

Electric Vehicle Uptake and Health

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Question

What is the relationship between electric car uptake and health including:

- *Impact on local air quality (qualitative and quantitative): particulate matter, NOx, and other relevant pollutants*
- *Potential impact on fossil fuel use, and implications for climate change and air quality*
- *Factors/considerations in gaining maximum health gain from electric car uptake (including supporting infrastructure)*

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1. Summary

This rapid literature review summarises evidence on the *relationship between electric car uptake and health*. The review found a limited but emerging evidence base derived predominantly from studies exploring the issue in the United States (US), China and Europe. The evidence base provides a mixed and complex picture given the heterogeneity of methodological approaches and contextual analyses to assessing impact. The report is structured as follows.

- Section 2 provides an overview of transport and pollution and its impacts on health
- Section 3 provides an annotated bibliography of literature that explores the health impacts of Electric Vehicles (EVs)
- Sections 4 and 5 provide an overview of the broader societal benefits and negative impacts of EV uptake
- Section 6 and 7 explore enablers and constraints to growth and impact of EVs

Transport analysts have predicted that the global car fleet of circa 1.2 billion (2018) could double by 2030. This growth has prompted concerns regarding the relationship between motorised transport, air quality and impacts on health, particularly in urban areas.

Transportation activities produce tailpipe and evaporative emissions, resuspension of road dust and particles from brake and tyre wear which impact on health. Globally, transportation is a major source of pollution, contributing to elevated levels of fine particulate matter (PM_{2.5}), ozone (O₃), and nitrogen dioxide concentrations etc.

Exposure to high concentrations of these pollutants has been reported to increase incidence of illness including Chronic Obstructive Pulmonary Disease (COPD), asthma, lung disease, heart disease and premature death thus having a direct impact on quality of life and the economy.

The World Health Organisation (WHO) estimates that more than 80% of people living in urban areas are exposed to air quality levels that exceed recommended (WHO) limits¹, threatening lives, productivity and economies.

Air pollution from all sources has fallen in many, though not all, countries in the global north in recent years, helped by stricter policies on emissions from vehicles. However, this has been offset by the switch to more polluting diesel vehicles. In contrast, **emissions are increasing in many low and middle income countries of the global south.** In China and India, air pollution is a particular concern related to the rapid growth in vehicle ownership that is outpacing the adoption of tighter controls on emissions from vehicles

The direct and indirect implications of vehicular emissions on the environment and human health highlight that current transportation systems are unsustainable, from environmental (air pollution and greenhouse gases (GHGs)), health (health impacts) and economic perspectives (cost of air pollution). One potential intervention to address this issue is the development and roll out of EVs.

¹ The WHO sets a limit of PM_{2.5} 25 µg/m³ 24-hour mean

Electric mobility can potentially transform the global transportation sector to provide more environmentally friendly and sustainable mobility options that can help in reducing air pollution, GHG emissions and health risks.

The global stock of EVs reached 1 million in 2015 and passed 2 million in 2016. As of 2020, there were 20 million electric cars on the world's roads (IEA, 2021: i). Electric car registrations increased by 41% in 2020. This rapid rise has been led by China, the US, Japan and several European countries.

The uptake of EVs has been driven by a number of factors, including technological progress, cost reductions (especially batteries), and policy support, including purchase incentives, driving and parking access advantages, and increased public charging infrastructure availability (IEA, 2021).

Evidence on the health effects associated with electric mobility is scarce. A limited number of papers have performed health analyses, of which studies from the US and China dominated, evidence drawn from Europe are emerging. Data from the global south is needed, particularly contexts where vehicle ownership is expected to grow rapidly (e.g. Uganda).

The studies identified by this rapid review highlighted that EV uptake supports reductions in GHG emissions and emissions of some criteria air pollutants. They do, however, suggest that increases or decreases (particularly of PM and SO₂) from EV uptake were dependent on context (i.e. linked to the nature of the energy grid, weight of EVs etc.).

When considering the EVs, it is important to note that **non-exhaust vehicle emissions arise irrespective of the fuel source As such it's important to consider the displacement of emissions from the vehicle itself to further up the energy-supply chain**, for example at an electricity generating facility, depending on the source of the electricity.

The limited literature on health effects highlights that a core aspect between EVs and human exposure is that pollution is shifted from urban areas (tailpipe emissions) to predominantly sub-urban or rural areas (location of power plants, considering that energy is generated from fossil sources).

A further consideration is that as tailpipe emissions are either reduced or eradicated by EVs, **the impact of non-exhaust emissions associated with usage becomes important. These include break and tyre wear as well as impact of road wear and dust resuspension.** Whilst these are issues associated with most forms of vehicular transport, reports suggest that switching to BEVs will increase particle pollution due to their heavier weight compared to conventional cars – particularly from tyre and break wear. However, there is a need for more comprehensive studies measuring non-exhaust particle emissions, especially of EVs.

In the US, studies estimated that electrification of vehicle fleets in urban areas leads to significant health benefits, even with EVs powered exclusively by fossil fuel plants. Vehicle Miles Travelled (VMT) – weighted mean benefits in the 53 urban areas are 6.9 ¢/mile (\$10,400 per 150,000 miles), 83% of which (5.7 ¢/mile or \$8600 per 150,000 miles) comes from reductions in PM_{2.5} attributable mortality.

A more mixed picture is provided by studies exploring the issue in China. Authors of one study conclude that vehicle emissions are being transferred to power plants, potentially yielding

dramatic exposure reduction. In some but not all cases, this transfer of emissions is expected to improve overall public health. However, this shift also transfers impacts to nonusers of the urban EVs, including potentially to low-income rural populations.

An emerging message in the literature is that EVs should be developed according to the cleanness of regional power mixes. This would lower their SO₂ and NO_x emissions and earn more GHG reduction credits. This has particular salience when considering efforts to incentivise uptake of EVs in the global south and north.

Studies drawn from the US suggest that in the majority of plausible scenarios of balanced growth, when the number of EVs and charging stations rises, there is a positive net benefit to society. The authors suggest that the migration from polluting vehicles to electric vehicles, ideally using electricity generated sustainably could significantly reduce the incidence of cardiopulmonary illness due to air pollution. This would lead not only to less employee absence from work through illness but also lead to broad improvements in quality and length of life.

Some consideration will also need to be paid to the nature of the vehicle fleet in particular areas and how targeted electrification can meet different objectives. In China, for example, widespread adoption of heavy-duty EVs would reduce nitric oxide and fine PM resulting in 562 (95% CI 410–723) fewer premature acute deaths. However, widespread adoption of heavy-duty electric vehicles does not reduce carbon dioxide emissions without the addition of emission-free electricity generation. By contrast, widespread adoption of light-duty electric vehicles robustly reduces carbon dioxide emissions, but results in lesser air quality improvements and fewer premature deaths avoided (145 [95% CI 38–333]) than the heavy-duty scenario.

Overall, the positive benefits of EVs for reducing GHG emissions and human exposure depends on the following factors with more studies needed to probe these issues :

- Type of EV,
- Source of energy generation,
- Driving conditions,
- Charging patterns,
- Availability of charging infrastructure,
- Government policies,
- Driving behaviours,
- Non-exhaust emissions
- Climate of a region.

This review concludes that, whilst promising, more evidence is needed about the potential air quality and public health benefits of EVs, including

- Optimal vehicle type prioritisation and the vehicles' ability to reduce acute health impacts due to air pollution.
- How air quality and climate interventions can operate in tandem to ensure the roll out of EVs has the desirable impact (i.e. decarbonising power generation and regenerative braking).
- Future modelling of transport needs to ensure targeted interventions.

- Analysis of the impact of interventions in different geographic areas.
- Analysis of the type of EVs that should be supported in different geographical locations.
- How the roll out of EVs can support ambitions for a green recovery from Covid-19 and the development of circular economies.
- The need for more studies focussed on the global south.

2. Transport and Ambient Pollution

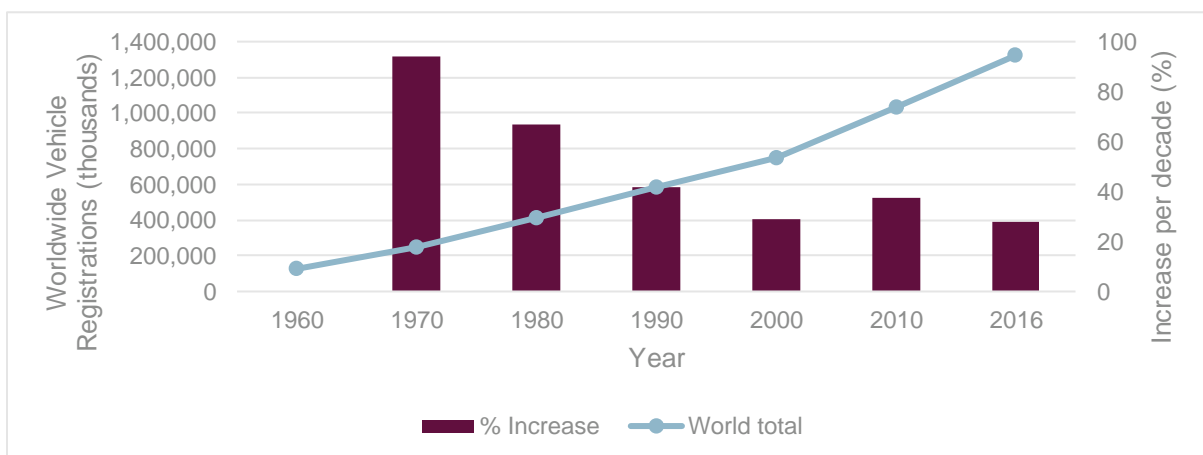
Transport analysts have predicted that, on the existing trajectory, the global car fleet of circa 1.2 billion could double by 2030 (World Bank, 2017: 6 – see table 1 and figure 1). In 2018, the majority of vehicles were powered by internal combustion engines (ICEs) that burn fossil fuels to create the mechanical energy required to drive the vehicle forward. ICEs are considered to be inefficient at converting fuel’s chemical energy to mechanical energy, losing energy to friction, pumping air into and out of the engine and wasted heat (Anenberg et al., 2019). Whilst the growth of the transport sector has brought advantages e.g. flexibility and access, it also has disadvantages. In particular, motorised transport is associated with a number of environmental, social and economic issues.

