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ABSTRACT

Federal and state policies in the U.S. subsidize electricity generation from 1.4 million rooftop solar arrays because of pollution avoidance benefits and grid congestion relief. Yet because these benefits vary across the U.S. according to solar irradiance, technologies of electricity generators, and grid characteristics, the value of these benefits, and, consequently, the optimal subsidy, are largely unknown. Policy, therefore, is unlikely to have induced efficient solar investments. This paper (1) provides the first systematic, theoretically consistent, and empirically valid estimates of pollution damages avoidable by solar capacity in each U.S. zip code, (2) relates these external benefits to subsidy levels in each U.S. state, and (3) estimates the share of these benefits that spillover to other states. It also measures the energy value of capacity across the U.S. and the value of transmission congestion relief in California. Environmental benefits are shown to vary considerably across the U.S., and to largely spillover to neighboring states. Subsidy levels are essentially uncorrelated with environmental benefits contributing to installed capacity that sacrifices approximately $1 billion per year in environmental benefits. Energy value is estimated to vary less than environmental benefits, while California rooftop solar is shown to generate no congestion relief.

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1 Introduction

Solar panels occupy more than one million rooftops across the United States and will soon occupy a million more (Solar Energy Industry Association 2016). Rapid growth of rooftop solar is impelled by a decade-long, exponential decline in technology costs and by generous federal and state subsidies and binding state mandates. Solar policies are intended to increase the supply of clean electricity that displaces polluting generation from fossil fuel plants. Many policies intend also to lower electricity transmission costs by expressly favoring rooftop solar over distant large-capacity solar farms. Such policies contribute to an ongoing and profound transition of the electric grid that upends the traditional role of electric utilities in coordinating investment.

Whether such policies appropriately value avoided pollution is largely unknown. Likewise, it is not understood if they direct capacity investments to their highest value locations along the electricity grid. A determination of public solar benefits and of optimal solar siting is not straightforward because solar generation, displaced pollution emissions, and marginal costs of electricity supply vary across space and time as a function of solar resource availability and regional electricity grid characteristics. Solar generation that avoids coal plant production, for instance, delivers more than twice the environmental benefits of generation that displaces natural gas supply, *ceteris paribus* (Edenhofer, 2011; Caulton et al., 2014; Jaramillo et al., 2007). Failure to account for heterogeneity in emissions resulting from marginal power generation can yield perverse policy outcomes, as Holland et al. (2016) observed in the context of electric vehicle subsidies. Similarly, the energy value of distributed solar capacity and its contribution to transmission cost avoidance depend upon where the capacity is sited. Though the energy value of solar capacity is appropriable by investors, state subsidies obscure the social benefits of generation, potentially leading to capacity allocation that foregoes energy value even within states.

This paper, therefore, investigates the efficiency of existing solar policy and capacity investments. It does so by building upon previous econometric modeling of marginal emissions (e.g., Graff-Zivin et al. 2014; Holland et al. 2016) to derive the first systematic, theoretically consistent, and empirically valid estimates of the spatially varying environmental benefits of solar capacity. Unique, monetized estimates of avoided environmental damages are generated for each of 30,105 zip codes across the U.S. These avoided damages are compared to the combined value of state and federal solar subsidies in order to provide the first comprehensive comparison of the streams of solar subsidies and environmental benefits. Also uniquely estimated in this paper via high-resolution air transport modeling are the magnitudes of *local* solar benefits—those appropriated within the states that investments are made. The energy value of solar capacity is estimated using data on electricity marginal costs at hundreds of grid management jurisdictions across the U.S. The contribution of solar capacity to alleviation of transmission constraints is also measured in California using local marginal prices that vary across hundreds of network nodes and reflect grid congestion costs.

Results suggest the discounted stream of subsidies to a typical rooftop solar array exceeds the discounted stream of environmental benefits by only a few hundred dollars, though environmental benefits and subsidies are negatively correlated in the data. Some panels are subsidized as much as $25,000 in excess of environmental benefits, while others are under-subsidized by as much as $10,000. Annual environmental benefits vary by a factor of 20 across the U.S., from $61 in Maynard, Mass. to $1,224 in Bloxom, Virginia. They also vary non-trivially within states. Yet virtually no solar policy accounts for heterogeneity in solar capacity benefits. More than 85 percent of environmental benefits spillover to neighboring states. This suggests that (1) free-riding may constrain efficient solar capacity investments in the U.S. absent national coordination; (2) local air quality improvements may be forsaken by state policies promoting only in-state capacity, and (3) state dollars for local air quality improvement may be better directed to other technologies or interventions.

Total benefits of solar generation—inclusive of energy values—are estimated to be greatest in the Midwest and Mid-Atlantic. They are least in the West, and particularly the West Coast, where approximately two-thirds of systems are located. These differences are primarily attributable to heterogeneity in marginal responding fossil generation. If installed solar capacity could be costlessly reallocated across states, annual total capacity benefits would increase by as much as $1.3 billion, reflecting predominantly gains in environmental benefits. In California, we find no evidence that rooftop solar capacity systematically relieves congestion. Approximately two-thirds of the 900,000 rooftop solar arrays is located upstream from transmission bottlenecks, contributing to congestion rather than relieving it. If capacity were efficiently allocated, congestion relief benefits in California would have been no more than $15 million in 2017—approximately 7% of total energy value.

This paper is related to work by Cullen (2013) and Novan (2015), who use similar econometric techniques to value wind energy. It is also related to Callaway et al. (2018), who evaluate the carbon emissions displaced by alternative technologies, including energy efficiency investments and solar panels. They estimate that solar is subsidized by $163-455 per MWh in excess of the value of carbon emissions avoidance. They do not consider avoidance of local air pollution emissions. Siler-Evans et al. (2013) is most similar to this paper in ambition. It estimates the value of carbon and criteria pollution emissions displaced by solar capacity in each of 22 U.S. subregions. As Graff-Zivin et al. (2014) note, however, their empirical approach is valid only under the assumptions that (1) all consumption in a region is met by power plants in the same region; (2) marginal electricity is supplied only by power plants whose generation is reported in a federal administrative record; (3) aggregate fossil-fuel generation is exogenous; and (4) ad hoc corrections for line losses are constant over location and time. The approach of Callaway et al. (2018) also relies on some of these assumptions.

Each of the assumptions of Siler-Evans et al. (2013) is relaxed in this paper. First, we estimate pollution responses as a function of electricity consumption, not potentially endogenous generation. Second, we condition on non-reported generation that may correlate with consumption. Third, we flexibly accommodate grid structure by modeling individual generator responses to consumption changes throughout interconnections that define electricity trading. Furthermore, we account for seasonal and diurnal patterns in solar generation and marginal emissions by estimating unique marginal effects for each plant in each hour of the day and each month of the year. Siler-Evans et al. (2013) abstract entirely from these known dynamics (Graff-Zivin et al. 2014). Finally, our generator-specific estimates of pollution responses afford high-resolution and high-fidelity modeling of avoided pollution damages. Siler-Evans et al. (2013) and Callaway et al. (2018), instead, generate estimates of marginal emissions only for aggregate regions. This poses no difficulty for valuing avoided emissions of globally mixing pollutants, like carbon, as in Callaway et al. (2018). But it hinders valuation of avoided local pollutant emissions, damages from which depend upon exposure of populations and economic production. Our high-resolution modeling of avoided emissions uniquely equips us to estimate the magnitudes of appropriable environmental benefits. This paper is also the first to empirically estimate grid benefits of rooftop solar.

This paper proceeds by considering the theory of solar policy and efficient capacity allocation in Section 2. Data and empirical methods are introduced in Section 3. Model results and simulations are presented in Section 4. Section 5 considers the implications of these results for solar policy, including the policy preference for distributed renewable energy capacity. A final section concludes.

2 Policy Design for Optimal Solar Siting

Electricity generation by coal, oil, and natural gas plants is responsible for considerable air pollution in the U.S. and other developed countries. In the U.S., it emits one-third of anthropogenic greenhouse gases that contribute to global warming. It also produces 60 percent of sulfur dioxide and 13 percent of nitrous oxide emissions that harm human health (U.S. Environmental Protection Agency 2012). Solar electricity generation, in contrast, emits no pollution. Were pollution costs borne by emitters, then solar generators would appropriate the benefits of emissions avoidance by escaping pollution costs. However, the pollution taxes or tradable permit programs that internalize pollution costs to emitters are rare in the U.S. and the rest of the world. Instead, uniform technology standards and other command and control regulations are the norm where pollution is regulated at all. Absent efficient prices on pollution, solar is undervalued, and the pollution avoidance benefit is unappropriated by the solar generator (e.g., Baker et al. 2013; Borenstein 2012; Pigou 1920). In such a suboptimal regulatory setting, policy to support solar capacity or generation can correct an under-provision problem.[1,2]

High fixed costs have made solar more costly than all other forms of power generation except offshore wind (Energy Information Administration 2013; Borenstein 2012). Consequently, solar's small share of electricity generation has been induced by favorable policy regimes that date to the oil embargo and energy crisis of the 1970s. Though solar accounted for 26 percent of U.S. electricity generating capacity additions in 2015, it constituted less than 2 percent of total generating capacity and provided only 0.6 percent of electricity generation (Energy Information Administration 2016a, Energy Information

[1]Solar policy like subsidies can never a first-best pollution control policy because unpriced pollution leads to under-priced dirty electricity generation, not over-priced clean generation. Solar policy lowers the cost of the homogeneous product electricity, rather than raising it (Borenstein 2012).

[2] Because the marginal costs of solar generation are essentially nil—the feedstock is free—policy promoting capacity is essentially analogous to policy promoting generation.

Administration 2016b). Of this, approximately 40 percent was provided by distributed generation capacity (Energy Information Administration 2017).

Public policies that support solar generation are common in the U.S. and other developed countries.[3] The federal government alone has expended billions of dollars on a 30 percent investment tax credit since 2010 (Borenstein and Davis 2016). Renewable Portfolio Standards are in effect in 29 states. Twenty-eight states exempt renewable capacity expenditures from sales taxes or allow deductions against income taxes. And net-metering policies common to 41 states subsidize generation by requiring utilities to credit customers for solar generation at rates that typically exceed wholesale electricity prices (North Carolina Clean Energy Technology Center 2018). California utilities, for instance, must pay retail rates in excess of $0.35 per kilowatt-hour for some distributed solar generation. Because retail rates bundle a variety of charges beyond the marginal cost of electricity, including transmission and distribution cost recovery charges and conservation incentives, the $0.19 per kilowatt-hour average retail rate is more than double prevailing wholesale prices for solar generation.

It is unlikely any of these policies approximates the second-best Pigouvian subsidy to solar generation. Virtually none varies policy support according to the avoided pollution damages, which we show vary considerably across and within states according to solar resource and electricity grid characteristics. All else equal, solar capacity is more valuable where solar resource is more abundant and generation potential is greater.[4] Even conditional

[3]Potential learning spillovers provide an alternative justification (e.g., Gillingham and Sweeney 2012; Nordhaus 2011). Such spillovers would constitute positive externalities in the technology market that weaken incentives for innovation. Combined with the negative externalities from pollution, they can cause clean technologies to be "doubly under-provided" in the absence of policy (Fischer 2008; Fischer and Newell 2008; Jaffe et al. 2005).

[4]For instance, the distribution of solar irradiance across the U.S. causes potential annual electricity generation from 4-kw of solar capacity to vary from 4.3 megawatt-hours (MWh) in Arlington, Washington to more than double that amount in parts of California's central valley. Figure 1 shows for each U.S. zip code the estimated annual electricity generation of a 4-kW capacity system. These estimates are produced using the System Advisor Model of the National Renewable Energy Laboratory available at: https://sam.nrel.gov/. Generation in MWh is alternating current.

on generation, however, capacity value varies according to the pollution intensities of marginal responding plants that adjust production in response to solar generation. The pollution intensities of marginal plants vary across hours of the day and across regions, particularly the three U.S. grid interconnections within which electricity trade is common but across which trade is rare. These marginal emissions may differ dramatically from average grid emission intensities.[5] Even conditional on marginal emissions, however, the value of avoided pollution also varies according to air transport and emissions deposition that govern the exposure of affected economic production and human populations. All else equal, a unit of pollution avoidance is most valuable upwind from major population centers.

