Health, Climate, and Energy Co-Benefits of 2020 Residential Solar Panel Mandate in California

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Abstract

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Background: Power plants are primary emitters of greenhouse gases and criteria air pollutants, which are associated with harmful health impacts including increased risk of premature mortality. Therefore, the residential solar panel requirement set forth by the California Energy Commission for the 2019 Building Energy Efficiency Standards, Title 24, Part 6, plays an important role in promoting public health.

Objective: We used the Co-Benefits of the Built Environment tool to estimate emissions reductions, health, and climate co-benefits resulting from the residential solar panel mandate from 2020 to 2050.

Methods: We projected the electricity demand impacts, calculated future local emissions factors to derive the associated emissions reductions, and employed reduced complexity models to estimate human health impacts.

Results: In California, we found 32,664 metric tons of cumulative averted criteria air pollutants, in addition to greenhouse gas reductions equivalent to removing 8.67 million gas-fueled cars from the road. By 2050, we conservatively estimate monetary co-benefits over $546.4 million

(health) and $2.88 billion (climate). Electric utility cost savings by 2050 exceeded the expected increased upfront cost of purchasing a new home under the mandate by more than twofold.

Significance: Co-benefits of building energy efficiency standards can be quantified and used as a strategic tool to optimize human and environmental health.

Introduction

1.1. Background

Stationary fuel combustion in energy-consuming sectors including electricity-generating power plants are primary emitters of criteria air pollutants (such as ozone, particulate matter, sulfur dioxide, and nitrogen dioxide) each year. These pollutants are associated with harmful health impacts and are regulated by the Clean Air Act. Sulfur dioxide (SO_2) is the leading cause of increased risk of morbidity and mortality from air pollution (1). Nitrogen oxides (NO_X) contribute to premature death and serious respiratory illness (e.g., asthma, chronic bronchitis) due to the formation of fine particles and ozone (2). Both SO_2 and NO_X also have direct environmental impacts, including ocean acidification, damage to forest ecosystems, and poor air quality with hazy conditions (2). NO_x and SO_2 emissions from the electric power sector have declined significantly in recent decades but have historically contributed a significant proportion of total US emissions (27% and 64% respectively as of 2014) (1). In 2020, the electric power sector was also the second largest contributor to total energy-related CO_2 emissions in the US (3). Over 80% of global greenhouse gas emissions come from CO_2, making it a major contributor to the effects of climate change (4).

Buildings are the largest energy use sector in the US, consuming 76% of all electricity, nearly 40% of all primary energy, and emitting a proportional amount of harmful air pollutants, including CO_2, SO_2, and NO_X (5). The human population is expected to grow from 7.7 billion to 9.7 billion by 2050, with 68% of that population living in urban areas (6,7). Significant infrastructure needs must be met to satisfy these demands. Policies, mandates, and building code standards play an important role in reducing these harmful emissions. For example, the Clean Air Act significantly reduced air pollution from the US power sector. By 2014, pollution controls under the Clean Air Act resulted in a 73% reduction and a 57% reduction in SO_2 and NO_X emissions from 1970 levels, respectively (1).

Renewable energy mandates, such as the California Energy Commission's 2019 requirement for solar panel systems in all new homes, can promote human and environmental health by reducing pollutant emissions associated with energy demand. Modeling tools, such as the Co-benefits of the Built Environment (CoBE) tool (8), can be used to quantify the health and climate co-benefits that result from these standards. These projections can help direct efforts and resources toward the implementation of energy conservation measures that are expected to yield the most benefits in terms of human and environmental health.

1.2. Co-Benefits Analysis

California's residential solar panel requirement is the first of its kind in the nation. The code change was brought forth by the California Energy Commission for the 2019 Building Energy Efficiency Standards, Title 24, Part 6, and took effect January 1, 2020 (9). Solar panel installations must be sized to meet the annual electricity usage of the dwelling; this includes end uses such as space heating, water heating, lighting, and plug load in most multi-family and single family homes. There are flexible aspects of the new standard, which allow builders to implement smaller photovoltaic systems paired with alternative energy efficiency measures such as thermal storage, rainwater catchment systems, and demand-responsive measures (10). There are also exceptions for homes that receive insufficient solar availability, and exceptions for homes of specific sizes. However, since most of the flexibility within the mandate requires an alternative energy efficiency measure, and because there are stringent enforcement requirements throughout the phases of design and construction, we assume in this analysis that all newly constructed homes will be subject to the requirement.

We projected the health and climate co-benefits of this renewable energy requirement from 2020 to 2050, first over the state of California, then over a larger potential region (the Pacific census region, which includes Washington, Oregon, California, Alaska, and Hawaii). The CoBE tool was employed in our analysis (8). Health co-benefits are estimated in terms of avoided premature death from reductions in emissions of criteria air pollutants, and includes the monetary valuation of mortality risk reductions. The CoBE tool also estimates co-benefits in terms of health cost savings (USD), avoided costs from climate damages (USD), energy savings (MWh), emissions reductions (metric tons), and energy cost savings (USD) attributable to the energy conservation measure under study.