Table 1: Historical trend of worldwide vehicle registrations

1960-2016									
	1960	1970	1980	1990	2000	2005	2010	2015	2016
Car registrations	98,305	193,479	320,390	444,900	548,558	617,914	723,567	923,590	973,353
Truck and bus registrations	28,583	52,899	90,592	138,082	203,272	245,798	309,395	337,250	348,919
World total	126,888	246,378	410,982	582,982	751,830	863,712	1,032,962	1,260,840	1,322,272

Source: Stacy et al. (2020) https://en.wikipedia.org/wiki/Motor_vehicle CC BY-SA 3.0

Figure 1: Historical trend of worldwide vehicle registrations



Source: Author's own. Created using data from Stacy, et al. (2020) https://cta.ornl.gov/data/tedbfiles/Edition36_Full_Doc.pdf

Concerns regarding the relationship between motorised transport, air quality and impacts on health have become prominent, particularly in urban areas. The World Health Organisation (WHO) estimates that more than 80% of people living in urban areas are exposed to air quality levels that exceed recommended (WHO) limits², threatening lives, productivity and economies. In a context of rapid urbanisation, the WHO estimates that globally, from 2008-2013, urban air pollution³ levels increased by 8% and are expected to rise further given continuing rapid urban development.

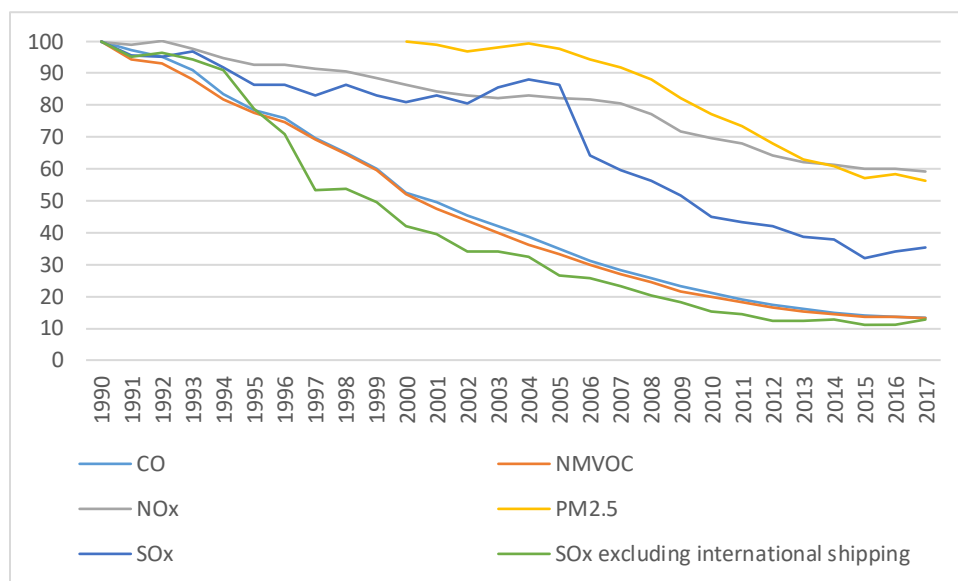
Transportation activities produce tailpipe and evaporative emissions, resuspension of road dust and particles from brake and tyre wear which impact on health (Rodrigue, 2020). Globally, transportation is a major source of air pollution, contributing to elevated levels of fine particulate matter (PM_{2.5}), ozone, and nitrogen dioxide concentrations etc. Transportation emissions are influenced by many factors, including economic development, (e.g. increased personal vehicle ownership and freight activity); changes in fuel quality and introduction of emission controls on vehicles and engines to comply with environmental standards. Emissions are further influenced by population size, activity (passengers per km), use efficiency (vehicles per km/passengers per km), fuel efficiency (litres/vehicles per km) and emission factors (grams/litres). For these reasons, transportation emissions change rapidly both over time and between countries (Anenberg et al., 2019).

Air pollution from all sources has fallen in many, though not all, countries in the global north in recent years, helped by stricter policies on emissions from vehicles. However, this has been offset by the switch to more polluting diesel vehicles. In contrast, emissions are increasing in many low and middle income countries of the global south. In China and India air pollution is a particular concern related to the rapid growth in vehicle ownership that is outpacing the adoption of tighter controls on emissions from vehicles (OECD, 2014).

² The WHO sets a limit of PM_{2.5} 25 µg/m³ 24-hour mean

³ **Air pollution** is the name for extremely small particles and gases in the **air** which can cause harm if you breathe them in. These include: gases such as nitrogen dioxide, ozone, sulphur dioxide and carbon monoxide. Particulate matter (PM), made up of solid and liquid particles such as soot and dust.

Figure 2: Trends in emissions of air pollutants from transport



Source: EEA, 2019. Reproduced under CC BY 2.5 DK.

Although transport emissions per capita in the global south are relatively low compared to OECD countries, around 90% of the increase in global transport-related carbon dioxide (CO₂) emissions is expected to occur in such settings resulting from increased vehicle ownership and freight distribution. LICs and MICs also suffer disproportionately from transport-generated pollution, particularly in Asia, Africa and the Middle East associated with the use of old and inefficient diesel vehicles and a lack of public and active transport networks (Anenberg et al., 2019).

Air pollutants, both exhaust and non-exhaust, commonly attributed to transport include carbon monoxide (CO), nitrogen oxides (NO and NO₂), volatile organic compounds (VOCs), ozone (O₃) and aerosol particles with a diameter less than 2.5µm (PM_{2.5}) (see Box 1 for more details). Exposure to high concentrations of these harmful pollutants has been reported to increase incidence of illness including Chronic Obstructive Pulmonary Disease (COPD), asthma, lung disease, heart disease (WHO, 2004) and premature death thus having a direct impact on quality of life and the economy (see next sub-section for more of a discussion of health impacts). It is also important to note that the impacts of air pollution can compound the effects of other environmental problems in complex ways.

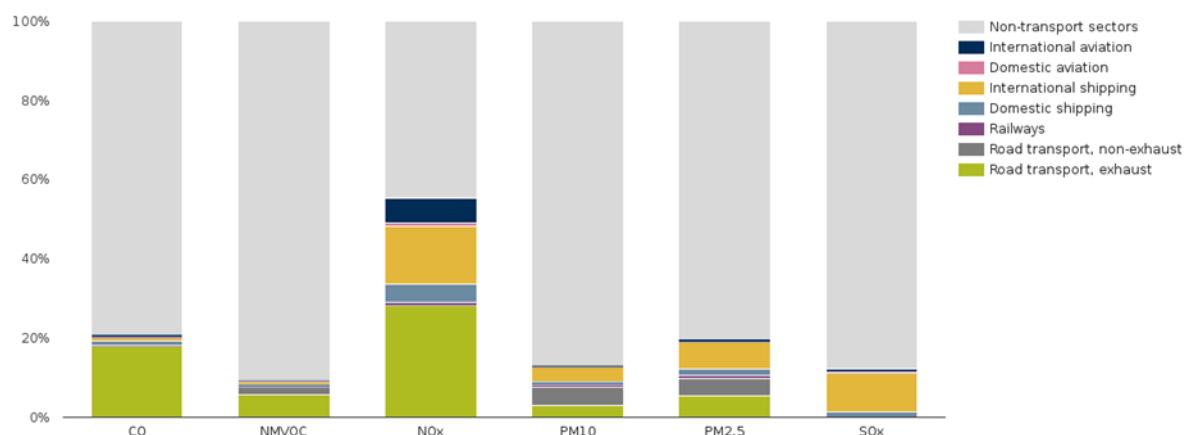
Box 1: Major pollutants from ICE vehicles

- **Particulate matter (PM):** Particles, measuring >10 micrometres in size (i.e. PM₁₀ and PM_{2.5}, can impact on human health. Particles in diesel vehicle exhaust are a major cause of PM pollution.
- **Volatile Organic Compounds (VOCs):** VOCs react with nitrogen oxides to form ground-level ozone. At ground level, ozone irritates the respiratory system, causing coughing, choking and reduced lung capacity. VOCs have been linked to some forms of cancer.
- **Nitrogen oxides (NO_x):** These pollutants form ground-level ozone and PM. NO_x can lead to lung irritation and increase susceptibility to respiratory infections like pneumonia and the flu.
- **Carbon monoxide (CO):** Formed when fossil fuels are burned. When inhaled, CO blocks oxygen from the brain, heart and other vital organs.
- **Greenhouse gases (GHG):** ICE vehicles emit carbon dioxide and other pollutants that contribute to global warming. Global warming is responsible for a range of public health risks. It has been linked to more frequent and intense heat waves as well as flooding, droughts and rising sea levels. Global warming and can give rise to spikes of infectious diseases.
- **Sulphur dioxide (SO₂):** Diesel fuel contains sulphur, creating sulphur dioxide when it is burned. SO₂ can react in the atmosphere to form PM, posing a particular risk to young children and asthma sufferers.

For a detailed discussion of Health Effects of Transport Related Air Pollution (2005)
https://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf

Whilst this review focuses on cars (and to a lesser extent buses) it is also important to consider the contribution to air pollution of other vehicles including aviation, shipping and rail etc. (see Figure 3).

Figure 3: Contribution of the transport sector to total emissions of the main air pollutants



Source: EEA, 2019. Reproduced under CC BY 2.5 DK.

Commentators suggest that the direct and indirect implications of vehicular emissions on the environment and human health highlight that current transportation systems are unsustainable, from environmental (air pollution and GHGs), health (health impacts) and economic perspectives (cost of air pollution) (IPCC, 2014).

The growing demand for motorised transport as well as concerns about air pollution represents both a challenge and an opportunity to capitalise on new vehicle technologies, and generate economic development benefits. One potential intervention to address this issue is the development and roll out of electric vehicles (EVs). Electric mobility has the potential to transform the global transportation sector and provide more environmentally friendly and sustainable mobility options that can help in reducing air pollution, GHG emissions and health risks. To deliver on the potential of EVs, a number of initiatives need to be rolled out in tandem including energy grid decarbonisation as well as efforts to address non-exhaust emissions (e.g. regenerative braking and plastic roads).

