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Air quality and public health co-benefits of 100% renewable electricity adoption and electrification pathways in Los Angeles

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Abstract

To demonstrate how a mega city can lead in decarbonizing beyond legal mandates, the city of Los Angeles (LA) developed science-based, feasible pathways towards utilizing 100% renewable energy for its municipally-owned electric utility. Aside from decarbonization, renewable energy adoption can lead to co-benefits such as improving urban air quality from reductions in combustion-related emissions of oxides of nitrogen (NO_x), primary fine particulate matter ($PM_{2.5}$) and others. Herein, we quantify changes to air pollutant concentrations and public health from scenarios of 100% renewable electricity adoption in LA in 2045, alongside aggressive electrification of end-use sectors. Our analysis suggests that while ensuring reliable electricity supply, reductions in emissions of air pollutants associated with the 100% renewable electricity scenarios can lead to 8% citywide reductions of $PM_{2.5}$ concentration while increasing ozone concentration by 5% relative to a 2012 baseline year, given identical meteorology conditions. The combination of these concentration changes could result in net monetized public health benefits (driven by avoided deaths) of up to \$1.4 billion in year 2045 in LA, results potentially replicable for other city-scale decarbonization scenarios.

1. Introduction

Energy is central to modern society and is essential for most daily activities—travel, cooking, residential heating and cooling, entertainment, etc. However, combustion processes that are traditionally used to produce energy release emissions that lead to climate change. An important strategy for solving the climate crisis involves transforming our power systems by replacing combustion of fossil fuels with renewable electricity sources such as solar and wind. Renewable energy adoption can also have important co-benefits on urban air quality including potential reductions in air pollutant emissions and corresponding changes in ambient air pollutant concentrations [1–8]. These changes in air pollutant concentrations are a crucial aspect to consider in renewable energy adoption because exposure to air pollutants such as ozone (O_3) and fine particulate matter ($PM_{2.5}$) is associated with premature mortality and numerous deleterious health consequences like asthma [9–12].

To combat the climate crisis and urban air pollution [13, 14], the city of Los Angeles (LA) has set ambitious goals for renewable energy adoption in recent years. (The geographic domain of LA is shown on figures 2 and 3(a)). In 2017, the LA City Council passed a series of motions directing the LA Department of Water and Power (LADWP, the municipal utility responsible for supplying power and water to 4 million residents of LA) to determine the feasible pathways of an electricity system powered by 100% renewable energy [15], along with the electrification of several sectors. A large-scale study was also authorized—the City of LA 100% renewable energy Study (LA100)—to determine the renewable resource mix and system upgrades required to achieve 100% renewable electricity and increased electrification in transportation, buildings and large municipal facilities while maintaining the current high degree of reliability by 2045 [16].

LA100 is the first-of-its-kind effort to create a bottom-up, science and policy-driven roadmap of various feasible technical and economic pathways to achieve a 100% renewable energy power system by 2045, through the collaboration of researchers across the National Renewable Energy Laboratory and academia, in close partnership with local authorities, and can serve as an example for other cities [17]. (See the supplemental information (SI) for more on LA100 modeling.) The broader LA100 effort evaluated four scenarios across three potential trajectories of LADWP customer electricity demand. Scenarios varied in their definition of achieving '100% renewable electricity' (e.g. if renewable energy certificates (RECs) could be used to offset fossil fuels; if LADWP is allowed to purchase existing nuclear generation) [15]. Customer electricity demand varied in levels of energy efficiency, electrification and demand flexibility. LA100 is a systems-level study that includes electricity demand modeling (i.e. residential and commercial buildings, electric vehicle and electric bus charging, water infrastructure and other industrial loads), power system investments and operations, distributed energy resources and distribution grid modeling, economic impact analysis, lifecycle greenhouse gas (GHG) analysis, and analysis of the environmental justice implications of select results including of the air quality and public health consequences.

This paper focuses on one aspect of the LA100 study: the co-benefits for air pollution and public health. Only a few past studies have investigated air quality and public health implications of renewable energy adoption in California [1, 3, 5]. Zapata *et al* (2018) reported a 14% reduction in annual population-weighted $PM_{2.5}$ concentrations and a 3.2% increase in summertime 8-hour O_3 concentrations in the South Coast Air Basin (SoCAB, where LA is located) when comparing a low-carbon energy scenario (i.e. statewide GHG emissions across the entire economic sectors are 80% below 1990 level) to a business-as-usual (BAU) scenario in year 2050 [1]. Wang *et al* (2020) showed the same trends in $PM_{2.5}$ and O_3 concentration changes comparing a net-zero GHG pathway to a BAU scenario in year 2050 in the LA Basin [3]. The net-zero GHG pathway in Wang *et al* (2020) assumes high energy efficiency, electrification among demand sectors and 85% renewable electricity generation, and requires offsetting the GHGs emissions using carbon capture and sequestration technology.

While previous studies proposed theoretical low- or net-zero GHG pathways based on national or state level regulations, this study for the first-time modeled the air quality and public health impacts of 100% renewable electricity adoption, developed in coordination with local policy implementation, which demonstrate how science can be more closely integrated with policy at the city scale. First, unlike prior work, the air quality and public health modeling was done for bottom-up scenarios developed using a dozen sector-specific models with unprecedented details to ensure feasibility and attainment of power sector performance metrics like grid reliability and adequate energy resources, including local distributed resources. Second, the assumptions regarding future emission projections of fuel transitions in the power sector and the electrification of multiple sectors are based on detailed grid and load modeling for each sector (instead of an integrated cross-sectoral approach used by prior work which loses details in individual sectors), region-specific activities changes and emission factors changes, in order to ensure the feasibility and accuracy of such projections.

