Heterogeneous Solar Capacity Benefits, Appropriability, and the Costs of Suboptimal Siting

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Abstract: This paper estimates that pollution damages avoidable by solar capacity vary considerably across zip codes in the United States and that they are uncorrelated with solar subsidy levels in each state. We estimate that $1 billion in avoided pollution damages would be gained annually from optimal siting of installed rooftop solar capacity. States are shown to appropriate a minority of these benefits from their solar investments because of interstate electricity and air pollution flows. This paper further measures the energy value of solar capacity across the United States and finds that rooftop solar does not relieve grid congestion.

JEL Codes: Q42, Q48, Q51, Q52

Keywords: rooftop solar, renewable energy, electricity, technology adoption, air pollution

SOLAR PANELS OCCUPY 2 MILLION rooftops across the United States and will soon occupy a million more (Solar Energy Industry Association 2020). Rapid growth of rooftop solar is impelled by a decade-long, exponential decline in technology costs and by generous federal and state subsidies and increasingly stringent state mandates for renewable generation. Solar policies are intended to increase the supply of clean electricity that

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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.

Despite the expanding role of solar policy in shaping the electricity grid, the efficiency of solar policies is not well understood. While Callaway et al. (2018) show that variation in avoided carbon emissions is not reflected in renewable energy policy, it is yet unknown whether solar policies reflect the value of other avoided pollution and grid-congestion relief, and whether they direct capacity investments to highest-value locations along the electricity grid. Determinations 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, regional electricity grid characteristics, and air pollution transport. 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 (Jaramillo et al. 2007; Edenhofer et al. 2011; Caulton et al. 2014).

Failure to account for heterogeneity in emissions resulting from marginal power generation can yield perverse policy outcomes, as Holland et al. (2016) and Callaway et al. (2018) observed in the context of electric vehicle subsidies and wind power generation, respectively. 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 via sales to utilities, state subsidies to generation, that is, net energy-metering policies, obscure the true value of generation that varies across space and time, potentially leading to capacity allocation that forgoes energy value even within states. Moreover, the network structure of the electricity grid and physical properties governing air transport suggest that air pollution avoidance benefits may not be appropriated by states making capacity investments and that a state's optimal investments may be in capacity beyond its borders.

In order to address these fundamental knowledge gaps, we investigate the efficiency of existing solar policy and capacity investments. We do so by building upon previous econometric modeling of marginal electricity generator pollution 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 United States. 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. We also use high-resolution air transport modeling to provide the first estimates of local solar benefits—those appropriated within the states that investments are made. Further, this paper estimates the energy value of solar capacity using data on electricity marginal costs at hundreds of grid management jurisdictions across the United States. The contribution of solar capacity to alleviation of transmission constraints is also measured using local marginal prices that incorporate grid congestion costs in California, the state in which most solar capacity is sited, and in the PJM territory that comprises the largest wholesale electricity market in the United States and spans 13 Midwest and Mid-Atlantic states.

Results suggest the discounted stream of subsidies to a typical rooftop solar array in the United States 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 subsidies in 2017 exceeded environmental benefits by as much as $22,000, while others undercompensated investors by as much as $800 per typical rooftop system. Annual environmental benefits vary by a factor of 20 across the United States, from $67 in Arlington, Washington, to $1,233 in Bloxom, Virginia. They also vary nontrivially within states. Yet virtually no solar policy accounts for heterogeneity in solar capacity benefits.

More than 90% of environmental benefits spill over to neighboring states, on average, suggesting that (1) free riding may constrain efficient solar capacity investments in the United States 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. In fact, half of states are estimated to increase local pollution-avoidance benefits at least 18% by investing in out-of-state capacity rather than in-state panels. Benefits to some states more than double.

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.

Further, we find no evidence that rooftop solar capacity systematically relieves congestion in California or the 13 states that comprise the PJM grid-operator territory. In California, for instance, approximately two-thirds of the 900,000 rooftop solar arrays are 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. In the PJM, however, congestion-relief benefits of optimal siting would comprise as much as 35% 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. Likewise, Graff Zivin et al. (2014) and Holland et al. (2016) evaluate the emissions impacts of electric vehicles relative to vehicles powered by internal combustion engines. Distinct from those papers, we model solar electricity generation and adapt the econometric approach to address seasonal variation in solar generation that correlates with load. This paper is also unique among these and other papers in expressly conditioning on solar generation that may otherwise bias marginal emissions estimates.

This paper 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 megawatt-hour (MWh) in excess of the value of carbon emissions avoidance. They do not consider avoidance of local air pollution emissions, as we do. 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 US 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 solar generation that is unreported in data from the Federal Energy Regulatory Commission and 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 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 1. Data and empirical methods are introduced in section 2. Model results and simulations are presented in section 3. Section 4 considers the implications of these results for solar policy, including the policy preference for distributed renewable energy capacity. A final section concludes.

1. POLICY DESIGN FOR OPTIMAL SOLAR SITING

Electricity generation by coal, oil, and natural gas plants is responsible for considerable air pollution in the United States and other developed countries. In the United States, it emits 27% of anthropogenic greenhouse gases that contribute to global warming. It also produces 50% of sulfur dioxide and 11% of nitrous oxide emissions that harm human health (US EPA 2019). 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 United States 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., Pigou 1920; Borenstein 2012; Baker et al. 2013).[1] In such a suboptimal regulatory setting, policy to support solar capacity or generation can correct an underprovision problem.[2]

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 23% of US electricity-generating capacity additions in 2019, it constituted only 5% of total generating capacity and provided only 2.6% of electricity generation (EIA 2020a, 2020b). Of this, 48% was provided by distributed generation capacity (EIA 2020a).

1. Solar subsidies can never be a first-best pollution control policy because unpriced pollution leads to underpriced dirty electricity generation, not overpriced clean generation. Solar policy lowers the cost of the homogeneous product electricity, rather than raising it (Borenstein 2012). Because the marginal costs of solar generation are essentially nil—the feedstock is free—policy promoting capacity is essentially analogous to policy promoting generation.

2. Potential learning spillovers provide an alternative justification for solar policy (e.g., Nordhaus 2011; Gillingham and Sweeney 2012). 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 underprovided" in the absence of policy (Jaffe et al. 2005; Fischer 2008; Fischer and Newell 2008). However, we are not aware of evidence of substantial unappropriated learning. Bollinger and Gillingham (2019), for instance, report only "very small learning spillovers" in solar installation. Policy makers claim that renewable energy policy creates "green jobs." To the extent that there are labor market failures, these may justify government intervention in the labor market, but not the electricity market. Moreover, there is scant evidence that renewable energy policies create jobs (Deschenes 2013). Notwithstanding evidence of economies of scale in solar panel production, for example, Kavlak et al. (2018), the associated cost reductions can be captured by firms making capacity investments, and, hence, scale economies do not a priori justify subsidies to solar capacity or solar generation (Borenstein 2012). Moreover, any individual country is unlikely to markedly affect the scale of the industry. The United States, for instance, represents only 16% of global solar capacity.

