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Impacts of the large-scale use of passenger electric vehicles on public health in 30 U.S. metropolitan areas

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Abstract

In addition to sound policies at the national level, the successful implementation of zero-emission vehicle goals requires commitments and actions at the regional level. This study quantified what the potential impact would be by 2050 of large-scale use of passenger electric vehicles (EVs) on air pollution (concentrations of fine particulate matter), public health, and associated economic gains across various metropolitan areas in the United States. Results were estimated and reported for 30 metropolitan areas. The study employed the U.S. Environmental Protection Agency CMAQ air quality model and the BenMAP health impact assessment tool. Results indicated that a large-scale uptake in EV passenger travel can improve air quality and reduce mortality. The top five metropolitan areas that would benefit the most from such transportation electrification are Los Angeles (1163 prevented premature deaths annually, corresponding to $12.61 billion health benefits), New York (576, $6.24 billion), Chicago (276, $3.00 billion), the San Joaquin Valley (260, $2.82 billion), and Dallas (186, $2.02 billion). These results provide important scientific input to national and regional policymakers in support of decision-making towards clean transportation. This study examined the status quo and latest updates on EV transition policies across different regions given that California and several northeast states have already expressed explicit clean transportation goals. Interrelated policy, technology, and behavioral measures toward bringing down barriers to EV adoption were also examined. The wide differences that exist in the electricity mix across various regions suggests that varying strategies are needed down the road to achieve clean electric mobility.

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Highlights

- Large-scale use of electric vehicles in passenger travel can reduce mortality
- EV-induced health benefits for 30 U.S. metropolitan areas are quantified
- Presents updates on transition to EVs in different regions
- Discusses various pathways toward lowering adoption barriers to EVs
- Shows how varying regional strategies are needed to reach an electric future

Keywords: Electric vehicles, air quality, health impacts, metropolitan areas, passenger travel, United States

1. Introduction

Vehicle electrification is considered an effective approach to achieve deep de-carbonization in transportation, reduce air pollution, and improve public health [1-6]. Transportation generates the largest share (29%) of greenhouse gas emissions in the United States (U.S.), and over 90% of the fuel used is petroleum-based, mostly gasoline and diesel [7]. Passenger transportation sources (e.g., light-duty cars, trucks, and motorcycles) are responsible for 60% of the fine particulate matter ($PM_{2.5}$) emissions and 43% of the nitrogen oxides (NO_x) emissions produced by all on-road transportation sources [8]. A fully-electric vehicle generates no tailpipe emissions, and hence is usually referred to as a zero-emission vehicle (ZEV). The global sales of electric vehicles (EVs) have steadily increased in recent years. The number of electric cars sold globally (and sales market share) was 0.8 million (< 1%) in 2016, 2.1 million (2.2%) in 2018, 3.1 million (4.1%) in 2020, and 6.6 million (8.3%) in 2021 [9,10]. In the U.S., sales more than doubled, from 0.3 million in 2020 to 0.7 million (with a share of 4.5%) in 2021 [9]. At the city level in 2021, passenger EV shares were 22% of sales in San Francisco, 11.9% in Los Angeles, 11.7% in Seattle, and 3.4% in New York City [11].

Many governments and companies have pledged to accelerate the transition to zero-emission cars and vans in order to achieve the goals of the Paris Agreement to limit global warming to well below 2°C (preferably to 1.5°C) compared to pre-industrial levels [12-16]. According to the Glasgow Conference of Parties (COP26) declaration, 28 national governments made commitments that all sales of new cars and vans would be zero emission by 2040, or no later than 2035 in leading markets. A total of 10 additional emerging and developing counties expressed a goal of working intensely toward accelerated proliferation and adoption of zero-emission vehicles [17]. Countries with leading vehicle manufacturing industries – such as the U.S., Germany, Japan, and China – did not sign on to the declaration at the time; while in the U.S. several regional governments signed up, including the states of California, New York, and Washington, and large cities such as Los Angeles, New York City, San Francisco, Atlanta, Ann Arbor, and Seattle [17,18]. The U.S. government announced an ambitious target of a 50% EV sales share by 2030, with a goal of installing 500,000 EV chargers nationwide, according to the Bipartisan Infrastructure Law (BIL, i.e., Infrastructure Investment and Jobs Act, H.R. 3684) passed in November 2021 [19] and the Electric Vehicle Charging Action Plan [20]. These will support a continued rise in EV adoption in the future.

Previous studies have assessed the potential impact of electric vehicles on air quality. Internal combustion engine (ICE) vehicles emit not only long-lasting climate warming species, such as carbon dioxide (CO_2), but also those with a short lifetime, such as $PM_{2.5}$, NO_x, and volatile organic compounds (VOCs). These substances react through gas-phase and aerosol chemical processes, forming secondary air pollutants in the atmosphere that can be transported to broad downwind regions. The adoption of EVs could reduce air pollution by mitigating carbon and other air pollutant emissions. Atmospheric chemical transport models (CTMs) have typically been utilized to quantify the air quality impact of EV adoption. Study areas have included the U.S. [6,21], the Northeast and Mid-Atlantic regions [22], Colorado [23], Texas [24], and the Greater Houston Area [2]. Generally, these studies reported better air quality resulting from vehicle electrification. For example, Nopmongcol et al. [21] reported that a 17% electrification rate for light-duty vehicles and various other mobile sources in the U.S. by the year 2030 would result in a reduction in $PM_{2.5}$ of 0.5 $\mu g\ m^{-3}$. A scenario with a higher EV adoption rate would be reasonable considering the current federal policies and EV growth trends globally.

The adoption of EVs could have a positive impact on public health. Exposure to ICE-vehicle-related air pollution is associated with increased adverse health effects, such as cardiovascular and respiratory diseases, hospitalizations, and premature mortality [25-28]. Concentration-response (C-R) functions, representing the relationship between air pollutant concentrations and human health, are derived from large amounts of air quality datasets and health impact records in epidemiological studies. Typically, poor air quality conditions coincide with an upsurge in adverse health effects. Increasing use of EVs could improve air quality and benefit human health. A limited number of studies have investigated the impact of EV adoption on public health within the U.S. [2,6,29,30]. For instance, Pan et al. [2] reported a decline in cases of premature deaths with increasing electrification rates of cars and trucks in the Greater Houston Area. However, the existing literature has mostly focused either on the national level, on a single state or metropolitan area, or on several states. A health impact assessment covering a large number of metropolitan areas, under a consistent modeling framework, would be helpful to support regional policymakers in their decision-making.

Therefore, in addition to sound policies at the federal level, the successful implementation of zero-emission vehicle goals requires commitment and action at the regional level. This study considers the impact large-scale use of passenger EVs would have in the U.S. by the year 2050, investigating potential impacts on concentrations of $PM_{2.5}$, public health, and associated economic gains. Specially, results are estimated for 30 metropolitan areas across the country. The study uses the U.S. Environmental Protection Agency (EPA) national emission inventory (NEI), the community multi-scale air quality (CMAQ) model [31], and the environmental benefits mapping and analysis program (BenMAP) [32].