In this study, we investigate how future renewable electricity adoption and electrification pathways could change air pollutant emissions, resulting air pollutant concentrations, and public health. To achieve this goal, we first establish a baseline inventory of emissions from a historical year (2012) that accounts for all known anthropogenic sources. Next, we quantify changes to air pollutant emissions under selected future LA100 scenarios projected to year 2045. We select two of the four LA100 scenarios including one that is compliant with meeting California's Senate Bill 100 goals by 2045 and a second that achieves the 100% renewable electricity target by 2035 with more stringent criteria defining how the target is met. Each scenario is evaluated across two customer electricity demand assumptions, namely moderate and high electrification load assumptions (see table 1). The scenario and electrification load assumption pairs were carefully chosen to reflect the lower and upper bounds of LA100-induced air quality and public health changes and to isolate the contribution of certain sectors to those changes. The baseline and future emissions inventories are then used as inputs to a state-of-the-science regional meteorology-atmospheric chemistry model, the Weather Research and Forecasting Model coupled with chemistry (WRF-Chem) [18], to quantify spatiotemporal patterns in air pollutant concentrations. Finally, simulated air pollutant concentrations are used to estimate the health impacts and economic valuation from exposure changes to air pollutants using U.S. Environmental Protection Agency (U.S. EPA)'s Benefit Mapping and Analysis Program—Community Edition (BenMAP-CE) [19].

2. Materials and methods

2.1. Renewable electricity and electrification scenario designs

We assess air quality and public health co-benefits of LA100 scenarios by first considering 2012 as a baseline, and then comparing among the future LA100 scenarios in year 2045, which was the final year for the power sector to achieve 100% renewable energy within the LA100 study. The future LA100 scenarios of focus represent different power sector eligibility criteria and 100% renewable electricity achievement year. Each scenario is then modeled for two levels of electrification, which ultimately affect emissions from portions of the transportation sector, residential and commercial buildings, and the Port of LA and Port of Long Beach (which are located adjacent to each other at the south corner of LA and referred to hereafter singularly as the Ports).

Table 1 summarizes the LA100-assigned scenario names and assumptions for energy supply and demand. The SB100 scenario is aligned with California Senate Bill 100 [20], which requires 100% zero-carbon electricity in California by 2045 based on retail sales but allows the purchase of RECs (renewable electricity credits; represents energy generated by renewable energy sources) to offset a portion of power generation provided by fossil fuel combustion. In addition, biofuels can be used as transitioning fuel prior to 2045, but are not allowed starting in 2045. Early & No Biofuels represents a scenario that achieves compliance with a more stringent 100% renewable energy definition among LADWP-owned power generation utilities (e.g. no RECs are allowed, nor biofuel combustion is allowed for power generation; however, hydrogen combustion is allowed.) starting in 2035, 10 years earlier than for SB100.

Each of these two supply side scenarios above is evaluated at two demand side load assumptions (i.e. moderate and high load electrification) for emission sources within the transportation sector (including light-duty vehicles (LDVs) and buses), the building sector (including water heating and spacing heating in commercial buildings, as well as space heating, water heating, cloth drying and cooking in residential buildings), and the Ports (including shore power usage from ocean-going vessels at berth, and cargo handling equipment and heavy-duty vehicles operating at the ports). Specifications of moderate and high electrification levels for these emission sources are included in SI. In short, while moderate electrification assumptions are generally consistent with current regulatory requirements in California, high electrification assumptions are more aggressive on electrification and match most of the goals set in the LA's Green New Deal (2019) [21].

2.2. Air quality modeling

In this study we use a state-of-the-science regional meteorology and chemistry model, the WRF-Chem Version 3.7 (WRF-Chem v3.7) [18]. This model uses an emissions inventory as an input, and then simulates pollutant transport and gas- and particle-phase chemistry that result in the formation of secondary pollutants like O_3 and secondary components of $PM_{2.5}$. All simulations are performed using three, two-way nested domains at horizontal resolutions of 18 km, 6 km and 2 km, respectively. LA is located in the innermost domain and is the focus of our model analysis (see figure S1 in the SI for a map of the modeled domain). Each domain uses 29 layers in the vertical from the ground to 100 hPa, although only the lowest atmospheric layer is used for analysis of pollutant concentrations. For each scenario we simulate January (winter), April (spring), July (summer), and October (autumn) as representative months per season in Southern California based on meteorology in year 2012. Details on model configuration and evaluation of model performance can be found in SI.

2.3. Emission inventory development

Gridded hourly emissions for the Baseline (2012) scenario for the innermost domain are constructed based on the most recent gridded source-specific raw emissions obtained from South Coast Air Quality Management District (SCAQMD) [22]. Annual-averaged daily emissions are provided for CO, NO_x, SO_x, total organic gases, total suspended particles, and NH_3, and are processed to gridded hourly emissions.

Gridded hourly emissions in the innermost domain for the future scenarios can be classified into two categories. First, for emissions sources within the city of LA that are directly influenced by LA100, we project emissions for future scenarios based on four factors: (1) gridded, source-apportioned, raw emissions (either from the 2012 baseline, or 2031 projections from SCAQMD if factors for scaling activity from 2031 to 2045 are available) [22]; (2) activity projections (either from LA100 energy model input assumptions and outputs or, when not available, from regulatory agencies) [16]; (3) emission factor projections (from regulatory agencies including SCAQMD for electricity generation and the building sector, California Air Resource Board (CARB) for the transportation sector, and past studies for the Ports and primary $PM_{2.5}$ from brake wear); and (4) electrification projections (from the LA100 electricity demand projections for the transportation, building sectors and the Ports). Second, for emissions sources not directly influenced by LA100 (within LA), and all emissions sources outside LA, we adopt emissions projections to year 2031 available from SCAQMD's 2016 Air

Table 1. Scenario names and key assumptions on power sector eligibility criteria and electrification levels.