Public policies that support solar generation are common in the United States and other developed countries. The federal government alone has expended billions of dollars on a 30% 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 typically subsidize generation by requiring utilities to credit customers for solar generation at retail rates that far exceed the sum of wholesale electricity prices and the documented, marginal grid benefits of distributed generation (North Carolina Clean Energy Technology Center 2018). California utilities, for instance, must pay retail rates in excess of $0.35 per kilowatt-hour (kWh) 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 in the United States is more than double prevailing wholesale prices for solar generation, a difference that dwarfs the benefits of distributed generation, half of which is exported to the grid.

It is unlikely that 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.[3] Even conditional 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 US 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.[4] 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.

3. For instance, the distribution of solar irradiance across the United States causes potential annual electricity generation from 4 kilowatt (kW) of solar capacity to vary from 4.3 MWh in Arlington, Washington to more than double that amount in parts of California's central valley. Figure 1 shows for each US 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 (https://sam.nrel.gov/). Generation in MWh is alternating current.

4. 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 United States caused electric cars to contribute more to pollution than conventional substitutes.

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 (and any other marginal external benefits) plus the private marginal cost of electricity supply, that is, the wholesale price in a competitive market. Yet rooftop solar receives a price per unit of generation that exceeds wholesale prices in states with net-metering policies that typically compensate solar generation at retail rates. These policies are likely to overcompensate for energy value, even accounting for the potential value of distributed energy generation that may avoid distribution costs, if not transmission costs.[5] Such policies also impose a homogeneity on generator compensation that does not reflect 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.[6] The efficiency of existing capacity allocations is investigated in the following sections.

2. DATA AND METHODS

A determination of pollution damages avoided by 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

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5. As we report in this paper, distributed generation capacity does not contribute to transmission cost avoidance in California or the PJM territory. Evidence on distribution cost avoidance by distributed solar capacity is scarce. As Cohen and Callaway (2016) and Cohen et al. (2016) demonstrate for California, the value of avoided distribution costs is equal to an average 0.4 cents per kWh.

6. Congestion relief and transmission investment avoidance are among the benefits of rooftop solar reported by advocates. See, for instance, https://www.greentechmedia.com/articles/read/distributed-energy-value-properly#gs.76cjxe and https://www.seia.org/research-resources/benefits-and-costs-solar-distributed-generation-arizona-public-service. Rooftop solar is credited, for instance, with helping California regulators avoid $2.6 billion in transmission investments. See https://pv-magazine-usa.com/2018/03/27/distributed-solar-and-efficiency-saves-california-2-6-billion-on-power-lines/.

solar capacity in each US 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.

2.1. 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.[7] As described above, the plant that operates on the margin will vary according to when and where the 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). Hourly power plant emissions are regressed on hourly electricity demand in each subregion of the power plant grid interconnection.[8] We do this for each of the 1,486 power plants in the United States and for each CO_2, SO_2, NO_X, and $PM_{2.5}$.

Specifically, we estimate:

$$\begin{aligned} y_{it} = & \sum_{h=1}^{24}\sum_{j=1}^{j(i)}\sum_{m=1}^{12}\beta_{ijhm}\text{LOAD}_{tj} \times \text{HOUR}_h \times \text{eGRID}_j \times \text{MOY}_m + \gamma_{ijhm}\sum_{j=1}^{j(i)} s_{jt} \\ & + \sum_{h=1}^{24}\sum_{m=1}^{120}\sum_{d=1}^{2}\alpha_{ihmd}\text{HOUR}_h \times \text{MOS}_m \times \text{DAY}_d + \epsilon_{it}, \end{aligned} \quad (1)$$

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

7. We assume that there is no rebound effect from solar adoption. Provided utility customers face traditional net metering, the opportunity cost of a unit of consumption 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, our estimates of avoided pollution damages will overstate true damages avoided.

8. Subregions are defined as eGrid subregions, which are geographical aggregations of electricity generators used by the US Environmental Protection Agency 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 New York–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.

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, nonreported generation, we condition on an index of contemporaneous solar generation in each subregion, s_{jt}. This index is determined for each hour of the sample by summing within subregion the product of plant-specific irradiance and plant capacity for all utility-scale solar.[9] An idiosyncratic error is denoted by ϵ_{it}. Equation (1) is estimated by ordinary least squares.

Distinct from Holland et al. (2016), 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 generation mix and in solar generation. It also absorbs average load differentials across weekends and weekdays via the DAY fixed effect. Like Holland et al. (2016), 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 nonreported generation. In particular, heating and cooling energy demand and utility-scale solar generation correlate with solar irradiance. If load increases due to cooling demand when solar generation is greatest, then failure to condition on irradiance would yield marginal emissions estimates that are biased down because observed load would vary more than the net load served by fossil generation.

We lack data on hydro generation, which may be correlated with net load. However, like Callaway et al. (2018), we assume that 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. Nuclear plant generation is likewise assumed to be orthogonal to load conditional on unique hourly fixed effects for each month because refueling and maintenance must be scheduled in advance and last for at least 10 days.

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9. Location-specific irradiance data are reported by the National Solar Radiation Database. We abstract from capacity factors, assuming these are constant conditional on irradiance. Hence, this index reflects variation in solar irradiance and the generation, itself, up to a scaling parameter.

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 US Environmental Protection Agency (EPA) for the years 2007–16, yielding 114.4 million plant-level, hourly observations for each pollutant.[10] 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.[11] Hourly electricity consumption is reported for each of 200 planning areas across the United States in Federal Energy Regulatory Commission (FERC) Form 714 filings. Hourly planning area consumption is aggregated to eGRID regions. 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 United States. 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.[12]

2.2. 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 kilowatt (kW) solar array in each of 30,105 zip codes in the United States using the California Energy Commission module of the System Advisor Model (SAM), 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 United States.[13] Typical system parameters are assumed in modeling system generation. We assume that 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 United States is summarized in figure 1. Summary statistics are reported in the top panel of table 1.

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10. See https://ampd.epa.gov/ampd/. Observations of pollutant emissions greater than six standard deviations from the mean are omitted.

11. See https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei.

12. 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.

13. More information about the typical meteorological year data is available at https://doi.org/10.1016/j.rser.2018.03.003.

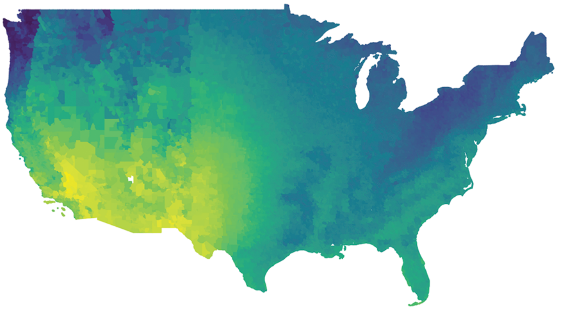

Figure 1. Total annual A/C electricity generation per 4 kW solar capacity. Depicted is modeled annual alternating current (A/C) electricity generation (in MWh) per 4 kW solar capacity for each US zip code. Generation is greatest in the Southwest.

