Supplemental Material

A. Estimating Abatement Cost

Here we describe methods for estimating average abatement cost for 200-megawatt (MW) solar arrays at the point of median solar generation in each state in the continental US. To arrive at our abatement cost estimates, we estimate lifetime total cost and total emissions reduction for each solar array. We describe these two calculations in turn. Our spreadsheet containing all calculations is available upon request.

Total Cost

Total cost of solar installations depends on both upfront cost of construction and revenues over time from electricity sales. To obtain estimates of upfront cost, we rely on the National Renewable Energy Laboratory's (NREL) engineering, procurement, and construction (EPC) cost tables. These tables record cost per direct-current watt of installed solar in each US state, accounting for location and capacity, and including the cost of transmission line construction. We begin with 2018 EPC cost by state,[1] then apply a national conversion factor to account for cost reduction through the first quarter of 2022,[2] and use an inflation calculator to express cost in 2016 dollars.

To produce estimates of revenues from electricity sales, we require estimates of the annual electricity production of grid-connected PV installations that account for the uneven distribution of solar irradiance across the US.[3] We obtain these using the National Solar Radiation Database (NSRDB) of NREL.[4] We collect hourly solar capacity factors from 2016 for locations across the continental US at a resolution of one point per 25 by 25 kilometers. Although there is natural variation in solar irradiance from year to year, we assume 2016 is essentially representative for our purposes. We then input these data to NREL's System Advisor Model (SAM) to estimate hourly solar generation from a 200-MW solar array at each grid point.[5] The estimates depend on parameters in SAM that include module type, directional orientation of panels, panel axis tilt, inverter efficiency, and system losses; in all cases we use default values. Finally, we find annual generation at each point by taking the sum over all hours of the year; [6] we next identify the point of median annual generation in each state, at which we estimate abatement cost.

To translate generation into revenues for each solar array by state, we multiply hourly (hour of the year) generation by hourly wholesale electricity price for 2016, and we then sum over hours in the year to

[1] Fu, Ran, David Feldman, and Robert Margolis. "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018." Golden, CO: National Renewable Energy Laboratory, 2018. NREL/TP-6A20-72399. NREL phased out its state-specific EPC cost estimates after this report.

[2] Ramasamy, Vignesh, Jarett Zuboy, Eric O'Shaughnessy, David Feldman, Jal Desai, Michael Woodhouse, Paul Basore, and Robert Margolis. "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022." Golden, CO: National Renewable Energy Laboratory, 2022. NREL/TP-7A40-83586.

[3] Our estimates do not include revenues from capacity payments, which are used in some locations to incentivize capacity investments. Accounting for these would reduce total and thus average cost in regions where such payments are made.

[4] Sengupta, Manajit, Yu Xie, Anthony Lopez, Aron Habte, Galen Maclaurin, and James Shelby. "The National Solar Radiation Data Base (NSRDB) for CSP Applications." *Renewable and Sustainable Energy Reviews*, vol. 89, June 2018, pp. 51–60., doi:10.1063/1.511771.

[5] PySAM Version 2.2.0. National Renewable Energy Laboratory. Golden, CO. <https://github.com/nrel/pysam>.

[6] Because 2016 is a leap year, we remove hourly generation (and price) observations from the leap day of February 29th so as to make these data compatible with hourly marginal emissions rates, which are from a generic (non-leap) year.

compute annual revenue. In areas not a part of a wholesale electricity market, we use engineering estimates of the shadow cost of changing electricity production by one unit. These price and cost data were generously provided by Severin Borenstein and James Bushnell by for the years 2014-2016, by state-utility.[7] We use the 2016 data and compute state-level averages of each hourly price weighted by utility electricity load. In the absence of reliable long-term forecasts of future wholesale electricity prices, our analysis holds hourly private marginal cost constant at observed 2016 values over the lifetime of the solar array.

