Equity implications of electric vehicles: A systematic review on the spatial distribution of emissions, air pollution and health impacts

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Abstract

Scaling up electric vehicles (EVs) provides an avenue to mitigate both carbon emissions and air pollution from road transport. The benefits of EV adoption for climate, air quality, and health have been widely documented. Yet, evidence on the distribution of those impacts has not been systematically reviewed, despite its central importance to ensure a just and equitable transition. Here we perform a systematic review of recent EV studies that have examined the spatial distribution of the emissions, air pollution, and health impacts, as an important aspect of the equity implications. Using the Context-Interventions-Mechanisms-Outcomes (CIMO) framework with a two-step search strategy, we narrowed down to 48 papers that met our inclusion criteria for detailed review and synthesis. We identified two key factors that have been found to influence spatial distributions. First, the cross-sectoral linkages may result in unintended impacts elsewhere. For instance, the generation of electricity to charge EVs, and the production of batteries and other materials to manufacture EVs could increase the emissions and pollution in locations other than where EVs are adopted. Second, since air pollution and health are local issues, additional location-specific factors may play a role in determining the spatial distribution, such as the wind transport of pollution, and the size and vulnerability of the exposed populations. Based on our synthesis of existing evidence, we highlight two important areas for further research: 1) fine-scale pollution and health impact assessment to better characterize exposure and health disparities across regions and population groups; and 2) a systematic representation of the EV value chain that captures the linkages between the transport, power and manufacturing sectors as well as the regionally-varying activities and impacts.

1. Introduction

Electric vehicles (EVs) have emerged as a central technology to decarbonize the transport sector and achieve climate stabilization [1]. Considering the recently announced decarbonization pledges, including the net-zero pledges, the International Energy Agency (IEA) projects that EVs can result in a net reduction of 580 Mt CO_2-eq emissions in 2030 which is 25% more than the net reduction projected for current policy scenario (i.e., 460 Mt) [2]. As gasoline combustion for running Internal Combustion Engine Vehicles (ICEVs) also causes air pollution, electrifying road transport is expected to bring substantial benefits for air quality and human health as well [3-6]. For instance, ambitious EV scenario is found to curb air-pollution-related premature deaths in China by around 17,000 in 2030, which is nearly 70% more than the premature deaths avoided in low-ambition EV scenario.

To ensure a just transition from ICEVs to EVs, it is crucially important to understand the distributional impacts and equity implications. However, despite a growing consensus that EV adoption would generally reduce emissions and pollution [2-6], how these impacts might vary across different locations or populations group within a large country or region remains poorly understood. A key concern of the justice-focused studies on EVs is to examine the changes geographical distribution of the social and environmental impacts of transport sector due to the shift from ICEVs to EVs. Such questions have been explored using different justice frameworks such as mobility justice [7] and environmental justice [8]. The shift from ICEVs to EVs may reduce the transport sector pollution, but also increase power and industry sector pollution due to the increased demand of power generation, and automobile parts such as batteries to run the EVs [2]. This will disproportionately impact the people living regions of power production and automobile battery manufacturing. More broadly, there is also a growing literature on the broader equity impacts of EVs and future modes of mobility, which considers not only the environmental impacts but also the social impacts on jobs and other political economy dimensions [9-11].

The pollution exposure and health damages are already highly inequitable at present. Globally, nearly 50% of the air-pollution-related deaths occur in China and India [12]. The average concentration of fine particulate matter ($PM_{2.5}$) across the African continent is almost 4.5 times higher than in the United States [13]. Environmental injustice also exists within a country. For instance, across the United States, the average $PM_{2.5}$ exposure among black and Hispanic populations is nearly 30% higher than white population [14]; in China, the average concentration for $PM_{2.5}$ is 30% higher for urban populations than rural populations [13]. With a focus on the transportation sector, it is also found that the transition from ICEVs to EVs can shift the air pollution from the richer urban areas where EVs are likely to get adopted to poorer rural areas where the power plants that generate electricity to run those EVs are located [8].

Given the large-scale transition to EVs that is anticipated in the coming decades, the future distribution of the emissions and health impacts from the transport sector will largely be shaped by EVs. Traditionally, the emissions and health impacts have been dominated by gasoline combustion used to fuel conventional vehicles. Looking to the future, EVs are projected to scale up rapidly; for instance, the share of EV cars in annual car sales is expected to increase from less than 10% to more than 30% between now and 2030 [2]. As a result, the future impacts of the transport sector will be influenced by, first and foremost, how quickly EVs penetrate the vehicle market, hence displacing the pollution impacts from gasoline use. In the meantime, new emissions and pollution may emerge in other sectors to support the EV transition, such as from generating electricity to charge the EVs [15-18]. This shift from the transportation sector to other sectors results in new mechanisms through which multiple locations may experience differential impacts.

By systematically reviewing the existing literature, we focus on one important aspect of the equity implications regarding the spatial distributions: *How would the transition to EVs for road transportation affect future emissions, air quality, and health impacts in different locations?* Our aim to highlight the role of cross-sectoral linkages between transport and other sectors on the emission and health impacts of EVs among different regions. Here, the term region indicates a county, province, or a country. That's because different sectoral activities, such as EV operation, power generation and vehicle production, tend to be located in different geographical locations. To support this overarching question, we ask three specific questions when synthesizing the findings from the literature: (1) Which factors or mechanisms are found to be critical in determining the spatial distributions of the impacts? (2) What types of quantitative methods have been used to quantify the spatial distributions? (3) What are the gaps in the existing methods that need to be improved to better quantify these mechanisms?

Methodologically, we first build a Context-Interventions-Mechanisms-Outcomes (CIMO) framework to decide our search scope and relevant inclusion and exclusion criteria. We then undertake a two-step search strategy, first starting with a broad search and then an expanded search based on the search results from the first step. Finally, we perform a careful review of each paper included in our final list to organize their findings about the implications on regional distribution and the relevant mechanisms.