Mean annual generation for a 4 kW system is 6,357 kWh. It varies by a factor of 2 from 4,344 kilowatt-hours (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.

2.3. 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 United States 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 Siler-Evans et al. (2013), Holland et al. (2016), and others.[14] 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 many 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

14. For further description of the AP3 model, see Clay et al. (2019).

Table 1. Summary Statistics

	Mean	SD	Min	Max
Solar generation:				
Annual kWh	6,357.4	656.1	4,344.7	8,647.3
Avoided pollution damages:				
Total annual dollars	568.4	358.1	66.6	1,233.0
CO_2	170.3	76.1	29.1	431.8
NO_x	55.0	35.0	6.6	127.3
$PM_{2.5}$	23.2	18.1	−5.4	580
SO_2	320.0	273.7	1.2	818.0
Subsidies:				
Annual subsidy	663.8	300.3	325.7	2,892.0
Subsidy less damages	95.4	512.6	−809.0	2,180.3
Energy value:				
Total annual dollars	247.0	35.9	138.6	371.1

Note. Annual kWh in the 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 present-day solar subsidies multiplied by annual generation at the zip code level. "Subsidy less damages" reports the difference between subsidy and damages. Positive values indicate oversubsidization. Both lines in the third panel present unweighted averages over all zip codes. The mean annual subsidy weighted by the number of panels in each zip is $987.8. The weighted "subsidy less damages" (where the subsidy and avoided damages are weighted by number of panels) is $728.0. 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.

2006 dollars that is adjusted for inflation using the consumer price index to 2014 dollars. Carbon dioxide emissions, not tracked by AP3, are valued at $41 per ton, the social cost of carbon calculated by the US Interagency Working Group on Social Cost of Carbon as updated in 2016 and reflected in 2014 dollars (IWGSCC 2016).

The spatial heterogeneity of pollution damages is depicted in figure 2, which shows the estimated damages from 1 ton of SO_2 emissions in each county of the contiguous United States. 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. Damages are least in Whatcom County, Washington ($2,005).

2.4. Subsidies

We seek to compare estimated environmental 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

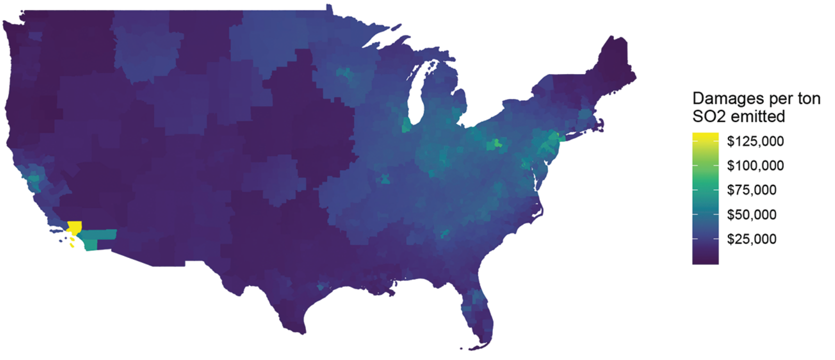

Figure 2. Damages per ton SO_2 emissions by county. Damages per ton of SO_2 are shown by county of pollution source. Damages are estimated by the AP3 model. Darker blue regions reflect relatively low damages. Green to yellow regions are those in which a ton of emissions is costlier.

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 (LBNL) "Tracking the Sun" project (Barbose et al. 2012, 2017). Because the value of incentive programs and the costs of installing panels have changed over time, we compute two subsidy values for each state: (1) current subsidies to reflect the value of today's incentive programs and (2) historical subsidies to reflect the value of time-varying incentives over the actual lifetimes of installed panels.[15] Current and historical subsidy values are calculated as the sum of federal and state incentives discounted at a 5% annual rate over a 20-year lifetime beginning, respectively, in 2017 or the year of installation. More details about subsidy calculations and data sources are reported in the appendix (available online). We report 2017 subsidy levels in table 2 and historical subsidies in table A.3 (tables A.1–A.6 are available online).

2.5. Electricity Value

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 United States. Where independent system operators (ISOs) manage the

15. Many incentives, including the federal ITC and various state incentives, are a function of installation costs. Declining system costs mean that these incentive values have declined over time. Other incentives have also changed over time; some have been introduced and others phased out. Our historical subsidy calculations attempt to account for these changes to allow readers to compare avoided damages and the incentive value at the time current capacity was installed. Our current subsidy calculations, instead, allow readers to compare avoided damages and the incentive value of installing a panel today.

Table 2. State Average Subsidies and Avoided Damages

State	Subsidy	Avoided Damages	Net Annual Subsidy	State	Subsidy	Avoided Damages	Net Annual Subsidy
Massachusetts	.35	.02	1,996	Alabama	.10	.08	98
New Hampshire	.18	.02	980	Wisconsin	.14	.12	94
Rhode Island	.17	.02	959	Virginia	.06	.05	93
Connecticut	.17	.02	943	Minnesota	.11	.10	60
New York	.17	.02	893	Kentucky	.07	.07	4
Vermont	.14	.02	684	Kansas	.10	.10	−4
California	.12	.03	672	Mississippi	.07	.08	−48
New Jersey	.28	.18	586	North Dakota	.09	.10	−52
Arizona	.10	.03	539	Iowa	.12	.13	−56
Oregon	.10	.02	499	Nebraska	.08	.09	−88
Utah	.08	.02	441	Georgia	.07	.09	−90
Maine	.09	.02	407	Louisiana	.12	.14	−135
Montana	.08	.02	406	Oklahoma	.06	.10	−262
South Carolina	.10	.04	398	South Dakota	.05	.10	−284
New Mexico	.08	.03	389	Illinois	.12	.17	−291
Idaho	.07	.02	359	Missouri	.09	.14	−348
Washington	.08	.02	356	Arkansas	.07	.13	−385
Texas	.09	.04	342	Maryland	.12	.18	−419
Colorado	.09	.05	306	Delaware	.11	.18	−478
Nevada	.07	.03	278	Michigan	.08	.17	−488
Wyoming	.06	.02	269	Indiana	.08	.18	−559
Tennessee	.11	.06	258	Ohio	.08	.18	−568
North Carolina	.08	.04	257	Pennsylvania	.08	.18	−607
Florida	.10	.08	130	West Virginia	.06	.18	−685

Note. Subsidy and average avoided damages are reported per kWh. Subsidy streams are discounted to present value at a 5% annual rate. Net annual subsidy is annual subsidy less total annual damages avoided. States are ordered by net annual subsidy.

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.[16] Both data sets were generously provided by Borenstein and Bushnell (2021), who assembled them to measure retail price deviation from the sum of private marginal costs and marginal external costs. We map these local marginal prices and system

16. Information is reported on FERC Form 714 surveys.

lambdas to zip codes using Department of Homeland Security HIFLD maps in order to estimate the value of solar generation in each zip code.[17]

LMPs reflect the sum of two shadow values from the constrained optimization performed by grid operators 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 that 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 (2021) note, FERC Form 714 surveys are not of uniformly high quality, so Borenstein and Bushnell (2021) incorporate data that are deemed most reliable, as described in their paper. System lambdas 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 (2021) 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 (CAISO) and by PJM for 2017. In both cases, "PNode" prices for day-ahead market clearing were employed.[18] Congestion prices are equal to the shadow value on transmission constraints for each network node.

