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Health co-benefits of achieving sustainable net-zero greenhouse gas emissions in California

Tianyang Wang[1,2,9], Zhe Jiang[3,4,9], Bin Zhao[3,5] ✉, Yu Gu[3], Kuo-Nan Liou[3], Nesamani Kalandiyur[2], Da Zhang[6,7] and Yifang Zhu[1,8] ✉

The achievement of net-zero greenhouse gas (GHG) emissions by 2100 is required to limit global temperature rise below 2 °C above preindustrial levels. Earlier accomplishments of net-zero GHG emissions in developed regions support this global target. Here, we develop a road map for California to achieve net-zero GHG emissions sustainably in 2050 by using detailed modelling of energy system transformation, cross-sectoral connectivity and technology penetration, as well as quantify the associated health co-benefits from reduced co-emitted air pollutants. We find that approximately 14,000 premature deaths can be avoided in California in 2050 and that these health co-benefits are disproportionately higher in disadvantaged communities (that is, 35% of avoided deaths will come from 25% of the state's population). The annualized monetary benefits (US$215 billion) exceed the GHG abatement cost (US$106 billion) by US$109 billion. This road map requires the use of bioenergy with carbon capture and sequestration technology to offset some GHG emissions. However, this technology comes at a price as it would emit a considerable amount of air pollutants and reduce health co-benefits by US$4 billion. Nevertheless, our analysis shows that ambitious GHG reduction efforts can provide substantial health co-benefits, especially for residents of disadvantaged communities.

To fight against global climate change, which is probably the greatest environmental and public health threat of this century[1], the concept of net-zero greenhouse gas (GHG) emissions has been increasingly discussed in the scientific community[2–4]. Both the Intergovernmental Panel on Climate Change[2] and the 2015 Paris Agreement[5] necessitate the target of global net-zero GHG emissions by the end of this century. Actions to reduce GHG emissions often reduce co-emitted air pollutants, such as nitrogen oxides (NO_x), reactive organic gases (ROG), particulate matter (PM, often measured as PM_{10} for particles ≤10 micrometres in aerodynamic diameter and $PM_{2.5}$ for particles ≤ 2.5 micrometres in aerodynamic diameter), ammonia (NH_3) and sulfur oxides (SO_x)[6]. Anthropogenic emissions are key contributors to ambient air pollutants such as $PM_{2.5}$[7,8] and ozone (O_3)[9], which have been linked to various adverse health outcomes[10–12]. Therefore, climate policies targeting on net-zero GHG emissions are likely to provide substantial co-benefits for ambient air quality and public health.

Previous studies have linked GHG reductions with health co-benefits using various health impact assessment methods, including epidemiological models, comparative risk assessments, microsimulations and life tables[13–19]. For example, Shindell and colleagues found that global CO_2 reductions may lead to 153 million fewer air pollution-associated premature deaths worldwide over the period of 2020–2100[14]. Campbell-Lendrum and Woodruff also analysed the global climate change-related burden of diseases using the comparative risk assessment method[17]. Most existing studies were performed at global or national scales and thus could not capture the spatial distribution of health impacts at local or even community levels due to model resolution limitations. Meanwhile, the GHG and air pollutant emissions in previous studies were primarily projected on the basis of changes in energy consumption and fuel types[13,20]. Such an approach does not account for GHG abatement technologies leading towards different levels of air pollutant emissions. The long-term local air quality and health impacts resulting from the transition towards net-zero GHG emissions remain unclear.

Such a knowledge gap can be filled by exploring the technology framework of a net-zero pathway in a highly polluted region. As the world's fifth-largest economy and the most populous state in the United States, California has one of the worst air qualities in the country. As a coastal state vulnerable to climate catastrophes, the state has also been a leading force in curbing climate change for decades. Assembly Bill 32, signed into law by Governor Arnold Schwarzenegger in 2006, was the first law of its kind in the nation and established targets to reduce GHG emissions to 1990 levels by 2020[21]. Senate Bill 32 (SB 32), signed in 2016, further extended the target to reduce statewide GHG emissions to 40% below the 1990 level by 2030[22]. The new carbon neutrality goal announced in 2018 was even more ambitious and highlighted the need to improve air quality and health simultaneously[23]. Consequently, developing a net-zero emission pathway for California and quantifying the associated health impacts can directly support these efforts and benefit the region in its long-term strategic planning. From the broad perspective of global net-zero emissions, understanding the interrelationship between climate polices and air quality in California will also expand the existing knowledge on integrated air quality management and climate change mitigation[24–27] and will serve as an

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[1]Institute of Environment and Sustainability, University of California, Los Angeles, CA, USA. [2]California Air Resources Board, Sacramento, CA, USA. [3]Joint Institute for Regional Earth System Science and Engineering and Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA. [4]Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China. [5]Pacific Northwest National Laboratory, Richland, WA, USA. [6]Institute of Energy, Environment, and Economy, Tsinghua University, Beijing, China. [7]Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA, USA. [8]Environmental Health Sciences Department, Fielding School of Public Health, University of California, Los Angeles, CA, USA. [9]These authors contributed equally: Tianyang Wang, Zhe Jiang. ✉e-mail: bin.zhao@pnnl.gov; yifang@ucla.edu

