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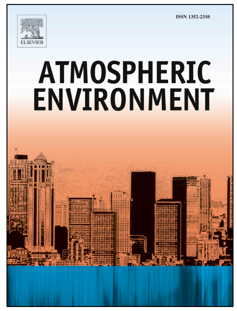

How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health

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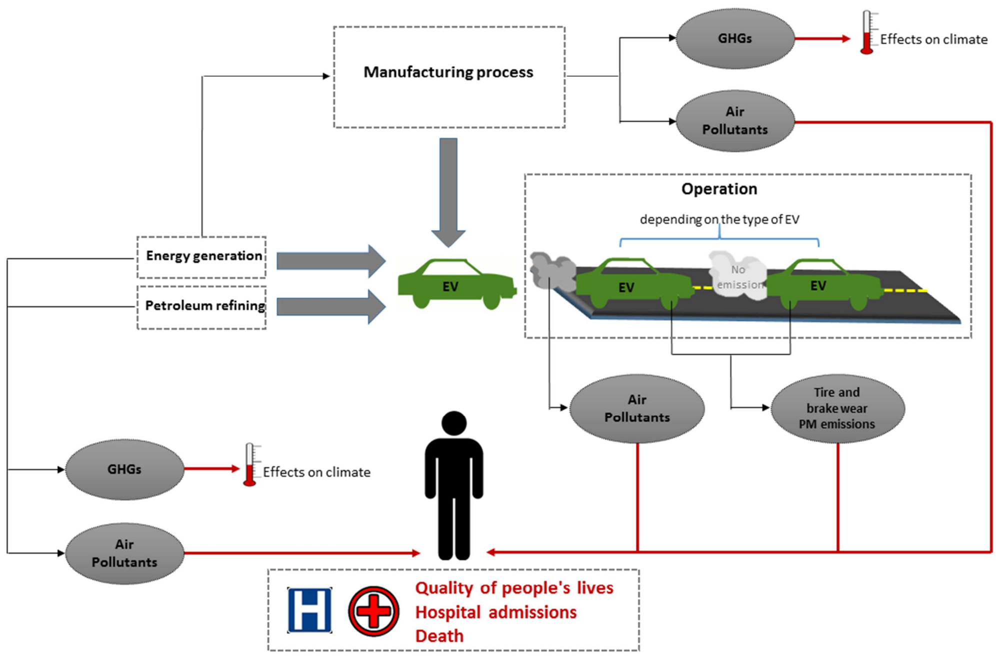
Manufacturing process
GHGs
Effects on climate
Air Pollutants
Operation
depending on the type of EV
No emission
EV
EV
EV
Energy generation
Petroleum refining
Air Pollutants
Tire and brake wear PM emissions
GHGs
Effects on climate
Air Pollutants
Quality of people's lives
Hospital admissions
Death

How clean are electric vehicles?

Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health

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Abstract

There is a growing need for a broad overview of the state of knowledge on the environmental aspects of Electric Vehicles (EVs), which could help policymakers in the objective of making road transportation more sustainable and environmental friendly. This study provides a comprehensive review of the effects of EVs adoption on air quality, greenhouse gas emissions, and human health. Specifically, we (i) synthesized relevant published literature related to environmental implication of EVs, (ii) quantitatively evaluated the effect of EVs on environment and human health, and (iii) identified research gaps and recommend future research areas for the adoption of EVs and their benefits to society. We assessed in total 4,734 studies and selected 123 articles of more detailed review, with 65 articles fulfilling the inclusion criteria. The studies reviewed consistently showed reductions in greenhouse gas emissions and emissions of some criteria pollutants. Particularly on PM and SO_2, the increases or decreases are very dependent on the context. Overall, the positive benefits of EVs for reducing greenhouse gas emissions and human exposure depends on the following factors: (i) type of EV, (ii) source of energy generation, (iii) driving conditions, (iv) charging patterns, (v) availbailty of charging infrastructure, (vi) govermnat policies, and (vii) climate of a regions. This study provides a comprehansive analysis and review on the benefits of electric mobility.

Keywords

Electric vehicles, Electric mobility Air pollution, Greenhouse gas emissions, Health, Human exposure, Review article.

1. INTRODUCTION

Road transportation is a significant source of air pollutants and greenhouse gases (Borken et al., 2011; Duarte et al., 2013; Nejadkoorki et al., 2008). Globally, emissions from traffic (percentage of emissions) account for 30% of nitrogen oxides (NO_x=NO+NO_2), 10% of PMs, 54% of CO, 14% of CO_2, and 47% of NMHC (Sokhi, 2011). These traffic-related atmospheric emissions are associated with direct and indirect human health effects (Chen et al., 2013; Pereira et al., 2014; Rice et al., 2016).

Of the direct effects, studies have reported that air pollutants (some of them are known as criteria 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 (Nicole, 2015; Zanobetti et al., 2009), Alzheimer's disease (Cacciottolo et al., 2017), dementia (Chen et al., 2017), and premature deaths (Guo et al., 2016; Jerrett et al., 2013; Kloog et al., 2012). For example, in Connecticut and Massachusetts in the United States, $PM_{2.5}$ emitted by road transportation is associated with 2.1% and 3.5% increases in cardiovascular and respiratory admissions, respectively (Bell et al., 2014). In New York City, all on-road mobile sources contribute to about 320 deaths annually due to $PM_{2.5}$ exposures (Kheirbek et al., 2016). The World Bank has estimated that premature deaths due to air pollution in 2013 alone cost the global economy about US $225 billion (World Bank, 2016).

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. Jacobson (2008) show that CO_2 emissions in the U.S. may increase annual air pollution deaths by about 1,000 per 1 ^oK rise in CO_2-induced temperature change.

These direct and indirect implications of vehicular emissions on the environment and human health suggest that the current transportation systems are unsustainable, from both the environmental (air pollution and GHGs), health (health impacts) and economic perspectives (cost of air pollution). Electric mobility is a promising technology which can transform the global transportation sector to provide more environmentally-friendly and sustainable mobility options that can help in reducing air pollution, greenhouse gas emissions, and health risks. Consumers, business, and governments increasingly appear to be promoting this technology. According to the International Energy Agency (IEA, 2016), there are about 1.2 million Electric Vehicles (EVs) worldwide. EV stock and market share by country are shown in Figure 1. In 2016, the market share of EVs continued to rise, with the highest shares in Norway (23%), Netherlands (10%), and Sweden (2%), followed by a 1% market share in France, the United Kingdom, and China.

In the U.S. and Canada, EV market share is 0.7% and 0.4% respectively. However, the size of the U.S. market means it has more than 400,000 EVs, or about 38% of the global EV stock. A number of policies have been put in place in many jurisdictions to increase sales in the US and Canada (IEA, 2016). For example, the State of California in US offers an incentive package of USD $2,500 to purchase an EV. The average incentive value for EV purchasers across the United States is US $1,000 (IEA, 2016). In Canada, the EV stock was about 18,450, or about 1.5% of the world's total EVs in 2015 (IEA, 2016). Financial and other incentives for EVs are offered in several Canadian provinces, and the National Energy Board (NEB) of Canada projects 700,000 EVs to be in operation on Canadian roads by 2035 (NEB, 2011).