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17. HIFLD maps available at https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-retail-service-territories.

18. For California, individual pricing locations (PNodes) are clustered using a spatial hierarchical clustering algorithm, resulting in 771 unique clusters. Each cluster is spatially defined by the area closest to each of the composite PNodes in a Voronoi polygon. Each cluster's hourly DAM price is a load-weighted combination of its composite PNode prices. The hourly LMP for a zip code consists of the cluster that comprises the plurality of the zip code's area. PNode locations were extracted from a deactivated CAISO-hosted interactive map. Validation of node location via inspection of Google Maps indicated a high degree of correspondence between the extracted coordinates and the spatial location of electricity substations. See Kirkpatrick (2018) for details. For PJM, zip codes are mapped to PNodes according to the mapping file provided on PJM's website: https://www.pjm.com/markets-and-operations/energy/lmp-model-info.aspx. As reported by PJM, this mapping reflects the geographically closest PNode to each zip code but does not necessarily reflect actual power flows. Any error in assigning zip codes to pricing nodes is assumed not to introduce systematic bias in valuing energy or congestion relief.

3. RESULTS

3.1. Estimates of Pollution Avoidance Benefits

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.[19] The empirical model is validated by summing the point estimates of plant emissions across all plants in the interconnection. On average, a 1 megawatt (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.[20] Figures A.1 and A.2 (figs. A.1–A.7 are available online) depict the summation of hour- and month-specific marginal responses across plants in the interconnection of the Electricity Reliability Council of Texas, which delivers electricity to Texas. These are reported for generation and each pollutant. Point estimates are depicted in blue, and 95% 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 A.1*a*, the sum of generation responses across the Texas interconnection is typically bounded between 0.6 and 1.2. During daylight hours (5 a.m. to 9 p.m.), the average response across Texas averages 0.97, with a mean 95% confidence interval of 0.69 to 1.18. Across interconnections, the average generation response is 0.85. Figures A.1*b* and A.2 depict the sum of pollution emissions across the Texas interconnection. These are expected to equal the emissions intensities of marginal responding plants, and the mean sum of these marginal responses is generally consistent with engineering estimates of plant emission rates for marginal responding plants. Some block bootstraps yield smaller marginal emissions responses than one may expect if a polluting plant marginally increases generation. This may reflect sampling uncertainty; these results generally lie outside the 95% confidence region. It may also reflect nonmarginal plant responses to marginal changes in load. We return to a discussion of uncertainty in these parameter estimates in section 3.4.

Given estimated marginal plant responses to changes in net load, 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 estimated at $568 per system per year, or $7,084 in present value terms over the lifetime of a typical 4 kW system.[21] This equates to about half of the average cost of an installed system. A

19. Parameter estimates and standard errors are available from the authors upon request.

20. 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 nonreporting generation. Plant sums may also differ from load changes due to sampling uncertainty.

21. Present value calculation assumes a 20-year lifetime and a 5% discount rate.

majority (56%) of these avoided damages is a consequence of reduced SO_2 emissions. Thirty 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 photovoltaic (PV) panels are presented for each zip code in figure 3. It shows the annual environmental damages avoided per 4 kW capacity of solar in each zip code in the United States. These avoided damages are greatest for systems installed in the Midwest and Mid-Atlantic states, including Delaware, Indiana, Maryland, 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 $92 in Klamath along the northern coast to $277 in Desert Hot Springs, located 100 miles east of Los Angeles.

Figure 3 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 3. 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% of 2014 electricity generation in the Western Interconnection (WECC) that serves the Mountain West and West Coast; 30% of generation was supplied by natural gas units. In the Midwest Reliability Organization that manages the Midwest grid of the Eastern Interconnection, coal constituted 60% of generation, while natural gas units supplied just 5% (NREL 2017). The relative dependence upon coal in the Eastern Interconnection makes it relatively likely that marginal responding plants

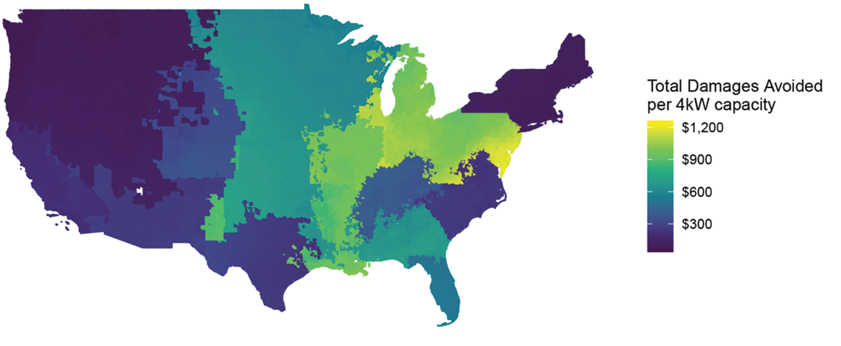

Figure 3. Total annual avoided environmental damages per 4 kW solar capacity. Zip-code-specific annual avoided pollution damages from 4 kW capacity in dollars. Darker shades of blue indicate lower annual damages. Brighter green to yellow regions indicate greatest pollution damage avoidance.

are coal plants. Moreover, avoided pollution emissions in the Eastern Interconnection reduce exposure of large populations in the greater Washington, DC, area, Boston, Philadelphia, and New York, making emissions reductions valuable. Such heterogeneity in the value of emissions reductions is shown in figure 2, which depicts the variation across the United States in damages from 1 ton of SO_2 emissions.

The second-best Pigouvian subsidy to solar generation and solar capacity is equal to the marginal external environmental benefits plus other marginal external benefits, which may include reduced congestion on the electricity grid and learning-by-doing adoption externalities. As we report later in this section, solar capacity does not generate congestion benefits measurable by local marginal prices, a finding consistent with Cohen et al. (2016), who estimate very small marginal benefits to the distribution grid of less than one-half cent per kWh. Likewise, Bollinger and Gillingham (2019) estimate only "very small learning spillovers" in solar installation. Given that the value of these other external benefits are small and unlikely to be negatively correlated with environmental benefits, optimal subsidies should correlate with environmental benefits. Yet we find environmental benefits and subsidies are negatively correlated in our data ($\rho = -0.17$).

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 $0.02. For a 4 kW system, the subsidy received by the typical installed system exceeds avoided environmental damages by $1,996 per year, or $25,000 over the system lifetime. The least generous subsidy was received by investors in South Dakota, where the average $0.05 per kWh subsidy is less than half as large as environmental benefits. Solar generation receives a subsidy that is $0.06–0.12 per kWh less than avoided damages in Maryland, Delaware, Michigan, Indiana, 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 $0.12/kWh exceeds avoided environmental damages by nearly 500%. The mean subsidy across US zip codes is $0.11/kWh.