■ : Included in the scenario   □ : Not included in the scenario

Scenario Name (and Abbreviation) / **Scenario Definition**		Current time reference	Compliant w/ Senate Bill 100		Early Target & No Biofuels Allowed	
		Baseline (2012) (Baseline (2012))	SB100 - Moderate (SB100 – M)	SB100 - High (SB100 – H)	Early & No Biofuels – Moderate (Early & No Biofuels – M)	Early & No Biofuels – High (Early & No Biofuels – H)
Electrification Level	Electrification Level for LDVs and Buses, Commercial and Residential Buildings, and the Ports	N/A	Moderate	High	Moderate	High
Target Compliance	LADWP achieves 100% renewable electricity by 2045		■	■	□	□
	LADWP achieves 100% renewable electricity by 2035		□	□	■	■
Target Measurement	Based on retail sales of electricity (less stringent)		■	■	□	□
	Based on generation (as opposed to retail sales)		□	□	■	■
Power Generation Source Constraints	LADWP-owned power plants can burn natural gas[a]		■	■	□	□
	No natural gas generation allowed in target year		□	□	■	■
	No biofuels allowed for power generation in any year[b]		□	□	■	■
	LADWP-owned power plants can burn hydrogen[c]		■	■	■	■
	Existing nuclear generation purchases allowed		■	■	■	■
Transmission Constraints	Allows upgrades to transmission beyond planned projects		■	■	■	■
	Builds new transmission corridors		□	□	□	□

[a] Burning natural gas would necessitate the utility to purchase RECs to meet the requirements of SB100. The allowed renewable energy sourcesneed to be within the CaliforniaClean Energy and Pollution Reduction Act (Senate Bill 350) Renewables Portfolio Standard (RPS) eligible resources, which include solar, wind, biomass, geothermal and others.

[b] While biofuels are allowed in years prior to the target year 2045 in the SB100 scenario, they are not allowed starting in 2045.

[c] LADWP-owned power plants are assumed to burn 100% hydrogen by 2045 to the extent they are utilized. Hydrogen fuel is produced and stored on-site at the plant using electricity.

Quality Management Plan (AQMP). Given that (1) SCAQMD has not developed gridded source-specific projections for pollutant emissions past 2031 and (2) the changes in regional total emissions from 2031 to 2045 are relatively small compared to the changes from 2012 to 2045 based on CARB's California Emissions Projection Analysis Model, we assumed these emissions stay constant from 2031 to 2045.

Details on future emission inventory development for each influenced sector (i.e. electricity generation, transportation, buildings and the Ports) can be found in SI. In short, we project absolute emissions based on fuel consumption and emission factors for the power sector, and scale baseline emissions (from year 2012 or 2031, depending on source) using activity, emissions factors, and electrification levels for emissions from the transportation sector, residential and commercial buildings, and the Ports. While the scaling method aligns with our emissions data and is the method applied in past relevant studies [2, 3], we calculate emissions from LADWP-owned power plants directly from fuel consumption and emission factors for the following two reasons. First, some LADWP-owned power plant units have been modified since 2012 and thus these changes to emissions have not been considered in the SCAQMD emission inventories. Second, there is no consistent data source for generating scaling factors for fuel consumption of power plants.

Anthropogenic emissions for the two outer domains in all scenarios are adopted from the 2012 emissions inventory from the CARB for areas within California [23], and from the 2011 National Emission Inventory for regions outside California [24]. Biogenic emissions are generated by the Model of Emissions of Gases and Aerosols from Nature coupled to WRF-Chem using model predicted meteorological conditions [25].

2.4. Health impact estimation and monetization

We use the BenMAP-CE version 1.5 [19] to estimate the health impacts (i.e. mortality and mobility) and economic valuation from exposure changes to $PM_{2.5}$ and O_3 pollution. The benefits associated with a pollutant reduction can be calculated based on a health impact function which describes the relationship between changes in the observed adverse health impact incidences and changes in the pollutant concentrations [26, 27]. We used health impacts functions used by the U.S. EPA in its regulatory impact analysis. The confidence intervals (CIs) of health outcomes are calculated using the Monte-Carlo method for uncertainties in the concentration-response functions. In this analysis, we estimate all-cause mortality due to long-term exposure to $PM_{2.5}$ and short-term exposure to O_3. As for morbidity estimation, $PM_{2.5}$-associated morbidities include hospital admissions, asthma emergency department visits, and acute myocardial infarction, and O_3-associated morbidity is asthma emergency department visits. We focused on mortality and morbidity outcomes listed above due to several reasons, including: associated economic damages are high (mortality); they are used by the State of California and other state agencies to do environmental justice analyses; emphasis placed on select outcomes by city residents. Since our future year of focus is 2045, population in LA is projected to 2045 in the quantification of health impact incidences. Monetizing these health benefits depends on the cost of illness (including the total medical costs plus the value of the lost productivity) for avoiding a disease incidence (i.e. morbidity), and the value of statistical life (the willingness to pay for a marginal reduction in risk of death in a society) for avoiding a fatality (i.e. mortality) in BenMAP. We used the available mortality and morbidity valuation functions in BenMAP for this quantification and report results in 2019 U.S. Dollars. All health and valuation results are aggregated and reported for the 15 City Council districts or the City of LA. Details on the equations and data sources used for evaluation of public health and its monetization can be found in SI.

