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Solar PV as a mitigation strategy for the US education sector

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Abstract

Solar photovoltaic (PV) is an important strategy to de-carbonize the energy sector in the United States and to reduce the health, environmental, and climate change damages associated with the production of electricity from fossil fuel sources. While the potential for solar PV in the residential and commercial sectors has been widely studied, the potential in educational buildings is largely unknown. Educational institutions account for 11% of total US building electricity consumption and 14% of building floorspace. These buildings also contribute to approximately 4% of total US CO2 emissions, thus playing a potentially important role in climate mitigation strategies. We estimate the electricity use for 132k educational institutions across the US and estimate electricity generation, greenhouse gas and health damaging air emissions reductions, and private and social costs and benefits that would result from adopting rooftop solar PV. We find that solar PV in US educational institutions could provide 100 TWh of electricity services annually, meeting 75% of these buildings’ current electricity consumption. We estimate the highest generation potential in Texas, California, and Florida with K-12 public educational institutions comprising the bulk of that generation. The provision of electricity services from rooftop solar PV on educational institutions could reduce health, environmental, and climate change damages by roughly $4 billion per year (assuming a social cost of carbon of $40/ton and value of statistical life of $10M in 2018 USD). Two key findings from this study are that: (i) the private costs of solar for educational institutions still exceed the private benefits from reduced electricity consumption across the entire country (unless a third party operation model is used, in which case some locations can have net-benefits), and (ii) with the exceptions of California and New York, the social health, environmental and climate change benefits exceed the levels of current incentives provided by the state and retail subsidies.

1. Introduction

Solar photovoltaic (PV) capacity has grown at an unprecedented rate over the last few years in the United States (US). Despite that increase, more than 60% of the electricity generated in the US comes from fossil fuel sources, compared to only about 2% that is now provided by solar PV [1]. In 2015, electricity generation accounted for 30% of all US greenhouse gas (GHG) emissions [1], contributing to annual health costs amounting to roughly 4% of the national gross domestic product [2]. Health effects arise mostly due to secondary formation of particulate matter <2.5 μm wide (PM_{2.5}) from sulfur dioxide (SO_{2}) emissions, with negative impacts in particular for at-risk populations such as asthmatics, the elderly, and low-income families [3–8].

The technical potential and costs/benefits of installing solar PV in the residential and commercial sectors have been quantified in detail in the literature. Gagnon et al [9] estimate that PV systems installed on small, medium, and large buildings in the US can generate 1400 TWh of electricity; Denholm and Margolis [10] estimate the residential sector alone can provide
419 TWh from rooftop solar PV. Recently, a study by Vaishnav et al [11] estimates annual state-level health and environmental benefits for residential and commercial systems to be on the range of $50/kW yr. Previous studies demonstrate that residential solar PV has been mostly adopted by high-income households, benefitting from publicly-funded incentives [11, 12]. As for non-residential adoption, an economic analysis of historical project costs by Barbose et al [13] demonstrates that installed prices are higher for tax exempt customer sites than for for-profit commercial sites. Despite these currently discouraging installation costs, educational institutions, like industrial facilities, often have large, flat roofs that might allow for greater economies of scale. Additionally, their low summer electricity consumption profiles and locations in residential communities could make them decent candidates for community solar projects [14]. The decreasing installation costs of solar PV may also make these projects potentially economical [15].

However, to date, little attention has been devoted regarding the use of solar PV in the education sector. Educational institutions account for 11% of total US building electricity consumption and 14% of building floorspace [16]. They contribute to approximately 4% of total US carbon dioxide (CO2) emissions, making them a decent target for climate mitigation strategies [17]. Many institutions, especially in higher education, have already set goals to reduce energy consumption and GHG emissions. According to the Bloomberg Philanthropies’ America’s Pledge Report, in 2016, 587 US universities with a total enrollment of 5.2 million students (25% of the US college and university student population), had voluntarily adopted GHG targets [18]. To date, 335 colleges and/or universities have GHG emissions inventories and 78 have defined climate action plans [19].

In this paper, we focus on estimating the potential electricity generation, emissions reductions, and private and social net-benefits of installing rooftop solar PV on educational institutions throughout the US. We consider public and private K-12 as well as higher education institutions [20, 21]. Ultimately, this analysis considers the technical potential and financial feasibility of installing these systems today, given the most recent and reliable data available and using the appropriate integrated assessment model. We include a sensitivity analysis that illustrates which levers might be pulled to make rooftop PV attractive for schools and/or society, but this paper does not include specific policy/scenario analyses or forecasts.

The rest of this paper is organized as follows. First, we explain our data and methods. Next, we present our results, which include regionally specific estimates of electricity generation from rooftop PV, avoided electricity consumption from the grid, emissions reductions, and the private and social costs and benefits. We also include a sensitivity analysis regarding inputs such as discount factor, system size, and the value of excess generation. Finally, we conclude and provide policy recommendations.