On average, subsidies are approximately equal to damages across states, but more than 25% of states provide subsidies that are at least $0.05 per kWh less than avoided damages. Another 25% provide subsidies that are too generous by at least $0.05 per kWh. Nearly 90% of the observed installations are in the most heavily oversubsidized states, with nearly two-thirds in California alone. Thus, when subsidies and damages are weighted by installed capacity, per-system subsidies exceed avoided environmental damages on average by several hundred dollars annually. The weighted average subsidy of $988 per year (per system) is approximately 380% of the weighted average environmental benefit, and 83% of the average system cost. These results are summarized in table 2, which reports by state estimated mean avoided environmental damages and subsidies per kWh of installed capacity and total annual net subsidy.

Subsidies have generally declined over time as system costs have fallen. Subsidy levels in Maryland, Pennsylvania, and Ohio were historically much closer to environmental benefits due to several years of high SREC prices, whereas subsidy levels in 2017 considerably undervalued environmental benefits. Other states that offer generous subsidies today offered substantially greater subsidies in the past, as summarized in table A.3.

3.2. Gains from Capacity Reallocation

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 United States is equal to $375.7 million per year. Installed capacity locations are shown in figure 4.[22] In order to assess the degree to which capacity is misallocated, we simulate environmental benefits under four alternative reallocations of existing systems in the United States. First, we imagine that all systems are reallocated 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 US census counts of detached, single-family houses by zip code (US Census Bureau 2017). Second, we restrict this intrastate reallocation by limiting to 30% 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).[23] A third simulation considers a national reallocation of solar capacity. And finally, the national reallocation is restricted in a fourth simulation to no more than 30% 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.

Results from these simulations are reported in table 3. The most conservative simulation we consider reallocates solar capacity within states to 30% of rooftops in zip codes that yield the greatest environmental benefits. This reallocation generates a

22. Panel locations are reported at the zip code level by LBNL's "Tracking the Sun" program. These data are aggregated from administrative and industry group data. LBNL disclosure agreements with various data providers preclude public reporting of 3% of panel locations. Thus, our data reflect 97% of installed panels.

23. 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% or more renewable generation (North Carolina Clean Energy Technology Center 2018).

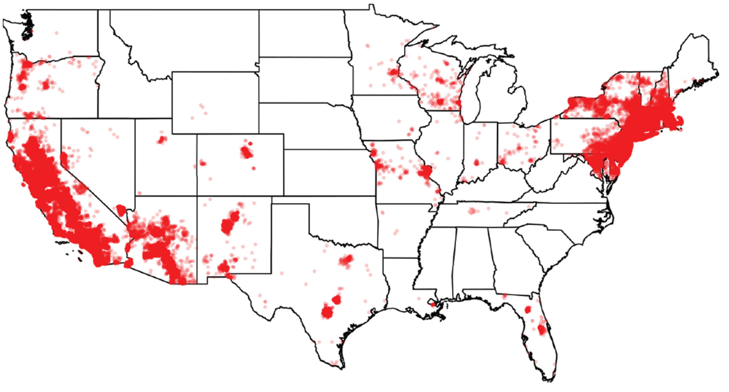

Figure 4. Installed rooftop solar arrays. Depicted in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays. Locations with fewer than 10 arrays per zip code are not depicted.

12% 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 5. Of the 12,840 zip codes across the United States in which rooftop capacity is currently installed, 90%—all but 1,296—would lose all capacity under a constrained intrastate reallocation. Of the 1.45 million rooftop arrays installed across the United States, 90% 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 17% greater environmental benefits, yielding a $63 million gain each year over existing capacity.

Table 3. Simulated Allocations of Installed Solar Capacity

	Installed Capacity	Interstate Reallocation	Interstate Reallocation Subject to Grid Stability	Intrastate Reallocation	Intrastate Reallocation Subject to Grid Stability
Total avoided damages (in millions USD)	375.7	1,687.7	1,641.5	438.3	421.0
Number of zip codes	12,840	471	1,540	463	1,296
Mean avoided damages (in USD/4 kW system)	490.0	1,171.5	1,136.3	355.4	333.6

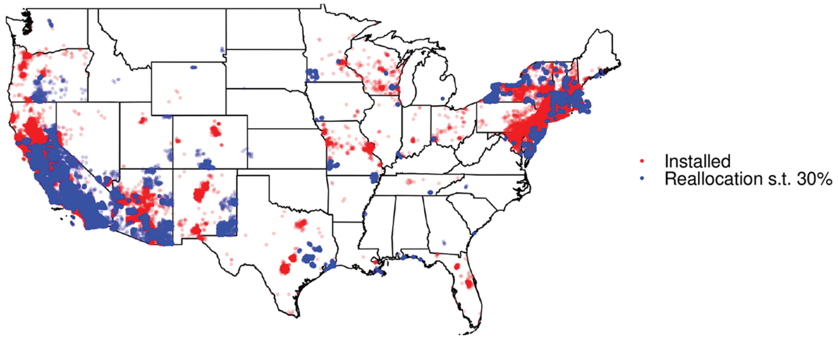

Figure 5. Intrastate reallocation of solar capacity subject to grid stability concerns. Depicted in blue are solar capacity locations following intrastate reallocation subject to grid stability concerns limiting solar to 30% of rooftops in any zip code. Shown in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays.

Reallocating capacity across state lines yields nearly a fivefold gain in environmental benefits, increasing annual benefits by $1.3 billion regardless of grid stability constraints. If solar were limited to 30% of zip code rooftops, it would optimally be allocated to only 1,540 zip codes in 10 states—Delaware, Illinois, Indiana, Maryland, New Jersey, Pennsylvania, Tennessee, Virginia, Wisconsin, and West Virginia. This is depicted in figure 6. Environmental benefits from solar capacity would be maximized subject to grid concerns

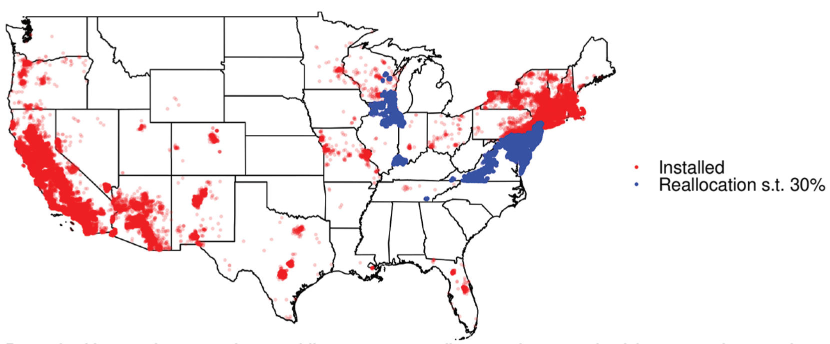

Figure 6. Interstate reallocation of solar capacity subject to grid stability concerns. Depicted in blue are solar capacity locations following interstate reallocation subject to grid stability concerns limiting solar to 30% of rooftops in any zip code. Shown in red are locations of installed solar capacity. Each dot represents 10 rooftop arrays. Dots are depicted in diminished opacity so that darker colors indicate greater density of arrays.

by adding 263,000 arrays to Illinois rooftops, only about 1,000 of which currently have solar panels. Maryland would also gain more than 350,000 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 $0.03 in environmental benefits per kWh compared to benefits as large as $0.18 on the East Coast.