Finally, to calculate the total present value of revenues, we sum discounted annual revenues over the lifetime of the array, which we assume to be 25 years (2023-2047). We use a discount rate of 3%, which is the central rate used by the Biden Administration in estimating the social cost of carbon.[8] We subtract the total present value of revenues from upfront cost to yield a total cost estimate (in 2016 dollars). This is the numerator in our average abatement cost metric.

Total Emissions Reduction

To calculate total emissions reduction, we first collect long-run hourly marginal CO2e emissions rates by state from NREL's Cambium dataset[9] for an average year within the array's 25-year lifetime starting in 2023, under a scenario of 95% economy-wide decarbonization by 2050.[10] Here, CO2e refers to an aggregation of carbon dioxide, methane, and nitrous oxide emission rates induced by changes to the composition of the electricity grid over the long term. This aggregation is prepared using 100-year global warming potentials for each greenhouse gas, as described in the IPCC's Fifth Assessment Report.[11] Additionally, we use Cambium's built-in parameters to specify that emissions factors reflect a combination of direct combustion and precombustion processes (i.e., fuel extraction, processing, and transport). We obtain total emission reductions by multiplying each hourly long-run marginal CO2e emissions rate by the corresponding hourly generation from 2016, and taking a sum over all 25 years. This forms the denominator in our average abatement cost metric.

Graphing Total Cost and Total Emissions Reduction

Figure 1 in the main text reports state-level estimates of average abatement cost. Figure SM1 decomposes those estimates into their two distinct elements, total cost and total emissions reduction. Overall, we observe considerable variation in both measures across states; favorability along one dimension does not guarantee favorability along the other.

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[7] The data are described and used in Borenstein, Severin, and James B. Bushnell. 2022. "Do Two Electricity Pricing Wrongs Make a Right? Cost Recovery, Externalities, and Efficiency." *American Economic Journal: Economic Policy*, 14 (4): 80-110.

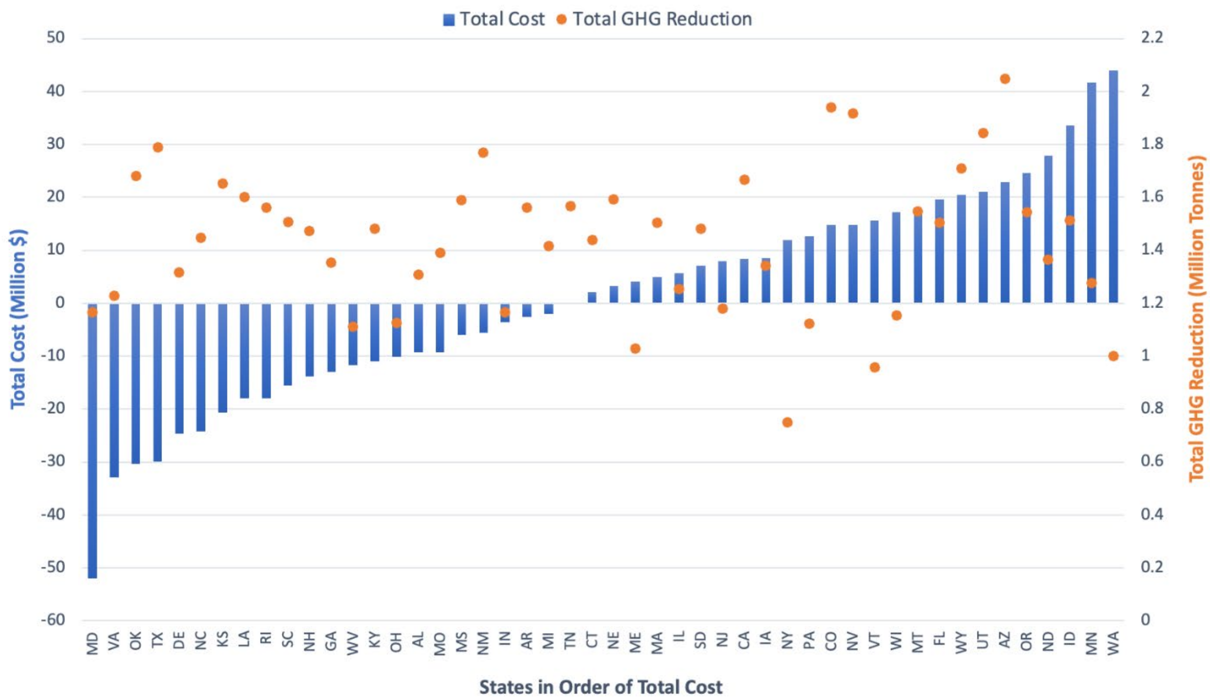
[8] "Discounting 101." Resources for the Future. 2022. https://www.rff.org/publications/explainers/discounting-101/.