2. Methods

2.1 Analytical framework

We use the Context-Interventions-Mechanisms-Outcomes (CIMO) framework to identify papers relevant for this review [19]. CIMO is commonly used to search policy-focused literature. We select this strategy because it aligns well with our goal to find papers that examined the mechanisms that drive the emission and health impact of EVs.

- For c*ontext* ("C"), our goal is to identify papers that examined the emission and health impacts of EVs in major world regions and countries.
- For *interventions* ("I"), we include policy and investment decisions that encourage the future development of EVs across its value chain.
- For *mechanisms* ("M"), we focus on identifying the mechanisms that determined the sub-national or cross-regional distribution of emission and health impacts of EVs.
- For *outcomes* ("O"), we are interested in three main outcomes: i) emissions, including the emissions of CO_2, SO_2, NO_x, primary $PM_{2.5}$, and volatile organic compounds (VOC); ii) pollution exposures, including ambient $PM_{2.5}$ and ozone concentration; and iii) health impacts, especially the premature deaths.

A detailed CIMO-based analytical framework is presented in Supplementary note 1.

2.2 Search strategy

Based on the CIMO framework, we searched for peer-reviewed papers published in English language between January 2010 and August 2022. We focused on papers published in 2010 and onwards because EV is a rapidly evolving technology, and its uptake has increased significantly only in the past decade.

Specifically, we took two steps to identify papers for our review.

Step 1: We first searched for relevant papers on ScienceDirect and Google Scholar using multiple relevant search strings. As our focus is not only on the emission and health impacts of EVs, but also on the distribution of those impacts, we added distribution-related keywords in our search strings. For example, to search for papers that studied the distribution of impacts by location, we used the following search string - "emission" AND "electric vehicle" AND "regional variation". We observed that using search strings with multiple keywords narrowed down the search considerably and provided a small number of results.

Step 2: We then expanded the search in two dimensions. First, we added additional keywords to search for paper on distributional impacts. We included keywords such as ‘equity’, ‘justice’, and ‘disparity’ in our search strings. Second, for the regions that are underrepresented in the initial search (e.g., Europe, India, and Africa), we added specific geographic regions in the search strings. This was because we realized that our initial search mostly yielded papers that analyzed impacts in China and the USA. The complete list of search strings for both steps is provided in Supplementary note 2.

Regarding our *inclusion criteria*, we only included papers that provided a quantitative assessment of the distribution of at least one outcome of interest (e.g., emissions, pollution, and/or health). Here we included papers that studied impacts across different population groups and/or locations because the studies that examine different populations often involve different regions too. Regarding our *exclusion criteria,* we did not include papers that did not perform a quantitative assessment of the distribution of emission and/or health impacts.

To ensure that we did not miss out on key papers, we reviewed the papers identified in *Step 1*. We then applied the same inclusion and exclusion criteria on the new papers identified in *Step 2*, and arrived at the final list of papers for the review.

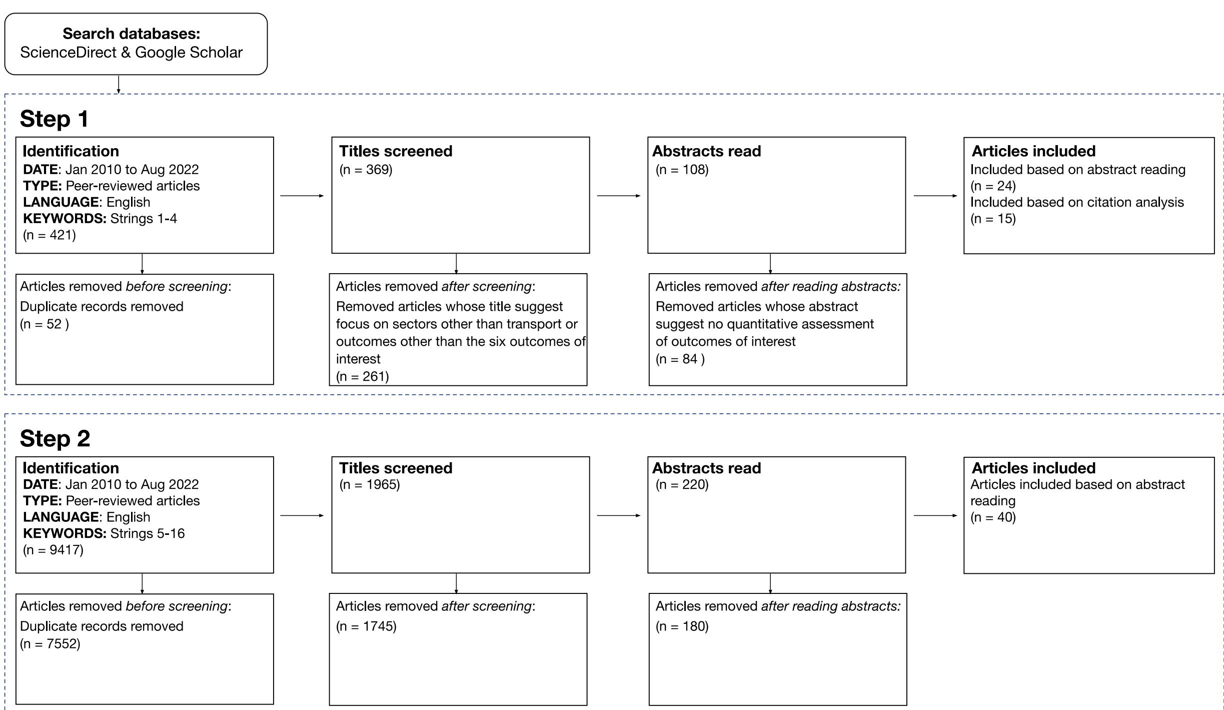

Figure 1. Overview of our search strategy, including the inclusion and exclusion criteria used to identify papers for this systematic review.