1.3. Significance

The CoBE tool has previously been used retrospectively to estimate health and climate co-benefits of building energy conservation measures that have already occurred (8). However, there is a critical need for developing a prospective co-benefits analysis to guide strategic decision making on new or proposed energy conservation measures. For example, a solar panel mandate may result in a significantly different distribution of health and climate co-benefits in a state with a cleaner energy grid (powered by renewable or lower-emission sources), compared to another state in which the electricity grid is more reliant on coal and fossil fuels. Emissions of air pollutants depend on many factors including the local fuel mix of the electric grid, and states in the US vary greatly in their electricity generation sources; in 2018, California ranked first in the nation as a producer of electricity from solar, geothermal, and biomass resources (11). The state's electricity generation is fueled primarily by natural gas, followed by renewables and nuclear sources. Petroleum- and coal-fired power plants did not contribute to California's net electricity generation in 2020 (11). While California's energy grid is considered to be relatively 'clean', recent research should be noted which found that by 2018, the health burden of gas in stationary air pollution sources surpasses that of coal in the US (12). Conversely, some southern and midwestern states rely more heavily on emissions-intensive fuel sources such as coal (coal-fired electric power plants still accounted for 91% of West Virginia's electricity generation in 2019) (13). Importantly, Buonocore et al. (2019) assessed the benefits of deploying renewable capacities in different regions of the US, and found that total benefits were highest in the upper Midwest, Great Lakes, and mid-Atlantic region, and were the lowest in California (14). Therefore, when considering adopting an energy conservation measure in a particular region, an analysis of the projected co-benefits can be useful to guide efforts toward locations in which health and climate co-benefits will be the greatest.

Health co-benefits are a frequently overlooked societal value in building code standards, and are not consistently considered in policy making or building design processes. Therefore, we evaluated two study areas (the state of California and the larger Pacific census region) using the

CoBE Projection method, introducing the health perspective and quantifying overlooked return on investment to mobilize further widespread adoption of high-performance buildings. We also aim to serve as an example of the importance of co-benefits analyses in strategic decision-making to maximize the varying distributions of health benefits between regions of the US. This paper describes a novel use of the CoBE Projection tool, prospectively estimating co-benefits of a new building energy conservation measure and satisfying these gaps in knowledge. Unlike previous co-benefits studies, our projection analysis considers future residential building electricity use patterns, new home construction and loss rates, electricity cost projections, forecasts of emission factors specific to the location of analysis, future health impacts associated with projected pollutant emissions, and projected climate damages to 2050.

Methods

2.1. How CoBE Works

CoBE quantifies health and climate co-benefits resulting from building-related pollutant emissions reductions. The general methodology of the CoBE tool follows three stages; the tool first calculates energy savings by subtracting energy use in a reduced energy scenario (e.g., the residential solar panel mandate) from energy use in a business-as-usual scenario (e.g., without the solar panel mandate). Then, the tool translates those energy savings into reductions in emissions of greenhouse gases and criteria air pollutants. Finally, CoBE quantifies the resulting health impacts and climate co-benefits (8). Our methods for the prospective analysis of each of these three stages are detailed in sections 2.2, 2.3, and 2.4.

2.2. Projection of Energy Savings

Prior CoBE studies only evaluated energy savings from building energy conservation measures in past years, up to 2016. In this study, energy consumption trends, building stock, and energy costs were projected out to 2050 for a prediction of the future impacts of the solar panel mandate. We estimated the energy demand reductions in both the state of California and the Pacific census region using data from the 2015 Energy Information Administration (EIA) Residential Energy Consumption Survey, the 2019 EIA Annual Energy Outlook, the U.S. Census Bureau American Community Survey, and the California Energy Commission.

We estimated the reduced residential electricity demand for each region using Equation 1 for the solar panel mandate scenario and the business-as-usual scenario. We also included an estimate of electric utility cost savings that would accrue for homeowners/occupants of homes that are subject to the solar panel mandate using data from the 2019 EIA Annual Energy Outlook (15).

Equation 1. Projecting electricity demand in the solar panel mandate scenario and the business-as-usual scenario for each year, 2020-2050.

$$\left(\frac{electricity\ use}{home}\right)_{year(i)} \times (\#\ of\ homes^{\dagger})_{year(i)} = (electricity\ demand)_{year(i)}$$

† In the solar panel mandate scenario, this was an annual estimate of only new construction homes added to the total housing stock. In the business-as-usual scenario, this was an estimate of each year's entire housing stock in the region of analysis.

We assumed that all new construction homes from 2020 onward would be in compliance and have net zero electricity demand from the electric power grid. Once the projected electricity demand was calculated for each scenario, we estimate the total annual electricity demand reductions for each year 2020 – 2050 by subtracting the annual electricity demand in the solar panel mandate scenario from annual electricity demand from the electric grid in the business-as-usual scenario.

