from the current average cost of €8,000 to approximately €4,300 by 2030 for a 50 kWh battery – doubling or tripling battery capacity while also making EVs more affordable will not be possible.[78] Improved range would mitigate concerns about access to charging stations, and operating costs would fall as vehicles are refuelled less frequently. So, while incentives and congestion zones are important for EV uptake, the battery sits at the centre of the discussion.

The use of cooling can impact battery range by up to 44% in an EV car and up to 13% in a refrigerated truck

Keeping cool in an EV car

Comfortable passengers

In any car, both the driver and passengers need to be comfortable. Comfort is determined not just by cushioned seats and spacious interiors, but by satisfactory air temperature and humidity.[79] Typically, people are most comfortable in a temperature range of 20–22°C.[80]

Discomfort in a vehicle has implications: it can impact consumer perceptions of the vehicle brand, but, more importantly, it affects health and safety. This is a particular risk when someone is driving long distances or for long periods of time in high temperatures.

Taxi drivers, who drive many hours a day, can suffer from dehydration in high temperatures, putting both themselves and their passengers at risk. Studies have found that increased ambient temperature correlates with decreased driver performance,[81] and heightens the risk of car accidents.[82] A study conducted in Spain found that the risk of motor vehicle crashes significantly increased during heatwaves.[83]

Opening the car windows is not always a solution. Dr Stephen Andersen, Director of Research at the Institute for Governance & Sustainable Development (IGSD), states that "most cars are not designed to drive easily with windows down due to wind resistance and turbulence. For safety, silence and comfort people put windows up and put AC on."

Operational power electronics and functional batteries

In an EV car, the need for cooling moves beyond just the passenger. The power electronics – the system that takes electricity from the battery to power the motor to turn the wheels – need to be maintained within a certain temperature window (on average 50°C, according to Jeff Bozeman, Vehicle Performance Owner at GM).

If that were not enough pressure on the cooling system, the electric battery in an EV needs to be kept within a temperature range of 20–30°C. Cedric Rouaud at Ricardo explains that "the battery needs to be maintained at around 25°C, not too dissimilar to the human body which is most happy at 21°C. Due to the need to keep the battery cool, we call the battery a fifth passenger."

If the battery becomes too cold, the chemical reactions start to slow, reducing battery performance and therefore the range of the EV.[84] If the battery becomes too hot, it starts to deteriorate and, at extreme temperatures, may be at risk of explosion[85] and irreversible damage.[86] Therefore, EVs require cooling systems that can ensure that the battery remains within the temperature window.

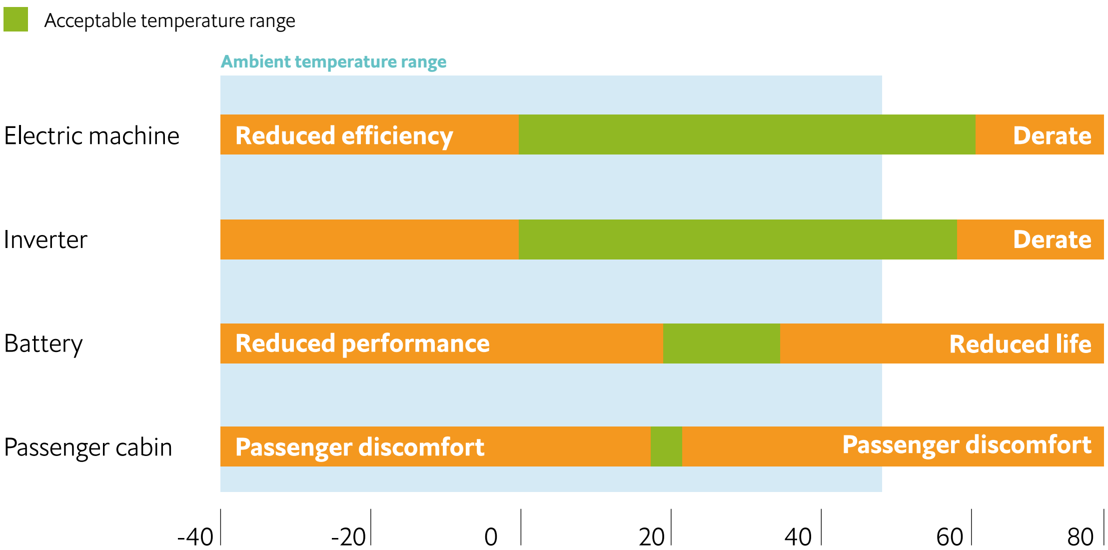
Darren Palmer, Global Product Development Director for Ford and Lincoln BEVs, notes that it is in the interests of car manufacturers to protect the battery since they provide warranties of up to eight years: "car manufacturers will not build a system that allows the battery temperature to get out of control – they simply would not allow it."

Combining all these cooling needs

The multiple cooling needs in EVs create challenges for manufacturers. Robert Morgan, Professor of Thermal Propulsion Systems at Brighton University, explains that it is important to think not just of cooling but of broader "temperature management". He says that "it is not just about keeping a device cool, it's about keeping it at the right temperature – it's as bad to over-cool something as it is to under-cool something."

Keeping cool

Different temperature requirements of different parts of an EV (°C)



Source: Ricardo

The use of cooling drastically reduces EV range

In a conventional car, petrol or diesel provides power to the AC system. Turning on the AC burns fuel, generating financial costs to the driver and environmental costs in the form of emissions. However, the amount of fuel consumed does not fundamentally impact the distance the vehicle can travel on a single tank of fuel. In contrast, turning on the AC in an EV can have a material effect on the battery capacity and range.

The advertised battery range for a new car is certified in a laboratory and generally does not account for real road conditions relating to heating and cooling. Dr Stephen Andersen describes this as "a false metric". Real road conditions differ from laboratory testing conditions and, according to Dr Andersen, the battery range advertised often differs drastically in practice.

In the summer months, the power requirement to cool the cabin and the battery in 30°C temperatures reduces the battery range by about

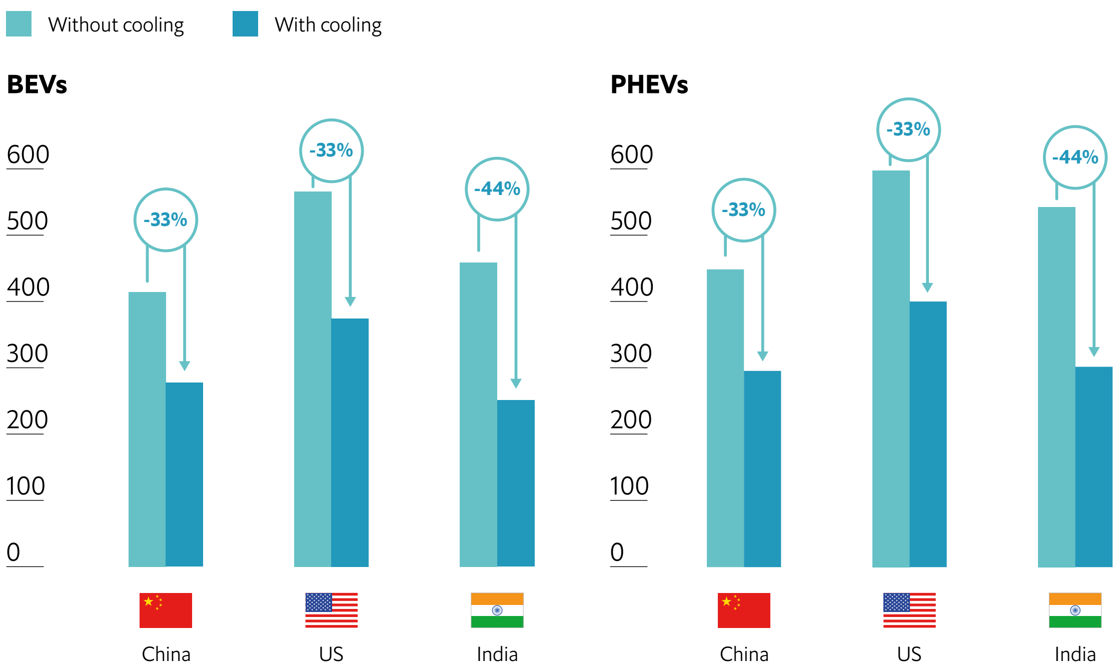
25%, according to Cedric Rouaud. In a Nissan Leaf, which is advertised to have a 270km range,[87] this can fall to 200km. In even higher temperatures of 40–45°C, the cooling requirement can reduce the range by half.[88] If an EV is parked in the sun in the midday heat, starting it up will require additional electricity, reducing the battery range before the vehicle is even in motion.

At the country level, our analysis shows that the reduction in range can be particularly significant in hot countries. Where average temperatures range between 10°C and 25°C – in China and the US, for example – the use of cooling in light EVs could reduce vehicle range by 33% for both BEVs and PHEVs.[89] By comparison, in hotter climates such as in India where the requirement for cooling is greater, the range could be reduced by up to 44%.

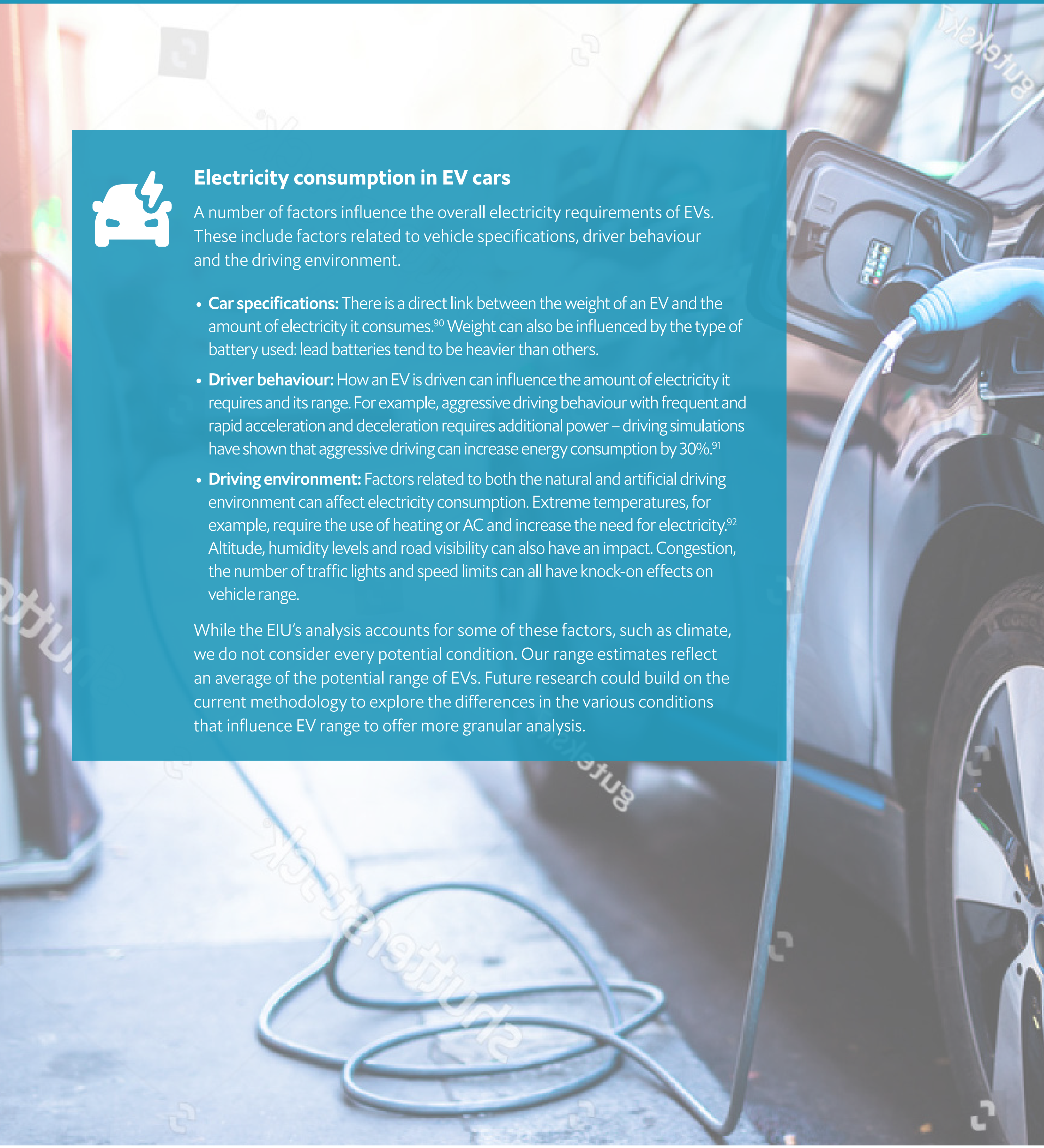
Most consumers are unaware of the impact of cooling on battery range. Cedric Rouaud claims that "they just have not been warned about it." This lack of knowledge exacerbates "range anxiety" because the range can drop at a fast rate unexpectedly. Furthermore, range gauges are not always particularly accurate. According to Darren Palmer, EV gauges have been too simplistic and have not taken into account the real conditions on a journey, and have therefore contributed to range anxiety.