By ignoring heterogeneity in avoided pollution damages, existing policies deviate from the second-best Pigouvian subsidy. But policy may not just fail to correctly value *every* unit of solar generation, it may fail to correctly value *any* unit. If policy incorrectly values pollution avoidance, it can obscure price signals that direct efficient investment, leading to suboptimal allocations of solar capacity. Likewise, state subsidies and capacity mandates may actually sacrifice local air quality improvements by failing to recognize local benefits from investments located in other states.

Existing solar policy is likely also to incorrectly price the energy value of solar generation. The efficient price received by solar operators is equal to the second-best pollution-avoidance subsidy plus the private marginal cost of electricity supply, i.e., the wholesale price in a competitive market. Yet rooftop solar receives a price per unit of generation that exceeds wholesale prices in 41 states with net-metering policies that typically compensate solar generation at retail rates. These policies over-compensate for energy value, but they also impose a homogeneity on generator compensation that does not reflect

[5] Failure to distinguish between average emissions rates and emissions caused by marginal changes in electricity load contributed to confusion about the environmental benefits of electric cars. Holland et al. (2016) showed that marginal emissions in some parts of the U.S caused electric cars to contribute more to pollution than conventional substitutes.

economic value. The marginal costs of electricity supply deviate within regional grids because of transmission capacity constraints, but retail rates do not so vary. Consequently, the incentives facing private investors do not reflect the underlying value to society of their investments. Absent policy that reflected heterogeneity in electricity marginal costs, it would be surprising if private investments in rooftop solar capacity yielded congestion relief benefits as its advocates claim. The efficiency of existing capacity allocations is investigated in the following sections.

3 Data and Methods

A determination of avoided damages from solar capacity proceeds by estimating spatially heterogeneous emissions avoided per unit solar generation. These emissions changes are input into an integrated assessment model that maps emissions into damages in order to value emissions changes. Finally, these values are attributed to potential solar capacity in each U.S. zip code by modeling potential generation as a function of solar irradiance and weather characteristics. Potential generation is also used to value the energy production of solar capacity using hourly, region-specific estimates of electricity marginal cost.

3.1 Marginal emissions

In order to estimate the emissions avoided by a unit of solar generation, it is necessary to identify which power plants respond to the marginal reduction in net load.[6] As described above, the plant that operates on the margin will vary according to when and where the

[6] We are assuming there is no rebound effect from solar adoption. Provided utility customers face traditional net metering, then the opportunity cost of a unit of generation does not change with solar generation (subject to settle-up limitations within some jurisdictions), so rebound should be minimal. However, to the extent that solar generation shifts marginal consumption into a lower tier of an increasing block-rate tariff or that solar generation serves to alleviate guilt from pollution caused by electricity consumption, then solar may induce some rebound. In the event that rebound is positive, then the estimates in this paper of avoided damages will overstate true damages.

unit of solar generation is produced. We determine these marginal emissions by adapting the reduced-form regression equations implemented by Graff-Zivin et al. (2014) and Holland et al. (2016) (HMMY). Hourly power plant emissions are regressed on hourly electricity demand in each subregion of the power plant grid interconnection.[7] We do this for each of the 1,486 power plants in the U.S. and for each CO_2, SO_2, NO_X, and $PM_{2.5}$.

Specifically, we estimate:

$$y_{it} = \sum_{h=1}^{24} \sum_{j=1}^{j(i)} \sum_{m=1}^{12} \beta_{ijhm} LOAD_{tj} \times HOUR_h \times eGRID_j \times MOY_m + \sum_{j=1}^{j(i)} s_{jt} + \sum_{h=1}^{24} \sum_{m=1}^{36} \sum_{d=1}^{2} \alpha_{ihmd} HOUR_h \times MOS_m \times DAY_d + \epsilon_{it}, \quad (1)$$

where y_{it} is pollutant emissions at plant i at time t; $LOAD_{tj}$ is a continuous variable measuring demand in eGRID subregion j at time t, and $HOUR$, $eGRID$, and MOY are indicator variables for each hour of the day, each eGRID subregion within the interconnection of plant i, and each month of the year (MOY), respectively. This yields for each plant and each pollutant a vector of marginal emissions coefficients, β_{ijhm}, equal to $24 \times j(i) \times 12$. Likewise, MOS and DAY are indicators for each month of the sample and weekdays, respectively. To control for potentially correlated, non-reported generation, we condition on an indicator of contemporaneous solar generation in each subregion, s_{jt}. An idiosyncratic error is denoted by ϵ_{it}. Equation (1) is estimated by ordinary least squares.

Distinct from HMMY, this model permits the hourly-plant-specific marginal emission responses to vary by each month of the year to account for seasonal patterns in the fossil-fuel

[7] Subregions are defined as eGrid subregions, which are geographical aggregations of electricity generators used by the U.S. Environmental Protection Agency and and the Energy Information Administration for policy analysis, including assessment of carbon footprints and renewable portfolio standards. We further aggregate some eGrid subregions with highly correlated loads. Specifically, NYCW, NYLI, and NYUP are combined with the NEWE to form a single NY-New England subregion; MROE is combined with the MROW to form a single MRO; RFCE and RFCM are combined with RFCW to form a single RFC; and SPNO is combined with SPSO to form a single SPP.

generation mix and in solar generation. It also absorbs average load differentials across weekends and weekdays via the DAY fixed effect. Like HMMY, it permits plant i's emissions to respond to increased demand anywhere within the interconnection via a distinct coefficient for demand in each of the eGRID regions within the interconnection. $LOAD_{tj}$ is treated as exogenous because retail electricity prices do not vary with wholesale prices with very few exceptions, and, hence, the derived demand is perfectly inelastic. Relative to the related literature, we uniquely condition on solar irradiance, s_{jt}, to control for potentially correlated non-reported generation. We lack data on hydro generation, which may be correlated with net load. However, like Callaway et al. (2018), we assume average temporal patterns of hydro production will not change in response to marginal changes in net load. This is because maximization of arbitrage opportunities tends to require that any displaced hydro generation on a given day is replaced on a subsequent day during a similar hour with similar marginal emissions. Thus, even if hydro generation is correlated with net load conditional on month-specific hour fixed effects, our estimates of marginal emissions responses are unlikely to be biased. Wind is assumed to be orthogonal to load conditional on the month-specific hour fixed effects.

Data on hourly emissions of CO_2, NO_X, and SO_2 from 1,451 power plants are obtained from the Continuous Emissions Monitoring System (CEMS) of the U.S. Environmental Protection Agency (EPA) for the years 2007-2015, yielding 114.4 million plant-level, hourly observations for each pollutant.[8] Hourly emissions of $PM_{2.5}$ are not directly reported by the CEMS. They are imputed by determining plant-specific $PM_{2.5}$ emissions intensities per unit generation and multiplying these intensities by hourly plant-level generation as reported in the CEMS. Annual $PM_{2.5}$ emissions used to compute plant emission intensities are obtained from the EPA's 2011 National Emissions Inventory.[9] Hourly electricity consumption is

[8]See https://ampd.epa.gov/ampd/.

[9]See https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei.

reported for each of 200 planning areas across the U.S. in Federal Energy Regulatory Commission (FERC) Form 714 filings. Hourly planning area consumption is aggregated to eGRID regions.[10] Solar irradiance data comprising the index, s_{jt} are obtained from the National Solar Radiation Database. Hourly measures of zip-code-level solar irradiance are obtained for the locations of all utility-scale solar capacity in the U.S. These irradiance observations are aggregated to eGRID subregions using utility-scale solar capacity weights. This yields weighted-average solar irradiance for each subregion and each hour.[11]

3.2 Solar generation

The marginal emission coefficients obtained from estimation of (1) for each plant are used to estimate the changes in emissions from marginal changes in hourly demand within the respective interconnection. These demand changes are estimated for the addition of a typical 4-kw solar array in each of 30,105 zip codes in the U.S. using the California Energy Commission module of the System Advisor Model, an open source program developed by the National Renewable Energy Laboratory for estimating the performance of renewable energy systems (Blair et al. 2013). For a typical meteorological year, SAM combines solar irradiance measured at 4-square-kilometer resolution and weather data from more than 1,000 weather stations to estimate system generation for solar panels installed in the continental U.S.[12] Typical system parameters are assumed in modeling system generation. We assume system tilt matches latitude and panel orientation is southward. These conditions are necessary to maximize generation in North America.

Modeled annual solar generation at each zip code in the contiguous U.S. is summarized in Figure 1. Summary statistics are reported in the top panel of Table 1. Mean annual

[10] Observations of pollutant emissions greater than six standard deviations from the mean are omitted.

[11] Variation in rooftop solar generation is reflected in load variation because it occurs behind-the-meter. Hence, it does not bias our parameter estimates and is safely subsumed into load.

[12] More information about the typical meteorological year data is available at http://www.nrel.gov/docs/fy08osti/43156.pdf.

generation for a 4-kW system is 6,357 kWh. It varies by a factor of 2 from 4,344 kWh in Arlington, Washington to 8,647.4 kWh in Lone Pine, California. The within-state standard deviation varies from 55.7 kWh to 636.6 kWh. The mean within-state standard deviation is 239 kWh.

3.3 Exposure and damages

Equipped with (a) modeled solar generation by zip code that yields reductions in net load within respective eGRID subregions; and (b) estimated emissions responses from each plant to marginal load changes within interconnections, we can estimate the annual change in pollutant emissions from each plant in the U.S. as a function of a unit solar capacity addition in a given zip code. To monetize emissions changes, we use AP3, an integrated air pollution model that translates (1) emissions into concentrations as a function of atmospheric transport and chemical processes, (2) concentrations into exposure as a function of population and economic production, and (3) exposure into harms as a function of dose-response relationships. AP3 is the successor to the AP2 model employed by Holland et al., (2016), Siler-Evans et al. (2013), and others.[13] AP3 uses the EPA's National Emissions Inventory together with a reduced complexity air quality model to estimate annual average pollution concentrations by county. AP3 reports the incremental contribution of emissions produced by each source to ambient concentrations in each county. This facilitates an analysis of which localities benefit from reduced emissions. Detailed population and vital statistics data are used to estimate exposures. Among the plethora of adverse health impacts associated with exposure to air pollution, the vast majority of damages are attributable to mortality effects. Increased mortality risk is valued using an EPA-recommended Value of a Statistical Life of $7.4 million in 2006 dollars adjusted for inflation using the consumer price index to 2014 dollars. Carbon dioxide emissions, not tracked by AP3, are valued at $41 per

[13] For further description of the AP3 model, see Clay et al. (Forthcoming)

ton, the Social Cost of Carbon calculated by the U.S. Interagency Working Group on Social Cost of Carbon as updated in 2016 and reflected in 2014 dollars (Interagency Working Group on the Social Cost of Carbon 2016).

The spatial heterogeneity of pollution damages is depicted in Figure 2, which shows the estimated damages from one ton of SO_2 emissions in each county of the contiguous U.S. Avoidance of SO_2 is the most valuable environmental benefit of solar capacity. Damages from SO_2 are estimated to be greatest in Los Angeles County, California ($130,280 per ton) and Bergen County, New Jersey ($93,905), where geographic conditions preclude pollution dissipation across space, and where population density is high, increasing exposure. Damages are least in Whatcom County, Washington ($2,005).

3.4 Subsidies

We seek to compare estimated damages avoided by solar generation to federal and state-level solar subsidies. In addition to the federal investment tax credit (ITC) for renewables, state incentives include sales and property tax exemptions, capacity subsidies, and solar renewable energy certificate (SREC) programs. We obtain information on the solar incentives offered by each state from the Database of Solar Incentives for Renewables and Efficiency (DSIRE) (North Carolina Clean Energy Technology Center, 2018) and from the Lawrence Berkeley National Laboratory's "Tracking the Sun" project (Barbose et al. 2017 and Barbose et al. 2012). The value of subsidy programs for each state is calculated as the sum of federal and state incentives discounted at a 5% annual rate over a 20-year lifetime. State subsidies exclusive of the federal ITC are also computed.

We assume solar array costs in each year from 2000 to 2016 are those reported by Barbose et al. (2017) and Barbose et al. (2012). These costs are used to calculate the value of the ITC, property tax excemptions, and other state incentives based upon system costs. For property tax exemptions, we assume the increase in property value subject to the property tax is equal to the system cost. Then we use state-level real-estate tax estimates calculated as the median real-estate tax payment divided by the median home value using data obtained from the 2017 American Community Survey (U.S. Census Bureau 2017). Similarly, sales tax exemptions are calculated based on the system cost using sales tax approximations equal to the sum of the state sales tax and the average local sales tax (Walczak and Drenkard 2017). We obtain SREC price data by digitizing the daily average prices from February 2017 to February 2018 reported by SREC Trade.[14] In our subsidy calculations, we use the mean price over the entire period. Net energy metering subsidies are valued as state-specific differences between average retail price and average marginal cost. The former are obtained from EIA (Energy Information Administration 2018). The latter were generously provided by Borenstein and Bushnell (2018) and are further discussed in Section 4.2. SREC and NEM subsidies generate benefit streams according to generation that is evaluated as state averages of zip-code specific generation estimates. The stream of subsidies is discounted to present value at 5 percent.