[9] Gagnon, Pieter, Elaine Hale, and Wesley Cole. *Long-run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data*. National Renewable Energy Laboratory, Golden, CO, 2022. https://data.nrel.gov/submissions/183.

[10] Cole, Wesley, J. Vincent Carag, Maxwell Brown, Patrick Brown, Stuart Cohen, Kelly Eurek, Will Frazier, Pieter Gagnon, Nick Grue, Jonathan Ho, Anthony Lopez, Trieu Mai, Matthew Mowers, Caitlin Murphy, Brian Sergi, Dan Steinberg, and Travis Williams. "2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook." Golden, CO: National Renewable Energy Laboratory, 2021. NREL/TP-6A40-80641.

[11] Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Figure SM1: Utility Scale Solar Abatement Cost by State



B. Variations on the Analysis

We report two alternative analyses that provide additional perspective on the estimated abatement cost and emissions reduction for each project. First, we compute the value of the solar subsidy available for a 200-MW solar array; and second, we report average abatement cost estimates by state at the point of *maximum* solar generation instead of median.

Computing the Solar Subsidy

Solar projects in the US have historically been eligible for a federal Investment Tax Credit (ITC), and they will continue to be eligible under the Inflation Reduction Act passed in August 2022, at a magnitude of 30% of upfront cost. In the main text (Figure 1), we report estimates of *unsubsidized* abatement cost of solar projects, because the ITC subsidy (largely) represents a transfer from taxpayers to renewables developers and any other entities that capture a part of the subsidy value.[12] However, the subsidy does affect the private cost of construction and is thus important to project decision-making. We estimate the solar subsidy for each project and report the subsidies on a $/tonne of CO2e basis. As depicted in Figure SM2, the magnitude of the ITC subsidy varies considerably across states, reaching its highest in New York ($63.04/tonne) and lowest in Arizona ($20.75/tonne). This variation is due entirely to differences in upfront construction costs and total emission reductions. The incidence of the subsidy – how it is shared between project developer and the institution with the carbon neutrality program – may also vary and is thus an empirical question.[13]

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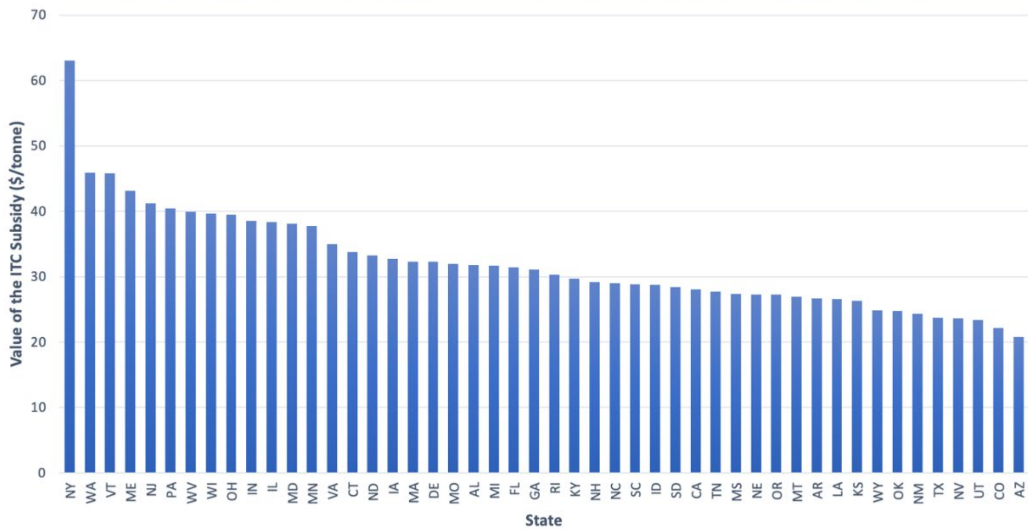
[12] In addition to the transfer, there is a social cost of raising public funds to pay for the subsidy.

