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Siting Solar PV Capacity to Maximize Environmental Benefits

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Abstract

The environmental benefits of solar electricity generating capacity vary across the U.S. according to solar irradiance, weather, conventional generation fleets, grid characteristics, and population. Though the 1.1 million distributed solar generation systems installed in the U.S are incentivized by local, state and federal programs, virtually none of these varies subsidies according to expected environmental benefits, which, to our knowledge, have not previously been estimated. This paper, therefore, develops a systematic and theoretically consistent measure of the spatially-differentiated environmental benefits of solar capacity across the U.S. These benefits, equal to $6,200 over the lifetime of a typical 4 kilowatt capacity system, are related to the federal and state subsidies that subsidize the typical system in excess of these benefits by $5,400. Yet, in 25% of zip codes, rooftop solar is under-subsidized by as much as $6,200. The magnitude of foregone environmental benefits due to suboptimal siting of solar capacity are estimated at as much as $1.2 billion annually.

JEL: Q42, Q48, Q51, Q52

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1 Introduction

Amid concerns about the depletion of fossil fuels and the unpriced damages their combustion imposes upon human and environmental health, authorities throughout the world promote renewable electricity generation technologies that can substitute for polluting power plants.

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In the United States and other Western countries, policy favors the small-scale, renewable generation of electric utility customers over large-scale generation undertaken by utilities and independent power generators. By 2016, solar PV was installed at 1.1 million U.S. homes, and distributed solar capacity totaled 11 gigawatts (GW), about 40 percent of total solar capacity nationwide. All states boasted at least 1 megawatt (MW) of distributed solar capacity except Alaska, North Dakota and South Dakota. Though solar accounted for 26 percent of U.S. electricity generating capacity additions in 2015, it constituted less than 2 percent of total generating capacity and provided only 0.6 percent of electricity generation (EIA 2016a, EIA 2016b).

Policy support for renewables is justified as second-best policy in the absence of pollution pricing. In the U.S., solar PV capacity additions are promoted by a federal investment tax credit equal to 30 percent of system cost. In addition, more than 30 states provide subsidies for distributed solar capacity. And 41 states subsidize distributed generation through net metering policies that compel utilities to buy excess distributed generation at rates exceeding wholesale prices. Municipalities and utilities also offer various incentives for distributed, or "rooftop" solar capacity.

The benefits of solar capacity vary by location for several reasons. First, the potential generation of a given unit capacity varies by weather and solar insolation, which varies systematically across the U.S. because of positioning relative to the sun. But capacity benefits also vary in idiosyncratic ways because of site specific characteristics, including shading from trees and buildings and directional and angular positioning of PV systems. Second, conditional on unit generation, benefits vary according to which alternative electricity generation is displaced by solar power. The marginal emissions of electricity demand vary across the U.S. according to characteristics of the electricity generation fleet and power flows (Zivin et al. 2014; Holland et al. 2015). For instance, a unit of generation that displaces relatively clean natural gas-fired electricity generation is less valuable from an environmental perspective than is a unit of solar generation that displaces production from a relatively dirty coal plant. Even conditional on fossil generation displaced, the value of avoided emissions will vary based upon the deposition of the emissions and exposed populations.

Hence, while intuition suggests Southwestern localities yield the greatest return from solar capacity investments due to their relatively high solar irradiance, solar installations in less sunny locations in the Northeast or Mid-Atlantic may yield greater environmental benefits because they displace dirtier generation that deposits emissions on larger populations. Moreover, because of heterogeneity in solar capacity benefits and the nature of air pollution flows, a jurisdiction's optimal policy may be to subsidize solar capacity outside the jurisdiction rather than within it.[1]

Despite the potential for sizable variance in the social (external) value of a unit of solar capacity, virtually none of the subsidy programs implemented in the U.S. at local, state, or federal levels accounts for this heterogeneity. Moreover, to our knowledge, none of the subsidy programs sets subsidies equal to external benefits as is necessary for efficient policy (e.g., Borenstein 2012; Pigou 1920). In fact, we are aware of no attempt by regulators or researchers to systematically and rigorously estimate the magnitudes of environmental benefits from solar capacity and generation. As a consequence, solar may be over-subsidized in some jurisdictions, yielding too much capacity, and under-subsidized in others, yielding too little capacity. Further, within jurisdictions, environmental benefits may be sacrificed by suboptimal siting of installed capacity.

[1] Solar capacity and generation may also vary spatially due to constraints in the transmission and distribution of electricity, rendering distributed solar capacity downstream of congestion more valuable than that which is located upstream. We abstract from these considerations for the time being for two reasons. First, it is difficult to systematically estimate the value to the grid because this value varies according to the specific characteristics of the grid at each location. In future work, we intend to price the value to the grid using locational marginal prices determined in markets operated by some independent system operators or regional transmission operators. Second, as Borenstein (2008) and others have noted, there is no evidence yet that distributed solar capacity has generated any value to the grid beyond the value of the generation. Admittedly, this is potentially attributable to capacity incentives that do not reflect value to the grid.

Therefore, this paper builds upon previous econometric modeling of marginal emissions (i.e., Zivin et al. 2014; Holland et al. 2015) to derive the first systematic, theoretically consistent, and empirically valid estimates of the spatially varying environmental benefits of solar PV capacity and generation. Unique, dollarized estimates of avoided environmental damages are generated for each of 30,105 zip codes across the U.S. These avoided damages are compared to the combined value of state and federal subsidies to solar capacity and generation in order to assess the efficiency of existing solar policy. Further, the magnitude of total environmental benefits from the existing stock of solar capacity is estimated using zip-code-level observations on virtually all installed systems. Finally, alternative siting of installed capacity is simulated to estimate the value of environmental benefits sacrificed to suboptimal siting.

We find that, on average, the sizable subsidies to solar generation exceed the value of environmental benefits by $5,400 for a typical 4 kilowatt (kW) system. Variation in environmental benefits is attributable chiefly to variation in avoided pollution exposure conditional on generation. That is, variation in regional generating fleet and emissions deposition dominate variation in solar irradiance. The most valuable sites for solar PV, therefore, are located in southeast Virginia and New Jersey, where subsidies are too low. If the fleet were optimized across the U.S. irrespective of state or electric grid region, then $13 million in annual environmental benefits would grow to $1.2 billion, even accounting for grid stability concerns that limit solar concentration at any locale.

The inefficiency of distributed solar siting contrasts with the relative efficiency of utility-scale capacity. Thus, this research suggests that while proponents of distributed generation celebrate the decentralized decision-making afforded by distributed energy resources (DERs) and the independence they provide from regulated utilities, such decentralization and independence comes at the cost of efficiency.[2] In fact, an economic

[2]California Governor Jerry Brown remarked in 2011 about his goal of 11GW of renewable DERs that,

rationale for the preferential treatment of distributed solar capacity is not straightforward and virtually unexplored. The billions of public dollars devoted to such policies, however, are expected to induce a transformation of the electric power industry likened in scope and magnitude to that which remade the telecommunications industry beginning in the 1980s (e.g., EEI 2013; NRRI 2015).

Before considering the implications of siting efficiency for the economics of utility-scale and rooftop solar PV capacity, this paper first considers in the next section the theory of optimal solar siting and efficient policy. Then, in Section 3, the data and empirical methods are introduced. Model results and simulations are presented in Section 4. And a final section considers the implications of these results for solar policy, including the policy preference for DERs.

2 Policy Design for Optimal Solar Siting

The primary rationale for government intervention in the market for solar capacity and generation is the unpriced cost of pollution from coal and natural-gas-fired electricity generation for which solar generation can substitute.[3] Power plant emissions include global pollutants like carbon dioxide (CO2) that contribute to global warming and local pollutants like nitrous oxides (NOX), sulfur dioxide (SO_2), and particulates ($PM_{2.5}$) that impose human health damages according to their regional deposition. Electric power generation emits one-third of anthropogenic greenhouse gases, 60 percent of sulfur dioxide, and 13 percent of nitrous oxides in the United States (U.S. Environmental Protection Agency 2012). It is the largest producer of carbon emissions around the world. Solar electricity generation, in

"This is tens of thousands of little decisions. The distribution is its strength and also its challenge."