2. Data and methods

We estimate the electricity generation, CO2, SO2, PM2.5, and NOx emissions reductions, and private and social net-benefits of installing solar PV on each K-12 and higher education public and private institution across the United States. We assume systems are installed today and use recent system installation costs as detailed in the following. We assume a system lifetime of 20 years and use alternative discount rates of 2% and 7% per year when computing the private and social net-benefits. We provide our results in terms of annual electricity generation, reduced emissions, and net-benefits.

We use the following modeling strategy, as shown in figure 1: (1) we estimate the available PV rooftop area for each US educational institution, (2) we estimate the hourly electricity output of the panels given the local irradiation for that site, (3) we estimate the hourly electricity demand of each institution, (4) we calculate the amount of electricity that can be saved annually from using the panels instead of acquiring the electricity from the grid by subtracting hourly demand from hourly PV generation, (5) we determine the value of electricity generated by the panels (i.e. electricity cost savings and excess generation sales), (6) we quantify the emissions of criteria air pollutants and GHGs avoided by the PV systems, and (7) we monetize the avoided health, environmental, and climate change (HE&CC) damages associated with the avoided emissions using two reduced form air quality models. In table 1, we summarize the different data sources that are used in our analysis. In the supplementary material (SM) section A (available online at stacks.iop.org/ERL/14/044004/mmedia), we provide a table of model assumptions and our treatment of uncertainty.

2.1. Available PV roof space (figure 1, step 1)

We construct a database of 132,592 educational institution building counts and locations (see figure 2) using three National Center for Education Statistics (NCES) datasets: the Integrated Postsecondary Education Data System—2014/2015 (for higher education institutions), the Common Core of Data—2014/2015 (for K-12 public institutions), and the Private School Universe Survey—2013/2014 (for K-12 private institutions) [22–24].

The Integrated Postsecondary Education Data System is a mandatory survey of postsecondary institutions that receive federal funding under Title IX (including degree- and non-degree granting); this dataset also includes non-federal funded schools, but that percentage is unknown [22, 31]. The Common Core of Data [23] and Private School Universe Survey
are both considered to include the entire population of public and private K-12 schools, respectively, which NCES uses for sampling frames. These datasets do not include rooftop space, and thus we have established a strategy to estimate such areas. Technical potential methods are often organized into three categories: constant-value methods, manual selection, and geographic information systems (GIS) methods. The first method is quick and simple on small study regions but is hard to validate. The second method is precise but time consuming and is hard to replicate on larger study regions. We opt for a data-driven GIS method that was developed by NREL and vetted in the literature. We use National Renewable Energy Laboratory (NREL) light detection and ranging (LIDAR) estimates of available rooftop space for 16 000 institutions that are included in NREL’s dataset (which account for 12% of all educational institutions in the NCES dataset). Although a total of 39 000 institutions are linked by NREL to LIDAR data, only 16 000 of these institutions are linked to open-street mapping (OSM) polygons. To characterize suitable rooftop space for solar PV on buildings in the US, NREL uses LIDAR data provided by the Department of Homeland Security (DHS) in combination with GIS methods and statistical modeling. First, NREL runs a shading simulation on the digital surface model for each city provided in the DHS dataset. Next, they classify roof orientation using the LIDAR dataset to determine the tilt and azimuth of each 1 m² space. Finally, they use NREL’s System Advisor Model (SAM) to determine generation profiles of each site, defining a suitability threshold for each of the 128 cities in the dataset. NREL links as...
many institutions as they can with OSM polygon data, which allows them to consider entire campuses that are associated with the institution address. If multiple institutions are co-located in an OSM polygon, NREL’s method is to proportionally distribute the roof space using the reported institution populations (taken from NCES). In the supplemental materials, section B we provide a detailed explanation of this dataset and their estimation procedure, and for more details the reader can refer to Gagnon et al. The advantage of using these estimates is that they are readily available and reasonably measure rooftop area.

In order to estimate the rooftop areas for the remaining institutions that are in the NCES dataset, but not in NREL’s rooftop estimates, we start by fitting simple linear regression models for each institution type to explain the observed NREL LIDAR rooftop estimates as a function of several institution- and county-level variables. We then use the results from that regression to predict the available PV rooftop area for the remaining institutions in our dataset. While more sophisticated regressions could be envisioned, we balanced the modeling parsimony and insight that could be provided and concluded that selecting a simple model would be preferable. Ultimately, we use the NREL LIDAR rooftop estimates for 12% of our total school building population (∼16 000) and then performed our own estimation of building rooftop space using linear regression models for the remaining 88% of the buildings in our dataset (∼117 000). These rooftop space estimates formed the foundation of the remaining technical potential and financial feasibility analysis outlined in this paper. SM section C provides additional information on the data and results from our estimation procedure.