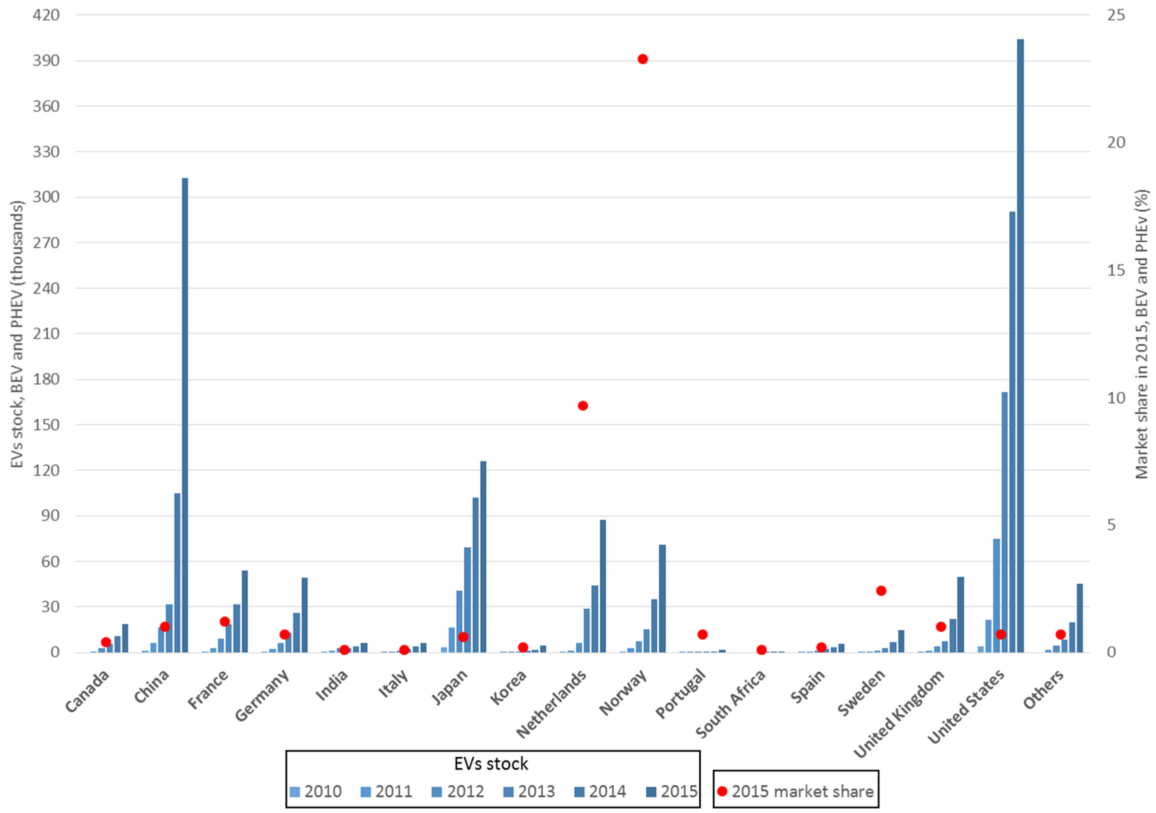


Figure 1. EVs stock (2010 – 2015) and market share (2015) by country, based on the data reported by the International Energy Agency (IEA, 2016).

While increasing the market share of EVs is an important part of achieving environmental goals, the actual environmental benefits from EVs depend on several factors, including the energy pathway, energy generation profile, type of air pollutants and GHGs, and type of EV. For example, 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 realized (Mahmoud et al., 2016). Huo et al. (2010) show that in China, where electricity is generated primarily from coal, EVs could increase SO_2 emissions by 3 to 10 times, and double NO_x emissions compared to gasoline-powered internal combustion engine (ICE) vehicles.

Regarding the type of air pollutants and GHGs, EVs do not necessarily have the potential to minimize all particulates and GHG emissions. For example, Huo et al. (2013) shows that in China, EVs can reduce GHG emissions by 20%, but increase PM_{10}, $PM_{2.5}$, NO_x, and SO_2. In the U.S state of Texas, Nichols et al. (2015) report that EVs can reduce GHG emissions, NO_X, PM_{10}, but generate significantly higher emissions of SO_2 compared to ICE vehicles. There is also evidence that non-exhaust PM emissions vary among EVs and ICE vehicles since non-exhaust emissions are influenced by vehicle weight (Simons, 2016; Timmers and Achten, 2016). For example, tire, brake, and road wear increase by approximately 50% for heavy vehicles compared to a medium (1,600 kg) and small (1,200 kg) car (Simons, 2016). On average, EVs are 24% heavier than ICE vehicles (Timmers and Achten, 2016).

Beyond energy generation and consumption, the type of EV is also an important factor that affects the environmental benefits from electric mobility. EVs are divided into four categories: i) Hybrid Electric Vehicles (HEVs) which are mainly powered by gasoline with small battery supporting the combustion engine, ii) Plug-in Hybrid Electric Vehicles (PHEVs) which are powered by both gasoline and electricity independently, iii) Battery Electric Vehicles (BEVs) which are solely powered by electricity, and; iv) Fuel Cell Electric Vehicle (FCEVs) which are powered by hydrogen. Figure 2 shows a simple comparison (for visual purposes only) between different types of EVs considering their source of energy, consumption, and emissions (tailpipe and power plant). Of these, Weiss et al. (2016) argue that BEVs with a large battery capacity can produce 2 to 3 times as much GHG emissions as HEVs, depending on the source of electricity generation and the time at which the BEV is charged from the grid (Michalek, 2016).

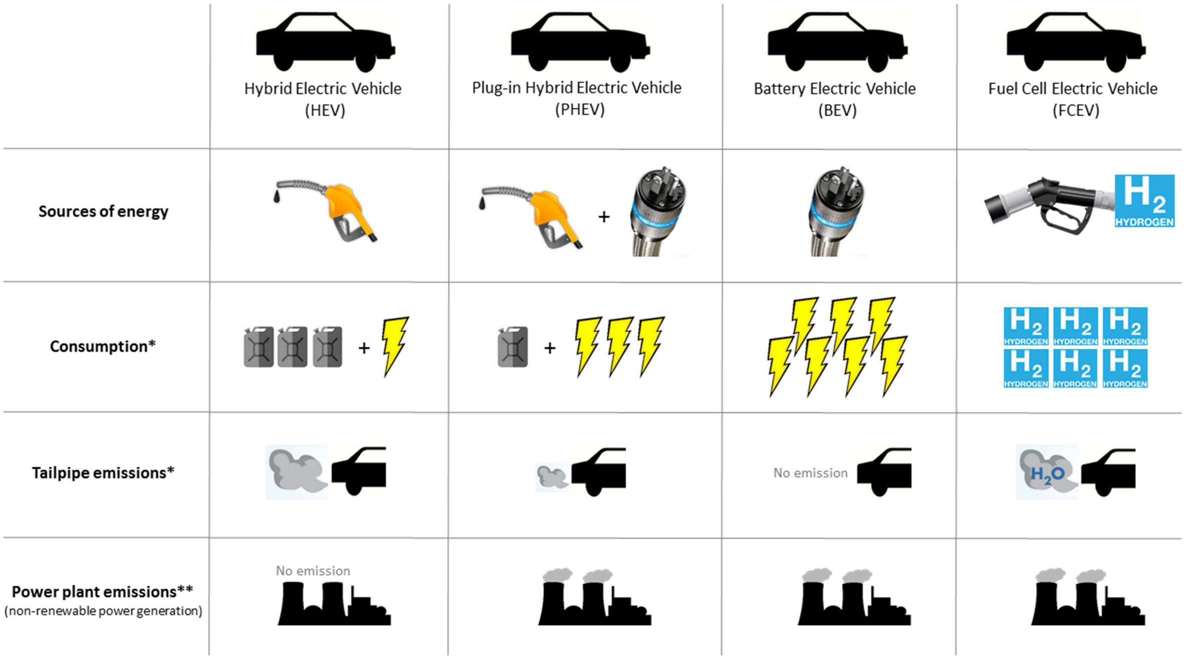
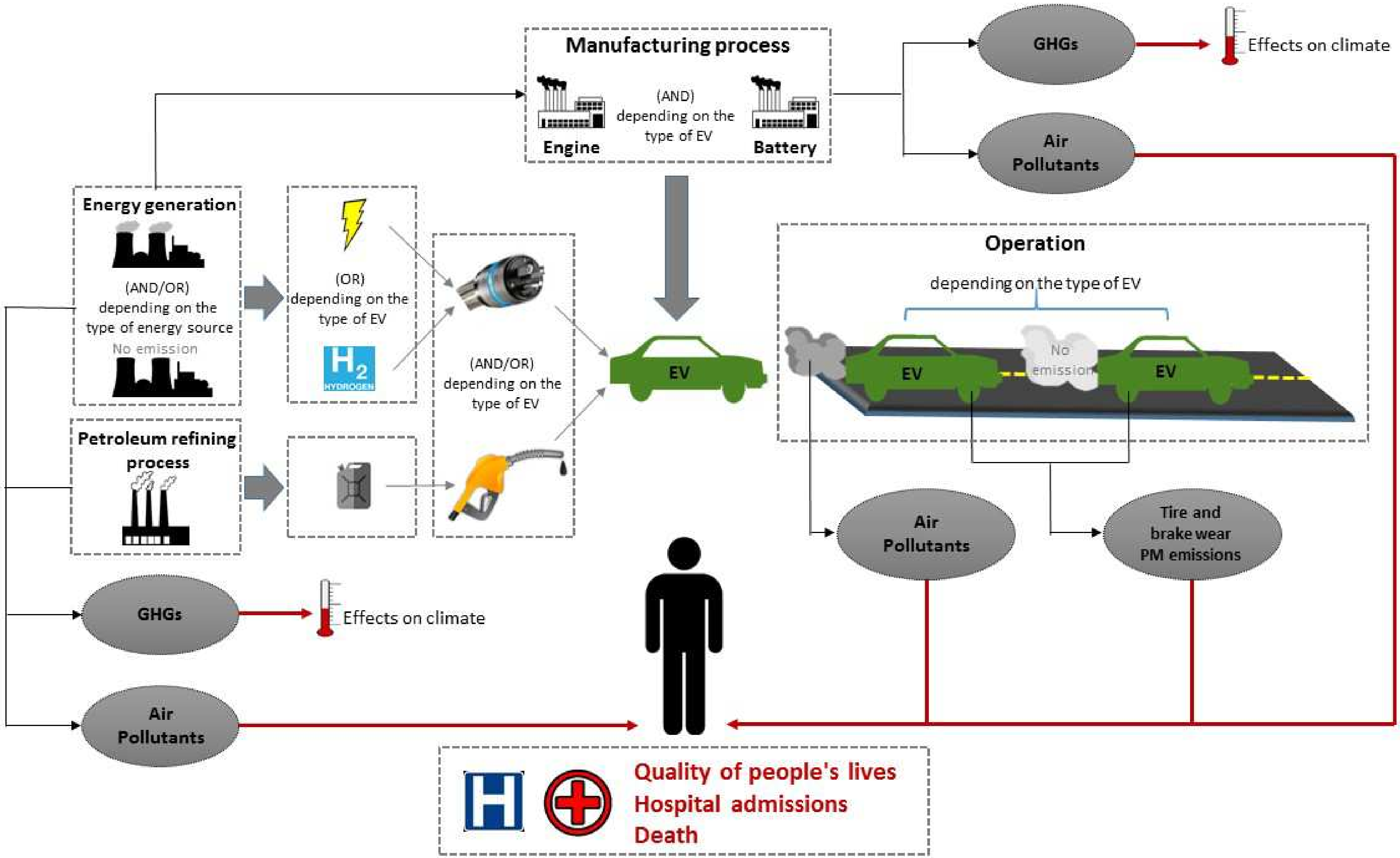