3. Results

3.1 Overview of the papers included in the review

As shown in Figure 1, we found 9838 papers from our initial 2-step search. After removing duplicates, we were down to 2334 papers. We then screened the title and abstract of these papers. We excluded the papers that were not specifically focused on EVs (e.g., papers that study transportation sector in general) or did not provide a quantitative assessment of the distribution of emissions or health impacts of EVs (e.g., those life-cycle analyses that only focus on processes but not the location of those processes). Given this focus, we only included papers which examined impacts of interventions focused on EVs. These interventions include policy or investment decisions to increase the adoption of EVs. These could also include future scenarios designed to estimate the emission and/or health impacts under varying levels of EV penetration. Based on these criteria, we arrived at a list of 79 papers. This initial list of 79 papers was screened by a group of eight people. The key screening question involve: year the research covered, country of interest, unit of analysis i.e., the location for which impacts were estimated, sectors assessed, emission and/or health variables assessed, and equity score for each emission and health variable.

After the initial screening, we narrowed down to 48 papers after this initial screening [3-6,8,15-18,20-58]. For these 48 papers included in our review, they were first read and reviewed by a group of eight people. Then, a second round of review was conducted by three authors of this study. We divided papers in a manner such that each single paper was read by at least two different people. For each paper, the reviewer is asked to summarize the information for the following aspects (Table 1):

Table 1. Information collected from each reviewer about the papers they reviewed

Metric	**Explanation**
Year	Timeframe of analysis
Country/Region of Interest	Country focus of analysis
Unit of analysis	Spatial resolution for estimating emission and/or health impacts, out of i) County, ii) Province, iii) Grid, i.e., area under a particular grid network, or iv) Region, i.e., one country or a set of countries

Sector of Interest	Sectoral focus of analysis, out of i) Gasoline-production, ii) Vehicle-manufacturing, iii) Power, and/or iv) Transport
Metric of Equity	Metric of equity for eight emission and health variables, including CO_2, NOx, SO_2, $Primary_{2.5}$, VOC, Ambient $PM_{2.5}$, Ozone, and Health impacts. Refer to section 3.2 for definition of metrics of equity.
Additional detail on impacts and their equity implications	Five questions on emission and health impacts of EVs, and their equity implications: • Does the paper estimate differences due to transport fuel, transport emission standards? • Does the paper discuss short term health impacts (e.g. NO_2 impacts)? • Does the paper estimate changes in impacts with time? • Does the paper mention terms such as 'energy justice', 'environmental justice', or 'mobility justice'? • Does the paper estimate impact for variables other than spatial distribution of emission and/or health impacts?

In case there were discrepancies or disagreements about the coding for the paper, we discussed these papers in detail among all the four co-authors and arrived at a decision based on our consensus. The final list of papers included in this review is provided as a Supplementary Data File.

Here we summarize the research scope of the 48 papers included in our review and highlight four general patterns (Figure 2).

First, the Global South countries were understudied, despite their central importance in shaping the climate and environmental future. More than half of the papers included in our study were focused on developed countries, mainly the United States [4,15-18,20-23,25,28-29,32-34,58] and European countries [6,30,36,46-49,52-53]. About 25% of papers examined emerging economies like China [3,5,8,26,31,39,41,45,51] and India [42,54], with more focused in China (about 20%). The remaining 25% of the paper had a multi-region [24,27,38,40,43,50,56-57] or global focus [35,37,44,45]. On the one hand, focusing on these major world regions is reasonable because the regional inequality concerns are particularly important for large countries/regions that are geographically diverse. On the other hand, the lack of attention on some important world regions, such as Africa, Southeast Asia, and Latin America, requires future attention. These regions are emerging new markets for EVs and are projected to be important contributors to future carbon emissions and air-pollution-related deaths [59-60]. Understanding the equity implications of transport electrification in these Global South regions will be critical for tackling both local and global sustainability futures.

Second, many studies already considered the impacts beyond just the transportation sector, though the sectoral coverage was still incomprehensive in most cases. The adoption of EVs, first and foremost, influences the emissions and pollution impacts from the transportation sector. Yet, cross-sectoral linkages are important to understand the life-cycle impacts of the whole EV value chain. For the papers included in our review, 90% of the studies covered both the transport sector and power sector, since the electricity generation activities have strong ties to support EV operations [3-6,8,15-18,20-23,25-36,38-43,45-50,52,54,56-58]. About half of the studies further examined gasoline production and vehicle manufacturing activities: 20% of the studies considered the changes in gasoline production and electricity generation activities to support the EV transition [21,27,31,33,35-36,38,43,54], while 10% of the studies considered the emissions and pollution impacts associated from the vehicle manufacturing activities [15,17,20,26,46], including the production of batteries for EVs and the manufacturing of materials required for vehicles (e.g., steel). However, only 20% of the studies included all four key sectors (i.e., transportation, power, gasoline production, and manufacturing) [4,23,25,28-30,42,49-50]. This pattern indicates that although the research community has started to recognize the importance of cross-sectoral linkages, a lot more needs to be done to account for the multi-sector, economy-wide impacts of EVs.