The foregoing simulations seek to optimize only environmental benefits. We report below the results of simulations that seek to maximize the sum of energy value and environmental benefits. We are not aware of evidence about how learning by doing or benefits to distribution systems vary across space. In the event these were negatively correlated with environmental benefits, then the gains in environmental benefits from reallocation of solar capacity in our simulations overstate efficiency gains by sacrificing these other solar capacity benefits.

3.3. State 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 that states or regional governments generally may also underinvest 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 A.6 and reported in table 4. Benefits from reduced CO_2 emissions are not included in appropriated shares as the assignment of benefits to specific locations would require strong assumptions that are not similarly required to assign benefits from reductions in local air pollution. Given the globally mixing nature of CO_2, shares of locally appropriated benefits are likely to be arbitrarily small if valued on a per capita basis at the US social cost of carbon. Across states, the mean share of local environmental benefits appropriated in the state that generates the benefits is 14%. Appropriated benefit shares are less than 1% in Arkansas, Delaware, Mississippi, Montana, Nebraska, North Dakota, South 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

Table 4. In-State versus Out-of-State Environmental Benefits

State	In-State Annual Benefits	Out-of-State Annual Benefits	Percentage In-State	State	In-State Annual Benefits	Out-of-State Annual Benefits	Percentage In-State
Florida	212	127	63	Wisconsin	13	522	2
Pennsylvania	160	703	19	Louisiana	11	741	2
Ohio	83	741	10	Delaware	8	939	1
New York	72	–6	108	Kansas	8	318	3
Georgia	65	311	17	Minnesota	8	391	2
New Jersey	63	846	7	Iowa	7	590	1
North Carolina	59	78	43	Arizona	7	75	8
Maryland	52	885	6	N. Hampshire	5	61	8
Kentucky	44	282	13	Arkansas	5	568	1
Texas	43	40	52	Rhode Island	5	59	8
Illinois	36	802	4	Maine	4	66	6
South Carolina	34	84	29	Mississippi	3	357	1
Michigan	34	750	4	Washington	2	26	8
Massachusets	32	29	53	Nevada	2	78	3
California	32	7	82	New Mexico	2	84	2
Alabama	30	321	9	Vermont	1	72	2
Missouri	28	664	4	Nebraska	1	404	0
Indiana	28	844	3	Utah	1	34	3
Virginia	27	133	17	Oregon	1	28	3
West Virginia	24	842	3	Idaho	0	31	1
Tennessee	20	281	7	South Dakota	0	417	0
Colorado	17	91	16	Wyoming	0	53	1
Connecticut	14	45	24	Montana	0	30	1
Oklahoma	14	310	4	North Dakota	0	395	0

Note. Reported are annual average avoided local pollution damages that accrue in state vs. those that accrue out of state. "Percentage In-State" indicates the percentage of total benefits accruing in the local, adopting state. States are ordered by magnitudes of in-state benefits. Benefits exclude CO_2 benefits that cannot be assigned to specific locations.

all benefits in the state.[24] California and Florida capture 82% and 62% of benefits, respectively, while Massachusetts and Texas each capture greater than half of all benefits from capacity investments. Massachusetts captures a large share of benefits despite the

24. Our estimates suggest that the typical New York array generates harms out of state, an effect that is theoretically possible because a relatively clean generator may adjust supply in a noncontinuous fashion due to load changes, allowing a relatively dirty generator to increase supply.

relatively small size of the state because it has a large population that benefits from reduced power plant emissions in surrounding states. Florida captures an estimated $212 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% of total benefits. A typical 4 kW system in California generates $32 in avoided pollution benefits annually for the state.

California, Colorado, Florida, Georgia, New York, North Carolina, Pennsylvania, and Texas each capture a greater share of their 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 36 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 greater than four to one. Table A.1 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 Illinois, Indiana, Louisiana, Michigan, New Jersey, Ohio, and West Virginia. A typical system in each of those states avoids more than $100 of environmental damages annually for Pennsylvania.

Given the transboundary distribution of avoided pollution benefits from solar capacity investments, states' optimal capacity investments may be located in other states. Therefore, we relate each state's maximum local pollution benefits from in-state capacity to the maximum local pollution benefits regardless of capacity location. Local pollution avoidance benefits of out-of-state capacity are greatest for all but eight states—California, Colorado, Delaware, Florida, Georgia, Oklahoma, South Carolina, and Texas. Local pollution avoidance benefits to Mississippi are estimated to be four times greater from capacity in New Mexico rather than Mississippi. Twelve other states, including Idaho, Minnesota, Oregon, and Vermont, also receive local benefit gains of 100% or greater from out-of-state capacity investments. Likewise, benefits to Connecticut, New York, and four other states are estimated to be at least 50% greater from nonlocal capacity. On average, the local pollution avoidance benefits appropriated by a state are 58% greater from optimal siting across state borders. These results, summarized in table 5, reveal forgone local environmental benefits from state subsidy and renewable portfolio standards regimes not crediting out-of-state capacity that reduces in-state pollution exposures. State maximization of local, appropriated benefits implies solar capacity investments in only 12 states.

3.4. Energy Value

Though policy is justified by nonappropriated environmental benefits, the value of solar capacity depends also upon the energy value of generated electricity. This varies

Table 5. Environmental Benefit Gain from Out-of-State Capacity Relative to In-State Capacity

State	Max. State Benefit Site	Percentage Benefit Gain	State	Max. State Benefit Site	Percentage Benefit Gain
Mississippi	Georgia	404	Rhode Island	Delaware	18
North Dakota	Missouri	265	North Carolina	South Carolina	18
Nebraska	Oklahoma	202	New Hampshire	Delaware	17
Montana	Colorado	200	Missouri	Oklahoma	16
Utah	Colorado	124	Ohio	Delaware	15
Vermont	Delaware	124	Louisiana	Oklahoma	15
Arkansas	Oklahoma	121	Pennsylvania	Delaware	10
Oregon	Colorado	121	West Virginia	Delaware	9
South Dakota	Missouri	117	Nevada	New Mexico	7
Idaho	Colorado	113	New Jersey	Delaware	4
Wyoming	Colorado	105	Kansas	Oklahoma	3
Virginia	Delaware	102	New Mexico	Colorado	2
Minnesota	Missouri	100	Massachusetts	Rhode Island	2
Illinois	Oklahoma	89	Kentucky	Tennessee	1
Tennessee	Missouri	64	Arizona	New Mexico	1
Washington	Colorado	64	Maryland	Delaware	1
New York	Delaware	61	California	California	0
Connecticut	Delaware	51	Colorado	Colorado	0
Alabama	Georgia	50	Delaware	Delaware	0
Iowa	Oklahoma	49	Florida	Florida	0
Maine	Delaware	42	Georgia	Georgia	0
Wisconsin	Missouri	35	Oklahoma	Oklahoma	0
Indiana	South Dakota	31	South Carolina	South Carolina	0
Michigan	South Dakota	18	Texas	Texas	0

Note. Reported for each state is the percentage gain in appropriated local environmental benefits from benefit-maximizing out-of-state capacity relative to in-state capacity. Also reported for each state is the state in which capacity benefits are maximized. States are ordered by the percentage gain from optimal out-of-state capacity siting. Benefits exclude CO_2 benefits that cannot be assigned to specific locations.