Figure 2. Schematic of different types of Electric Vehicles (EVs) and their sources and consumption of energy and emission from tailpipe and energy generation. (*) The quantitative information presented here is for visual purposes only. This information is not standardized or quantitative.(**) Since technology may vary between power plants, we did not present quantitative information for visual purposes.

Taken together, this information suggests that the evaluation of the environmental implications of EVs adoption and use is complex, which may be overlooked or undervalued in current strategies. Figure 3 presents an overview of the relationship between EVs and the environment, considering factors such as the manufacturing process, electricity generation, fuel or energy consumption, and their emissions impacts. Such an "emissions chain" makes it clear that the environmental impacts of EVs are heavily context dependent. Some previous studies have only focused on specific emissions chains, including the manufacturing process (Michalek et al., 2011), energy generation (Lee et al., 2013; Van Vliet et al., 2011), and operation (Ji et al., 2015, 2012). To that end, there is a dire need to thoroughly review the studies in literature that may help to fully evaluate the environmental aspects of EVs considering the complexity and scope of this issue. This study is a step in this direction.



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126 **Figure 3.** Overview of the relationship between various aspects of EVs and environment.

To our knowledge, the first literature review on the environmental implications of EVs was performed by Lester and colleagues in 1995 (Lave et al., 1995). Their study focused on the environmental impacts of discharging lead-acid batteries. Few recent studies have reported reviews on other issues related to the environment, which includes non-exhaust PM emissions (Timmers and Achten, 2016), CO_2 emissions (Helmers and Marx, 2012), and noise (Batista et al., 2015). Some others studies have explored the environmental performance of EVs based on vehicle environmental rating methodologies, including a life cycle approach, driving cycle, and the real-life testing of cars (Batista et al., 2015). Table 1 shows previous review studies in the literature on EVs and the aspects they considered.

Table 1. Review studies on EVs in the literature.

First author and year	Aspect investigated
Lester et al. (1995)	Environmental impacts of discharging lead-acid batteries.
Bradley et al. (2009)	The relationship between sustainability impact assessments for PHEVs and basic design consideration (architecture, energy management systems, drivetrain component function, energy storage trade-offs and grid connections).
Sovacool (2010)	The relationship between PHEVs and public health benefits (considering a basic analysis of transportation and health).
Helmers et al. (2012)	Technical characteristics of BEVs and CO_2 emissions.
Faria et al. (2013)	The impact of the electricity mix and use profile in the life-cycle assessment of EVs (GHG emissions).
Batista et al. (2015)	Methodological review on the environmental rating to evaluate and compare the environmental performance of EVs (emissions and noise).
Weiss et al. (2015)	Environmental (CO_2 emissions), economic, and social performance of electric two-wheelers.
Vivanco et al. (2016)	Methodological review on the environmental assessment methods (life cycle assessment – LCA, and hybrid – LCA) and environmental input-output databases used as a source of bias in EVs studies.
Timmers et al. (2016)	Non-exhaust PM emissions from EVs.
Hirose (2017)	Materials used in FCEVs and its environmental implications related to NO_x and CO_2 emissions.

Note: studies are in chronological order.

These review studies provide a broad assessment of the environmental benefits of EVs. However, a comprehensive review of EV benefits for the environment is lacking in the literature.

In particular, studies on health impacts of EVs are not fully discussed in the literature and are still missing. In the present study, we conduct a full review of EVs that works from the emissions chain framework from the manufacturing, power sources, tail pipe emissions and human health impacts as shown in in Figure 3. For example, what are the effects of electric mobility on emissions and human health considering the type of EVs, type of air pollutants and GHGs, and study context? Our research addresses this gap, reviewing the available literature to provide a comprehensive overview of the effects of electric mobility on air quality, GHG emissions, and human health. Specifically, we performed a systematic review in order to (i) evaluate and synthesize the published literature, (ii) identify spatiotemporal patterns and trends in existing studies on the environmental implications of EVs, (iii) conduct a quantitative analysis of the effect of EVs on the environment, and (iv) identify research gaps and recommend new research areas. We also address the possibility of expanding scientific networking to increase the understanding of EV benefits in areas of the world where there is a growing potential for the adoption and use of electric mobility.

2. METHODOLOGY

2.1. Systematic review process: search strategy, selection criteria, and extraction of data

We performed a systematic search in PubMed, ISI web of knowledge, Google Scholar, and ScienceDirect using the following keywords: “electric vehicles”, “electric mobility”, “environment”, “air pollution”, “air quality”, “greenhouse gases”, “health impacts”, and “human exposure”. There were no temporal restrictions related to the year that the studies were published. The search was performed between February and March of 2017.

We screened all resulting titles and abstracts and reviewed full texts of articles that met the inclusion criteria. Studies were included if they reported quantitative results for atmospheric emissions and/or health effects associated with the growing market share of EVs. Studies that presented only pollution/health effects associated with energy generation (e.g., grams of pollutant/kWh) or associated with economic benefits were not included in the analysis. There was no restriction on the type of EV. Only peer-reviewed articles written in English were selected, while published commentaries and editorials were excluded.

A comprehensive dataset was extracted from each study which includes information on: first author, publication year, period of analysis, projections (if the study accounted for future projections), atmospheric emissions (air pollutants and GHGs), transportation mode, type of EV, method (e.g., life cycle, inventories, lab test, air quality modeling etc.), atmospheric emission outcome (e.g., g/km, g/vehicle, mass of particulate and/or gaseous reduction, mass of particulate and/or gaseous per year etc.), health outcome (exposure metric), and spatial analysis (if the study accounted for spatial variation). Authors were contacted for additional information or clarification where needed.

2.2. Quantitative analysis

We quantitatively evaluated the effect of EVs on atmospheric emissions based on the findings reported by each study. This allows for a simple comparison of the environmental benefits of electric mobility according to the type of EVs, and air pollutants, and GHGs. To that end, we converted each reported result into a quantitative scale by assigning values ranging from 1 to 3, where 1 represents zero benefits in reducing emissions, 2 medium benefits, and 3 high benefits. Zero benefit (value 1) means that under all circumstances evaluated (e.g., simulations, sensitivity analysis, models), the EV in analysis did not reduce emissions (compared to conventional internal combustion vehicles). Medium benefit (value 2) means that under some circumstances, the EV presented lower emissions than conventional vehicles. Finally, a high benefit (value 3) was assigned when the EV showed a reduction in emissions under all circumstances. Note that the value 1 (zero benefits) includes cases where an EV is the same or worse than a conventional vehicle in terms of atmospheric emissions. The literature presents results from various ways (unstandardized) and based on numerous criteria (e.g., energy generation, fleet characteristics, etc.). This is a restriction for creating a more robust quantitative assessment (e.g., meta-analysis). Therefore, we decided to perform a basic quantitative analysis based only on three simple parameters – zero (value 1), medium (value 2), and high benefits (value 3). The aim of the quantitative analysis was to provide a quantitative snapshot of the effects of EVs on atmospheric emissions, and not to provide a precise effect size of the association between emissions and EVs.