There are several novel aspects to this study. First, by quantifying the health and economic benefits resulting from large-scale vehicle electrification for 30 metropolitan areas, this study becomes the first EV-related health impact study to focus on such a large number of cities. The study also provides detailed spatial distributions for preventable premature mortality at the metropolitan and county levels. These can serve as a database that future studies can use for reference or comparison. Regional policymakers or researchers may find results from this study useful for their EV-related cost-benefit analyses for each metropolitan area. Second, for health impact estimation, this study utilizes the epidemiological concentration-response relationships from Turner et al. [33], newly recommended by the U.S. EPA in 2021, reflecting the updated knowledge of linkages between ambient $PM_{2.5}$ concentrations and long-term premature mortality. Third, recent policy updates on transition to EVs in different regions are presented, providing a general picture of the status of EV uptake across the United States. Various pathways (e.g., policy, technology, and behavior pathways) impacting EV adoption and interaction are discussed. This can be helpful to inform decisions about lowering adoption barriers.

2. Materials and Methods

2.1. Scenario design and emission inventories

Projections for new light-duty EV sale shares in the United States vary, as presented in Fig. 1. The projections are based on government regulations, institutional research, or expert insights. These projections include the following:

(1) The Bipartisan Infrastructure Law set a goal of 50% light-duty EV sales share by 2030 [19].

(2) Scenarios with almost full penetration of passenger EVs in the U.S. by 2050 were considered in Fulton et al. [1]. The study assumed double average fuel economy for electric cars compared to ICE cars, and a continued increase in fuel efficiency for both EVs and conventional vehicles. Based on calculations using the International Energy Agency (IEA) Mobility Model, the study estimated that CO_2 emissions from passenger travel would drop by 95% due to the transition to EVs by 2050.

(3) The United Nations Sustainable Development Solutions Network (SDSN) released a report titled the America's Zero-Carbon Action Plan, which suggested at least 30% of new sales would be light-duty zero-emission vehicles by 2030 and 100% of new sales by 2040 [34,35].

(4) The Zero-emission Vehicle Mandate in California requires that, by 2035, 100% of new sales of passenger cars and trucks in the state be zero-emission vehicles, according to California governor's Executive Order N-79-20, in September 2020 [36,37].

(5) The Electric Power Research Institute (EPRI) suggested light-duty electric and plug-in electric vehicles could comprise 75% of new vehicle sales and 70% of vehicle miles traveled by 2050 [38]. The study mentioned that, although the purchase price of EVs would be remain slightly higher than ICE vehicles through 2050, lower fuel and maintenance costs could drive down the total costs of EVs.

(6) Projections of new light-duty EV share of sales are conservative in the Annual Energy Outlook (AEO2022), released by the U.S. Energy Information Administration (EIA) [39].

(7) Similar to Fulton et al. [1], Bloomberg New Energy Finance (BNEF) assumed 100% of the world's vehicles would run on electricity or hydrogen by mid-century, to reach net-zero

emissions in road transport by 2050 [40]. Projections from several other sources are described in Muratori et al. [41].

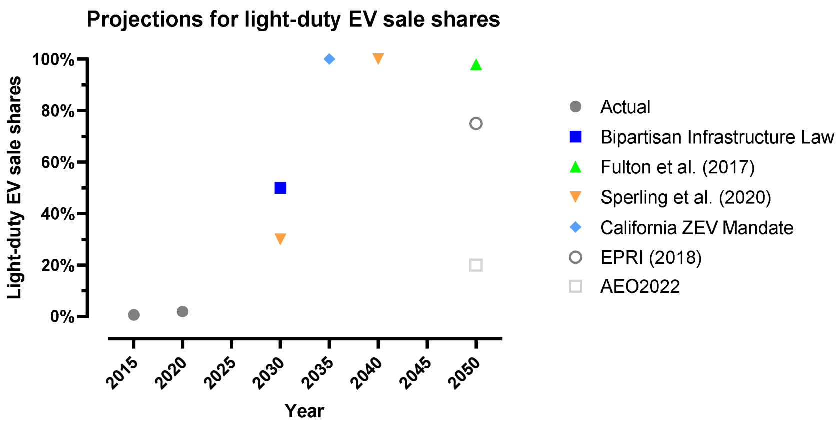

Fig. 1. Projections for new light-duty electric vehicle (EV) share of sales. These projections are based on government regulations, institutional research, or expert judgments. Acronyms: ZEV – Zero-emission Vehicle; EPRI – Electric Power Research Institute; AEO – Annual Energy Outlook. More details are listed in Table S1.

This study aims to assess how much air quality and health might improve through vehicle electrification. To this end, this study utilized the projection (i.e., the scenario of "two revolutions") of Fulton et al. [1], which suggested almost full uptake of EVs in passenger travel in the U.S. by 2050 and provided an estimation of a 95% reduction in emissions. This is referred to as the "Electric Vehicle 2050" (EV2050) scenario in this study. Another simulation case, referred to as the Baseline (BASE) case, serves as the baseline to which the future scenario was compared. The BASE case utilized the U.S. EPA National Emissions Inventory of 2011 (NEI2011) [42]. The NEI2011 included mobile, point, area, and biogenic sources. Emissions from on-road mobile sources were estimated as:

$$E = \sum EF_{c,f,v,r,p,s} \times VMT_{c,f,v,r,p,s} \times (1 - F_t) + \sum EF_{c,f,v,r,p,s} \times VPOP_{c,f,v,r,p,s} \times (1 - F_t) \qquad (1)$$

where E is total emission amounts; EF is emission factor; the subscript c is county, f is fuel type, v is vehicle type, r is road type, p is emission process, and s is species; VMT is vehicle miles traveled; $VPOP$ is vehicle population; and F_t is the removal efficiency of control technology t. VMT and VPOP data are also referred to as motor vehicle activity. Activity data were provided by state and local air pollution control agencies. The U.S. EPA collected the activity data and compiled them into county-level annual or monthly inventories. For all states except California, emission factor inventories were based on the outputs generated by the U.S. EPA Motor Vehicle Emissions Simulator (MOVES) [43]. California emissions were based on Emission Factor (EMFAC). More details, as well as descriptions of other emission sources (e.g., power generation and industrial processes, residential, agricultural, and biogenic sources), appear in Pan et al. [26] and Jung et al. [44].

For the EV2050 scenario, this study adjusted emission factor inventories for the vehicle type categories of passenger travel, namely, passenger car, passenger truck, transit bus, school bus, and motorcycle. Vehicles fueled by both gasoline and diesel were included. Emission processes from both on-network vehicles (i.e., from vehicles moving along the roads) and vehicles off-network (e.g., starts, extended idle, evaporative, permeation, and refueling) were considered. The F_t value in Equation (1) was assigned 95% to reflect significant reductions in emissions. It should be noted that the 95% reduction mentioned in Fulton et al. [1] is for CO_2 emissions. This study assumed that the large-scale applications of EVs would lead to similar reductions in emissions of air pollutants as those of CO_2. The reduction rates in emissions of air pollutants, however, could be different. The rates would vary with different emission processes and control technology.