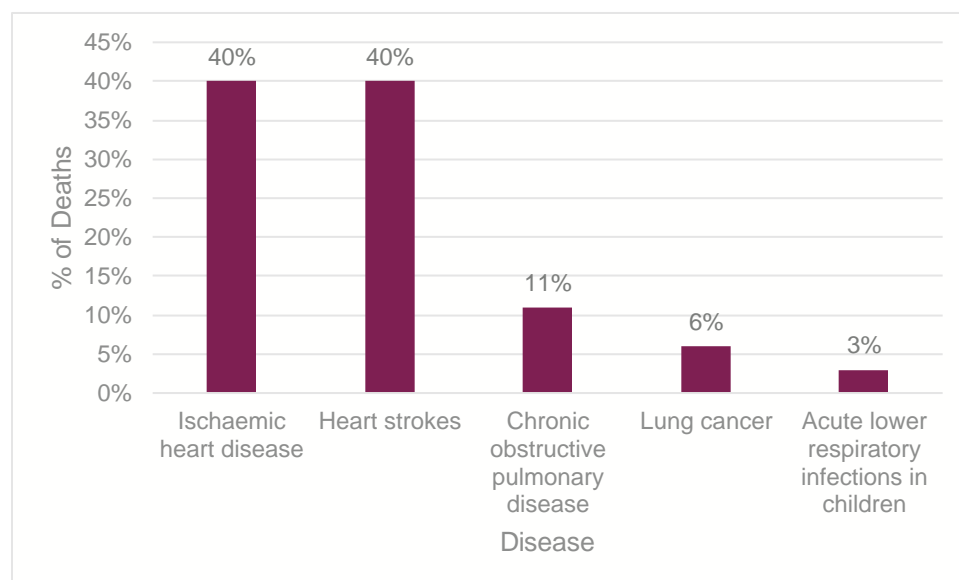
Transport Emissions and Impact on Health

The effects of air pollution on human health are well documented in a range of epidemiological studies; exposure increases the risk of lung cancer, heart disease, bronchitis and other cardiorespiratory conditions (Kelly & Fussell, 2015). The economic cost of this health loss is also significant, the World Bank estimates that globally in 2013 air pollution led to \$5.11 trillion in welfare losses, and \$225 billion in lost labour income (World Bank & IHME, 2016). The World Bank concludes that air pollution “is not just a health risk but also a drag on development... causing illness and premature death, air pollution reduces the quality of life. By causing a loss of productive labour, it also reduces incomes” (ibid: 2).

According to the WHO (2014), outdoor air pollution kills more than 3.5 million people a year globally (see Figure 4 for a breakdown by disease) and has now become the biggest environmental cause of premature death, overtaking poor sanitation and a lack of clean drinking water. In OECD countries, road transport is likely responsible for about half of this death toll. In most OECD countries, the death toll from heart and lung diseases caused by air pollution is much higher than

from traffic accidents. In turn the OECD (2014) has estimated that people in its member countries would be willing to pay USD 1.6 trillion to avoid deaths caused by air pollution.

Figure 4: Global outdoor air pollution caused deaths. Breakdown by disease



Source: Author's own. Created using data from WHO, 2014.

https://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf

A variety of sources are responsible for air pollutants and these vary across contexts. In many developing and emerging economies, small boilers are important sources. Air pollution from heating and cooking is also a major cause of death. Electricity generation, industry and shipping (in coastal areas) also generates harmful air pollutants. However, in many countries, road transport is a growing and sometimes the major source of air pollutants (OECD, 2014).

Studies that have examined the impact of transport related emissions on mortality have highlighted the extent of the issue. Anenberg et al, (2019: i) estimated that emissions from the transportation sector were responsible for 11.7% of global PM_{2.5} and ozone mortality in 2010 and 11.4% in 2015. Despite growth in vehicle ownership and vehicle distance travelled, the global fraction of air pollution-related premature deaths that are attributable to transportation tailpipe emissions stayed approximately the same, reflecting transportation emissions reductions in a number of key settings and increases in others. More research is, however, required to explore the geographical distribution of morbidity and mortality and the extent to which increased vehicle use in the global south has offset improved emission standards in the global north.

According to Anenberg et al. (2019), previous estimates of the global mortality burden from transportation emissions attributable to PM_{2.5} and ozone range from 165,000 in 2010 (Lelieveld et al. 2015) to 376,000 in 2005 (Silva et al., 2016) (see Table 2 for comparison of estimates). These estimated premature deaths correspond to 5% to 10% of global PM_{2.5} mortality and 16% of global ozone mortality.

Table 2: Comparison of global results from this study with other estimates in the literature

Study	Analysis Year	Sector Description	Methods	Result
Anenberg et al. (2019)	2010	Tailpipe emissions from on-road diesel, other on-road, shipping, non-road mobile sources	PM2.5 RR: GBD 2017 IER Ozone RR: GBD 2017 Resolution: 0.1°x0.1° Emissions: ICCT (Miller & Jin, 2018), ECLIPSE (Klimont et al., 2017; Stohl et al., 2015)	Deaths: 361,000 (258,000–462,000) TAF: 11.7%
Anenberg et al. (2019)	2015	Tailpipe emissions from on-road diesel, other on-road, shipping, non-road mobile sources	Ibid	Deaths: 385,000 (274,000–493,000) TAF: 11.4%
Chambliss et al. (2014)	2005	all mobile equipment powered by gasoline and diesel engines such as on-road passenger vehicles and commercial trucks, rail transportation, off-road agricultural and construction equipment	PM2.5 only: GBD2010 IER Resolution: 0.5° x 0.67° Emissions: Representative Concentration Pathway 8.5 (van Vuuren et al., 2011)	Deaths: 242,000 TAF: 8.5%
Lelieveld et al. (2015)	2010	Road and non-road transport on land	PM2.5 RR: GBD2010 IER Ozone RR: Ostro (2004) Resolution: 1.1° x 1.1° Emissions: Emissions Database for Global Atmospheric Research (EDGAR)	Deaths: 165,000 TAF: 5%
Silva et al. (2016)	2005	Land transportation, shipping, and aviation	PM2.5 RR: GBD2010 Ozone RR: Jerrett et al. (2009) Resolution: 0.5° x 0.67° Emissions: Representative Concentration Pathway 8.5 (van Vuuren et al., 2011)	Deaths: 376,000 TAF: 13.8% of anthropogenic PM2.5- and ozone related deaths
Weagle et al. (2018)	2014	Transportation	Concentration only Resolution: 0.1° x 0.1° Emissions: EDGAR v4.3 (Crippa et al., 2016), MIX (Li et al., 2017)	TAF: 8.6%

Source: Author's own. Created using data from Anenberg et al., 2019; Chambliss et al., 2014; Lelieveld et al., 2015, Silva et al., 2016, and Weagle et al., 2018.

Note: RR = relative risk; IER = Integrated Exposure Response curve; ICCT = International Council on Clean Transportation; GBD = Global Burden of Disease; TAF = Transportation-attributable fraction.

More broadly, despite recent progress in the adoption of more stringent vehicle emission standards, transportation emissions remain a major contributor to ambient air pollution and its associated health impacts at the global, national, and urban scales (Anenberg et al. 2019). At the global scale, comparison of estimates for 2005, 2010, and 2015 indicates that the health impacts of transportation emissions are increasing rather than decreasing. It is clear that further efforts are needed to develop emissions standards, expand the global uptake of standards; strengthen compliance and enforcement practices; and, importantly in the context of the report, to accelerate fleet turnover to remove vehicles and equipment with older technology.

It is broadly accepted that air pollution varies by location. As noted by the OECD (2014) economic growth brings a societal demand for clean air, but it also brings a rise in vehicle ownership and vehicle kilometres driven. Between 2008 and 2011, China's car population doubled from around 50 million to circa 100 million. While in OECD countries there has been a downward trend in emissions of pollutants from road transport over the last two decades, this has been off-set by a shift from less-polluting gasoline vehicles to more-polluting diesel vehicles. As a result, mortalities have not fallen in line with the overall decrease in air emissions. In much of the rest of the world, the shift to diesel has reinforced the prevailing upward trends in emissions. In India, this tendency has historically been amplified by large subsidies for diesel (OECD, 2014: 4). Air quality is now an issue of concern with initiatives and civil society campaigns focused on the issue. Public concern around the issue is increasing, driven by increasing evidence of the links between ill health and poor air quality (see box 2).

Box 2: *Ella Adoo-Kissi-Debrah Air pollution death ruling (BBC, 2020 - <https://www.bbc.co.uk/news/science-environment-55352247>)*

On 16 December, Southwark Coroner's Court in London found that air pollution "made a material contribution" to the death of nine-year-old Ella Adoo-Kissi-Debrah. At the conclusion of the two-week inquest, Mr Barlow said Ella had been exposed to "excessive" levels of pollution. The pollutants included nitrogen dioxide (NO₂) - a gas emitted by combustion engines that can irritate the airways and aggravate respiratory diseases.

She had lived near the South Circular Road in Lewisham and died in 2013, following an asthma attack. Ella had a rare type of acute asthma; she was particularly susceptible to the toxic gases and particles in air pollution. In his verdict, the coroner Philip Barlow said the cause was "multi-factorial. It was down to both genes, and the environment". Levels of NO₂ near Ella's home exceeded WHO and European Union guidelines.

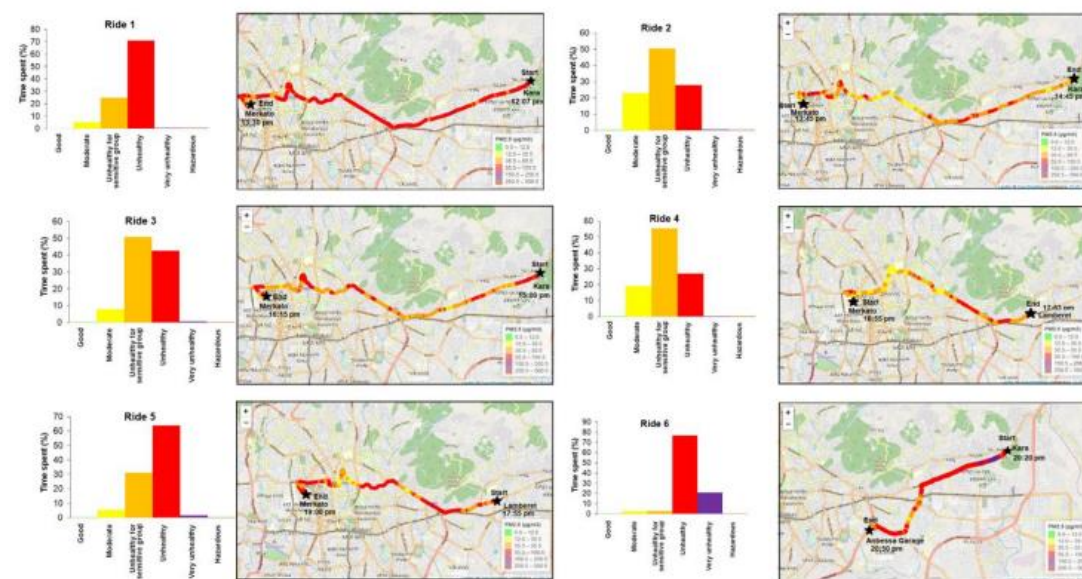
Of the direct effects, studies have reported that air pollutants emitted by vehicles are associated with asthma (Gonzalez-Barcala et al., 2013; Svendsen et al., 2012), high blood pressure (Cao et al., 2011; Weichenthal et al., 2014), lung cancer (Fajersztajn et al., 2013; Guo et al., 2016), diabetes, Alzheimer's disease (Cacciottolo et al., 2017), dementia, and premature deaths (Guo et al., 2016; Jerrett et al., 2013; Kloog et al., 2012).