[13] Developers and institutions could also structure projects to take advantage of additional incentives for renewable energy investment made available through the Inflation Reduction Act of 2022, for instance, by using domestically produced materials, or siting on brownfields and in certain "energy communities." See Friedman, Scott, Jonathan Stoel,

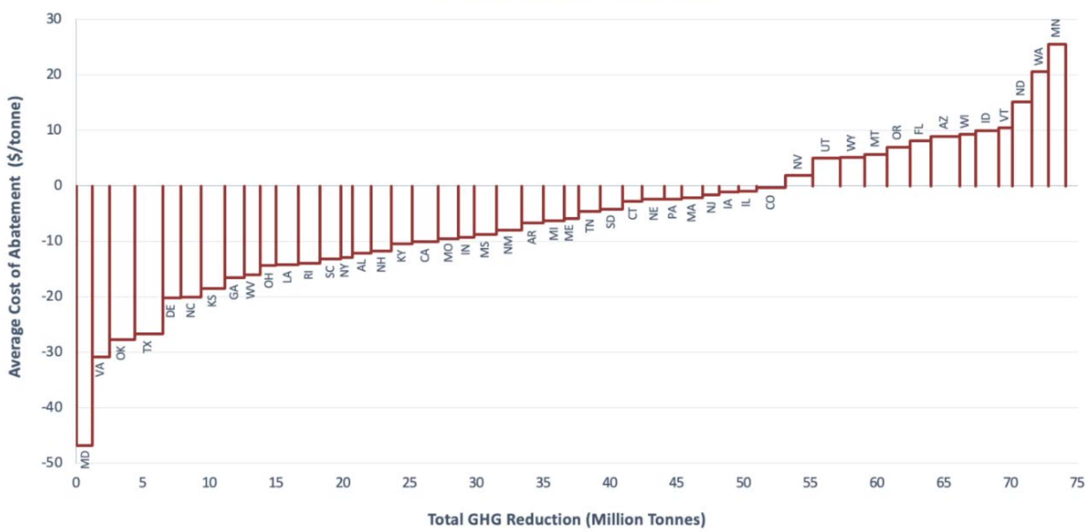
Figure SM2: Difference Between Unsubsidized and Subsidized Abatement Cost by State



Maximum Solar Generation

We also replicate our abatement cost calculations using the point of maximum generation in each state, rather than the median. This exercise causes state abatement cost to shift downward across the board, as Figure SM3 shows, with abatement costs now ranging from -$47/tonne (Maryland) to $25/tonne (Minnesota). There is some minor shifting in the ordering of states as compared to Figure 1, but the main takeaway from this figure is that cross-state variation in cost remains high. This, in turn, suggests that there are cost savings from non-local action at the top of the distribution of solar generation potential as well as in the middle.

Figure SM3: Abatement Cost Curve for Utility Scale Solar Projects by State
Maximum Generation Scenario



Mary Anne Sullivan, and James Wickett. "The IRA's transformative tax incentives for solar energy projects and manufacturing operations." (2022, August 15). Online: <https://www.jdsupra.com/legalnews/the-ira-s-transformative-tax-incentives-4082010/>.