2.2. Air quality simulation

A WRF-SMOKE-CMAQ-based modeling system was utilized to simulate the ambient concentrations of air pollutants. The Weather Research and Forecasting (WRF) model v3.7 [45] was employed to prepare meteorological conditions, which would impact both emissions and air quality. The WRF model is a mesoscale numerical modeling system developed for meteorological research applications and operational forecasting. Initial and boundary conditions to the WRF model were drawn from the North American Regional Reanalysis (NARR), at a spatial resolution of 32 km and a temporal resolution of 3 h [46]. The WRF preprocessing system (WPS) performed interpolations to convert the 32 km gridded NARR data to 12 km grid cells used in this study. The Sparse Matrix Operator Kernel Emissions (SMOKE) model v3.6 [47] was used to process emissions. Emission inventories are typically in annual or monthly total, and at the county level. The SMOKE model performed temporal allocation, spatial allocation, and chemical speciation to convert emission inventories to hourly gridded species, which could be directly used in the air quality model. Motor vehicle activity inventories were spatially allocated to be concentrated along the main routes, by using the TIGER/Line Shapefiles data [42]. Two sets of emissions, for the BASE case and the EV2050 case, were prepared for air quality simulations.

The Community Multi-scale Air Quality (CMAQ) model v5.0.2 [31] was utilized to simulate air quality. The CMAQ model predicts the evolution of gas and particle phase air pollutants, under the impacts of emissions, atmospheric transport, chemistry reaction, and deposition. This could be represented as:

$$\frac{\partial \varphi_s}{\partial t} + \nabla \cdot [\varphi_s \mathrm{V}] = \nabla \mathrm{K} \nabla \varphi_s + Emis_s + Chem_s + Aero_s + Otr_s \quad (2)$$

where φ_s is the concentration of species s at a specific location as a function of time t; V is wind vector; K is turbulent eddy diffusivity; $Emis$ is emission rate; $Chem$ is gas-phase chemistry; $Aero$ is aerosol dynamics, particle formation, and deposition; and Otr is other processes [31,48]. The WRF meteorological model, SMOKE emission tool, and CMAQ air quality model all run at a spatial resolution of 12 km per pixel; and the simulation domains cover the contiguous U.S., southern Canada, and northern Mexico. The CMAQ domain contains 459 × 299 grid cells horizontally and 27 layers vertically. The simulation time periods are January, April, July, and October of 2011 for the baseline case. Details of the configuration options used in WRF and CMAQ are listed in Pan et al. [26]. The Software for Model Attainment Test – Community Edition (SMAT-CE) was utilized to bias-correct the CMAQ-simulated $PM_{2.5}$ concentrations, which were then used for health impact assessment. Evaluations of model performance using 2011 $PM_{2.5}$ observations were included in Figs S1 and S2.

2.3. Health impact estimation

The Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) v1.5 [32,49] was utilized to estimate premature mortality and economic value associated with changes in ambient $PM_{2.5}$ concentrations. This study used the log-linear format concentration–response (C–R) function:

$$\Delta y = \left(1 - e^{-\beta \cdot \Delta x}\right) \times y_0 \times Pop \qquad (3)$$

where Δy is the change in the incidence of premature mortality; β is the C–R coefficient, reflecting the relationship between air pollutant concentrations and health effects; Δx is the change in air pollutant concentrations; y_0 is the baseline incidence rates; and Pop stands for the affected population. This study used the C–R relationship (β=0.00583) from Turner et al. [33], recommended by the U.S. EPA in 2021 [50]. Turner et al. [33] used data from the nationwide American Cancer Society Cancer Prevention II Study (ACS CPS-II), and evaluated 669,046 participants (>29 years old) over 12,662,562 person-years of follow up and 237,201 observed deaths. The epidemiological reference reported relative risks of 1.06 (95% confidence intervals: 1.04-1.08) for every 10 μg m^{-3} increase in $PM_{2.5}$. In this study, Δx is the differences in ground-level $PM_{2.5}$ concentrations between the BASE case and EV2050 case. The baseline incidence rates come from the Center for Disease Control and Prevention (CDC) [51]. The 2010 block-level population data from the U.S. Census Bureau were processed and allocated to the study domain using the PopGrid software [32]. The county-level population scaling ratios for each year from 2000-2050, provided by Woods and Poole [52], were pre-installed in BenMAP. The year of population used in this analysis is 2050.

The BenMAP used the Value of Statistical Life (VSL) method to calculate the economic value of avoided premature mortality. The current mean VSL used by the U.S. EPA is $8.705 million (2015$), based on 26 value-of-life studies [50]. This study used the following valuation function:

$$Econ = \Delta y \times VSL_{2015} \times IGA \times CL \qquad (4)$$

where $Econ$ is the calculated economic value in 2050; Δy is prevented premature mortality; VSL_{2015} is the VSL value in 2015; IGA is the income growth adjustment factor, which is set to be 1.375 for mortality in 2050; CL is the cessation lag value (0.906), according to the U.S. EPA [32].

In this study, the grid resolution for BenMAP calculations is 12 × 12 km, the same as the CMAQ simulations; and the BenMAP simulation domain covers the entire contiguous U.S. After obtaining premature mortality estimations from BenMAP at each air quality grid cell, these results were aggregated to a coarser spatial scale. This study presented the results for 30 metropolitan areas, at both the metropolitan and county levels. This study selected 30 metropolitan areas based on the definitions used by the U.S. Census Bureau, and listed the counties included in each metropolitan area. For each county, this study found the corresponding state code and county code, defined in the U.S. Federal Information Processing Standard (FIPS) (see Tables S2-S8). Since outputs from BenMAP were listed in the format of “FIPS state code, county code, and health impact value”, this study could then match the BenMAP estimation to the county of interest. This study provided the economic gains for 30 metropolitan areas as well, using a similar approach. Additionally, this study reviewed and presented several major updates related to EV transition in different regions.

3. Results

3.1. Impacts of large-scale use of EVs on air quality

Fig. 2 depicts the changes in concentrations of ground-level $PM_{2.5}$ resulting from large-scale use of EVs in 2050. Domain-wide declines in $PM_{2.5}$ concentrations are shown in the continental U.S., the result of significant reductions in passenger transportation emissions, atmospheric transport processes, and chemical reactions. Relatively large decreases in $PM_{2.5}$ are found in California and the eastern United States. California shows the highest $PM_{2.5}$ reductions; specifically, the Greater Los Angeles Area and San Joaquin Valley would have $PM_{2.5}$ reductions of more than 1 $\mu g\ m^{-3}$. Other regions, also exhibiting moderate $PM_{2.5}$ reductions due to EV adoption, include the Northeast (e.g., the metropolitan areas of New York, Philadelphia, Washington D.C., and Boston), Midwest (several states), Southeast (e.g., the metropolitan areas of Atlanta and Birmingham, and state of North Carolina), and Texan cities (e.g., Houston and Dallas). Since most of the areas with large $PM_{2.5}$ reductions are located in highly populated urban areas, the improved air quality conditions are expected to benefit the health of residents in these areas.