Emissions from traffic are also associated with indirect human health effects that result from increasing atmospheric GHGs and associated changes in climate. Public health impacts are projected to increase due to climate change and extreme weather events (e.g., storms, floods, and droughts), increasing number of wildfires, and variations in levels of air pollutants (both indoor and ambient air pollution) (IPCC, 2014). For example, mortality (total deaths) increased by 50% in Europe in the summer of 2003 due to a heat wave and O₃ exposure (Dear et al., 2005). Carreras et al. (2015) reported that temperature range is a strong risk factor for hospital admissions from respiratory infections due to PM exposure in South America

Box 3: Exposure of Bus Drivers and Commuters to Transport Related Air Pollution in Addis Ababa (Avis et al., 2018)

Studies have also explored the issue of occupational exposure. The work of Ngo et al. (2015) explored average exposure to PM_{2.5} µg/m³ amongst bus drivers, mechanics and street vendors in Nairobi during an eight hour period. Findings suggested that bus drivers and street vendors may be particularly vulnerable to air pollution due to prolonged exposure in highly polluted areas.

Findings from Avis et al. (2018) illustrate that bus drivers and commuters who spend extended periods of time on Addis Ababa’s roads are exposed to consistently poor air quality. Across the journey’s studied air quality levels ranged between PM_{2.5} 49 ± 19 µg/m³ and 105 ± 45 µg/m³. According to the US EPA air quality index, this range entails air quality that is consistently unhealthy for sensitive groups or unhealthy. Histograms illustrate the percentage of each journey spent in different levels of air quality and highlight the consistently poor air quality that bus driver’s and commuters are exposed to during the study period.



Source: Avis et al., (2018).

Whilst air pollution impacts on all who are exposed, understanding vulnerability to air pollution presents a unique challenge for researchers. Authors commonly refer to vulnerability as the level of exposure of human life, property and resources to the impact from hazards (in this case air pollution) (Fussell, 2007; O’Brien et al., 2009). Factors, such as sex, age, education, and occupational exposure can modify the relationship between hazards and mortality (Kan et al.,

2008). Further to this, the effects of air pollution exposure on health are considered greater in people from lower socioeconomic backgrounds (O’Neil, 2003). The WHO (2004: 30) defines vulnerability as “the likelihood of being unusually severely affected by air pollutants either as a result of susceptibility to the effects of these substances or as a result of a greater than average exposure”. When considering the impact of air pollution on health it is therefore important to consider how this may vary from area to area, group to group and individual to individual (see box 3 on occupational and commuter exposure in Addis Ababa – Ethiopia).

3. Assessing the Health Impacts of EVs

EVs

The global stock of EVs (see box 4) reached 1 million in 2015 and passed the 2 million in 2016. As of 2020, there were 20 million electric cars on the world’s roads (IEA, 2021: i). Electric car registrations increased by 41% in 2020. This rapid rise has been led by China, the US, Japan and several European countries. Despite the pandemic-related worldwide downturn in car sales in which global car sales dropped 16%, around 3 million electric cars were sold globally in 2020 (a 4.6% sales share), and Europe overtook China as the world’s largest EV market for the first time. Electric bus and truck registrations also expanded in major markets, reaching global stocks of 600,000 and 31,000 respectively (IEA, 2021: i).

Box 4: Overview of Electric Vehicles

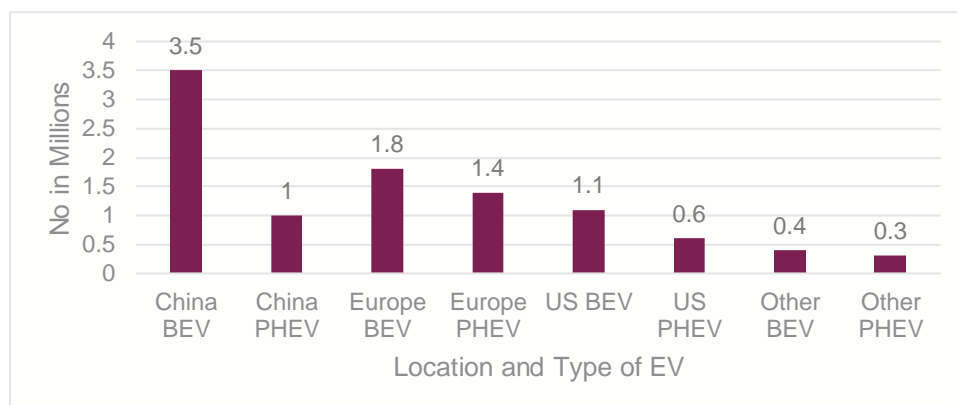
Electric vehicles use electric motors to drive their wheels. They derive some or all of their power from large, rechargeable batteries. The distance an EV can drive between recharges is known as its range. Different categories of EV include:

- **All-electric EVs/Battery Electric Vehicles (BEVs)**, where the battery is the only power source. Most current (non-luxury) models have a quoted range of 80-120 miles (130-190 km). In practice, range varies according to driving style, terrain and the use of auxiliary equipment such as heating/air conditioning.
- **Plug-in Hybrids (PHEVs)** can switch between running on electricity or fossil fuels. They typically have a smaller battery, and therefore a lower battery powered range of between 10-40 miles (15-60 km). However their maximum range is equivalent to a petrol car. Both plug-in hybrid and all-electric EVs are recharged by plugging them in to the electricity grid (see image).
- **Hybrids (HEVs)** which do not plug in, such as the Toyota Prius, have a much smaller battery which is recharged while driving. HEVs can drive in electric mode for a few miles.
- **Fuel Cell Vehicles** generate their own electricity on-board from a fuel such as hydrogen, and do not need to plug in to the electricity grid to recharge. Re-fuelling is similar to a petrol car.

The uptake of EVs has been driven by a number of factors, including technological progress, cost reductions (especially batteries), and policy support, including purchase incentives, driving and parking access advantages, and increased public charging infrastructure availability (IEA, 2021). Past and current governments have supported measures to encourage uptake of EVs as they contribute to a wide range of transport policy goals. These include improving air quality and reducing noise pollution. The uptake may also have an important role in the ‘least cost pathway’ to the 2050 net zero greenhouse gas emission target (IEA, 2021).

Battery electric vehicles (BEVs) dominated sales over plug-in hybrid electric vehicles (PHEVs) in most countries until 2014, but PHEV sales have grown, and as of early 2016 were nearly equal to BEV sales worldwide (see Figure 5). PHEVs have a considerable range advantage but sacrifice all-electric driving to achieve this (IEA, 2021) (see Image 1).

Figure 5: Global electric passenger car stock, 2020



Source: Author's own. Created using data from IEA, 2021

Image 1: Schematic of different types of Electric Vehicles (EVs) and their sources and consumption of energy and emission from tailpipe and energy generation. (*) The quantitative information presented here is for visual purposes only. This information is not standardised or quantitative. () Since technology may vary between power plants, the authors did not present quantitative information for visual purposes.**

This image has been removed for copyright reasons. The image can be viewed at <https://doi.org/10.1016/j.atmosenv.2018.04.040>

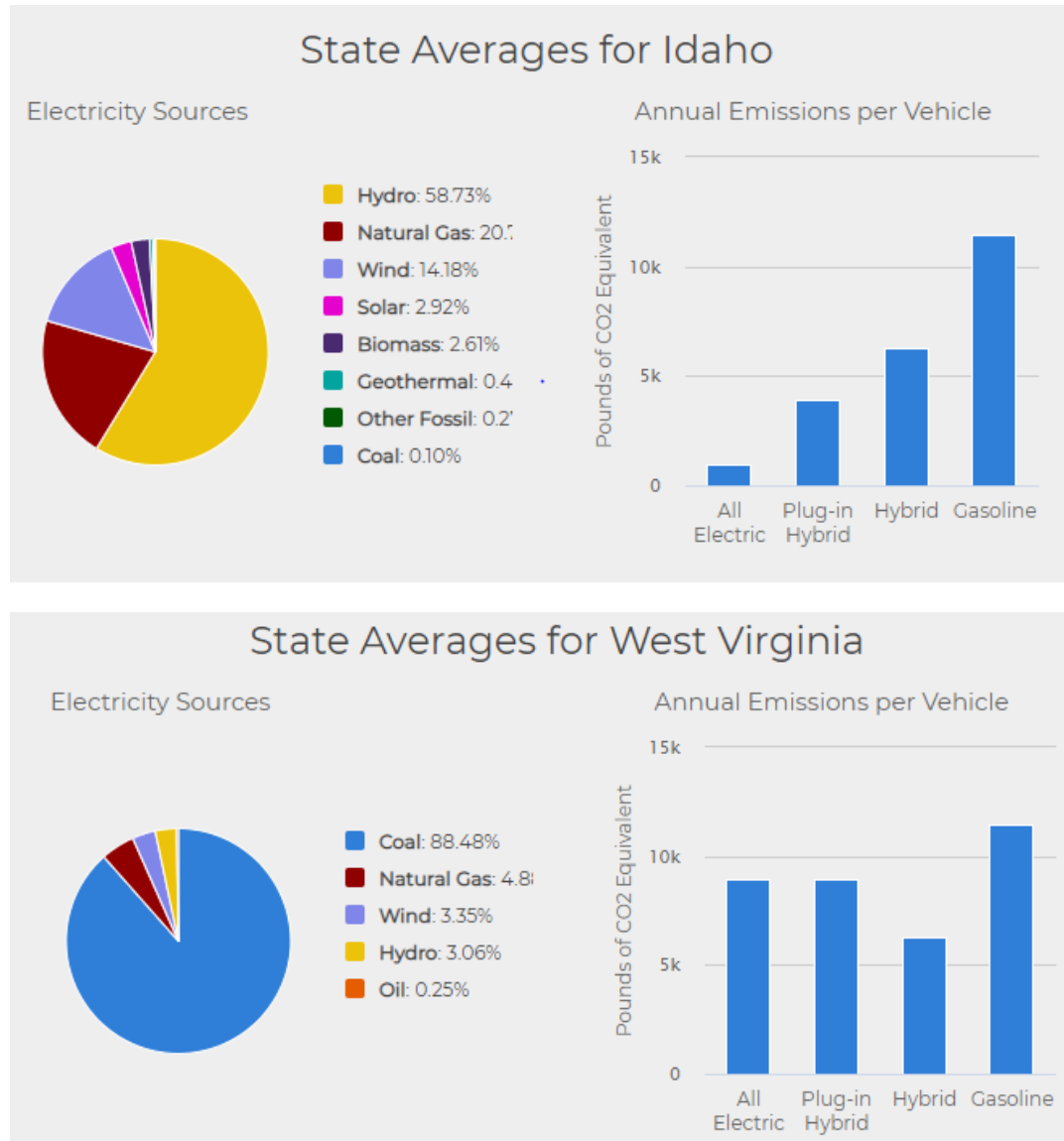
Source: Requía et al, 2018: 66

When considering the EVs, it is important to note that non-exhaust vehicle emissions arise irrespective of the fuel source (conventional fuel, electric, fuel-cell, hydrogen, etc.). As such it is important to consider the displacement of emissions from the vehicle itself to further up the energy-supply chain, for example at an electricity generating facility, depending on the source of the electricity.