3. Results

3.1. Emission inventory for the baseline and future scenarios

We find that citywide total air pollutant emissions from all economic sectors will decrease between 2012 and future LA100 scenarios in 2045, even when considering increases in population and economic activity. Figure 1 shows the emissions of NO_x and primary $PM_{2.5}$ as examples. Emissions of other air pollutants can be found in SI. Citywide total emissions of NO_x (primary $PM_{2.5}$) are reduced by 60% (6%), 62% (11%), 60% (6%) and 62% (11%) under the 2045 SB100—Moderate, SB100—High, Early & No Biofuels—Moderate, and Early & No Biofuels—High scenarios, respectively, as compared to the 2012 baseline.

Citywide total air pollutant emissions can be divided into two groups. The first group includes emissions from sources *directly* influenced by LA100 (i.e. LDVs and buses, buildings, the Ports, and the LADWP-owned power plants; hereafter referred to as 'LA100-influenced sources'). We assume that the LA100 scenarios *only* influence future emissions changes from these sources. In addition, assumed decreases in pollutant emission factors projected by SCAQMD's 2016 AQMP affect the comparison between Baseline (2012) and future LA100 scenarios for emissions from this group as well [14]. The second group includes emissions from sources that might be indirectly influenced by LA100 scenarios (e.g. changes to refining volumes in the 'Oil and Gas Industry') or that are not influenced by LA100 scenarios (i.e. 'Other' and 'Medium and Heavy-Duty Vehicles' in figure 1). Changes in emissions from

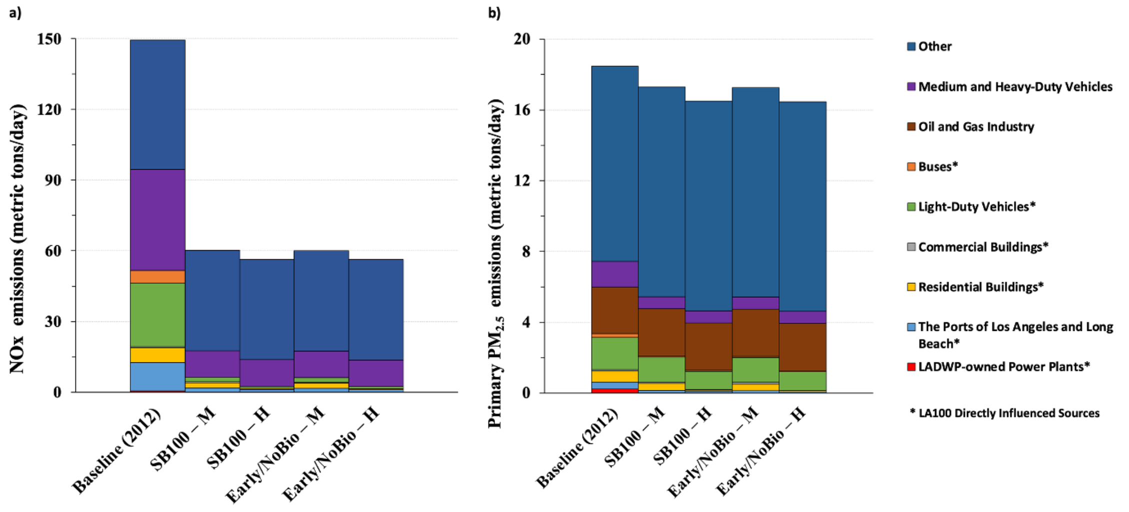

Figure 1. Annually averaged daily (a) NO_x and (b) primary $PM_{2.5}$ emissions from all anthropogenic sources in the city of Los Angeles for all scenarios. Emissions for future scenarios (SB100—Moderate, SB100—High, Early & No Biofuels—Moderate and Early & No Biofuels—High) are projected to year 2045. Emissions that are directly influenced by LA100 include those from buses, LDVs, commercial buildings, residential buildings, the ports of Los Angeles and Long Beach, and LADWP-owned power plants. Note that 'LADWP-owned Power Plants' include only those located in SoCAB. The sources labeled 'Other', 'Medium and Heavy-duty Vehicles' and 'Oil and Gas Industry' are not directly influenced by LA100, but are shown for context. Examples of major contributing sources to the 'Other' category include off-road equipment, Regional Clean Air Incentives Market (RECLAIM) and aircraft for NO_x; and commercial cooking, road dust and industrial processes for primary $PM_{2.5}$. RECLAIM is a cap-and-trade program implemented by SCAQMD targeting at reducing NO_x and SO_x emissions from stationary sources. ('Other', 'Medium and Heavy-Duty Vehicles' and 'Oil and Gas Industry' are included in the emissions inventories used in air quality modeling.).

this group are outside of the scope of this analysis, thus any differences between 2012 and future LA100 scenarios emissions for this group are due to emission projections adopted from SCAMQD's AQMP. The reductions in NO_x emissions from the LA100-influenced sources contribute to approximately 50% of the reductions in citywide total NO_x emissions; the reductions in primary $PM_{2.5}$ emissions from the LA100-influenced sources are slightly higher than the reductions in citywide total primary $PM_{2.5}$ emissions (because increases in primary $PM_{2.5}$ emissions from the 'Oil and Gas Industry' and 'Other' categories offset the reductions from the LA100-influenced sources).