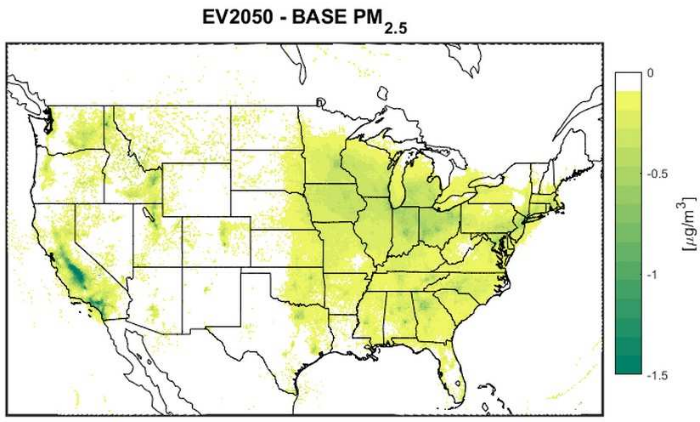

Fig. 2. The changes in surface $PM_{2.5}$ concentrations due to large-scale use of electric vehicles in 2050. These are the differences in $PM_{2.5}$ between the EV2050 case and the BASE case (EV2050 minus BASE).

3.2. Health benefits

The distributions of prevented premature mortality attributable to $PM_{2.5}$ reductions for several metropolitan areas in the Pacific West are presented in Fig. 3 and Table S3. The Greater Los Angeles Area would obtain substantial health benefits due to the large-scale use of passenger EVs, with 1,163 cases of prevented premature mortality annually in the entire area. The county-level distributions are Los Angeles county (595 cases), Orange (203), Riverside (177), San Bernardino (159), and Ventura (30). These significant numbers result from the notable air quality improvement from EV adoption, as well as the large population size in the area. The San Joaquin Valley would obtain 260 annual prevented premature deaths. The figure was higher than 30 cases in four counties: Fresno (84 cases), Kern (43), Tulare (34), and San Joaquin (32). The San Francisco Bay Area, comprised of several counties, would obtain a total of 180 prevented premature deaths. By county, Santa Clara (50), Alameda (45), and Contra Costa (39) all would exceed 30 cases. The Sacramento-Roseville area would benefit from 90 prevented premature deaths, with 59 cases in Sacramento county. Seattle-Tacoma, WA, would see 44 prevented premature deaths, with 24 cases in King county (city of Seattle). Estimations of prevented premature mortality resulting from large-scale passenger EV adoption for the metropolitan areas in other regions are shown in Figs. S3-S8 and Table S4-S8. These regions include the Mountain West, Midwest, West South Central, Northeast, and Southeast. Detailed descriptions of the quantitative results can be found in the Supplementary Material.

Fig. 3. Distributions of prevented premature mortality attributable to $PM_{2.5}$ reductions resulting from large-scale use of passenger electric vehicles in 2050, for several metropolitan areas in the Pacific West. Results are exhibited at the county level. Results in tabular format are listed in Table S3. Results for the metropolitan areas in other regions are presented in Figs. S3-S8 and Table S4-S8.

To tackle the air pollution challenges, California was granted the authority to enact its own emission standards decades ago, under the federal Clean Air Act. California set more stringent emission rules than federal standards. Currently, fourteen other states have followed California ZEV standards, which mandate a minimum percentage for zero-emission passenger vehicle sales [53]. There has been recent progress in the Mountain West in support of transition to EVs. In order to address supply chain shortages, a Nevada-based mining company received investments from the federal government to separate and process rare earth materials [54]. These minerals and materials are crucial in the production of technological devices, such as battery technology. Colorado revised the use of Volkswagen funds to focus investment on transportation electrification [55]. In the Midwest, EV sales started to reach markets in many areas in 2018 [56]. The Texas Commission on Environmental Quality (TCEQ), through its

Texas Emissions Reduction Plan (TERP), currently provides a $2,500 rebate for the purchase or lease of a new light-duty electric or fuel cell vehicle [57].

The Transportation and Climate Initiative (TCI) is a collaboration of twelve states in the northeast and Washington D.C. to reduce GHG emissions and air pollutants from the transportation sector [58,59]. The TCI proposed a cap for transportation CO_2 emissions, as well as investments to advance equitable development. Arter et al. [60] estimated that, among total on-road mobile sectors in the TCI region, light-duty cars and trucks contributed to 59% of $PM_{2.5}$-related premature deaths. Similar to the case in California, New York State (NYS) set a goal for all new passenger cars and trucks sold in NYS to be zero-emission by 2035, according to Legislation (A.4302/S.2758) signed in September 2021 [61]. NYS also set the goals of reducing by 2050 overall GHG emissions by 85%, establishing a zero-emission electricity sector by 2040, achieving 70% renewable energy generation by 2030, and channeling no less than 35% of the overall benefits from investments to disadvantaged communities, as outlined in the state's Climate Leadership and Community Protection Act (CLCPA) [62]. In New York city, however, zero-emission vehicles only made up less than 1% of the ~1.9 million registered passenger vehicles [11], this potentially due to a lack of charging stations in dense residential settings. In the Southeast, Georgia offered the EV manufacturing company Rivian $1.5 billion in tax incentives to build a factory east of Atlanta. The factory is planned to produce up to 400,000 EVs a year, according to the Georgia Department of Economic Development [63].

3.3. Economic values

Fig 4 depicts the estimates of health and economic gains for 30 U.S. metropolitan areas, sorting from highest to lowest. These estimates suggest significant prevented premature deaths and substantial economic benefits can be gained through large-scale vehicle electrification by 2050. The five metropolitan areas with the highest health benefits are Los Angeles, CA (1163 prevented premature deaths annually, corresponding to $12.61 billion), New York, NY-NJ-CT-PA (576, $6.24 billion), Chicago, IL-IN-WI (276, $3.00 billion), the San Joaquin Valley, CA (260, $2.82 billion), and Dallas, TX (186, $2.02 billion). Eight metropolitan areas can obtain economic gains between $1 billion and $2 billion, including Atlanta, GA ($1.96 billion), San Francisco, CA ($1.95 billion), Washington D.C., DC-VA-MD-WV ($1.69 billion), Philadelphia, PA-NJ-DE-MD ($1.61 billion), Houston, TX ($1.28 billion), Detroit, MI ($1.17 billion), Phoenix, AZ ($1.11 billion), and Minneapolis-St. Paul, MN ($1.01 billion).