Third, studies at fine spatial resolution were still insufficient. More than 60% of the papers only examined the emissions and pollution impacts for the whole region, without demonstrating the potential differential impacts across states, provinces or counties within one region [5-6,15-16,18,20-23,25,27,30,35-40,43-44,46-50,52-53,55-57]. We find that 15% of the papers examined the differential impacts across provinces [3,26,29,31,41-42,51]. This spatial scale is helpful for informing real-world decisions since many energy and climate decisions are made by provincial/state governments and relevant decision makers. Only 25% of the papers took a further step to study finer resolution impacts that vary across counties or spatial grids that are finer than states/provinces [4,8,17,24,28,32-34,45,54,58]. Most of these finer-scale studies used air quality modeling methods to simulate the geographic distributions of the pollution concentrations. To estimate the gridded emission as input to air quality models, these studies often treat power sector emissions as point sources (based on current locations of plants) and transportation sector emissions as non-point sources (based on information on road infrastructure and traffic volumes). Despite the efforts to obtain fine-scale emission impacts, studies still often make simplified assumptions based on present-day spatial patterns, i.e., scaling down the baseline power/transportation sector emissions across all the spatial grids within the same province/state. These simplifications, though justifiable in most cases [61], don't properly account for the nuance of EV impacts depending on which power plants and vehicle choices are being displaced [62,63].

Finally, methodologically, the majority of the studies that examined the distribution of EV impacts were based on scenario analyses, e.g., designing counterfactual scenarios for the past or policy-relevant scenarios for the future. These scenario-based analyses allowed them to estimate and compare how sectoral activity could change with a higher share of EVs in the vehicle fleet, which in turn changes the emissions of both greenhouse gases and air pollutants. To account for the pollution and health impacts from these changes in emissions, some studies used air pollution models (e.g., WRF-CMAQ or WRF-Chem [3,5,33,45]) and health impact assessment methods (e.g., concentration-response relationships from epidemiological studies [5,32-34]) to estimate the corresponding exposure and health damages. These additional modeling and data needs are likely the underlying methodological reason contributing to our previous finding that much fewer studied examined pollution and health impacts compared to the CO_2 impacts.

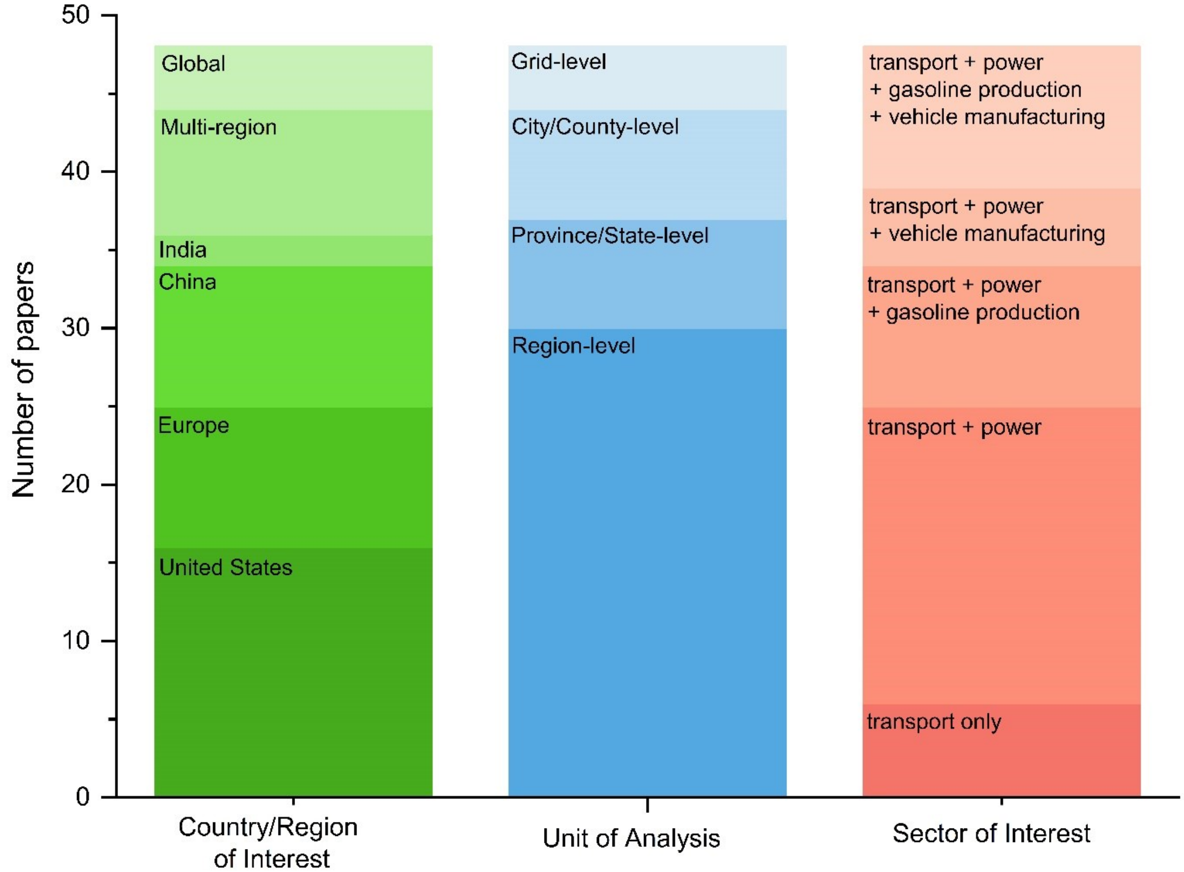

Figure 2. Summary of the scope of the papers included in this review (N=48). Here "Multi-region" include the studies that focused on several countries in different regions of the world, such as comparative studies between China, United States and Germany [24] or between four developing countries and four developed countries [56]. "Grid-level" studies include the studies that use spatial grids finer or comparable to county/city level and were often studies using air quality modeling.