When considering just LA100-influenced sources, NO_x (primary $PM_{2.5}$) emissions from 2012 to 2045 decrease by 88% (38%), 95% (61%), 88% (38%), and 95% (62%) from Baseline (2012) to SB100—Moderate, SB100—High, Early & No Biofuels—Moderate, and Early & No Biofuels—High, respectively. LDVs are the dominant contributor to LA100-influenced NO_x (52%) and primary $PM_{2.5}$ (54%) emissions in Baseline (2012) and the largest contributor to reductions in LA100-influenced emissions from the current baseline to future LA100 scenarios. LDV fleet modifications in future LA100 scenarios result in NO_x (primary $PM_{2.5}$) emission reductions of more than 50% (30%) below the 2012 baseline. In addition to LDVs, residential buildings and the Ports also contribute to NO_x and primary $PM_{2.5}$ emissions, and reductions in LA100 scenarios. In year 2045 for scenarios with moderate (high) electrification, residential buildings (the Ports) become the largest LA100-influenced source of emissions for NO_x. Residential buildings and the Ports are also the second largest LA100-influenced source type for primary $PM_{2.5}$ emissions in scenarios with moderate and high electrification, following LDVs, respectively. These two sources collectively make up 30%–40% of the LA100-influenced NO_x and primary $PM_{2.5}$ emissions reductions that occur between the Baseline (2012) scenario and future LA100 scenarios. LADWP-owned power plants, buses and commercial buildings are minor contributors to citywide NO_x and primary $PM_{2.5}$ emissions.

In addition, NO_x emissions from sectors not directly affected by LA100 ('Other', 'Medium and Heavy-Duty Vehicles' and 'Oil and Gas Industry' in figure 1) decrease by 45% from the baseline to future scenarios owing to decreased emission factors projected by SCAQMD's 2016 AQMP, which is based on state and regional air quality regulations implemented by the end of 2015. Primary $PM_{2.5}$ emissions from sectors not directly affected by LA100 increase slightly (<1%) from the baseline to future scenarios.

3.2. Simulated air quality for the baseline and future scenarios

Assuming identical meteorology across all simulated scenarios, reductions in air pollutant emissions can lead to simulated reductions in $PM_{2.5}$ concentrations

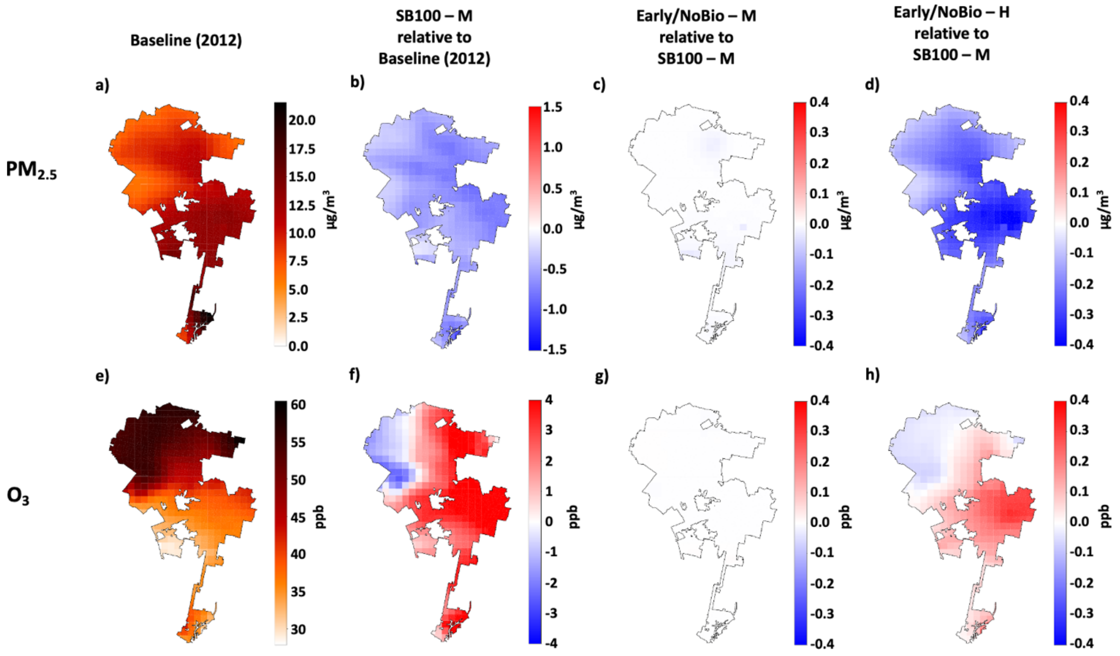

Figure 2. Spatial patterns of simulated annual daily average $PM_{2.5}$ (panels a-d), and July daily maximum 8-hour average O_3 (panel e–h) concentrations in Los Angeles for Baseline (2012) (panels a and e), differences between Baseline (2012) and SB100—Moderate (2045) (panels b and f), differences between SB100—Moderate (2045) and Early & No Biofuels—Moderate (2045) (panels c and g), and differences between SB100—Moderate (2045) and Early & No Biofuels—High (2045) (panels d and h).

across the entire LA and simulated increases in O_3 concentrations for most parts of LA in 2045 compared to the 2012 baseline as shown by figure 2.

Reductions in $PM_{2.5}$ concentrations are simulated for future LA100 scenarios in 2045 across LA due to lowered primary $PM_{2.5}$ emissions and other precursor emissions contributing to secondary $PM_{2.5}$ when comparing to Baseline (2012). The city averaged annual daily $PM_{2.5}$ concentration in 2045 is reduced by 6% when comparing SB100—Moderate (10.0 μg m^{-3}) to Baseline (2012) (10.6 μg m^{-3}) and is reduced by 8% when comparing Early & No Biofuels—High (9.8 μg m^{-3}) to Baseline (2012). $PM_{2.5}$ for Early & No Biofuels—Moderate is similar to SB100—Moderate with absolute differences within ± 0.06 μg m^{-3}, indicating a very small impact of transitioning from natural gas to hydrogen-powered power plants in 2045. The comparison between Early & No Biofuels—High and SB100—Moderate shows decreases in $PM_{2.5}$ concentrations across LA (maximum reduction = 0.45 μg m^{-3}) and are dominated by increases in electrification levels.