As illustrated above, the generation of electricity used to both charge EVs, as well as in the manufacturing process accounts for a significant % of emissions related to EVs. ICCT (2018) comment that increased renewable energy and more efficient power plants will support the decarbonisation potential of EVs. According to ICCT (2018: 6-7), “the carbon intensity of electricity is expected to drop by more than 30% by 2030 in most markets that still have relatively high fossil fuel combustion”. An example of the impact that the source of electricity has on the carbon reduction potential of EVs can be drawn from the US (US Department of Energy – Alternative Fuels Data Centre⁴). Here it is shown that where electricity is derived from coal power stations the potential impact of EV is significantly reduced when compared to those states where electricity is generated from renewable sources.

⁴ https://afdc.energy.gov/vehicles/electric_emissions.html

Figure 5: Electricity Sources and Emissions



Source: U.S. Department of Energy. Reproduced under *Copyright terms*.

A further consideration is that as tailpipe emissions are either reduced or eradicated by EVs, the impact of non-exhaust emissions associated with usage becomes important. These include brake and tyre wear as well as impact of road wear and dust resuspension. Whilst these are issues associated with most forms of vehicular transport, the increased weight of EVs may exacerbate these issues. As noted by the UK Governments Air Quality Expert Group (2019), non-exhaust emissions from road traffic contribute to airborne concentrations of both fine and coarse particles and that estimates from the National Atmospheric Emissions Inventory indicate that the emissions from brake wear, tyre wear and road surface wear collectively now exceed those from the exhaust of the UK vehicle fleet.

Pollution and EVs

Particles: Energy generation accounts for a significant amount of PM emissions from EVs. However, with the introduction of renewable energy into the grid, non-exhaust PM emissions (e.g., brake, tyre wear) may become the main source of PM. Some studies have shown that fleet electrification has a limited contribution in reducing non-exhaust emissions. In some cases, EVs can increase non-exhaust emissions (Timmers & Achten, 2016). The important factor here is vehicle weight (Requia et al., 2018). Non-exhaust particles arise from a range of vehicle-related sources. The main contributors are the following (see also footnote on regenerative brakes⁵):

- **Brake wear.** Via the application of pressure to the braking system, the frictional process causes abrasion both of the brake pad and of the surface of the disc or drum leading to the release of particles.
- **Tyre wear.** Tyres are abraded through use, this leads to release of quantities of small rubber particles which cover a wide range of sizes. Smaller abraded particles are liable to become airborne contributing to non-exhaust particles in the atmosphere.
- **Road surface wear.** Road surface wear particles are released through use. .
- **Re-suspended road dust.** Dusts from a number of sources accumulate on road surfaces. These originate from dry and wet deposition of airborne particles. Abrasion products from the vehicle may deposit on the road contributing to the road surface dusts.

Gaseous Pollutants: Quantitative analysis presented by Requia et al. (2018) indicates that EVs may have a significant impact on gaseous emission reduction, especially on NO₂, VOCs, and CO. According to the literature, regional differences, ambient concentrations, and energy sources are strong modifiers of the association between EVs and gaseous pollutants. This is related to the significant impact of the energy sector on gaseous emissions.

GHG Emissions: According to the literature reviewed, CO₂ emissions due to EV penetration are less sensitive to the variation of source of energy generation than particulate and gaseous pollutants. A number of studies have shown that even with a high percentage of electricity generated by coal power plants, EVs may still reduce emissions of CO₂. For example, in China where the electricity grid is mostly dominated by coal generation, BEVs can reduce CO₂ emissions by 20%, but increase PM₁₀, PM_{2.5}, NO_x, and SO₂ emissions (Requia et al., 2018).

Annotated Bibliography

A number of countries have implemented policies incentivising use of EVs. However, more evidence is needed about the potential air quality and public health benefits of electric vehicles, including optimal vehicle type prioritisation and the vehicles' ability to reduce acute health impacts due to extreme air quality events (Horton et al., 2021). In a similar vein, Requia et al. (2018) comment that the environmental consequences of EV uptake are increasingly understood, but the literature and knowledge on their health impacts is limited. This sub-section provides an overview of a number of papers that have attempted to quantify the benefits of EV uptake on public health.

⁵ EVs often deploy regenerative braking which does not rely on frictional wear of brake materials so should have lower brake wear emissions. However, tyre and road wear emissions increase with vehicle mass.

Given methodological differences across papers and the importance of contextual factors more research is required. A broad summary is provided below.

The studies reviewed consistently showed reductions in GHG emissions and emissions of some criteria pollutants. Particularly on PM and SO₂. The increases or decreases were dependent on the context.

Evidence on the health effects associated with electric mobility is scarce. From the literature reviewed, a limited number of papers performed a health analysis, of which studies from the US and China dominated, evidence drawn from European studies is emerging. Data from the global south is needed, particularly contexts where vehicle ownership is expected to grow rapidly (e.g. in many countries in the global south).

The limited literature on health effects highlights that a core aspect between EVs and human exposure is that pollution is shifted from urban areas (tailpipe emissions) to predominantly sub-urban or rural areas (location of power plants, considering that energy is generated from fossil sources).

In the US, studies estimated that electrification of vehicle fleets in urban areas leads to large benefits, even with EVs powered exclusively by fossil fuel plants. Vehicle Miles Travelled (VMT) - weighted mean benefits in the 53 urban areas are 6.9 ¢/mile (\$10,400 per 150,000 miles), 83% of which (5.7 ¢/mile or \$8600 per 150,000 miles) comes from reductions in PM_{2.5} attributable mortality.

A more mixed picture is provided by studies exploring the issue in China. Here, vehicle emissions are being transferred to power plants, potentially yielding dramatic exposure reduction. In some but not all cases, this transfer of emissions is expected to improve overall public health. However, this shift also transfers impacts to nonusers of the urban EVs, including potentially to low-income rural populations.

An emerging message in the literature is that EVs should be developed according to the cleanness of regional power mixes. This would lower their SO₂ and NO_x emissions and earn more GHG reduction credits. This has particular salience when considering efforts to incentivise uptake of EVs in the global south and north.

In the US for example, studies suggest that in the majority of plausible scenarios of balanced growth, when the number of EVs rises and so does the number of charging stations, there is a positive net benefit to society. The authors suggest that the migration from polluting vehicles to electric vehicles, ideally using electricity generated sustainably could significantly reduce the incidence of cardiopulmonary illness due to air pollution. This would lead not only to less employee absence from work through illness but also lead to broad improvements in quality and length of life.

Some consideration will also need to be paid to the nature of the EV fleet in particular areas. Horton et al. (2021) for example found that widespread adoption of heavy-duty EVs would reduce nitric oxide and fine PM resulting in 562 (95% CI 410–723) fewer premature acute deaths than the non-electrified baseline scenario. However, widespread adoption of heavy-duty EVs does not reduce carbon dioxide emissions without the addition of emission-free electricity generation. By contrast, widespread adoption of light-duty EVs robustly reduces GHG emissions, but results in lesser air

quality improvements and fewer premature deaths avoided (145 [95% CI 38–333]) than the heavy-duty scenario.

Overall, the positive benefits of EVs for reducing GHG emissions and human exposure depends on the following factors with more studies needed to probe these issues:

- Type of EV,
- Source of energy generation,
- Driving conditions,
- Charging patterns,
- Availability of charging infrastructure,
- Government policies,
- Climate of a region.

Requia, W. et al. (2018). How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. *Atmospheric environment*. Volume 185. <https://doi.org/10.1016/j.atmosenv.2018.04.040>

This study provides a review of the effects of EVs adoption on air quality, GHG emissions and human health. They:

- synthesised relevant published literature related to environmental implication of EVs,
- quantitatively evaluated the effect of EVs on environment and human health,
- identified research gaps and recommend future research areas for the adoption of EVs and their benefits to society.

The authors assessed 4,734 studies and selected 123 articles for more detailed review, with 65 articles fulfilling the inclusion criteria. The studies reviewed consistently showed reductions in GHG emissions and emissions of some criteria pollutants. Particularly on PM and SO₂, the increases or decreases were dependent on the context. Overall, the positive benefits of EVs for reducing GHG emissions and human exposure depends on the following factors:

- type of EV,
- source of energy generation,
- driving conditions,
- charging patterns,
- availability of charging infrastructure,
- government policies,
- climate of a region.

Evidence on the health effects associated with electric mobility is scarce. From the literature reviewed, only 6 articles performed a health analysis, of which 3 articles were from the US, 2 from China, and 1 from the Netherlands.

The limited literature on health effects highlights that a core aspect between EVs and human exposure is that pollution is shifted from urban areas (tailpipe emissions) to predominantly sub-urban or rural areas (location of power plants, considering that energy is generated from fossil sources).