3.5 Electricity marginal costs

Energy value of solar generation is determined by location and hour-specific electricity marginal costs. Electricity marginal costs are measured in one of two ways for each region of the U.S. Where Independent System Operators (ISOs) manage the electricity grid, marginal costs are measured as local marginal prices (LMPs) published by the ISOs for each hour and each node of the network. Where LMPs are not reported, marginal costs are measured as the hourly "system lambda" reported to the FERC by grid operators.[15] Both data sets were generously provided by Borenstein and Bushnell (2018), who assembled them to measure

[14] https://www.srectrade.com/app/markets/dashboard/33891; Delaware and Illinois prices are reported separately: https://www.srecdelaware.com/documentation/; https://www.srectrade.com/blog/srec/srec-markets/illinois.

[15] Information is reported on FERC Form 714 surveys.

retail price deviation from the sum of private marginal costs and marginal external costs. We map these local marginal prices and system lambdas to zip codes in order to estimate the value of solar generation in each zip code.

LMPs reflect the sum of two shadow values from the constrained optimization performed by grid operator to dispatch generation. The first is the value common to all LMPs that reflects the marginal cost of serving load. The second is the shadow value on transmission constraints between nodes of the network. These constraints abide by laws of physics and ensure line capacity is not exceeded. These shadow values vary for each node of the ISO grids, reflecting congestion costs. For those hours in which an ISO network is free of congestion, LMPs converge to the common shadow value on the load constraint. Amid congestion, prices at nodes upstream of constraints fall, reflecting negative shadow values, and prices at nodes downstream of constraints rise, reflecting positive shadow values attributable to the dispatch of out-of-merit-order generation necessary to reach congested nodes.

The system lambda is an engineering calculation of the shadow cost of a marginal change in production. As Borenstein and Bushnell (2018) note, FERC Form 714 surveys are not of uniformly high quality, so they incorporate data that are deemed most reliable, as described in their paper. System lambdas also likely do not reflect scarcity rents or full congestion costs and transmission losses. Neither LMPs nor system lambdas reflect distribution losses, which Borenstein and Bushnell (2018) estimate as a time-varying hourly rate from EIA Form 861 data. These losses are used to scale marginal cost calculations and are estimated to average 6.2%.

Congestion relief benefits of solar capacity are evaluated using hourly LMPs and congestion prices reported by the California Independent System Operator for 2017. Congestion prices are equal to the shadow value on transmission constraints for each network node.

4 Results

Estimation of equation 1 yields 13,724,160 parameter estimates of interest—a unique coefficient for each of 1,452 reporting fossil generators in each hour of the day and month of the year for each pollutant (and plant generation) and for each regional load within the plant interconnection.[16] The empirical model is validated by summing the point estimates of plant emissions across all plants in the interconnection. On average, a one MW change in hourly load across the interconnection should induce an offsetting and approximately equal response in fossil generation to the extent fossil generators operate on the margin.[17] Figures 3 and 4 depict the summation of hour and month-specific marginal responses across plants in the Electricity Reliability Council of Texas, the interconnection that delivers electricity to Texas. These are reported for generation and each pollutant. Point estimates are depicted in blue and 95-percent confidence intervals generated by block-bootstrap are bounded by the series shown in black. Each gray series represents a sum of coefficients from a unique bootstrap sample. As shown in Figure 3a, the sum of generation responses across the Texas interconnection is typically bounded between 0.6 and 1.2. During daylight hours (5am to 9pm), the average response across Texas averages 0.97, with a mean 95-percent confidence interval of 0.69 to 1.18. Figures 3b and 4 depict the sum of pollution emissions across the Texas interconnection. These are expected to equal the emissions intensities of marginal responding plants. Across interconnections, the average generation response is 0.85. We return to a discussion of uncertainty in section 4.3.

The second panel of Table 1 reports summary statistics for estimated annual total damages avoided and estimated annual avoided damages from each modeled pollutant for a 4-kW capacity system in each zip code. Mean damages avoided across the country are

[16] Parameter estimates and standard errors are available from the authors upon request.

[17] Coefficients may exceed unity due to self-generation necessary to power plant operations. It may be less than the marginal change in load due to imports from other interconnections or responses from non-reporting generation. Plant sums may also differ from load changes due to sampling uncertainty.

estimated at \$569 per system per year, or \$7,091 in present value terms over the lifetime of a typical 4kW system.[18] A majority (57%) of these avoided damages is a consequence of reduced SO_2 emissions. Twenty-nine percent of avoided damages are due to reduced CO_2. Reduced NO_X is responsible for 10% of avoided damages, while 4% are due to reduced $PM_{2.5}$.

These total avoided damages from rooftop solar PV are presented for each zip code in Figure 5. It shows the annual environmental damages avoided per 4-kW capacity of solar in each zip code in the U.S. These avoided damages are greatest for systems installed in the Midwest and Mid-Atlantic states, including Delaware, Maryland, Missouri, New Jersey, and Virginia, where the average annual avoided damages per 4-kW system are equal to about \$1,100. Avoided damages are least in the West and Northeast and equal to about \$80 per year in states such as Connecticut, Massachusetts, Rhode Island, and Washington. In California, where two-thirds of rooftop solar capacity is sited, annual avoided environmental damages range from \$91 in Klamath along the Northern coast to \$279 in Desert Hot Springs, located 100 miles east of Los Angeles.

Figure 5 demonstrates that environmental benefits of solar capacity are far more sensitive to grid characteristics and pollution exposure than to solar resource. Solar resource is greatest in the Southwest, as figure 1 shows. Yet avoided damages are least in the West, as shown in figure 5. Avoided damages are greatest in the Midwest and the Mid-Atlantic, where the generation fleet is considerably dirtier than the West. Coal accounted for only 27 percent of 2014 electricity generation in the Western Interconnection (WECC) that serves the Mountain West and West Coast; 30 percent of generation was supplied by natural gas units. In the Midwest Reliability Organization that manages the Midwest grid of the Eastern Interconnection, coal comprised 60 percent of generation, while natural gas units supplied just 5 percent (National Renewable Energy Laboratory 2017). The relative dependence upon coal in the eastern interconnection makes it relatively likely that marginal

[18]Present value calculation assumes a 20-year lifetime and a 5% discount rate.

responding plants are coal plants. Moreover, avoided pollution emissions in the Eastern Interconnection reduce exposure of large populations in the greater Washington, D.C. area, Boston, Philadelphia, and New York, making emissions reductions valuable. Figure 2 demonstrates the heterogeneity across the U.S. in damages per unit pollution. It depicts the variation across the U.S. in damages from emission of one-ton of SO_2.

The second-best Pigouvian subsidy to solar generation and solar capacity is equal to the external environmental benefits. Yet we find environmental benefits and subsidies are negatively correlated in our data ($\rho = -0.15$). The most generous subsidies have accrued to adopters in Massachusetts, where the average subsidy is valued at \$0.35 per kWh and avoided environmental damages are estimated at barely \$0.01. For a 4-kW system, the subsidy received by the typical installed system exceeds avoided damages by \$1913 per year, or \$25,000 over the system lifetime. The least generous subsidy was received by investors in South Dakota, where the average \$0.04 per kWh subsidy is less than half as large as environmental benefits. Solar generation receives a subsidy that is \$0.08-0.12 less than avoided damages in Indiana, Maryland, Michigan, Missouri, Ohio, Pennsylvania, and West Virginia, where avoided damages are estimated to be greatest at around \$0.18 per kWh. A 4-kW system in these states optimally receives an additional \$500 subsidy per year. In California, a typical subsidy of \$0.11/kWh exceeds damages by nearly 600 percent. The mean subsidy across U.S. zip codes is \$0.10/kWh. On average, subsidies are approximately equal to damages across states, but more than 25 percent of states provide subsidies that are at least \$0.05 per kWh less than avoided damages. Another 25 percent provide subsidies that are too generous by at least \$0.05 per kWh. These results are summarized in table 2, which reports by state estimated mean damages and subsidies per kWh of installed capacity, as well as annual net subsidies.

Given the estimated environmental benefits from a typical 4-kW solar array in each zip code, the total annual environmental benefits of the installed capacity in the U.S. is equal to

$353.3 million per year. Installed capacity locations are shown in figure 6. In order to assess the degree to which capacity is misallocated, we simulate environmental benefits under four alternative reallocations of existing systems in the U.S. First, we imagine that all systems are relocated within states to areas in which they yield greatest environmental benefits subject only to the restriction that each panel be located on a residential rooftop. Counts of residential rooftops are obtained from U.S. Census counts of detached, single-family houses by zip code (U.S. Census Bureau 2017). Second, we restrict this intrastate reallocation by limiting to 30 percent the share of rooftops in any zip code containing solar panels. This accounts in a stylistic fashion for concerns about grid stability that some contend practically limit the penetration of renewables in any part of the grid (Coddington et al. 2012).[19] A third simulation considers a national reallocation of solar capacity. And finally, the national reallocation is restricted in a fourth simulatiomn to no more than 30 percent of rooftops in any zip code.

Reallocation of solar capacity within states is unlikely to fundamentally change grid dispatch of generating units. These are considered marginal changes due to the relatively small share of renewable capacity in most states. A national reallocation of capacity results in changes in load that are less defensibly marginal, potentially biasing our estimates of changes in environmental benefits. However, Holland et al. (2018) provide evidence that marginal emissions are relatively invariant over much larger ranges of load than those we consider here. They use local polynomial regressions of hourly environmental damages on hourly load to show that damage functions are approximately linear, particularly over 50-100 gigawatt (GW) ranges of hourly load. Our unconstrained national load reallocation displaces only about 4-5 GW of hourly load.

[19]Grid stability concerns were prevalent a decade ago. They figure less prominently in grid planning today, as evidenced by renewable portfolio standards in California, Hawaii, New Jersey, New York, and Vermont that mandate 50 percent or more renewable generation (North Carolina Clean Energy Technology Center, 2018).

Results from these simulations are reported in Table 3. The most conservative simulation we consider reallocates solar capacity within states to 30 percent of rooftops in zip codes that yield the greatest environmental benefits. This reallocation generates a 13 percent gain in environmental benefits equal to $45 million per year. The locations of reallocated solar capacity are depicted (in blue) relative to the installed solar capacity (in red) in Figure 9. Of the 12,840 zip codes across the U.S. in which rooftop capacity is currently installed, 97 percent—all but 386—would lose all capacity under a constrained intrastate reallocation. Of the 1.45 million rooftop arrays installed across the U.S., 90 percent would be sited in different zip codes in order to maximize environmental benefits (subject to grid stability concerns). Cities in California's Inland Empire and Desert regions east of Los Angeles gain the most systems, whereas locations in Northern California lose the most.

An unconstrained reallocation of solar capacity within states generates 18 percent greater environmental benefits, yielding a $63 million gain each year over existing capacity. Reallocating capacity across state lines yields nearly a five-fold gain in environmental benefits, increasing annual benefits by $1.3 billion regardless of grid stability constraints. If solar were limited to 30 percent of zip code rooftops, it would optimally be allocated to only 2,312 zip codes in nine states—Delaware, Illinois, Indiana, Iowa, Maryland, Missouri, New Jersey, Pennsylvania, and Virginia. This is depicted in figure 10. Environmental benefits from solar capacity would be maximized subject to grid concerns by adding 394,000 arrays to Missouri rooftops, only about 10,000 of which currently have solar panels. Maryland would also gain more than 300,000 systems, where currently only 11,000 are located. Substantial gains from national reallocation of solar capacity reflect the misallocation of capacity in California, where nearly two-thirds of all rooftop solar is located. It generates only $0.02 in environmental benefits per kWh compared to benefits as large as $0.18 on the East Coast.