In contrast to $PM_{2.5}$ concentrations, simulated increases in daily maximum 8-hour average O_3 concentrations occur across LA for July except in the northwest area (the San Fernando Valley region, where the highest O_3 concentrations was simulated in Baseline (2012)). City averaged O_3 concentrations increase by 5% from Baseline (2012) (43.8 ppb) to SB100—Moderate (46.0 ppb) in year 2045. When comparing among the future LA100 scenarios in 2045, Early & No Biofuels—High shows slight increases in daily maximum 8-hour O_3 concentrations across LA except the northwest area relative to SB100—Moderate (figure 2(h)), leading to 0.2% increase in city averaged O_3 concentrations. These differences in O_3 are dominated by increased electrification levels; removing natural gas power plants plays a very small role as indicated by figure 2(g). Figure 2(g) shows that O_3 concentrations are nearly identical for SB100—Moderate and Early & No Biofuels—Moderate, with the maximum difference being less than 0.001 ppb.

3.3. Public health impacts and corresponding monetization for the baseline and future LA100 scenarios

Results on annual mortality and morbidity incidences due to $PM_{2.5}$ and O_3 concentration changes are aggregated to each of the 15 city council districts constituting LA as shown by figure 3(a). Since transitioning from natural gas to hydrogen yields only small influences on O_3 and $PM_{2.5}$ concentrations in year 2045 (figure 2), we only discuss the comparison between Baseline (2012) and SB100—Moderate (2045) and between SB100—Moderate (2045) and Early & No Biofuels—High (2045) in the main body

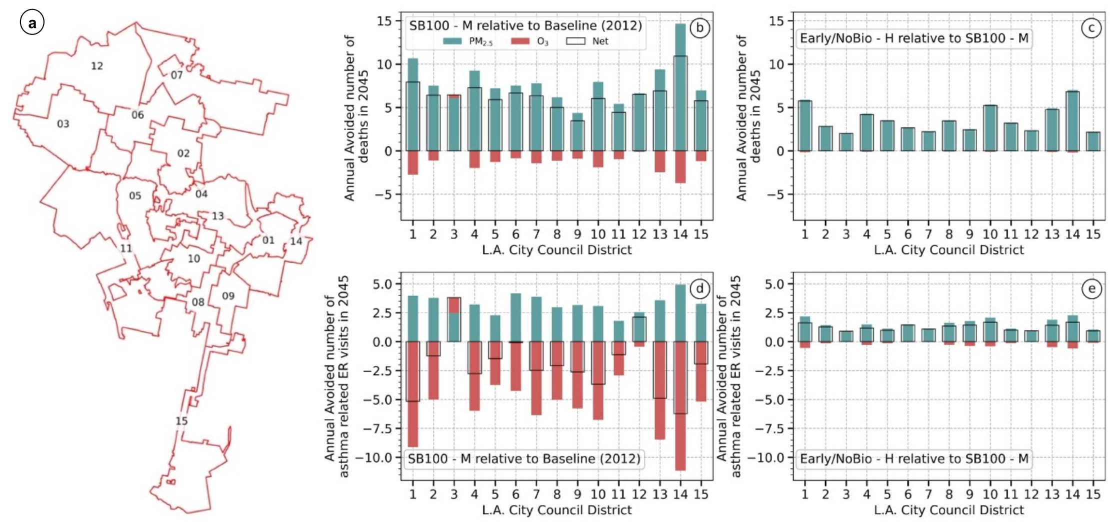

Figure 3. Health benefits and penalties due to air pollutant concentrations changes. Fifteen Los Angeles city council districts annotated by district number are shown in panel (a). Avoided mortality and ER visits for SB100—Moderate relative to Baseline (2012) are in panel (b) and (c), and for Early & No Biofuels—High relative to SB100—Moderate in panel (d) and (e). Note that the numbers of incidences shown for citywide total values are rounded to integers; the numbers of incidences shown here at district level are not rounded to integers.

of this paper; results of the other comparisons can be found in SI.

Changes in air pollutant exposures from current to future LA100 scenarios lead to overall public health benefits except for increased asthma-related emergency room (ER) visits. Figure 3 includes simulated changes in $PM_{2.5}$- and O_3-induced annual all-cause premature mortality incidences and asthma-related ER visits at district level. The effects of altered $PM_{2.5}$ concentrations on cardiovascular hospital admissions and heart attacks are included in SI. When comparing SB100—Moderate to Baseline (2012), about 96 deaths (95% CI of 67–130) are avoided in the year 2045 in LA, with the increase owing to O_3 concentration increase being more than offset by the $PM_{2.5}$ reductions. Avoided deaths due to reductions in $PM_{2.5}$ are largest in district 14, although this is also where maximum deaths due to an increase in O_3 occur, which offsets some benefits from decreased concentration of $PM_{2.5}$. In 2045, asthma-related ER visits increase in most districts because the disbenefit from increases in O_3 concentrations outweighs the benefit from $PM_{2.5}$ reductions. A total of 30 (95% CI of 20–40) additional ER visits occur in SB100—Moderate compared to the 2012 baseline. In addition, cardiovascular hospital admissions and heart attacks incidences are reduced in all districts due to decreased $PM_{2.5}$ concentrations. When comparing Early & No Biofuels—High to SB100—Moderate, about 53 (95% CI of 36–71) deaths are avoided in year 2045, and 19 (95% CI of −10–48) fewer ER visits take place. Maximum health benefits occur in districts 1, 10, and 14 due to the larger population and reductions in $PM_{2.5}$ concentration.

As shown by figure 4, when combining all public health endpoints together, future LA100 scenarios could yield nearly a billion U.S. dollars of avoided health impacts (thus monetized net benefits) in 2045 alone as compared to current air pollution because the overall benefit from $PM_{2.5}$ reduction outweighs the disbenefit from O_3 increases. (Note: all benefits are reported in 2019 U.S. dollars.) A comparison of SB100—Moderate to Baseline (2012) reveals average monetized net benefits of $900 million (95% CI of $–480–$3000 million) in 2045. Early & No Biofuels—High yields maximum air quality improvements, reaching $1.4 billion (95% CI of $–470–$4400 million) compared to Baseline (2012). Avoided mortalities in Early & No Biofuels—High compared to SB100—Moderate provide approximately $500 million (95% CI of $20–$1400 million) net benefit in 2045 and is mainly attributed to the higher electrification levels. Among all districts, the districts on the east end of the city and central LA (districts 1, 10, 13 and 14) benefit most in the three scenario comparisons as shown by figure 4. This observed pattern is a combination of high population density and relatively larger concentration changes for these districts (figure 2). In addition, the valuation of avoided mortality accounts for about 99% of the valuation, while benefits associated with other health endpoints (e.g. hospital admissions, ER visits) are much smaller.

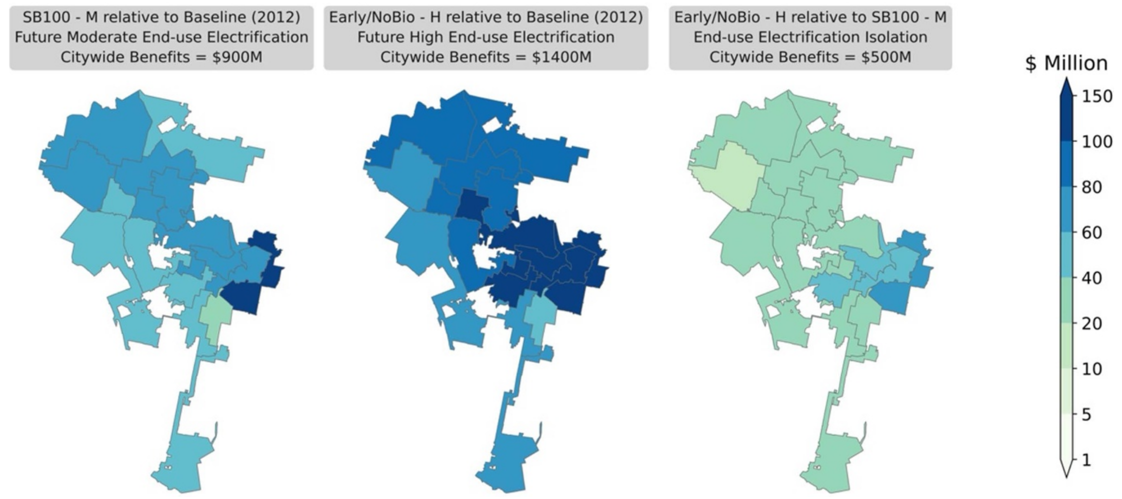

Figure 4. Monetized health benefits (in 2019 U.S. dollars) for the 15 Los Angeles city council districts across LA100 scenarios. Note that these benefits are in 2045 alone, and do not include any cumulative benefits since 2012.

4. Conclusion and discussion

Overall, our results suggest that the renewable energy adoption pathways investigated in LA100 can lead to reductions in major air pollutant emissions including NO_x and primary $PM_{2.5}$. Reduced emissions contribute to citywide reductions in $PM_{2.5}$ concentrations and slight increases in O_3 concentrations in LA (owing to the complex chemistry of ozone formation), assuming current (i.e. 2012) meteorology conditions. These concentration changes yield significant citywide benefits in public health including avoided premature deaths, which can lead up to millions of U.S. dollars of monetized net benefits in the single modeling year (2045) we analyzed. The benefits in air quality improvements and avoided health incidences can have an implication on the distributional justice associated with clean energy transition, details of which can be found in Cochran and Denholm (2021) and Hettinger *et al* (2021) [16, 28].

Changes in air pollution concentrations and public health that result from the LA100 scenarios are dominated by increases in electrification in transportation and end-use sectors as compared to the fuel transition in the power sector. Among the electrified sectors, the electrification of LDVs is crucial for citywide emission reductions. Note that the share of LDV primary $PM_{2.5}$ emissions that come from brake wear increases to the majority in future LA100 scenarios, which has implications for the design of future air quality management strategies and regulations. In contrast with electrification of multiple sectors, transitioning four LADWP-owned power plants within SoCAB from natural gas to hydrogen had a very small impact on city-scale air pollution because those plants are not a large contributor to LA-wide emissions. Nevertheless, gas-fired power plants can be an important contributor to near-source air pollutant exposure and the effects of combustion of hydrogen on emissions of NO_x and the health of adjacent communities should be further studied.