The authors comment that although the findings of particular studies are inherently related to their contextual inputs in terms of electricity generation, manufacturing, and geography, the studies reviewed show that in general, EVs may have a role in reducing air pollution and its consequences for human health. Particularly on health, a core aspect of human exposure is that traffic-related air pollution is shifted from the road to energy generation stations. Here, the spatial distribution of population (urban and rural population) is the main aspect. Roads tend to impact more urban population, while power plants impact more rural population. Overall, the positive benefits of EVs for reducing atmospheric emissions and human exposure depends on type of EV and source of energy generation. The authors conclude from the literature reviewed that:

- Differences in urban-rural exposure is a significant element that should be considered by future research and to guide the electric mobility sector.
- From a population exposure perspective, the spatial distribution of the population is a key factor to consider when rolling out EVs.
- The authors identify some significant knowledge gaps.
 - Most studies have focused on the type of EV and source of energy generation.
 - Further research should explore the other factors in order to expand the understanding of all elements related to electric mobility through a robust EV life cycle emissions analysis.
 - From a global perspective, there is a significant geographical gap in knowledge on the environmental benefits of EVs, when compared with the spatial distribution of EV share, fuel consumption, and renewable electricity production.
 - Several countries with a high percentage of renewable sources have potential to reduce oil consumption, emissions and human exposure with a shift to electric mobility.
- Most of the studies were carried out in the US or China. Evidence in other regions are scarce and needed, since there is a significant spatial variation of the aspects affecting EVs benefits, including driving patterns, source of energy generation, charging infrastructure, charging patterns, public policy, and climate.

Horton, D. et al. (2021). Effect of adoption of electric vehicles on public health and air pollution in China: a modelling study. [https://doi.org/10.1016/S2542-5196\(21\)00092-9](https://doi.org/10.1016/S2542-5196(21)00092-9)

In this modelling study, the authors used the Weather Research Forecast and Community Multiscale Air Quality Modelling System air quality model to simulate the interplay between weather and atmospheric chemistry. They in turn used this model to examine potential co-benefits of EV adoption during an extreme pollution episode in China.

Horton et al. found that widespread adoption of heavy-duty EVs would reduce nitric oxide and fine PM resulting in 562 (95% CI 410–723) fewer premature acute deaths than the non-electrified baseline scenario. However, widespread adoption of heavy-duty EVs does not reduce carbon

dioxide emissions without the addition of emission-free electricity generation. By contrast, widespread adoption of light-duty EVs robustly reduces GHG emissions, but results in lesser air quality improvements and fewer premature deaths avoided (145 [95% CI 38–333]) than the heavy-duty scenario. Economic effects of human health endpoints and carbon dioxide reductions for adoption of light-duty EVs are nearly double those of a heavy-duty EVs scenario (US\$155 million vs \$87 million).

Choma, E. et al. (2020). Assessing the health impacts of electric vehicles through air pollution in the United States. *Environment International*. Volume 144. <https://doi.org/10.1016/j.envint.2020.106015>

Motivated by recent developments in epidemiology and reduced-form air pollution modelling, as well as reductions in power plant emissions, the authors conduct an updated assessment of health benefits of light-duty vehicle electrification in large metropolitan areas (MSAs) in the US.

They find that electrification leads to large benefits, even with EVs powered exclusively by fossil fuel plants. Vehicle Miles Travelled (VMT) - weighted mean benefits in the 53 MSAs are 6.9 ¢/mile (\$10,400 per 150,000 miles), 83% of which (5.7 ¢/mile or \$8600 per 150,000 miles) comes from reductions in PM_{2.5} attributable mortality. Variability among the MSAs is large, with benefits ranging from 3.4 ¢/mile (\$5100 per 150,000 miles) in Rochester, NY, to 11.5 ¢/mile (\$17,200 per 150,000 miles) in New York, NY. This large variability suggests incentives should vary by MSA and presents an opportunity to target areas for EV deployment aimed at maximising public health benefits. Impacts are smaller when EVs disproportionately replace newer ICE models but EVs still lead to positive benefits in all MSAs. Vehicle electrification in urban areas is an opportunity to achieve large public health benefits in the US in the short term.

The analysis presents a clear case for substituting conventional ICE vehicles with EVs in urban areas. Public health benefits of reduced air pollution exposures are substantial and accrue in every MSA. In some MSAs the benefits per mile are quite large and support a public policy argument for stimulating the rapid replacement of current gasoline and diesel cars and light-duty trucks with EVs. This is true even when electricity is fully supplied by fossil fuel plants.

Goldman School of Public Policy (2021). 2035 Report: Transportation. Goldman School of Public Policy.

<http://www.2035report.com/transportation/wp-content/uploads/2020/05/2035Report2.0-1.pdf?hsCtaTracking=544e8e73-752a-40ee-b3a5-90e28d5f2e18%7C81c0077a-d01d-45b9-a338-fcaef78a20e7>

In this report, the authors analyse the economic, human health, environmental, and electric grid impacts of a future in which ground transportation is all-electric. They mobilise two scenarios to compare and contrast potential futures. The DRIVE clean and No New Policy scenario. The total transportation sector pollutant and carbon dioxide (CO₂) emissions reductions in the DRIVE Clean scenario are considered to be significant and:

- avoid approximately 150,000 premature deaths
- equate to nearly \$1.3 trillion in health and environmental savings through 2050.

The DRIVE Clean scenario slashes ground transportation sector CO₂ emissions by 60% in 2035 and by 93% in 2050, relative to 2020 levels. Total transportation sector emissions fall by 48% in 2035 and by 75% in 2050, relative to 2020 levels. The DRIVE Clean scenario is also seen to support consistent job gains in 2020-2035, peaking at over 2 million jobs in 2035 compared to the No New Policy scenario.

Challenges do exist, to enable the DRIVE Clean scenario, U.S. EV-charging infrastructure must provide drivers with the convenience provided by existing fuelling stations. The pace of the required infrastructure scale up is viewed as challenging but achievable, and the costs are modest compared with the benefits of widespread EV deployment. With policy support, domestic and global EV manufacturing capacity can scale to meet the DRIVE Clean goals. The DRIVE Clean scenario requires that annual U.S. electric light duty vehicle sales grow from 331,000 - 15 million plus by 2030.

The authors conclude that to deliver this ambitious agenda, new policies and regulations will be needed to achieve the accelerated 100% electric vehicle sales goal.

Ji, S. et al. (2012). Electric Vehicles in China: Emissions and Health Impacts. *Environ. Sci. Technol.* 46 4. <https://pubs.acs.org/doi/10.1021/es202347q>

In this paper the authors compare emissions (CO₂, PM_{2.5}, NOX, HC) and environmental health impacts (primary PM_{2.5}) from the use of conventional vehicles (CVs) and EVs in 34 major cities in China. The authors note that in China, population exposure may be lower with EV penetration because most of the population lives in urban centres. However, considering the environmental justice aspects in this analysis, the use of EVs in China is changing the geographic distribution of health effects, from the urban population to a small number of people living in rural areas.

The authors conclude that for most cities, the net result is that primary PM_{2.5} environmental health impacts per passenger-km are greater for e-cars than for gasoline cars (3.6x on average), lower than for diesel cars (2.5x on average), and equal to diesel buses. In contrast, e-bikes yield lower environmental health impacts per passenger-km than the three CVs investigated: gasoline cars (2x), diesel cars (10x), and diesel buses (5x). Their findings highlight the importance of considering exposures, and especially the proximity of emissions to people, when evaluating environmental health impacts for EVs.

The authors conclude that vehicle emissions are being transferred to power plants, potentially yielding dramatic exposure reduction. In some but not all cases, this transfer of emissions is expected to improve overall public health. However, this shift also transfers impacts to nonusers of the urban EVs, including potentially to low-income rural populations. Specifically, CV emissions and intakes generally occur within the urban area where the vehicle is used. With CVs, urban residents produce emissions and also bear the impacts (though causing within-urban distributional impacts).

Huo, H. et al. (2013). Climate and environmental effects of electric vehicles versus compressed natural gas vehicles in China: a life-cycle analysis at provincial level. *Environ Sci Technol.* 47 (3). <https://pubmed.ncbi.nlm.nih.gov/23276251/>

In this paper the authors examine fuel-cycle emissions of GHGs, PM_(2.5), PM₍₁₀₎, NO_(x), and SO₍₂₎ of CNGVs and EVs relative to gasoline ICEVs and hybrids, by Chinese province. The authors found that on average, BEVs can increase emissions of PM₁₀ and PM_{2.5} by approximately 360% and 250%, respectively. However, the authors highlighted that these results vary significantly in some Chinese provinces depending on the energy grid, where BEVs can cause a decrease in PM emissions. The authors conclude that EVs should be developed according to the cleanness of regional power mixes. This would lower their SO₍₂₎ and NO_(x) emissions and earn more GHG reduction credits.

Ke, W. et al. (2017). Assessing the Future Vehicle Fleet Electrification: The Impacts on Regional and Urban Air Quality. *Environ. Sci. Technol.* 51, 2. <https://pubs.acs.org/doi/abs/10.1021/acs.est.6b04253>

This study considers the Yangtze River Delta (YRD) region in China to investigate whether EVs can improve future air quality. The Community Multiscale Air Quality model enhanced by the two-dimensional volatility basis set module is applied to simulate the temporally, spatially, and chemically resolved changes in PM_{2.5} concentrations and the changes of other pollutants from fleet electrification. Ke et al. (2017) estimated that a scenario with 20% of private light-duty passenger vehicles and 80% of commercial passenger vehicles electrified with BEV technology (most plausible scenario, according to the authors) can reduce average PM_{2.5} concentrations by 0.4–1.1 µg/m³. Total PM_{2.5} emissions reductions under this scenario are estimated to be 0.2%. However, considering emissions only from power plants (mainly coal-based), 2.4% increase is expected. From on-road, it is estimated a reduction of 29%. This paper concludes that the fleet electrification in the YRD region could generally play a positive role in improving regional and urban air quality.

House, M. & Wright, D. (2019) Using the health benefits of electric vehicles to justify charging infrastructure incentives. *Int. J. Electric and Hybrid Vehicles.* <https://www.inderscience.com/info/inarticle.php?artid=99983>

This paper compares the financial costs of building EV charging infrastructure using empirical data with health costs to see if there is a net benefit. They have found that in the majority of plausible scenarios of balanced growth, when the number of vehicles rises and so does the number of charging stations, there is a positive net benefit to society.

The authors suggest that the migration from polluting vehicles to EVs, ideally using electricity generated sustainably could significantly reduce the incidence of cardiopulmonary illness due to air pollution. This would lead not only to less employee absence from work through illness but also lead to broad improvements in quality and length of life.