2.2. Estimating solar PV hourly generation at each institution (figure 1, step 2)
We use NREL’s TMY3 data, which provides hourly solar irradiance for 936 locations across the contiguous US. We assign each educational institution to the geographically closest location for which we have solar irradiance data. We then use the method outlined in Lorenzo [36], which is also used in Vaishnav et al [11], to estimate hourly power output for the systems installed at each institution. We assume the PV panels will cover 100% of the suitable roof space and then relax this assumption in our sensitivity analysis.

2.3. Estimating hourly load profiles for each institution (figure 1, step 3)
We use the typical hourly load profiles for ‘secondary schools’ compiled by the US Department of Energy (DOE) for each of the TMY3 locations [26]. These reference building load profiles are specific to 16
different climate zones across the US. The DOE characterizes the secondary school reference buildings as having an average floor area of 210 887 \text{ft}^2 and two stories. Assuming the floor area divides evenly among stories, this equates to a roof area of approximately 100 000 \text{ft}^2. The 95th percentile of the OSM-linked rooftop area data is 90 000 \text{ft}^2 and the 95th percentile of the regression estimated rooftop area across all educational institutions is 77 000 \text{ft}^2 (see SM section B for more details of rooftop area summary statistics). We scale the building load profile linearly using the building roof space for each institution, assuming the ratio between the net-power and peak load remains the same across building sizes. See SM section D for a detailed description of how we estimate net-power and load scaling.

2.4. Electricity cost savings, net-metering, and third-party ownership (TPO) (figure 1, steps 4 and 5)
First, we calculate the electricity savings from using the PV power instead of grid electricity by computing the difference between hourly solar PV generation and hourly load. We assume that if load exceeds hourly generation in that hour, the remaining power is bought from the grid (again, see SM section D for a description of net-power estimation). Electricity cost savings are determined by multiplying the difference between hourly solar production and load by a volumetric electricity price ($/\text{kWh}$), which we assume to be the state-average 2016 commercial retail rate (henceforth referred to as the ‘retail rate’)$^4$.

We also estimate demand cost savings. We do so as follows: (1) the demand charge accounts for 20% of the average rates for educational institutions and (2) rooftop solar PV can provide average monthly demand savings of 20%. Ultimately, we adjust the retail rate as follows to account for the demand cost savings and appropriately reduce the volumetric rate:

\[
\text{Commercial.Rate}_{\text{State}} = \frac{\text{Avg.Rate}_{\text{State}} * 0.8}{\text{Avg.Rate}_{\text{State}} * 0.20} \times 0.20.
\]

(1)

The Avg.Rate represents the state-average 2016 commercial retail rate. Therefore, the first part of the Commercial.Rate approximates the variable rate observed for each state and the second part approximates the demand savings for each state. These assumptions are informed by a demand rate analysis following a method outlined in Darghouth et al$^{[37]}$, where we simulate secondary school DOE reference building loads in 15 cities across the US using NREL’s SAM$^{[38]}$ (see SM section E for more details). Our results are similar to those found in Darghouth et al$^{[37]}$, which demonstrated that rooftop PV systems on schools in the US could yield demand charge savings of approximately 17% on average. In the sensitivity analysis, we vary the demand charge rates and fractional savings.

Finally, we characterize net-metering and TPO scenarios. Net-metering policies vary widely across the US, although it is established in most states at some capacity (see SM section F for a table of net-metering policies currently outlined in the DSIRE database$^{[39]}$). Therefore, in this analysis we assume net-metering is available to educational institutions across the US. We consider two scenarios as bounding cases for valuing the excess electricity generated by the PV systems: (1) retail rates and (2) locational marginal prices (LMPs). Valuing excess generation with the retail rate closely approximates net-metering policies in effect today (e.g. customers are allowed to roll over monthly applied power credits over a 12 month period); this scenario is the ‘best case’ scenario from the institution’s perspective. However, if net-metering policies are financed by spreading costs over the entire rate base, there is a transfer of resources from those who do not install PV to those who do install these systems$^{[11]}$. We estimate this cross-subsidy as the difference between the retail and LMPs for that institution, and we consider it a social cost in this scenario. The ‘worst case’ net-metering scenario experienced by institutions would be when excess generation is valued at the LMP$^{[5]}$; this scenario is sensible since small, distributed power sources may be valued by using an avoided cost calculation or considering costs associated with distribution.

The TPO scenario is characterized as the difference between the regular annual electricity consumption costs to the educational institutions (without PV) and the costs of electricity if schools purchased electricity at a TPO-defined rate. This TPO-defined rate is assumed to be less than the retail rate. Here, annual electricity costs to the school at the TPO-defined rate are estimated as the annualized cost of owning the PV systems, assuming commercial owners can take advantage of the Federal Investment Tax Credit (ITC) and that excess generation is valued at the LMP. Table 2 describes each of the three benefit-cost analysis (BCA) scenarios for valuing electricity cost savings and excess generation sales that we consider in this study.

2.5. Installed price of system (figure 1, step 6)
We use Lawrence Berkeley National Laboratory’s (LBNL) Tracking the Sun X (TTS10) data on recently observed solar PV system prices in 2015 and in 2016. Since a previous study by Barbose et al$^{[13]}$ finds that tax-exempt sites have higher average installation costs than for-profit commercial sites, we limit our LBNL dataset consideration to only school, government and

$^4$ In this analysis, we do not use time-of-use rates due to their highly specialized, utility-specific structure (e.g. utilities often design them to be revenue-neutral).

$^5$ Following Vaishnav et al$^{[11]}$, we download hourly LMP data for year 2015 for representative aggregate pricing nodes in each state from the IST/RTO data portals. Generation nodes reported by neighboring ISOs are used for states not in an electricity market. See Horner$^{[28]}$ section 4.3.2. and table 4.4 for additional information regarding this data.
non-profit sites to derive an estimate for project installation cost. There are approximately 1046 projects out of the roughly 800,000 projects meeting these criteria in the LBNL TTS10 database (see SM section G for more details). These projects represent 11 states in the US, with the top three most represented being California, Maine, and Arizona [15]. The mean project cost from these observations is approximately $3800 kW⁻¹. We use this mean value to estimate project costs for all systems in our combined educational institution dataset, varying this assumption in our sensitivity analysis. We also include annual operations and maintenance (O&M) costs of $15/kW yr and inverter replacement costs of $120 kW⁻¹ at year 10 [40]. We assume O&M and inverter replacement costs are constant across the US. We do not include the decommissioning cost of the system at the end of its useful life in our analysis.

2.6. PV system rebates (figure 1, step 6)

We include rebates when estimating the upfront project costs. We use the state-average rebates ($/kW) observed in the LBNL TTS10 database for school, government, and non-profit installations on recently observed projects in 2015 and in 2016 [15]. The rebate values identified range from $100 to $1700 kW⁻¹. Since the Federal ITC only applies to residential, commercial, industrial, investor-owned utility, cooperative utilities, and agricultural PV projects, these are not included in our non-TPO BCA scenarios; however, we do assume third parties can take advantage of the ITC [41, 42]. In SM section F, we provide a table of available state-level rebates assumed in our analysis as well as a table of rebates currently outlined in the DSIRE database.

2.7. Valuing health, environmental, and climate change benefits (figure 1, step 7)

We estimate marginal avoided damages from reducing emissions of CO₂, SO₂, NOₓ and PM2.5 that arise from using the electricity generated by the solar PV systems instead of grid electricity. First, we estimate the avoided marginal emissions damages in each Emissions & Generation Resource Integrated Database (eGRID) sub-region characterized by the Environmental Protection Agency (EPA) using the time of day, by season emissions factors posted in the Center for Climate and Energy Decision Making ‘Electricity Marginal Factors Estimates’ website by Azevedo et al [43]. These estimates are produced by our research group using an approach similar to the one described in Siler-Evans et al [44, 45] and used in the literature to assess the emissions and damages consequences from renewables, energy efficiency, and storage [11, 46–51]. Marginal damages reported on this website are marginal emissions reductions that are translated to damage reductions using two integrated air quality models: AP2 and EASIUR [29, 45, 52]. These models estimate the dispersion of pollutants and the resulting concentration in all US counties and then rely on dose-response functions to estimate physical impacts. Finally, these models monetize the impacts by using estimates for such inputs as the value of statistical life (which is assumed to be $10M in 2018 USD with a relative risk of 1.06 for concentration-response relation) and the value of lost commodities [52]—for a reference point, the EPA recommends a central estimate of $9.3 million ($2018) for studies seeking to quantify mortality risk reduction benefits [53]. For the climate change benefits, Azevedo et al [43] multiply the CO₂ emissions outputs from AP2 and EASIUR by the social cost of carbon, which they assume to be $40/ton CO₂ following EPA’s Social Cost of Carbon for Regulatory Impact Analysis [30, 54]. For our analysis, we use the marginal emissions damage factors by eGRID sub-regions for the year 2016 reported in Azevedo et al [43]. We multiply time of day marginal emissions damage factors by the hourly electricity generation from the solar system for each institution to estimate the hourly damages avoided, and then compute the total marginal damages for year 2016.

2.8. Private and social net-benefits (figure 1, step 8)

We estimate the annualized benefits and costs to the educational institutions and society separately. Costs to educational institutions include PV systems capital costs, annual O&M costs, and an inverter replacement at year 10, minus any available rebates (which will effectively reduce the capital cost). The annual benefit to the educational institution is comprised of the cost savings from electricity that does not need to be purchased from the grid, as well as the value of excess electricity that the institution can now sell back to the grid. As previously described, the TPO option is characterized as the difference between the regular annual electricity consumption costs to the educational institutions (without PV) at the retail rate and

| Scenario | Value of offset consumption | Value of excess generation |
|----------|-----------------------------|---------------------------|
| Net-metering at LMPs | State-average 2016 commercial retail rate | LMP |
| Net-metering at retail rates | State-average 2016 commercial retail rate | State-average 2016 commercial retail rate |
| Third-party ownership | School purchases electricity from the TPO at a rate reduced from the State-average 2016 commercial retail rate. We estimate the rate by amortizing the cost of the system for a 20 year lifetime. |

* Each scenario also includes an estimate for the demand savings, using the described methodology.
annual electricity consumption costs at a lower TPO-defined rate.

Social costs include any rebates made available to the educational institutions, which tax payers need to support. Costs also include the Federal ITC in the TPO scenario as well as the cross-subsidy in the aforementioned net-metering scenario where institutions sell excess generation at the retail rate. The social benefits are the monetized annual benefits associated with the reduction in CO2, SO2, NOx and PM2.5 emissions.

The following simplified equations depict how we calculate net-benefits for each educational institution, considering the three BCA scenarios for valuing electricity savings and excess generation described in table 2.

Net-metering scenario, with excess generation from the PV system valued at the LMP:

\[
\text{School.NB.LMP} = - \{\text{[Installation - Rebate]} + [(\text{Offset x Retail}) + (\text{Excess x LMP})] - \text{O&M - Inv} \}.
\]

Net-metering scenario, with excess generation from the PV system valued at the retail rate:

\[
\text{School.NB.Retail} = - \{\text{[Installation - Rebate]} + [(\text{Offset + Excess x Retail})] - \text{O&M - Inv} \}.
\]

Third-party ownership scenario:

\[
\text{School.NB.TPO} = \text{Annual Electricity} \times \text{Cost @ Retail} - \text{Annual Electricity} \times \text{Cost@ TPO.rate}
\]

Annual Electricity Cost @ TPO.rate = Annualized \times [−\{Installation – Rebate – ITC\} + [(Offset × Retail) + (Excess × LMP)] − O&M − Inv.}

\[
\text{School.NB.TPO} = -[\text{Rebate} + \text{ITC}] + [\text{Offset + Excess}] \times \text{Marginal Damages}
\]

In these equations, School.NB.LMP and Social.NB.LMP represent the school and social net-benefits, respectively, when excess generation from the PV system is valued at the LMP rate. School.NB.Retail and Social.NB.Retail represent the school and social net-benefits, respectively, when excess generation from the PV system is valued at the retail rate. School.NB.TPO and Social.NB.TPO represent the school and social net-benefits, respectively, when the PV systems are owned and operated by third-party owners and schools purchase electricity from the third-party owners. Note, in order to systematically estimate a TPO rate that is lower than the current retail rate for each state, we ultimately assume that the third parties are compensated by the schools at a rate that breaks even over the lifetime costs of the systems. Therefore, in order to estimate conservative cost savings for the schools (e.g. TPOs could design rates that yield better economics for them as well as for the schools), net-benefits are estimated to be zero for TPOs in this analysis. Installation represents the total installation cost for each educational institution, Rebate represents the state-average rebates ($/kW) observed in the LBNL TTS10 database, Offset represents the hourly solar PV generation consumed by the educational building, Excess represents the difference between hourly solar PV generation and hourly load when the PV generation exceed the load, Retail represents the state-level average 2016 commercial retail rate, LMP represents the hourly locational marginal price, O&M represents the annual operations and maintenance costs, Inv. is the annualized cost of the inverter replacement, ITC represents the 30% Federal ITC, and Marginal Damages represented the monetized health, environmental, and climate change damages associated with hourly offset emissions. Although not captured in these simplified equations, we take the present value of annual school benefits (i.e. electricity cost savings and excess generation sales) and annual school costs (i.e. O&M and inverter) for each year the system is in operation. Similarly, we take the present value of annual social benefits (i.e. avoided damages) and annual social costs (i.e. retail cross-subsidy) for each year the system is in operation. Therefore, we arrive at a net-benefit from the perspective of schools and society for each educational institution, assuming a project lifetime of 20 years. In this paper we present annualized net-benefits, using alternate discount rates of 2% and 7% [11]. We also report values by dividing the school and social annualized benefits and costs by the system peak capacity to arrive at per-kilowatt estimates of annual benefits and costs. When reporting aggregated results, we sum the annualized benefits and costs of all the systems in the unit of aggregation (e.g. a state) and divide by the sum of the total system capacity within the unit. See SM section H for a detailed description of BCA equations used in this analysis.

2.9. Sensitivity analysis

We perform parametric sensitivity analyses on seven key inputs in our analysis: (1) project installation costs, (2) discount factor, (3) available rebates, (4) system size, (5) project lifetime, (6) social cost of carbon, and (7) annual emissions/damages levels. We also consider the best- and worst-case scenarios for demand charge costs and fractional savings for the educational institutions. We vary each of these inputs separately and report varying outcomes in a spider plot and tables.
Reference SM section I on limitations and future study, including discussion of our geographic scope and focus on PV deployment rather than production and disposal.

3. Results

3.1. Total PV technical potential and avoided emissions on US educational institutions

We estimate a total available rooftop space of 0.4 billion m² for all US educational institutions. This results in a total installed generation potential of 64 GW or 100 TWh of annual electricity generation, serving 75 million students and teachers in the associated educational institutions and meeting 75% of their current electricity consumption from the grid [16]. The electricity output generated by solar PV at educational institutions thus corresponds to roughly 3% of total US electricity consumption [55]. As a comparison, Gagnon et al [9] find the total available rooftop space for all commercial and residential buildings to be approximately 8 billion m², resulting in a total technical potential of 1.1 TW of installed capacity or 1400 TWh of annual energy generation. These values are understandably larger since educational institutions constitute 14% of commercial floorspace, suggesting the available rooftop PV space for educational institutions should be a similar fraction of space [56].

Avoided emissions associated with solar PV on all US educational facilities amounts to approximately 60M metric tons of CO₂ per year, 7K metric tons of PM₁.₅ per year, 45K metric tons of NOₓ per year, and 45K metric tons of SO₂ per year. As previously mentioned, the US education sector is estimated to be responsible for 4% of total US CO₂ emissions [17], which equates to roughly 211 million metric tons yr⁻¹ [57]. Therefore, this paper estimates that solar PV could reduce the education sector carbon footprint by 28%.

3.2. Varying PV technical potential and avoided emissions across the US

In figure 3 we illustrate our estimates of the potential PV generation in different states. When reporting aggregated results, we sum the annualized estimated generation of all the systems in the state and divide by the sum of the total system peak capacity within that state. In terms of absolute generation potential, we find that Texas, California, and Florida (with K-12 Public educational institutions comprising the bulk of that generation) have the largest technical potential. We estimate that 11% of the institutions do not have suitable roof space for solar PV based on NREL’s LIDAR and GIS modeling and our own linear regression modeling. See SM section K for state- and county-level generation maps.

In figure 3 we also illustrate our estimates of total offset CO₂, PM₁.₅, NOₓ, and SO₂ emissions in each state from the solar PV systems installed on K-12 public, K-12 private, and higher education institutions. We separate the CO₂ emissions plot from the other criteria air pollutants, because the total offset metric tons are in different orders of magnitude. We find that the top five states generating electricity from solar PV on schools (Texas, California, Florida, North Carolina and Illinois) are not the exact same top five states that offset CO₂ emissions (Texas, California, Florida, Illinois, and Ohio) nor are they the same top five states.
that offset PM<sub>2.5</sub>, NO<sub>x</sub>, and SO<sub>2</sub> emissions (Texas, Illinois, Ohio, Indiana and Pennsylvania).

### 3.3. Private net-benefits of US school PV to educational institutions

We estimate net-benefits from PV systems to educational institutions under three scenarios: (1) net-metering with excess generation valued at the LMP, (2) net-metering with excess generation valued at the retail rate, and (3) TPO. In figure 4, we show annualized private net-benefits for educational institutions for the different scenarios explored (using a 7% discount rate). When reporting aggregated results, we sum the annualized net-benefits of all the systems in the state and divide by the sum of the total system peak capacity within that state. We find that there is no private case to adopt solar unless it is third-party owned and operated. Even in states such as California, with large rebates and high PV generation potential, these investments do not break-even. In table 3, we show that even when a lower discount rate is assumed (2%) the scenarios that do not involve a third-party do not pass the private BCA. It should be noted that provision of the ITC improves the net-benefits of the TPO scenario by up to 100% and 670% in the 2% and 7% discount rate scenarios, respectively. In SM section L we provide histograms of annualized school benefits (offset electricity cost savings + excess generation sales) and costs (installation—rebate + O&M + inverter) to educational institutions across the US and in each state, organized by institution type.

### 3.4. Social net-benefits of US school PV to the public

In figure 5, we provide the annualized net-benefits to society under the same three scenarios reported for the schools (again, using a 7% discount rate). When reporting aggregated results, we sum the annualized net-benefits of all the systems in the state and divide by the sum of the total system peak capacity within that state. We find that in most of the US, the HE&CC benefits provided by the installation of solar PV at US educational institutions exceeds the subsidies/
incentives that are provided when the business model is that the educational institutions install and own the systems (with the exceptions of California, New York, Delaware, New Hampshire, Nevada, and Vermont—which have relatively high rebate levels). Midwestern states like Wisconsin and Ohio have the highest aggregated social net-benefits, under current policies and grid generation portfolios. However, under a third-party operated model, the costs of the subsidies/incentives exceed the societal benefits, since third-party operators will have access to an additional subsidy/incentive: the Federal ITC. In SM section L we show the distribution of these results across all institutions in our dataset.

Figure 5. Annualized social net-benefits ($/kW) for three scenarios: selling excess generation at the LMP (left), selling excess generation at the retail rate (right), and third-party ownership (bottom), assuming a 7% discount rate. When reporting aggregated results, we sum the annualized net-benefits of all the systems in the state and divide by the sum of the total system peak capacity within that state. In SM section L we show the distribution of these results across all institutions in our dataset.

Figure 6. Avoided damages from CO$_2$, SO$_2$, NO$_x$ and direct PM$_{2.5}$ emissions when compared to the rebates and cross-subsidy paid by the public when excess generation is valued at the retail rate for the 10 states with the largest health, environmental, and climate change avoided damages. All values are reported in millions of dollars. In this plot we used the EASIUR model to monetize the emissions damages avoided.
Overall, the provision of electricity services from rooftop solar PV on educational institutions is estimated to create annualized HE&CC benefits on the order of $4 billion per year. In figure 6 we present the highest-ranking states in terms of avoided HE&CC damages and compare those monetized benefits with the social costs for incentivizing the adoption of such PV systems. We find that the HE&CC benefits provided by these systems would generally exceed the level of the incentives—with the exceptions of California and New York, where the rebates exceed the health, environmental, and climate change benefits provided by these PV systems. For instance, we estimate that California would need to value carbon at $160/ton CO₂ to make the current PV incentive for educational institutions pay off (compared to the roughly $40/ton CO₂ that we used in the rest of this paper). It is worth noting that it is not difficult to find literature arguing that CO₂ emissions should be valued at more than $160/ton [58–60]. Alternatively, California would need to provide incentives of $350 kW⁻¹ to meet carbon offsets currently valued at $40/ton CO₂ (compared to the current average incentive value of $1400 kW⁻¹ in the LBNL TT5T10 dataset [15]). Other states could substantially increase their rebates to match the HE&CC benefits that solar PV at educational institutions could provide. For example, Pennsylvania could have a rebate of up to $958 kW⁻¹, which would break even with the societal benefits provided from solar PV at educational institutions. Even if we assumed Pennsylvania valued the reduction in carbon emissions at $0/ton CO₂, it would still make sense in terms of the health and environmental benefits provided from reducing criteria air pollutant emissions from the main electric grid by providing a rebate to solar PV at educational institutions of up to $590 kW⁻¹. See SM section M for a state-by-state analysis on this topic.

3.5. Sensitivity analysis

We perform parametric sensitivity analyses on seven key inputs in our analysis: (1) project installation costs, (2) discount factor, (3) available rebates, (4) system size, (5) project lifetime, (6) social cost of carbon, and (7) annual emissions/damages levels. We also consider the best- and worst-case scenarios for demand charge costs and fractional savings for the educational institutions. We vary each of these inputs separately and report varying outcomes in a spider plot and tables. In all baseline scenarios, we assume excess generation is sold back at the LMP (see SM section N for sensitivity analysis results assuming excess generation is sold back at the retail rate).

Figure 7 depicts the parametric sensitivity analysis for the first six aforementioned key inputs. We parametrically adjust the baseline values listed in table 4 from −50% to +50%, using 10% increments.

Values depicted in figure 7 are the median private and social annualized net-benefits from the full distribution across all educational institutions (see SM section N for separate CDFs of net-benefits for each sensitivity input). We find that median educational institution net-benefits become positive when the average available rebate is $2700 kW⁻¹ (or 3.5 times the current average available rebate of $780 kW⁻¹) and is available for all institutions. We also find that private net-benefits are overall most sensitive to installation cost and discount rate. Finally, it seems that the costs of rebates to society may outweigh the benefits if project sizes grow at the same rate as rebate increases.

Table 5 depicts the parametric sensitivity analysis for annual emissions levels/avoided damages. Here, we consider annually increasing and decreasing avoided damages ranging from −5% to 5% of the baseline assumption (i.e. constant avoided damages). We find that even if the avoided damages decreased each year by 5% (from external factors de-carbonizing the electricity grid) our median net-benefits to society would still be positive.

Table 6 depicts the scenario analysis for changes in demand rates and savings. We use the 25th and 75th percentile ‘Fraction of Average Rate for Demand Charge’ and ‘Estimated Demand Savings from PV’ values taken from our demand rate analysis that we conducted for 15 reference educational institutions across the US (SM section E). We construct a best-case scenario, in terms of overall cost savings to educational institutions, by matching the 25th percentile demand charge fraction with the 75th percentile demand savings value. The worst-case scenario is then the opposite combination. We find that median net-benefits to educational institutions are only marginally different between the best-case and worst-case scenarios.

4. Conclusion and policy implications

In this paper, we estimate the potential electricity generation, emissions reductions, and private and social net-benefits of installing rooftop solar PV on educational institutions throughout the US. Importantly, we find that the private costs of solar for educational institutions still exceed the private benefits from reduced electricity consumption across the entire country (unless a third party operation model is used, in which case some locations can have net-benefits). Furthermore, with the exceptions of California and New York, the social health, environmental and climate change benefits exceed the levels of current incentives provided by the state and retail subsidies.

We estimate a total installed generation potential of 64 GW or 100 TWh of annual electricity generation, serving 75 million students and teachers in the associated educational institutions and meeting 75% of
their current electricity consumption from the grid \[16\].

We find regional heterogeneity in the private and social benefits of solar PV, similar to the findings from a study by Siler-Evans \textit{et al} \[45\]. We find energy output to be highest in the Southwest and lowest in New England. Furthermore, we find solar PV to have the highest health, environmental, and climate change benefits in regions where it is offsetting carbon-intensive and high-polluting technologies such as coal-fired power plants in the Midwest. California, Texas, and Florida have the highest technical potential for educational institution PV electricity generation. Similarly, these states have some of the highest estimated social benefits under current grid generation portfolios (whereas Midwestern states like Wisconsin and Ohio have the highest aggregated social net-benefits, under current policies and grid generation portfolios). The adoption of solar PV may have other effects that were left out of this study, such as requiring other electricity generation sources to cope with solar intermittency and variability—putting additional strain on the viability of electricity generating resources such as nuclear and coal. Within the scope of our analysis, our conclusions fall into three categories.

4.1. TPOs are currently the most economically viable option for educational institutions

Ultimately, we find that at the level of rebates observed in the LBNL dataset and current electricity rates, it is not economically viable for educational institutions to purchase these systems outright in any state. Our sensitivity analysis demonstrates private net-benefits become positive when the average available rebate is raised from $780 to $2700 kW\(^{-1}\). The private net-benefits also become positive if system costs drop from an average $3800 kW\(^{-1}\) to about $1100 kW\(^{-1}\), which some forecasts suggest are possible in the future \[61\]. However, a TPO scenario that allows for educational institutions to divert the capital and annual costs of owning a system is estimated to be economically viable in some parts of the country. It is assumed that the TPO would offer educational institutions a contract electricity rate that is derived from the lifetime cost of the system to the TPO (including an ITC) and that is less than the current annual cost of electricity for the educational institutions. Other options for reducing grid electricity consumption or for promoting solar energy adoption at schools with potentially superior cost-benefit ratios include purchasing renewable energy credits, pursuing energy efficiency strategies, performing retrofits of existing systems, or serving as a generation platform for community solar projects \[14, 62\].
Worst-case 41% (75th percentile) at rates that would exceed total HE&CC benefits. California, Nevada, Vermont, and Delaware, might be currently offering PV rebates to educational institutions at rates that would exceed total HE&CC benefits if all institutions installed rooftop PV. For instance, it is estimated that California would need to value carbon at $160/ton CO₂ to make the current PV incentive for educational institutions pay off (compared to the roughly $40/ton CO₂ reported in the EPA’s Social Cost of Carbon for Regulatory Impact Analysis [54] and used in this paper). See SM section M for a state-by-state analysis on this topic.

Solar PV will be an important strategy to de-carbonize the energy sector in the United States, and to reduce the health, environmental, and climate change damages associated with the production of electricity from fossil fuel sources. While the potential for solar PV in the residential and commercial sectors has been widely studied, the potential in educational buildings is largely unknown. Our analysis identifies which regions in the US stand to gain the most HE&CC benefits from solar PV on educational institutions. Moreover, our work provides a baseline analysis for efficient school PV incentive design. From a private perspective, our ownership models (school ownership scenario versus TPO scenario) provide bounding conditions in the current energy market. Our findings suggest that solar PV on educational institutions can serve an important role in US emissions mitigation strategies if attractive economic options are made available to them.

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Associated content

The online supplementary material includes descriptive summaries of the LBNL and NREL datasets, details of methods used to predict roof space and analyze data, discussion of available rebates and net-metering across the US, county-level results and additional details of the sensitivity analysis (e.g. varying air quality model results).

Notes

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