3.2 Summary of the distributional impacts

We focus on spatial distributions as one key aspect of equity consideration. For the outcomes being examined in each study (i.e., emissions, air pollution, and/or health), we classified the finding into three broad categories: 1) All winning, i.e., as a result of EV transition, the paper found all the regions being covered in the study would always benefit from a reduction in emissions, pollution or health damages; 2) Winners and losers, i.e., in all scenarios examined in the study, it is always the case that some regions would benefit while others may suffer from the EV transition; and 3) Scenario dependent, i.e., the paper found that losers may occur only in specific setting and the distributional consequences would depend the scenario designs.

To illustrate how we classified the studies, here we use one paper as an example, i.e., Ji et al. 2015, "*Environmental Justice Aspects of Exposure to $PM_{2.5}$ Emissions from Electric Vehicle Use in China*" [8]. This paper found that the primary $PM_{2.5}$ emissions would decrease in regions where EVs are adopted, making these regions "winners". In contrast, increased EV adoption would result in an increase in primary $PM_{2.5}$ emissions in regions where electricity for running EVs is generated, making them "losers". These patterns of winners and losers were found in all scenarios they examined. Thus, in our synthesis, we categorize this study as "Winners and losers" for their key outcome on "primary $PM_{2.5}$ emissions".

Based on our synthesis of all 48 papers, we highlight three key insights (Figure 3). First, while the majority of the studies did quantify the varying CO_2 emissions across subnational or regional units, very few studies quantified the regional disparities in air pollution and health. As we were interested in examining both carbon and air pollution emissions, we included papers in review even if they only provided spatial distribution CO_2 emissions and did not examine air quality or health impacts. We found that more than 90% of the papers provided evidence on regional variations in CO_2 emissions as a result of EV transition [3-4,15-18,20-50,52-58]. In comparison, less than 25% of the papers provided information on the regional variations in precursor air pollutant emissions (e.g., SO_2, NO_x, primary $PM_{2.5}$, or VOC) [3-6,8,22,31-33,40-42,45,51,54,56], exposure to ambient air pollution (e.g., ambient $PM_{2.5}$ or O_3) [3-5,22,32-34,41,45,54], or the health impacts (e.g., premature mortality) [3,5,22,32-34,41,45]. Since air pollution and health impacts are highly local, this finding underscores the importance of analyzing the pollution and health disparities in order to understand the local effects from transport electrification.

Second, among the studies that examined the regional variation in addition to the aggregate impacts, many identified plausible unequal outcomes where the EV transition creates winners and losers across regions. For some studies [4-6,8,15-18,20-23,26,28,30-31,36-37, 40,42-44,48,50,53,56-58], such tradeoffs exist in all scenarios being examined, while other studies found tradeoffs only in a subset of the scenarios under certain conditions [3,29,33-35,38,41,51,55]. For instance, Peng et al 2018 found net reduction in air pollutants and CO_2 emissions across all regions when the penetration of renewables reached 40% of the electricity mix; otherwise, the deployment of EVs would exacerbate the emissions and pollution impacts in some regions [3]. Our synthesis thus highlights the importance of going beyond the aggregate impacts that are often positive (e.g., net reduction in emissions or health exposure/damages for the whole region). A detailed assessment of regionally-varying impacts is needed to understand the local impacts of EV transition.

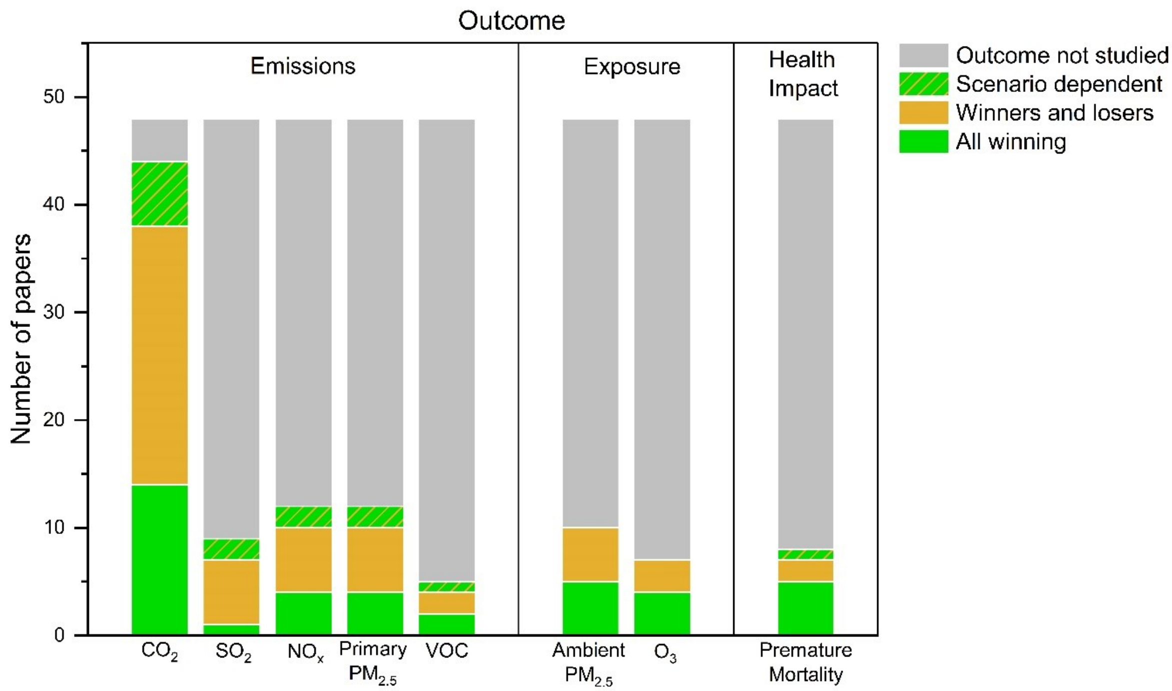

Figure 3. Summary of the findings on the regional distribution of the EV impacts (Number of papers: N=48). "Outcome not studied": the outcome on emissions, exposure or health was not studied in the paper. "All winning": all the regions being covered in the study would always benefit from a reduction in emissions, pollution or health damages as a result of EV transition. "Winners and losers": in all scenarios/cases, some regions would benefit while others may suffer from the EV transition. "Scenario dependent": depending on the scenarios, losers may occur in specific setting and scenario conditions.