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

contrast, emits no pollution, but its supply is constrained by the availability of sunlight. The feedstock for solar generation is free, so variable costs are nil. Still, high fixed costs make solar more costly than all other forms of power generation except offshore wind (Energy Information Administration 2013; Borenstein 2012). Consequently, solar's small share of electricity generation has been induced by favorable policy regimes that date to the oil embargo and energy crisis of the 1970s.

Economists agree that the efficient solution to such externalities is a tax on emissions equal to their marginal damages, or a tradable permit system that attains an equivalent permit price (e.g., Borenstein 2012; Pigou 1920). Were such a tax imposed, the pollution externality would be internalized by the plant operator and the cost of dirty electricity would rise. Solar generation, which emits no pollution, would become relatively cheaper. However, such pollution taxes are uncommon. Instead, command and control regulations are the norm in jurisdictions that regulate pollution at all.

In the absence of policy that fully corrects the pollution externality, solar generation is undervalued; it displaces a portion of dirty electricity generation and avoids attendant pollution, the benefits of which do not accrue entirely (or even largely) to the solar electricity generator (Baker et al. 2013). Thus, much as the negative externality from coal-fired generation is optimally taxed, the positive externality from solar generation might be justifiably subsidized. Indeed, net-metering policies subsidize generation by requiring utilities to purchase exports to the electric grid at rates that typically exceed wholesale electricity prices. California utilities, for instance, must pay retail rates for distributed solar generation. Retail rates bundle a variety of charges beyond the marginal cost of electricity, including transmission and distribution cost recovery charges and conservation incentives. At $0.19 per kilowatt-hour, the average rate is more than double prevailing wholesale prices for solar generation. The public benefits likely do not justify such substantial subsidy (Borenstein 2008); Muller et al. (2011) estimate that a one kilowatt-hour reduction in coal-fired generation avoids \$0.036 of damages from local pollutant and carbon emissions.

A per-unit subsidy to solar generation can never be first-best because unpriced pollution leads to under-priced dirty generation, not over-priced clean generation. Because fossil-fired electricity generation and renewable electricity generation are (perfect) substitutes in end-use, a subsidy to solar power lowers the wholesale price of electricity, potentially lowering the rates that consumers face, thereby, inducing additional electricity consumption. The optimal policy induces less consumption.

Thus, the solar adoption rebates offered by many U.S. states can be justified as a second-best response to the externalities in environmental and technology markets. They are but one way authorities incentivize distributed solar generation investments. Twenty-four states offer tax credits for solar capacity investments. Twenty-eight states exempt renewable capacity expenditures from sales taxes or allow deductions against income taxes. Such tax credits, deductions, and rebates lower the upfront cost of solar adoption, and are, thus, first-order equivalent policies. Moreover, because the feedstock for solar generation is free, the marginal cost of solar generation is essentially zero. Therefore, the incentives for solar capacity installation effectively operate as subsidies to solar generation, much as do net-metering policies in forty-three states.

While the federal investment tax credit for solar capacity equal to 30 percent of system cost is homogeneous across the U.S. and state and and local policies are typically invariant to system characteristics, including location within political boundaries, theory suggests these incentives should be differentiated for several reasons.

First, the solar energy generation potential of any given unit of solar PV capacity varies according to solar irradiance, i.e. the quantity of sunlight available for energy production. This varies according to the earth's position relative to the sun and according to weather and climate. Fog and cloud cover, for instance, diminish solar irradiance, and hot temperatures impede technology performance, reducing the efficiency with which solar PV converts sunlight to electricity. Generation potential, thus, varies across the U.S. and within states. Figure 1 shows the estimated annual electricity generation in MWh of alternating current for a 1kW rooftop system in each zip code of the U.S.[4] Mean annual generation in the U.S. is 1.33 MWh, with a standard deviation of 0.15. The minimum generation occurs near Yakima, Washington and is equal to 47 percent of the maximum generation, 1.8 MWh, in Taft and Maricopa, California. Even within states, there can be considerable variation. Because of coastal fog and cloud cover, areas like San Francisco and San Diego have lower solar electricity generation potential than inland areas, like Sacramento, Bakersfield, and Riverside, California. Generation potential varies by about 25 percent within California largely due to weather.

Second, the magnitude of avoided marginal damages is also a function of the type of electricity generation solar production displaces. An average coal plant, for instance, emits twice the carbon dioxide-equivalent emissions of a typical natural gas plant, and considerably greater quantities of other pollutants, too, including NOX, SO_2, and particulate matter (Edenhofer, 2011; Caulton et al., 2014; Jaramillo et al., 2007). Nuclear and hydroelectric plants emit still less air pollution. These and other types of plants fire to meet demand according to their positions in the merit order, or dispatch curve, such as the modeled dispatch curve depicted in Figure 2. Baseload generation is provided by lowest marginal cost plants, like nuclear plants, and, historically, coal, while plants with higher marginal costs fire only during periods of high demand. Likewise, some plants are better able to ramp up and ramp down production to follow changes in demand. Generating fleets vary by region, and importantly across the three U.S. grid interconnections within which electricity trade is common but across which trade is rare.

Electricity demand typically follows a diurnal cycle in which it increases gradually over

[4]These estimates are produced using the PVWatts model of the National Renewable Energy Laboratory available at: http://pvwatts.nrel.gov.

the course of the day to peak in the late afternoon and early evening. Figure 3 depicts average electricity demand in the PJM region that incorporates mid-Atlantic states, demonstrating the diurnal pattern. Consequently, the mix of generators producing electricity varies over the course of the day, and, in particular, the type of plants that operate on the margin vary. Likewise, solar generation follows a distinct diurnal pattern, with peak generation occurring just ahead of peak demand. Moreover, electricity demand and solar generation exhibit annual patterns that vary by location, as shown for solar in Figure 4. For instance, the highest daily demand in California occurs during summer months, when demand for air conditioning is high. But in the Northeast, daily load is also high in winter due to home heating demand.The seasonal and diurnal patterns of solar generation also varies according to the orientation of solar panels. While south-facing panels in the U.S. maximize generation, west-facing panels tend to produce relatively more electricity during peak demand, prompting interest in incentives for west-facing systems. In our simulations in Section 5, we assess the environmental benefits of such a change in system orientation.

Given that the fleet of power plants varies by region, and, thus, the merit order of plant dispatch, and given that the demand these plants must meet and the demand solar PV can serve varies by region, the determination of avoided emissions is location-specific and not straightforward. Moreover, a unit of pollution imposes damages that vary spatially according to the deposition of the emissions and affected human populations. Actions to avoid emissions that deposit in heavily populated areas, thus, are more valuable, *ceteris paribus*, than actions that avoid emissions deposition in rural areas. For instance, avoided emissions from an east coast power plant may be less valuable than avoided emissions at an inland plant because the coastal plant's emissions deposit at sea, rather than on land. Air pollution transport modeling work provides estimates of how units of pollution emitted in any given location affect populations as a function of where they are deposited. In the subsequent sections, we employ the AP 2 Model (Muller et al. 2011) to value avoided emissions at each of 1,451 power plants in the U.S.

As the foregoing discussion highlights, an accurate determination of avoided emissions and their respective values in terms of foregone damages, depends upon much more than the calculation of average aggregate emissions rates. Indeed, in assessing the environmental benefits of a unit of solar generation, it is necessary to determine what are the *marginal* emissions that a *marginal* unit of solar generation displaces, i.e., what is the change in emissions due to a marginal change in electricity demand net of solar generation. Failure to distinguish average emissions from marginal emissions can yield incorrect policy guidance. For instance, average emissions suggest that electric vehicles are less-polluting than gasoline vehicles. Yet the marginal change in emissions caused by plugging in electric vehicles varies by region, and is positive in some regions, suggesting electric cars are dirtier than gasoline-powered cars (Zivin et al. 2014, henceforth GZKM). In fact, the marginal emissions framework implies the average electric car in the U.S. imposes external damages on the order of about $2,000, rather than external benefits (Holland et al. 2015, henceforth HMMY). In the subsequent section, we estimate the marginal emissions avoided by rooftop solar generation by adapting the GZKM and HMMY frameworks to account for time-varying solar generation.