We did not perform a quantitative analysis for health effects. The literature on health effects associated with EVs is scarce. This will be discussed further in section 3.2.

3. EFFECTS OF ELECTRIC MOBILITY ON THE ATMOSPHERIC ENVIRONMENT AND HEALTH

We assessed the title and abstract of 4,734 studies. From those studies, we selected 123 for text review, from which 65 articles fulfilled the inclusion criteria. Figure 4 presents a flow chart showing the number of studies identified, included, and excluded from the analysis. In Appendix 1, we present the details (full bibliographic information and the data extracted) of the 65 articles that met the inclusion criteria.

Of this sample, Figure 5 displays the number of studies by year of publication. The oldest study that fulfilled the inclusion criteria was published in 2001, and the newest study in 2017. The highest number of studies were published in 2015, with 12 articles. Figure 6 highlights the geographic location of the studies, showing that the 65 papers in the sample were published for 16 countries across the world. A total of 22 studies reported results at the regional/city scale, 41 at the country scale, and 2 at the continental scale (e.g. Europe). Since the studies that focused on Europe did not report results by country, we did not include these studies in Figure 6. For context, Figure 6 also offers a global perspective of some indicators associated with electric mobility, including EV share, petroleum consumption, and clean electricity production.

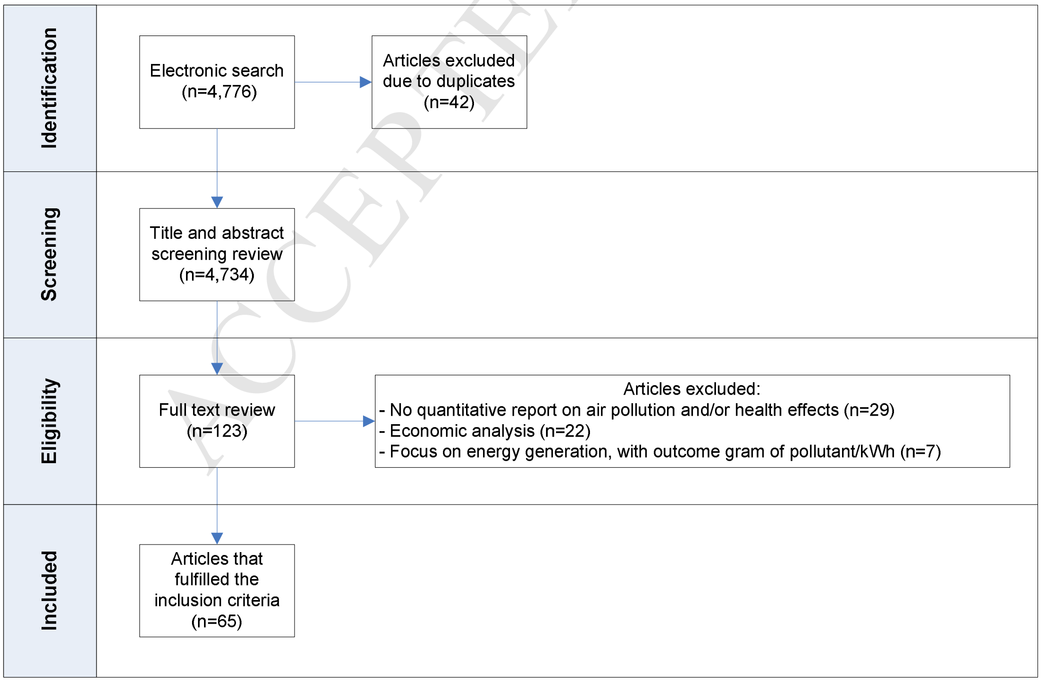

Figure 4. Systematic screening stage for the papers in the literature.

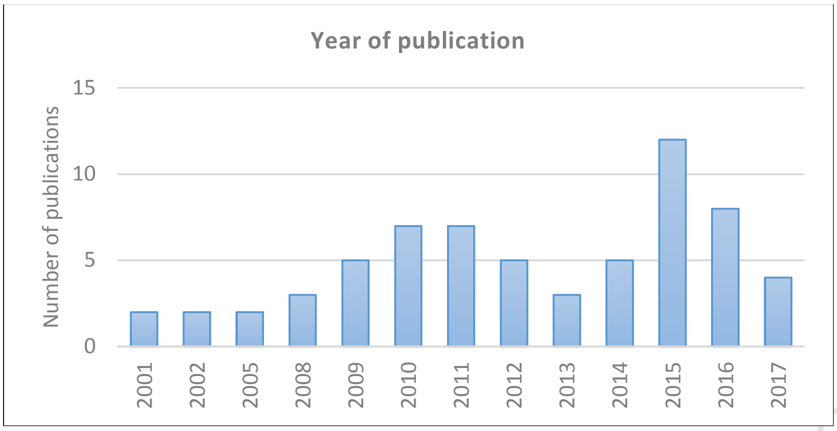

Figure 5. Number of EV related publications by year.

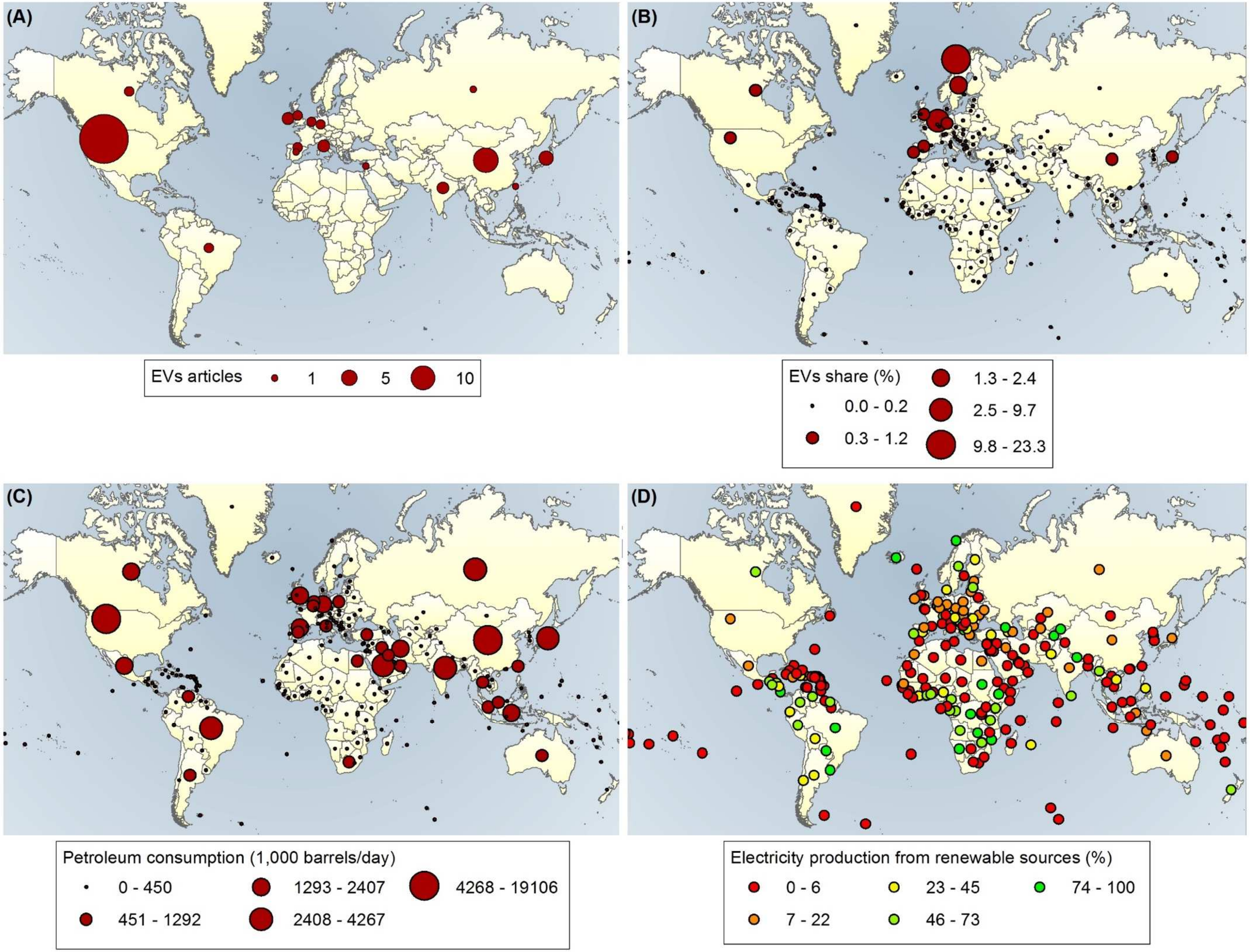

Figure 6. Global perspective of EVs articles and indicators related to electric mobility. Notes: (A) EVs articles that fulfilled the inclusion criteria of the present study; (B) Market share of EVs, BEV + PHEV, in 2015, based on the data reported by the International Energy Agency (IEA, 2016); (C) Total petroleum or gasoline consumption in 2014, based on the data reported by the U.S Energy Information Administration – EIA (EIA, 2014); (D) Electricity production from renewable sources in 2010, including hydroelectric power station, based on the data reported by the World Bank(World Bank, 2010).