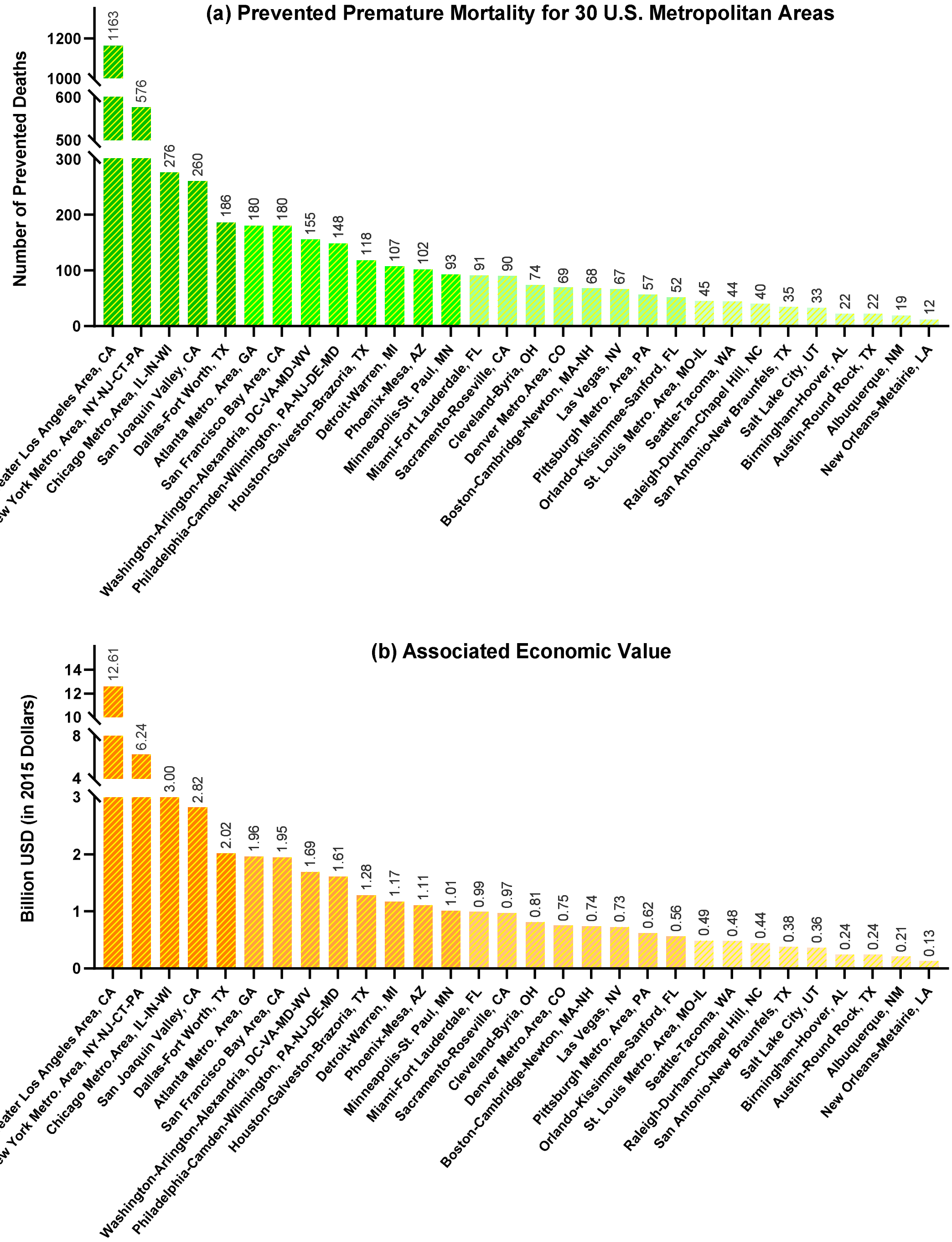

Fig. 4. Estimates of prevented premature mortality attributable to $PM_{2.5}$ reductions resulting from large-scale vehicle electrification in 2050, for 30 U.S. metropolitan areas, panel (a), and the associated economic value, panel (b).

4. Discussion

4.1. Uncertainties and limitations in the assessments in this study

There are several uncertainties and limitations in the assumptions and results of this study. First, full electric vehicle use in 2050 is assumed in this assessment. The current markets include various types of EVs, such as battery electric vehicle (BEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and fuel cell electric vehicle (FCEV). BEVs and FCEVs are considered full electric, generating no emissions from tailpipe exhaust or fuel evaporation. HEVs and PHEVs are partially driven by internal combustion engines, although these vehicles still emit less pollutants than conventional vehicles. The future adoption of full electric vehicles would lead to substantial reductions in mobile emissions. Additionally, this assessment assumes non-exhaust emissions would be largely reduced. Emission controls from the non-exhaust modes (e.g., brake and tire wear) would require further technology improvement. However, if these is no significant improvement in control technology for non-exhaust emissions, the health impact results in this study could be over-estimated.

One major limitation of this study is that only changes in on-road emissions from passenger travel are assessed. Upstream emissions from energy generation, vehicle manufacture, and road infrastructure are more complex and not included. These important aspects related to vehicle electrification require further analysis. A life-cycle assessment performed by Wolfram et al. [64] suggested that carbon emissions were still reduced when indirect emissions from the EV supply chain were factored in. Because this study focuses on better understanding the health impacts from transportation emissions controls, emissions changes in non-transport sectors are not included. Results for other sectors that will impact future chemical conditions in the atmosphere, such as power, building, and agriculture, could vary. Future studies could focus on individual non-transport sectors and perform in-depth analyses [65-67]. As with transport sectors, significant emissions controls in non-transport sectors will be needed. Another limitation is that the meteorological inputs in the air quality simulation are kept unchanged. Further research could be conducted to investigate the air quality impacts of emissions changes under a potential changing climate [68]. Other factors are kept constant in this assessment, e.g., the mileage driven by EV in 2050 is assumed to be the same as current condition. The demographic changes (e.g., population density and composition) are not fully considered.

Using 2011 emissions as a base case amplifies the health impact results since, in the U.S. and most developed countries, emissions of $PM_{2.5}$ as well as of its precursors have decreased in recent years. Additionally, in the health impact estimation, all $PM_{2.5}$ species are assumed to have the same toxicity. It could be possible that some species are more toxic than others, or particulate emissions from certain sectors are more harmful. Thus, the estimated health impacts from air quality upgrades could be higher or lower than current calculations. What's more, this study considers economic gains from prevented premature mortality, which accounts for more than 90% of the monetized benefits from improving public health [26]. Besides mortality, vehicle electrification would impact various morbidities, such as hospitalizations, emergency room visits, asthma exacerbations, and minor effects. The economic gains of reducing these morbidities could be calculated using medical costs or lost earnings related to illness [69]. The large-scale adoption of passenger EVs is expected to obtain economic benefits from the prevention of morbidities as well. Another measure of premature mortality is the number of years of life lost (YOLL) in the population, which is used for standard economic evaluation in Europe. YOLL takes into account the age at which deaths occur, assigning greater weight to deaths at a younger age. YOLL is calculated from the number of deaths multiplied by a global standard life expectancy at the age at which deaths occur [70].