The authors conclude since health benefits accrue to governments, businesses, and individuals, these results justify the use of government incentives for charging station deployment and this paper quantifies the impact of different levels of incentive.

4. Broader Societal Benefits of EV Uptake

Broader benefits of EV uptake include fuels savings, maintenance savings, environmental impacts from reduced CO₂ emissions, health impacts from reduced PM_{2.5} and PM_{2.5} precursors in tailpipe emissions, increased national security through reduced reliance on fossil fuel, economic development benefits, and grid resource benefits from transportation electrification (Malmgren, 2016).

Malmgren (2016: 2) in a study quantifying the societal benefits of EVs comment that when examined in the context of the societal cost test, According to Malmgren (2016), societal benefits are benefits that affect society as a whole, often through the reduction of negative externalities such as environmental or health impacts. They are not paid for by the energy provider or vehicle operator. They are captured from society through socialised costs such as healthcare expenses and taxes. Societal benefits for EVs include national security benefits, better air quality and health, domestic economic development and environmental benefits.

Operations and Maintenance

EVs have far fewer moving parts than conventional ICE vehicles. The battery, motor, and electronics associated with the drive train require no regular maintenance. Oil changes become obsolete and there are no other fluids to change aside from brake fluid. Brakes on an electric vehicle require less maintenance than brakes on a conventional car since wear on the brakes of an EV is significantly reduced due to regenerative braking (Malmgren, 2016).

Reduced motoring and fleet costs: Switching to EVs can be economically advantageous for fleet operators, in both the public and private sector, and car drivers more widely. As electricity is cheaper than petrol and diesel per mile, EVs are cheaper to operate. EVs are also mechanically simpler than conventional vehicles so are likely to be more reliable and need less servicing, lowering costs for consumers and businesses.

Impact of Carbon Emissions on the Environment

Burning fossil fuels produces CO₂, a GHG linked to climate change. The US Environmental Protection Agency (EPA) and other federal agencies use the Social Cost of Carbon (SCC) to estimate climate benefits of CO₂ emissions reduction. BEVs have significantly lower impact on climate change and urban air quality, compared to conventional vehicles. The single most important opportunity to improve the BEV's impact lies in the supply mix of the electricity. Ensuring the usage of more renewable energy will drastically reduce the impact of the BEV.

Driving an EV (e.g. Nissan Leaf) instead of driving an ICE powered vehicle (e.g. Honda Civic) will result in a carbon emissions reduction of about 4,096 pounds per year (Malmgren, 2016: 4). Based on the Stanford estimate for the social cost of carbon, the value of reduced carbon emissions over the 10 year life of the vehicle would equate to roughly US\$4,506.

National Security

Estimates of national security externalities associated with acquiring a fossil fuels range from approximately 95 cents/gallon to US\$4.00/gallon. In the US, the National Defence Council

Foundation estimated that in 2006, oil-related security externalities cost US\$825 billion per year adding US\$8.35 per gallon to oil refined in Persian Gulf (Malmgren, 2016).

Security costs associated with foreign oil supply include vulnerabilities in supply, regional instability and military conflict resulting from dramatic wealth disparities stemming from oil distribution and control, and lack of accountability, free-markets and democratic reform in oil wealthy governments. Malmgren (2016: 6) estimate that driving an EV will save about 344 gallons of gas a year, which is 3440 gallons over the life of the vehicle. When this 3440 gallons is multiplied by the 95 cents per gallon national security premium, the national security savings from owning an EV is US\$3,268.

Noise

According to the European Environment Agency, road traffic is the single biggest contributor to noise pollution in England. Noise from conventional vehicles affects human health and damages the environment. The WHO estimates that the noise impact of road traffic is second only to pollution as the biggest environmental impact of vehicles. In England alone, the annual social cost of urban road noise is estimated to be £7–£10 billion (Local Government Association UK⁶).

According to the Local Government Association UK⁷, the potential reduction in noise should be transformative for those living close to busy roads and city centres. A reduction of urban noise levels by 3dB can reduce annoyance effects by 30%. At average central London speeds, the reduction in vehicle noise arising from the use of EVs is approximately 8dB.

Economic Development

Jobs

The switch to EVs will and is disrupting the vehicle manufacturing industry, creating uncertainty, and redistributing power within the industry. Transport and Environment (2017) reflecting on how the shift to EVs will impact on jobs in the EU note that the evidence suggests jobs will change in the automotive industry but there will be a net increase in employment across the economy of 500-850 thousand. Estimates of how many jobs will be lost in automotive are highly uncertain but, according to Transport and Environment (2017), are likely to be none or few in the medium term to 2030.

More positively, IEDC (2013) suggest that the switch to EVs is expected to generate increased demand for existing jobs and create new jobs in the automotive industry. Studies have suggested that job growth in EV industries will outweigh reduction of jobs in traditional fuel industries, resulting in net job growth. EVs will also create additional economic development opportunities by improving quality of life, reducing energy spending, and decreasing reliance on foreign oil (IEDC, 2013). More evidence is required from the global south on how the roll out of different types of EVs can support

⁶ <https://www.local.gov.uk/case-electric-vehicles>

⁷ <https://www.local.gov.uk/case-electric-vehicles>

a number of societal goals (see box 5 on E Boda Boda) as well as research undertaken by the World Resource Institute on E buses in China⁸.

Income generation

According to the Local Government Association UK, EVs can serve a role in supporting income generation for public and private sectors. There are many different models for the deployment of charging infrastructure. This includes models where provision is led by private firms who will take on the commercial risks and the local authority exposure is minimal. There is also potential for charging infrastructure to raise revenue for councils or to be installed for little capital expenditure.

Different models will be appropriate for different areas. Higher-power charge points and charge points in busy locations are likely to be more profitable and the best choice will also depend on the local authorities' appetite for taking on risk and the availability of government grant funding. Some councils have already shown that charging infrastructure can be a revenue generating opportunity

Box 5: E-boda boda roll out in Uganda (provided by Gabriel Okello - Cambridge Institute of Sustainable Leadership):

A significant component of the Ugandan transport sector is the motorcycle industry, currently, Kampala alone has over 400,000 motorcycles compared to 15,979 motorcycles in 2007 (UN, 2018). The introduction to e-mobility or e-boda bodas presents an opportunity to decarbonise the motorcycle industry.

Switching to electric powered motorcycles in dense urban cities like Kampala can significantly reduce air pollution caused by fuel-powered motorcycles, address noise pollution and reduce costs spent on buying fuel. Electric-powered motorcycles would not require fragile hardware such as a clutch, transmission, or internal combustion engine, minimising mechanical failure and expenses associated with the repair.

A number of companies including Bodawerk International limited, Zembo Modjo e-mobility and Motor Care Uganda are exploring the feasibility of electric boda adoption in Uganda. Some companies are converting existing petrol-powered boda bodas to e-bodas while others are importing new electric-powered motorcycles. Uganda could use a combination of hydroelectricity and solar to provide e-boda bodas with green energy. Areas of current exploration include:

- Testing how robust e-boda bodas that have been converted are compared to petrol powered boda bodas under similar conditions.
- The social-economic benefits of switching to e-boda bodas
- Distance covered by a single charge and performance of electric boda bodas. Pilots have shown that distance covered by single charge can be increased with better technology.
- Charging stations that need to be developed before extensive deployment can take place.
- Knowledge, attitudes and perception of riders towards e-bodas in comparison to fuel powered boda bodas.
- Fuels savings and maintenance savings (Oil change, Tyres, spark plugs, brakes, automatic transmission fluid etc.)
- Impact on economy (potential gains versus potential losses).
- Cost of charging versus fuel costs

⁸ <https://www.wri.org/insights/beyond-electric-cars-china-leads-electric-buses-india-could-follow-suit-electric>

for councils. Transport for Greater Manchester and Oxford City Council have been looking at how they can generate income.

EVs as a Grid Resource

EVs can also play the role as a grid resource. EVs serve an important transportation function, but, they are typically in use for mobility less than 5% of the time. This limited use, coupled with the storage capability of EV batteries means that EV load on the grid can be flexible and also serve as a storage or regulation resource for the grid (IRENA, 2019).

EV deployment growth would allow a higher share of variable renewable energy (VRE) in the power system, via five areas of interaction (IRENA, 2019):

- actively using the mobile battery storage system in the vehicle;
- use of second-hand batteries in a “second life” role as stationary battery storage systems;
- widespread deployment of charging technologies and infrastructure;
- evolution in the charging behaviour of EV owners, for example, in which they become comfortable with variable charging rates and times;
- provision of other ancillary services from EVs to the grid, such as frequency regulation, shaving peak demand, power support to enhance operation, and reserve capacity to secure the grid by stored energy in its batteries.

5. Negative Impacts of EV Use

While increasing the market share of EVs is an important part of achieving environmental goals, the actual environmental benefits (and impacts) from EVs depend on several factors (see Image 2 for example). Critics of EV roll out comment that EVs can cause significant impacts on the environment, power system, and other related sectors. According to Ji et al. (2015) factors influencing the impact (positive and negative of EVs) include the energy pathway, energy generation profile, type of air pollutants and GHGs, and type of EV.

Emissions and Pollutant Types

A core aspect of EVs is that the source of transportation-related air pollution is shifted from the road to electricity generating stations (Ji et al., 2015). If the electricity is generated from non-renewable sources (e.g., coal, oil), the promise of EVs for reducing air pollutants and GHGs may not be fully realised (Mahmoud et al., 2016). Huo et al. (2010) show that in China, where electricity is generated primarily from coal, EVs could increase SO₂ emissions by 3–10 times, and double NO_x emissions compared to ICE vehicles.

In contrast, Meeagie (2014) argue that when examining the entire lifecycle of GHG emissions from EVs (including manufacture, transportation, and disposal), they are about a quarter less than for ICEs, even when the electricity use comes almost entirely from coal-fired power stations.

Image 2: Overview of the relationship between various aspects of EVs and environment.

This image has been removed for copyright reasons. The image can be viewed at

<https://doi.org/10.1016/j.atmosenv.2018.04.040>

Source: Requía et al, 2018: 67

Regarding the type of air pollutants and GHGs, EVs do not necessarily have the potential to minimise all particulates and GHG emissions:

- Huo et al. (2013) shows that in China, EVs can reduce GHG emissions by 20%, but increase PM₁₀, PM_{2.5}, NO_x, and SO₂.
- In the US state of Texas, Nichols et al. (2015) report that EVs can reduce GHG emissions, NO_x, PM₁₀, but generate significantly higher emissions of SO₂ compared to ICE vehicles.
- There is also evidence that non-exhaust PM emissions, for example, tyre, brake, and road wear, vary among EVs and ICE vehicles since non-exhaust emissions are influenced by vehicle weight. On average, EVs are 24% heavier than ICE vehicles (Timmers & Achten, 2016).