To provide a better indication of how the sample research can be categorized, Table 2 presents an overview of the papers aggregated by their key attributes and the region in which the study took place. First, the table shows that a majority of studies occurred in North America followed by Europe and the Asia-Pacific region. Research in other parts of the world is comparatively lacking, and no research has taken place in continental Africa (Figure 6). A small subset of studies that examined a mix of locations, such as the United States and China in a comparative analysis, are grouped under the 'Mixed' category.

Of the pollutants analyzed, most focused on CO_2 emissions (51 papers), followed by NO_X (32 papers), VOC (18 papers), SO_2 (17 papers), $PM_{2.5}$ (16 papers) and CO (15 papers). The majority of studies for each pollutant occurred in North America, with the exception of NO_2, where three of the four studies were conducted in Europe. Light-duty vehicles, such as passenger cars, were the primary transportation mode of analysis (63 papers), with the majority of these occurring in North America. A subset examining buses, bikes, and motorcycles occurred more in the Asia-Pacific region. In terms of the EVs studied, a majority examined the environmental impacts of BEVs (42 papers) followed by PHEVs (31 papers). HEVs (19 papers) are less studied, and research on FCEVs is comparatively rare, occurring only in North America. Finally, there are two studies on electric bikes that were conducted in the Asia-Pacific region. Most papers utilized ICE vehicles as a comparator to EVs, especially in North America.

For the emissions chain, the categorization reveals that 44 papers employed a life cycle analysis, considering all aspects of the EV emissions from manufacturing to operations. Among those, 22 studies occurred in North America, 12 in Asia Pacific, 5 in Europe, 1 in South America and 4 were mixed studies. Other studies generally included lab tests, air quality modelling, or emissions inventories considered different aspects of the emissions chain together or in isolation. Most papers considered both power plant and traffic emissions.

Table 2. Categorization of study sample.

	Asia-Pacific	Europe	Middle East	North America	South America	Mixed	Grand Total
Pollutant							
PM	1	2	-	4	-	-	7
$PM_{2.5}$	6	2	-	7	-	1	16
PM_{10}	1	1	-	4	-	2	8
NO_x	8	3	-	19	-	2	32
NO_2	-	3	-	1	-	-	4
SO_x	1	1	-	3	-	-	5
SO_2	5	-	-	10	-	2	17
O_3	1	-	-	6	-	-	7
VOC	4	3	-	11	-	-	18
CO	2	3	-	10	-	-	15
CO_2	9	10	1	25	1	5	51
Others	1	1	-	6	-	-	8
Transportation Mode							
Light-duty	12	13	1	31	1	5	63
SUV	2	-	-	2	-	2	6
Motorcycle	3	1	-	1	-	-	5
Bike	2	-	-	-	-	-	2
Bus	3	1	-	2	-	-	6
Urban delivery trucks	-	-	-	1	-	-	1
Type of Vehicle							
ICE	9	8	1	19	1	5	43
HEV	3	4	1	10	-	1	19
PHEV	2	6	-	21	-	2	31
BEV	10	12	-	15	1	4	42
FCEV	-	-	-	5	-	-	5
Electric bikes	2	-	-	-	-	-	2
Emissions Chain							
Life cycle	12	5	-	22	1	4	44
Inventory - e.g. Moves	-	3	-	7	-	1	11
Lab test	-	1	-	3	-	-	4
Air quality modeling model	2	3	-	7	-	-	12
Other methods	-	3	1	4	-	1	9
Power plant emissions	12	10	-	27	1	5	55
Traffic emissions	12	11	1	32	1	5	62
Spatial Report							
Yes, fine scale	3	2	-	8	-	-	13
Yes, coarse scale (by state/city)	5	-	-	3	-	1	9
No	4	11	1	22	1	4	43
Health Report							
Yes, dose-response	-	-	-	2	-	-	2
Yes, intake fraction	2	1	-	1	-	-	4
No	10	12	1	30	1	5	59
Future Projection							
Yes	8	8	-	24	1	2	43
No	4	5	1	9	-	3	22
Regional Total	12	13	1	33	1	5	65

Note: the size of the blue bars was defined based on the quantitative information from individual rows.

In terms of health impacts, only a handful of papers linked the EV emissions chain to human health outcomes, with two studies in North America considering dose response. Beyond these, two studies in Asia-Pacific, one in Europe, and one in North America considered intake fraction. A majority of studies did not perform a spatial analysis of the variation of EV-related air pollution across their study area, instead focusing on generalized results. On the other hand, a majority did include future projections of air pollution based on different emission scenarios. Of the few that reported both results with spatial variation and future projections, the majority occurred in North America, following by Asia-Pacific, and Europe.

3.1. Evidence on atmospheric environment

Atmospheric emissions from fossil fuel burning vary significantly depending on the emission source and type of air pollutants or GHGs (Metcalfe and Derwent, 2005). For example, CO is emitted when the carbon in fuels does not completely burn due to lack of oxygen. Globally, vehicle exhaust contributes roughly 54% of all CO emissions, while power plants account for less than 5% (Sokhi, 2011). Traffic is also the main source of black carbon or "soot particles" accounting for ~35% of global emissions, whereas power plants emit about 0.5% (Z. Shen et al., 2014; Wang, 2015). On the other hand, the largest source of SO_2 and CO_2 is fossil fuel combustion in power plants, which generate ~73% and ~25% of global emissions, respectively (IPCC, 2014; Smith et al., 2011). Finally, for PM emissions, power generation and motor vehicles contribute 6.4% and 1.4% of $PM_{2.5}$, respectively (Huang et al., 2014).

Spatial variation is also an important aspect of traffic-related atmospheric emissions. This is mostly related to the substantial difference in emissions sources and air pollution controls among different countries (Lelieveld et al., 2015; Metcalfe and Derwent, 2005). For example, due to fast urban and industrial expansion during the last few decades, China, India, and other developing countries have one of the highest average concentrations of $PM_{2.5}$, exceeding 100 $\mu g/m^3$ in some urban centers (van Donkelaar et al., 2014; Zhang and Cao, 2015). On the other hand, high-income countries (especially, in Europe, the Americas, and the Western Pacific Region) have significantly reduced the level of $PM_{2.5}$ (van Donkelaar et al., 2014). However, the scenario is very different for CO_2 emissions. In general, both developed countries and nations with emerging economies account for the highest CO_2 emissions per capita (World Bank, 2010).

Science- and knowledge-based policies have been the most effective approach in guiding new strategies, helping societies to create sustainable and more inclusive cities in all sectors, including the economy, energy, transportation, and public health. Therefore, it would be interesting to compare the amount of scientific research by countries with air pollution/GHGs hot spots. Figure 7 shows a comparative global map from CO_2 and $PM_{2.5}$ emissions, and also a map of the number of articles published on EVs and atmospheric emissions that met our inclusion criteria. There is a significant gap between levels of emissions and national scientific research productivity, with the largest difference occurring in Canada, Middle East, and Australia, considering CO_2 emissions. Observing $PM_{2.5}$ emissions, we can note the largest difference is in Africa and South America.

Given that one major drawback of EVs may be that the air pollution source is shifted from roads to power plants, an analysis by type of emission particles and gasses is a key factor for a better understanding of the complex relationship between EVs and emissions. Therefore, we present below a comprehensive analysis of this relationship by dividing it into two categories – air pollutants (criteria pollutants) and GHG emissions.