3.3 Key mechanisms for the unequal regional impacts

We further delve into the subset of the papers that examined the regionally-varying impacts (i.e., the non-grey segments in Figure 3). The goal here is to identify key mechanisms that contributed to inequitable outcomes. We find that the drivers, processes and mechanisms that connect the EV transition with the resulting distributional impacts are quite complex (Figure 4).

First, multiple energy-related sectors would be influenced by the operation and manufacturing of EVs. The increase in EV adoption will directly affect the transport sector (e.g., lowering gasoline and diesel consumption). In the meantime, the increase in EV adoption would also result in changes in the power sector (e.g., increasing electricity generation) and the industrial sector (e.g., lowering gasoline and diesel production, and increasing battery and material production). In this step, the key determinants for the regionally-varying impacts are the locations of the relevant energy activities, shaped by the energy markets and EV supply chains [3-6,8,15-18,20-58].

Second, the amount of CO_2 and air pollutant emissions vary across sectors and relevant energy activities, which in turn results in differential regional impacts. In terms of tank-to-wheel emissions (i.e., the emissions from driving vehicles), gasoline ICEs have lower levels of NOx and SO_2 emissions, but higher levels of NMVOC and CO_2 emissions than diesel ICEs. In terms of well-to-tank emissions (i.e., the emissions from production, processing, and delivery of transport fuels), gasoline ICEs have higher levels of emissions for CO_2 and air pollutants (including NOx, SO_2, $PM_{2.5}$ and NMVOC). In addition, coal-based power generation emits substantial amounts of SO_2 and NOx, and the mining activities as part of the battery production process also emits SO_2. The emissions from these upstream activities may lead to unintended impacts in regions different from where EVs are being deployed. We find the regional differences in the emission factors (i.e., emissions per unit energy activities) play an important role especially for the air pollutant emissions. Such differences are driven not only by fuel type and efficiency of locally-used technologies, but the stringency of air pollution control policies for the transport, power, and industrial sectors also play a crucial role [3-6,8,15-18,20-58].

Finally, the precursor air pollutant emissions would influence the concentrations of air pollution, such as fine particulate matter ($PM_{2.5}$) and ozone (O_3), affecting the pollution exposure level of local residents. In this step, the regionally-varying impacts can be further influenced by the non-linear atmospheric processes, such as local meteorological conditions that would affect the wind transport of pollution as well as the chemical formation of secondary pollutants such as secondary aerosols and O_3 [3-5,32-34,41,45,54]. Finally, the human health impacts from the exposure to ambient air pollution are affected by characteristics of the exposed population. Here the additional factors that would widen the regional variations include the size and vulnerability of the populations [3-5,32-34,41,45]. In addition to $PM_{2.5}$ and ozone, NO_2 from transport emissions has been found to have short-term health impacts, such as increasing risks of asthma attack, allergy, and other respiratory diseases [64-66]. However, none of the reviewed studies on EVs estimated these short-term health damages from NO2 exposure, highlighting an important area for future research.

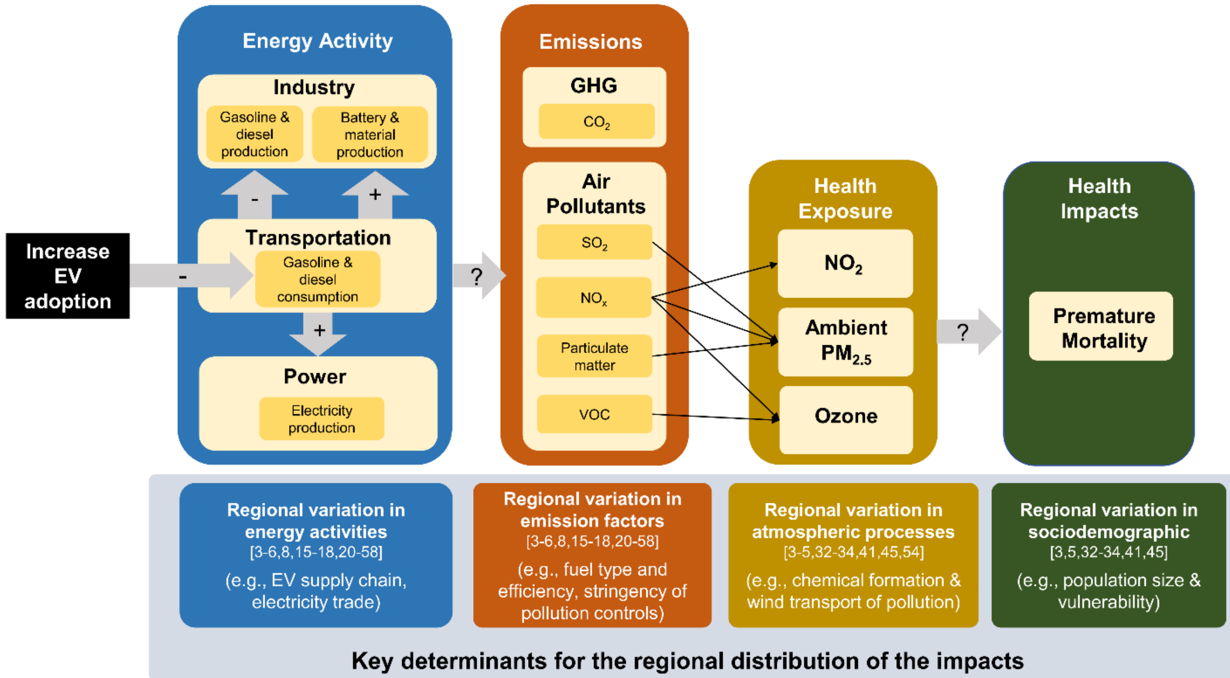

Figure 4. A schematic of the key mechanisms for electric vehicles to influence energy, emissions, and health effects, as well as the associated regional distributions. The “+” and “-” signs indicate whether the related energy activities would increase or decrease as a result of EV transition. The “?” sign suggests that the influence is unclear and case-dependent.