Energy Usage and Generation

BEVs provide zero-vehicle-emissions driving (for both CO₂ and pollutant emissions), but the “upstream” CO₂ can be substantial, for example in countries with dominant coal power generation. Previous studies of both GHGs and air pollution found that the electricity mix is critical for decision-making, with the potential to make EVs better or worse than ICEVs or hybrids, depending on the grid emissions (Tessum et al., 2014). To deliver on the promise of EVs, electric grids must be considerably decarbonised (to 600 grams (g)/kWh or less) for EVs to have a CO₂ advantage relative to similar sized hybrid ICE vehicles. Carbon intensities will need to continuously improve in the future, since hybrids and other ICE vehicles will also become more efficient (IRENA, 2019).

Present power systems could face huge instabilities with enough EV penetration. As noted by Salge and Oudalov (2020), the electrification of road transport will shift energy requirements from petrol to power systems. This could put strains on our power networks and risk overloading grids unless they plan for it and investments are made. On a national level, new EV demand spikes in the morning and evening, in combination with retirements of traditional generating capacity, can cause power generation and transmission inadequacy in certain hours and days.

Type of EV

Beyond energy generation and consumption, the type of EV is also an important factor that affects the environmental benefits from electric mobility.

Reports suggest that switching to BEVs will increase particle pollution due to their heavier weight compared to conventional cars – particularly from tyre and break wear. However, there is a need for more comprehensive studies measuring non-exhaust particle emissions, especially of EVs. OECD (2020) found that when all particle sources associated with cars are counted, including secondary particles, BEV passenger cars and SUVs contribute less PM_{2.5} and PM₁₀ than diesel

or petrol cars. PM emissions are reduced by 6-42% on switching to a BEV from a conventional ICE car, depending on the size of the BEV and which car it replaces (for example a bigger decrease is seen for diesel cars). A reduction is seen even for heavier BEVs with a longer electric range of 460km, this indicates that even heavier, longer range EVs will have a positive impact on air quality.

Raw Materials

The EV uptake and related battery production requirements imply increased demand for new materials and therefore entail increased attention to raw materials supply (IEA, 2019). Batteries for EVs can require rare elements such as lithium and cobalt, which has raised environmental and ethical issues in countries where these elements are mined. There are also concerns over 'peak lithium' and future shortages constraining growth in the EV market (Hirst, 2020).

Traceability and transparency of raw material supply chains are key instruments to help address the criticalities associated with raw material supply by fostering sustainable sourcing of minerals. The development of binding regulatory frameworks is important to ensure that international multi-stakeholder co-operation can effectively address these challenges. This includes efforts to support (IEA, 2019):

- battery end-of-life management;
- second-life applications of automotive batteries;
- standards for battery waste management and environmental requirements on battery design,

Initiatives to address these issues are crucial to reduce the volumes of critical raw materials needed for batteries and to limit risks of shortages.

Potential Health Impacts

Health impacts of vehicle electrification also show large spatial variability, making it crucial to assess location-specific impacts (Holland et al., 2016). This is due to both different grid mixes and to the large spatial variability of PM impacts (Holland et al., 2016).

Extremely low frequency (ELF) magnetic field (MF) exposure in EVs has raised public concern for human health. Exposure to 50 and 60 Hz MFs exceeding 0.3–0.4 μT may result in an increased risk of childhood leukaemia, although a satisfactory causal relationship has not yet been reliably demonstrated (Yang et al., 2019).

Yang et al. (2019) monitored ELF MF in three shared vehicles over two years. The measurements were performed at the front and the rear seats under acceleration and constant-driving modes. They found that the broadband B value was significantly changed with replacement of the components and the tyres while regular checks or maintenance did not influence the measured B values in the vehicle. The variation of the major spectral components of B was larger for the repaired cars, compared to the results from the cars with regular maintenance. These results highlight the necessity of regularly monitoring the ELF MF in EVs, especially after major repairs or accidents, to protect car users from MF exposure.

6. Enablers of Growth and Impact of EVs

It is important to acknowledge that various challenges exist to support the roll out of EVs and to ensure that their impact is maximised. These will vary across countries and indeed within. According to Hirst (2020 – see also Box 6), for the most benefit, EV deployment requires four concurrent strategies:

- electrification of vehicles;
- provision of sufficient charging equipment;
- decarbonisation of the electricity generation;
- integration of electric vehicles into the grid.

To achieve a tipping point in sales, EVs will likely need to achieve near parity on a first cost basis with ICE vehicles, and provide sufficient amenities (such as driving range and recharging convenience), such that consumers do not consider them inferior or comparable to ICEs. IEA (2019) comment that EV uptake growth has and will be enabled by the following:

Policies play a critical role. Leading countries in electric mobility use a variety of measures such as fuel economy standards coupled with incentives for zero- and low-emissions vehicles, economic instruments that help bridge the cost gap between electric and conventional vehicles and support for the deployment of charging infrastructure. Increasingly, policy support is being extended to address the strategic importance of the battery technology value chain.

Technology advances are delivering substantial cost cuts. Key enablers are developments in battery chemistry and expansion of production capacity in manufacturing plants. Other solutions include the redesign of vehicle manufacturing platforms using simpler and innovative design architecture, and the application of big data to right size batteries.

Private sector response to public policy signals confirms the escalating momentum for electrification of transport. In particular, recent announcements by vehicle manufacturers are ambitious regarding intentions to electrify the car and bus markets. Battery manufacturing is also undergoing important transitions, including major investments to expand production. Utilities, charging point operators, charging hardware manufacturers and other power sector stakeholders are also boosting investment in charging infrastructure.

Box 6: Norway and Support for EVs (Hirst, 2020)

Norway has had significant success in supporting EV market penetration. In Norway, the number of electric passenger cars has increased substantially over the last decade: in 2008 the number of BEVs was around 1,200. In 2019 there were just under 290,000. If PHEVs were included the number of cars which were powered (at least in part) by electricity numbered 420,000 in 2020. According to official estimates there were 2.8 million registered cars in 2019 with electric cars accounting for around 9% of the total stock. The Norway Government has committed to the end of sales of conventional vehicles in 2025 (Hirst, 2020: 23).

Incentives driving Norway's success have been long-term and financial. Incentives have been designed to make EV ownership less expensive than conventional petrol or diesel vehicles. The support Norway provides includes:

- **Exemptions from the vehicle registration tax for Battery EVs (1990-).** Norway levies a registration or import tax on cars, which can reach EUR 10,000 or more depending on the car model's CO₂ emissions. BEVs are exempted from the tax. PHEVs also pay a lower tax. The exemption is expected to run out at the end of 2020, but due to the low-emissions, BEVs will still pay a lower amount.
- **Low annual road tax (1996-).** Battery EVs pay lower road tax. Instead of NOK 3,060 or (~EUR 367), owners of BEVs pay NOK 435 (~ EUR 52). The annual tax increased to half the rate of fossil fuelled cars in 2018 and will increase to full rate in 2020.
- **Free municipal parking (1999-).** Local governments can decide on incentives such as access to bus lanes and free municipal parking.
- **Reduced company car tax (2000-).** A 40% reduction on the company car tax.
- **Exemption from 25% VAT on purchase (2001-).** Battery EVs are exempted from paying the value added tax of 25% on the purchase or leasing rate. The VAT exemption for electric cars is prolonged until 2020
- **No charges on ferries or toll roads (2009-).** Battery EVs enjoy exemptions from road tolls and ferries.

Altogether, this approach makes the total cost of ownership less expensive for Plug-In EVs than for a comparative internal combustion engine vehicle.

7. Constraints to Growth and Impact of EVs

Whilst EVs have been identified as playing a role in addressing issues around poor air quality, climate change and their public health impacts, a number of barriers exist that need to be addressed to support uptake. These barriers have been classified into five categories: technical, policy, economic, infrastructure, and social (Adhikari et al., 2020: 5-6) and will manifest in different ways depending on the context analysed:

- **Technical Barriers:** Limited range (one-time travel distance at full charge); Lack of evidence on reliability and performance; Limited battery life; Fewer EV models.
- **Social Barriers:** Lack of knowledge on EVs; Lack of environmental awareness regarding EVs; Consumers' limited understanding of the product quality of EVs.

- **Economic Barriers:** Higher purchase price; Battery replacement cost; Higher electricity price for charging; Lack of credit access for EVs.
- **Infrastructure Barriers:** Lack of charging stations; Lack of repair and maintenance workshops; Limited domestic industry.
- **Policy Barriers:** Lack of long-term planning and goals on the government's part; Absence of tax exemptions; Absence of awareness raising about EVs.

In particular issues around cost, charging infrastructure and public perceptions of EVs are prevalent within the literature (see Table 3).

Although energy costs for hybrid and plug-in EVs are generally lower than for similar ICE vehicles, purchase prices, according to Alternative Fuels Data Center (AFDC⁹) can be significantly higher. AFDC continue that prices are likely to equalise with conventional vehicles, as production volumes increase and battery technologies continue to mature.

Lee and Clark (2018) note that, trends in battery costs and the prices of EVs are declining. If these trends continue, EVs could be cost competitive with ICE vehicles over their lifetime early in the next decade. They note that this does not mean that ICEs are in danger of losing their markets, since consumers must become comfortable with EVs.

The commercial success of the electric vehicle will require the development of a charging infrastructure that is accessible, easy to use, and relatively inexpensive (Transport & Environment, 2020). Without enough charge points EV ownership is not practical. There is currently some uncertainty as to how many EV charge points are needed, and where they should be located – at home, on the road network, in streetlamps etc. Developments in EVs and battery technology mean some vehicles already have the range necessary to meet the needs for most journeys without having to charge. However, range anxiety – fears over the distance EVs can travel between charges – is often cited as one of the key barriers to people opting to buy EVs. Linked to this is the availability of charging points. In particular, public charge points are often unevenly distributed across countries, meaning access to charge points is variable.

Table 3: Hurdles to Development and Solutions

This table has been removed for copyright reasons. The table can be viewed at

https://www.iedconline.org/clientuploads/Downloads/edrp/IEDC_Electric_Vehicle_Industry.pdf

Source: IEDC, 2013: 11

⁹ https://afdc.energy.gov/fuels/electricity_benefits.html

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