4.1 Appropriated environmental benefits

Because solar capacity investments affect pollution concentrations as a function of (1) emissions changes at marginal (responding) generators potentially located across vast electricity grids, and (2) the transport and mixing of emissions in the atmosphere, avoided exposures may not occur local to solar capacity investments. The inability of an investor to appropriate the benefits of avoided emissions is precisely the motivation for solar subsidies. Like individual agents, however, states are likely only to appropriate a fraction of the environmental benefits of capacity investments they subsidize. This suggests states or regional governments generally may also under-invest in solar generation. In order to assess the return to state investments in solar subsidies and the magnitude of the state-level externality problem, we compute the shares of environmental benefits from local pollution mitigation that are appropriated by the states in which solar capacity investments are made. These are determined as averages of in-state capacity benefits across zip codes.

The appropriated shares of damages avoided by reduced NO_X, SO_2, and $PM_{2.5}$ emissions are depicted for each state in figure 8 and reported in table 4. Across states, the mean share of environmental benefits appropriated in the state that generates the benefits is 15 percent. Appropriated benefit shares are less than 1 percent in Arkansas, Delaware, Montana, Nebraska, North Dakota, and Wyoming, where annually appropriated avoided damages range from \$0.20 to \$8 per 4-kW system. In contrast, solar capacity installed in the average zip code in New York generates virtually all benefits in the state.[20] California and Massachusetts capture 77 percent and 72 percent of benefits, respectively, while North Carolina and Florida each capture greater than half of all benefits from capacity investments. Massachusetts captures a large share of benefits despite the relatively small size of the state because it has a large population that benefits from reduced power plant emissions in

[20] Our estimates suggest the typical New York array generates harms out-of-state, an affect that is theoretically possible because a relatively clean generator may adjust supply in a non-continuous fashion due to load changes, allowing a relatively dirty generator to increase supply.

surrounding states. Florida captures an estimateed $200 in annual environmental benefits per 4-kW capacity, the greatest magnitude of in-state benefits of any state, reflecting marginal plant responses in Florida that deliver few benefits to other states. Pennsylvania appropriates $151 in annual benefits—19 percent of total benefits. A typical 4-kw system in California generates $24 in avoided pollution benefits annually for the state.

California, Colorado, Florida, Georgia, New York, North Carolina, and Pennsylvania each captures a greater share of its solar generation benefits than any other individual state. Elsewhere, the single greatest beneficiary of solar generation is not the state in which solar capacity is located. For 34 states, the largest, single out-of-state beneficiary receives more than twice the benefits of the local state in which capacity is sited. For more than half, the ratio of benefits is four to one. Table 5 reports for solar capacity in each state the single other state that benefits most from the capacity investment. It also reports the magnitude of annual benefits to the largest single out-of-state beneficiary, as well as the ratio of those benefits to in-state benefits. A typical 4-kW system in Maryland and Delaware generates annual benefits to residents of Pennsylvania in excess of $170 per year. Pennsylvania is also estimated to be the single largest beneficiary of solar capacity in Arkansas, Illinois, Indiana, Michigan, New Jersey, Ohio, and West Virginia. A typical system in each of those states generates more than $100 annually for Pennsylvania.

4.2 Energy value

Though policy is justified by non-appropriated environmental benefits, the value of solar capacity depends also upon the energy value of generated electricity. This varies within and across states according to characteristics of generators and the electricity grid. As previously discussed, solar policy in many states causes prices received by rooftop solar generators to deviate from energy value and to be invariant to local variation imposed by transmission constraints. To estimate locations in which solar capacity is of greatest total value, we sum estimates of marginal avoided damages and estimates of the marginal costs of electricity generation.

Table 6 reports the average annual energy value of solar capacity by state. It is greatest in Rhode Island, Maryland, Connecticut, and Delaware, where it is equal to \$321 to \$348 for a 4-kW system. Energy value is least in Washington, North Dakota and Minnesota where it is estimated to be less than \$200. The average value of annual generation from a 4-kW system in California is estimated to be \$261. The sum of energy value and avoided pollution damages is greatest in Maryland, Delaware, and New Jersey, where annual total benefits are estimated to range from \$1408 to \$1483. Annual benefits of capacity in Maryland are estimated to exceed those of capacity in Montana, Oregon, and Washington by about \$1,200 per year. Total benefits are least in Oregon at \$282 per year. Annual energy and environmental benefits of California capacity are an estimated average \$452. A 4-kw system is worth \$15,000 more in present value located in Maryland than Oregon. Energy value and environmental benefits are modestly negatively correlated in the data ($\rho = -0.14$).

Because the energy value of solar capacity depends partly upon whether it contributes to or alleviates transmission congestion, and because congestion relief is deemed one of the benefits of distributed solar capacity, we assess whether installed capacity in California avoids transmission costs using hourly LMPs and congestion prices in 2017. If the more than 900,000 rooftop solar arrays in California contributed to congestion relief, then the mean, generation-weighted congestion price would be positive, indicating that the typical rooftop system generates electricity downstream from a bottleneck, where it is particularly valuable. It thus contributes to congestion relief. If mean congestion prices are negative, then the typical array is sited upstream from a bottleneck, generating electricity where it is relatively abundant and contributing to congestion.

Valuing hourly rooftop solar congestion benefits in each zip code in a typical year at the congestion price of the most proximate network node realized in 2017, we estimate the average rooftop solar array in California does not generate congestion relief benefits. The annual value of congestion relief benefits is $-1.09, indicating the system is installed at a node typically upstream of a transmission bottleneck, where generation is relatively cheap when transmission constraints bind. Across zip codes, congestion relief benefits of a 4-kW system vary from $-66.27 to $85.17 for 2017. The greatest misallocation of solar capacity occurs in the San Diego metropolitan area. In Chula Vista, a city east of San Diego, 7,800 rooftop systems generated an estimated $374,000 less value in 2017 than they would have generated if the grid were not congested. Installed panels in some San Diego zip codes also generated negative congestion benefits. Yet installed capacity in other zip codes in San Diego are estimated to have generated the greatest congestion relief in the state, valued at as much as $286,500 in 2017. Figure 7 depicts the spatial distribution of energy value per kW capacity in 2017. The figure shows that the most congested parts of the grid are located in the Los Angeles and San Diego areas, but that the least congested nodes of the network are nearby.

Only one-third of California rooftop systems (318,455) generate positive congestion value. The sum of these values was $4.87 million in 2017, or 7 percent of total energy value generated by those systems. It is 2.7 percent of the approximately $181 million in total energy value generated by the entire installed rooftop capacity in the state. These congestion relief benefits, however, were more than offset by 591,000 systems that contributed to congestion by generating upstream from bottlenecks, foregoing $5.85 million in energy value that would have been realized in the absence of congestion at those nodes.

Reallocation of a 4-kW system from an area of low congestion value to one of high congestion value increases the annual energy value by as much as $150 per year, or $1,870 in present value dollars over the 20-year lifetime of the system.[21] Any sizable reallocation of rooftop solar capacity to high value network nodes causes prices to converge, lowering the

[21] Assumes a 5-percent discount rate.

gains from a marginal reallocation. The potential gains from such a reallocation, then, are bounded from above by the difference in current energy value and the product of current local marginal prices and optimized solar capacity. We estimate these gains assuming solar is reallocated to highest local marginal price zip codes subject to the constraint that solar occupies no more than 30-percent of zip code rooftops in order to mitigate grid stability concerns. Energy value of installed capacity is estimated to increase by $15 million per year or 8.5 percent of current energy value.

4.3 Uncertainty and sensitivity

The results reported in this section are estimated with uncertainty for several reasons. First, the SAM model used to estimate zip-code-specific solar generation predicts generation with some error. Freeman et al. (2014) validate popular solar models against observational records at select solar sites. The SAM model exhibits an annual error of $+/-5$ percent, considerably less than the annual error of the PVWatts model, a version of which is employed by Siler-Evans et al. (2013) and Callaway et al. (2018) and by many solar installers to predict generation for residential customers. The hourly root mean squared error of the SAM model is 4 percent.

Second, the 13,724,160 marginal emissions parameters are also estimated with uncertainty. This uncertainty is depicted in figures 3 and 4 for the sum across Texas generators of plant-specific emissions and generation responses. Each marginal plant response is estimated 750 times from bootstrap samples blocked by day. For each block-bootstrap sample, all plant emission responses are estimated. The sum of marginal emissions responses is depicted in gray for each bootstrap sample. The mean across these estimates is depicted in blue, and a 95-percent confidence interval is defined by the series plotted in black. The average coefficient of variation ranges from 0.373 for SO_2 to 0.0506 for CO_2. Uncertainty in zip code avoided emissions given solar generation is characterized by sampling from the bootstrapped distribution of plant emissions coefficients. The 95-percent confidence intervals of these 30,105 avoided emissions estimates is available from the authors upon request. In Texas, for example, the average across-zip code standard deviation in total damages per 4kW installation is \$3.75, less than 2% of average total damages across Texas (\$200.84). Though these parameters are estimated fairly precisely, the effect of this uncertainty is to render the marginal emissions of some zip codes statistically indistinguishable. This, in turn, implies some uncertainty in gains from reallocation of capacity within Texas.

Finally, uncertainty characterizes the translation of emissions changes to monetized damages. Holland et al. (2016) consider sensitivity of damages to key parameters of the AP2 model, the predecessor of the AP3 model we employ. Model results are sensitive to assumptions about the value of a statistical life, the social cost of carbon, and the dose-response function relating particulate matter concentrations to mortality. The cumulative uncertainty causes uncertainty in the environmental benefits of solar capacity, the gains from reallocations of solar capacity, and the transfers across states implicit in solar capacity investments.

Also, to the extent that pollution emissions are restricted by binding emissions caps, as intended by some EPA programs and state carbon policies, then our estimates of avoided damages are too high (Holland et al. (2016). As Holland et al. (2016) note, however, it is likely that caps in some of these pollution markets were not binding during the study period, diminishing concern about this source of bias in our estimates.

Our empirical estimates of marginal emissions coefficients for each plant allows flexible modeling of pollution responses across the grid without imposing assumptions about the technologies of generators or the capacities of transmission lines connecting them. This flexibility comes at the cost of being backward looking. Our analysis is based upon historical data from January 1, 2007 to December 31, 2015. Changes to the electricity grid may change these marginal emissions rates and marginal damages, affecting the benefits of solar capacity investments. We do not attempt to model the future electricity grid. There are reasons, however, to expect marginal emissions and damages will be relatively stable for the foreseeable future. Even as renewable capacity grows, lowering average emissions, renewables are typically not marginal, so marginal emissions will be governed by coal and natural gas plant emission intensities, not those of renewables. Indeed, Holland et al. (2018) show marginal damages are relatively constant over substantial ranges of load, demonstrating that even large changes in net load do not imply large changes in marginal emissions. Though they also show that marginal damages have not changed dramatically in the eastern and western interconnections for large ranges of load over the periods 2010-2012 and 2014-2016, marginal damages are estimated to have statistically significant trends. Marginal damages in the Eastern interconnection are decreasing overtime, whereas they are increasing in the Western interconnection. A convergence of marginal damages across the U.S. diminishes the gains from efficient capacity siting across interconnections.

5 Discussion

Advocating for a statewide goal of 12 GW of clean, local electricity generating capacity in 2011, California's Governor, Jerry Brown, remarked,"This is tens of thousands of little decisions. The distribution is its strength and also its challenge."[22] This paper shows distributed decisions nationwide have produced an installed capacity of more than 1.4 million rooftop solar arrays that neither maximizes energy value of solar generation nor avoided damages from fossil-fuel generation. The misallocation of solar capacity chiefly sacrifices environmental benefits that vary across the U.S. mostly due to heterogeneity in the technologies of marginal responding fossil generators and their locations relative to

[22] http://articles.latimes.com/2011/jul/26/business/la-fi-small-renewables-20110726

population centers.

The misallocation of solar capacity may partly reflect heterogeneity in solar demand among investors, but federal, state, and local policies distort the prices private investors receive. No solar policy accounts for heterogeneity in environmental benefits. Thus, none provides the second-best Pigouvian subsidy to solar generation or solar capacity. A second-best Pigouvian subsidy would provide correct price signals to direct efficient allocation of solar capacity within or across states. Absent subsidies that reflect heterogeneous environmental benefits, it is unsurprising private investments fail to maximize these benefits.

Policy also distorts prices private investors receive for the energy value of their generation. Net metering policies common to 41 states pay solar generators at rates exceeding wholesale prices or electricity marginal costs. These prices are also invariant to congestion benefits. Unsurprisingly, therefore, there is no evidence that California's more than 900,000 rooftop solar arrays help to alleviate congestion, even though congestion relief is a purported benefit of distributed solar capacity.