Furthermore, the conclusions made about the regional distributions are often determined by which sectors and mechanisms are being considered. We also found that only a small number of papers examined how these regional distributions changed with time. Cross-region equity can be defined and operationalized in different ways. Yet, most of the studies included in our review do not clearly state what definition of equity they adopted and what metrics were used.

We therefore select the following three papers as example to demonstrate what regional distributions and relevant mechanisms they studied, and what are the relevant equity definitions/metrics that we think the authors may have used implicitly (Figure 5):

- *Example 1:* Wu et al. 2017 [56] compared the emissions of CO_2 and air pollutants between developed countries (Germany, France, US, and Japan) and developing countries (China, Russia, India, Brazil). Compared to conventional gasoline-based vehicles, they found that utilizing EVs reduces transport-related CO_2 emissions in all regions. However, the associated air pollutant emissions may increase in developing countries due to their dependence on thermal power generation combined with the high line loss rates in electricity transmission.

Here the cross-region equity could be defined as countries emitting their fair share of mitigation burden and that people in the developing and developed countries face similar pollution exposure. It was operationalized by comparing the CO2 emissions and air pollutant emissions across countries at different developmental stages and income levels.

- *Example 2:* Ji et al. 2015 [8] examined the $PM_{2.5}$-related health impacts due to the urban use of EVs in China. Although deploying EVs reduced emissions from the transportation sector in the urban areas, it increased the air pollutant emissions from the power sector in rural areas where most power plants are located. This further led to regionally-varying health impacts.

  Here cross-region equity could be defined as rural and urban populations face similar levels of pollution exposure and health impacts, which was operationalized by comparing the air pollutant emissions and ambient PM2.5 concentrations in rural and urban areas.

- *Example 3:* Hung et al. 2021 [30] explored the impacts of electricity trade on the carbon footprints across regions in Europe. They found that the trade of electricity could relocate the electricity generation activities to other regions, thus influencing the distribution of the CO_2 emissions across regions.

  Here cross-region equity is that countries emit their fair share of emissions based on its consumption of electricity, which was operationalized by comparing the production versus consumption-based emissions across regions.

The three examples above, along with other papers included in our review, demonstrated the importance of cross-sectoral linkages and relevant mechanisms in determining the regional distributions. Given the complexity and numerous forms of linkages, it also becomes clear from our synthesis that none of the existing papers cover all relevant sectors, mechanisms and processes that could impact the regional distributions of the emissions and health impacts, highlighting the need for future research (see more discussions in the next section).

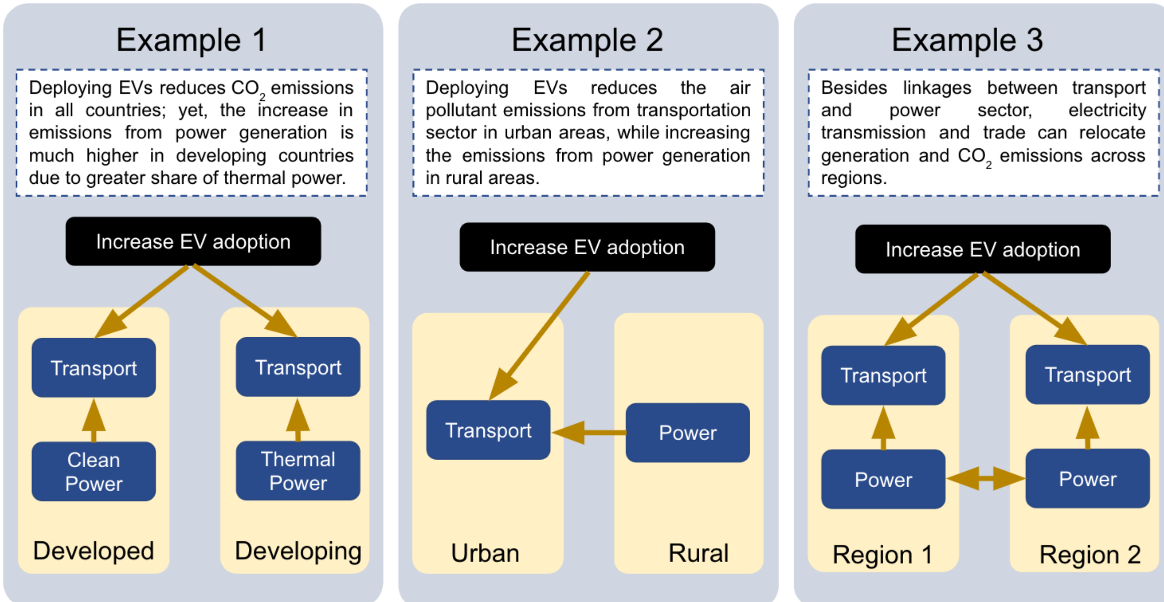

Figure 5. Illustrative examples to demonstrate the mechanisms through which electric vehicles influence the regional distribution of the impacts. Examples 1, 2, 3 are based on Wu et al. 2017 [56], Ji et al. 2015 [8], and Hung et al. 2021 [30], respectively.

4. Discussion and conclusion

Based on the Context-Interventions-Mechanisms-Outcomes (CIMO) framework, we used a two-step search strategy to identify and review papers that assessed impacts of EV transition on the spatial distribution of emissions, air quality and health. We find that the distributional impacts often vary across the outcomes of interest (e.g., CO_2 emission vs. air quality, vs. health) and across scenario assumptions (e.g., the cleanness of the electricity used to power the EVs). Many factors influence spatial distribution. For instance, while the locations of EV adoption often benefit from cleaner vehicles, other locations that support the production of electricity, battery, or other materials may suffer from increased emissions and impacts.

Our review also demonstrated that assessing the equity implications of EVs is analytically challenging. First, it involves complex drivers and cross-sectoral dynamics that are difficult to characterize. The adoption of EVs not only influences the energy consumption in the transportation sector. It also drives changes in other sectors and locations, such as the power generation activities to supply the electricity as well as the battery and manufacturing activities to produce the EVs. Besides emissions, the ambient pollution level is further influenced by atmospheric chemistry and transport processes, while the associated human health impacts are also shaped by the size and vulnerability of the exposed population. Methodologically, characterizing the complex cause-effect relationships from energy activities to emissions and health imposes new challenges to the quantitative representation of the coupled energy-human systems. It requires pushing the frontiers of both systems modeling and empirical evidence.

We also find that most studies still lack a clear definition of equity and how it is operationalized, which may limit the usefulness of the studies to inform real-world decisions. Policymakers and other stakeholders have increasingly highlighted the importance of equity in designing and implementing policies to support the transition towards EVs and other low-carbon technologies. However, our review suggests that most papers did not explicitly explain what is meant by equity and how to measure equity for different outcomes and equity principles. It underscores the importance of putting equity at the center of energy research, as proposed by the research community in recent years [67-68].

While existing research has provided useful methods and insights to capture the equity implications, we highlight two important areas where future research is urgently needed. First, we need more information about the pollution and health impacts at a fine spatial scale. Although many studies have quantified the impacts on emissions, taking further steps to assess the air pollution and health disparities is important to understand the impacts on human wellbeing. Second, a systematic representation of the linkages between the transport, power and manufacturing sectors is needed to better understand the region-specific activities and impacts. Although many studies have started to consider upstream activities, limited research has provided a holistic view of the whole EV value chain with a solid representation of all the important cross-sectoral linkages. To further examine the equity-related impact of the shift to EVs, it is crucial to assess its impact on labor across the automobile value chain. Strategies designed to develop EV industry to spur local job growth in a country could lead to worsening of pollution and health impacts at sub-national levels [70-71]. However, with the increasing need for developing strategies for just energy transition, governments are increasingly facing the challenge of addressing economic, environmental, and climate concerns together. They may not always be able to identify win-win solutions, but it is crucial to examine these trade-offs.

Conceptually, a framework that provides a comprehensive assessment of the regional distributions needs to include the following elements (Figure 6): a) for energy and emissions: representation of the whole value chain of EVs, including not only the cross-sectoral linkages (e.g., between transportation and power and industrial sectors) but also the relevant market linkages within each sector (e.g., electricity trade and EV supply chain), and b) for exposure and health: representation of the atmospheric processes and sociodemographic factors that may further result in regional differences in pollution formation and transport, as well as the associated disparities in population exposure and health impacts. Arguably, including all these system linkages is neither feasible nor desirable in one research project. Nevertheless, this conceptual framework summarizes all mechanisms that were found to be important in the papers we reviewed. It provides the big picture and a potential roadmap for future research to better quantify the regionally varying impacts of EV transition on emissions, air quality and health.

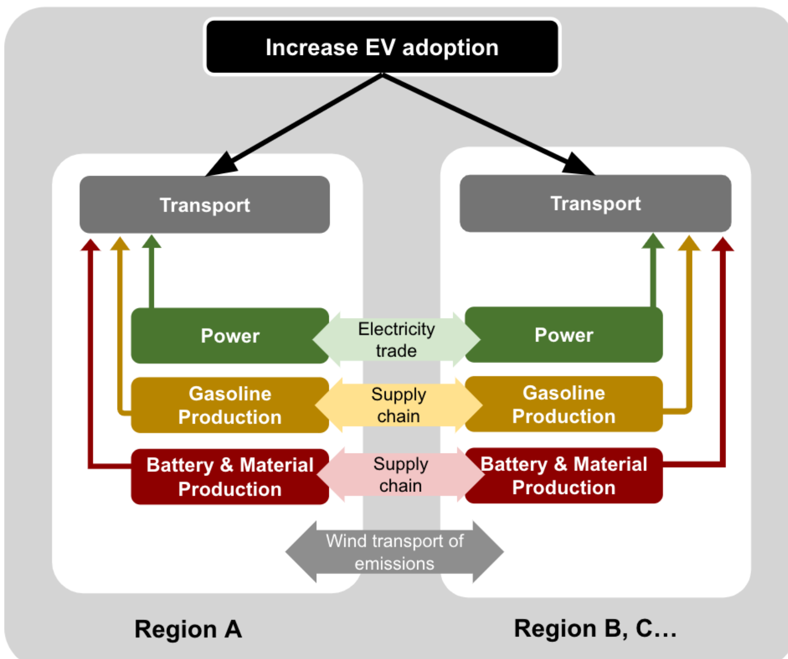

Figure 6. A conceptual framework to assess the regionally varying impacts of electric vehicles, with considerations of cross-sectoral and cross-regional linkages.

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Data availability statement:

The data that support the findings of this study are openly available (https://docs.google.com/spreadsheets/d/1LW6TRxy_-GcT5MUOE7N6HwRQbeG6LF7Aqr3UdwqnPxc/edit?usp=sharing).

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