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 in energy value introduced 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 A.2 reports the average annual energy value of solar capacity and total benefits by state. Energy value is greatest in Connecticut, Delaware, Maine, and Rhode Island, where it is equal to \$324–\$344 for a 4 kW system. Energy value is least in Minnesota, North Dakota, and Oregon, 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 $262. 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 $1,416 to $1,491. 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. A 4 kW system in Maryland is worth $15,000 more in present value than a system in Oregon. Annual energy and environmental benefits of California capacity are an estimated average $452. Energy value and estimated environmental benefits are modestly negatively correlated across the United States ($\rho = -0.14$). Though energy value is, in principal, appropriable by solar investors, we nevertheless report results from capacity reallocations intended to maximize environmental benefits and energy value in table A.4. Gains are approximately equal to those from reallocation according to environmental benefits alone, reflecting greater heterogeneity in environmental benefits than energy value.

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 employ hourly LMPs and congestion prices in 2017 to assess whether installed capacity in California avoids transmission costs. 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 likely 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, we estimate that the average rooftop solar array in California does not generate congestion relief benefits. The annual value of congestion relief benefits is $–1.09, indicating that the typical system is installed at a node commonly 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 is estimated to have generated some of the most valuable electricity in the state, valued at as much as $286,500 in 2017. Figure A.3 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% of total energy value generated by those systems. It is 2.7% 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, forgoing $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 energy value, inclusive of congestion value, to one of high energy 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.[25] Any sizable reallocation of rooftop solar capacity to high value network nodes causes prices to converge, lowering the 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% of zip code rooftops, mitigating grid stability concerns. Energy value of installed capacity is estimated to increase by $15 million per year or 8.5% of current energy value.

Similarly in the PJM territory that serves 13 Midwest and Mid-Atlantic states, installed rooftop solar capacity is estimated to likely contribute to congestion rather than relieve it. Among the reported PJM rooftop arrays, the average congestion value is negative, implying injections of power into the grid during times of congestion where it is least valued upstream of a bottleneck. The annual congestion value of reported systems is –$755,000, less than the expected value that would have been achieved by random capacity assignment. Reallocation across PJM nodes to maximize energy value subject to grid stability concerns yields as much as $4.2 million in congestion relief benefits. Unconstrained reallocation yields up to $6.2 million in congestion-relief benefits, 35% of total energy value, or as much as $73 per system per year.

Because wholesale electricity prices are not generated for distinct locations along distribution networks, as they are for locations along transmission networks, we cannot ascertain whether marginal solar generation alleviates constraints along the distribution system or generates other benefits to the grid. Hence, we can only identify heterogeneity in the energy value of solar across FERC planning areas or across transmission nodes in California and the PJM territory.

3.5. 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

25. A 5% discount rate is assumed.

observational records at select solar sites. The SAM model exhibits an annual error of ±5%, 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%.

By assuming systems are oriented south as necessary to maximize solar generation, we overestimate solar generation potential of panels that (1) are not oriented due south due to rooftop characteristics, or (2) experience shading due to vegetation or surrounding structures. Panel orientation, or azimuth, is reported in state administrative records for approximately 130,000 residential solar arrays in California. For these systems, 50.5% are oriented within 15 degrees of due south, and 75% are predominantly oriented south with azimuths within ±45 degrees. The distribution of azimuth for these panels is shown in figure A.7. We can also relate our model generation to actual system generation for 500 systems in California for which monthly generation and zip code are reported in state records. For each of these zip codes, we relate our zip code and month-specific model estimates of generation per unit capacity in a typical meteorological year to the month-specific average generation of systems installed in corresponding zip codes. Relative to generation of these installed systems, our model overestimates generation by approximately 6%. This, in turn, suggests that our estimates of environmental benefits are overstated by approximately 6%.[26] This implies that the optimal Pigouvian subsidy that we estimate may be 6% too high.

Second, the 13,724,160 marginal emissions parameters are also estimated with uncertainty. To assess this uncertainty, we estimate for Texas and the western United States marginal plant response to marginal net load changes from 750 bootstrap samples blocked by day and drawn with replacement. For each block-bootstrap sample, all plant emission responses are estimated. This uncertainty is depicted in figures A.1 and A.2 for the sum across Texas generators of plant-specific emissions and generation responses to a 1 MW change in net load. The sum of marginal emissions responses generated from each bootstrap sample is depicted in gray for each hour of the day and each month of the year. The mean across these estimates is depicted in blue, and a 95% 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 avoided emissions

26. Because our model generates estimates of avoided environmental damages that are unique by hour of day and type of day, i.e., weekend or weekday, and because variation in system orientation may affect the diurnal profile of generation, environmental benefits may vary more or less than proportionate to the monthly variation in model and observed system generation. However, as the distribution of system azimuth is approximately symmetric around 180 degrees, variation in diurnal profiles of systems with azimuth greater than 180 degrees should be offset by systems with azimuth less than 180 degrees. Thus, it seems likely our estimate of environmental benefits is overstated by at most 6%.

from zip-code-specific solar generation is characterized by sampling from the bootstrapped distribution of plant emissions coefficients. The 95% confidence intervals of these 30,105 avoided emissions estimates for each pollutant are available from the authors upon request. In Texas, the mean standard deviation across zip codes in total damages avoided by a 4 kW solar array is $3.75, less than 2% of average total damages across Texas ($200.84). Across the western United States and Texas, the standard deviation in mean damages across zip codes is nearly six times greater than the average standard deviation of bootstrapped zip code damages, which is equal to 6.8% of average damages across the regions. 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 solar capacity.

Uncertainty in gains from solar capacity reallocations is assessed by reallocating capacity according to our point estimates of marginal emissions responses, which determine the estimated damages avoided by capacity in each zip code. We simulate the gains from these reallocations of capacity for each of the 750 bootstrap samples in Texas and the West in order to reflect the uncertainty associated with gains from a given capacity reallocation. The estimated gain from unconstrained reallocation across the WECC is $144 million, the standard deviation of gain is $38 million, and the 95% confidence interval of gain is $69–$217 million. Likewise, intrastate reallocations within Texas and the states comprising the Western Interconnection yield gains that are statistically significant with 95% confidence. These results are summarized in table A.5.

Third, 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.