4.2. Policy, technology, and behavior pathways to lower EV adoption barriers

In order to achieve the health and economic benefits stated in this study, continued efforts at both the national and regional levels are needed to promote the transition to EVs. There are several impacting pathways that can help to accelerate the transition. Fig. 5 is a simplified chart of policy, technology, and behavioral pathways and their interactions to lower EVs adoption barriers.

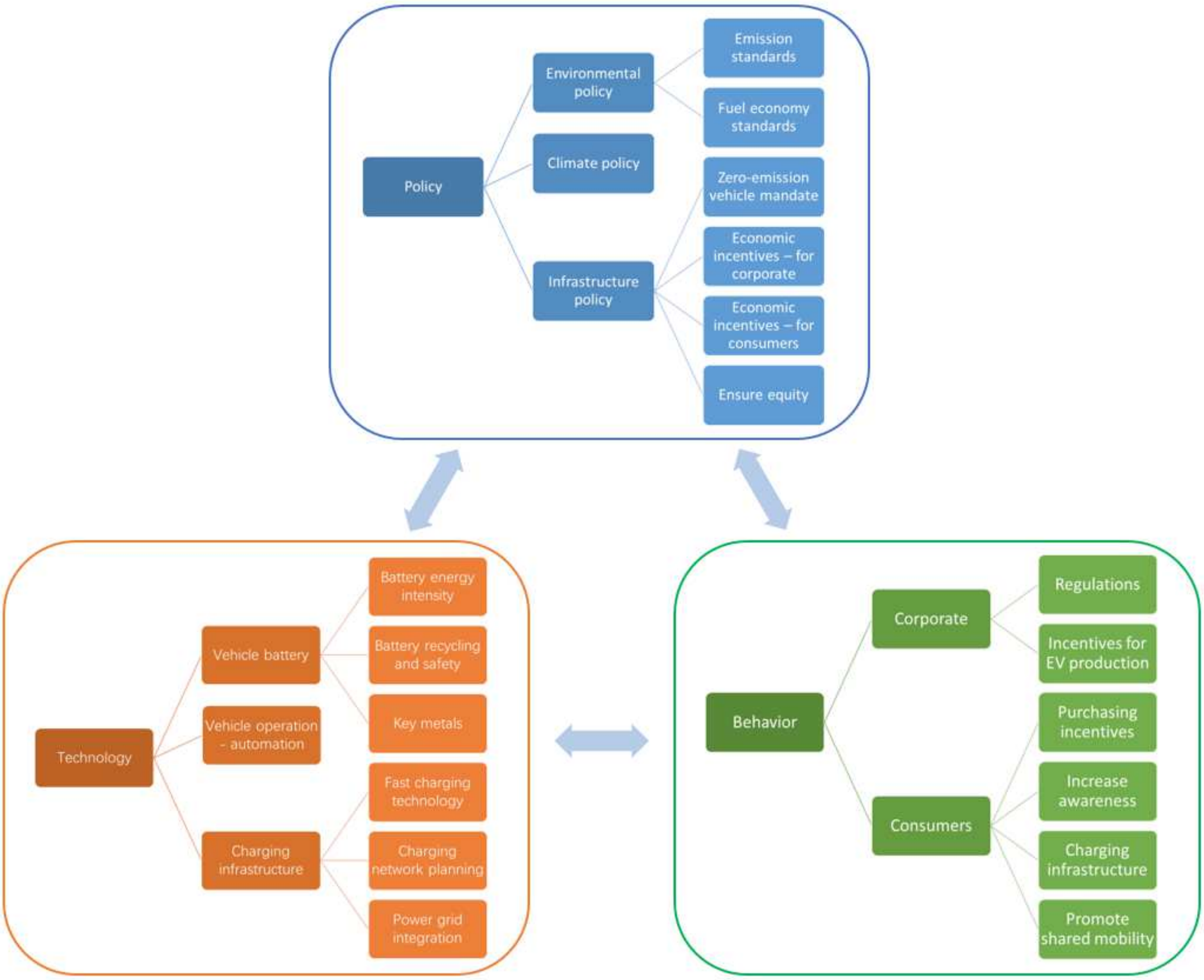

Fig. 5. A simplified chart of policy, technology, and behavior pathways and their interactions to lower EVs adoption barriers.

In terms of policy, environmental policies (e.g., stringent emission standards and fuel economy standards) have often been proposed and enforced by the federal government and California. These regulations put constraints on emissions of new vehicle sales. In April 2022 the National Highway Traffic and Safety Administration (NHTSA) released its new Corporate Average Fuel Economy standards, which would require an average fuel efficiency of approximately 49 miles per gallon (20.83 kilometers per liter) for passenger cars and light trucks by 2026, an approximately 10 miles per gallon (4.25 kilometers per liter) increase relative to 2021 [71]. Climate policy (i.e., putting a price on carbon use) is considered an effective way to reduce energy consumption and mitigate CO_2 emissions [72]; while it is unlikely to be approved any time soon at the national level. Infrastructure policies, like the zero-emission vehicle (ZEV) mandate, along with subsidies/incentives, can help the transition to EVs. The Inflation Reduction Act of 2022 provides federal tax credit of $7,500 for EVs and $4,000 for used EVs, and eliminates the 200,000-unit sales cap. State governments can consider state ZEV programs, state EV manufacturing/purchase incentives, private charger incentives, public charger promotions, and EV registration fee waivers. Local governments can consider city EV fleet targets, streamlining the EV supply equipment-permitting process, city EV purchase subsidies, parking benefits for EVs, carpool lane access for EVs, workplace charging, and outreach events [73]. Importantly, it is necessary to increase incentives for underserved populations and build infrastructure ensuring equity and reducing environmental injustice.

Technological innovation needs to play a key role in EV-related industrial development. Advances in vehicle battery technology are essential. Increased battery energy intensity and improved efficiency, as well as design schemes for battery recycling and assuring safety, are all necessary. It is also critical to secure the key minerals and materials (e.g., lithium, cobalt, nickel, and graphite) used in battery manufacturing. Demand for such materials is expected to rise exponentially. In March 2022 the federal government determined it would use the Defense Production Act to encourage domestic production of critical materials by supporting feasibility studies for new mining and processing projects, as well as recovery of minerals from mine waste [74]. Development of a charging infrastructure is another key technological factor. This includes progress in fast charging technology, fair charging network planning, and integrating charging stations with the power grid [75]. Building charging stations at home, at business and recreational locations (e.g., commercial buildings, malls, parks), as well as in highway corridors is needed. The Joint Office of Energy and Transportation, created through the BIL, aims to facilitate collaboration between the federal energy and transportation departments [20,76]. The office would support the deployment of EV chargers and the zero-emission fueling infrastructure through the National Electric Vehicle Infrastructure (NEVI) Formula Program [77]. In addition, better vehicle operation, such as vehicle automation, would help to save energy at the vehicle level.