2.2.1 Electricity use per home

For the business-as-usual scenario, we used the EIA's 2019 Annual Electricity Outlook data for total annual projected residential consumption from the electric power grid in the Pacific region (EIA reference case) to extract the percent change in electricity consumption per year through 2050 (16). This was an average of -0.8% per home per year. We chose to select the EIA's reference case and its underlying assumptions over the EIA's other 'side case' projections in the Annual Energy Outlook because the reference case is the best assessment of energy markets through 2050, intended to be a reasonable baseline case for energy consumption by sector and source (17).

When estimating growth rates of electricity consumption under the solar panel mandate scenario, we used electricity consumption trends for new homes only. Data from the Residential Electricity Consumption Survey was used which compared average electricity consumption per household in the West region (which encompasses California and the Pacific census region, and also includes the Mountain census region) between homes constructed in different decades. We noted an average growth rate in electricity consumption of 0.0002442% per year in newly constructed homes (18). We assumed this rate to be constant throughout the projection period in the solar panel mandate scenario.

For each scenario and region, we calculated electricity consumption per home using Equation 2. We estimated starting-year electricity consumption at 28.8 MMBtu/year for the Pacific Region (18) and 24.5 MMBtu/year for California, which we derived from the California Energy Commission and the US Census Bureau (19,20).

Equation 2. Projecting electricity consumption per home in the solar panel mandate scenario and the business-as-usual scenario for each year 2020-2050.

$$\left(\frac{electricity\ consumption}{home}\right)_{year_i} \times \left(growth\ rate\ of\ \frac{electricity\ consumption}{home\ \dagger}\right)_{year_{i+1}}$$

$$+ \left(\frac{electricity\ consumption}{home}\right)_{year_i} = projection\left(\frac{electricity\ consumption}{home}\right)_{year_{i+1}}$$

† For the solar panel mandate scenario, this rate was limited to newer homes only (built in 2001 on, as defined by the California Energy Commission). For the business-as-usual scenario, this rate was for the entire residential building stock.

2.2.2 Number of homes

We used estimates of occupied homes from the US Census Bureau (for California) and the EIA (for the Pacific region) in 2019 as the baseline, estimated at 17.9 million households in the Pacific region (21) and 12.8 million in California (20). These baseline estimates aligned with the US Census Bureau's estimates of population by state, indicating that California comprises 74% of the total population of the Pacific region (22).

We then calculated a growth rate in the number of annual new homes constructed per year based on historical trends from the US Census Bureau American Community Survey for both regions (20). The growth rate was estimated at 1.27% per year for California and 1.26% per year in the Pacific region. Both rates were assumed to be constant throughout the projection period. In the business-as-usual scenario, all homes in each region were included for estimating the total residential sector electricity consumption (not just for new homes that are subject to the solar mandate). Therefore, in addition to new homes that are added to the total household mix, we incorporated a regional housing unit loss rate to account for demolitions (0.67 housing units lost per 1,000 units per year for the West region), which we derived from the American Housing Survey for a full picture of the housing stock in a given year (23). The number of applicable homes in each scenario for each year in the projection period was calculated using Equation 3.

Equation 3. Estimating number of applicable homes in each region, scenario, and year from 2020-2050.

$$
\begin{aligned}
&(\#\ of\ occupied\ housing\ units)_{year(i)} \\
&\quad \times growth\ rate\ \left(\frac{annual\ new\ home\ additions}{year}\right)_{year(i+1)} \\
&\quad + (\#\ of\ occupied\ housing\ units)_{year(i)}\ - (housing\ unit\ loss\ rate^{\dagger}) \\
&\quad = (projection\ of\ housing\ units\ in\ region)_{year(i+1)}
\end{aligned}
$$

† Housing unit loss rate was only included in the business-as-usual scenario.

2.3. Projection of Emission Factors

Emission factors, or rates of pollutants released per unit of electricity generated, are expected to change over time as electric power plants transition to cleaner fuel sources and renewable energy becomes more prevalent (12,24). Emissions from electricity generation vary greatly by geographic location and are influenced by fuel switching, fuel efficiency improvements, improvements in performance due to economic influences, or any occurrence that alters the emissions-producing process from electricity generation (25).

For the best region-specific projection of the emissions intensity of electricity generation in future years, we developed a data library of emission factors from 2019-2050 for 22 US subregions (eGRID regions from the Emissions Generation and Resource Integrated Database) using EIA's 2019 Annual Energy Outlook forecasts of electricity generation and associated pollutant emissions (26). The EIA Annual Energy Outlook projects emissions for CO_2, SO_2, and NO_x out to 2050 using their Electricity Market Module, which predicts the electricity source (mix of power plants that will meet electricity demand) at the census region level by modeling electricity load and demand, electricity capacity planning, electricity fuel dispatching, and electricity finance and pricing. Based on fuel prices and electricity demands, the Electricity Market Module determines the most economical way to supply electricity within environmental and operational constraints (27). The EIA Annual Energy Outlook's emissions projections come from the EIA's integrated model, the National Energy Modeling System, which captures interactions of economic changes and energy supply, demand, and prices (28). To develop a data library of projected emissions factors in each eGRID region and for each year in the projection period, we divided the EIA's projected emissions of NO_X, SO_2, and CO_2 (in tons) by the EIA's projected electricity generation (in MWh) from all power plants in the same eGRID region.