Covering less ground

Average range reduction from the use of cooling in light EVs by country (2020, km per battery charge)



Source: EIU analysis based on multiple sources



Electricity consumption in EV cars

A number of factors influence the overall electricity requirements of EVs. These include factors related to vehicle specifications, driver behaviour and the driving environment.

- **Car specifications:** There is a direct link between the weight of an EV and the amount of electricity it consumes.[90] Weight can also be influenced by the type of battery used: lead batteries tend to be heavier than others.
- **Driver behaviour:** How an EV is driven can influence the amount of electricity it requires and its range. For example, aggressive driving behaviour with frequent and rapid acceleration and deceleration requires additional power – driving simulations have shown that aggressive driving can increase energy consumption by 30%.[91]
- **Driving environment:** Factors related to both the natural and artificial driving environment can affect electricity consumption. Extreme temperatures, for example, require the use of heating or AC and increase the need for electricity.[92] Altitude, humidity levels and road visibility can also have an impact. Congestion, the number of traffic lights and speed limits can all have knock-on effects on vehicle range.

While the EIU's analysis accounts for some of these factors, such as climate, we do not consider every potential condition. Our range estimates reflect an average of the potential range of EVs. Future research could build on the current methodology to explore the differences in the various conditions that influence EV range to offer more granular analysis.

Cooling adds costs

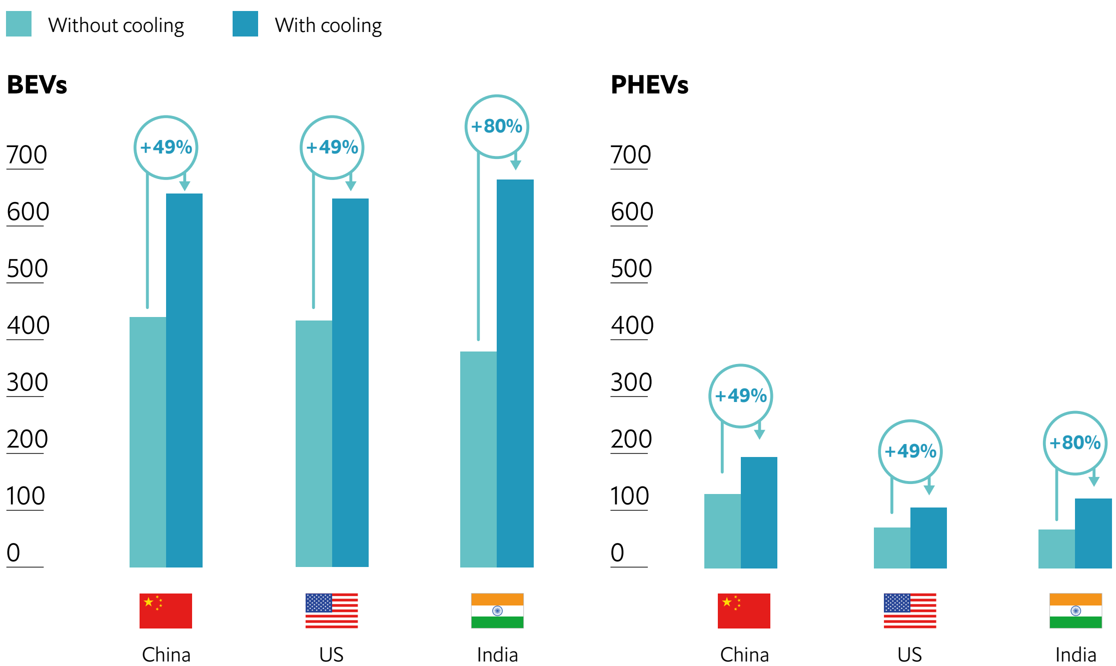
The additional electricity required for cooling also adds cost. Our analysis shows that, without the need for cooling, the annual cost of recharging the battery in a BEV amounts to approximately US$440 in China and $430 in the US; however, the need for cooling can increase these costs by almost half (49%). In India, where annual charging costs are lower than in China and the US, cooling needs could increase these costs by 80%.

+49%

The need for cooling can increase the cost of recharging a battery by almost half.

The cost of cooling

Average operating costs from the use of cooling in light EVs by country (2020, $ per year)



Source: EIU analysis based on multiple sources[93]

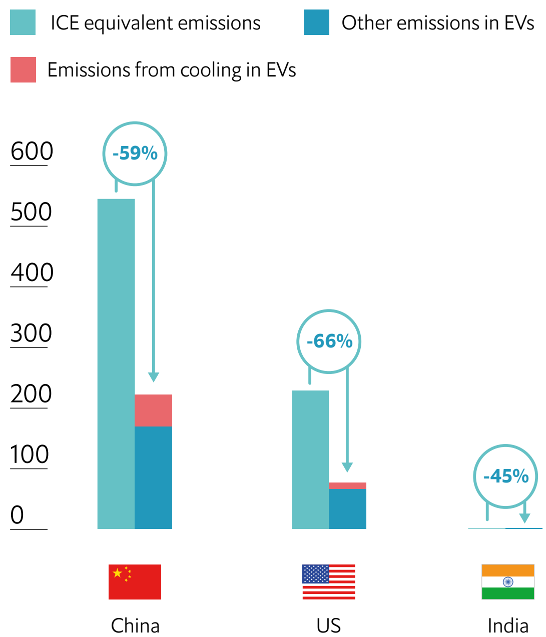
Charging EV batteries can contribute to emissions

Electricity requirements for cooling increase total electricity consumption by EVs. Between 2020 and 2030, BEV and PHEV light vehicles in China will require electricity generation of 1,130 TWh, a third of which will provide cooling. Electricity requirements in the US and India, where the EV market is smaller, will be 280 TWh and 4.1 TWh, respectively, over the same period. One-third of this electricity will provide cooling in the US, while 44% of it will provide cooling in India.

Electricity requirements for cooling can feed through to emissions if the electricity used to recharge the battery is generated from fossil fuels – in other words, oil, gas or coal. Across China, the US and India, cooling requirements are likely to account for 24%, 14% and 44% of total environmental emissions from light EVs between 2020 and 2030, respectively.

The environmental burden of cooling

Total emissions from light EVs by cooling contribution (2020-2030, $MtCO_2$)



Source: EIU analysis based on multiple sources

Heating in an EV

A major difference between conventional vehicles and EVs is the way in which heating functions. In conventional vehicles there is a supply of waste heat from the engine that can be used to heat the cabin. In an EV, the quality of the heat from the battery is not good for climate control so heaters are needed.

Car manufacturers are focusing on the role of heat pumps – which use an AC system to provide heating – to solve heating challenges. While the focus of this report is on the role of cooling, making EV heating more efficient should also be a priority for the car and truck industry.

Keeping cool in an EV truck

Keeping passengers cool is no different

Trucks are larger and heavier than cars. Their additional weight means they require additional power to move, so their battery capacities are bigger. In trucks without TRUs, cooling is required to cool only the passenger cabin, the battery and the power electronics, as in a car. As a result, cooling requirements as a proportion of the overall electricity requirement are smaller than in light EVs. A transport expert at a major foundation explains that "cabin cooling in a truck is not that big of a deal. And probably easier than for cars – you have more space to put batteries and truck manufacturers can buy the same cooling units that are being made for cars so can take advantage of the product developments."

Refrigerated trucks need at least 10% more electricity for cooling

Trucks with TRUs, however, pose a serious cooling challenge. They have a refrigeration unit that cools the cargo space to the necessary temperature to allow temperature-sensitive goods such as food or vaccines to be transported long distances.[94] In the words of Robert Morgan, trucks with refrigerated units "present a sheer challenge of carrying enormous goods around and keeping them cool – they demand a huge battery and cooling requirement." This is particularly the case for long-haul trucks.

Refrigerated food for all

The lack of adequate cold storage and refrigerated transport causes the loss of around 200m tonnes of food each year.[95] Estimates suggest that India has less than 15% of the refrigerated trucks that the country needs, and less than 1% of the packhouses.[96] As a result, just 4% of the country's food moves through the cold chain (compared with 70% in the UK and 10% worldwide), and 40% of certain harvested crops are discarded before reaching the consumer.[97] The need for more refrigerated transport must be met at the same time as overcoming challenges around cooling use.

The uncontrolled environment that road transport refrigeration equipment is required to operate in, as well as its weight and space constraints, make it much more challenging to provide constant temperature management than in stationary refrigeration equipment. Food products are transported either at medium temperature (0°C to 8°C) or low temperature (-18°C to -25°C). Most transport refrigeration systems need to be able to operate at both these ranges, often simultaneously in different compartments. Since trucks can encounter a wide range of ambient temperatures depending on routes and weather, most intermodal containers need to be able to operate in temperatures ranging from -30°C to 50°C.[98]

Refrigerated trucks have to account for additional factors. For example, their doors are opened frequently to unload, which exposes the TRU to outdoor heat. As Brian Batavia, Technical Director at Bollinger Motors, notes, trucks sometimes need a system that continues to manage the TRU temperature while a truck is parked with the engine off. Since passengers do not travel in the TRU, strong insulation can seal up the refrigerated box, which protects it against the outside air temperature. Jeff Bozeman claims that "it's a simpler structure than a car body".

Does our analysis underestimate the need for cooling in refrigerated trucks?

We assume that refrigeration accounts for 8% of total electricity requirements in trucks with TRUs.[99] Experts note that this can vary from 8% to 20%, and we use the lower end of this range as a conservative assumption. However, in reality, the actual electricity requirement for cooling in trucks with TRUs could be significantly higher due to a number of reasons:

- **Truck specifications:** Trucks and their TRUs vary greatly in size, shape and weight depending on their use, and this determines their cooling needs.
- **Door openings:** The frequency of opening doors impacts the temperature of the cabin and the TRU, which can influence electricity consumption. This is a particular concern for trucks in urban environments that stop frequently to make deliveries.
- **Driving time:** For delivery trucks it is not just about the distance travelled but the length of time the truck is driving with the TRU in operation.
- **Driving environment** (as previously discussed in the context of cars).

Further research could build on the current methodology to explore the differences in the various conditions that impact the use of cooling in EVs to offer more granular analysis. For more in-depth research on the use of cooling in refrigerated trucks please consult: Ricardo, the Centre for Sustainable Road Freight, the Cold Chain Federation, and the University of Brighton Sir Harry Ricardo Laboratories.

The need for cooling reduces truck range

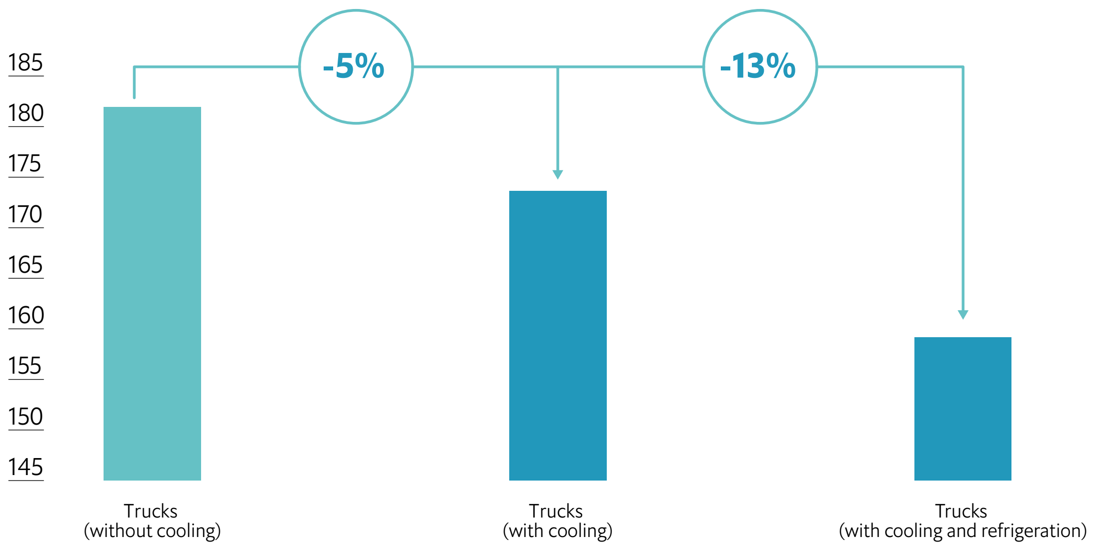
In trucks with TRUs, refrigeration can reduce range by approximately 13% on average, which can present a major challenge to stakeholders.[100] EV truck range is on average 182km, and they often travel much longer distances than cars. With the 13% reduction in range to accommodate refrigeration, refrigerated trucks need to recharge every 159km, which presents an operational challenge. In addition, it takes longer to charge a battery for a refrigerated truck compared with that of a car.