3 Data and Methods

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.[5] 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

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

the reduced-form regression equations implemented by GZKM and HMMY. Hourly power plant emissions are regressed on hourly electricity demand in each NERC region of the interconnection of the power plant. We do this for each power plant in the U.S. and for each major pollutant.

Specifically, we estimate:

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

where y_{it} is pollutant emissions at plant i at time t; $LOAD_{tj}$ is a continuous variable measuring demand in NERC region j at time t, and $HOUR$, $NERC$, and MOY are indicator variables for each hour of the day, each NERC region within the interconnection of plant i, and each month of the year (MOY), respectively. This yields for each plant and each pollutant a vector of marginal emissions coefficients, β_{ijhm}, equal to $24 \times j(i) \times 12$. Likewise, MOS and DAY are indicators for each month of the sample and weekdays, respectively. An idiosyncratic error is denoted by ϵ_{it}. Equation (1) is estimated by ordinary least squares with 24-hour lag Newey-West standard errors reported. Distinct from HMMY, this model permits the hourly-plant-specific marginal emission responses to vary by each month of the year to account for seasonal patterns in the fossil-fuel generation mix and in solar generation. It also absorbs average load differentials across weekends and weekdays via the DAY fixed effect. Like HMMY, it permits plant i's emissions to respond to increased demand anywhere within the interconnection via a distinct coefficient for demand in each of the NERC 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.

Data on hourly emissions of CO2, NOX, and SOX from 1,451 power plants are obtained from the Continuous Emissions Monitoring System (CEMS) of the U.S. Environmental Protection Agency (EPA) for the years 2007-2011, yielding 50.8 million plant-level, hourly observations for each pollutant.[6] 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 by multiplying these intensities by hourly plant-level generation as reported by the CEMS. Annual $PM_{2.5}$ emissions used to compute plant emission intensities are obtained from the EPA's 2011 National Emissions Inventory.[7] Hourly electricity consumption is reported for each of 200 planning areas across the U.S. in Federal Energy Regulatory Commission (FERC) Form 714 filings. Planning area consumption is aggregated to NERC region to generate hourly load by NERC region.[8]

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 unit of solar capacity in each of 30,105 zip codes in the U.S. using PV Watts. PV Watts is a model developed by the federal National Renewable Energy Laboratory to estimate solar PV system generation. Zip-level generation is modeled according to Perez et al. (2002) and Dunlap et al. (1994) using hourly radiance images from weather satellites, daily snow cover data, and monthly averages of water vapor, trace gases, and atmospheric aerosols recorded at a resolution of 10-square kilometers.

Because weather characteristics affect the performance of solar photovoltaics, the 10-kilometer, satellite-based irradiance data are combined with surface weather station data from the National Solar Radiation Database to estimate direct and alternating current electricity output for given solar PV system parameters. Because an averaging of weather

[6]See https://ampd.epa.gov/ampd/.
[7]See https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei.
[8]Observations of pollutant emissions greater than six standard deviations from the mean are omitted.

conditions across years would aggregate away potentially important variation in weather characteristics, e.g., temperature, cloud cover, and rain, we employ TMY3 weather data, which employ daily weather observations across 20 years to assembl an annual record that reflects typical weather patterns at each of 1,020 weather stations.[9]

We assume typical system parameters in modeling system generation, including mean or median tilt, inverter efficiency, etc. While virtually all installed systems face southward in order to maximize generation, we separately estimate generation with south and west facing systems in each zip code in order to determine whether west-facing systems generate more or less pollution damage avoidance than south facing systems.

Equipped with (a) modeled solar generation by zip code that yields reductions in net load within respective NERC regions; and (b) estimated emissions responses from each plant to marginal load changes within interconnections, we can estimate the annual change in pollutant emissions from each plant in the U.S. as a function of a unit solar capacity addition in a given zip code. The values of these emissions changes are a function of exposure to the emissions, dose-response relationships, and valuation of responses. Like HMMY, we use the AP2 integrated assessment air pollution model to estimate ambient, county-level concentrations from emissions at each reported pollution source in the contiguous U.S. AP2 maps these concentrations to exposures, physical effects, and monetary damages. Exposures reflect 2011 population estimates at the country level from the U.S. Census. Estimated physical effects incorporate a wide range of effects as reported in Muller and Mendelsohn (2007), including premature deaths, crop yield impacts, and building degradation. As in HMMY, the vast majority of damages are attributable to mortality effects, which are valued using a $6 million value of a statistical life.

[9]More information about the TMY3 data are available at http://www.nrel.gov/docs/fy08osti/43156.pdf.

4 Results

Table 1 reports summary statistics for estimated annual total damages avoided and estimated annual avoided damages from each modeled pollutant for each 1kW capacity in each zip code. Mean damages avoided across the country are estimated at $116 per kW per year, or $6,200 in present value terms over the lifetime of a typical 4kW system.[10] A majority (70%) of these avoided damages are a consequence of reduced SO_2 emissions. Twenty percent of avoided damages are due to reduced CO2, 6% and 3% of avoided damages are generated by lower $PM_{2.5}$ and NOX emissions, respectively.

These avoided damages, or environmental benefits of rooftop solar PV, are presented for each zip code in Figure 5. It shows the annual environmental damages avoided per kW capacity of solar in each zip code in the U.S. These avoided damages are maximized for systems installed in Southwestern Virginia, where the average annual damages per kW are equal to about $330. A typical 4kW system, thus, delivers environmental benefits equal to $1320 per year. The avoided damages are least in central Missouri and the vicinity of Concord, New Hampshire, where the estimated damages avoided are negative, suggesting panels installed in these locations impose environmental damage rather than abate it. The estimated damages are estimated to be $24 per kW capacity per year. The smallest, positive avoided pollution damages, i.e., nonnegative environmental benefits, occur along the Oregon, Washington border in the Pacific Northwest.

The estimates of negative damages in parts of Missouri and the Northeast may obtain for at least two reasons. First, the estimates of increased regional pollution from an incremental increase in solar generation could be a consequence of sampling error. Second, solar generation can theoretically increase pollution by inducing the marginal plant to alter its generation in a non-marginal–or discrete–way, thereby inducing another, potentially

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

dirtier plant, to ramp to meet the demand no longer served by the relatively clean marginal plant.

More generally, Figure 5 demonstrates that avoided damages are greatest in the SPP, which incorporates all or parts of Arkansas, Kansas, Louisiana, Mississippi, Missouri, New Mexico, Oklahoma and Texas, and in the RFC, which includes all of New Jersey, Delaware, Pennsylvania, Maryland, District of Columbia, West Virginia, Ohio, Indiana, Lower Michigan and portions of Upper Michigan, Wisconsin, Illinois, Kentucky, Tennessee and Virginia. Avoided damages in these areas range from \$200-350 per kW per year. Damages are estimated to be much lower in the WECC, which incorporates 14 Western states, including California. Avoided damages in WECC are estimated at \$25-50 per kW per year. This result is in contrast to conventional wisdom that solar PV is most valuable in the West because of relatively high solar irradiance. Comparing, Figure 5 to Figure 1, it is apparent that avoided damages are far more sensitive to the conventional generation that is displaced than to solar irradiance. The relatively sunny WECC region is also characterized by a relatively clean generating fleet, especially in California. And, in particular, the marginal unit during periods of solar generation is particularly low-polluting relative to other regions of the country. As a consequence, the 623,000 systems installed in California generate among the lowest environmental benefits of any system in the country. Avoided damages are greater in the central U.S. and the mid-Atlantic region because marginal generation is relatively dirty and because dirty generating units are located nearer to population centers, like New York, Philadelphia, Chicago, and Boston. Damages from CO_2, SO_2, NOX, and $PM_{2.5}$ are depicted in figures 6-9, respectively.