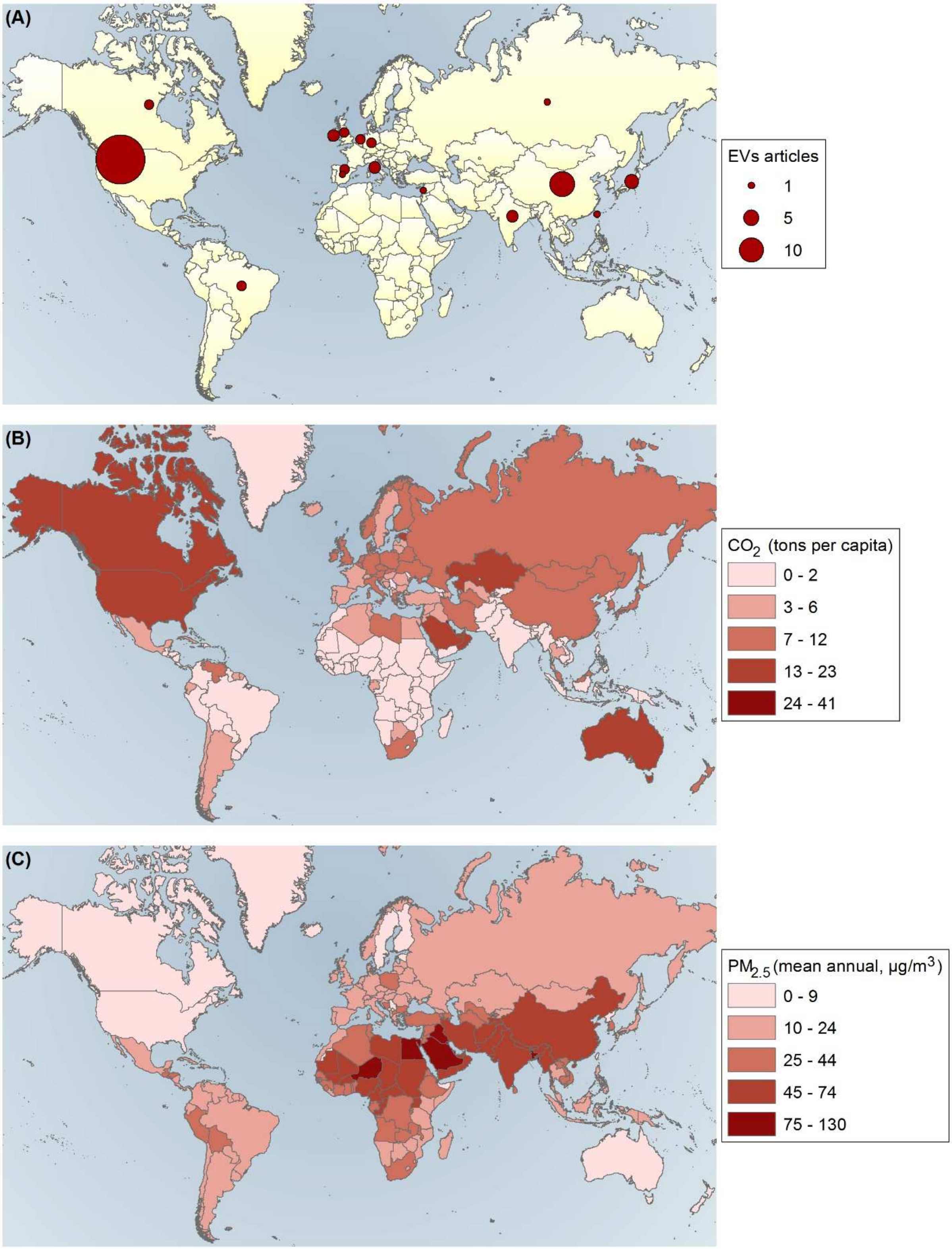

Figure 7. EV related articles and amount of CO_2 and $PM_{2.5}$ emissions across the world. Notes: EVs articles that fulfilled the inclusion criteria of the present study (A); CO_2 emissions in 2010 based on the data reported by the World Bank (World Bank, 2010) (B); $PM_{2.5}$ emissions in 2010 based on the data reported by the World Bank (World Bank, 2010) (C).

3.1.1. Air pollutants

i) Particles

Although the results of studies are inherently related to their emissions context, Figure 8 displays a general quantitative analysis of results for each type of air pollutant. Studies have provided evidence that the introduction of EVs offers moderate potential for reductions in PM emissions. Our quantitative analysis illustrated in Figures 8 shows that the most frequent values (value assigned to each study, as we described previously) are below 2.5. Only for HEV (PM_{10} emissions), we observed an average value of 3, indicating that HEVs may offer substantial benefit in reducing PM_{10} emissions. As an example here, Weis et al. (2016) demonstrated that PEVs and some BEVs have higher life cycle particulate emissions than HEVs in the current U.S. grid scenario (with higher percentage of power generation from coal). Specifically, on BEVs, the authors suggest that time of charge is an important aspect in order to reduce life cycle emissions. In their previous work (Weis et al., 2015), they show that controlled charging of EVs can significantly reduce particulate emissions from power plants.

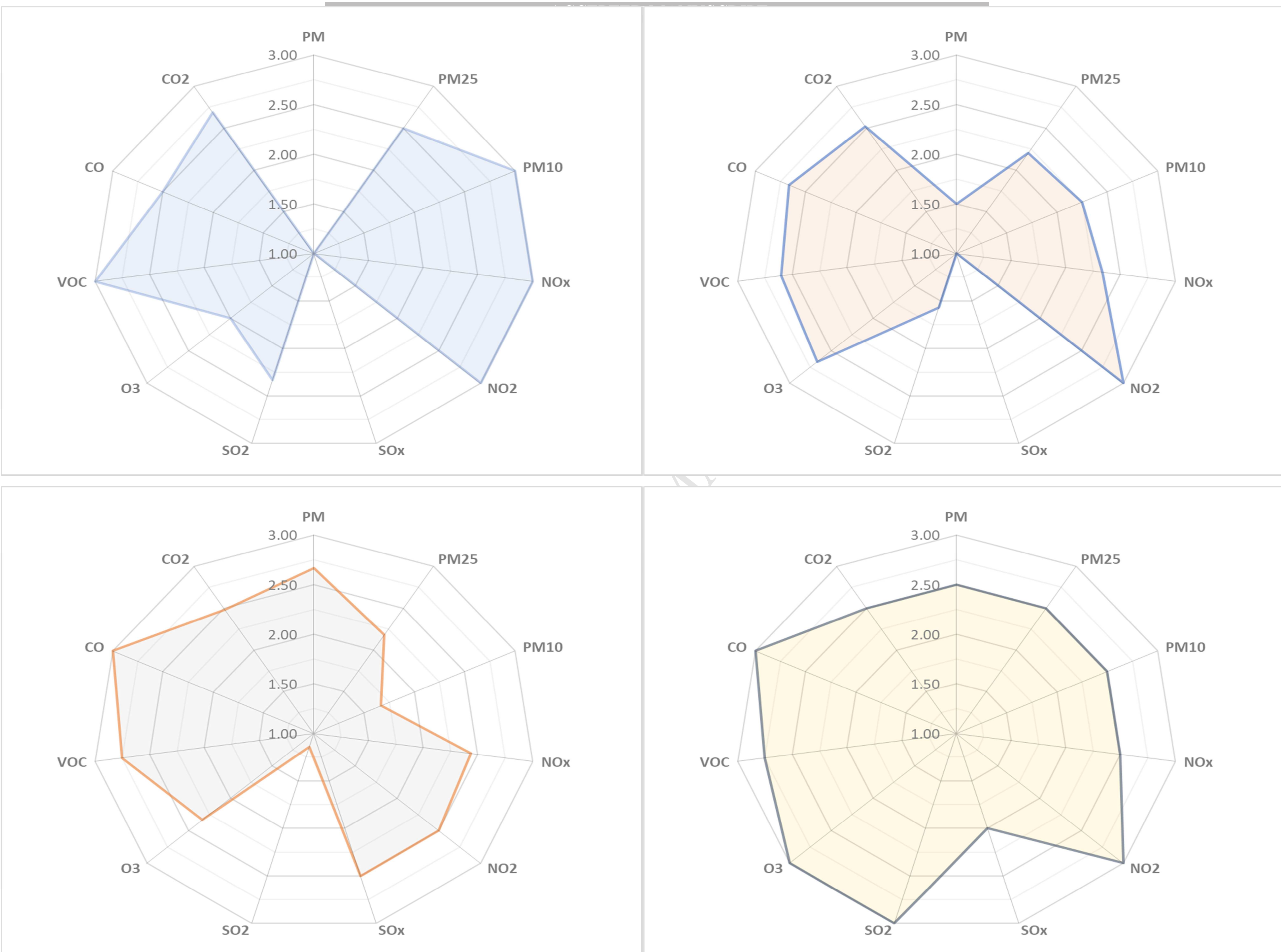

Figure 8. Quantitative analysis of avearge air pollutants by type of EVs.
Note 1: top left (HEV), top right (PHEV), bottom left (BEV), and bottom right (FCEV).
Note 2: the scale displayed in these charts are based on the quantitative analysis (described in section 2.2), where 1 represents zero benefits in reducing emissions, 2 medium benefits, and 3 high benefits.