The foregone energy and environmental benefits of rooftop solar capacity constitute a cost of policies that favor investments in distributed generation capacity over utility-scale capacity investments that are governed by price signals that appropriately value energy, if not avoided pollution. Policy can be better targeted to achieve efficient capacity allocations. Subsidies can vary with site-specific environmental benefits and compensation for energy value can vary with local marginal costs. Still, incentive programs will invariably be plagued by free riding among inframarginal solar adopters who take advantage of incentives even though they would make capacity investments absent policy. Hughes and Podolefsky (2015), for instance, estimate a rebate elasticity of solar adoption in California of about 0.5, suggesting considerable program cost per additional kW of installed capacity.[23]

[23]In similar analysis, Rogers and Sexton (2015) estimate a public cost per additional kW capacity under the California Solar Initiative in excess of $3,000, equal to at least half the total cost per unit of capacity installed under the program.

Inframarginal adopters not only limit additionality of public expenditures, but also diminish the likelihood that capacity is installed in highest-benefit areas. The cost-effectiveness of solar policy is, thus, diminished relative to direct public investments in capacity like those made by regulated utilities or utility-contracted independent generators.

The historic role of utilities in directing grid investments is threatened by generous subsidies in many states to rooftop solar capacity relative to central-plant solar. The persistence of utilities is also threatened by net-metering policies in many states that allow solar adopters to avoid paying for fixed costs of the grid that are apportioned in volumetric energy charges. This fixed-cost avoidance raises the burdens on non-solar adopters, potentially inducing further solar adoptions—or grid defections—and still higher burdens on non-adopters. Such an unraveling of the market for grid electricity is termed the "utility death spiral," and it could yield autarchic markets like those that existed a century ago. If rooftop solar capacity yields no congestion relief, as we show in California, then the persistence of a policy preference for distributed generation solar must reflect other policy maker objectives.

These results also highlight a cost of policy preferences that favor within border renewable energy generation over renewable electricity imports. Twenty-nine states have renewable portfolio standards that are intended to reduce emissions of globally mixing greenhouse gases and improve local air pollution. For many states, the greatest carbon mitigation and improvement in local air quality may be achieved by capacity investments in other jurisdictions. We have shown that the greatest single beneficiaries of state investments in solar capacity tend not to be the states in which the investments are made, but rather other states that are linked via physical processes of the electric grid and air transport. Coasian transactions among states could achieve greater efficiency in solar siting decisions.

This analysis also shows that states capture only 15 percent of the local pollution benefits generated by solar capacity investments.[24] Therefore, these are prone to free-riding even among local and state jurisdictions that subsidize it, warranting intervention at the national level where benefits are more fully appropriated. Despite the risk of free-riding by states and local jurisdictions, we find that state subsidies are essentially uncorrelated with in-state benefits or benefit shares, though the states capturing least benefits do subsidize at the lowest rates.

Substantial spillovers of solar capacity benefits also suggest the EPA's Cross State Air Pollution Rule that caps pollution emissions of regulated states could incentivize solar adoption by crediting states for the share of their solar capacity investments that avoid pollution in downwind states. It also implies states intending to improve air quality for their respective residents may optimally employ policy instruments other than solar generation subsidies. Holland et al. (2016), for instance, estimate that only 19 percent of damages from in-state vehicle tailpipe emissions are exported out of state through air transport. States can also subsidize pollution abatement at in-state sources, thereby limiting subsidies to emissions changes at out-of-state, downwind generators.

6 Conclusion

This paper provides the first systematic, theoretically consistent and empirically valid estimates of the heterogeneous environmental benefits of rooftop solar capacity investments across the U.S. The average environmental benefits are equal to $569 per year, though these would increase if capacity were allocated across states—or even within them—in order to maximize these benefits. These benefits are estimated to be greatest in the U.S. Midwest and Mid-Atlantic regions and least in the West, including California, where nearly two-thirds of rooftop systems are located. The average rooftop investment is subsidized

[24]The share of CO_2 mitigation benefits appropriated by states is arbitrarily small if these are apportioned worldwide according to population.

at a rate approximately equal to its external benefits, yet subsidies are uncorrelated with environmental benefits, so systems generating the greatest external benefits are under-subsidized. On average, only 15 percent of external benefits are appropriated within states where capacity investments are made; the rest spillover to other states with implications for state and federal air pollution control policy.

Though distributed generation capacity like rooftop solar is intended to alleviate grid congestion, we find no evidence that the 900,000 systems installed in California provide congestion relief. This result and evidence of rooftop capacity misallocation are indicative of policies that obscure efficient prices from private investors. They also suggest persistence of a wide-spread policy preference for rooftop over utility-scale solar reflects objectives other than least-cost pollution avoidance.

References

Baker, Erin, Meredith Fowlie, Derek Lemoine, and Stanley S Reynolds, "The economics of solar electricity," *Annual Review of Resource Economics*, 2013, *5* (1), 387–426.

Barbose, Galen, Naim Darghouth, Samantha Weaver, and Ryan Wiser, "Tracking the Sun V: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998-2011," July 2012. Lawrence Berkeley National Laboratory. Online at https://emp.lbl.gov/publications/tracking-sun-v-historical-summary. Last visited 2018-10-08.

_ , _ , _ , and _ , "Tracking the Sun X: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States," July 2017.

Lawrence Berkeley National Laboratory. Online at https://emp.lbl.gov/publications/tracking-sun-x-installed-price. Last visited 2018-10-08.

Blair, Nate J., Aron P. Dobos, and Paul Gilman, "Comparison of photovoltaic models in the System Advisor Model," 2013. NREL Conference Paper NREL-CP-6A20-58057. National Renewable Energy Laboratory. Online at https://www.nrel.gov/docs/fy13osti/58057.pdf. Last visited 2018-10-08.

Borenstein, Severin, "The Private and Public Economics of Renewable Electricity Generation," *The Journal of Economic Perspectives*, 2012, *26* (1), 67–92.

_ **and James Bushnell**, "Do two electricity pricing wrongs make a right? Cost recovery, externalities, and efficiency," 2018. Working Paper 24756. National Bureau of Economic Research. Online at https://www.nber.org/papers/w24756. Last visited 2018-10-08.

_ **and Lucas W Davis**, "The distributional effects of US clean energy tax credits," *Tax Policy and the Economy*, 2016, *30* (1), 191–234.

Callaway, Duncan S, Meredith Fowlie, and Gavin McCormick, "Location, location, location: The variable value of renewable energy and demand-side efficiency resources," *Journal of the Association of Environmental and Resource Economists*, 2018, *5* (1), 39–75.

Caulton, Dana R, Paul B Shepson, Renee L Santoro, Jed P Sparks, Robert W Howarth, Anthony R Ingraffea, Maria OL Cambaliza, Colm Sweeney, Anna Karion, and Kenneth J Davis, "Toward a better understanding and quantification of methane emissions from shale gas development," *Proceedings of the National Academy of Sciences*, 2014, *111* (17), 6237–6242.

Clay, Karen, Akshaya Jha, Nicholas Z. Muller, and Randy Walsh, "The external costs of shipping petroleum products by pipeline and rail: Evi- dence of shipments of crude oil from North Dakota," *The Energy Journal*, Forthcoming.

Coddington, M., B. Mather, B. Kroposki, K. Lynn, A. Razon, A. Ellis, R. Hill, T. Key, K. Nicole, and J. Smith, "Updating Interconnection Screens for PV System Integration," February 2012. National Renewable Energy Laboratory. Online at http://www.osti.gov/servlets/purl/1036038/. Last visited 2018-10-08.

Cullen, Joseph, "Measuring the environmental benefits of wind-generated electricity," *American Economic Journal: Economic Policy*, 2013, *5* (4), 107–33.

Energy Information Administration, "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013," May 2013. Energy Information Administration. Online at http://www.eia.gov/forecasts/aeo/electricity_generation.cfm. Last visited 2018-10-08.

_ , "Today in Energy: California Has Nearly Half of the Nation's Solar Electricity Generating Capacity," February 2016. Energy Information Administration. Online at http://www.eia.gov/todayinenergy/detail.php?id=24852. Last visited 2018-10-08.

_ , "Today in Energy: Wind Adds the Most Electric Generation Capacity in 2015, Followed by Natural Gas and Solar," February 2016. Energy Information Administration. Online at https://www.eia.gov/todayinenergy/detail.php?id=25492. Last visited 2018-10-08.

_ , "Today in Energy: More than half of small-scale photovoltaic generation comes from residential rooftops," June 2017. Energy Information Administration. Online at http://www.eia.gov/todayinenergy/detail.php?id=24852. Last visited 2018-10-08.

_ , "State electricity profiles," January 2018. Energy Information Administration. Online at https://www.eia.gov/electricity/state/. Last visited 2018-10-08.

Fischer, Carolyn, "Emissions pricing, spillovers, and public investment in environmentally friendly technologies," *Energy Economics*, 2008, *30* (2), 487–502.

— **and Richard G Newell**, "Environmental and technology policies for climate mitigation," *Journal of Environmental Economics and Management*, 2008, *55* (2), 142–162.

Freeman, Janine, Jonathan Whitmore, Nate Blair, and Aron P Dobos, "Validation of multiple tools for flat plate photovoltaic modeling against measured data," October 2014. National Renewable Energy Laboratory. Online at https://www.nrel.gov/docs/fy14osti/61497.pdf. Last visited 2018-10-08.

Gillingham, Kenneth and James Sweeney, "Barriers To Implementing Low-Carbon Technologies," *Climate Change Economics*, 2012, *3* (04), 1–21.

Graff-Zivin, Joshua S, Matthew J Kotchen, and Erin T Mansur, "Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies," *Journal of Economic Behavior & Organization*, 2014, *107*, 248–268.

Holland, Stephen P, Erin T Mansur, Nicholas Z Muller, and Andrew J Yates, "Are there environmental benefits from driving electric vehicles? The importance of local factors," *American Economic Review*, 2016, *106* (12), 3700–3729.

Holland, Stephen P., Erin T. Mansur, Nicholas Z. Muller, and Andrew J Yates, "The remarkable decline in air pollution from the U.S. electricity sector over 2010-2017," in "in" Presented at Triangle Resource and Environmental Economics Seminar, October 2018.

Hughes, Jonathan E and Molly Podolefsky, "Getting green with solar subsidies: evidence from the California solar initiative," *Journal of the Association of Environmental and Resource Economists*, 2015, *2* (2), 235–275.

Interagency Working Group on the Social Cost of Carbon, "Technical update of the Social Cost of Carbon for regulatory impact analysis," 2016. Online at https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf. Last visited 2018-10-08.

Jaffe, Adam B, Richard G Newell, and Robert N Stavins, "A tale of two market failures: Technology and environmental policy," *Ecological Economics*, 2005, *54* (2), 164–174.

Jaramillo, Paulina, W Michael Griffin, and H Scott Matthews, "Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation," *Environmental Science & Technology*, 2007, *41* (17), 6290–6296.

National Renewable Energy Laboratory, "Electricity Generation Baseline Report," 2017. National Renewable Energy Laboratroy. Online at https://www.nrel.gov/docs/fy17osti/67645.pdf. Last visited 2018-10-08.

Nordhaus, William, "Designing a friendly space for technological change to slow global warming," *Energy Economics*, 2011, *33* (4), 665–673.

North Carolina Clean Energy Technology Center, "Database of state incentives for renewable energy," 2018. Online at http://www.dsireusa.org/. Last visited 2018-10-08.

Novan, Kevin, "Valuing the wind: renewable energy policies and air pollution avoided," *American Economic Journal: Economic Policy*, 2015, *7* (3), 291–326.

Pigou, AC, *The Economics Of Welfare*, Macmillan and Co., London, 1920.

Siler-Evans, Kyle, Inês Lima Azevedo, M Granger Morgan, and Jay Apt, "Regional variations in the health, environmental, and climate benefits of wind and solar generation," *Proceedings of the National Academy of Sciences*, 2013, *110* (29), 11768–11773.

Solar Energy Industry Association, "Million Solar Milestone," 2016. Online at https://www.seia.org. Last visited 2018-10-08.

U.S. Census Bureau, "American Community Survey 2017," 2017. Online at https://www.census.gov/programs-surveys/acs/news/data-releases/2017/release.html. Last visited 2018-10-08.