Despite the relatively low environmental benefits generated from solar PV in California, the state was home to about 60% of all distributed generation systems installed in the U.S. California has provided incentives for rooftop solar PV for decades. In 2007, the state introduced the most aggressive incentive program in the U.S., dedicating \$2 billion of ratepayer and taxpayer funds to rebates for installed capacity.[11] There are 88,700 systems in Arizona, and 70,700 systems in Massachusetts, the states with the next greatest number of systems. North Dakota is home to only three systems, the fewest of any contiguous U.S. state, followed by Oklahoma (9), and Nebraska and South Dakota, each with 16. Virginia, the state in which environmental benefits per unit of solar capacity are greatest, has the 9th fewest solar adoptions among contiguous U.S. states. Only 1,400 systems, just over 1% of the total in the U.S are installed there. Avoided damages, thus, do not predict the number of installations in a zip code. In fact, the correlation between avoided damages and installations is negative ($\rho = -.22$). This phenomenon is not surprising given that environmental benefits are not appropriated by adopting households. Given net-metering policies common to most U.S. states, the return on solar PV investments are greatest not where environmental benefits are greatest, but rather where electricity rates and solar irradiance are high, as they are in California.

The solar adoption and generation subsidies offered by the federal government, states, and localities are presumably intended to internalize the positive externality associated with solar adoption. But because the avoided pollution damages of a given unit solar capacity vary by location, so, too, must the efficient subsidy. Subsidies vary at the state and local level, reflecting policy differences across jurisdictions. But the federal investment tax credit is homogeneous across the U.S. And variation in state-level incentives reflects heterogeneous political preferences, but is negatively correlated with variation in environmental damages.

In order to examine the relative efficiency of heterogeneous total solar incentives across the U.S., we compute the value of federal and state incentives and compare them to the estimated value of avoided pollution.[12] State-level total incentives are computed by assuming a standard 4kW system at a cost of $14,800. The federal investment tax credit is equal to

[11] See Hughes and Podolefsky (2015) 2015 for more information about the California program.

[12] Municipalities and individual utilities offer additional incentives that are not included in this analysis.

30% of system cost, i.e. $4,440. To this subsidy, state rebates and tax incentives are added, as are estimated subsidies delivered via net metering provisions. To compute net-metering subsidies, the difference in state average retail electricity rates and state average wholesale prices is multiplied by annual system generation. Twenty years of these net-metering subsidies are discounted to a present value net-metering subsidy assuming a 5% discount rate. These subsidies per unit generation are then multiplied by the estimated generation of a 4kW system and added to capacity subsidies to yield a net present value of federal and state capacity incentives for typical systems. Estimates of annual avoided damages over the assumed 20-year life of the solar panels are also discounted at a 5% rate to generate present value avoided damages over the life of the system.[13]

On average, a typical 4kW system is over-subsidized by an estimated $5,400, yet solar is under-subsidized in 26% of zip codes. It is most under-subsidized in West Virginia, where avoided damages are among the greatest. West Virginia permits net metering of solar generation, but otherwise offers no incentives beyond the federal investment tax credit. The value of the federal credit and the discounted present value of the net metering subsidy is $8,400 for a typical system. Yet this incentive falls short of the value of avoided damages by $6,200. Systems are also under-subsidized in Indiana, Ohio, Pennsylvania, Missouri, Oklahoma, New Jersey, Delaware, and Kansas. Incentives exceed avoided damages by the greatest margins in Rhode Island, New York, Connecticut, Idaho, and California. Rhode Island provides $21,600 in incentives beyond the value of avoided damages. This includes a $1,150 rebate per kW capacity, as well as sales tax and property tax credits worth $3,600 for the typical system. In California, the average incentive exceeds the estimated value of avoided damages by $15,600. Subsidies most closely match the external environmental benefits in South Dakota, Texas, and Virginia, where estimated environmental benefits and total incentives differ by less than $1,000. Figure 10 depicts the difference between damages

[13] Additional details are available from the authors.

and incentives by zip code.

Given the estimated environmental benefits from one kW of capacity in each zip code, the total annual environmental benefits of the installed capacity in the U.S. is equal to \$13.9 million. As is evident by the relatively low environmental benefits of solar in the West and California's disproportionate share of solar installations, existing solar is not sited to maximize environmental benefits. In order to estimate the magnitude of environmental benefits forsaken to suboptimal siting, we simulate environmental benefits under four alternative reallocations of existing systems across the U.S. First, we imagine that all systems are relocated to the areas in which they yield the greatest environmental benefits subject only to a restriction that each panel must be located on a residential rooftop. Zip-code-level Counts of detached, single-family homes from the 2015 American Community Survey proxy for residential rooftops. A second simulation considers the reallocation of solar capacity within states, subject to the availability of rooftops. Finally, a third and fourth simulation reallocate systems across the U.S. and within states, respectively, subject to the constraint that total installations within a zip code may not exceed 15% of rooftops. This constraint is imposed to reflect concerns about grid stability amid high penetration of intermittent renewables at any node of the grid.

Results from these simulations are reported in Table 2. Under a complete reallocation of systems, annual environmental benefits increase nearly 100-fold to \$1.3 billion. Systems are located on every rooftop in each of 369 zip codes with average total avoided damages equal to \$318. Most panels are located in Toms River, New Jersey, 60 miles east of Philadelphia, where total installations increase 22-fold from 968 to 21,809. Avoided damages there are estimated at \$322 per 1kW capacity per year. Other states optimally housing installed capacity include Delaware, Indiana, Maryland, Virginia, and West Virginia. New Jersey houses 400,000 more systems than it does today, and Virginia accommodates more than 243,000, up from 43 today. No systems are optimally installed in California, Arizona, or Massachusetts, the three states most populated by rooftop solar in 2016. In fact, the substantial increase in environmental benefits in this simulation is afforded, in part, by the reallocation of more than 70,000 systems from Massachusetts, where they generate environmental damages rather than benefits. Figure 11 depicts the current locations of systems (in blue) and their locations if systems were optimally sited throughout the country without constraints (in red).

Allowances for grid stability concerns diminish total annual environmental benefits by nearly \$70 million to \$1.22 billion. Panels are sited across 2,166 zip codes in 11 states with average annual avoided damages equal to \$304. Toms River, New Jersey houses 18,000 fewer systems. Total installations in New Jersey and Virginia fall to 201,341 and 63,553, respectively. In this simulation, PV systems are installed also in Wisconsin, Pennsylvania, Kentucky, Illinois, and the District of Columbia. These systems are depicted in Figure 12.

A national reallocation of solar capacity is unlikely, a point to which we return in the following section. Optimal solar siting within states is perhaps more plausible as states could target incentives to achieve efficient siting. Thus, we consider how total annual environmental benefits are affected by optimal reallocations of state installed capacity with and without accommodations for grid stability concerns. An unconstrained state-level reallocation increases environmental benefits 17-fold to \$239 million. Constraining intra-state reallocations to 15% solar concentration in any zip code, reduces environmental benefits by \$9 million. Siting of systems pursuant to these simulations is shown in Figures 13 and 14.

5 Discussion

In 2011, in advocating for a statewide goal of 12 GW of clean, local electricity generating capacity, California Governor Jerry Brown remarked,"This is tens of thousands of little decisions. The distribution is its strength and also its challenge."[14] As the analysis of

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

the preceding section reveals, distributed decisions have produced an installed capacity of distributed solar that does not maximize avoided damages from fossil-fuel electricity generation. In fact, environmental benefits would be two orders of magnitude greater were the installed capacity sited to maximize these benefits. But, of course, the environmental benefits are not appropriated by the solar adopter because generous incentive programs offer subsidies independent of avoided damages. In many cases, subsidies are independent even of generation. Thus, households optimally invest in rooftop solar if the returns on their investments, inclusive of subsidies, exceeds the opportunity cost of funds. Because of net metering policies, these returns are likely to be greatest where generation potential is greatest and where electricity rates are high. Thus, the foregoing analysis does not imply irrationality on the part of individual adopters.