It is also worth noting that while we show reduction in air pollutant emissions from LA100 renewable energy adoption pathways, ∼90% of citywide primary $PM_{2.5}$ emissions remain in the future LA100 scenarios due to three main reasons. First, we only included LA100-induced changes to sources that are directly influenced by LA100 in this analysis. Including any indirect changes that LA100 might cause in categories such as the oil and gas industry ('Oil and Gas Industry' in figure 1), which currently supplies fossil fuel based energy inputs, such as gasoline, to sectors directly affected by LA100, were beyond the scope of this analysis. However, in reality, electrifying a large fraction of the LDV fleet would be likely to cause changes in oil and gas demand, which could impact future emissions in this category indirectly. Based on Federal Highway Administration Highway Statistics, one LDV on average uses approximately 10 barrels of oil equivalent annually in the US in 2016 [29]. Zhu *et al* (2022) investigated 80% GHG emissions reduction scenarios in 2050 California and assumed petroleum demand for in-state refining is reduced by 90% [30]. Second, regulations not enforced by the city are not considered in this analysis (i.e. not considered in the emissions projections to 2045), and yet should lead to greater emissions reductions. For example, CARB's Advanced Clean Trucks Regulation requires increases in the percentage of zero-emission trucks in manufacturers' annual California sales and will reduce emissions from 'Medium and Heavy-Duty Vehicles' in figure 1. Third, LA100 scenarios are designed to target sectors that maximize GHGs reductions, which are not necessarily the sectors with the largest air pollutant emissions. The fractions of primary $PM_{2.5}$ emissions from LA100-influenced sources to all anthropogenic emissions in LA are below 20% for all current and future scenarios. Controlling other major primary $PM_{2.5}$ emission sources such as commercial cooking and industrial processes (included in the 'Other' category in figure 1) will be important to achieve further air quality improvements.

Nevertheless, reductions in $PM_{2.5}$ concentrations induced by LA100 yield citywide public health benefits, but increases in O_3 concentrations are temporarily counter productive. Increases in O_3 concentrations due to NO_x reductions is a widespread issue for the greater LA basin because of the complexity of ozone chemistry and the state of the atmosphere in SoCAB [31, 32]. (The underlying ozone chemistry is explained in the SI.) This phenomenon is also found in other metropolitan areas such as the San Francisco Bay Area, Denver and Houston [3, 33, 34]. The increase in O_3 concentrations despite decreases in NO_x emissions can be thought of as a temporary 'growing pain' that the city is likely to deal with to ultimately reduce O_3 from decreasing NO_x emissions. Additionally, reducing air pollution emissions from the greater LA Basin is crucial for improving air quality in LA. CARB and SCAQMD are pursuing aggressive air quality and climate mitigation plans, including the 2022 State Strategy for the State Implementation Plan, the 2022 Climate Change Scoping Plan Updates, and the 2022 AQMP [35–37]. (Note that the assumed emission reductions in these plannings are not considered in our emissions projections in the 2045 scenarios.) In addition to developing and implementing mitigation measures similar to LA100, these plans will reduce NO_x emissions in sectors not directly influenced by LA100 and emissions from surrounding areas of LA. With the additional NO_x emission reductions in LA and its neighboring regions, it is likely that LA could transition from the 'NO_x-saturated' regime to the 'NO_x-limited' regime earlier than 2045. Thus, joint effort by city, district, and state governments can substantially reduce GHG and air pollution emissions from different sectors and potentially realize even greater health benefits.

Finally, it is also worth noticing that future climate change, which was not considered in this study, may partially or fully offset the air quality and public health benefits associated with the clean energy scenarios investigated in this study. Here, we assumed current (i.e. 2012) meteorology conditions in the air quality modeling of the 2045 scenarios, which is consistent with the meteorology conditions used in the future energy demand and generation modeling (that provide inputs to future emission inventory development). However, past studies have shown that climate change can affect emissions, atmospheric transport and chemical reactions via altered temperature, circulation patterns, etc [38, 39]. For example, Zhu *et al* (2019) found that climate change can lead to increases in both $PM_{2.5}$ and O_3 concentrations in 2035 SoCAB [40]. Thus, future studies and policy makers should take into consideration the impact of climate change on the effectiveness of clean energy adoption.

To the authors' knowledge, this is the first-ever 100% renewable electricity adoption study to be initiated by a U.S. utility system the size of LADWP that reflects detailed, science and policy-driven scenarios based on bottom-up, sector-specific grid and load modeling and that investigates co-benefits on air quality and public health. While GHG reductions require global effort to curb warming, air pollutant reductions provide immediate co-benefits to local communities, which could reinforce the motivation of renewable energy adoption at city scale [41]. The outcomes of this study, together with other aspects of LA100 study were referenced by the city of LA leadership as providing a blueprint for its recently announced goal to achieve 100% renewable electricity by 2035, one decade earlier than originally planned [21]. As the Intergovernmental Panel on Climate Change updates its goal of limiting global warming from 2 °C to 1.5 °C in its most recent assessment[42], localized action at city level on GHG emission reductions and renewable energy adoption are even more prudent than ever. This study demonstrates how a mega city through a focus on power sector decarbonization along with electrifying several demand sectors that can benefit from the decarbonized electricity can obtain net co-benefit from air pollution mitigation in addition to achieve above proportional share of GHG mitigation [43], and can serves as a blueprint for other cities seeking science-based and cross-sector strategies for creating deep regional decarbonization plans, while maintaining the reliability of energy systems.

Data availability statements

The source code and documentation for the WRF/Chem model can be downloaded at: www2.mmm.ucar.edu/wrf/users/. BenMAP-CE model can be downloaded at: www.epa.gov/benmap. The LA100 emission inventories generated during this study and other LA100 specific activity data are available at https://maps.nrel.gov/la100/la100-study/data-viewer.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

G H and G A B -W conceived and designed the study; Y L and V R performed the research and wrote the paper; G A B -W, G H and K T S mentored Y L; J Z, P V, S—M L, X Z and K T S contributed to the research. All authors contributed to editing the paper.

Conflict of interest

The authors declare no competing interests.

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