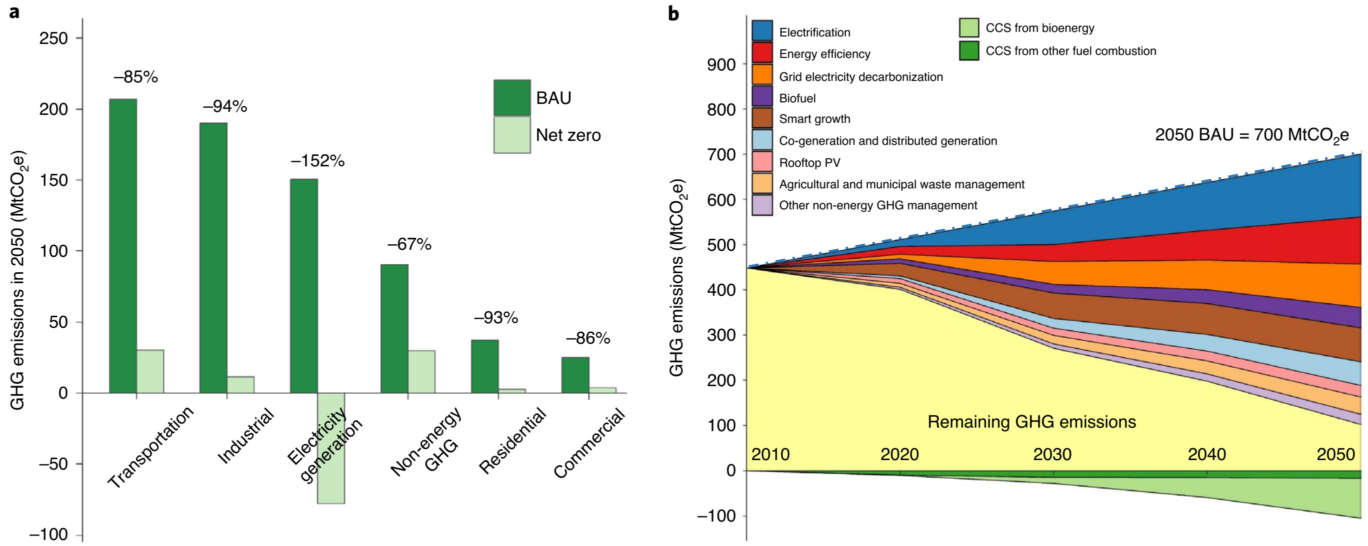

Fig. 1 | A road map for California to achieve net-zero GHG emissions in 2050. a, A road map showing sectoral GHG reductions for California to achieve net-zero GHG emissions in 2050. **b**, Strategies grouped into eleven categories reduce emissions from 700MtCO$_2$e in the 2050 BAU scenario to 0MtCO$_2$e in the net-zero scenario.

example for other regions and countries to jointly mitigate GHG and air pollution.

In this paper, we aim to develop a new, cross-sectoral integrated model that fully couples detailed energy technologies and GHG reduction strategies with air pollutant emissions and combine it with high-resolution air quality and health impact models to assess the co-benefits and cost of achieving net-zero GHG emissions in California. Here, we define net-zero emissions as a reduction in net anthropogenic GHG emissions to zero after accounting for carbon offsets. With the integrated model, we disaggregate the total GHG reductions into different strategies and capture their contributions to co-emitted air pollutants. We then assess the health co-benefits of implementing net-zero emission strategies for all Californians and people in disadvantaged communities. By comparing the net-zero strategy with an alternative GHG reduction pathway, we also discuss the potential trade-offs between climate benefits and air quality co-benefits of net-zero emission policies.

Results

We first construct a business-as-usual (BAU) scenario with total GHG emissions of 700 million metric tons CO$_{2\text{-equivalent}}$ (700 MtCO$_2$e) in 2050 on the basis of government forecasts of the population[28], the gross state product[29] and the 2010 base-year energy consumption structure from the State Energy Data System[30], as well as the increases in energy consumption projected by our original Model of Energy and Emission Technology in California (MEET-CA, see Supplementary Information for details). We have updated the GHG projection method for this BAU scenario since our previous study[31] to better reflect the sector-specific energy consumption associated with the economy development. No additional climate policies after 2010 are applied to the BAU scenario, and GHG emissions increase by 56% from 2010 to 2050 in the BAU scenario (Fig. 1a,b). For air quality, we do not assume the attainment of the National Ambient Air Quality Standards (NAAQS) in the BAU scenario since there has not been a clear policy and technology road map to achieve them although the attainment of NAAQS is required by law earlier than 2050.

We then develop a net-zero scenario for California with a decadal GHG mitigation road map using the MEET-CA to sustainably achieve the net-zero GHG emissions target in 2050 (Fig. 1a,b). The net-zero scenario is developed by working backwards from the zero CO$_2$e emission constraint to determine the changes in infrastructure and technology over time necessary to meet the target. The road map is built on a series of mitigation strategies illustrated in Table 1 and Supplementary Table 1. The long-term strategy progress and adoption rates in this net-zero scenario are constrained by technology feasibility, policy plausibility, resource availability and many other factors (see Supplementary Information for details). Meanwhile, our designed road map will emit 230 MtCO$_2$e in 2030 and meet California's midterm climate goal as required by SB 32 (that is, $<$259 MtCO$_2$e). While our short-term road map is mainly constrained by the requirements of SB 32, we also balance the deployment of strategies so that (1) long-term strategies such as electrification and carbon capture and sequestration (CCS) can be planned in advance to ensure sustained GHG reductions and (2) strategies that lead to stranded costs can be avoided.

The transition towards sustainable net-zero GHG emissions would require a systematic change in the current energy consumption pattern supported by deep decarbonization technologies and more-stringent policies. In addition, we find that to achieve the net-zero target, offsets or negative emission sources, such as the bioenergy with CCS (BECCS) technology, are necessary to balance the GHG emissions that cannot be easily reduced with existing technology in the given time frame. After the application of all technology, policy and resource constraints, we select the pathway with the minimum BECCS usage as the optimal net-zero scenario for analysis. As a key negative GHG emission source, BECCS power plants will provide 88 MtCO$_2$e of GHG offsets in 2050. Another 17 MtCO$_2$e of GHG offsets will be provided by CCS in natural gas power plants and co-generation facilities.

Our road map identifies end-use energy electrification, increased energy efficiency and electricity decarbonization as the core mechanisms, contributing to 140 Mt (20%), 104 Mt (15%) and 96 Mt (14%) of the total GHG reduction in 2050, respectively (Table 1). These core mechanisms are supplemented with several other strategies to further reduce GHG emissions. The transportation sector is the largest GHG emission source in California. Therefore, electric vehicles are introduced to the net-zero scenario with a high adoption rate, which substantially reduces tailpipe emissions by 64 MtCO$_2$e (Supplementary Table 1). To further reduce GHG emissions from

Table 1 | GHG reductions from the business-as-usual by strategy categories in the 2030 and 2050 target years