This analysis does suggest, however, that if transactions costs were low and policy reflected heterogeneity in environmental benefits from solar capacity, then the optimized siting simulated in the preceding section could be more closely achieved. That is, a potential solar adopter seeking only to maximize the return on his investment should be indifferent between purchasing solar panels for his rooftop or another rooftop, all else being equal. Policies in at least half of U.S. states, however, preclude third-party sales of electricity, e.g., from one homeowner to another.[15] Such prohibitions are ostensibly imposed to protect grid stability, though solar advocates contend that they function merely as protection for utilities.

Several immediate implications for policy emerge. First, federal incentives should reflect national heterogeneity in environmental benefits, conferring greater subsidies to those installed systems that are likely to yield greater environmental benefits. And likewise, states should vary their incentives according to variation in environmental benefits within their borders. Second, states should permit third party sales of distributed solar generation in

[15] http://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2015/01/3rd-Party-PPA_0302015.pdf

order to facilitate investments in optimally sited solar capacity. Though this analysis has abstracted from site-specific solar irradiance characteristics, e.g., shading from trees and buildings, these site characteristics are likely to induce even greater variation in site-specific environmental benefits than that estimated in this analysis. The efficiency gains from third party sales and other efforts to improve the match of capital to high-benefit sites are, thus, greater than those estimated here.

Third, while jurisdictions can improve the efficiency of incentive programs by tying subsidies to expected site-specific environmental benefits, free riding by inframarginal adopters will impede optimal solar siting. Hughes and Podolefsky (2013), 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. In fact, in similar analysis, Rogers and Sexton (2015) estimate a public cost per additional kW capacity under the California Solar Initiative in excess of $3,000, equal to at least half the total cost per unit of capacity installed under the program. Inframarginal adopters, thus, limited additionality. Moreover, these imframarginal adopters are less likely than the marginal adopters to install capacity in highest-benefit areas. If the objective of solar incentive programs is to maximize the displacement of fossil fuel generation or the avoidance of attendant air pollution damages, the policy should seek to exclude inframarginal adopters in low benefit locales. That is, policy should specifically target high-benefit locales, and exclude low-benefit locales. Such policy may be perceived as discriminatory. However, state and federal tax systems are discriminatory, conferring benefits and costs according to marital status, family size, homeowner status, electric vehicle adoption, charitable giving, and so on. A more discriminating solar policy seems consistent with the tradition in the U.S. of using the tax code to incentivize or discourage behaviors.

Finally, these results also highlight a cost of policy preferences that favor within border renewable energy generation over renewable electricity imports and local generation over utility-scale. Twenty-nine states have renewable portfolio standards that are presumably intended to achieve at least one of two environmental objectives: a reduction in globally mixing greenhouse gases and a reduction in local pollutants. To the extent the state objective is the former, namely a reduction in CO2 emissions, then states should prefer to fund solar capacity where avoided CO2 emissions are greatest, irrespective of state boundaries, because a unit of emissions affects the state and its residents regardless of where the unit is emitted. Assuming states and their residents are not indifferent to criteria air pollution, they should also favor solar installations where total environmental benefits are greatest, conditional on CO2 emissions reductions. In so far as objectives are clean local air, then this analysis points toward optimal public investments outside local boundaries because of the pattern of emissions depositions. That is, a state may benefit more from reducing emissions outside the state lines than within them because of patterns of air pollution transport. An exploration of these issues is the subject of future research.

Virtually all state and local solar policy favors distributed generation over utility-scale generation by limiting capacity subsidies to small systems and mandating purchases of distributed generation at rates exceeding wholesale solar generation prices. This policy preference for distributed generation systems persists in spite of economics that may favor utility-scale systems. In particular, this research highlights that "tens of thousands of little decisions"–indeed, millions of little decisions–yield an installed capacity that is inefficient because of constraints facing distributed generation system investors (adopters), e.g., the availability of rooftops, and by the deviation of individual incentives from public objectives. Utility-scale investors are less constrained in siting their solar capacity, and direct public investment in capacity–as opposed to incentives–can yield more efficient siting that maximizes investment returns inclusive of environmental benefits. Given the dramatic variation in environmental benefits both across and within states, a policy preference for uncoordinated capacity investments is difficult to justify.

Distributed generation is presumed to provide benefits to the electricity grid. In particular, it may avoid or delay capital expenditures to improve transmission capacity by siting generation capacity at load centers, and perhaps, downstream from congested nodes on the grid. To date, however, there is little evidence that the existing one million distributed generation systems provide these benefits or even that they were incentivized in areas where grid benefits would be greatest. At the same time, even solar advocates acknowledge that the bi-directional electricity flows required of distributed generation also impose costs on the electricity grid, requiring upgrades to distribution systems. Distributed generation also avoids line losses in transmission that may constitute 1-7% of generation. At the same time, however, distributed solar generation is lost as it moves across the distribution system. These losses are estimated to be on the order of 7% of system exports to the grid, which vary by home and location but are equal to roughly have of system production.

Distributed generation also avoids land rental costs and environmental damage from conversion of natural habitat to utility-scale solar farms. At the same time, however, distributed generation sacrifices economies of scale that persist in solar capacity even as the costs of the panels continue to fall.

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Table 1: Estimated Avoided Damages Summary Statistics

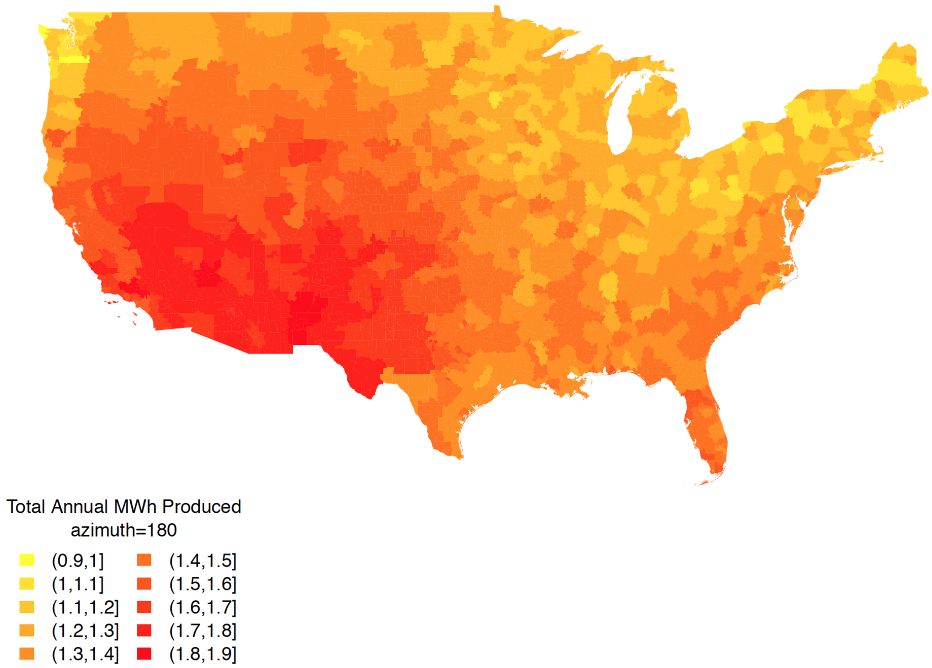
	Mean	Std. Dev	Min	Max
Total Damages	116.9	104.5	-24.2	330.4
CO_2	23.5	8.8	2.8	53.6
SO_2	82.2	92.6	-27.4	274.2
NOX	3.6	4	-0.6	20.2
$PM_{2.5}$	7.4	5.0	-2.2	16.4

Table 2: Simulated Allocations of Installed Solar Capacity

	Installed	U.S	U.S. s.t. Stability	State	State s.t. Stability
Total Avoided Damages	13.9	1,290.0	1,220.0	239.0	230.0
Number of zips	12,579	369	2,166	981	2,437
Mean Avoided Damages	105.2	318.5	303.7	109.6	75.9

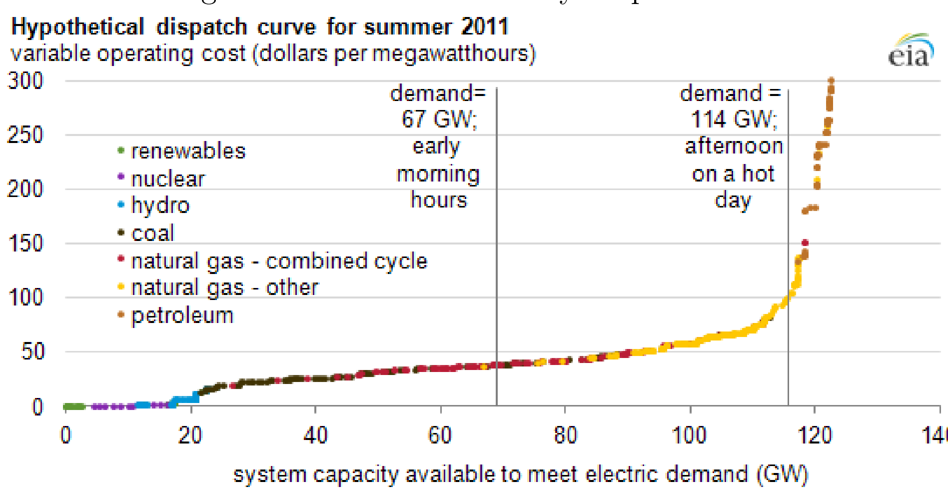
Avoided damages in millions of U.S. dollars. Mean avoided damages are averaged across zip codes with positive counts of installs and are per kW capacity.

Figure 1: Annual AC Electricity Generation per 1kW Capacity Across the U.S.



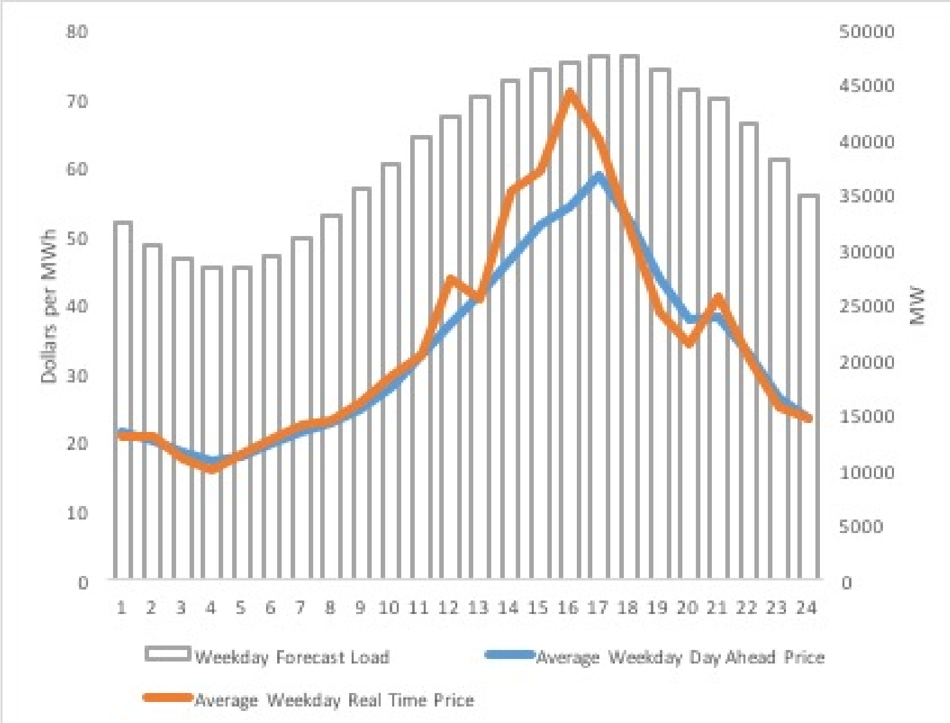
Annual AC electricity generation in MWh per 1kW capacity for each zip code across the U.S. Estimates are generated using PV Watts, a modeling tool developed by the National Renewable Energy Laboratory.

Figure 2: Modeled Electricity Dispatch Curve



The dispatch curve above demonstrates the order in which generating units are dispatched to meet demand according to their marginal generating costs. This curve is for a hypothetical collection of generators and does not represent an actual electric power system or model results. The capacity mix (of available generators) differs across the country; for example, the Pacific Northwest has significant hydroelectric capacity, and the Northeast has low levels of coal capacity. Credit: Energy Information Administration

Figure 3: Average Weekday Load and Prices for PJM



Depicted is average load and average day ahead and real time prices for electricity in the PJM control area. Load (in MW) is measured on the right axis. Prices (in dollars per MW) are measured against the left axis.

Figure 4: Monthly Solar Generation Per kW (in kWh)