We consider, in particular, the sensitivity of our results to the assumed value of a statistical life (VSL), as this is a critical determinant of the level of benefits from reduced air pollution emissions. The EPA's preferred VSL of $7.4 million ($2006) is an average of estimates from 26 studies, most of which are drawn from the revealed preference (hedonic wage) literature. Because in AP3 the VSL is applied uniformly to risks faced by all persons, regardless of age, income, or other demographics, our estimated benefits of avoided pollution scale proportionately to the VSL. Consequently, we can readily consider how our results would differ according to alternative VSL assumptions. For instance, the mean annual avoided damages from a 4 kW system would be $284 rather than $568 if the VSL were 50% smaller than we assume. The present value of the system would decline to $3,542. Subsidies in California would exceed environmental benefits by

700% (as opposed to 300% in our baseline estimates). And the weighted average system subsidy would exceed environmental benefits by 865%. In contrast, if the VSL were 50% larger than we assume, then estimated avoided damages would equal or exceed subsidies in 28 states, and the weighted average subsidy would exceed avoided damages by only 40%.

Because any change to VSL scales proportionately to damages, the gains from reallocation of panels will not scale proportionately. In particular, a 50% reduction in the VSL will reduce the gains from panel reallocation by greater than 50% because avoided damages decline more in high-value (high-avoided damages) areas than in low-value areas. Conversely, the gains from panel reallocation increase more than proportionate to the increase in VSL. A reduction in VSL increases the energy value of solar panels as a share of total benefits, but in only six states would even a 50% reduction in the VSL cause the dominant source of benefits to switch from avoided damages to energy value.

Finally, our empirical estimates of marginal emissions coefficients for each plant allow 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, 2016. 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 or diffusion of grid-connected technologies like electric vehicles. There are reasons, however, to expect that 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 that 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 2010–12 and 2014–16, 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 United States diminishes the gains from efficient capacity siting across interconnections.

We consider the sensitivity of our results to the evolution of grid infrastructure and generating technologies by separately estimating marginal emissions over the period 2012–16. Notably, this is a period of low natural gas prices induced by expansion of domestic gas production. It caused an increase in gas-fired electricity generation and a decline in coal-fired generation. Estimates of annual pollution damages avoided by solar capacity derived from these marginal emissions estimates are reported in table A.6. The value of total annual pollution avoided by a 4 kW system is $127 lower ($473) than when estimated over our full sample of data. This reflects a decline in avoided sulfur dioxide harms equal to $108, a consequence of the substitution of relatively low-emitting natural gas generation for coal generation.

Also, to the extent that pollution emissions are restricted by binding emissions caps, as intended by some EPA programs and state carbon policies, 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. The stringency of such policies in the future is another source of uncertainty. To the extent that they become more stringent and caps bind, the value of avoided emissions estimated here declines.

4. 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."[27] This paper shows that distributed decisions nationwide have produced an installed capacity of more than 1.4 million rooftop solar arrays that neither maximized energy value of solar generation nor avoided damages from fossil-fuel generation. This constitutes a misallocation of solar capacity provided the cost of solar capital does not correlate with environmental gains. They do not. Lawrence Berkeley National Laboratory reports system costs and system sizes for 18 states from 2009 to 2018. These data reveal that capital costs are negatively correlated with our estimates of avoided pollution damages ($\rho = -0.15$), energy value ($\rho = -0.01$), and total value ($\rho = -0.15$). The misallocation of solar capacity chiefly sacrifices environmental benefits that vary across the United States mostly due to heterogeneity in the technologies of marginal responding fossil generators and their locations relative to population centers.

The allocation of solar capacity in the United States may partly reflect heterogeneity in solar demand among adopters. However, solar electricity is indistinguishable from fossil-fuel generation in end use, and investment returns from capacity investments should be valued relative to other investment opportunities that presumably do not vary by the environmental benefits of solar capacity. Therefore, any heterogeneity in demand for solar must be attributable to preferences for private provision of public goods or for signaling benefits that accrue to solar adoption. While preferences for environmental protection may vary across states, any such preferences are presumably best satisfied by investment in solar capacity that maximizes these benefits, regardless of location. In particular, altruism is commonly defined as utility over the aggregate provision of a public good, and "warm glow," or "impure," altruism is defined as utility over one's own provision of a public good. Such preferences, thus, depend upon the environmental benefits generated by solar investments and, therefore, do not explain high rates of

27. See http://articles.latimes.com/2011/jul/26/business/la-fi-small-renewables-20110726.

adoption in low-benefit locales. Individuals could, instead, make such investments in high-benefit locales regardless of where they reside. Likewise, while there is yet no evidence in the economics literature of utility from signaling solar panel adoption, the benefits of such signaling and preferences for those benefits may negatively correlate with environmental benefits of solar adoption. Reallocation of panels may, then, sacrifice some utility from signaling. Such utility, however, could presumably be derived from the signaling of capacity investments where environmental benefits are greatest, not necessarily on one's rooftop.[28]

For these reasons, solar capacity allocations likely reflect the fact that federal, state, and local policies distort the prices private investors receive. No solar policy accounts for heterogeneity in environmental benefits, and, 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 that private investments fail to maximize these benefits.

Policy also distorts prices private investors receive for the energy value of their generation, which is appropriable. 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 or systems installed in the most populous US grid-operator territory help to alleviate congestion, even though congestion relief is a purported benefit of distributed solar capacity.

The forgone 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. 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

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28. Moreover, the literature on conspicuous consumption and positional goods yields a conclusion that such expenditures reduce welfare by inducing wasteful expenditures. Thus, the sacrifice of such opportunities may not diminish the gains from siting solar panels where their environmental and energy values are greatest.

investments in capacity like those made by regulated utilities or utility-contracted independent generators.

These results also highlight a cost of policy preferences that favor within-border renewable energy generation over renewable electricity imports or displacement of upwind fossil generation. 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 is estimated to 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. Substantial spillovers of solar capacity benefits also suggest that the EPA's Cross State Air Pollution Rule, which 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.

Given our estimate that states capture only an average 15% of the local pollution benefits generated by solar capacity investments within their respective borders, states intending to improve air quality for their respective residents may optimally employ policy instruments other than solar subsidies.[29] Holland et al. (2016), for instance, estimate that only 19% 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. Substantial benefit spillovers also suggest that state investments in solar capacity 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 subsidize at the lowest rates.

5. 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 United States and demonstrates that existing solar capacity is poorly situated to maximize these benefits or the energy value of solar generation. The typical rooftop solar array in the most populous state and electric grid region yields no congestion relief to the electric grid. Thus, electricity-generating capacity investments by

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

households given historical subsidies sacrifice environmental value relative to investments made by an informed planner. The vast majority of environmental benefits are estimated to accrue outside of states in which investments are made, and most states are estimated to optimally promote capacity at out-of-state locations in order to maximize local air quality benefits to their residents. Such substantial benefit spillovers diminish state incentives for solar generation absent interstate agreements or credit markets and posit a role for federal 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 that persistence of a widespread policy preference for rooftop over utility-scale solar reflects objectives other than least-cost pollution avoidance.

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