Strategy	GHG reduction (MtCO$_2$e)		Key attributes in 2050
	2030	2050	
Electrification	74	140	• 85% electrification rate in the residential and commercial sectors
			• 60% electrification rate in the industrial sector
			• Deep electrification in the transportation sector (75% for LDV, 33% for bus, 10% for classes 3–6 (10,000 < GVWR ≤ 26,000 lbs) trucks and 5% for classes 7 and 8 (GVWR > 26,000 lbs) trucks)
Energy efficiency	37	104	• Building energy efficiency increases by 1% per year
			• Industrial energy efficiency increases by 0.8% per year
			• Vehicle efficiency increases (cumulative 30% for LDV and 15% for trucks)
Grid electricity decarbonization	51	96	• 85% of grid electricity generated from carbon-free renewable sources: bioenergy (35%), wind (21%), solar (13%), large hydro (15%) and other (1%)
Biofuel	19	45	• 50% renewable fuels in cars and trucks
			• 35% renewable fuels in the industrial sector
			• 30% renewable fuels in the residential and commercial sectors
Smart growth	57	74	• Sustainable land use and transportation planning help reduce per capita passenger VMT by 25% and per capita freight VMT by 10%
Co-generation and distributed generation	21	52	Co-generation facilities supply:
			• 80% of thermal energy in the industrial sector
			• 25% of thermal energy in the residential and commercial sectors
Rooftop PV system	16	26	Rooftop solar panels supply:
			• 10% of the energy consumption in residential and commercial sectors
			• 1–3% of the energy consumption in the industrial sector.
Waste management	19	47	Reduce methane emissions from:
			• Dairy manure and other livestock by 70%
			• Landfill, wastewater and other waste treatment facilities by 95%
Other non-energy GHG management	10	14	• Reduce short-lived climate pollutants (for example, SF$_6$, CFCs and HFCs) and other non-energy GHGs (for example, nitrogen fertilizer) by 70% compared with the BAU scenario
CCS	28	105	Apply CCS technology into:
			• Bioenergy and natural gas power plants (80% facility × 80% capture rate)
			• Other small-scale co-generation and distributed generation facilities (50% facility × 60% capture rate)

LDV, light-duty vehicles; EV, electric vehicles; BEV, battery electric vehicles; PHEV, plug-in hybrid electric vehicles; GVWR, gross vehicle weight rating; VMT, vehicle miles travelled; PV, photovoltaic; SF$_6$, sulfur hexafluoride; CFCs, chlorofluorocarbons; HFCs, hydrofluorocarbons.

transportation sources, 50% of the fossil fuel used by the remaining internal combustion engine vehicles should be replaced by biofuel, and smart growth strategies need to be enforced to promote travel efficiency. End-use energy electrification is also applied to industrial, commercial and residential sectors to reduce direct combustion, contributing to 36, 23 and 16 MtCO$_2$e reductions, respectively (Supplementary Table 1).

All-sector electrification would substantially increase the electricity demand by 104% without the application of additional strategies. Our model applies a moderate 0.4–1% yr^{-1} energy efficiency improvement for end-use devices under the net-zero scenario, which substantially limits the growth of the electricity load. To reduce the electricity demand from the grid, the net-zero scenario applies co-generation and distributed generation strategies in the industrial, commercial and residential sectors to supply electricity locally and continue to improve energy efficiency. In addition, rooftop PV systems are installed to supply 10% of the energy in the residential and commercial sectors and 1–3% of the energy in the industrial sector. After applying all strategies and assumptions, our model shows that the total energy consumption for grid electricity generation under the net-zero scenario is 2.1 exajoules (EJ, $=10^{18}$ joule), 19% higher than the BAU. End-use electrification is coupled with electricity decarbonization to reduce the net carbon intensity of electricity in California. In the BAU scenario, the major energy source for electricity generation is natural gas. In the net-zero scenario, we design a mixed energy supply feedstock (Table 1 and Supplementary Fig. 5), which includes the comparable usage of bioenergy, wind and solar alternative energy sources as all three have demonstrated technical applicability but still suffer from high costs and technical difficulties in large-scale implementations. To ensure a stable electricity system, 10% of the grid electricity is still generated by natural gas in the net-zero scenario. Therefore, the overall energy carbon intensity in the electricity generation sector decreases from 70 g CO$_2$ MJ^{-1} in the BAU to 11 g CO$_2$ MJ^{-1} in the net-zero scenario, not counting the CO$_2$ offsets provided by the CCS process. Nuclear energy is not considered as a popular future strategy for electricity decarbonization given its controversial environmental impacts, earthquake risks and low public acceptance in California[32,33].

The MEET-CA then projects air pollutant emissions on the basis of energy growth rates, technology and energy mixes, and technology-specific emission rates. Although the BAU scenario does not require NAAQS attainment, it does incorporate many

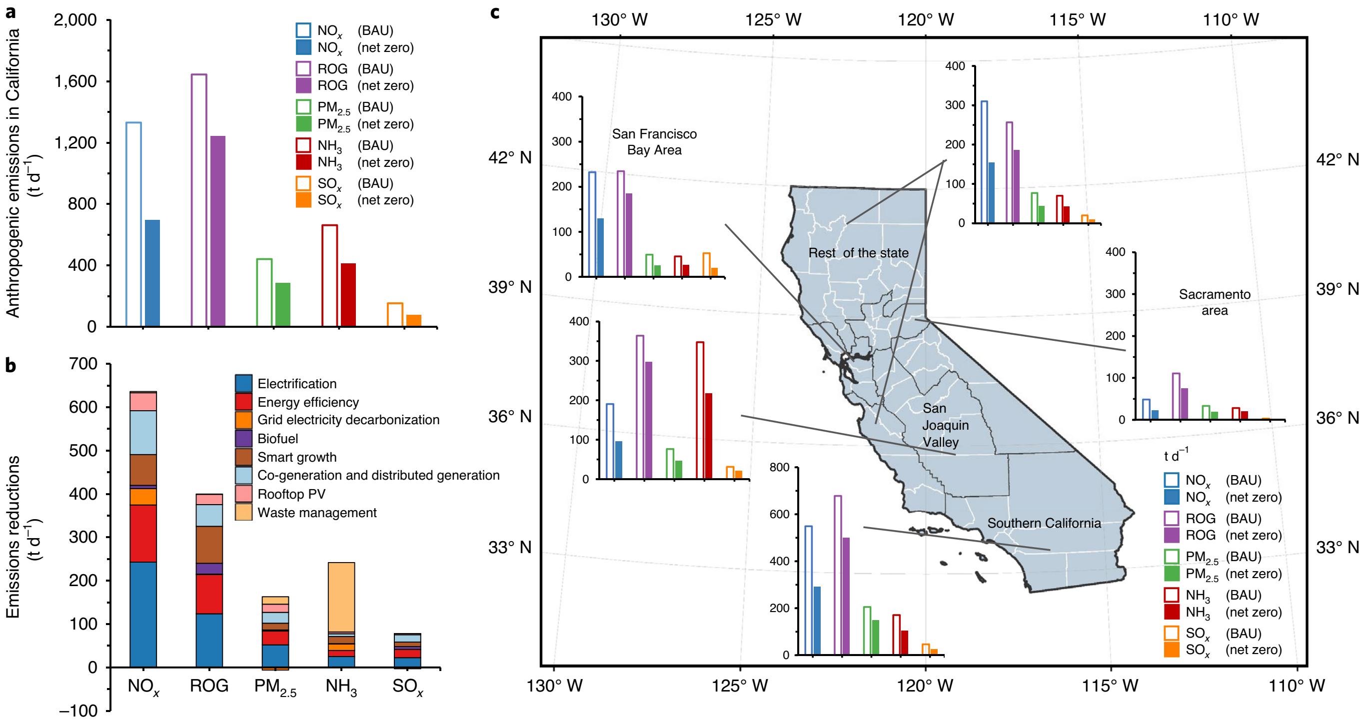

Fig. 2 | Air pollutant emissions in California in 2050. a, Model projections for emissions of air pollutants (NO_x, ROG, $PM_{2.5}$, NH_3 and SO_x) in California under BAU (no fills) and net zero (solid fills) in 2050. **b**, Emission reductions disaggregated by strategies. **c**, Emissions in five regions of California under BAU and net-zero scenarios in 2050.

existing control regulations on NO_x, ROG, SO_x and primary $PM_{2.5}$ in California. As shown in Fig. 2a, compared with BAU, the net-zero scenario leads to substantial reductions in anthropogenic air pollutant emissions in California in 2050 (that is, 48% NO_x, 24% ROG, 36% $PM_{2.5}$, 38% NH_3 and 49% SO_x, respectively). Figure 2b further attributes these emission reductions to individual strategies described in Fig. 1b and Table 1. Of the core mechanisms, end-use energy electrification and increased energy efficiency contribute the most to air pollutant emission reductions. By contrast, grid electricity decarbonization leads to very minor air pollutant emission reductions and even slightly increases $PM_{2.5}$ and SO_x emissions. This is because in the net-zero scenario, 35% of the grid electricity comes from bioenergy power plants, which have higher emission rates for air pollutants than conventional natural gas power plants in the BAU scenario. The CCS process in power plants reduces CO_2 emissions but has limited effects in reducing air pollutant emissions[34]. Spatial analysis (Fig. 2c) shows that air pollutant emission reductions in the net-zero scenario would mainly occur in metropolitan areas and major transportation corridors, such as Southern California, the San Francisco Bay Area and San Joaquin Valley, where baseline emissions are high.

The emission inventory for each scenario is converted to 4 km × 4 km grids for ambient air quality modelling. $PM_{2.5}$ and O_3 concentrations under the BAU and net-zero scenarios are projected using the Weather Research and Forecasting Model with Chemistry (WRF-Chem) version 3.9.1. A health impact analysis is then conducted to estimate the public health benefits of achieving net-zero GHG emissions using the Environmental Benefits Mapping and Analysis Program (BenMAP-CE, version 1.3.7). We analyse all-cause mortalities due to changes in $PM_{2.5}$ and O_3 exposures on the basis of concentration response functions (CRFs) derived from a recent epidemiological study[12]. More information about the parameters for ambient air quality modelling and health impact analysis are available in Methods and Supplementary Information.

Achieving net-zero GHG emissions can bring substantial air quality and public health co-benefits by reducing regional $PM_{2.5}$ (Fig. 3a) but may slightly increase O_3 (maximum daily 8 h average, or MDA8) concentrations in metropolitan areas (Fig. 3b). Overall, the net-zero scenario can reduce the annual average ambient $PM_{2.5}$ concentration by 5.0 $\mu g\, m^{-3}$ (population weighted) but can increase the annual average O_3 by 0.5 ppb (population weighted). Together, achieving net-zero GHG emissions can bring a public health co-benefit of a mortality reduction of 14,000 deaths annually, consisting of 14,400 avoided mortalities from reduced $PM_{2.5}$ exposure (Fig. 3c) and an increase in mortalities from elevated O_3 exposure (Fig. 3d). In addition to the mortality reductions, net-zero strategies can (1) reduce acute respiratory symptoms in 8.4 million adults, (2) reduce asthma exacerbation in 1.0 million children, (3) decrease the number of work-loss days by 1.4 million and (4) decrease the number of cardiovascular hospital admissions by 4,500 (Supplementary Table 12). Note that these estimated co-benefits might be less if NAAQS attainment is required in the BAU scenario (see detailed discussion in Supplementary Information).

The negative GHG emissions provided by BECCS are necessary for California to achieve the net-zero target. However, in the context of air quality co-benefits, biomass combustion emits relatively high levels of air pollutants, even though all BECCS plants in the scenario are projected to install emission control devices and will meet the emission standards in California. Meanwhile, although already implemented in the United States (for example, Illinois, Oklahoma and Kansas), BECCS requires a substantial amount of land and water resources, which could be another challenge to California. Therefore, we develop an alternative deep decarbonization (ADC) scenario that replaces BECCS power plants with carbon-neutral renewables such as wind, solar and geothermal power plants. Under this scenario, 83 $MtCO_2e$ would be emitted in 2050, which is approximately 81% below the 1990 level. Regarding air pollutants, this ADC scenario minimizes the electricity

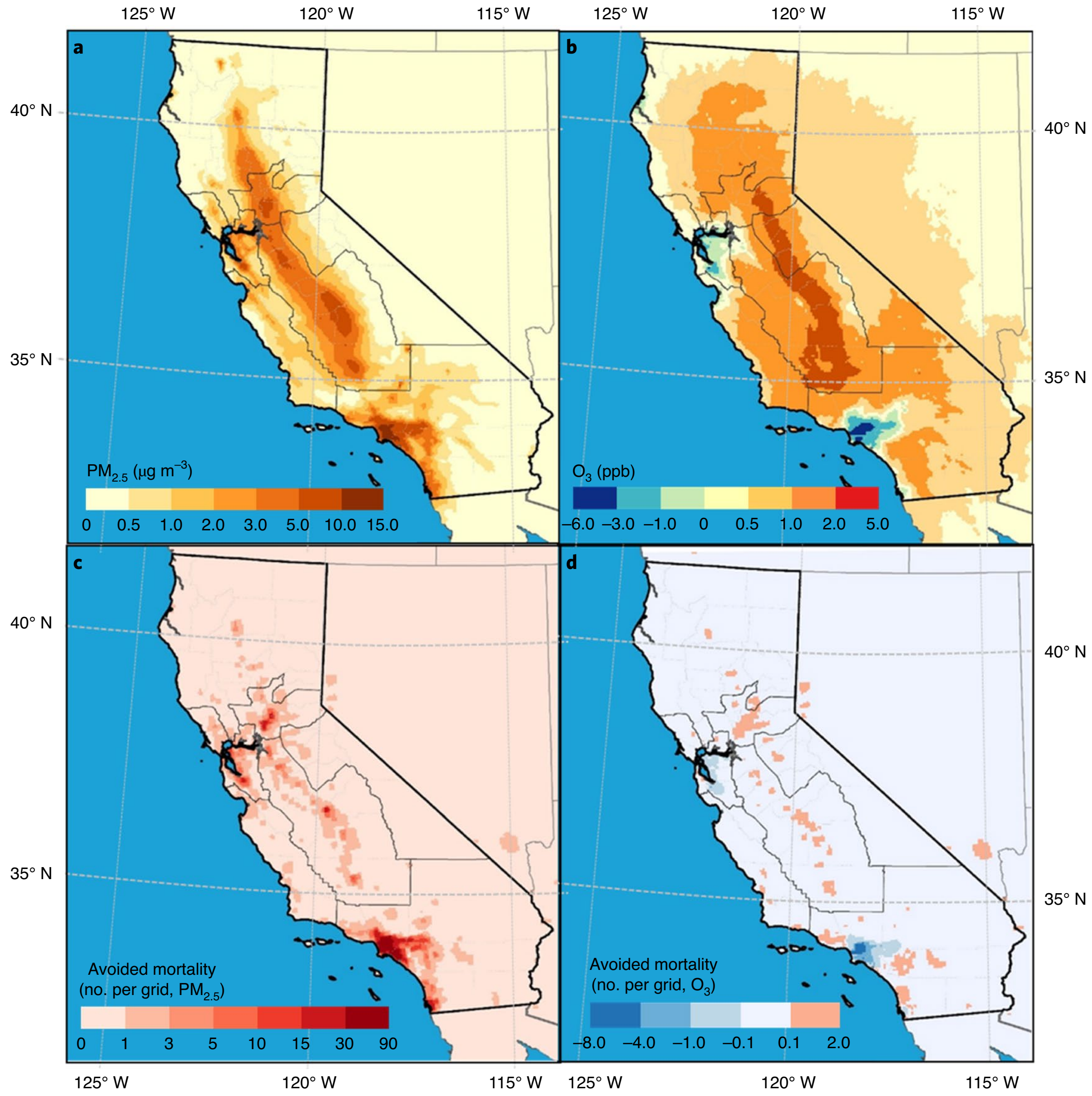

Fig. 3 | Reductions in the annual average $PM_{2.5}$ and MDA8 O_3 concentrations and avoided mortality in 2050 from the BAU to the net-zero scenario. **a**,**b**, Reductions in the concentrations of ambient $PM_{2.5}$ (**a**) and MDA8 O_3 (**b**). **c**,**d**, Avoided mortality due to changes in exposure to $PM_{2.5}$ (**c**) and O_3 (**d**). Yellow colours indicate decreased ambient air pollutant concentrations in the net-zero scenario; red colours indicate decreased mortality in the net-zero scenario; blue colours indicate increased air pollutant concentrations and mortality in the net-zero scenario.

generated from combustible sources and emits much less pollutant than the net-zero scenario in the electricity generation sector (Fig. 4a). Overall, ADC leads to an additional 0.12 μg m^{-3} reduction in the population-weighted $PM_{2.5}$ concentration (Fig. 4b) and can avoid 370 $PM_{2.5}$-related mortalities in California compared with the net-zero scenario (Fig. 4c). No notable changes are observed in O_3 concentrations and O_3-associated mortality.

We then conduct an extensive sensitivity analysis to determine the 95% confidence interval (CI) of the mortality reductions; the CIs range from 10,100 to 17,900 for the net-zero scenario and from 10,400 to 18,400 for the ADC (Table 2). The 95% CIs account for uncertainties associated with (1) economy and population projections, (2) the technology, policy and energy efficiency parameters in the model and (3) health impact analysis parameters using the Monte Carlo method (see Supplementary Methods for more details).

Utilizing the high-resolution modelling data, we further quantify that, for both the net-zero and ADC scenarios, approximately 35% of the air quality-related health co-benefits occur in disadvantaged communities (Table 2 and Supplementary Fig. 10). Here, we follow the designation of disadvantaged communities in CalEnviroScreen 3.0, which includes approximately 25% of California's population[35]. Our analysis suggests that achieving net-zero GHG emissions in California will probably deliver a disproportionately higher share of health co-benefits to citizens in disadvantaged communities.

The co-benefits of the avoided all-cause mortality in the net-zero and ADC scenarios are monetized using the values of a statistical life (VSL). The monetized co-benefits for mortality reductions, together with the monetized co-benefits for morbidity reductions and social cost of carbon (SCC), are compared with the annualized GHG abatement cost to estimate the net benefit of deep decarbonization in California (Table 2). In 2050, the central estimates of the monetized benefit in California, including the direct GHG reduction benefit and public health co-benefits of climate policies, exceed the total GHG abatement cost for both scenarios. The net-zero scenario brings US$7 billion more direct climate benefits than the ADC scenario by achieving a more ambitious

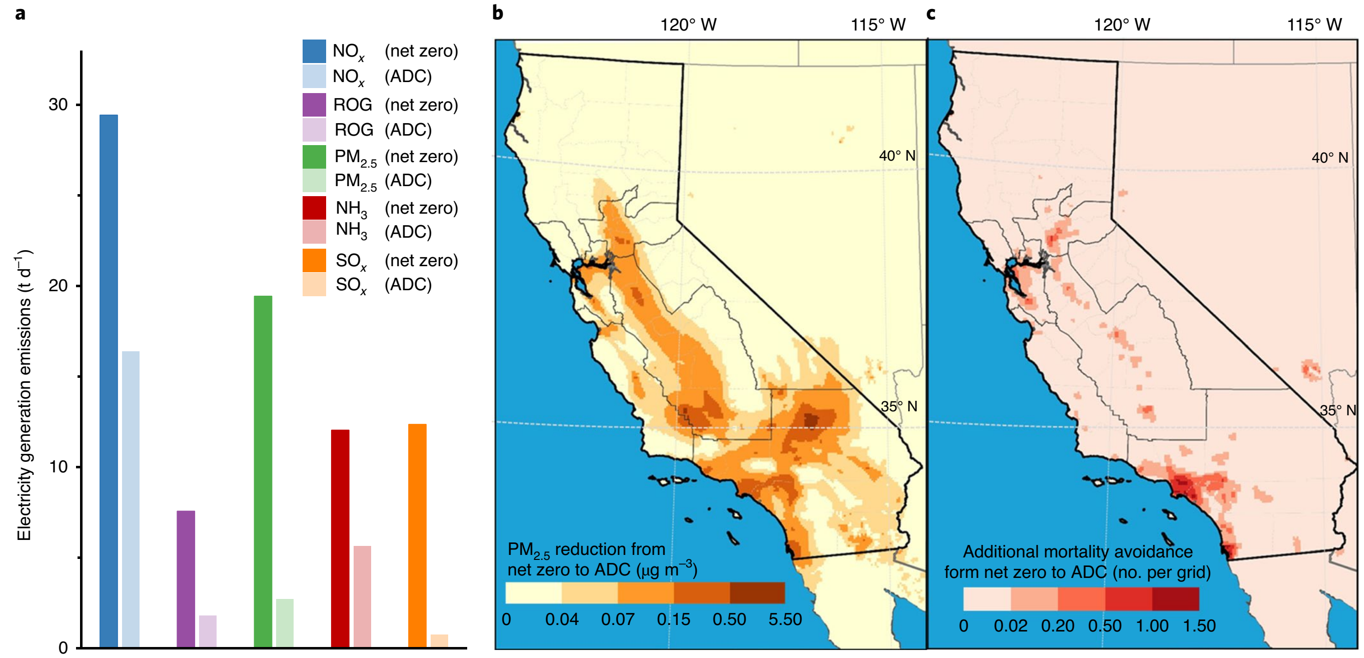

Fig. 4 | Air pollutant emissions from the electricity generation sector of the ADC scenario and associated $PM_{2.5}$ and health benefits. a, Difference in California statewide air pollutant emissions from the electricity generation sector between net zero and ADC. ADC differs from net zero in that ADC excludes BECCS and thus does not result in net-zero GHG emissions. **b**, The resulting changes in the ambient $PM_{2.5}$ concentration. **c**, $PM_{2.5}$-associated mortality. Yellow colours indicate decreased ambient $PM_{2.5}$ concentrations in ADC; red colours indicate decreased mortality in ADC.

Table 2 | Benefits and costs of the net-zero and ADC scenarios in 2050 relative to BAU

	Net zero	ADC
GHG emission reductions ($MtCO_2e$)	700	617
Annual mortality avoidance	14,000	14,400
	(10,100–17,800)	(10,400–18,300)
Mortality avoidance in disadvantaged communities	5,000	5,100
	(3,600–6,300)	(3,700–6,400)
Annual monetized co-benefit[a] (US$1 billion)	158	162
	(19–498)	(22–501)
Direct benefits of GHG reduction[b] (US$1 billion)	57	50
Annual GHG abatement cost (US$1 billion)	106	105
	(48–160)	(42–166)
Net benefit[c] (US$1 billion)	109	107
	(−30–455)	(−36–453)

[a]Monetized co-benefits include both mortality and morbidity reduction benefits. [b]We use the central estimates for the SCC to estimate the direct GHG reduction benefits. [c]The uncertainty of net benefit does not include the uncertainty associated with the SCC due to data availability.

climate target. However, we show that the net-zero scenario leads to US$4 billion fewer health co-benefits and a higher GHG abatement cost than the ADC scenario in the region. Therefore, the cost–benefit comparison between net-zero and ADC also indicates that, under the existing technology framework, the pursuit of a sustainable net-zero GHG emissions society will need to balance the direct CO_2 abatement cost, global climate benefit and local public health benefits.

As stated before, the range of the mortality avoidance in Table 2 captures uncertainties associated with (1) economy and population projections, (2) the technology, policy and energy efficiency parameters in the model and (3) health impact analysis parameters. In addition, our monetized net benefit estimates account for the uncertainties associated with GHG abatement cost and health valuations (for example, VSL and cost of illness). Overall, these modelling parameters may expand the range of health co-benefit estimates but will not alter our main finding that deep decarbonization can bring substantial health co-benefits to Californians.

Discussion

We investigate the potential for California to sustainably achieve net-zero GHG emissions by 2050 and demonstrate that the net-zero target is feasible with existing and emerging technologies. Consistent with previous studies[16,36,37], our analyses show that achieving the long-term net-zero GHG emission target in 2050 requires immediate action, higher adoption rates of new technologies and stronger policy supports in all major sectors through systematic and strategic planning. While the GHG reduction goals are designed for 2030 and 2050 in California, our road map is informed by the broad objective of limiting global warming to well below 2 °C through global net-zero emissions. Therefore, an important implication of our study is that long-term strategies need to be planned in advance and implemented at the regional level to ensure sufficient GHG reductions in the mid- to late century globally.

We demonstrate the critical role of commercially deployed BECCS technology in achieving the net-zero target. First, electricity can be generated with negative GHG emissions in BECCS power plants. By contrast, other cleaner carbon-neutral renewables, such as the wind and solar extensively used in the ADC or the nuclear power analysed by other studies, may achieve only zero GHG emissions. Second, the combustion feature of BECCS will allow the implementation of co-generation technologies to supply both electricity and thermal energy simultaneously. Hence, utilizing BECCS instead of noncombustible renewable energies also offers lower electrification requirements and implementation costs, especially in the industrial sector. Third, unlike other types of carbon sinks, such as oceans and forests, BECCS is a detachable mitigation tool added to biomass power plants and is thus less affected by natural environments, such as temperature increases and tree logging. Nevertheless, there are still challenges, both technical and societal, to be addressed before BECCS can be deployed at scale[38]. These high uncertainties in BECCS may bring additional uncertainty to the net benefit of the net-zero strategy estimated in this study.

The drastic changes in energy consumption and combustion patterns brought by the net-zero GHG emissions will result in notable reductions in air pollutant emissions, leading to considerable environmental and public health co-benefits in most areas. Although reductions in NO_x can cause increases in MDA8 ozone and make it more challenging to meet the ozone NAAQS in some urban locations, the GHG reduction brings substantial net health co-benefits to California. Currently, climate policies are driven primarily by reducing GHG emissions, while air pollution policies aim to protect public health. A better understanding of air quality and public health co-benefits could increase the social and economic acceptability of carbon policies[14]. Our study extends previous knowledge on the relationship between carbon policies and air quality by showing that achieving net-zero GHG emissions is tightly connected to air quality benefits, especially in populous and highly polluted regions in California. For example, GHG reduction strategies can effectively reduce ambient $PM_{2.5}$ in the Los Angeles Basin and the San Joaquin Valley (Figs. 3 and 4) and help these areas attain the NAAQS regulated by the US Environmental Protection Agency (EPA)[39]. Meanwhile, compared with global long-term climate benefits, air quality and public health co-benefits are mainly local and can be both short and long term, which may be more attractive to regions and nations that are not well motivated by the idea of GHG mitigation.

Air pollution is inequitably distributed among communities due to spatial differences in emission sources and ambient concentrations, raising serious concerns about environmental justice. Recently, Tessum et al.[40] reported that ambient $PM_{2.5}$ is disproportionately inhaled by Black and Hispanic minorities in the United States. Studies in California also found that some climate polices may not effectively improve environmental equity in terms of reducing air pollution emissions in disadvantaged communities[41,42]. Using a high-resolution modelling approach, we show that the net-zero pathway may lead to a greater-than-proportional air quality co-benefit in disadvantaged communities in California, thus supporting ongoing efforts to promote environmental equity. The tight connections among GHG mitigation, air quality and environmental equity described here call for interdisciplinary approaches to address multiple climate and environmental burdens simultaneously.

The detailed strategy-emission connection of the MEET-CA model allows us to decompose the total air pollutant emission reductions of the proposed scenarios to gain insights into the contributions of individual strategy. For example, electricity decarbonization using BECCS is found to have minor or even negative impacts on air pollutant emission reductions. Consequently, an interesting finding of this study is that there could be a trade-off between local air quality and global climate when negative GHG emissions are necessary to achieve ambitious climate mitigation goals. Conversely, such a trade-off also needs to be considered in the context of the overall health benefits of climate policies. Compared with inaction, ambitious GHG reduction efforts, regardless of the numerical stringency of the target, can provide substantial health co-benefits, which often exceed the implementation costs. To regions and countries with dirtier energy sources (for example, coal), our estimated trade-off could be even smaller compared to the overall climate benefits of GHG mitigation.

A strength of our study is the relatively comprehensive characterization of California's energy system and its connection to air pollution and public health at local and community scales. This is achieved through a cross-sectoral integrated technology model that fully couples detailed energy technologies with air pollutant emissions and its integration with high-resolution modelling of air quality, public health and mitigation cost estimation. Note that the cost is only used as a criterion for scenario evaluation, not a criterion for strategy selection and optimization. In addition, some unintended health co-harms due to mitigation strategies, such as increased indoor air pollution due to building energy efficiency improvement measures[43,44], are not considered in this study but warrant future research. Moreover, while the health co-benefits in this study are quantified on the basis of CRFs derived from epidemiological studies, these functions may not fully capture the time lags for chronic disease reductions. This could lead to additional uncertainties in the health co-benefit estimates over time, especially from long-term exposure to mortality[45,46], and warrants further investigation. Besides CRF, there are other state-of-the-art health impact assessment methods, such as comparative risk assessments[17,47], microsimulations[18,48] and life tables[19,49]. The application of these methods may allow a more comprehensive and accurate assessment of the health benefits of GHG mitigation. These remaining issues could be solved by developing a more integrated modelling approach that comprehensively optimizes mitigation strategies on the basis of the economic cost, the direct climate benefit, health co-benefits and unintended health co-harms, which warrants further in-depth research.

Methods

Our integrated approach involves a new energy and emission technology model for scenario development and emission projection, a high-resolution air quality model for ambient concentration simulation and a health impact assessment model. First, we design an original cross-sectoral energy and emission technology model (that is, MEET-CA) featuring detailed GHG mitigation strategies for scenario development. The MEET-CA is composed of four parts: (1) an energy demand module, (2) a GHG emission inventory module, (3) an air pollutant emission inventory module and (4) a cost module. The first two parts are interconnected on the basis of the GHG reduction targets and the selection of GHG mitigation strategies. We then feed the energy consumption and technology choice outputs into the third module to project the emission inventory for seven air pollutants (CO, NH_3, NO_x, PM_{10}, $PM_{2.5}$, SO_x and ROG). The cost module estimates the GHG abatement cost of a selected policy scenario on the basis of GHG reductions from individual technology/strategy and the corresponding unit cost (US$ tCO_2e^{-1}). In MEET-CA, we collect the unit CO_2 abatement costs of individual measures on the basis of the best available data from various studies[50–58] (Supplementary Table 7). All monetary values in this study are expressed as US$$_{2017}$ unless otherwise specified. Note that this bottom-up approach does not account for the cost reductions associated with the learning curve. It does not distinguish spatial variations in the strategy implementation cost either. Most important, we do not expect all new policies and technologies to be cost effective in the implementing stage. Therefore, the cost module is designed to compare the relative economic plausibility of different pathways and does not provide a criterion for scenario selection. The net-zero scenario used in this study is optimized by minimizing the BECCS usage under a number of policy, technology and resource availability constraints. See the Supplementary Information for more information regarding detailed model structures, projection methods and scenario assumptions (Supplementary Figs. 1 and 2).

The anthropogenic emission inventory projected by MEET-CA is then processed into 4 km × 4 km grids on the basis of high-resolution spatial distribution information provided by the California Nexus project (CalNex 2010)[59] for ambient air quality modelling. We then simulate the ambient $PM_{2.5}$ and O_3 concentrations in 2050 under different scenarios (BAU, net zero and ADC) using WRF-Chem version 3.9.1. For all scenarios, we simulate the hourly ambient air quality at a 4 km × 4 km resolution in January, April, July and October, which represent the winter, spring, summer and fall seasons, respectively. The meteorological initial and boundary conditions are generated from the Final Operational Global Analysis data (ds083.2) of the National Centers for Environmental Prediction at a 1.0° × 1.0° and 6 h resolution for the year 2010. The biogenic emissions are calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN)[60]. Other natural emissions, including dust, sea salt and wildfire emissions, are calculated on the basis of previous studies and databases[61–68] and are driven by the 2010 meteorology. In this study, we do not consider the possible influences of climate change on the meteorology and natural emissions in California, which should be explored in future studies. See Supplementary Information for more information regarding the detailed modelling parameters and simulation performance.

Exposures to ambient $PM_{2.5}$ and O_3 have been linked to a number of mortality and morbidity health outcomes. In this study, we quantify the all-cause mortality burdens due to long-term exposure to $PM_{2.5}$ and O_3 using CRFs derived from the American Cancer Society Cancer Prevention Study II[12]. BenMAP-CE (version 1.3.7)[69] developed by the US EPA is used to quantify the total and spatial distribution of mortality changes between the BAU and the two policy scenarios. Mortalities in disadvantaged communities are estimated by overlaying the gridded mortality incidence outputs from BenMAP with the disadvantaged community's layer from CalEnviroScreen v3.0 using ArcGIS (version 10.5.1). The disadvantaged communities in CalEnviroScreen 3.0 are identified on the basis of a series of geographic, socioeconomic, public health and environmental hazard criteria pursuant to SB 535, which requires the prioritization of GHG reduction investments in disadvantaged and low-income communities[35]. We also use BenMAP to estimate health co-benefits from several $PM_{2.5}$-associated morbidity reductions in the net-zero scenario, including acute respiratory symptoms, asthma exacerbation, work-loss days and hospital admissions[70–73].

Health co-benefits are monetized to compare with direct GHG reduction benefits and abatement cost. For health co-benefits associated with mortality reductions, we apply the EPA-recommended VSL of $US\$_{2011}$8.7 million with the Weibull distribution[54] and further adjust the VSL in 2050 for income growth over time, assuming a 0.7% increase per year. For morbidity, we estimate the monetized benefit range of total morbidity reductions from all diseases, accounting for the uncertainties associated with CRF parameters and the valuations of illness in the BenMAP default methods (see Supplementary Information for details). The EPA SCC method is used to estimate direct GHG reduction benefits[74]. The uncertainty range of cost estimates is also generated using the Monte Carlo method, assuming the true unit cost of individual measures follows a uniform distribution within the highest and the lowest cost estimate range provided in Supplementary Table 7.

Our health co-benefit estimates account for uncertainties from three aspects: (1) economy and population projections, (2) technology, policy and energy efficiency parameters in the model and (3) health impact analysis parameters. We first conduct three sets of sensitivity analyses to identify the mortality reduction distributions of each of the three uncertainty aspects. Drawing on these distributions, we capture the total uncertainties incorporating all three aspects using the Monte Carlo method. In the first two sets of sensitivity analyses, we first project the GHG emission distributions by changing the respective parameters (that is, economy and population projections in Set 1 and technology, policy and energy efficiency parameters in Set 2). We then select the 10th and 90th percentiles as the representative cases to project the air pollution emission inventory and simulate ambient air quality using the WRF-Chem. Next, we use the simulated ambient air quality data to estimate the 10th and 90th percentiles of mortality reductions. Finally, we determine the distribution of mortality reductions on the basis of central estimates in the main study and the 10th and 90th percentile numbers. In the third sensitivity analysis, the mortality reduction distribution is directly calculated by BenMAP using the Monte Carlo method, accounting for uncertainties in the CRF parameters. See the Uncertainty Analysis section in Supplementary Information for more-detailed information on the sensitivity analysis methods and modelling results.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available from the corresponding authors (B.Z. and Y.Z.) on request.

Code availability

The code of WRF-Chem model is available at http://www2.mmm.ucar.edu/wrf/users/download/get_source.html; the code of BenMAP is available at https://www.epa.gov/benmap/benmap-downloads; the custom CRFs used for the health impact assessment are available from the corresponding authors (B.Z. and Y.Z.) on request.

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Author contributions

Y.Z., T.W., B.Z. and Y.G. conceived and designed the research. T.W., Z.J. and B.Z. performed the research. D.Z. proposed the equity analysis idea. T.W., B.Z., Y.Z. and Z.J. wrote the manuscript and Y.G., K.-N.L., N.K. and D.Z. reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to B.Z. or Y.Z.

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Software and code

Policy information about availability of computer code

Data collection	GREET 2016: an open-source life-cycle analysis software with emission factors, published by Argonne National Laboratory EMFAC 2017: an open-source mobile source emission factor databased from the California Air Resources Board BenMAP-CE, v.1.3.7: an open-source computer program that calculates the number and economic value of air pollution-related deaths and illnesses published by U.S. EPA
Data analysis	Rstudio, version 3.4.4: open-source integrated development environment for R, a programming language for statistical computing and graphics. WRF-Chem v 3.9.1: the Weather Research and Forecasting (model coupled with Chemistry. The model is used for investigation of regional-scale air quality in California ArcGIS 10.5.1: a geographic information system for generating maps and conducting spatial analysis MS Excel 2016

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The data that support the findings of this study are available from the authors on reasonable request.
Figure 3: modeling results for ambient air quality and mortality by grid;Figure 4: modeling results for ambient air quality and mortality by grid; Figure S8 WRF-Chem

model output; Figure S9: WRF-Chem model output; Figure S10: geographic boundary of disadvantaged communities; Figure S15: WRF-Chem output and BenMAP output.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The submitted manuscript developed a detailed technology roadmap for California to sustainably achieve net-zero GHG emissions in 2050 with a novel, cross-sectoral energy and emission technology model. It evaluated the effects of individual GHG mitigation strategies on GHG and air pollutant emission reductions, and estimated the associated co-benefits on ambient air quality and public health at local and community levels.
Research sample	N/A
Sampling strategy	N/A
Data collection	All raw data used by this study are collected from open-source databases
Timing and spatial scale	The modeling base year is 2010, and the modeling target year is 2050, covering the State of California and its neighboring area, at a 4km*4km grid.
Data exclusions	No data were excluded from analysis
Reproducibility	N/A
Randomization	N/A
Blinding	N/A

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Methods

n/a	Involved in the study
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