U.S. Environmental Protection Agency, "Cleaner Power Plants," April 2012. Online at http://epa.gov/airquality/powerplanttoxics/powerplants.html. Last visited 2018-10-08.

von Stechow C. Edenhofer O, Pichs-Madruga R. Sokona Y. Seyboth K. Matschoss P. Kadner S. Zwickel T. Eickemeier P. Hansen G. Schlomer S., *Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, Cambridge, UK: Cambridge University Press, 2011.

Walczak, Jared and Scott Drenkard, "State and local sales tax rates in 2017," January 2017. Tax Foundation. Online at https://files.taxfoundation.org/20170131121743/TaxFoundation-FF539.pdf. Last visited 2018-10-08.

Table 1: Summary Statistics

	Mean	St. Dev.	Min	Max
	Solar Generation			
Annual kWh	6357.4	656.1	4344.7	8647.3
	Avoided Pollution Damages			
Total Annual Dollars	568.9	373.0	60.7	1224.7
CO2	166.2	71.6	24.2	396.0
NOx	55.4	38.1	4.6	126.9
PM25	22.7	18.0	−3.5	57.9
SO2	324.6	285.5	1.1	885.3
	Subsidies			
Annual Subsidy	599.9	269.2	218.8	2,843.8
Subsidy Less Damages	31.0	492.9	−800.7	2,089.5
	Energy Value			
Total Annual Dollars	247.0	35.9	138.6	371.1

Notes: Annual kWh in first panel is estimated annual solar generation in kWh. The second panel reports the total and pollution-specific dollar values of avoided pollution emissions (in dollars). The third panel reports Annual Subsidy calculated as the net present value per kWh of all solar subsidies multiplied by annual generation. "Subsidy less damages" reports the difference between subsidy and damages. Positive values indicate over-subsidization. Mean "Annual Subsidy" and "Subsidy less damages" are weighted by installed capacity. The bottom panel reports the mean annual energy value of generation measured as the product of hourly average marginal cost of electricity supply and hourly generation.

Table 2: State Average Subsidies and Damages

State	Subsidy	Avoided Damages	Net Ann. Subsidy	State	Subsidy	Avoided Damages	Net Ann. Subsidy
Mass.	0.33	0.01	1913	Virginia	0.06	0.05	80
Rhode Island	0.15	0.01	844	Florida	0.08	0.07	70
Connecticut	0.14	0.01	778	Kentucky	0.07	0.07	24
New York	0.14	0.01	764	Mississippi	0.07	0.07	-32
California	0.11	0.02	627	Kansas	0.08	0.09	-47
N. Hampshire	0.12	0.01	599	Minnesota	0.09	0.10	-54
Vermont	0.11	0.02	537	Georgia	0.07	0.09	-69
Arizona	0.09	0.03	479	Wisconsin	0.11	0.12	-77
Utah	0.08	0.02	445	Nebraska	0.08	0.10	-107
Maine	0.09	0.01	429	N. Dakota	0.08	0.10	-153
Oregon	0.09	0.02	416	Oklahoma	0.06	0.09	-171
S. Carolina	0.10	0.04	391	Lousiana	0.11	0.15	-215
New Jersey	0.24	0.18	378	Iowa	0.10	0.14	-292
Idaho	0.07	0.02	361	Illinois	0.12	0.18	-341
Washington	0.08	0.02	356	Arkansas	0.07	0.13	-380
Montana	0.07	0.02	338	S. Dakota	0.04	0.10	-415
New Mexico	0.07	0.03	320	Delaware	0.11	0.18	-469
Tennessee	0.11	0.06	279	Michigan	0.08	0.17	-482
Nevada	0.07	0.03	277	Maryland	0.10	0.18	-506
Wyoming	0.06	0.02	275	Missouri	0.08	0.16	-540
Colorado	0.08	0.05	272	Ohio	0.08	0.17	-561
Texas	0.06	0.04	193	Pennsylvania	0.08	0.18	-600
N. Carolina	0.07	0.04	171	Indiana	0.07	0.18	-626
Alabama	0.10	0.08	119	West Virginia	0.06	0.18	-678

Notes: Subsidy and average Avoided Damages are reported per kWh. Subsidy streams are discounted to present value at a 5 percent annual rate. Net Annual Subsidy is annual subsidy less total annual damages avoided. States are ordered by Net Annual Subsidy.

Table 3: Simulated Allocations of Installed Solar Capacity

	Installed	U.S	U.S. 30%	State	State 30%
Total Avoided Damages	353.3	1,693.0	1,659.0	416.7	398.7
Number of zips	12840	745	2312	513	1370
Mean Avoided Damages	243.9	1168.7	1145.2	287.6	275.2

Notes: Total Avoided Damages reported in millions of U.S. dollars. Mean avoided damages per 4-kW system are reported in dollars.

Table 4: In-state vs. Out-of-state Environmental Benefits

State	In-state Ann. Benefits	Out-of-State Ann. Benefits	Percent In-state	State	In-state Ann. Benefits	Out-of-State Ann. Benefits	Percent In-state
Florida	200.53	140.93	60.37	Wisconsin	13.46	499.84	3.04
Pennsylvania	151.33	666.19	18.50	Louisiana	11.54	647.88	2.13
Georgia	94.94	324.52	22.16	Mississippi	10.09	429.20	2.26
Ohio	82.21	731.61	10.10	Kansas	8.41	265.24	3.08
N. Carolina	67.03	69.10	50.66	Delaware	8.36	929.52	0.89
New York	64.94	-12.17	125.89	Minnesota	7.62	402.70	1.86
New Jersey	60.83	806.82	9.42	Arizona	6.50	74.76	7.91
Maryland	51.48	878.24	5.54	N. Hampshire	4.93	45.11	9.97
Alaska	51.48	327.37	12.42	Iowa	4.73	446.67	1.05
Illinois	42.19	868.02	4.70	Rhode Island	4.62	40.38	10.37
Texas	40.12	97.40	47.02	Maine	3.68	50.72	6.82
Kentucky	38.07	346.17	13.40	Arkansas	3.40	696.81	0.74
Virginia	34.20	330.51	16.35	Washington	2.23	25.36	8.12
S. Carolina	34.16	103.52	24.84	New Mexico	1.78	126.82	2.03
Michigan	33.39	738.91	4.48	Nevada	1.69	63.88	2.52
Massachusetts	31.33	12.74	72.05	Nebraska	1.33	416.32	0.41
Indiana	27.21	827.21	3.18	Vermont	1.28	55.78	2.27
Missouri	27.10	821.87	4.06	Utah	0.96	35.51	2.66
California	24.15	8.13	77.63	Oregon	0.84	29.08	2.82
West Virginia	22.16	796.49	2.66	Wyoming	0.48	72.57	0.70
Tennessee	19.57	253.54	7.42	Idaho	0.42	31.46	1.32
Colorado	17.20	90.11	16.12	South Dakota	0.35	414.54	0.11
Oklahoma	13.90	259.31	5.12	Montana	0.27	64.92	0.82
Connecticut	13.59	28.83	32.42	North Dakota	0.20	414.88	0.05

Notes: Reported are annual average avoided damages that accrue in-state versus those that accrue out of state. "Percent In-State" indicates the percentage of total benefits accruing in the local, adopting state. States are ordered by magnitudes of in-state benefits.

Table 5: Benefits to Largest Out-of-State Beneficiary

State	Beneficiary	Ann. Benefits	Ratio to In-state Benefits	State	Beneficiary	Ann. Benefits	Ratio to In-state Benefits
Delaware	Pennsylvania	173.24	20.73	Connecticut	New York	66.90	4.92
Maryland	Pennsylvania	171.86	3.34	Kansas	Illinois	66.55	7.91
New Jersey	Pennsylvania	159.93	2.63	Oklahoma	Illinois	66.18	4.76
Indiana	Pennsylvania	159.35	5.86	Georgia	Alabama	65.29	0.69
W. Virginia	Pennsylvania	151.71	6.85	Kentucky	Ohio	64.50	1.69
Ohio	Pennsylvania	151.68	1.84	Vermont	New York	64.38	50.13
Michigan	Pennsylvania	141.56	4.24	Tennessee	Ohio	61.25	3.13
Illinois	Pennsylvania	118.70	2.81	Virginia	N. Carolina	58.03	1.70
Arkansas	Pennsylvania	103.23	30.39	Mississippi	Pennsylvania	47.28	4.68
Pennsylvania	New York	100.57	0.66	N. Carolina	S. Carolina	32.53	0.49
Missouri	Ohio	92.69	3.42	New York	Mass.	29.57	0.46
Louisiana	Pennsylvania	89.13	7.73	Florida	Georgia	22.06	0.11
Iowa	Ohio	81.07	17.14	New Mexico	Illinois	13.98	7.86
Wisconsin	Ohio	78.47	5.83	Texas	Illinois	12.84	0.32
Nebraska	Ohio	77.70	58.24	Arizona	California	11.64	1.79
S. Dakota	Ohio	77.03	217.16	Colorado	Texas	11.42	0.66
N. Dakota	Ohio	76.70	389.84	Nevada	California	9.74	5.78
Minnesota	Ohio	76.50	10.04	Wyoming	Colorado	9.55	19.72
Alabama	Georgia	73.08	1.42	Montana	Ohio	7.48	28.09
S. Carolina	N. Carolina	70.21	2.06	Utah	California	4.95	5.13
Rhode Island	New York	68.63	14.85	Idaho	California	4.12	9.78
Maine	New York	68.38	18.59	Oregon	California	3.78	4.49
Mass.	New York	67.83	2.16	Washington	California	3.52	1.58
N.Hampshire	New York	67.10	13.62	California	Arizona	1.36	0.06

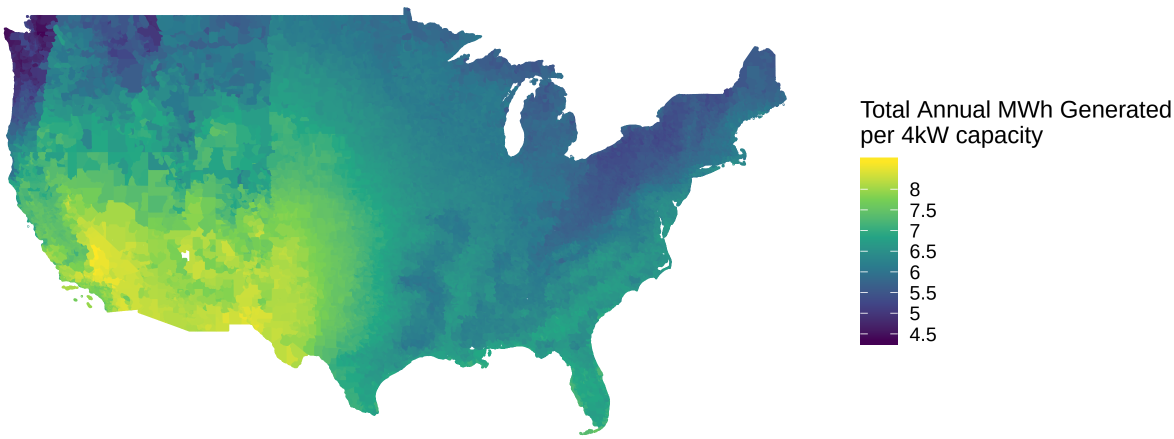
Notes: Reported for each state is the different state in which maximum environmental benefits accrue, the magnitudes of those benefits, and the ratio of those benefits to the benefits that accrue in-state. States are ordered by the magnitudes of benefits accruing to a different state.