A large portion of ambient $PM_{2.5}$ concentration is formed indirectly from precursors like sulfur dioxide (SO_2) and nitrogen oxides (NO_x) (29). In this study, we included emissions factors for NO_X, SO_2, and CO_2 as primary pollutants emitted from power plants, and did not include other secondary pollutants such as fine particulate matter (specifically $PM_{2.5}$). While exposure to $PM_{2.5}$ has been linked to mortality through a variety of causes (and if included in this study, would be expected to increase our projections of premature mortality), the ambient concentrations of secondary $PM_{2.5}$ depend on modeling the reaction of gas-phase precursors to sulfuric and nitric acids and other existing pollutant concentrations in the air. There is a non-linear and complex interaction between all these components which requires atmospheric modeling to determine the contribution of each of these precursors to $PM_{2.5}$ concentration, and therefore was considered out of the scope of this study. Additionally, previous CoBE studies also included CH_4 and N_2O as greenhouse gases in the analysis (8). We excluded these pollutants from our projection because they made up only a small portion of total climate co-benefits contributed by each of the greenhouse gases; based on co-benefits results from MacNaughton et al. (2018), 99% of US climate co-benefits were achieved due to averted CO_2 emissions. CH_4 contributed 0.2 % of total climate savings in the US, and N_2O contributed only 0.4 % (8).

2.4. Health and Climate Co-Benefits

2.4.1. Health

After reviewing over 60 peer-reviewed publications on different models and methods used to estimate health impacts of air pollution, we identified two improvements to CoBE's prior health impact analysis method for this study: a finer spatial resolution for the sources of emissions, and increased specificity of emissions sources (emissions representative of the full electric grid rather than just coal-fired power plants). To achieve these objectives, we employed three peer-reviewed reduced complexity models (RCMs); Estimating Air pollution Social Impact Using Regression (EASIUR), AP2 (Air Pollution Emission Experiments and Policy), and Intervention Model for Air Pollution (InMAP) (30–32).

These tools relied on simplified representations of the complex physical and chemical mechanisms that link emissions to pollutant concentrations, as opposed to conventional chemical transport models that are more complex and computationally demanding. Our goal was to capture the essential elements of air pollution health impact modeling without shifting the focus of this study primarily toward atmospheric and chemical transport modeling, and away from the overall objective of estimating health and climate co-benefits of a renewable energy policy. The

RCMs were selected over other methods because they did not require advanced air quality modeling techniques prior to estimating health impacts; they derived atmospheric information from existing models (e.g., WRF-Chem), included detailed spatial resolution according to the location of the emissions source, accounted for population sizes, and were simpler and faster to use than other methods in the literature (e.g., CMAx, CMAQ). The RCMs were open source tools, frequently employed in the peer-reviewed scientific literature to model health impacts of air pollution, and were most compatible with our vision of enhancing the spatial resolution and the specificity of emissions sources (each RCM allowed us to select elevation as a model input, to distinguish between emissions from power plants and emissions from onsite energy generation). The RCMs estimate health impacts of air pollution in terms of the standard measure of the value of premature mortality risk, the Value of Statistical Life, which represents a typical person's willingness to pay for reductions in mortality risks, applied uniformly across populations regardless of age, race, or income (33).

We integrated eGRID region-level data on electric power plant emissions from EIA with the RCM data for a weighted average of health impacts in terms of USD and avoided premature mortalities per ton of emissions avoided, defined as death that occurs before the average age of death in a population (34). Our health impacts were specific to each region and its local power plant mix (30–32,35). To do this, we plugged the plant-level emissions of CO_2, NO_X, and SO_2 for all US counties into the RCM to model the national health impact caused by those emissions. In the RCM, we used a concentration response function reflecting a 1.4% increase in mortality risk per µg/m3 increase in the annual average exposure to $PM_{2.5}$ (36). We chose the 'elevated' stack height to represent electric power plant emission sources, and a value of statistical life of $11.2 million (2017 USD) based on Environmental Protection Agency (EPA) guidelines and adjusted for inflation and income elasticity (37). For each of the 22 eGRID regions, we calculated the average health impact in USD from all power plants within the region. Last, to estimate the premature mortalities associated with these emissions, we divided the dollar per ton impact in each region by the value of statistical life.

2.4.2. Climate

To estimate climate co-benefits of reductions in greenhouse gas emissions, CoBE assigns a monetary value to greenhouse gas emissions reductions based on the US Government's social cost of carbon methodology (38). The social cost of carbon is a value of damages avoided for a reduction in CO_2 emissions, and considers impacts on agriculture, forestry, fisheries, property damages, increased energy expenditures, and other long-term damages done by greenhouse gas emissions. The social cost of carbon is expected to increase over time because future emissions will produce larger incremental damages as systems become more stressed under the effects of climate change. Therefore, for a projected estimate of future-year climate co-benefits of an energy conservation measure, we used the US Government's established projected values of the social cost of carbon for each year 2019-2050 (38). These projections were developed through an interagency process which included the EPA and the Departments of Agriculture, Commerce, Energy, Transportation, and Treasury, who employed three integrated assessment models commonly used to estimate these values: the FUND, DICE, and PAGE models, which were also used in the Intergovernmental Panel on Climate Change assessment. These models were given equal weight and combine climate processes, economic growth, and feedbacks between the climate and the global economy (38). Since the effects of climate change will be felt over many years, the social cost of carbon accounts for a time preference by including a discount rate, which reflects the human tendency to prefer financial benefits at the present time rather than in the future. We used the middle of the range of discount rates (3%), which ranged from $51.24 2018 USD per metric ton of CO_2 in 2020 to $84.18 2018 USD in 2050 (38).

Results

3.1. Electricity Demand Reductions and Energy Cost Savings

Based on projections from the EIA Annual Energy Outlook, California's electricity generation in the starting year of the projection period is primarily fueled by renewables (49.04%) and natural gas (39.9%). By 2050, renewables fuel 83.69% of total electricity generation in California, and natural gas fuels only 17.3%. Conversely, coal and petroleum fuel 1.66% of total electricity generation in California in 2020, and 0.0016% by 2050 (26). Under the solar panel mandate scenario in California, electricity demand from the electric power grid will be reduced by 701.64 million MWh cumulatively (Figure 1a) between 2020 and 2050 (1.14 billion MWh in the Pacific region). In California, this is an average of 22.63 million MWh per year (36.63 million MWh per year in the Pacific region) of electric power demand reduced from the grid and replaced with renewable energy due to the residential solar panel mandate.

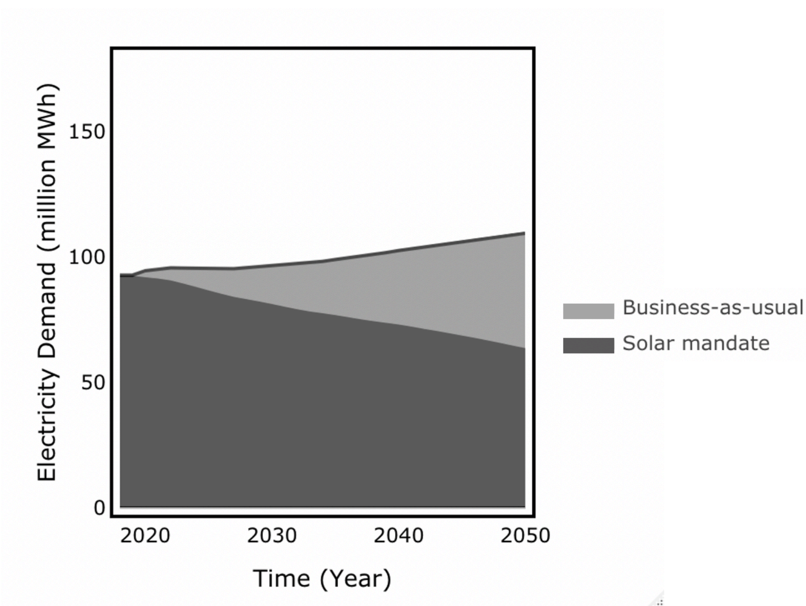

Figure 1a. Annual residential sector electricity demand in the state of California (millions of megawatt-hours) from the electric power grid between 2020 and 2050 in the solar panel mandate scenario and the business-as-usual scenario.

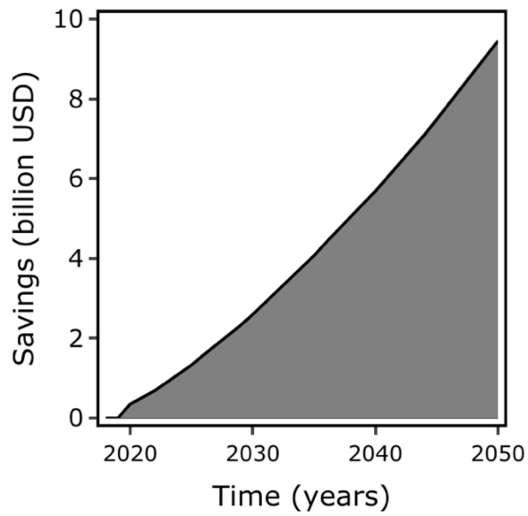

Figure 1b. Annual energy cost savings for applicable residents in the state of California in the solar panel mandate scenario (2020 USD) from 2020-2050.

For the occupants of the homes subject to the solar panel mandate, this also means a decrease in utility bills. In California, the annual electric utility cost savings (Figure 1b) will reach $9.45 billion in 2020 USD by 2050 USD ($15.29 billion by 2050 in the Pacific region).

3.2. Emissions Reductions

The displacement of demand from the electric power grid due to the solar panel mandate in California will result in a cumulative total reduction of 39.86 million metric tons of CO_2 (Figure 2) between 2020 and 2050 (186.43 million metric tons of CO_2 cumulatively in the Pacific region).

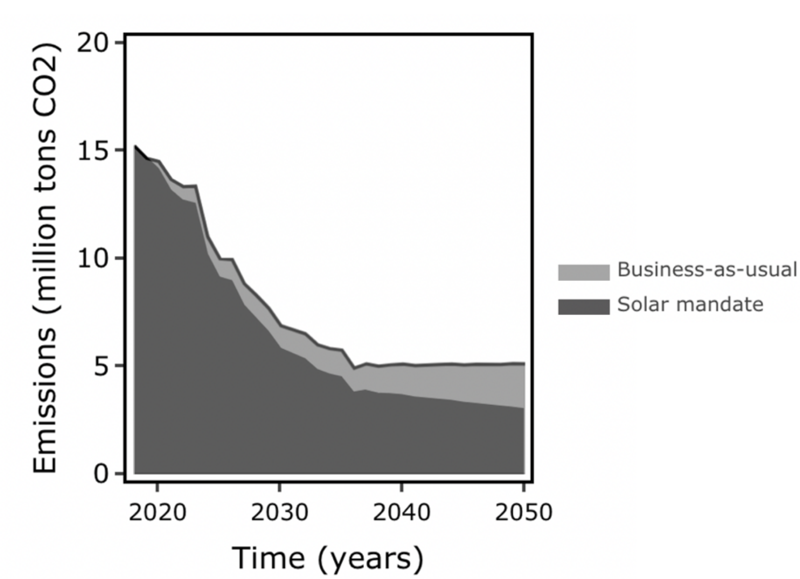

Figure 2. Annual CO_2 emissions from electric power plants due to residential sector demand from the electric grid (million metric tons) in the state of California from 2020-2050 under (1) business-as-usual scenario and (2) the solar panel mandate scenario. The shaded region represents the CO_2 emissions reductions co-benefit of the solar panel mandate in the state of California.

Due to their harmful health effects, emissions of NO_x and SO_2 (criteria air pollutants) are particularly important to mitigate. Cumulatively between 2020 and 2050 in California, reductions in demand from the electric grid will reduce emissions of NO_X by 28,973 metric tons, and emissions of SO_2 by 3,691 metric tons (Figure 3) (cumulative reductions of 104,464 metric tons of NO_x and 11,219 metric tons of SO_2 in the Pacific region).

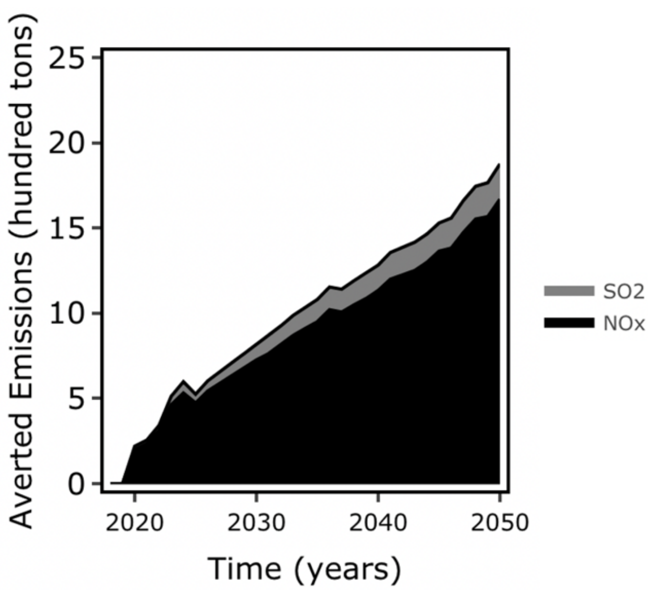

Figure 3. Annual averted NO_X and SO_2 emissions (hundreds of metric tons) from 2020-2050 in the state of California resulting from reduced demand from the residential sector on the electric power grid due to the solar panel mandate.

3.3. Health and Climate Co-Benefits

Health impacts in CoBE are estimated at the national level in terms of avoided premature mortalities resulting from the averted NO_x and SO_2 emissions. The avoided premature mortalities resulting from the emissions reductions in California are estimated between 37.56 and 57.12 cumulatively by 2050 (between 120.62 and 198.96 in the Pacific region) (Table 1).