Behavior is another important aspect of successful EV adoption. Corporations (i.e., the private sector) would be expected to increase EV production in response to regulations or subsidies and incentives. In order to fulfill tighter regulations, businesses would transfer production to the EV industry, and would manufacture EVs with higher energy intensity, and thus fewer emissions. With the support of subsidies and incentives, businesses would increase EV production and market supply, and offer new

EV models. Several factors could affect the behavior of consumers. First, purchasing incentives, in combination with reliable products, may be attractive to consumers and lead them to decide to buy EVs. Second, increasing consumer awareness and engagement is helpful to avoid situations where various EVs models would be available in the market, yet consumers remain unaware of them. Third, consumers will not choose EVs in the absence of a sufficient charging infrastructure. Last but not least, promoting the use of shared mobility would be helpful in further reducing vehicle travel and emissions [1,35]. This involves the use of public transit, pooled use of ride-hailing, and active travel, such as walking and cycling.

The potential health benefits estimated in this study may outweigh the costs of transitioning from ICE vehicles to EVs. Comparative analysis of the total cost of ownership (TCO) of ICE vehicles and EVs could be one way to analyze the costs [78]. TCO considers the capital cost, operating cost, and the vehicle resale value. A study by the National Center for Sustainable Transportation [78] suggested that the average capital cost difference between an EV and an ICE vehicle was about $14,000 in 2020; the difference would reduce to about $7,000 in 2030 due to the fall in the cost of ZEV technologies and economies of scale. An EV would have a lower operating cost than an ICE vehicle; the average operating cost difference would be $2,500 to $4,000. The average TCO difference between an EV and an ICE vehicle was about $7,000 in 2020; the TCO of an EV would remain higher than that of an ICE vehicle by 2030. The total number of vehicles in California is about 14.2 million in 2020. Simply to say, in California, the overall TCO for transitioning the entire 2020 vehicles to EVs would be $99.4 billion (i.e., $6.6 billion per year, to reach the year 2035 ZEV target). In this study, the total health benefits in the four metropolitan areas in California would be ($12.61 + $2.82 + $1.95 + $0.97 = $18.35) billion. The health benefits in the entire state of California would be higher, about $21.1 billion annually. These benefits would result from large-scale EV uptake in 2050, equivalent to a 95% reduction in emissions from passenger vehicles. The benefits could be obtained earlier, if California could achieve the ZEV goal in 2035. Then, the costs would be less than the estimated health benefits.

The pathways presented in Fig. 5 might not exactly apply to other developed and developing countries. For instance, many developed countries have already adopted strong policies that support the transition to EVs. The EV shares of new cars are relatively high in these countries, including Norway (83.5%), Iceland (51.7%), Sweden (28.7%), the U.K. (16.5%), Germany (13.5%), and France (12.3%), in the first quarter of 2022 [79]. A Bloomberg analysis suggested that EV share would increase quickly, after crossing a 5% threshold. EV share in Norway crossed the 5% threshold in 2013, and reached 83.5% in eight years. Sweden, the U.K, Germany, and France passed the 5% tipping point in early or middle 2020 [79]. Some developing countries (e.g., Congo, countries in Middle East and Latin America) have rich resources of key minerals for battery production, however, underdeveloped EV industries. It would be needed for leading markets to provide their support for developing countries through technological assistance and financial investment.

4.3. Varying strategies among regions are needed to reach an electric future

This study suggests significant health and economic benefits can be obtained in areas across the United States. However, varying strategies are needed to reach an electric future for each region. Electrifying passenger travel vehicles would lead to an increment in electricity consumption. Thus, large-scale vehicle electrification requires de-carbonization of the power sector. To reach to midcentury net-zero emission goals, the power sector will also be experiencing strong de-carbonization [80]. Projections for the power sector indicate a large increase in the share of renewables in the long term [39]. However, the energy structure (i.e., fuel mixes of resources used to generate electricity) shows large variations comparing different regions. As depicted in Fig. 6, gas is a major fuel in most of the eGRID (Emissions and Generation Resource Integrated Database) subregions [81]. California, New York, and Texas have notable fractions of cleaner fuel and renewables. Specifically, California has a mix of solar (17%), wind (7%), hydro (9%), geothermal (4%), and nuclear (8%); Upstate New York, high fractions of hydro (35%) and nuclear (31%); New York City, high fractions of nuclear (30%); and Texas, high factions of wind (20%). Florida's electricity generation is dominated by gas (75%); Missouri and Illinois, dominated by coal (62%). Thus, in the near term, a gradual increase in EV adoption requires local planning efforts to take marginal emissions (from electricity) into consideration. States/regions with high fractions of cleaner fuel and renewables may find it easier to support the deployment of EVs. While states/regions with electricity generation mainly from coal-fired plants will need to spend more effort on cleaning their power grids.

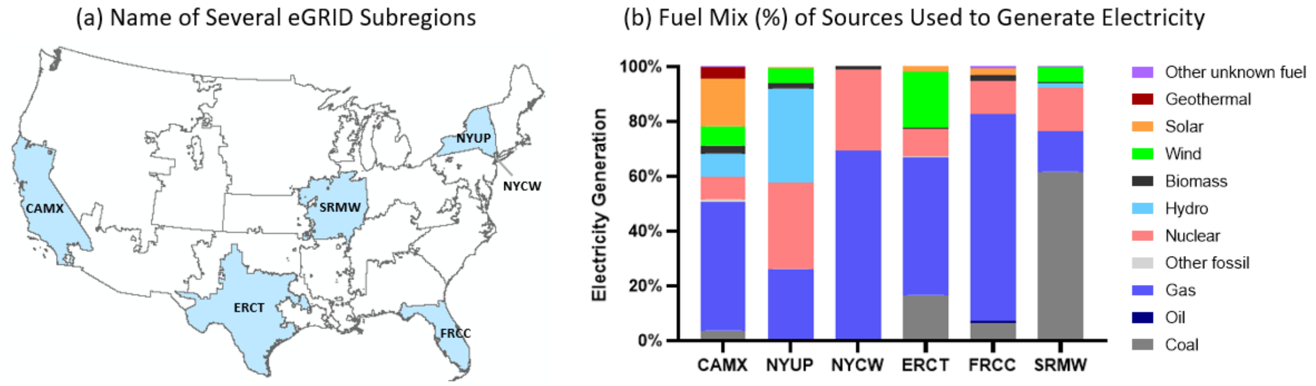

Fig. 6. (a) Name of several eGRID subregions, and (b) fuel mix (%) of sources used to generate electricity. Data source: U.S. EPA Emissions and Generation Resource Integrated Database (eGRID 2020). CAMX – mainly California; NYUP – Upstate New York; NYCW – New York City and Westchester; ERCT – mainly Texas; FRCC – mainly Florida; SRMW – mainly Missouri and Illinois.