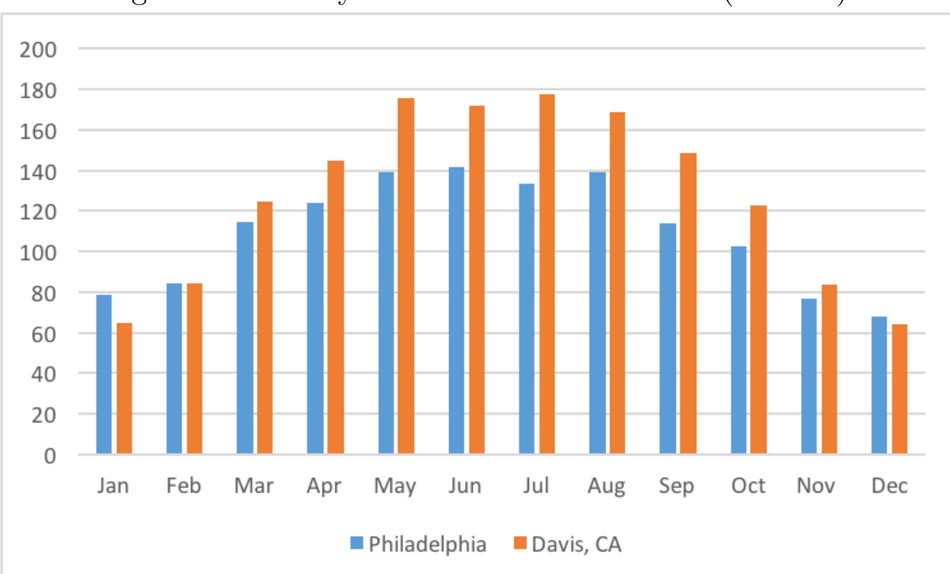


Figure 5: Annual Avoided Damages Per kW Capacity

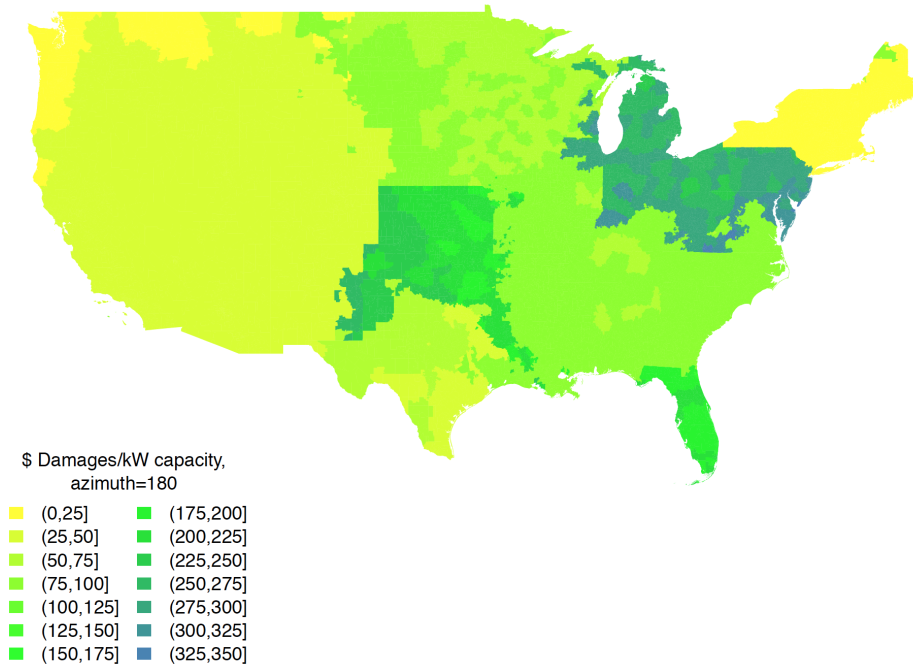


Figure 6: Annual Avoided CO_2 Damages Per kW Capacity

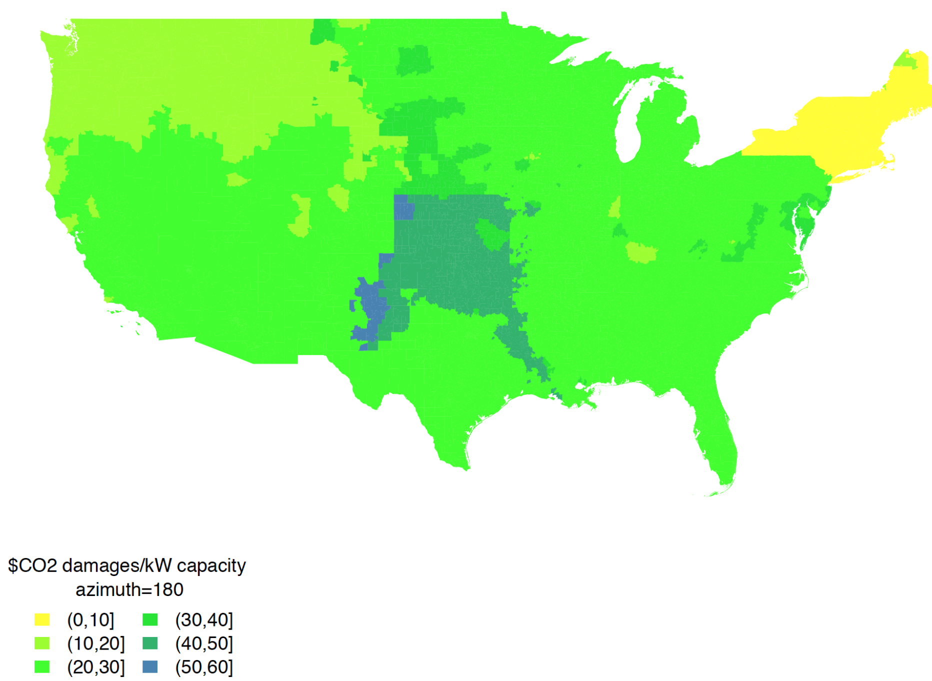


Figure 7: Annual Avoided SO_2 Damages Per kW Capacity

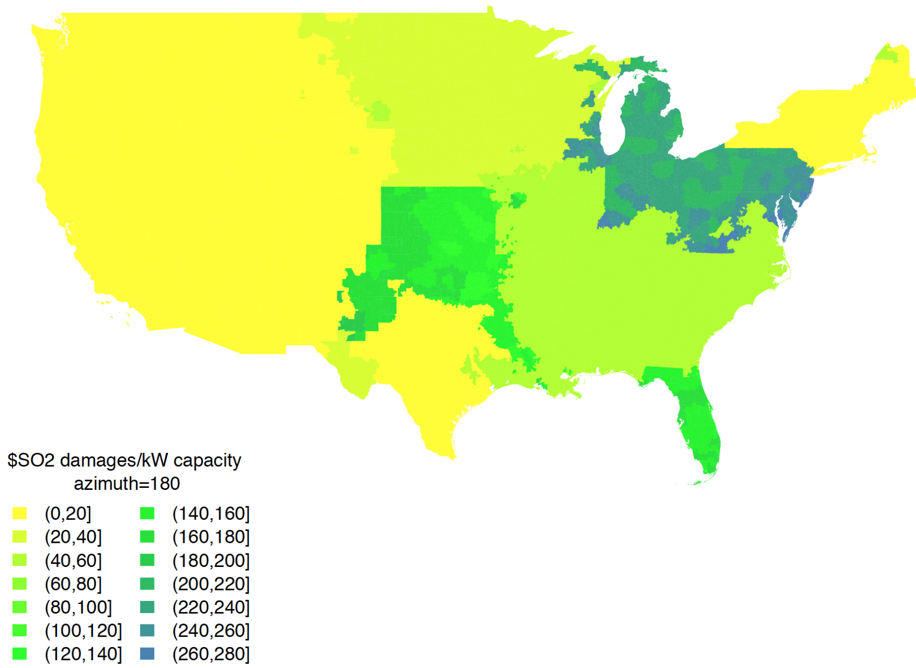


Figure 8: Annual Avoided NOX Damages Per kW Capacity

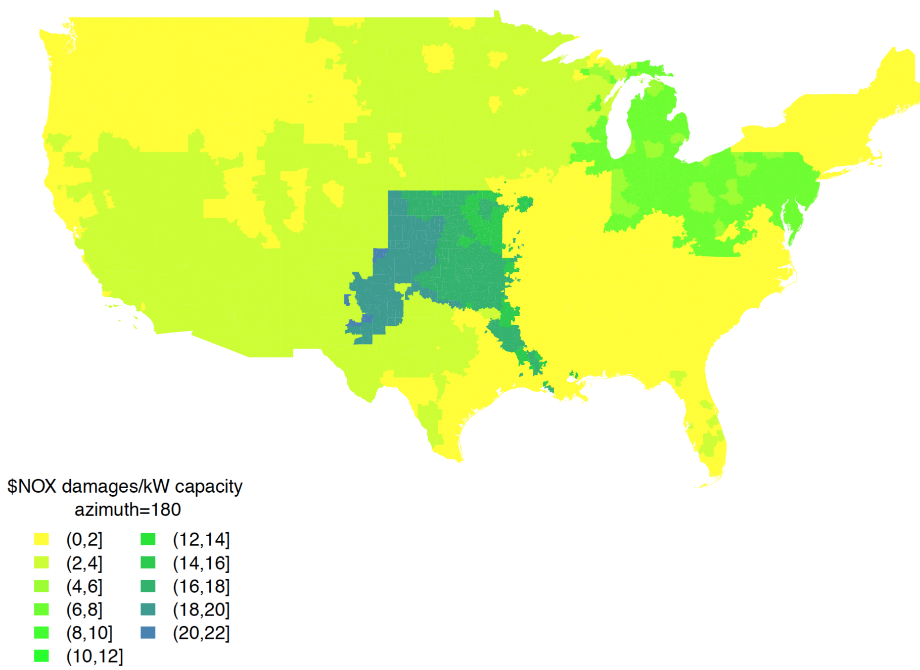


Figure 9: Annual Avoided $PM_{2.5}$ Damages Per kW Capacity

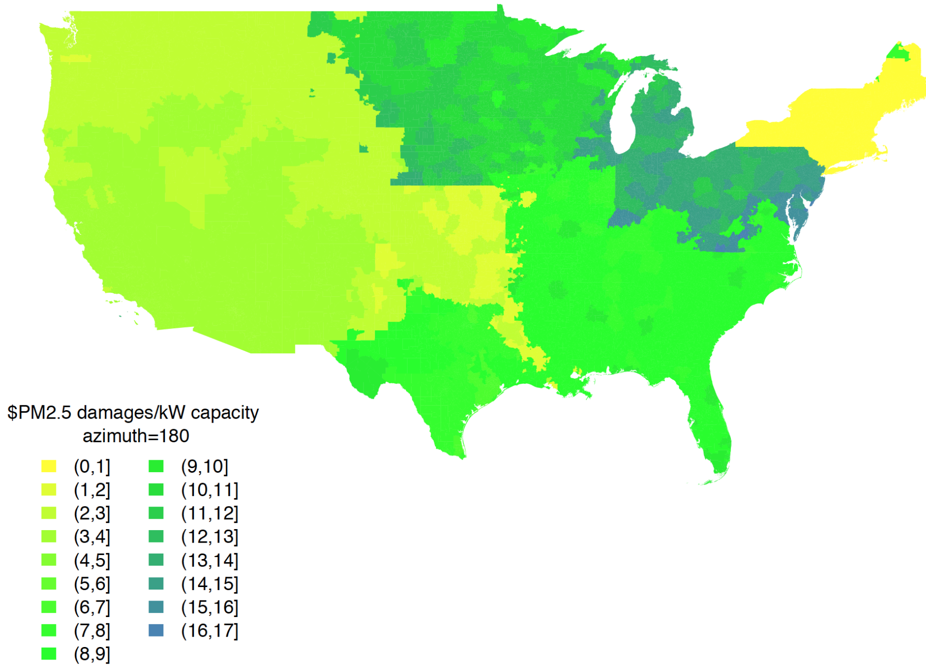