Besides air pollution attributed to EVs under different charging scenarios, other specific examples have also shown that the energy grid and the location of emissions (on roads or at power plants) are key aspects. In China, Huo et al. (2013) examined fuel-cycle emissions of particulate matter and found that on average, BEVs can increase emissions of PM_{10} 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. In the Yangtze River Delta region in China, 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 to 1.1 $\mu g/m^3$. 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%.

In Ontario, Canada, the adoption of EVs (PHEV and FCEV) has also been related to increase in particulate matter emissions (PM_{10} and $PM_{2.5}$) from coal burning using the province's generation grid as it existed in 2010 (Kantor et al., 2010), although coal-burning generation has since been eliminated. In the U.S., EVs powered by clean energy sources (e.g., wind, water, solar) reduce $PM_{2.5}$ emissions significantly (Tessum et al., 2014). In California, U.S., the greater the share of coal in the generation mix, the greater the negative impacts of EVs on air quality (Huo et al., 2015). For example, a scenario with increasing the share of coal-fired power plants and the introduction of BEVs in California could increase PM emissions by 30%.

Energy generation accounts for the higher amount of PM emissions from EVs. However, with the introduction of renewable energy into the grid, non-exhaust PM emissions (e.g., brake, tire wear) may become the main source of PM (Huo et al., 2015). 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 (Simons, 2016; Timmers and Achten, 2016). The important factor here is vehicle weight. On average, EVs are 24% heavier than conventional vehicles (Timmers and Achten, 2016). For example, non-exhaust emissions increase by approximately 50% when compared to a medium (1,600 kg) and small (1,200 kg) vehicle. In Barcelona and Madrid, Spain, EV uptake scenarios (~ 13, 26, and 40% of the fleet) would offer an insignificant impact on PM reductions (< 5% reductions) mainly due to the high influence of non-exhaust emissions (Soret et al., 2014). According to the authors, in Spain, PM exhaust emissions represent about 35% of total road traffic emissions.

ii) Gaseous pollutants

Considering only gaseous pollutants (excluding CO_2, which will be discussed in the next section – GHG emissions), NO_x was the most studied gas, followed by VOC and SO_2. Based on this sample, EVs have greater potential for reductions in emissions of gases than PM. The quantitative analysis shown in Figure 8 indicates that EVs may have a significant impact on gaseous emission reduction, especially on NO_2, VOC, and CO. For example, Ferrero et al. (2016) assessed the effect of EV scenarios on air quality in Milan, Italy. They show that a scenario with 50% of light vehicles replaced by EVs would decrease NO_2 and NO_x concentrations (only tailpipe emissions) by 5.5% and 14.1%, respectively. Soret et al. (2014) reported that emissions from electricity generation due to EV (PHEVs and BEVs) charging has an insignificant impact on NO_2 (<3µg/m^3) in Barcelona and Madrid, Spain, where renewable energy sources represent 33% and nuclear energy 21% of the energy generation profile.

In Denver, U.S., an aggressive scenario with 100% of PHEVs would reduce NO_x emissions by 27 tons per day (16% lower than in the base case) from on-road mobile sources, and would increase by 3 tons per day (2% higher than in the base case) from power plants (mostly using natural gas) (Brinkman et al., 2010); VOC emissions would be reduced by 57 tons per day (24%) from on-road mobile sources. In Taiwan, the replacement of all light-duty vehicles with EVs would reduce on-road emissions of CO, VOC, and NO_x by 85%, 79%, and 27%, respectively. Overall emissions (on-road + electricity generation) of these pollutants would also be substantially reduced by EV penetration (Li et al., 2016). With respect to CO, HEVs have the potential to reduce CO emissions by 17% in the U.S (Colella et al., 2005). Considering here the introduction of FCEVs using hydrogen produced in coal power plants, it has the potential to reduce CO emissions by 52% (Colella et al., 2005). In Dublin, Ireland, a scenario with 25% EVs market penetration is estimated to reduce CO emissions by 14% (Brady and O'Mahony, 2011).

On the other hand, studies have shown that EVs have an insignificant effect in reducing SO_2 emissions. Some investigations have suggested that EVs may increase SO_2 ambient concentrations. For example, Wu et al. (2017) estimated air pollution benefits from EVs in 8 countries and found that EVs increase SO_2 emissions in all of them, including China, Russia, India, Brazil, Germany, France, U.S., and Japan. Specifically, in the U.S., Nichols et al. (2015) demonstrate that considering the 2012 electricity grid in Texas (~ 50% from natural gas, 25% from coal, 25% renewable and nuclear), PHEVs can reduce emissions of NO_x and CO in urban areas, but produce significantly higher life-cycle emissions of SO_2 (emissions rates is 0.72 g/mile, while for conventional vehicles is 0.0077 g/mile). In Taiwan, EV penetration would increase SO_2 emissions from electricity generation (mostly thermal power plants) by 29%. Total emissions (on-road and power plants) would be increased by 11% (Li et al., 2016).

Ground-level O_3 is another gaseous pollutant that has been associated with modest benefits from EV penetration. Brinkman et al. (2010) and Li et al. (2016) suggest that O_3 response is mixed, depending on spatial variability and atmospheric conditions, since O_3 is a secondary pollutant transformed in the atmosphere through chemical reactions between NO_x and VOC in the presence of sunlight. In the Denver metropolitan area, 100% PHEV penetration would reduce O_3 concentrations by 2 to 3 ppb on days with peak maximum 8-hour average O_3 level (Brinkman et al., 2010). In California, U.S., BEVs and PHEVs are associated with localized O_3 increases in some cases. The most substantial benefit from the introduction of EVs in California occurs on days with peak maximum 8-hour average O_3 concentration (6 ppb decrease in O_3 level) (Razeghi et al., 2016). Nopmongcol et al. (2017) modeled the air quality impacts of electrifying vehicles and off-road equipment across the U.S. and found similar results, with O_3 concentrations reduced by 1 ppb. In Taiwan, the annual average concentration of O_3 would be reduced by 3% in urban areas and 5% in rural areas (Li et al., 2016).

According to the literature selected in our analysis, 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 (as we presented previously). Clean energy has been fully recommended in order to obtain greater benefits in reducing gaseous pollutants. Spatial variability of the primary energy mix may account for over 70-160% of the average amount of emissions (Nansai et al., 2002). Substantial reductions are likely to occur at periods and places of greater ambient concentrations and during high pollution events, especially for O_3 (Li et al., 2016).

3.1.2. GHG emissions

Most studies have considered CO_2 emissions to link GHGs with electric mobility. From the 65 articles that fulfilled the inclusion criteria, 51 reported results for CO_2 emissions. Figure 8 indicates that EVs are associated with substantial reductions in CO_2 emissions. According to the literature reviewed, CO_2 emissions due to EV penetration are less sensitive to the variation of source of energy generation than particulate and gaseous pollutants. In other words, some studies have shown that even with a high percentage of electricity generated by coal power plants, EVs may still reduce emissions of CO_2. For example, in China where the electric grid is mostly dominated by coal generation, BEVs can reduce CO_2 emissions by 20%, but increase PM_{10}, $PM_{2.5}$, NO_x, and SO_2 emissions by 360%, 250%, 120%, and 370%, respectively (Huo et al., 2013). However, when we focus on government targets for GHG emissions reduction, studies have reported that EVs can reduce petroleum imports, but it will be challenging for EVs to achieve the government goals for CO_2 reduction (Doucette and Mcculloch, 2011; W. Shen et al., 2014).

3.2. Evidence on health effects

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 United States, 2 from China, and 1 from the Netherlands. Evidence in other regions is badly needed, especially when we observe a global map (Figure 9) showing the gap between national scientific research productivity and deaths due to air pollution by country.