It would be helpful to assess the air quality impact of marginal emissions from electricity at the regional level. Powering EVs with fossil fuels would lower the total benefit from EV penetration [5,24,82,83]. Peng et al. [5] employed the WRF-Chem air quality model (i.e., one type of CTMs), and found that deployment of alternative-energy vehicles coupled with de-carbonization of electricity generation would yield the highest benefits in China. To represent de-carbonized electricity in their simulations, emission factors for coal and gas power plants were reduced. Ou et al. [83] utilized the Global Change Analysis Model (GCAM, a technical-economic integrated assessment model), which included representations of energy production, transformation, and end use. The study reported reductions in net CO_2 emissions in the U.S. resulting from high EV adoption, even for a scenario where all electricity increments were from fossil fuels. Thompson et al. [24] examined the emission impact of three charging scenarios, including nighttime charging and charging profiles based on the maximization of battery lifetime and driver convenience. The study reported a rise in NO_x emissions from electricity generation units (EGUs) during vehicle charging time, and a decline in NO_x from transportation sources; for all scenarios, the changes in mobile emissions dominated the air quality impact. Since different charging methods would affect the diurnal variations of emissions from EGUs, future regional-level EV air quality impact studies could consider various temporal allocation profiles for EGUs emissions.

This study indicates that large-scale use of passenger EVs can contribute to health benefits not only in urban centers, but also in suburban and relatively rural areas. However, rural communities may face some specific challenges regarding EV adoption. Residents in rural areas rely more on vehicles for travel, and rural households usually have lower incomes. It is expected that the EV market share in rural areas would be smaller than that in urban areas. Preferences for large vehicles (trucks and SUVs) by rural residents may not be met by current EV models; lower incomes and fewer charging stations could pose barriers and bring equity concerns; longer trips and beliefs about EV performance may also pose barriers [84]. To achieve the desired health benefits in rural areas, it is important to increase support for EV adoption in small and rural communities. There could be some strategies, such as seeking more public input into the decision-making process, developing criteria for defining underserved communities, designing income-differentiated consumer incentives, providing equitable investments in charging station buildout, and developing metrics for evaluating if investments demonstrably provide benefits for underserved communities [59,85,86]. These will help to accelerate the transition to an equitable, clean, and affordable low-carbon transportation sector.

The large-scale adoption of passenger EVs could decrease oil use, reduce dependence on fossil fuels, and lessen exposure to fuel price volatility. Under electrification, lower oil demand from passenger vehicles could contribute to shrinkages in oil markets in the long run. Additionally, clean energy policies may lead to declines in investments in the oil industry. For instance, California governor's 2020 Executive Order required termination of the issuance of new hydraulic fracturing permits by 2024 [36]. Kah [87] suggested that there could be periodic oil price spikes along with a long-term decline of oil prices. Less stability in oil-producing countries could lead to disruptions in oil supply and hence oil price spikes, which might cause further transitions away from oil use in the passenger transportation sector. Recent oil price spikes have made some consumers turn to EVs, though barriers remain (e.g., lack of chargers) at this early stage of EV transition [88]. Oil production plays a significant role in economic development in some U.S. states or regions, such as the Gulf Coast region. In the long term, oil-producing regions will need to seek major changes in power generation and fuel consumption, and gradually transition workers to clean fuel jobs.

5. Conclusion

This study considers a scenario with almost full uptake of passenger EVs in the U.S. in 2050, based on current federal policies and EVs projections. Air quality and health impact assessments over a large number of metropolitan areas across the country are then performed. In general, results indicate that large-scale use of passenger EVs could reduce concentrations of $PM_{2.5}$, prevent premature deaths, and obtain economic benefits in all 30 metropolitan areas. These results could provide important scientific input to national and regional policymakers in support of decision-making towards clean transportation. However, it should be noted that there are limitations in the assumptions of this study, such as a projected 2050 population that runs a 2011 mileage, a 2050 air quality that differs from 2011 only for the adoption of the electric vehicles, and that all the electricity needed for the vehicles is produced by renewables without new emissions. Future studies with improved assumptions and better models are needed. For instance, technical-economic models with more detailed representations of technology and energy pathways can be utilized. There are numerous progresses on EV transition policies at both the federal and regional levels in the U.S. in the past two years. Thus, this study performs a review of the recent policy updates and discusses various pathways toward lowering adoption barriers to EVs. The large differences in the electricity mix across various regions suggests that varying strategies are needed to reach an electric future.

There are several policy implications from this study. First, more EV-related cost-benefit analyses at regional or local levels are needed. The year 2050 is chosen as a target year, as this study intends to investigate the long-term societal benefits of a large-scale EV uptake. Ultimately, in 2050, almost all of emissions from passenger vehicles are assumed to be reduced; this study estimates the potential health and economic gains for 30 metropolitan areas. However, many factors could affect the scale and speed of EV transition over different regions. These factors include population growth and demographic changes, potential vehicle activity increase due to economic drives, the stringency of regional clean transportation policies, new infrastructure building, energy structure, climate change, and so on. In order to support regional policy-making, it is necessary to take these factors into consideration and formulate scenario that better reflects the regional reality. The conduction of interdisciplinary research will be needed. Second, the benefits of EV adoption on air quality and public health are quite clear, based on this assessment as well as previous literature work; it is also important to accelerate the implementation of this mitigation strategy. The current EV shares of new cars are still relatively low in most of U.S. cities. Except for several cities in the west coast, passenger EV shares in many cities are far below 10%. The realization of wide-scale EV deployment involves with not only environmental and climate policies, but also economic, infrastructure, technology, and energy policies. The future deep reductions in transportation emissions require collaborations from different sectors. For instance, the creation of the Joint Office of Energy and Transportation is innovative in policy design to facilitate EV transition. Third, a system approach (considering the policy, technology, and behavior pathways) is needed to promote the transition to EVs. Positive EV transition policies include setting mid-term and long-term ZEV goals, enforcing stringent emission and fuel economy standards, and formulating targeted economic incentives. Development of charging infrastructure includes building new changing stations, unifying charging standards, and enhancing charging services. Improvement of battery supply chain includes advancing vehicle battery technology, designing schemes for battery recycling, and securing critical minerals and materials. Increase of EV application includes promoting EV adoption in governmental and public services, providing benefits for EV use, and increasing consumer awareness and engagement.

Author contributions

Shuai Pan: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. Wendi Yu: Investigation. Lewis M. Fulton: Formal analysis, Writing – review & editing. Jia Jung: Investigation, Writing – review & editing. Yunsoo Choi: Formal analysis, Writing – review & editing. H. Oliver Gao: Conceptualization, Formal analysis, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

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