Table 6: Energy Value and Total Benefits by State

State	Ann. Total Benefits	Ann. Energy Value	State	Ann. Total Benefits	Ann. Energy Value
Maryland	1483	340	Kentucky	643	236
Delaware	1479	322	Virgnia	624	312
New Jersey	1408	298	Tennessee	593	216
West Virginia	1345	288	Colorado	546	218
Illinois	1328	236	New Mexico	545	277
Pennsylvania	1326	272	N. Carolina	529	250
Indiana	1303	237	S. Carolina	521	244
Ohio	1259	249	Nevada	506	258
Missouri	1251	222	Texas	500	258
Lousiana	1220	244	Arizona	478	218
Michigan	1207	239	California	452	262
Iowa	1113	223	Rhode Island	427	348
Arkansas	1013	219	Maine	409	325
Wisconsin	978	231	N. Hampshire	404	322
S. Dakota	853	206	Wyoming	400	237
Nebraska	845	201	Connecticut	400	324
Oklahoma	837	248	Mass.	398	322
Kansas	818	233	New York	387	301
Minnesota	816	198	Vermont	369	278
N. Dakota	800	192	Utah	360	254
Geogria	769	224	Idaho	341	243
Florida	726	221	Montana	321	227
Alabama	708	218	Washington	289	204
Mississippi	690	218	Oregon	282	196

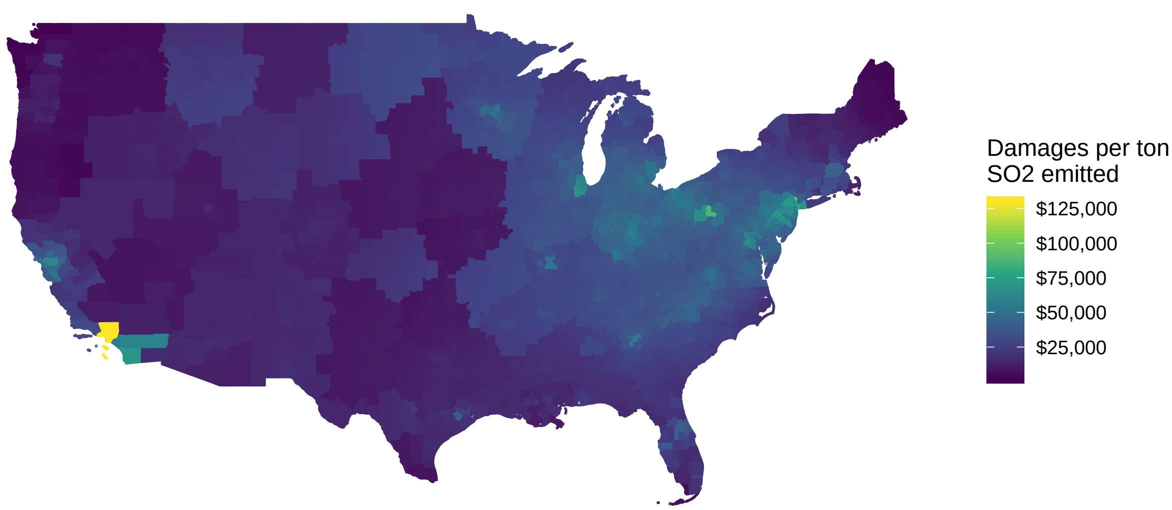
Notes: Reported in dollars for each state is the estimated total annual benefit of 4-kW solar capacity determined as the sum of energy value and avoided damages. Also reported are energy values (in dollars). States are ordered by the magnitudes of total benefits.

Figure 1: Total Annual A/C Electricity Generation per 4kw Solar Capacity



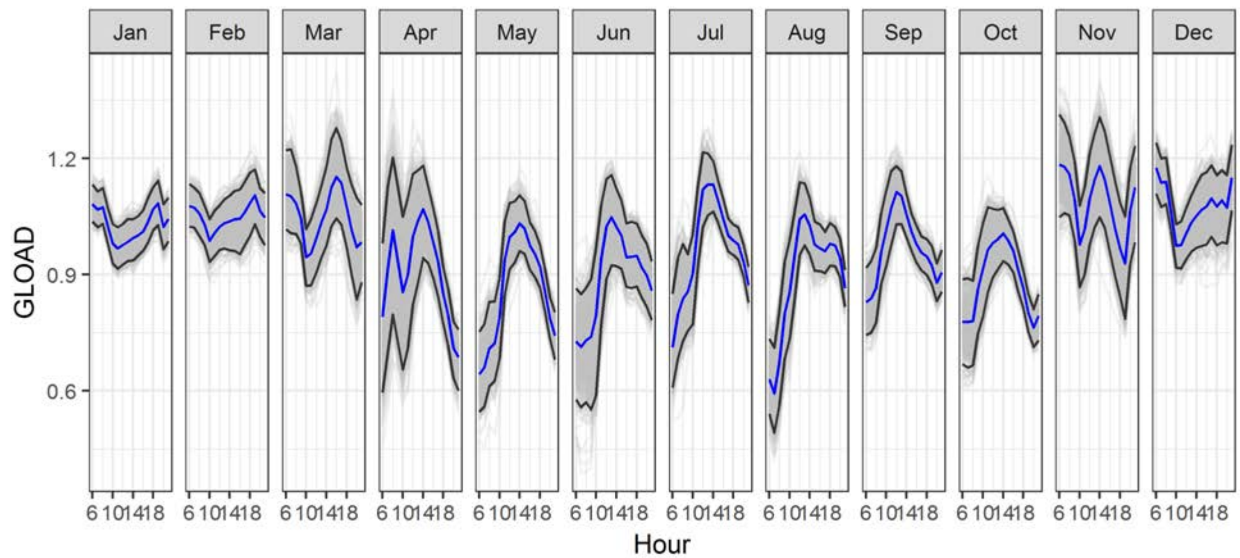
Depicted is modeled annual alternating-current (A/C) electricity generation (in MWh) per 4-kW solar capacity for each U.S. zip code. Generation is greatest in the Southwest.

Figure 2: Damages Per Ton SO_2 Emissions by County

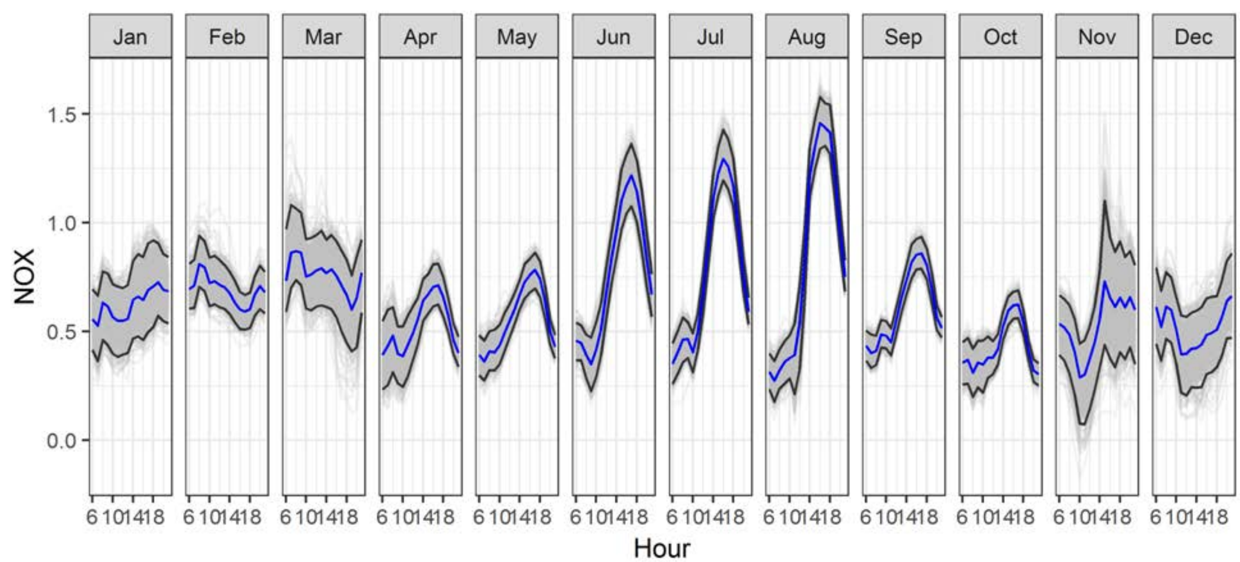


Damages per ton of SO_2 are shown by county of pollution source. Damages are estimated by the AP3 model. Darker blue regions reflect relatively low damages. Green to yellow regions are those in which a ton of emissions is costlier.

Figure 3: Marginal Emissions by Month and Daylight Hour and 95% CI



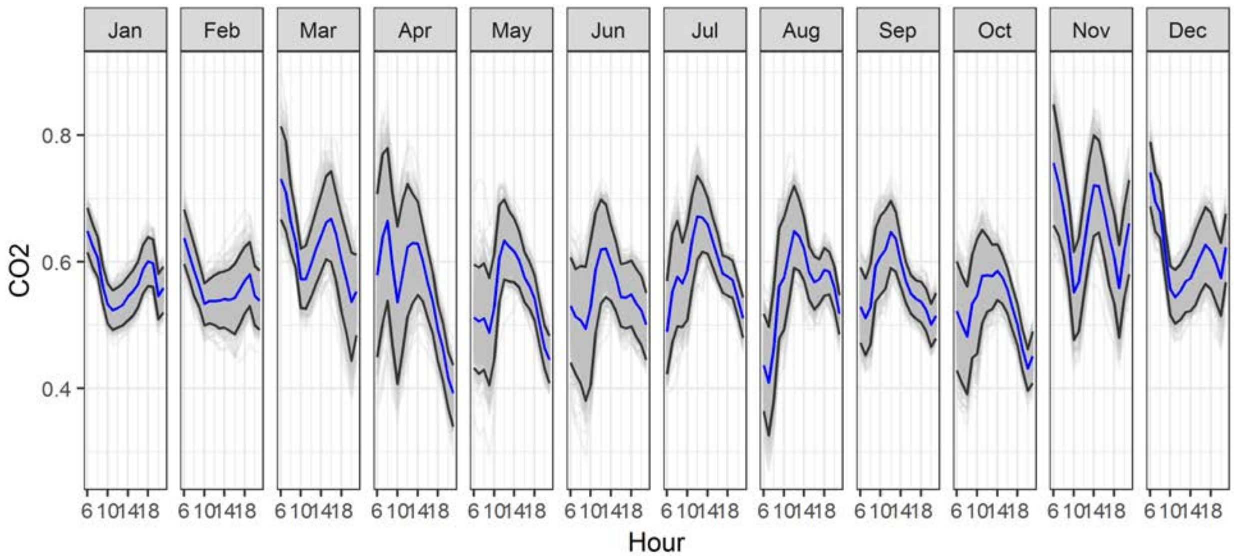
(a) Generation (and $PM_{2.5}$)



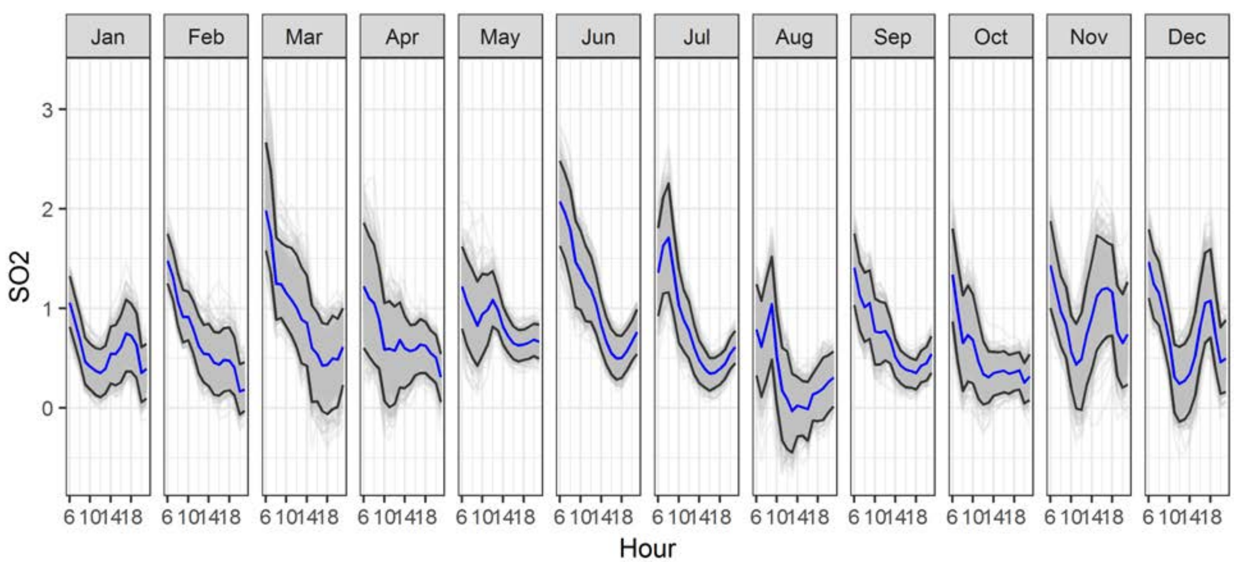
(b) NO_X

Depicted in blue for each daylight hour and each month of the year are the mean sum of plant generation and emissions responses to a 1MW change in load. These are shown for the Texas interconnection. Each grey series shows the sum of plant-specific coefficients for one of 750 block-bootstrap samples. A 95-percent confidence interval is bounded by the series shown in black.