Table 1. National cumulative avoided premature mortalities (deaths occurring before average age of death) from 2020-2050 resulting from reduced exposures to SO_2 and NO_X associated with the solar panel mandate in California and the Pacific Census Region.

Avoided premature mortality	
California	
AP2	37.56
InMAP	44.43
EASIUR	57.13
Pacific Census Region	
AP2	120.62
InMAP	152.97
EASIUR	198.96

Based on the value of statistical life, the projected cumulative health co-benefits from averted NO_x and SO_2 emissions by 2050 in California range from $442.56 million (AP2) to $673.11 million (EASIUR) 2020 USD in California (cumulative estimates range from $1.42 billion to $2.34 billion in the Pacific region). By 2050, California's mid-range (InMAP) annual monetary health co-benefits reach $29.94 million (Figure 4), with upper and lower estimates ranging from 25.06 million (AP2) to $35.57 million (EASIUR) 2020 USD. Cumulative climate co-benefits for California based on the social cost of carbon were valued in the mid-range at $2.88 billion 2020 USD, with upper and lower estimates ranging from $991.43 million to $4.08 billion (in the Pacific region, cumulative estimates range from $4.87 billion to $19.62 billion). The annual climate co-benefits in 2050 reached $183.1 million for California (Figure 4), with upper and lower estimates ranging from $68.99 million to $252.09 million USD.

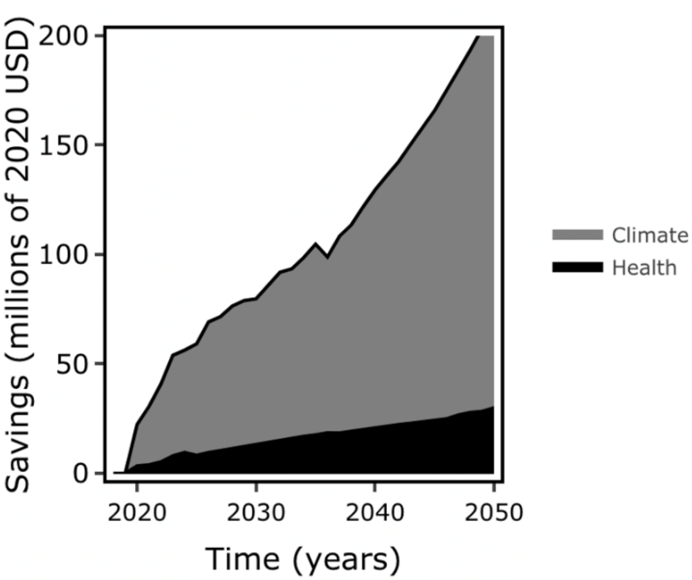

Figure 4. Mid-range (InMAP) annual health co-benefits based on the value of statistical life (2020 USD), and annual climate co-benefits based on the social cost of carbon (2020 USD), in California under the solar panel mandate scenario from 2020-2050.

Discussion

4.1. Interpretations

Our projection of emissions factors which inform our emissions projections in the business-as-usual and solar panel mandate scenario are based on the EIA 2019 Annual Energy Outlook (26). Therefore the underlying EIA methodology is reflected in our results; the causes of any peaks, valleys, and plateaus in our emissions projections come from the EIA's integrated model (the National Energy Modeling System), which captures projected interactions of economic changes and energy supply, demand, economic growth, world oil prices, and oil and natural gas technology and resources. Additionally, the model incorporates projections of carbon tax or cap-and-trade policies, and generally assumes that current laws and regulations that affect the energy sector are unchanged throughout the projection period (28). While these factors cause some variations in emissions trends, the general underlying assumption is that energy production will continue to rely on cleaner fuel mix over time, resulting in a gradual reduction in emissions from the electric power sector, which is reflected in our results.

According to the EPA, an average gas-fueled passenger vehicle emits about 4.6 metric tons of CO_2 per year (39); therefore, after thirty years, the total cumulative averted greenhouse gas emissions from the reduced electricity demand in California would be equivalent to removing 8.67 million average gas-fueled passenger vehicles from the road over the same period, which is an annual average reduction of over 288,000 gas-fueled cars per year (an average reduction of 1.35 million gas-fueled cars per year in the Pacific region).

While the cost of a new home is expected to increase by $8,400 USD as a result of the solar panel mandate (40), we found a cumulative total of $134.97 billion USD in electric utility cost savings throughout the projection period for California. This is a savings of over $650 per household per year, resulting in a full payoff of the upfront costs in approximately 13 years, with continued electric utility savings thereafter.

While California's projected health and climate co-benefits estimates are each significant (mid-range estimates of $523.53 million for health and $2.88 billion for climate benefits in 2020 USD), climate co-benefits were 5.5 times greater than health-co-benefits for the 30-year study period. This relationship is expected to shift based on the location and energy conservation measure being implemented; for example, Buonocore et al. (2019) found variation in benefits between different US regions and types of renewable energy deployed, including generally higher health benefits in the eastern half of the US (14). Variations depended on differences between primary fuel types displaced, emissions displaced, and benefits per emission reduction (14).