Figure 10: NPV of Avoided Damages less NPV of Incentives per kW

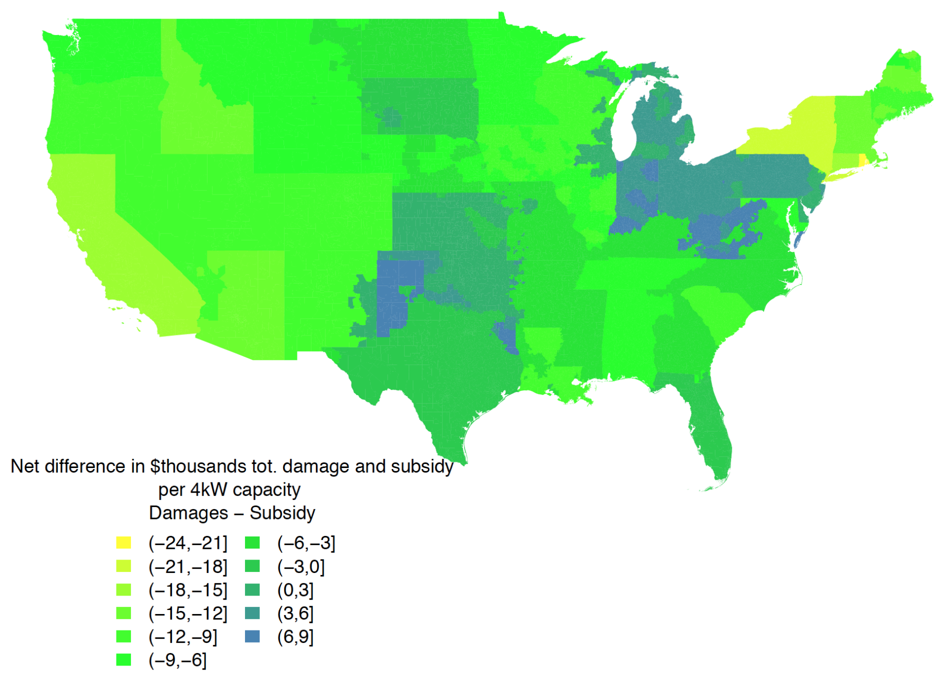


Figure 11: National Reallocation of Installed Capacity

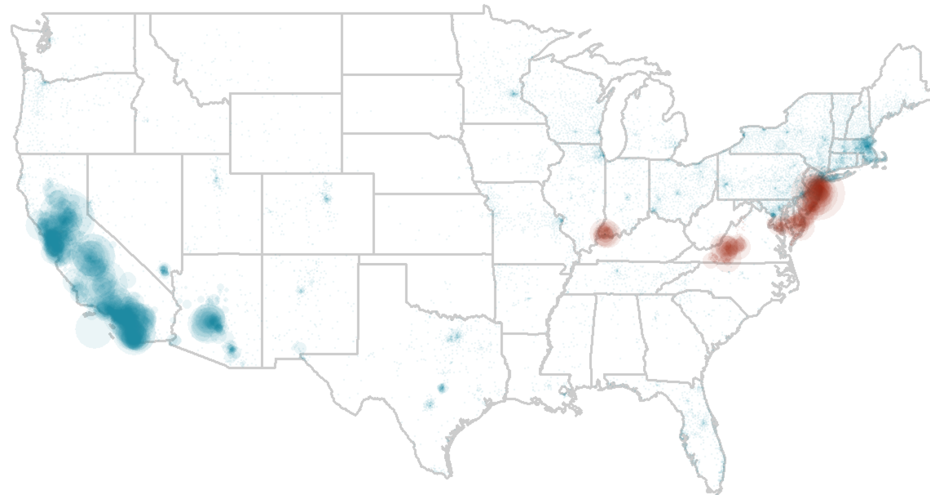


Figure 12: National Reallocation of Installed Capacity Subject to Grid Stability Concerns

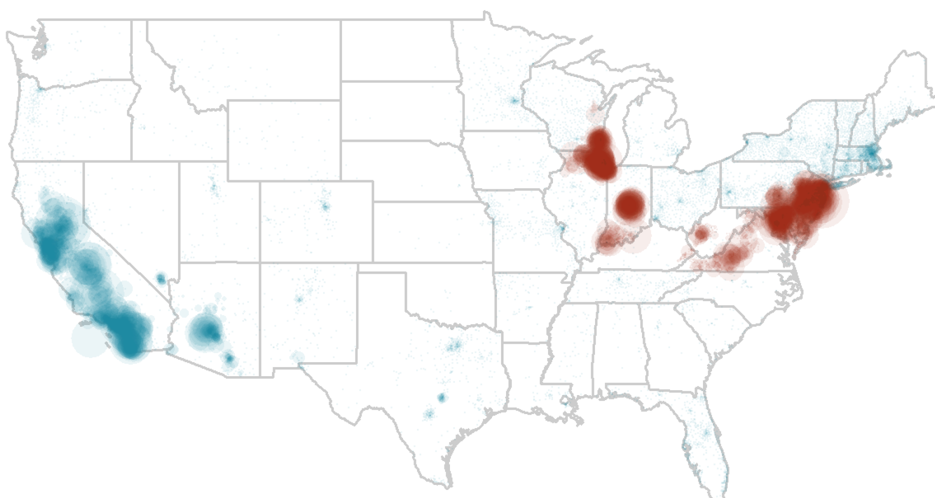


Figure 13: Intra-state Reallocation of Installed Capacity

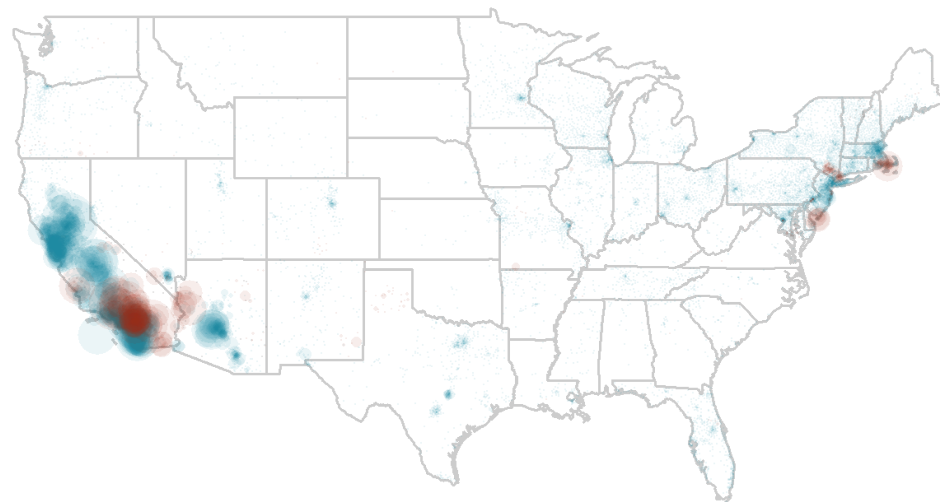


Figure 14: Intra-state Reallocation of Installed Capacity Subject to Grid Stability Concerns