The need for cooling in trucks increases costs and emissions

Additional electricity requirements for cooling can increase operating costs in trucks without TRUs by 5%, and by up to 14% for trucks with TRUs. And, although EV trucks have 86% lower emissions than an equivalent fleet of ICE trucks in China, and 87% lower emissions than in the US, the need for additional electricity for cooling EV trucks creates environmental costs. In both China and the US, our analysis finds that cooling requirements account for an estimated 5% of total emissions in EV trucks.

The more the cooling, the lower the range

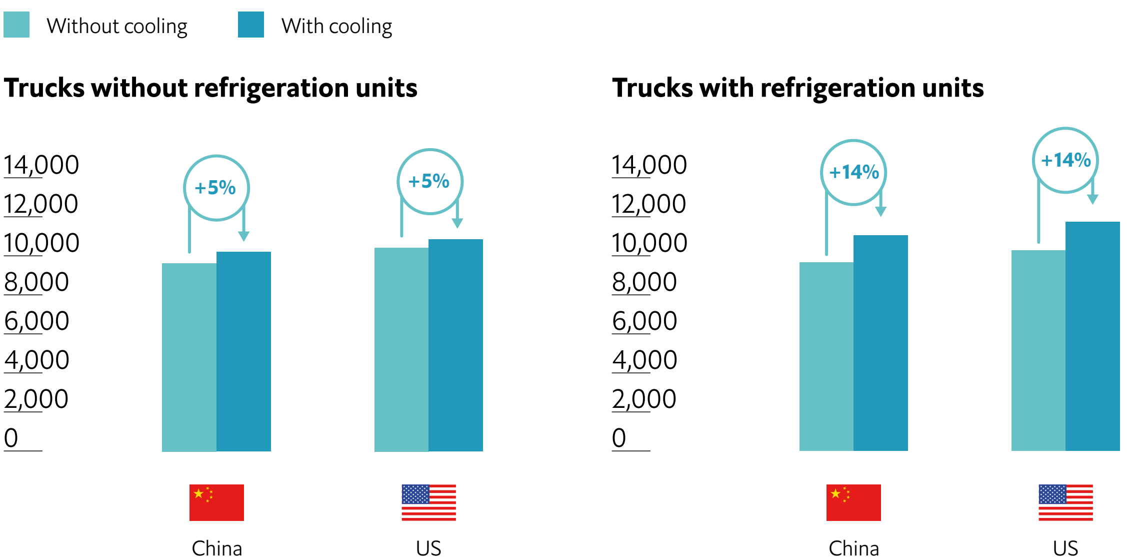
Range reduction from the use of cooling in trucks without and with TRUs (2020, km per battery charge)



Source: EIU analysis based on multiple sources

The cost of cooling

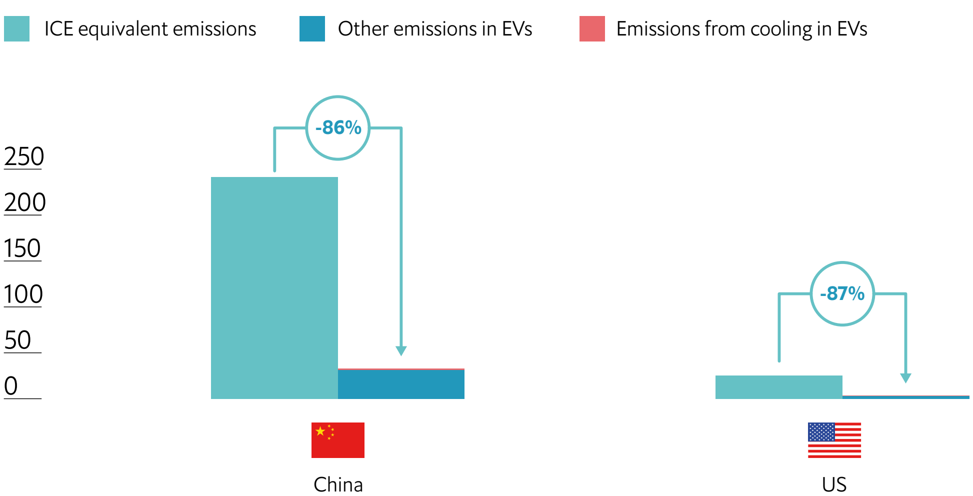
Average operating costs from the use of cooling in medium and heavy-duty EV trucks by country (2020, $ per year)



Source: EIU analysis based on multiple sources[101]

The environmental burden of cooling

Total emissions from EV trucks by cooling contribution (2020-2030, $MtCO_2$)



Source: EIU analysis based on multiple sources

Buses

Buses are a unique challenge: they often operate routes of 12 hours or more daily, while maintaining a safe and comfortable interior temperature for occupants and frequently opening their doors to let passengers on and off.[102] Even for conventional buses, cooling systems can be a challenge that can be overlooked. As mayor of London, Boris Johnson discovered this when he led a policy to bring back the infamous London Routemaster bus but failed to take into account the need for cooling.[103] With no opening windows on the upper deck, temperatures of over 40°C were recorded during a heatwave.[104] In 2015, Transport for London had to refit all 550 of the nicknamed "roastmasters".[105]

EV buses are even harder to rollout. Uptake grew by 32% in 2018[106] and is expected to triple by 2025.[107] China has led the way, with EV buses accounting for almost a quarter of bus sales in 2018.[108] In addition to reduced tailpipe emissions, EV buses are quieter and have lower operational costs than their ICE counterparts.[109]

Singapore's tropical climate has been a challenge for the country's EV bus system. The buses are expected to run upwards of 20 hours a day, but the relatively high cooling load, exacerbated by frequent stopping and opening of the doors which allows the climate-controlled air to escape, affects range.[110] Installing air curtains at bus entrances has led to a reduction of power consumption from cooling of 20–28%, according to a 2020 study.[111] Air curtains essentially force a wall of air between the bus interior and the outdoors,[112] reducing heat exchange by up to 80%, and freeing up the bus battery for a longer range.[113]

Limitations to truck research: What future research is needed?

Given limitations in the availability of data on the EV truck market, the analysis is conducted at a high level based on broad assumptions, which include the following:

- Limited previous research has been conducted on the electricity requirements for EV trucks and the implications of cooling on electricity usage. As a result, our analysis is driven by aggregate assumptions of total electricity requirements. Based on discussions with experts, we assume that the electricity usage for space cooling in the passenger cabin in a truck is the same as in a light vehicle.
- Our analysis on refrigerated trucks assumes that trucks with TRUs account for 5% of the truck market.[114] Given the nascency of the EV refrigerated truck market, our assumptions about the electricity requirements are based on the fuel requirements for conventional fuel-powered TRUs relative to trucks without TRUs.

With more granular data, the current research can be expanded in the future to account for particular nuances in the EV truck market.

Addressing the pressure placed on battery range from cooling in both cars and trucks is critical for driving EV uptake, which is a key component of reaching net zero.

More efficient cooling is one way this pressure can be reduced. The next section discusses potential efficient cooling options.

More efficient cooling can help address consumer concerns about battery range and costs

Concerns over the battery range create major barriers to EV adoption. Cooling exacerbates these concerns. One way to overcome these barriers is to directly improve the efficiency of cooling systems. Another way is to reduce the need for cooling in the first place.

Changing cooling systems directly can drive efficiency

Both conventional cars and EVs use vapour compression systems to cool passenger cabins. These systems remove "the heat from an enclosed space, and [release] it somewhere else" to lower temperatures.[115,116]

Advanced design technologies can help to reduce electricity usage for cooling and extend range by up to 5%. Replacing chemical refrigerants in heating and cooling systems with CO_2 refrigerants could extend driving ranges by up to 38%.[117] Several manufacturers, including Tesla, Volkswagen and Daimler, have committed to integrating state-of-the-art technologies or CO_2-based AC systems.[118,119]

A 5% extension of battery range could help the average BEV in the US travel an extra 20km, while a 38% extension could increase range by almost 160km. Our analysis shows that these changes could result in a reduction in operating costs of between 4.8% and 27.5% across all markets. Annual costs in India could fall from US$222 per car/user to $190 where high electricity needs from the hot climate result in higher operating costs.

Across the US, China and India – currently among the largest EV markets globally – the total electricity required to power EVs could fall by 58–334 TWh (equivalent to a 4.1–23.6% reduction) between 2020 and 2030. Similarly, across these markets, CO_2 emissions could decrease by 8–45 $MtCO_2$ (a 2.6–5.0% reduction). China would garner the biggest gains because of the size of its EV market.

Focus of our analysis

Our analysis focuses on three countries: the US, China and India. These countries were selected based on the following criteria:

- The size of their existing EV market and the projected rate of its growth – we selected countries with a large EV market in order to capture the potential gains from improving the energy efficiency of EV cooling systems.
- The climate in these countries – we selected countries with a relatively high ambient temperature where cooling requirements in vehicles are high, and therefore more efficient cooling solutions can have an impact on range and costs.

Future research could extend the analysis to the global level. This would require more in-depth analysis of the EV markets across different countries and regions, and the cooling requirements in each.

Indirect changes can also reduce the need for cooling

Improving the efficiency of AC units in cars is the first step in reducing electricity use, but it is not sufficient by itself. Only when combined with a reduction of the need for AC more broadly can it be fully effective.

Reducing the need for AC in the car

Cars that use less glass, solar-glazing glass and blinds absorb less heat from sunlight. Solar warmth through glass can be the largest contributor to heat gain in a car.[120] According to Dr Andersen of IGSD, "the amount of horizontal glass in the car, e.g. a sunroof, along with heat-absorbing interiors, can double the amount of AC you require in the car. If the stylists want to allow more glass then AC engineers will have to put in a bigger AC system." Of course, glass is a necessity for visibility, but using solar-reflective glazing can prevent some transmission of solar energy and keep the vehicle cooler. In 2006, NREL tested its Sungate EP technology, which reduced average air and seat temperatures by 7.1°C and 8.7°C, respectively. This is equivalent to a 67% reduction in total solar energy entering the vehicle.[121] As Robert Morgan, Professor of Thermal Propulsion Systems at Brighton University, explains, "instead of changing the glass itself, car designers can add sun blinds – as with pulling down a blind in a room, these work by using material to directly block out the sun while the car is parked."[122]

Paint can reduce the temperature of the vehicle. Paint colour matters: lighter colours reflect rather than absorb heat. A LBNL study determined that silver cars require 13% less AC capacity to cool a cabin compared with black cars.[123] The reflectivity of paint can also help. NREL found that adding a reflective coating to a car roof keeps the roof 9–10°C cooler, although studies have shown that such a reduction does not always translate to similar reductions in the cabin temperature, and in fact captures only 15% of the benefit.[124]

Remote-controlled cooling allows the driver to start cooling the car before entering it.[125] Some EVs also allow users to schedule cooling.[126] These functions help reduce range anxiety because the car can be cooled while it is still plugged in with zero loss of battery power. Darren Palmer at Ford explains that the car "uses only a fraction of the energy to maintain that temperature". According to an NREL study, pre-cooling before entering a car saves 31.2% of AC energy that is otherwise needed during the 20 minutes the car takes to cool down.[127]

Zonal cooling cools the user rather than the entire car to save energy. As Cedric Rouaud from Ricardo explains, "local cooling is on its way. It is inefficient to be cooling the entire car if nobody is in the rear." This approach includes specialised air vents directed above the driver's and passengers' heads or at their laps. According to the NREL study, "adding an AC vent to the driver's headliner or lap area improved driver cooling by approximately 5°C and 4°C respectively."[128] Another effective approach is neck coolers that blow air onto a high-blood-flow area, according to Jeff Bozeman at GM.

Cooled seats are also becoming more popular. Most cooled seats allow air to flow through the fabric of the seat, keeping the greatest surface area in contact with the occupant cool.[129] According to John Rugh, project leader for the NREL's Vehicle Ancillary Loads Reduction Project, "If all passenger vehicles had ventilated seats, we estimate that there could be a 7.5% reduction in national air-conditioning fuel use."[130] Combining cool seats with remote-controlled cooling prevents passengers from sitting on a hot seat when they first enter a vehicle. Timothy Craig, Lead Technical Consultant at Melrose Technologies, notes that zonal cooling can reduce power demand for AC by 30–50% at the hottest part of a journey.[131]

Shaded parking prevents solar energy from reaching the car altogether. The NREL 2006 study found that fully shaded parking can reduce energy consumption by nearly 75% compared to the energy consumption needed to cool down a car parked in direct sun.[132]

Fixing the gauge

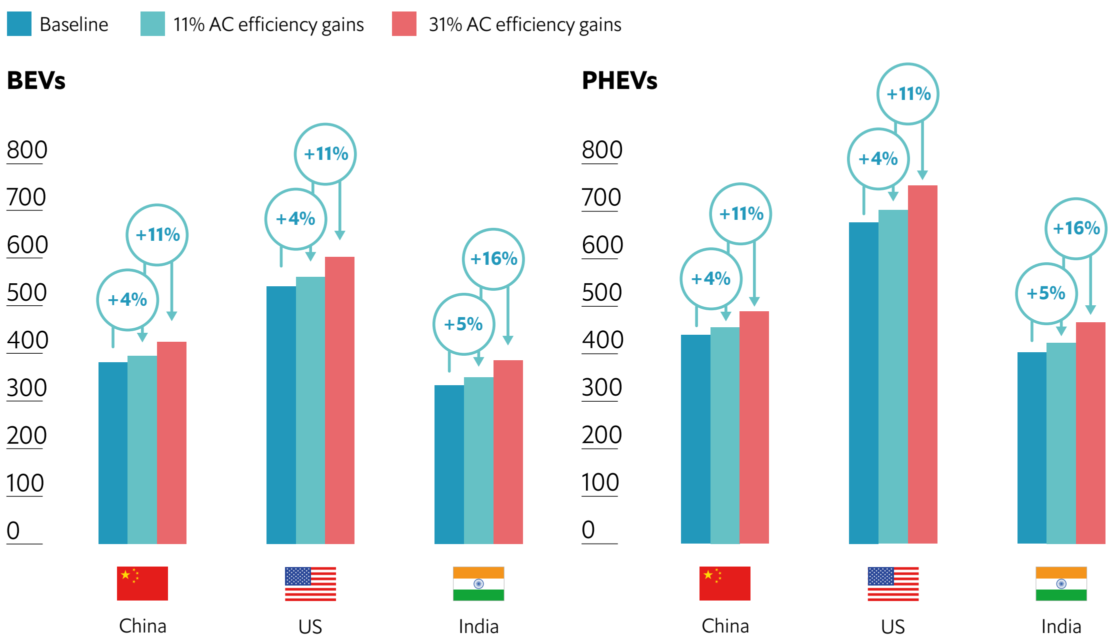
Sudden demand for heating or cooling in an EV exacerbates range anxiety. Dashboard gauges are not able to anticipate temperature change demands that affect the battery. If the gauge could more accurately predict road conditions, drivers could have a more realistic understanding of the range potential. According to Darren Palmer, "The first thing to fix is the gauge – if you know what you're going to get, you can plan properly." Improvements in machine learning and big data should allow vehicles to better calculate outside temperatures and conditions and more accurately and quickly estimate the range.

Although potential energy requirement reductions differ across measures and the point at which cooling is being used throughout the journey – for example, the initial cool-down phases versus the steady-state phase – our analysis shows that indirect interventions can reduce AC electricity consumption in EVs by 11–31%. Thermal control alone can result in 11% less consumption[133] and, when combined with localised conditioning, this can grow to 31%.[134]

These efforts could translate into a 4–11% improvement in battery range in China and the US, and a 5–16% improvement in countries with a hotter climate such as India. In monetary terms, China and the US could save US$25–70 per user annually, while India could save $35–95 per user.

Driving further

Range improvements from indirect measures to increase the efficiency of cooling in cars (2030, km per battery charge)

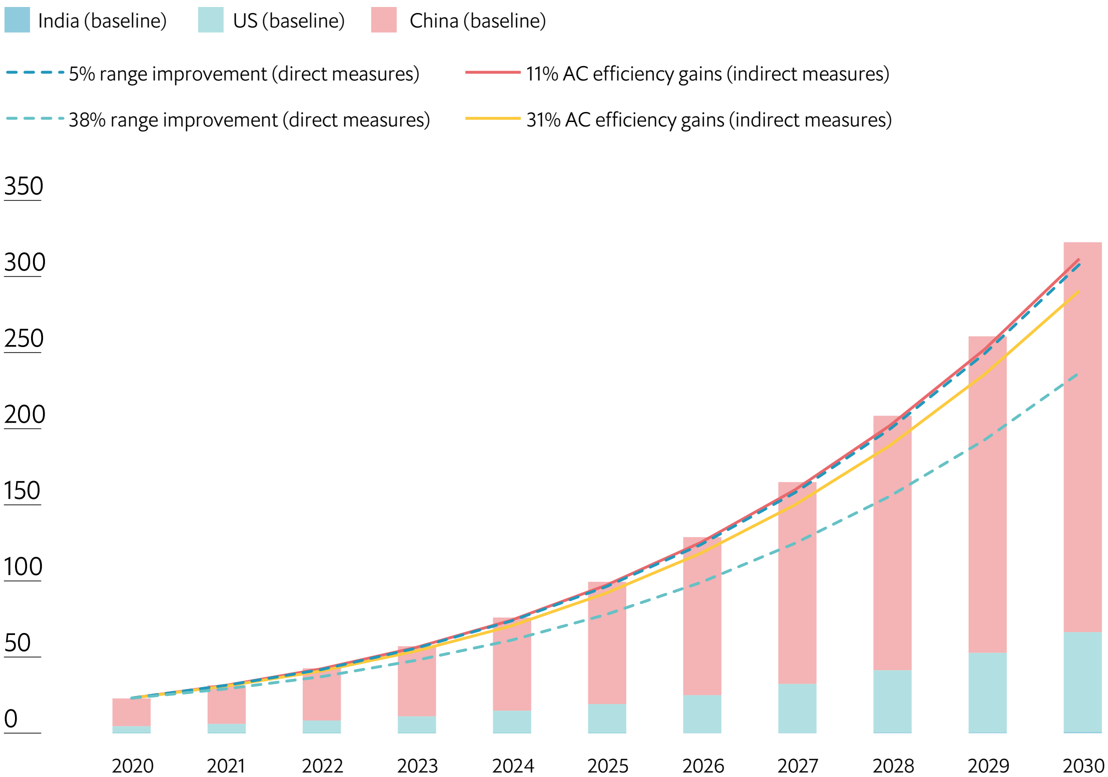


Source: EIU analysis based on multiple sources

Across the entire fleet of operating light EVs in the US, China and India, indirect measures could drive a 44–124 TWh decrease in electricity demand from 2020 to 2030 (equivalent to a 3.1–8.8% reduction) and reduce emissions by 6–17 $MtCO_2$ to 2030 (a 2.0–5.6% reduction). Over 80% of this reduction would be felt in China compared with 17% in the US and less than 1% in India.[135]

Saving energy

Reduction in electricity consumption by light EVs under alternative scenarios to improve AC efficiency (Terawatt-hours)



Source: EIU analysis based on multiple sources

Direct and indirect emissions

Our analysis looks only at indirect emissions, and excludes the direct emissions from the use and leakage of hydrochlorofluorocarbon (HCFC) or hydrofluorocarbon (HFC) refrigerants that are used in mobile AC units. As a result, the analysis underestimates AC use emissions in EVs.

Any measures to lower the environmental impact of mobile cooling in EVs need to include reducing refrigerant leaks and shifting to low global-warming potential (GWP) refrigerants.

Direct changes to cooling systems in trucks

The AC systems used in trucks are similar to those used in light-duty vehicles, driving similar efficiency gains of between 5–38% battery range extension.[136] The reduced need for electricity could translate into reduced operating costs of 4.8–27.5% on average. This could result in up to 70 TWh across China and the US in 2020-30, with associated reductions in CO_2 emissions of up to 9.3 $MtCO_2$. These reductions are fairly modest because of the slow uptake of electric trucks (5.5% and 2.5% market share in China and the US, respectively, in 2030).

Indirect changes to reduce cooling in trucks

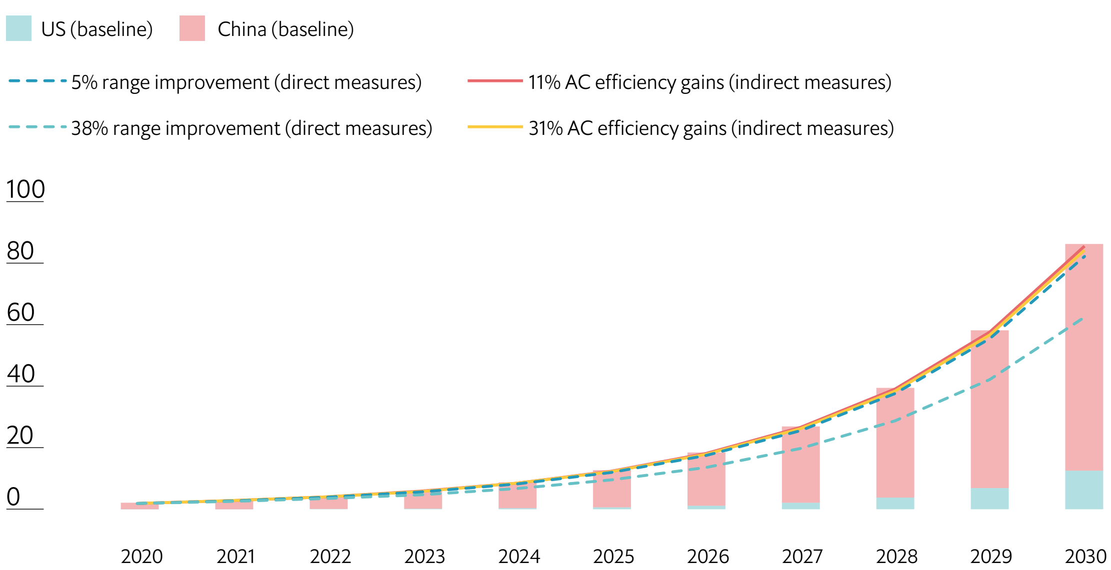
Indirect measures can also reduce the need for cooling in trucks. As with EV cars, using special glass, reflective paint, remote-controlled cooling, zonal cooling and shaded parking can all help drive a reduction of up to 31% in the cooling load on trucks without TRUs. This could result in a 2–5% range increase.

Installing better insulation in refrigerated trucks can similarly improve the range of TRUs by 2–5%. An NREL study found that by installing insulation in the cabin walls and structural channels, the cooling load in the cabin can be reduced by 34%.[137] A study by the World Bank found that efficiency and demand reduction measures, such as switching to vacuum insulated panelling – a special type of insulation – in TRUs could reduce indirect emissions by 30–50%.[138]

We expect similar levels of reduction in the operating costs of electric trucks to be achieved. Across the US and China -- two of the biggest markets for electric trucks -- total emissions between 2020 and 2030 could be reduced by 0.3-0.8 $MtCO_2$.[139]

Saving energy

Reduction in electricity consumption by EV trucks under alternative scenarios to improve AC efficiency (Terawatt-hours)



Source: EIU analysis based on multiple sources

Pack your thermals

The cost of EV batteries prevents manufacturers from adding additional batteries to store electricity. According to one study, "If the battery cost was a non-issue, electrical energy storage would be the obvious option".[140]

Instead of just relying on electrical energy in a battery, EVs can also store thermal energy in a thermal storage device. Yulong Ding, Director of the Birmingham Centre for Energy Storage, and his team have developed a thermal storage device for EVs. Its role is to power heating and cooling, thereby freeing up the battery to solely power the car's driving function. The thermal storage device can also help maintain the battery pack at its optimal operating temperature range. The Centre's long-term goal is to convert petrol stations into thermal charging stations. Heat and cold will be produced in advance at the stations to expedite the charging and to increase the energy efficiency. Long-term, all heat and cold will be produced at the stations by renewables and from waste energy from other industrial processes.

Hydrogen solutions

Hydrogen fuel-cell vehicles, like BEVs, are powered by an electric motor; however, hydrogen fuel-cell EVs produce the electricity themselves using the fuel cell.[141] As The Economist explains, "Instead of storing and then releasing electricity gathered from the mains in the way that a battery does, a fuel cell generates current from a chemical reaction between hydrogen and oxygen. The oxygen comes from the air. The hydrogen, suitably compressed, is stored in a tank on board the vehicle, and is replenished at a filling station, like petrol."[142]

Fuel-cell vehicles can drive about 500km – further than the current range of BEVs. They can also be refilled, like a conventional car, in a matter of minutes, rather than hours as required by battery charging.[143] A particular area for consideration of hydrogen is EV trucks – with the longer distances required, hydrogen fuel cells can take up less space and weight than adding additional battery capacity, although there are efficiency considerations.[144]

Energy is required to make hydrogen, and the amount of energy which hydrogen provides is significantly lower than the amount needed to produce it.[145] According to Yulong Ding, hydrogen fuel-cell vehicles are very energy-inefficient because of the low primary energy source-to-hydrogen conversion efficiency. So while hydrogen offers a solution for long-haul trucks, it is not the most efficient option available.[146]

Rent a battery

Like all batteries, EV batteries burn out. This has led manufacturers to trial a battery-swapping model where customers lease the battery from the manufacturer. When the battery is exhausted, it is replaced. Amandeep Singh, Chief at Corporate Planning for Honda Motors, explains "With battery swapping, you can own the vehicle but you don't need to own the battery. It's a subscription model." The cost of purchasing an EV falls because a customer buys the car without the battery and then rents the battery from a swap station. Battery swap stations have fully charged batteries ready for customers, so there is no wait time for charging.

Tesla has tested battery swapping, but stopped it in 2013.[150] Industry news sources put this down to batteries degrading over time and varying battery standards across car manufacturers.[151] Renault also offered a battery-swapping scheme on new sales of the Renault Zoe from 2014 to 2019. During this period, leasing sales accounted for 60% of overall Zoe sales.[152] While customers who bought a new car with this option can continue to use it, it is not offered on new sales as, according to one news source, Renault stopped offering the scheme as the prices of EVs overall have come down.[153] But the news is not all bad: Nio, a Chinese EV manufacturer, has made a success of battery swapping. In June 2020 it completed its 500,000th swap.[154] A swap takes just three minutes and, according to Electrek, extra battery packs can be kept on board so drivers can conduct swaps themselves.[155] This solution is particularly efficient for commercial vehicle operators.

Here comes the sun

Solar power is generated at the times of the day when the sun is strongest. Channelling this power to reduce pressure on the battery could be an effective solution to the reduced range challenge.

To date, solar panels on cars have not generated large amounts of energy: a 2017 Toyota model, for example, added just 6km of range.[147]

Manufacturers are focused on fixing this: in 2019, Toyota announced plans to start public road trials of a new solar-panelled Prius that can drive 44.5km using just solar power on a full charge, and 56.3km if it is recharging while driving.[148] Lightyear, a 2016 start-up, has created a bottom-up "solar EV" that uses a lightweight design with about 1,000 solar photovoltaic cells. The output of these solar cells equates to an average extra 32km of range per day, with a maximum of just over 70km. The company aims to produce 946 vehicles from 2021.[149] To be practical, solar solutions for now have to be employed in addition to existing batteries.

The early bird gets the worm

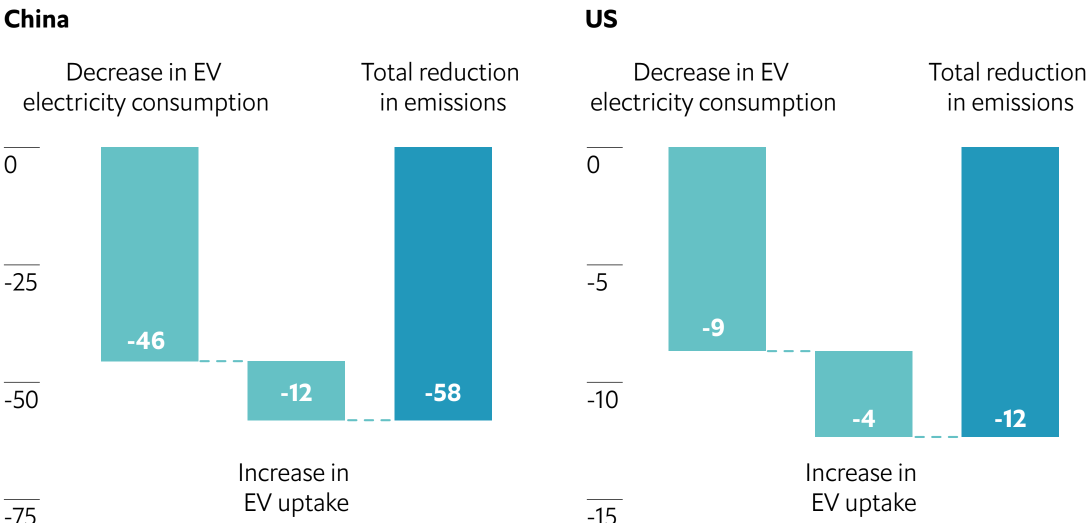
As more regulations are put in place to support the transition to EVs, conventional car manufacturers will have to sell EVs to stay in the market. And with the range extension that cooling efficiency provides, EV sales will rise. Electricity costs account for about 10% of the overall costs of EVs,[156] and improved cooling efficiency can reduce these costs by almost 3%. Resources for the Future estimates that a 1% reduction in EV cost can drive sales by up 2.67%,[157] which means efficient cooling has the potential to increase sales by over 7%. It is possible that the reduced range anxiety that accompanies more efficient cooling could increase this figure, but data on the relationship between improved EV range and uptake does not currently exist.

A reduction in emissions

Efficient cooling has the potential to reduce emissions both by reducing EV electricity use and increasing uptake.[158] But a 7% increase in uptake will result in only a small uptick in the market share of EVs relative to conventional vehicles. In China, we estimate a 0.6% increase in market share from 45.5% currently to 46.1% in 2030 for EV cars, and a 0.2% increase from 5.5% to 5.7% for EV trucks over the same period. If reduced range anxiety does radically increase uptick, the resulting change to the market share of EVs, and the associated emissions reduction, could be much larger.

Going all in

Maximum potential reduction in total CO_2 emissions across vehicle types* with a decrease in EV electricity consumption and increase in EV uptake (2020-2030, $MtCO_2$)



* Note: Includes EV and non-EV cars and trucks. Values may not sum due to rounding.
Source: EIU analysis based on multiple sources

Rising electricity demand and its impact on power systems

In November 2020, the EIU published the report, "The Power of Efficient Cooling", which identifies the contribution of efficient cooling in supporting the power sector's transition to net zero.

The report explains that demand for electricity is not constant throughout the day. Consumers often demand electricity at the same time, and power providers have to meet surges in demand at a moment's notice. Meeting peak demand is particularly costly for the power sector.

An increase in EV uptake means an increase in EV charging. If EVs are charged during peak times, peak demand will rise accordingly. The IEA estimates that the share of EV charging in peak demand could rise to as high as 10% by 2030, up from 0.3% today.[159] Other studies have estimated the contribution of BEV charging to peak load at about 6% of the total peak load by 2030.[160]

Efficient cooling can reduce stress on the grid and lower costs associated with building out extra power capacity to meet electricity demand from EVs. Read the report here.

Further research needed: The role of range in consumer decisions

Historical data on consumer priorities when purchasing a car is limited, and it is hard to isolate the impact of an improvement in range on consumer purchasing decisions. This is particularly the case because other consumer-influencing decisions also change: as EV range has improved, the cost of EVs has fallen and charging infrastructure has become more readily available.[161] Therefore, an increase in sales cannot be directly attributed to an increase in range.

To fully understand the impact of reducing range anxiety on new EV sales, consumer surveys on the factors that drive consumer decisions at the point of purchasing the vehicle are needed. To date, most consumer surveys focus on readiness to purchase an EV and provide data that cannot be used to isolate the impact of range improvements on sales uptick.

What needs to happen to capture the benefits of efficient cooling

Educating consumers. Car manufacturers believe that design is crucial in attracting consumers. Appearance forms consumers' first impressions of a car. In practice, manufacturers often prioritise design over cooling efficiency. According to Stephen Andersen of IGSD, "it is often the job of car stylists, rather than the thermal engineers, to locate the AC vents. For example, Mini Coopers have retro vents like the original mini for stylistic purposes but they are in the wrong location to provide the cooling and are too small or too large to be efficient." Thermal engineers need to be involved at the early stages of car design to ensure efficiency as well as attractiveness.

But more needs to happen: educating consumers about the role of cooling systems in determining car range and operating costs, and teaching them how to recognise an efficient cooling system, can help replace preferences for design with preferences for efficiency. Extending this awareness-building to how driving habits impact range can also help make efficiency a priority for consumers.

Introducing regulation. Implementing emissions and efficiency standards for EVs will bring battery range challenges to the fore. More specifically, policymakers must ensure that manufacturers carry out testing regimes to prove that their vehicles meet efficiency standards and that these tests include the impact of AC units. Testing also needs to take place on real roads rather than in laboratories to address the "false metric" around battery range and to ensure that information about real road conditions reaches the consumer. If regulators in charge of fuel efficiency include engineers who understand the role of cooling in vehicles, this will facilitate the disclosure of critical metrics around range and emissions.

Fostering innovation. Funding and running innovation programmes that focus on cooling solutions to improve EV range can inspire private sector progress. The stylistic nature of the car business necessitates rewarding manufacturers for successes, especially new environmentally friendly features in consumer vehicles. Policymakers, foundations and philanthropic organisations could consider replicating the Rocky Mountain Cooling Prize – a competition that brings together industry leaders to find a residential cooling solution that will reduce climate impact fivefold – for the automotive sector and bring industry leaders together to seek out solutions for more efficient mobile cooling.

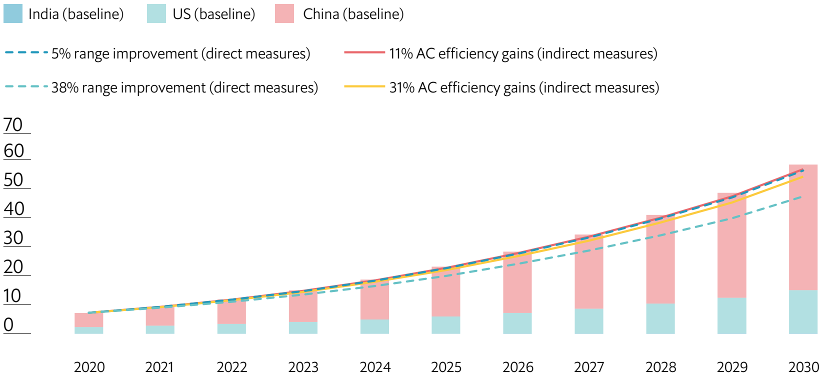
Improving research around how to transition to net zero logistics fleets is critical. Most investments and product deployment in trucks and buses are adapted from light vehicles, but this will change as battery prices fall. The truck market in particular is heterogeneous – there are many different vehicles with different range requirements. These nuances, and how trucks are used, need to be considered separately so truck-specific cooling solutions can be developed.

Solving together. Voluntary measures can drive change in improving EV range. Collaboration between the private and public sectors on financing can help overcome the need for high capital expenditure to make wider EV rollout possible. International technology committees and cooperative research programmes enable companies and other stakeholders to get together to share technologies and experiences. Initiatives such as the Global Green Freight Action Plan bring together governments, the private sector, civil society, and other actors to enhance the environmental and energy efficiency of the movement of goods.[162] Initiatives such as the new Corporate Electric Vehicle Alliance bring a wide range of businesses such as Amazon and IKEA to help them meet EV targets and to aggregate corporate demand for EVs.[163]

Joined-up thinking. To make net zero possible, all stakeholders need to take a systems-level approach to what energy-related service is required and how to provide it in the most cost- and emissions-effective way.[164] Stakeholders need to break down siloed thinking and work together.[165]

Appendix

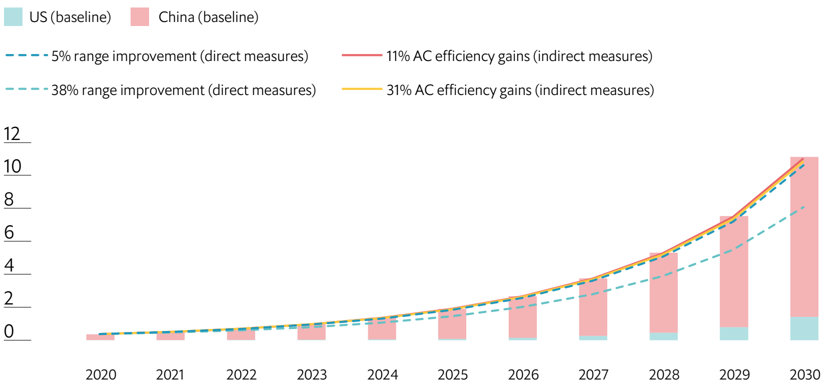
Reduction in CO_2 emissions by light EVs under alternative scenarios to improve AC efficiency ($MtCO_2$)



Note: Includes BEV and PHEV light EVs

Source: EIU analysis based on multiple sources

Reduction in CO_2 emissions by EV trucks under alternative scenarios of direct and indirect measures to improve AC efficiency ($MtCO_2$)



Note: Includes trucks with and without refrigeration units

Source: EIU analysis based on multiple sources

Overall potential savings for EV cars

		Average range improvement (2030)	Average reduction in operating costs (2030)	Total reduction in electricity demand (to 2030)	Total reduction in CO_2 emissions (to 2030)
Direct measures to improve the efficiency of cooling systems	China	**5-38%**	**5-28%**	**4-24%** (46-268 TWh)	**3-17%** (6-37 $MtCO_2$)
	US	**5-38%**	**5-28%**	**4-23%** (11-65 TWh)	**2-10%** (1-8 $MtCO_2$)
	India	**5-38%**	**5-28%**	**2%-14%** (0.1-0.6 TWh)	**2-14%** (0.02-0.1 $MtCO_2$)
Indirect measures to reduce the need for cooling	China	**4-11%**	**4-10%**	**3%-8%** (35-100 TWh)	**2-6%** (5-14 $MtCO_2$)
	US	**4-11%**	**4-10%**	**3%-9%** (9-24 TWh)	**1-4%** (1-3 $MtCO_2$)
	India	**5-16%**	**5-14%**	**3%-7%** (0.1-0.3 TWh)	**3-7%** (0.02-0.06 $MtCO_2$)

Source: EIU analysis based on multiple sources

Overall potential savings for EV trucks

		Average range improvement (2030)	Average reduction in operating costs (2030)	Total reduction in electricity demand (to 2030)	Total reduction in CO_2 emissions (to 2030)
Direct measures to improve the efficiency of cooling systems	China	**5-38%**	**5-28%**	**4%-26%** (11-61 TWh)	**4-26%** (2-8 $MtCO_2$)
	US	**5-38%**	**5-28%**	**5%-27%** (1-8 TWh)	**5-27%** (0.2-0.9 $MtCO_2$)
Indirect measures to reduce the need for cooling	China	**1-2%** (without TRUs), **2-5%** (with TRUs)	**0.8-2%** (without TRUs), **2-5%** (with TRUs)	**0.8-2%** (2-6 TWh)	**0.8-2%** (0.3-0.8 $MtCO_2$)
	US	**1-2%** (without TRUs), **2-5%** (with TRUs)	**0.8-2%** (without TRUs), **2-5%** (with TRUs)	**0.9-2%** (0.2-0.7 TWh)	**0.9-2%** (0.03-0.08 $MtCO_2$)

Source: EIU analysis based on multiple sources

Reduced CO_2 emissions from direct improvements to cooling systems in cars and trucks combined with an increase in EV uptake

	Reduction in transport emissions by fuel type ($MtCO_2$, % of total reduction)				
	Oil emissions	Coal emissions	Gas emissions	Renewable energy emissions	Total
China	-12.5 **(22%)**	-41.8 **(72%)**	-3.0 **(5%)**	-0.79 **(1%)**	-58.1 **(100%)**
US	-3.7 **(30%)**	-3.3 **(27%)**	-5.2 **(42%)**	-0.16 **(1%)**	-12.3 **(100%)**

Source: EIU analysis based on multiple sources

Methodology Paper

Growth in the electric vehicle (EV) market holds significant scope to reduce the overall emissions associated with road transport. However, the environmental gains from EV use can be constrained by cooling systems which reduce the range of EVs, increase their use of electricity, and increase overall emissions. Enhancing the efficiency of cooling systems can therefore unlock additional environmental gains. Furthermore, by extending the range of EVs and reducing the user costs of operation through reduced electricity requirements, efficient cooling solutions can also overcome some of the barriers to the adoption of EVs and contribute to their uptake.

Using an Excel-based modelling approach, developed alongside an extensive data audit and literature review, we estimate the potential gains from investing in, and implementing, innovations in EV cooling systems which reduce the overall electricity requirements of the vehicle. The model assesses the impacts of cooling systems on the range, user costs and environmental costs of EVs under different scenarios including:

- **Baseline ("do-nothing") scenario** – the baseline scenario estimates and forecasts the electricity demand for EVs, and the associated user costs and environmental costs, based on forecasts of growth in the EV market and under the assumption that no changes are made to the current levels of cooling efficiency.
- **Efficient cooling scenarios** – these scenarios assess the potential reduction in electricity demand for EVs which results in an extension of the range on a single charge. For the same distance of travel, the reduced electricity use therefore reduces EV operating costs and emissions. Efficient cooling scenarios include both solutions that directly improve the efficiency of mobile cooling systems, and solutions that reduce the overall need for cooling in vehicles.

The model forecasts EV operating and environmental costs under the different scenarios up to 2030 for the following vehicle types:

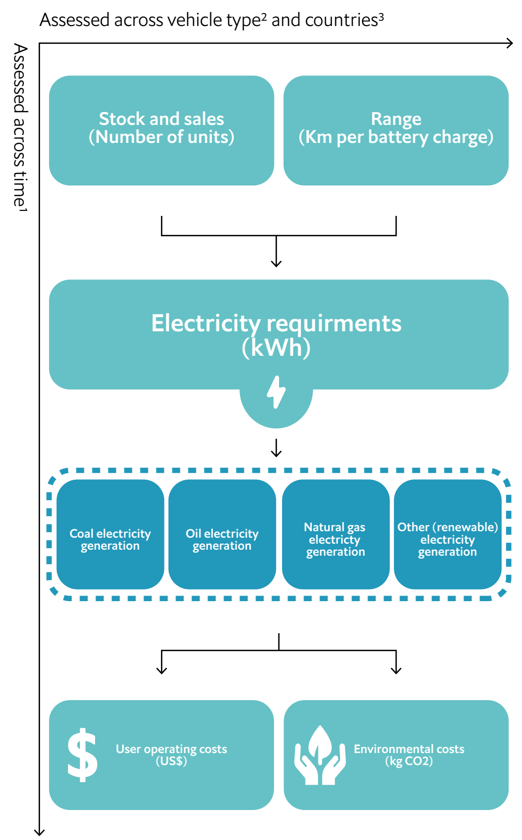
- **Light vehicles** – including battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) varieties of passenger cars and light commercial vehicles.
- **Trucks** – including medium- and heavy-duty trucks both with and without transport refrigeration units (TRUs).

For light vehicles, the analysis is conducted at the country level for China, the US and India. For trucks, given the nascency of the market in India and the lack of available data, the analysis covers only China and the US.

Baseline scenario

As a first step, we develop baseline forecasts for the electricity requirements for EVs and the associated user costs and environmental costs using the approach discussed below.

Baseline scenario assessment



Notes:

1 The analysis covers the period 2010–2030

2 Two classes of vehicle type are covered in the analysis – light vehicles (which include BEV and PHEV passenger cars and light commercial vehicles), and trucks (which include medium- and heavy-duty trucks, with and without TRUs)

3 Countries covered include India (for light vehicles only), China and the US

1. Estimating baseline EV demand. To build baseline estimates of the operating and environmental costs of EVs under current levels of cooling efficiency, we use forecasts of demand for light vehicles and trucks.

- **EV light vehicle sales** – our projections of the annual sales of light vehicles, including BEV and PHEV passenger cars and light commercial vehicles, are based on data from EV-Volumes. We use market share estimates from the IEA to fill data gaps in sales figures for India.
- **EV light vehicle stock** – as above, we use EV-Volumes data on the stock of light vehicles to 2030. This data assumes that the stock in any given year is equal to stock in the previous year, with an adjustment factor of 1% for depletion, plus current year sales.
- **EV truck sales** – historical data on sales for medium- and heavy-duty trucks from 2010 to 2019 are obtained from the IEA. We use projections of the constant annual growth rate (CAGR) of the EV truck market based on forecasts provided by Prescient & Strategic (P&S) Intelligence. Further, we assume that 5% of trucks in the market include TRUs based on World Bank analysis.[166]
- **EV truck stock** – historical and projected stocks for EV trucks are estimated based on sales data, adjusted to account for the depletion of stock over time. It is assumed that 1% of previous year stock is depleted each year.

2. Estimating average vehicle range. The average vehicle range is estimated as the distance that can be travelled in kilometres on a single charge.

For light vehicles, the range is estimated in each market based on the average battery capacity of PHEVs and BEVs sold in that market (using EV-Volumes data) and the electricity requirements for each kilometre of travel.

The electricity requirements are estimated based on literature and split by cooling and non-cooling requirements to assess the implications of cooling for the range. Further, this split accounts for the difference in electricity requirements for space cooling in different countries based on their ambient temperatures. It is assumed that the electricity requirements for PHEVs are proportional to the requirements for BEVs on the basis of the average size of their batteries. Any other fuel requirements for PHEVs are assumed to be met through other non-electric sources, such as diesel or petrol.

Similarly for trucks, the range is estimated based on average battery capacity and electricity requirements per kilometre of travel. Data is obtained from literature and assumed to be the same across countries covered (China and the US) given the similarity in their ambient temperatures. Further, it is assumed that the electricity requirements for cooling in trucks are similar to those of light vehicles. Hence, any additional electricity requirements for trucks are assumed to be for non-cooling purposes. In the case of trucks with TRUs, any additional electricity requirements for the refrigeration units are added to the electricity requirements for cooling.

The baseline analysis assumes that the electricity requirements for cooling EVs (both light vehicles and trucks) remain constant in each country over time.

Note on data limitations for EV trucks

Given limitations in the availability of data on the EV truck market, the analysis is conducted at a high level based on broad assumptions, including the following:

- Data on growth in the market for EV trucks is limited and our analysis is therefore based on a constant annual growth rate between 2020 and 2030 instead of year-on-year projected growth.
- Limited previous research has been conducted on the electricity requirements for EV trucks and the implications of cooling for electricity usage. As a result, our analysis is driven by aggregate assumptions of total electricity requirements. Based on discussions with experts, we assume that the electricity usage for space cooling in the passenger cabin of a truck is the same as for a light vehicle.
- Our analysis of refrigerated trucks assumes that they account for 5% of the truck market. Given the nascency of the EV refrigerated truck market, our assumptions about the electricity requirements are based on the fuel requirements for fuel-powered TRUs relative to trucks without TRUs.

With more granular data, the current research can be expanded in the future to account for particular nuances in the EV truck market.

Assumptions on electricity requirements for EVs (kWh per km)

	Climate	Cooling electricity requirements	Non-cooling electricity requirements	Total electricity requirements
Light vehicles (BEVs)	Normal climate (up to 25°C) - China and US	**0.07 kWh** per km	**0.13 kWh** per km	**0.20 kWh** per km
Light vehicles (BEVs)	High climate (above 25°C) - India	**0.11 kWh** per km	**0.13 kWh** per km	**0.24 kWh** per km
Trucks (without TRUs)	Normal climate (up to 25°C) - China and US	**0.07 kWh** per km	**1.37 kWh** per km	**1.44 kWh** per km
Trucks (with TRUs)	Normal climate (up to 25°C) - China and US	**0.20 kWh** per km	**1.37 kWh** per km	**1.57 kWh** per km

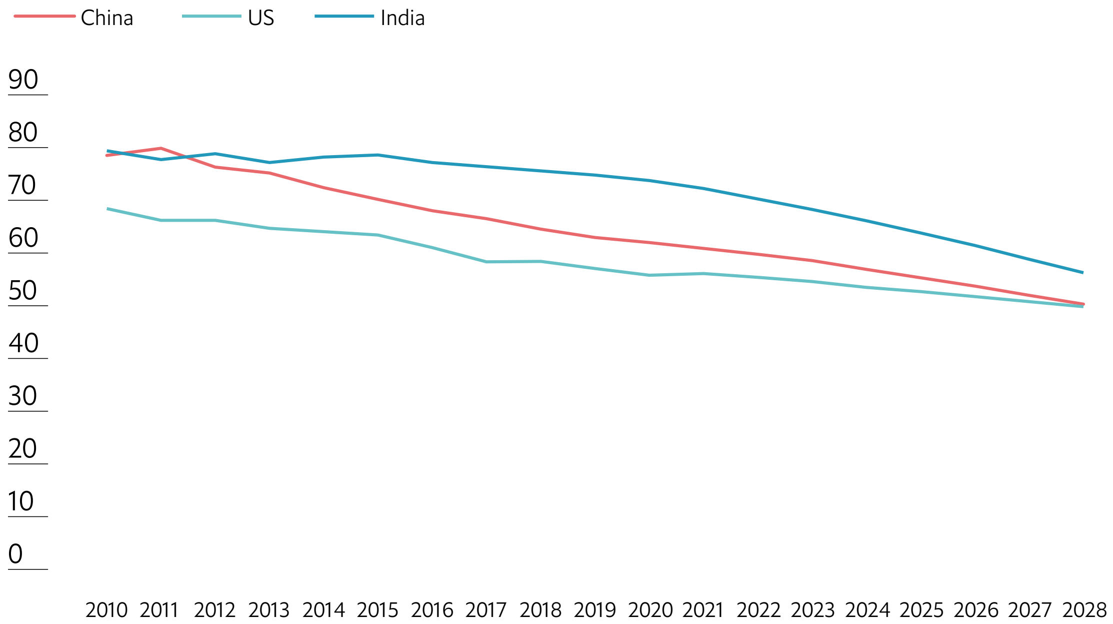
Source: EIU analysis based on multiple sources

3. Estimating total electricity requirements. The total electricity requirement for EV light vehicles and EV trucks in each market is estimated based on the vehicle range and forecasts of EV stock.

To estimate the total annual electricity requirement for an average vehicle, we estimate the annual frequency of recharge. This is estimated using data on the average distance travelled per year by light vehicles and trucks in each market from multiple country-specific research sources, the estimated range, and the average battery capacity of different vehicle types.

Further, to account for differences in the emission intensities from using different fuels for electricity generation, the total estimated electricity demand for EVs is split by fuel source. The split of fuel sources for electricity generation for EVs is assumed to be the same as the split for total electricity generation in each country using EIU data which accounts for changes in the fuel mix across countries over time.

Share of fossil fuels in total fuel mix by country (2019-2030, %)



Source: EIU data and analysis

4. Estimating EV user operating costs. The financial cost to users from operating EVs is assumed to include only the cost of recharge. Other costs including the cost of maintenance or battery replacement are excluded. These costs are estimated based on the electricity requirements for EVs and the electricity cost.

The unit cost of electricity in each market is obtained from the World Bank and is used as a proxy of the cost per unit of electricity required to operate EVs.

5. Estimating EV environmental costs. The environmental costs from EVs are estimated as the CO_2 emissions that result from generating the required electricity. Any environmental emissions associated with the manufacturing of EVs are excluded.

We use EIU data on the emission intensity of electricity generation by fuel source in each country to estimate total CO_2 emissions. Over time, changes in the emissions from electricity generation for EVs are reflective of both growth in EV demand which increases emissions, and changes in the fuel mix towards more renewable fuel sources which decreases emissions.

For PHEV light vehicles, in addition to the emissions from electricity generation, we also account for the direct emissions from fuel combustion in their use of petrol or diesel. This is estimated as a proportion of the emission intensity per kilometre of travel for ICE vehicles, adjusted to account for the share of fuel requirement offered by the battery pack in PHEVs. Data on the emission intensity of ICE vehicles is obtained from the International Council on Clean Transportation (ICCT).

Efficient cooling scenarios

We use scenario analysis to assess the impact of climate-friendly cooling solutions on the electricity requirements, and the resulting impacts on the user operating costs and the environmental costs associated with electricity generation. Different types of scenarios are assessed, as discussed below.

1. Direct measures which make EV cooling more energy-efficient. One potential way to reduce the total electricity consumed by EVs is to make mobile AC systems more efficient such that they use less electricity to generate the same level of cooling. The impact of solutions that improve the efficiency of AC units in EVs is assessed by adjusting either the electricity requirements for cooling in EVs (which has an impact on the range) or the estimated range of EVs based on existing literature on the level of feasibility of efficiency gains. The resulting impact on total electricity consumed by EVs is estimated, holding demand for EVs constant.

2. Indirect measures which reduce the need for mechanical cooling in EVs. Electricity demand for cooling can also be reduced by minimising the need for mechanical cooling. Potential solutions are discussed in the report and could include solar glazing and shaded parking. In our model, this is assessed by adjusting the total estimated electricity demand for EVs. The potential for reduction is informed by a literature review of academic studies which assess the implications of the potential solutions of interest for electricity requirements for EVs.

For each type of scenario, both direct and indirect, we assess the impact on electricity demand for EVs and the resulting impact on user costs. To assess the impacts on environmental costs, we consider two potential channels of impact:

- First, the reduction in electricity requirements for EVs under both types of scenarios has a direct impact on emission levels.
- Second, the increase in vehicle range and reduction in user operating costs can both contribute to an increase in demand for EVs at the expense of demand for ICE vehicles, which can have a resulting impact on emissions. We assume that total market demand for vehicles (EVs and ICE vehicles) remains constant, hence an increase in demand for EVs implies a one-for-one reduction in demand for ICE vehicles. The difference in emission levels for ICE vehicles compared to EVs provides an additional channel through which emissions are reduced.

As an extension to the research conducted in this report, further analysis could consider a more granular, bottom-up approach to capture the nuances and variation in the EV market. Battery capacities and EV ranges vary significantly both within and across countries. Within countries, differences arise across EV models and differences in user behaviour. Across countries, variations in temperature form a major point of difference in EV ranges, in addition to differences as a result of the types of EV models sold in each market. The current research captures some of the nuances, however, at a more aggregated level using averages across different models and countries. Further research could therefore explore these differences in more detail to provide greater depth of insight.

Furthermore, the current research focuses on the benefits arising from energy-efficient cooling solutions in EVs in the form of reduced costs. Additional research might also explore the overall economic implications and the extent to which any losses for ICE manufacturers are replaced by gains to EV manufacturers as the market transitions towards EVs.

Endnotes

1. https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/#:~:text=Global%20net%20human%2Dcaused%20emissions,removing%20CO2%20from%20the%20air
2. https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf
3. https://eciu.net/analysis/briefings/net-zero/net-zero-why
4. https://www.energy-transitions.org/wp-content/uploads/2020/09/Making-Mission-Possible-Full-Report.pdf
5. EVs can still contribute to emissions through their AC systems which use refrigerant gases which, when leaked, contribute directly to global warming. In addition, plug-in hybrid EVs produce emissions when using the internal combustion engine, but none when they are in all-electric mode. Both fully electric and plug-in hybrid EVs also produce life-cycle emissions, for example in maintenance, disposal and recycling.
6. While only 0.1% of electricity in China is generated using oil, the significant reduction in oil emissions comes from the shift from conventional vehicles to EVs.
7. https://www.energy.gov/eere/vehicles/articles/internal-combustion-engine-basics#:~:text=The%20engine%20consists%20of%20a,in%20turn%20rotates%20the%20crankshaft.&text=After%20the%20piston%20compresses%20the,piston%20during%20the%20power%20stroke
8. EIU analysis based on OICA 2015 data on vehicles in use. Available at: http://www.oica.net/category/vehicles-in-use/
9. https://www.edfenergy.com/for-home/energywise/how-do-electric-cars-work#:~:text=Electric%20cars%20function%20by%20plugging,they%20feel%20lighter%20to%20drive
10. Fuel-cell vehicles are another type of EV that use only electricity – they produce electricity using a fuel cell powered by hydrogen rather than drawing electricity directly from a battery. https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work
11. https://newmotion.com/en_GB/the-electric-range-of-an-ev/
12. https://www.energy.gov/eere/electricvehicles/electric-vehicle-basics
13. Light commercial vehicles weigh up to 3.5 tonnes, and medium- and heavy-duty trucks weigh more than 3.5 tonnes.
14. The EIU estimates that approximately 56.5% of all electricity generated across the world is generated from fossil fuels.
15. EVs can still contribute to emissions through their AC systems which use refrigerant gases which, when leaked, contribute directly to global warming. In addition, plug-in hybrid EVs produce emissions when using the internal combustion engine, but none when they are in all-electric mode. Both fully electric and plug-in hybrid EVs also produce life-cycle emissions, for example in maintenance, disposal and recycling.
16. https://afdc.energy.gov/vehicles/electric_emissions.html#:~:text=Direct%20and%20Well%2Dto%2DWheel%20Emissions&text=Conventional%20vehicles%20with%20an%20internal,EVs%20produce%20zero%20direct%20emissions
17. https://www.eea.europa.eu/signals/signals-2017/infographics/range-of-life-cycle-co2/image/image_view_fullscreen
18. https://cop25.mma.gob.cl/en/climate-ambition-alliance/
19. https://www.iea.org/reports/tracking-transport-2020
20. https://www.forbes.com/sites/energyinnovation/2019/11/11/how-to-reach-us-net-zero-emissions-by-2050-decarbonizing-transportation/#5a42423b2040
21. https://www.forbes.com/sites/energyinnovation/2019/11/11/how-to-reach-us-net-zero-emissions-by-2050-decarbonizing-transportation/#5a42423b2040
22. https://www.forbes.com/sites/energyinnovation/2019/11/11/how-to-reach-us-net-zero-emissions-by-2050-decarbonizing-transportation/#5a42423b2040
23. https://www.reuters.com/article/us-environment-norway-autos-idUSKBN1ES0WC; https://elbil.no/english/norwegian-ev-policy/#:~:text=The%20Norwegian%20Parliament%20has%20decided,hold%20a%2050%20%25%20market%20share
24. https://www.transportenvironment.org/press/california-sets-worlds-first-sales-target-emissions-free-trucks#:~:text=Last%20night%2C%20California%20adopted%20the,electric%20trucks%20and%20hydrogen%20trucks
25. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet
26. https://www.bbc.co.uk/news/science-environment-54981425
27. https://europe.autonews.com/automakers/frances-new-13000-ev-incentive-most-generous-europe
28. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/electric-mobility-after-the-crisis-why-an-auto-slowdown-wont-hurt-ev-demand
29. https://ww3.arb.ca.gov/msprog/lct/vehiclescrap.htm
30. For most vehicle types, including cars, motorcycles and vans (up to and including 3.5 tonnes).
31. https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/ulez-where-and-when?intcmp=52227
32. EV Volumes
33. Refrigerated trucks account for 5%.
34. Based on data provided by P&S Intelligence
35. https://www.alixpartners.com/media/13453/ap-electric-vehicle-consumer-study-2019.pdf
36. https://www.smmt.co.uk/2020/09/billions-invested-in-electric-vehicle-range-but-nearly-half-of-uk-buyers-still-think-2035-too-soon-to-switch/
37. https://www.edfenergy.com/electric-cars/benefits#footnote-cost-of-100-miles-in-petrol-car
38. https://www.nrdc.org/stories/electric-vs-gas-it-cheaper-drive-ev
39. https://www.mdpi.com/2032-6653/8/4/996/pdf
40. https://newmotion.com/en/ev-driver-survey-report-2020/
41. https://www.edfenergy.com/electric-cars/benefits#footnote-cost-of-100-miles-in-petrol-car
42. https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf
43. https://www.infosys.com/industries/automotive/white-papers/documents/disruptor-automotive-ecosystem.pdf
44. https://www.tesla.com/en_GB/about
45. https://www.ft.com/content/65cad29a-b7c3-4f1c-bb69-443c1c063ed3, https://www.cnbc.com/2020/02/08/why-tesla-stock-seems-expensive-even-compared-to-other-tech-stocks.html

46. https://www.businessinsider.com/elon-musk-tesla-likely-20-million-electric-vehicles-year-2030-2020-9?r=US&IR=T#:~:text=Elon%20Musk%20says%20Tesla%20will,what%20it%20produced%20last%20year&text=CEO%20Elon%20Musk%20said%20Tesla,what%20Tesla%20produced%20in%202019
47. https://www.greencarreports.com/news/1130367_gm-s-27b-plan-450-mile-range-affordable-models-among-30-evs-by-2025
48. https://www.wsj.com/articles/auto-makers-charge-ahead-with-electric-vehicle-plans-11595156400
49. https://www.wsj.com/articles/auto-makers-charge-ahead-with-electric-vehicle-plans-11595156400
50. https://www.mckinsey.com/business-functions/marketing-and-sales/our-insights/how-consumers-behavior-in-car-buying-and-mobility-changes-amid-covid-19
51. https://www.iea.org/commentaries/as-the-covid-19-crisis-hammers-the-auto-industry-electric-cars-remain-a-bright-spot
52. https://webstore.iea.org/download/direct/3007
53. https://www.iea.org/commentaries/as-the-covid-19-crisis-hammers-the-auto-industry-electric-cars-remain-a-bright-spot
54. https://www.iea.org/commentaries/as-the-covid-19-crisis-hammers-the-auto-industry-electric-cars-remain-a-bright-spot
55. https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf
56. https://www.alixpartners.com/media/13453/ap-electric-vehicle-consumer-study-2019.pdf
57. Referring to all cars (both EVs and conventional vehicles) sold in Europe, plus Turkey and Israel.
58. https://www.jato.com/electric-cars-cost-double-the-price-of-other-cars-on-the-market-today/
59. https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/
60. https://www.jato.com/electric-cars-cost-double-the-price-of-other-cars-on-the-market-today/
61. https://www.ft.com/content/a7e58ce7-4fab-424a-b1fa-f833ce948cb7
62. https://www.economist.com/special-report/2013/04/20/the-great-powertrain-race
63. https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf
64. https://www.nissan.co.uk/vehicles/new-vehicles/leaf.html#:~:text=FOR%20CITY%20DRIVING-,A%20range%20up%20to%20168%20Miles,drives%20to%20school%20and%20work
65. https://www.tesla.com/en_gb/models
66. https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf
67. https://www.woodmac.com/news/editorial/electric-vehicle-range-anxiety-whats-your-limit/
68. https://www.mckinsey.com/~/media/mckinsey/industries/automotive%20and%20assembly/our%20insights/the%20road%20ahead%20for%20e%20mobility/the-road-ahead-for-e-mobility-vf.pdf
69. https://www.ucsusa.org/sites/default/files/attach/2019/07/2019-EV-Survey.pdf
70. https://www.virta.global/blog/ev-charging-101-how-much-electricity-does-an-electric-car-use#:~:text=An%20average%20electric%20car%20consumes%20approximately%200%2C20%20kWh%2Fkm.&text=On%20a%20daily%20basis%2C%20this%20makes%20approximately%2047%20kilometers%20of%20driving
71. https://www.transportenvironment.org/sites/te/files/publications/20180725_T%26E_Battery_Electric_Trucks_EU_FINAL.pdf
72. https://www.iea.org/reports/global-ev-outlook-2020
73. https://www.alixpartners.com/media/13453/ap-electric-vehicle-consumer-study-2019.pdf
74. https://dealercenter.cargurus.com/industry-insights/2019-electric-vehicle-survey/
75. https://www.transportenvironment.org/sites/te/files/publications/20180725_T&E_Battery_Electric_Trucks_EU_FINAL.pdf
76. Our analysis on the truck market excludes India and covers only the US and China as a result of the nascency of the EV truck market in India where sales are currently limited.
77. https://www.transportenvironment.org/sites/te/files/publications/20180725_T&E_Battery_Electric_Trucks_EU_FINAL.pdf
78. https://www.ft.com/content/a7e58ce7-4fab-424a-b1fa-f833ce948cb7
79. https://www.researchgate.net/publication/325536892_The_solutions_to_electric_vehicle_air_conditioning_systems_A_review/link/5cb34fd292851c8d22ec2d1f/download
80. https://www.researchgate.net/publication/266177060_Parameters_and_Models_of_the_Vehicle_Thermal_Comfort#:~:text=Thermal%20comfort%20in%20vehicles%20represents,%2Ddefined%20values%20%5B1%5D
81. https://www.tandfonline.com/doi/full/10.3109/02656736.2014.922222 ; https://pubmed.ncbi.nlm.nih.gov/8851073/ ;
82. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4762150/ ; https://www.researchgate.net/publication/277777938_High_Ambient_Temperatures_and_Risk_of_Motor_Vehicle_Crashes_in_Catalonia_Spain_2000-2011_A_Time-Series_Analysis
83. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4671248/#:~:text=Overall%2C%20the%20risk%20of%20crashes,driving%20performance%20in%20hot%20conditions.
84. https://www.sciencedirect.com/science/article/pii/S1364032111003418
85. Interview with Shyamasis Das.
86. https://www.porscheengineering.com/filestore/download/peg/en/pemagazin-01-2011-artikel-waermemanagementvonfahrzeugenmitelektrischemantrieb/default/78115e66-c26a-11e4-a19d-001a64c55f5c/Thermal-Management-in-Vehicles-with-Electric-Drive-System-Porsche-Engineering-Magazine-01-2011.pdf
87. https://www.nissan.co.uk/vehicles/new-vehicles/leaf.html#:~:text=FOR%20CITY%20DRIVING-,A%20range%20up%20to%20168%20Miles,drives%20to%20school%20and%20work
88. Interview with Cedric Rouaud
89. https://saemobilus.sae.org/content/2013-01-0040/
90. https://agronomy.emu.ee/wp-content/uploads/2017/04/Vol15SP1_Berjoza.pdf
91. https://www.researchgate.net/publication/260307927_Impact_of_driving_characteristics_on_electric_vehicle_energy_consumption_and_range
92. https://core.ac.uk/download/pdf/82767966.pdf
93. The only operating costs that we account for in this analysis are the costs of electricity to recharge EV batteries. Any additional maintenance costs or costs of battery replacement are excluded. In the case of PHEVs, the costs of other fuel requirements are excluded.
94. https://www.driverknowledgetests.com/resources/whats-a-refrigerated-trailer-and-how-does-it-work/
95. https://www.birmingham.ac.uk/news/thebirminghambrief/items/2018/04/a-cool-world-the-energy-conundrum-we-are-not-discussing.aspx
96. https://www.birmingham.ac.uk/Documents/college-eps/energy/Publications/india-third-agricultural-revolution-birmingham-energy-institute.pdf
97. http://naturalleader.com/wp-content/uploads/2016/04/UTC-Nottingham-Report_3-30_FINAL.pdf
98. http://www.gluckmanconsulting.com/wp-content/uploads/2015/04/FS-6-Transport-Refrigeration-final.pdf

99. https://www.grimsby.ac.uk/documents/defra/trns-refrigeenergy.pdf
100. The EIU estimates the average range for trucks with and without TRUs based on estimates of the average battery capacity and the electricity requirements per kilometre of travel. See the Methodology section of this report for further detail on the methodology and assumptions used in the analysis. As our estimate for cooling use in a refrigerated truck is more conservative relative to expert opinion, the impact of cooling on range could be even more significant.
101. In our analysis, the only operating costs that we account for are the costs of electricity to recharge EV batteries. Any additional maintenance costs or costs of battery replacement are excluded.
102. https://files.wri.org/s3fs-public/barriers-to-adopting-electric-buses.pdf
103. https://www.theguardian.com/uk-news/2015/sep/18/routemaster-buses-in-london-to-be-refitted-with-windows-that-open
104. https://metro.co.uk/2015/07/01/which-is-the-hottest-mode-of-transport-in-london-as-temperatures-hit-37c-5274910/
105. https://www.theguardian.com/uk-news/2015/sep/18/routemaster-buses-in-london-to-be-refitted-with-windows-that-open
106. https://www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300
107. https://www.greentechmedia.com/articles/read/global-electric-bus-adoption-is-set-to-triple-by-2025
108. https://www.greentechmedia.com/articles/read/global-electric-bus-adoption-is-set-to-triple-by-2025
109. https://wrirosscities.org/sites/default/files/how-to-enable-electric-bus-adoption-cities-worldwide.pdf 3
110. https://landtransportguru.net/electric-buses-in-singapore/
111. https://link.springer.com/article/10.1007/s12239-020-0015-x
112. https://www.semanticscholar.org/paper/Feasibility-of-Using-Air-Curtains-in-Urban-Buses-Pathak-Khoo/93142da92212be8fab683d7ae39528b72f8318d5?p2df
113. https://www.distributedenergy.com/home/article/13018675/guest-commentary-air-curtain-energysaving-advancements-open-doors-to-new-uses ; http://www.crossflowindia.com/Busair_curtains.html
114. https://openknowledge.worldbank.org/bitstream/handle/10986/34087/Mobile-Cooling-Assessment-of-Challenges-and-Options.pdf?sequence=4&isAllowed=y
115. https://www.glaciervehicles.com/vans/refrigerated/vapor-compression-refrigeration/; https://www.researchgate.net/publication/325536892_The_solutions_to_electric_vehicle_air_conditioning_systems_A_review/link/5cb34fd292851c8d22ec2d1f/download
116. Most systems also connect the AC system for the passenger cabin with the liquid cooling system needed for the battery in what is called a "secondary loop". The loop redirects cooling to wherever it is needed within the system, cabin or battery, or both.
117. https://medium.com/naturalrefrigerants/electric-cars-could-extend-driving-range-with-an-environmentally-friendly-heating-ac-system-d81400825d58
118. https://r744.com/articles/8495/vw_to_roll_out_co2_mac_in_new_electric_car_series
119. https://www.sae.org/publications/technical-papers/content/2019-24-0244/
120. https://www.sciencedirect.com/science/article/pii/S2095809918312529
121. https://www.sciencedirect.com/science/article/pii/S2095809918312529
122. https://heatisland.lbl.gov/sites/default/files/Cool_cars_final_LBNL_project_report_v015_2011-08-08.pdf
123. https://heatisland.lbl.gov/sites/default/files/Cool_cars_final_LBNL_project_report_v015_2011-08-08.pdf
124. https://www.sciencedirect.com/science/article/pii/S2095809918312529
125. https://easyelectriclife.groupe.renault.com/en/day-to-day/range/pre-conditioning-and-your-electric-cars-range/
126. https://www.jaguarwesthouston.com/research/cabin-pre-conditioning.htm
127. https://www.nrel.gov/docs/fy15osti/63551.pdf
128. https://www.nrel.gov/docs/fy15osti/63551.pdf
129. https://auto.howstuffworks.com/air-conditioned-seat.htm
130. https://www.greenbiz.com/article/ventilated-auto-seats-improve-fuel-economy-new-research-shows
131. The hottest part of the journey refers to the period of peak cooling power demand.
132. https://www.nrel.gov/docs/fy15osti/63551.pdf
133. https://theicct.org/sites/default/files/publications/PV_Tech_Trend_Thermal_20180917_0.pdf
134. http://www.igsd.org/wp-content/uploads/2019/03/ICCT-IGSD-Mobile-AC-2019.pdf
135. See the appendix for charts on emissions.
136. https://www.fluorocarbons.org/mac-systems-2019/
137. https://www.sciencedirect.com/science/article/pii/S2095809918312529
138. https://openknowledge.worldbank.org/bitstream/handle/10986/34087/Mobile-Cooling-Assessment-of-Challenges-and-Options.pdf?sequence=4&isAllowed=y
139. See the appendix for charts on emissions.
140. https://www.researchgate.net/publication/325536892_The_solutions_to_electric_vehicle_air_conditioning_systems_A_review
141. https://www.bmw.com/en/innovation/how-hydrogen-fuel-cell-cars-work.html#pwjt-1
142. https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit?gclsrc=aw.ds&gclid=CjwKCAiAkan9BRAqEiwAP9X6UYNNsS_Fn7ctrum4Q98-nBXeKUBon-3h2JKopgIC0MauPh248gNbExoCbOQQAvD_BwE&gclsrc=aw.ds
143. https://www.economist.com/science-and-technology/2017/09/25/electric-vehicles-powered-by-fuel-cells-get-a-second-look
144. https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit?gclsrc=aw.ds&gclid=CjwKCAiAkan9BRAqEiwAP9X6UYNNsS_Fn7ctrum4Q98-nBXeKUBon-3h2JKopgIC0MauPh248gNbExoCbOQQAvD_BwE&gclsrc=aw.ds
145. https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit?gclsrc=aw.ds&gclid=CjwKCAiAkan9BRAqEiwAP9X6UYNNsS_Fn7ctrum4Q98-nBXeKUBon-3h2JKopgIC0MauPh248gNbExoCbOQQAvD_BwE&gclsrc=aw.ds
146. This is the case unless the heat produced during the conversion is efficiently recovered and utilised, for example through the future thermal charging stations.
147. https://www.pv-magazine.com/2019/07/12/toyota-shows-off-solar-prius-with-860-w-output-from-34-efficient-cells/
148. https://www.pv-magazine.com/2019/07/12/toyota-shows-off-solar-prius-with-860-w-output-from-34-efficient-cells/
149. https://www.sae.org/news/2020/03/lightyear-one-solar-ev
150. https://www.torquenews.com/5474/how-can-tesla-battery-swap-work-now-after-million-mile-batteries

151. https://electrek.co/2020/01/17/ev-battery-swapping-is-dead-in-us-but-china-wants-to-make-it-happen/
152. https://www.autocar.co.uk/car-news/new-cars/renault-ends-battery-leasing-electric-zoe
153. https://www.autocar.co.uk/car-news/new-cars/renault-ends-battery-leasing-electric-zoe
154. https://electrek.co/2020/06/02/nio-battery-swap-electric-cars-completes-500000-swaps/
155. https://electrek.co/2020/06/02/nio-battery-swap-electric-cars-completes-500000-swaps/
156. http://www.ehcar.net/library/rapport/rapport079.pdf
157. https://media.rff.org/documents/WP_19-05_Leard.pdf
158. See the appendix for estimates of the reduction in CO2 emissions by fuel type from direct improvements to EV cooling systems and an increase in EV uptake.
159. https://webstore.iea.org/download/direct/3007
160. https://aeee.in/projects/ev-a-new-entrant-to-indias-electricity-consumer-basket/
161. https://www.energy.gov/articles/history-electric-car; https://www.iea.org/reports/global-ev-outlook-2020
162. https://www.ccacoalition.org/en/resources/global-green-freight-action-plan-reducing-climate-and-health-impacts-goods-transport#:~:text=The%20goal%20of%20the%20Global,freight%20transport%20around%20the%20world
163. https://www.ceres.org/news-center/press-releases/major-companies-join-new-alliance-accelerate-transition-electric
164. https://www.clean-cooling.ac.uk/resources/CleanCoolingLandscapeAssessment%2012-18.pdf
165. This includes working together to reduce emissions from refrigerants used in vehicle AC.
166. https://openknowledge.worldbank.org/bitstream/handle/10986/34087/Mobile-Cooling-Assessment-of-Challenges-and-Options.pdf?sequence=4&isAllowed=y

LONDON

20 Cabot Square
London, E14 4QW
United Kingdom
Tel: (44.20) 7576 8000
Fax: (44.20) 7576 8500
Email: london@eiu.com

GENEVA

Rue de l'Athénée 32
1206 Geneva
Switzerland
Tel: (41) 22 566 2470
Fax: (41) 22 346 93 47
Email: geneva@eiu.com

NEW YORK

750 Third Avenue
5th Floor
New York, NY 10017
United States
Tel: (1.212) 554 0600
Fax: (1.212) 586 1181/2
Email: americas@eiu.com

DUBAI

Office 1301a
Aurora Tower
Dubai Media City
Dubai
Tel: (971) 4 433 4202
Fax: (971) 4 438 0224
Email: dubai@eiu.com

HONG KONG

1301 Cityplaza Four
12 Taikoo Wan Road
Taikoo Shing
Hong Kong
Tel: (852) 2585 3888
Fax: (852) 2802 7638
Email: asia@eiu.com

SINGAPORE

8 Cross Street
#23-01 Manulife Tower
Singapore
048424
Tel: (65) 6534 5177
Fax: (65) 6534 5077
Email: asia@eiu.com