4.2. Limitations

We are assuming 100% compliance with the solar mandate, which is expected to lead to a small but not trivial overestimate of the co-benefits. Housing developers that secure building permits before 2020 will also not be subject to the rule, which will allow for a significant amount of grandparented, non-compliant homes to be built in the 2020 and potentially other years within our projection period. However, we considered this to be relatively minor and out of scope of this analysis. This analysis was also conducted using pre-pandemic data, and some changes from increased work at home may increase California electricity use patterns in the near term, but long-term impacts are not anticipated (41).

We did not include a feasibility analysis of residential solar panel implementation in the proposed Pacific census region. Our primary motivation in showing the co-benefits in the Pacific region is to demonstrate the estimated potential energy savings, avoided climate damages, and avoided premature mortalities that would occur if more states were to follow the lead of California in adopting renewable energy measures. We also assumed: a uniform reduction in electricity demand, applied evenly to all hours of the day and times of the year; a consistent construction market, including that builders will not increase or decrease the rates of construction of new homes in response to the new policy, and that unforeseen events will not impact population growth; that the solar panel mandate was the only cause of the integration of solar panels in homes, rather than because of personal choice, other new or existing policies and building standards, or other reasons for installing renewable energy.

We acknowledge that there may be unintended consequences of reduced electric utility bills, such as increased electricity consumption, potentially resulting in the need to source power from the grid at peak times of the day. We also acknowledge that there may be health and equity implications of disconnecting a large portion of the population from the electric power grid, making electricity more expensive for those who do not have newly constructed homes and rely on conventional, non-renewable electric power sources. We also acknowledge that the increase in up-front costs of solar panel systems may make home-buying unaffordable for some persons.

It should be noted that there is no consensus in the assessments of value of statistical life valuations. One review found that values range from $1 million to $24 million 2013 USD (33). Therefore, we accepted the valuation used by the EPA, adjusted for inflation and income elasticity (37). Additionally, the value of statistical life does not apply monetary values to specific lives saved or lost (42). A 2017 USD year was used to compute the monetary health co-benefits results. Importantly, it should be noted that our estimated health impact per unit of emissions is not a projection. The inputs into the reduced complexity models included the most recent eGRID electricity emissions data and a static value of statistical life, which are both representative of the base year of the projection. In order to develop a defensible projection of health impacts of air pollution, significant additional analysis would be required, including developing yearly estimates of the value of statistical life to 2050 (these projections do not currently exist in the scientific literature to our knowledge), and replacement of the RCMs with a new model that would account for future changes health impacts per ton of emissions.

In previous retrospective CoBE analyses (8), more than 99% of climate co-benefits in the US came from CO_2. Therefore, in this projection module of CoBE, we only included CO_2 and not including any other greenhouse gases. We did not calculate projected emission factors for $PM_{2.5}$, since CoBE does not calculate co-benefits resulting from primary emissions of $PM_{2.5}$ or O_3 from electricity generation; SO_2 and NO_x are precursors to $PM_{2.5}$ formation in the atmosphere, and react with sulfuric and nitric acids as well as nitrogen oxides in a complex and non-linear fashion. Estimating the primary $PM_{2.5}$ emissions in CoBE would require additional modeling which is beyond the scope of this study. Consequently, our estimates of health and climate impacts are conservative.

Based on a literature review, we determined that our valuation of the social cost of carbon is conservative because it omits important consequences of climate change associated with economic damage, such as sea level rise, tropical cyclones, heat extremes, labor productivity, ocean acidification, and human migration. However, because there is no clear consensus on a recommended value of the social cost of carbon available in the literature, we incorporated the methodology used by the EPA and US Government (38,43).

4.3. Conclusion

With the added projection capability in CoBE, the future health and climate co-benefits of California's residential solar panel mandate are quantified, which can be used to inform decision-making and ultimately promote the deployment of other renewable energy policies. This study also illustrates that California's solar panel mandate offers a significant return on investment in terms of health and climate co-benefits, previously ignored in regulatory impact analyses. Here, we projected that implementing the residential solar panel mandate in California will prevent between 38 and 57 premature mortalities (between 121 and 199 premature mortalities in the Pacific region), and yield a mid-range estimate of $3.41 billion 2020 USD in combined cumulative health and climate co-benefits by 2050, in addition to a cumulative total of $134.97 billion USD in electric utility cost savings by 2050 ($15.74 billion combined cumulative health and climate co-benefits and $218.42 billion cumulative electric utility cost savings in the Pacific census region). Since health impacts have not been previously included in the impact analyses of the solar panel mandate, the application of this framework and the CoBE Projection tool can contribute to a more comprehensive comparative assessment of the potential health and climate co-benefits that can be achieved through the implementation of residential solar panel requirements throughout different regions of the US. Further state-specific analyses are needed, with priority given to states where there is a greater reliance on coal fuel sources.

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