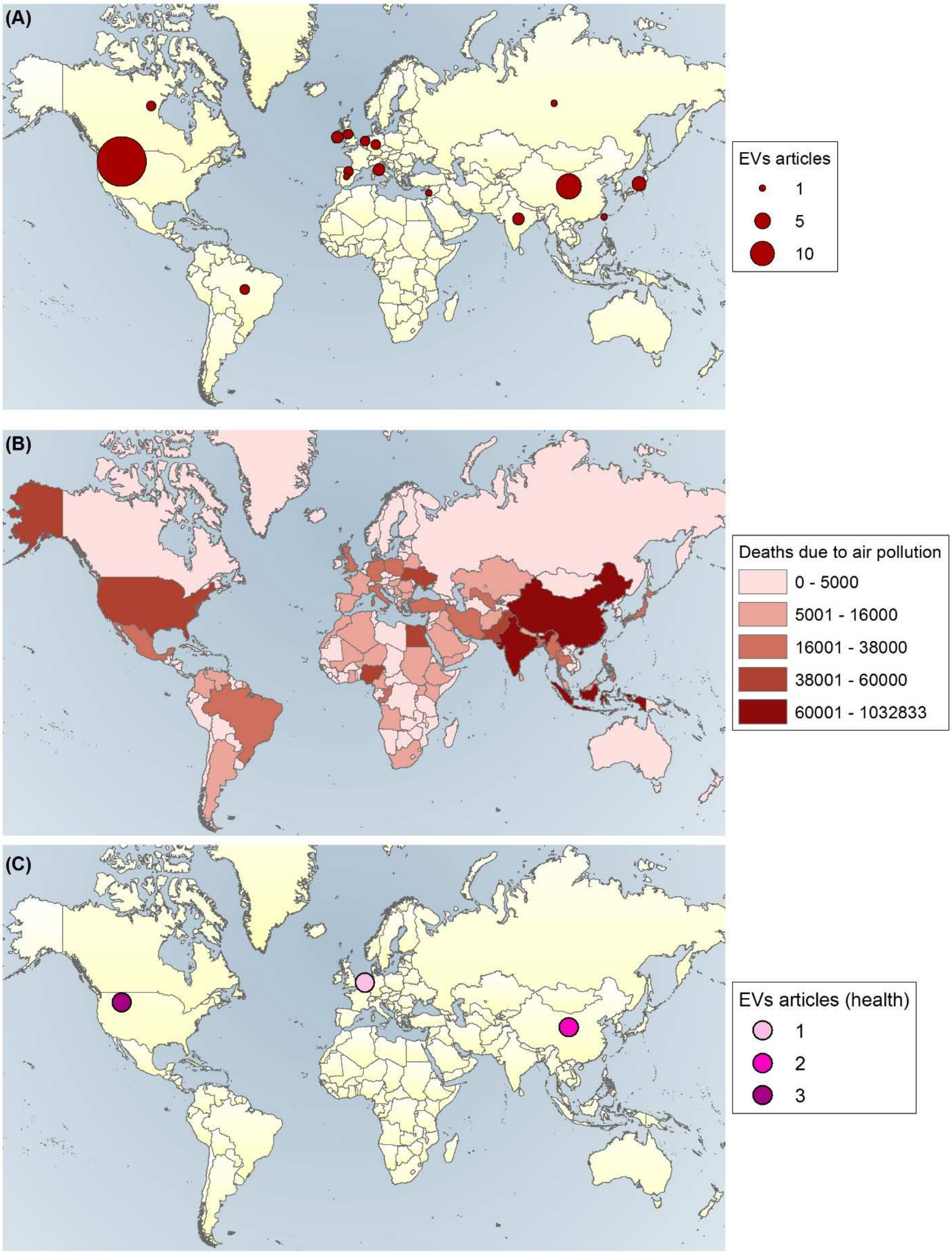

Figure 9. EV related articles and health impacts (deaths attributable to ambient air pollution). Notes: EVs articles that fulfilled the inclusion criteria of the present study (A); Deaths attributable to ambient air pollution in 2012, based on the data reported by the World Health Organization - WHO(WHO, 2012) (B); EVs articles that fulfilled the inclusion criteria of the present study and that considered health analysis (C).

The limited literature on health effects has shown 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). 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 wrestle with in considering EVs. For example, in China, population exposure may be lower with EV penetration because most of the population lives in urban centers (Ji et al., 2012). 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 (Ji et al., 2015). In the United States, EVs may significantly increase population exposure to air pollution from power plant emissions in some rural areas (Nichols et al., 2015).

Clean electricity sources are fully recommended in order to achieve the greater health benefits and to minimize the injustice aspect. Jacobson et al. show that in the US, EVs charged by renewable energy could save 3,700 to 6,400 lives annually (Jacobson et al., 2005). Tessum et al. (2014) show that the health impacts in the US may increase by 80% when vehicles use corn ethanol or coal as energy source. On the other hand, health impacts may be reduced by 50% if the vehicles are powered by natural gas, wind, water, or solar energy.

4. CONCLUSIONS, GLOBAL PERSPECTIVES, AND FUTURE CHALLENGES

We reviewed an extensive body of literature on the environmental and public health benefits of electric mobility, organizing and assessing the literature, synthesizing qualitative and quantitative evidence, and assessing their findings. This review can be useful for policymakers to develop new strategies in EVs technology and for future research directions in order to make road transportation more green, sustainable and environmetally-friendly.

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. Basically, 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.

However, we have identified some significant knowldge gaps. Most of the studies have focused on the type of EV and source of energy generation. Further research should explore the other factors in order to expand our understanding of all elements related to electric mobility through a roboust EV life cycle emissions analysis. In addition, from a global perspective, there is a significant geographical gap in the scientific knowledge on the environmental benefits of EVs, especially when compared with the spatial distribution of EV share, petroleum consumption, and electricity production from renewable sources. Several countries with a high percentage of renewable sources have the potential to reduce oil consumption, emissions and human exposure with a shift to electric mobility. Most of the studies were carried out in the United States or China. Evidence in other regions are relatively scarce and are badly 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.

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	Asia-Pacific	Europe	Middle East	North America	South America	Mixed	Grand Total
Pollutant							
PM	1	2	-	4	-	-	7
$PM_{2.5}$	6	2	-	7	-	1	16
PM_{10}	1	1	-	4	-	2	8
NO_x	8	3	-	19	-	2	32
NO_2	-	3	-	1	-	-	4
SO_x	1	1	-	3	-	-	5
SO_2	5	-	-	10	-	2	17
O_3	1	-	-	6	-	-	7
VOC	4	3	-	11	-	-	18
CO	2	3	-	10	-	-	15
CO_2	9	10	1	25	1	5	51
Others	1	1	-	6	-	-	8
Transportation Mode							
Light-duty	12	13	1	31	1	5	63
SUV	2	-	-	2	-	2	6
Motorcycle	3	1	-	1	-	-	5
Bike	2	-	-	-	-	-	2
Bus	3	1	-	2	-	-	6
Urban delivery trucks	-	-	-	1	-	-	1
Type of Vehicle							
ICE	9	8	1	19	1	5	43
HEV	3	4	1	10	-	1	19
PHEV	2	6	-	21	-	2	31
BEV	10	12	-	15	1	4	42
FCEV	-	-	-	5	-	-	5
Electric bikes	2	-	-	-	-	-	2
Emissions Chain							
Life cycle	12	5	-	22	1	4	44
Inventory - e.g. Moves	-	3	-	7	-	1	11
Lab test	-	1	-	3	-	-	4
Air quality modeling model	2	3	-	7	-	-	12
Other methods	-	3	1	4	-	1	9
Power plant emissions	12	10	-	27	1	5	55
Traffic emissions	12	11	1	32	1	5	62
Spatial Report							
Yes, fine scale	3	2	-	8	-	-	13
Yes, coarse scale (by state/city)	5	-	-	3	-	1	9
No	4	11	1	22	1	4	43
Health Report							
Yes, dose-response	-	-	-	2	-	-	2
Yes, intake fraction	2	1	-	1	-	-	4
No	10	12	1	30	1	5	59
Future Projection							
Yes	8	8	-	24	1	2	43

No	4	5	1	9	-	3	22
Regional Total	12	13	1	33	1	5	65

Highlights

- This study provides a comprehensive review of the effects of EVs adoption on air quality, greenhouse gas emissions, and human health.
- We assessed in total 4,734 studies and selected 123 articles of more detailed review.
- Most of the studies were carried out in the United States or China.
- The studies reviewed show that in general, EVs may have a role in reducing air pollution and its consequences for human health.
- This review can be useful for policymakers to develop new strategies in EVs technology and for future research directions