Figure 4: Marginal Emissions by Month and Daylight Hour and 95% CI



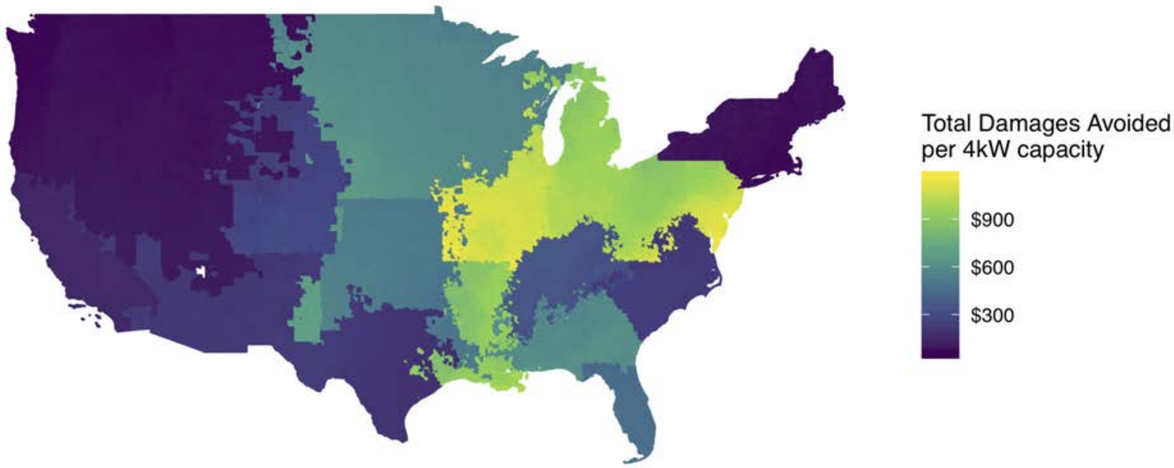
(a) CO_2



(b) SO_2

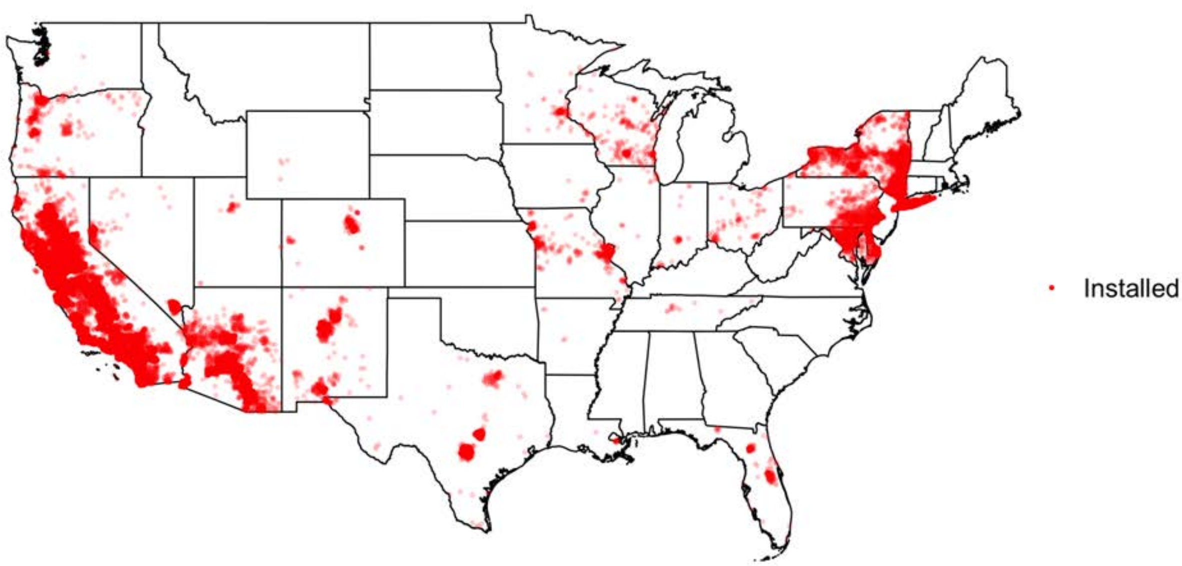
Depicted in blue for each daylight hour and each month of the year are the mean sum of plant generation and emissions responses to a 1MW change in load. These are shown for the Texas interconnection. Each grey series shows the sum of plant-specific coefficients for one of 750 block-bootstrap samples. A 95-percent confidence interval is bounded by the series shown in black.

Figure 5: Total Annual Avoided Environmental Damages per 4kw Solar Capacity



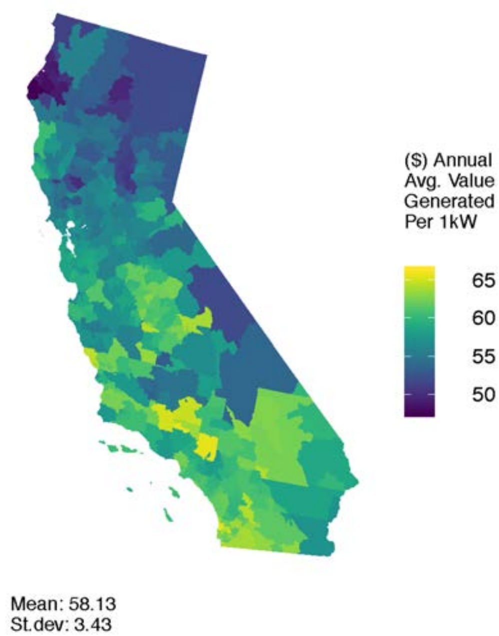
Zip-code specific annual avoided pollution damages from 4kW capacity in dollars. Darker shades of blue indicate lower annual damages. Brighter green to yellow regions indicate greatest pollution damage avoidance.

Figure 6: Installed Rooftop Solar Arrays



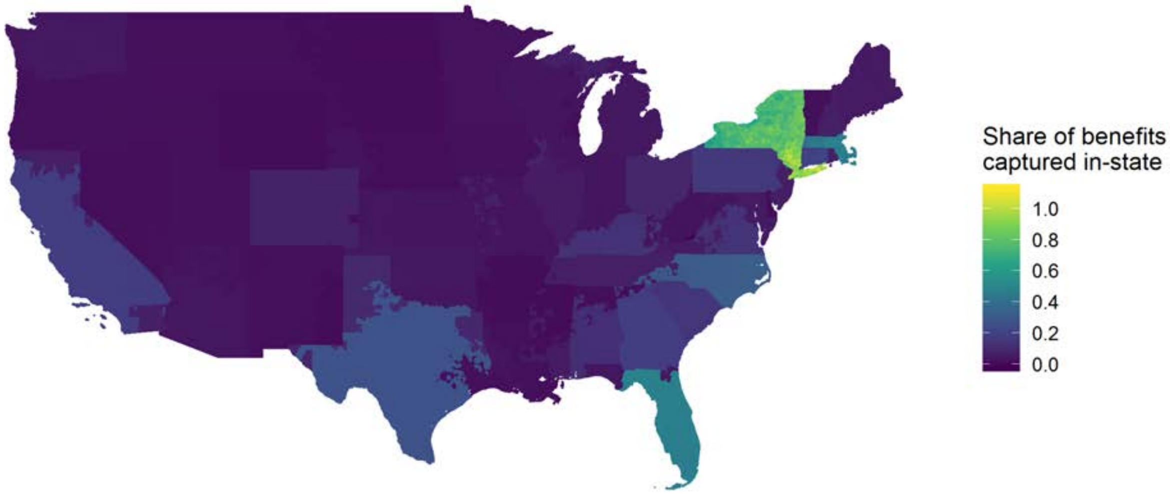
Depicted in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays.

Figure 7: Annual Value of Electricity Generation per kW



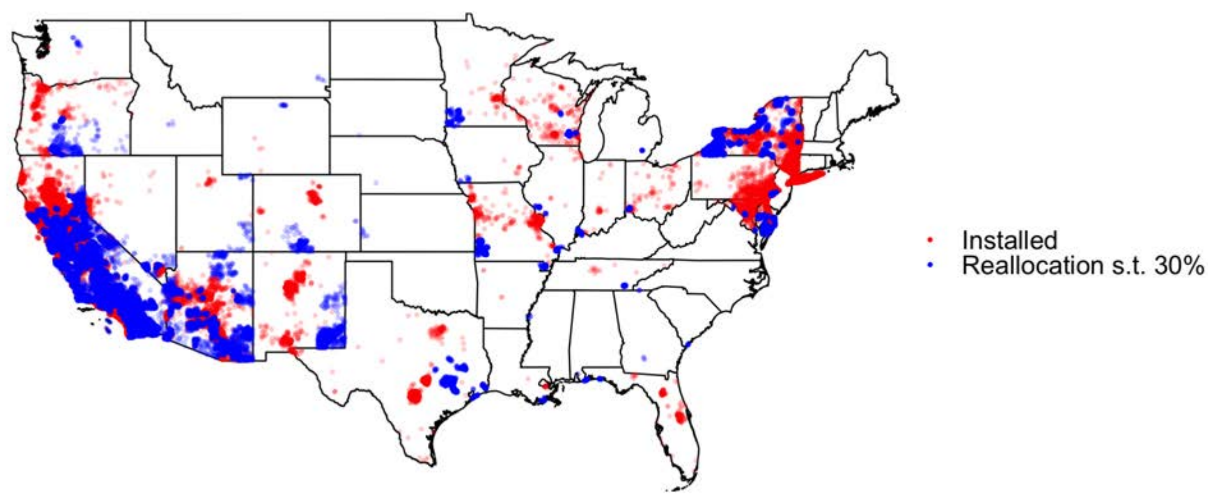
Shown by zip code is the annual value in dollars of electricity generated per kW solar capacity in 2017 as determined by local marginal prices at the most proximate network node.

Figure 8: In-State Shares of Avoided Local Pollution Benefits



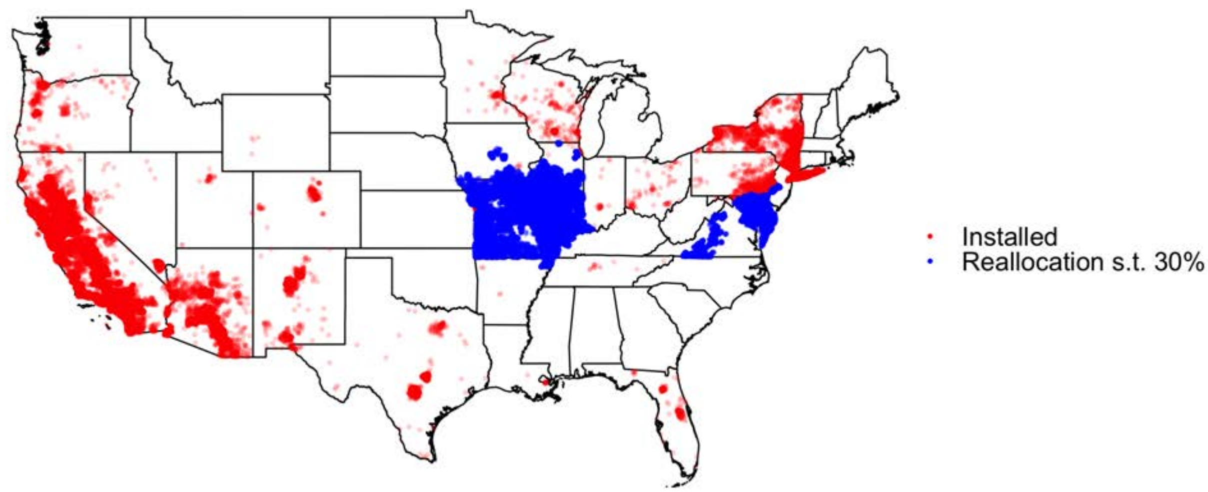
Share of avoided pollution damages appropriated by the state in which a unit solar capacity is installed.

Figure 9: Intrastate Reallocation of Solar Capacity subject to Grid Stability Concerns



Depicted in blue are solar capacity locations following intrastate reallocation subject to grid stability concerns limiting solar to 30 percent of rooftops in any zip code. Shown in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays.

Figure 10: Interstate Reallocation of Solar Capacity subject to Grid Stability Concerns



Depicted in blue are solar capacity locations following interstate reallocation subject to grid stability concerns limiting solar to 30 percent of rooftops in any zip code. Shown in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays.