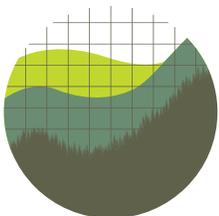


Making the Most of Distributed Energy Resources

*Subregional Estimates of the Environmental Value
of Distributed Energy Resources in the United States*



Institute for
Policy Integrity

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Executive Summary

Distributed Energy Resources (DERs), like rooftop solar and battery storage, have the potential to generate significant social benefits by displacing pollution-emitting electricity generators. Accurately compensating DERs for this environmental and public health value, which some regulators and experts call the “E-Value,” is imperative for making the most out of DERs’ potential. Doing so will ensure DERs are deployed, and used, when and where they create the most value for society. In practice, however, calculating the E-Value of DERs is difficult without a detailed model of the electric power sector because the benefits of avoided air pollution can vary significantly by location and time of day or time of year.

This report provides a new set of hourly E-Values for the whole United States, broken down into 19 subregions, using an open-source reduced-order dispatch model.¹ Critically, these granular estimates are shown to vary considerably by geography, hour, and season. The patterns uncovered by these estimates can help policymakers design economically efficient DER policies to reduce air pollution from electricity generators. Because these results come from an open-source model, they can be particularly useful for regulators with mandates to use publicly available data in their decisionmaking² or for those who desire to do their own analysis.

This report reveals three novel insights based on the hourly E-Values generated by the model. First, the E-Values of DERs depend crucially on the location of the DER, as some regions have more pollution-intensive electricity generators than others. Second, unlike the production cost savings of DERs (which are generally greater during periods of high electricity demand), there is no general and consistent pattern that can effectively characterize the E-Value of DERs throughout the day. Finally, the E-Value of DERs can be large – potentially greater than the benefits of avoided electricity production costs, and generally greater than what commonly used heuristics would suggest.

Policymakers can use these estimates and insights to create effective DER policies and programs. These findings highlight the need for more accurate and granular valuation of DERs, without which investments in DER technologies are likely to be either meager or misdirected. Policymakers using E-Value estimates in the design of DER compensation schemes or the assessment of other DER policies can rest assured they are making the most of DERs’ potential to deliver social benefits in their jurisdiction.

The modeling results make clear four specific policy implications. First, the relative magnitude of E-Value can tip the scales in favor of DERs. Accounting for both the E-Value and the benefits of avoided energy of DER deployment nearly doubles the benefits of DERs in comparison to valuing the avoided energy alone. Ignoring the E-Value of DERs will therefore result in the deployment of fewer DERs than what is optimal.

Second, the E-Value can identify where in the country different DER technologies are most effective. For example, investing in energy efficiency lightbulbs create the most value where the nightly E-value is the largest, and likewise, efficient air-conditioning and rooftop solar should be directed towards the regions with a high E-Value during summer’s midday. Policymakers should use the E-Value when deciding which technologies to support and where they should be deployed.



Third, general policies rewarding DERs during certain times of day might not effectively capture the benefits of DERs because there is no general and consistent daily pattern in E-Values across all regions. Instead, policymakers interested in granular time-of-day policies must model the specific benefits of a DER's deployment within their region.

Finally, policies must account for both the climate and public health benefits of DERs when calculating the E-Value. Each component makes up roughly half of total E-Value's on average. Ignoring the either component of the E-Value will result in inefficient DER deployment even if the other component is accounted for.

This report proceeds by first establishing the elements that determine the E-Value of DERs, including marginal generators, marginal emissions, pollutant type, location, and timing. With that established, this report then briefly characterizes the model used to calculate the subregional E-Values of DERs and finally summarizes the modeling results. Before concluding, this report discusses the important role of E-Value in policymaking and the several policy implications. Interested readers are directed to Appendix A to learn more about the reduced-order dispatch model, and Appendix B for a table of average E-Values for each subregion, season, and time-of-day.

The Environmental Value of Distributed Energy Resources

DERs are small energy resources that can reduce or supply a portion of onsite demand for electricity.³ Most DERs do not emit greenhouse gases or local air pollutants that can be harmful to human health and the environment.⁴ When a pollution-free DER reduces the need for pollution-emitting bulk power generation, there are benefits – potentially large benefits – from the avoided pollution. These environmental benefits are fundamental to the characterization of a DER's overall value to society, and, when monetized, are referred to as the E-Value of a DER.

Businesses and individuals typically consider only the benefits of avoided electricity costs when deciding how to invest in and operate DERs. This means that they are bound to ignore the E-value of DERs when making their decisions in the absence of any policy intervention. Because they consider a limited scope of benefits, this behavior results in an underinvestment in DERs.

In response to this problem, some jurisdictions have implemented policies to encourage adoption of additional DERs for the purpose of decarbonizing the electricity grid; this trend is expected to continue as the need to decarbonize electricity grows.⁵ However, as regulators strive to understand how to fit DERs into the larger electricity landscape, it is essential that they not only incorporate the E-Value of DERs, but do so accurately. If not, DERs could be deployed in an inefficient way that does not maximize the benefits they can provide or even work against state policy goals.⁶

Fortunately, there are readily available concepts and tools to help policymakers quantify the E-Value of DERs.⁷ The rest of this section describes the determinants of the E-Value of DERs and the general procedure to calculate it.

Elements Determining the E-Value of DERs

Unlike the private benefits of DERs, such as avoided energy costs, which can be easily deduced from the price of electricity, calculating the E-Value of DERs requires multiple steps. These straight-forward steps to calculate the E-Value of DERs are summarized below, and the rest of this section goes into more detail on those different steps.

Marginal Generator and Marginal Emissions

A major determinant of a DER's E-Value is which electricity generator it displaces. Although many generators produce electricity simultaneously, usually only one responds to DER-induced changes in the demand for bulk-power electricity. The responding generator must adjust its production to match marginal changes in demand in real time. For this reason, the generator responding to DERs at any given moment is the “**marginal generator.**”

Identifying the marginal generator displaced by a DER is the crucial first step in calculating the E-Value of a DER. The marginal generator could be a high-polluting oil plant or a relatively low-emissions natural gas plant, which means that a DER could displace either a larger or smaller amount of harmful emissions. The electricity grid operator, managing the balance of supply and demand in real time, determines which generator is marginal and can directly report this

information to the public. Alternatively, because the market operator follows consistent rules to balance supply and demand, the marginal generator can be deduced from a simulation of the electric power sector.

The pollution emissions avoided when the marginal generator decreases its electricity production by a marginal amount are the “**marginal emissions**” of electricity in that moment.⁸ The volume and type of pollutant avoided vary depending on the marginal generator’s fuel type and other characteristics, like plant efficiency or pollution-control technology. Therefore, knowing only the generator type is not enough to accurately determine the environmental and public health effects. Instead, it is important to have direct observation of marginal emissions from the marginal generator.

Marginal Emissions vs. Average Emissions

The marginal emissions of electricity are different than average emissions of electricity. Marginal emissions capture how generators (and emissions) respond to DER-induced changes in electricity demand and supply. Average emissions, in comparison, represent all pollution from electricity divided by the quantity of electricity generated in a given time period. This means that average emissions fail to capture the true change in pollution due to DERs.

Pollutants, Location, and Timing

The environmental and public health effects of marginal emissions depend crucially on the type of marginal emissions, as well as the location and timing of those emissions. In particular:

- (a) Different pollutants have different environmental and health effects. While greenhouse gases accumulate globally and cause global damages, some air pollutants remain local and cause harm relatively nearby. Local air pollutants, like sulfur dioxide, particulate matter, and nitrous oxides, contribute to serious human health consequences for populations near where they are emitted, like asthma and heart disease.⁹ Policymakers can use a number of public health models to quantify how different doses of these pollutants affect human health.¹⁰ They can then monetize these health effects using standard estimates, like the value of statistical life;
- (b) Pollutants emitted in densely populated areas or near highly vulnerable populations, like low-income communities and communities of color, will cause more damage because of whom or how many people they harm; and
- (c) Pollutants can have different effects depending on ambient weather conditions, like sunlight or temperature, so policymakers should know the precise timing of the marginal emissions.

Putting all of these elements together allows policymakers and stakeholders to quantify and monetize the E-Value of DERs. To do so accurately requires granular data on detailed marginal emissions rates and public health models.

Straight-forward Steps to Calculate the E-Value of DERs

1. Identify the electricity generator on the margin.

This “marginal generator” is the last generator required to balance supply and demand. As a result, this generator (or group of generators) will reduce their output in response to DER-induced reduction in demand for bulk-power electricity.

2. Quantify the marginal emissions from the marginal generator.

These are the pollution emissions per unit of additional electricity from the marginal generator. This varies by fuel type and electricity generator attributes (e.g. fuel, efficiency, and other technologies) and so is best measured directly (e.g. through EPA’s Continuous Emissions Monitoring System (CEMS)).¹¹

3. Monetize the environmental and public health damages of the marginal emissions.

These monetized harms of pollution emissions depend on the type of pollutant, where the marginal emissions are located, and when the pollutants are emitted – both in terms of time of day and time of year. These public health effects can be quantified and monetized using several possible tools.¹²

4. Calculate the benefits of avoided pollution per unit of DER deployment.

Multiplying the marginal emissions (tons/MWh) by the monetized damages per unit of emissions (\$/ton) gives an economic value for the environmental benefit of avoided pollution per MWh reduction in bulk-power electricity.¹³



General Model Description

This section presents a brief outline of the reduced-order dispatch model. Interested readers are directed to Appendix A for a more detailed description of the model and its application in this report.

The reduced-order dispatch model uses publicly available data on large fossil-fuel electricity generators to simulate historical hourly electricity production in a pre-specified geographic area.¹⁴ For every week in the sample period, the model ranks electricity generators from lowest cost to highest cost.¹⁵ This reflects the fact that low-cost electricity generators are typically called on to produce electricity before high-cost ones. With this weekly ranking, the model then identifies for every hour which electricity generators can be called upon to collectively produce enough electricity as was produced historically for the hour, but at the lowest possible total cost.

In this way, the model identifies the last electricity generator required to balance supply and demand as the marginal electricity generator. The pollution emitted from the marginal generator (in tons/MWh) represents the marginal emissions for that hour – the increase (or decrease) in pollution for a one-unit increase (or decrease) in the demand for fossil-fuel electricity.

Although this model is relatively simple, it captures several of the complexities inherent in the electric power system, including the required downtime of thermal plants and weekly variation in plant efficiency and fuel prices. However, it does not capture transmission or distribution constraints, nor does it model non-fossil resources.¹⁶

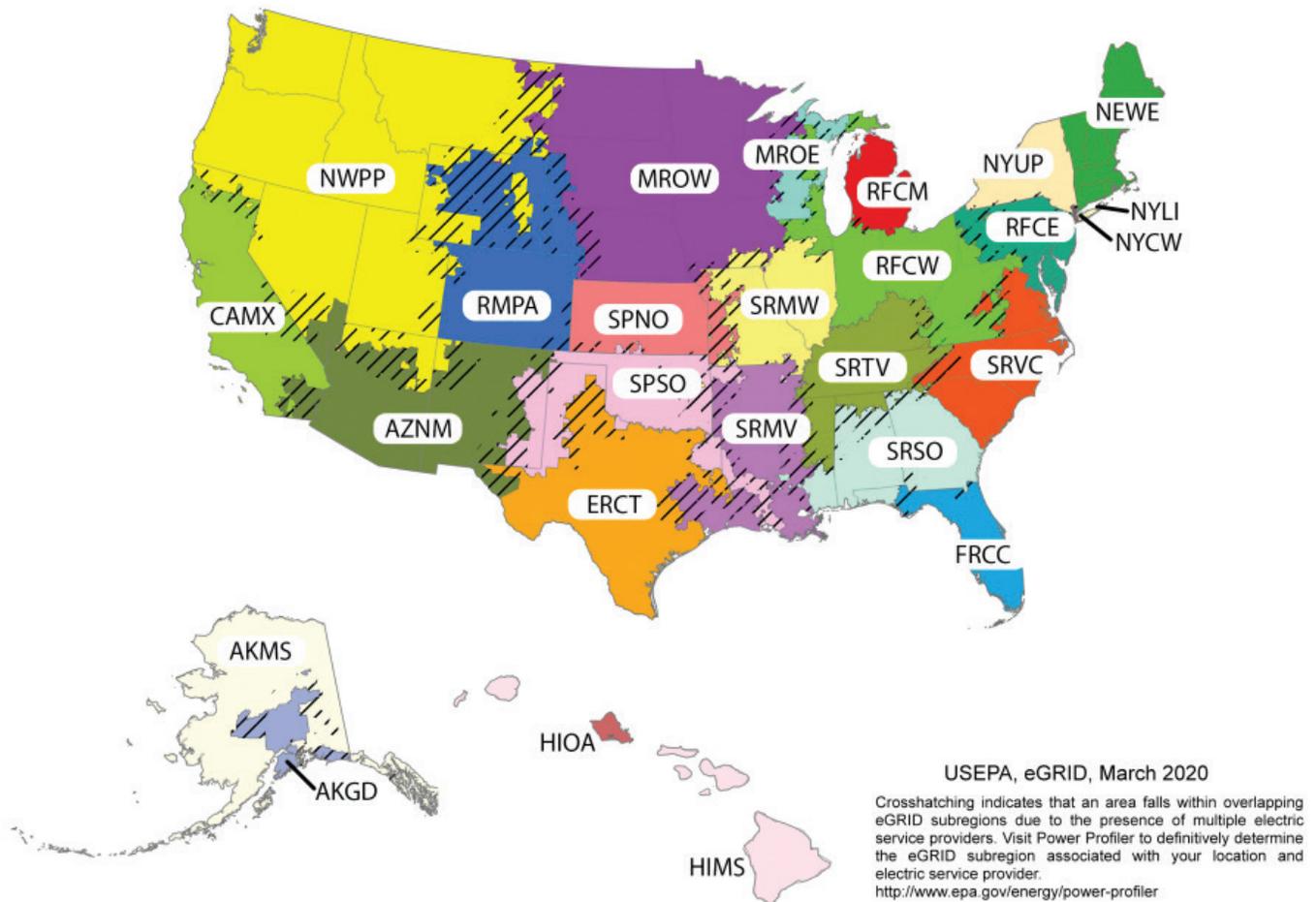
This report presents results using the reduced-order dispatch model with data from the year 2018, and geographic regions based on EPA's Emissions & Generation Resource Integrated Database (eGRID) regions as displayed in Figure 1.¹⁷ This modeling exercise directly outputs hourly marginal emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon dioxide (CO_2) for each subregion, and therefore simultaneously completes steps 1 and 2 required to calculate the E-Value. For step 3, this report uses location-specific monetized damages of NO_x and SO_2 from the Estimating Air Pollution Social Impact Using Regression (EASIUR) model, and monetized damages of CO_2 based on to the Social Cost of Carbon (SCC) developed by the federal Interagency Working Group (IWG).¹⁸ Finally, in step 4, this report calculates the hourly E-Value by multiplying the marginal emissions and monetized damages for each pollutant and summing the resulting product across all pollutants measured.

Data limitations prevent this report from monetizing the damages of primary particulate matter pollution emitted from electricity generators (i.e., black carbon) because EPA's CEMS does not report primary particulate matter pollution data. Rather, the E-Value estimates in this report quantify only the damages of secondary PM_{2.5} that are produced from chemical interactions in the atmosphere involving SO_2 or NO_x . Because PM reductions are responsible for a significant portion of benefits from federal regulations of emissions from power plants, and so a "substantial portion of the benefits of all federal regulation,"¹⁹ it stands to reason that the omission of this important data means that the E-Value estimates presented in this report are a lower bound.²⁰

Evidence suggests that PM is a non-threshold pollutant, which means that it is harmful even at low doses.²¹ Therefore, it is important to know the full magnitude of PM emissions. In order to incorporate the full effects of particulate matter into the subregional E-Values, hourly primary particulate matter pollution estimates must be imputed from annual

measurements from electricity generators or modeled directly.²² With these estimates, the E-Value can be updated to include total harms of particulate matter using location-specific monetized damages of primary particulate matter from the EASIUR model. Incorporating the total harms of particulate matter from the marginal electricity generator will increase the E-Value estimates in some regions and may change when and where the E-Value is the greatest.

Figure 1 – eGRID subregions defined by the EPA



Note: NYUP, NYCW, NYLI, and NEWE are aggregated into a single region (NPCC) in the E-Value modeling exercise.

Results

The reduced-order dispatch model and monetization tools uncover the hourly environmental value of DERs for 19 regions in the continental United States. As a reference for policymakers, the season and time-of-day average E-Values are presented in Appendix B. The modeling results show the following conclusions.

The E-Value of DERs Varies by Region

Results from the reduced-order dispatch model suggest the E-Values of DERs can vary significantly by subregion. Figure 2 displays hourly maps of the E-Value of DERs for each subregion averaged by season and time of day. This figure shows that the E-Value depends largely on the geographic region, and less so on the time of day and season. This variation is because some regions use more pollution-intensive fuels to generate electricity than others. For example, the Great Lakes and Ohio Valley regions are heavily dependent on coal electricity generators, which emit a large amount of CO₂ and SO₂ per MWh. The E-Value is relatively small in California where little-to-no electricity is generated by coal electricity generators.

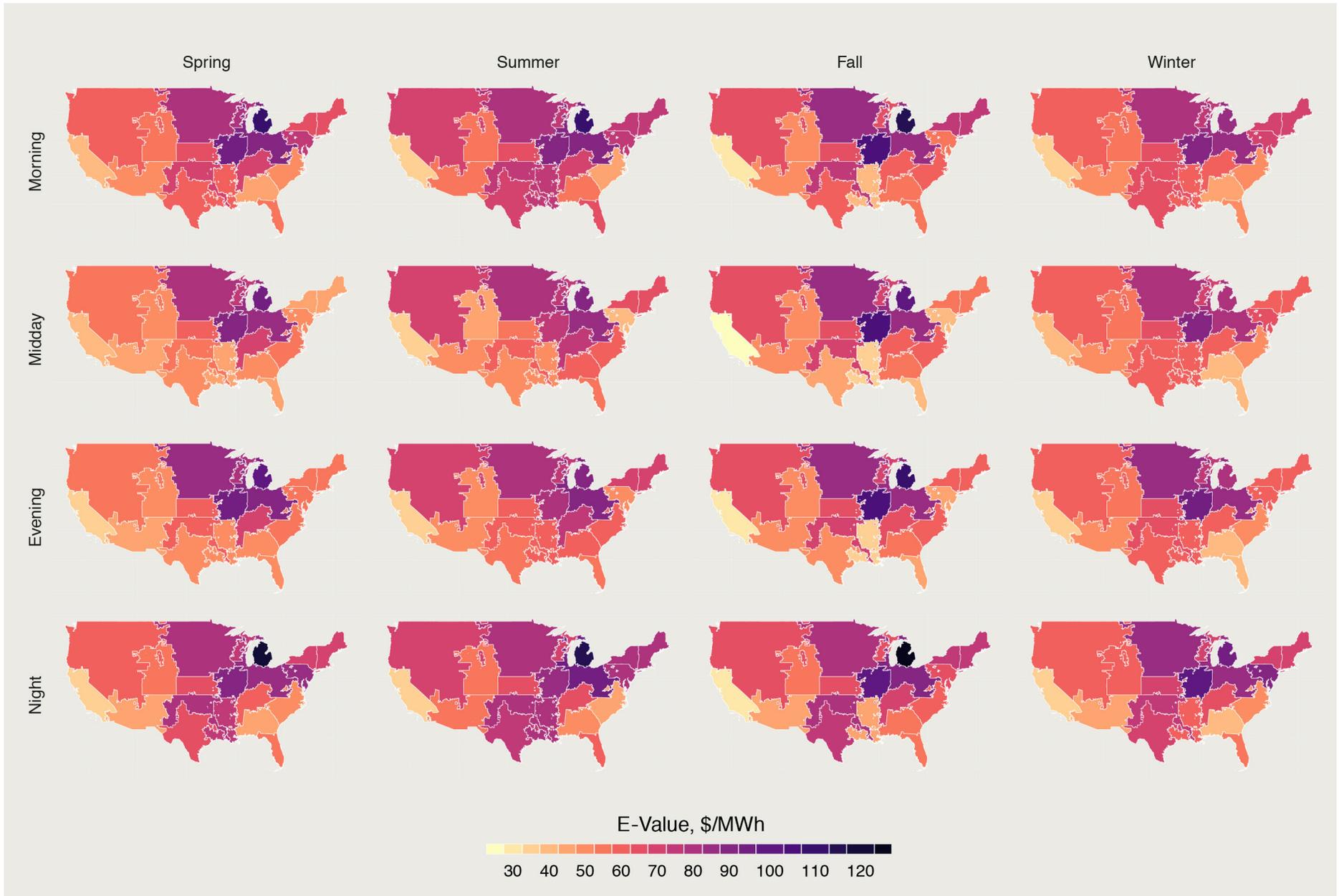
Other than geographic location, population density can be a large determinate of the E-Value of DERs. Densely populated areas experience more damage from a given amount of pollution as more people are exposed. Results in Figure 2 show there are consistently higher E-Values in the Northeast compared to the Rocky Mountains, in part because the former is more densely populated than the latter. Analysis on the electric power sector done by the EPA illustrates this point in the context of PM_{2.5}: a ton of PM_{2.5} released in the eastern region of the United States causes between \$130,000 and \$320,000 in damages, whereas the same ton in the western part of the United States causes \$24,000 to \$60,000 in damage.²³

Heidi Besen



E-Values vary by geographic region because some regions use more pollution-intensive fuels to generate electricity than others.

Figure 2 – Map of Subregional Average E-Value by Season and Time-of-Day



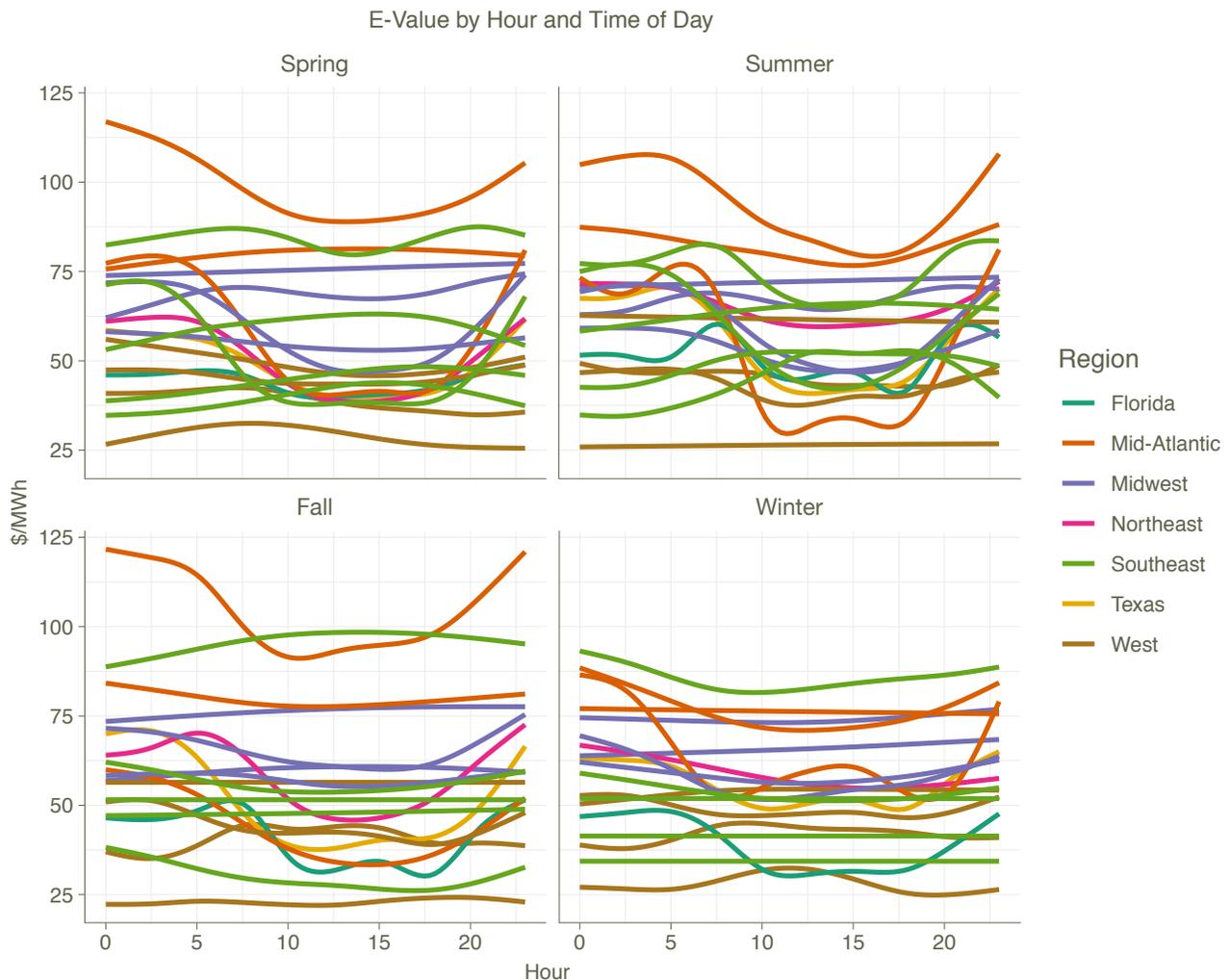
Seasons are defined according to equinoxes and solstices. Each time period is 6 hours long; Morning begins at 4 am, Midday at 10 am, Evening at 4 pm, and Night at 10 pm.

The E-Value of DERs Does Not Follow a General or Consistent Daily Pattern

Generally, the hourly E-Value can vary significantly throughout the day, as the marginal electricity generator, marginal emissions, and associated health benefits change hourly. If the hourly E-Value were to follow a consistent and general daily pattern, policymakers could use this information to better design DER compensation policies by, for example, compensating DERs the most during the time of day they generate the most social value.²⁴ But, if the E-Value does not follow a consistent and general pattern, policy makers would have to directly observe hourly marginal emissions or model the specific region to accurately compensate DERs for their intra-day variation in E-Value.

Figure 3 presents the average hourly E-Value for each subregion and season in an attempt to uncover whether there is any general pattern that can inform DER compensation policies that vary throughout the day. This figure shows there is no consistent and strong pattern throughout the day or season, especially in comparison to the variation among regions at a specific time of year. If anything, there is sometimes a pattern that is contrary to the pattern in energy costs: In some subregions, the E-Value of DERs is smaller in the middle of the day during “peak demand” periods. This is likely because a natural gas plant is the marginal generator during the day, and a relatively more pollution-intensive coal electricity generator is the marginal generator during the night.

Figure 3 – Smoothed Hourly Average E-Value of Subregions by Season

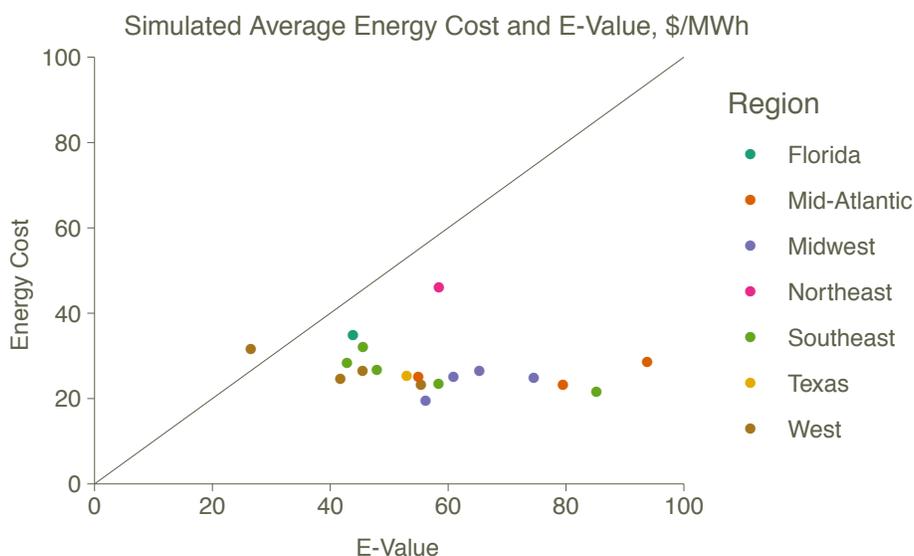


Each subregions color is based on the geography of the corresponding NERC region.²⁵

The E-Value of DERs Can Be Large

The average E-Value of DERs, across all 8760 hours in a year and 19 geographic regions, was \$57/MWh (with a median of \$54/MWh). This value is nearly twice the average cost of electricity simulated by the reduced-order dispatch model (\$27/MWh), and greater than the national average wholesale price of electricity in 2018 (\$44/MWh).²⁶ Figure 4, which displays the simulated average production cost and average E-Value of DERs in every subregion, shows this relationship holds for every subregion except one.

Figure 4 – Simulated Energy Cost Compared to the E-Value of DERs

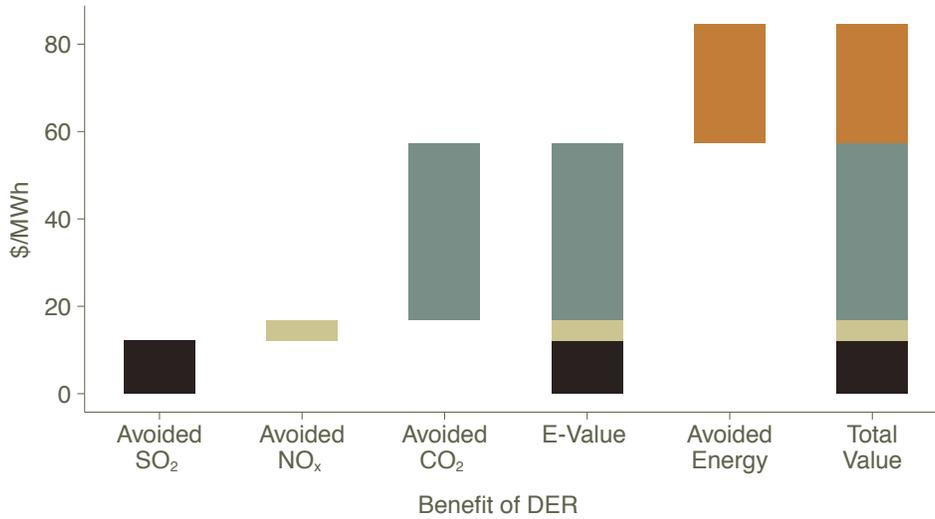


Each subregions color is based on the geography of the corresponding NERC region. The diagonal line represents equality between the two values, and subregions to the lower right of the diagonal lines have an average E-Value greater than average simulated energy cost.

Benefits from avoided greenhouse gas emissions make up nearly half of the E-Value. Decomposing the E-Value of DERs, as done Figure 5, shows the avoided CO₂ pollution is a large component of a DER's benefits on average across all regions and hours. By using the Social Cost of Carbon, the E-Values presented in this report capture, at least in part, the large future damages from climate change (including from coastal storms, extreme weather events, and human health impacts, such as mortality from heat-related illnesses induced by the use of fossil-fuels). Ignoring the benefits of avoided greenhouse gas emissions will provide an underestimate of the total benefits of DERs. For example, recent analysis by the EPA evaluating only the public health benefits of DERs, excluding avoided GHG emissions, range from \$17 to \$40/MWh on average.²⁷

Finally, the E-Value of DERs are large relative to the estimated environmental value based on average pollution emissions from electricity production. This means that basing policy decisions on the commonly used heuristic of average pollution emissions instead of marginal pollution emissions leads to inefficient deployment. The divergence between the average pollution emissions and the marginal emissions depends on how the marginal electricity generator differs from the average electricity generator in terms of fuel-type, efficiency, location, and other technical features. The E-Value using the marginal emissions is greater than an E-Value equivalent based on average emissions when, for example, an oil plant is on the margin in a region composed largely of relatively cleaner natural gas electricity generators.

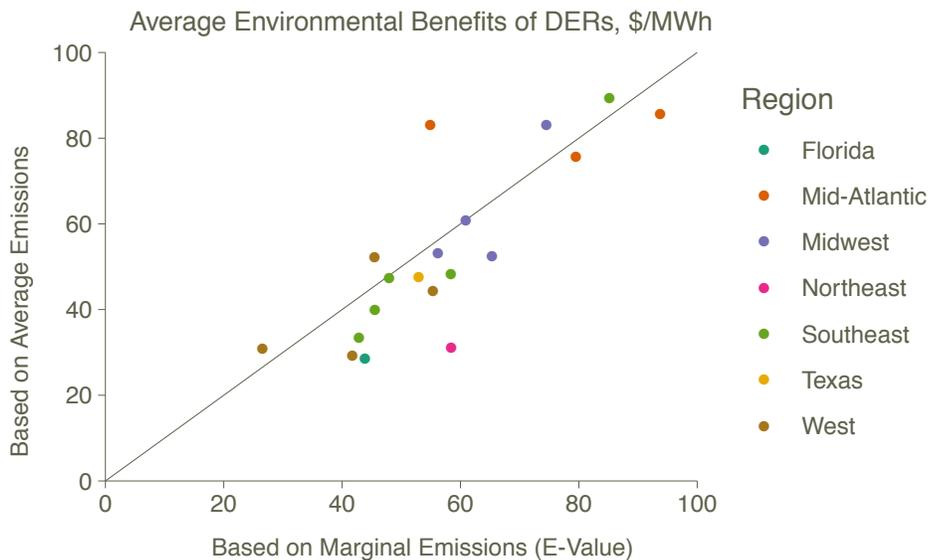
Figure 5 – Decomposition of a DERs' Benefits



Average hourly benefit of DERs across all hour-subregions in 2018. Avoided pollution (SO₂, NO_x, and CO₂) are monetized as described in the General Model Description section of this report. Avoided Energy represents the avoided fuel, operations, and management costs of bulk-power electricity by DERs. These benefits are not exhaustive; DERs can provide additional benefits not listed in this figure such as avoided line losses and avoided capital costs.²⁸

The output of the reduced-order dispatch model shows an E-Value equivalent based on average emissions is less than the E-Value based on marginal emissions in 75% of hourly subregion observations. Figure 6 supports this statistic by showing the sample mean of each measure across all 19 subregions. Here, the E-Value of DERs is larger on average when it is based on marginal emissions. Because the reduced-order dispatch model does not include pollution-free resources like nuclear power and hydroelectric dams, the E-Value using actual average emissions (instead of simulated) would likely be even smaller – suggesting a heuristic based on average emissions could greatly undercount the benefits of DERs.

Figure 6 – Comparing E-Value Based on Average and Marginal Emissions



Like Figure 4, regions are defined according to the general geography of NERC regions and the diagonal line represents equality between the two values.

E-Value and Public Policy

DERs are becoming a fixture in the modern grid and policymakers have a variety of reasons for intervening to support DER deployment. First, policies that traditionally guide the electricity market are not designed to govern decentralized resources and so do not consider locational factors. Second, many longstanding policies overlook external costs that come with electricity production from thermal electricity generators, and so do nothing to correct a serious market failure which DERs can address. Third, newer policies to reduce greenhouse gas emissions can be complemented by – or even heavily rely on – greater deployment of DERs.

The E-Value can and should have significant bearing on how DER-focused policies are shaped. This section explores both the general importance of using the E-Value in DER policy and the implications of this report's specific findings.

The Importance of E-Value for DER Policy

Several states are adopting policies that support DER deployment as part of their emissions-reduction goals. Considering the E-Value for different DER technologies can help determine if DER-bolstering policies can achieve the desired pollution reductions. The E-Value can also highlight important policy impacts, such as whether DERs are providing the maximum possible social benefits or which type of DER offers the most benefits in a certain location. In practice, the E-Value can be applied anytime a DER reduces demand from the bulk-power system. The environmental and public health benefits the DER provides are applied in proportion to the number of MWh of bulk-power avoided. This information can ensure that the right type of DER is being deployed at the right time and location by sending the proper price signals.

The E-Value can help policymakers optimize policies that target specific DER technologies or programs, like distributed solar generation, battery storage, and energy efficiency. For example, a solar panel generating 1 MW of electricity reduces the demand for bulk-power electricity and so provides society the benefit of reduced air pollution, represented by the hourly E-Value at that point in time. So, if solar panels generate electricity when and where E-Value is highest, they can provide greater benefits to society. This is why establishing a tax credit offsetting installation costs of rooftop solar will benefit society more if it supports the deployment of solar that displaces an oil plant situated in a low-income community. Accounting for the E-Value when designing such a tax credit would accomplish exactly that.

DERs Policies Can Directly Incorporate the E-Value of DERs

The E-Value can not only inform DER investment, it can also be directly incorporated into policy design. For example, most rooftop solar is compensated a flat rate based on the retail rate of electricity through **net energy metering** policies. As an alternative, regulators can use a **value-stacking approach that is based on DERs' various attributes or services**. A value-stacking approach would compensate DERs for their avoided energy and their E-Value. This is more economically efficient than net energy metering because it accounts for all of the values DERs bring to the power grid.²⁹

Similarly, if decisionmakers know the E-Value of charging (or discharging) an energy storage system at any given point in time, they can use this information to determine the values to bill (or compensate) energy storage assets in order to maximize their benefits. A battery discharging 1 MW of electricity generates environmental benefits that are best captured by the E-Value for that hour. If energy storage owners discharge their batteries when the E-Value is high and charge their batteries when the E-value is low, they can provide social benefits by decreasing environmental damages of electricity production.³⁰ Because energy storage technologies can more easily respond to price signals than most other DERs, it is crucial they are compensated and charged the E-Value accordingly.

Demand response is another similar case: Demand response that conserves 1 MW of electricity not only avoids the cost of electricity production but also provides society with the benefits of avoided pollution, an economic benefit equal to the E-Value for that hour. But, without the E-Value, customers might reduce their demand only when retail electricity prices are high, rather than when the sum of the E-Value and electricity prices are high. The latter approach produces greater social benefits.

The E-Value can also help demonstrate in what parts of the country implementing different energy efficiency policies can create the most benefit. Energy efficiency measures, like replacing incandescent lightbulbs with LEDs, provide greater social benefits when they are deployed in places that rely on electricity from more pollution-intensive electricity generators, like parts of the Midwest, or places with a higher nighttime E-Value.³¹ Similarly, locations with a higher E-Value during summer's midday should potentially deploy more efficient air-conditioning before investing in energy efficiency lighting. Knowing the E-Value can also aid federal programs – like the Department of Energy's Weatherization Assistance Program – so that they direct energy efficiency investments towards regions with a higher E-Value on average.

The E-Value should be used in DER policy and can be applied across DER technologies. The next part of this section goes into greater detail about the specific policy implications of the subregional E-Values in this report's findings.

Policy Implications of Results

The Relative Magnitude of E-Value Can Tip the Scales in Favor of DERs

When decisionmakers know that E-Values can be relatively large compared to costs in the electric system, they are better equipped to set welfare-maximizing policies. The average E-Value of DERs across this report's findings was \$57/MWh (with a median of \$54/MWh). This value is nearly twice the average cost of electricity simulated by the reduced-order dispatch model (\$27/MWh), and greater than the national average wholesale price of electricity in 2018 (\$44/MWh).³² The fact that the average E-Value exceeds production costs and wholesale electricity prices should clearly signal to policymakers and other stakeholders that DERs can be a worthwhile investment on their environmental merits alone. In states where DERs are being targeted by policies to reduce greenhouse gas emissions, this makes the case very clear cut. But even in states where investments in DERs are primarily weighed based on private costs and benefits, showing that the E-Value *can* exceed private costs creates a strong signal about optimal resource allocation.

E-Value Can Indicate Where Different DER Investments Are Most Effective

When E-Value is not a deciding factor in setting policy or making DER investments, these policies inevitably exclude considerations of location and scale. This is because absent a DER policy to account for each resource's E-Value, private

investment and use of DERs is governed largely by their private benefit – avoided production costs, without regard for location. This suggests DER policies based only on the private production costs are ignoring most of the social value of DERs, and so will likely deploy DERs ineffectively. For example, DER investment based only on the cost of electricity would occur largely in the Northeast, whereas the environmental and public health benefits of DERs suggest they should be a higher priority in parts of the Midwest and Mid-Atlantic.

State policymakers can look at the results presented in this report and see if and when their state has a high E-Value. Though an E-Value of any magnitude should be accounted for in DER policy, states with high E-Values may choose to prioritize DER investment because the benefits can be so large.

General Time-of-Day Policies May Not Be Effective for DERs

Designing policies according to general patterns is common practice for setting retail electricity rates. For example, utilities, or policymakers, sometimes identify a “peak demand” period during the day and set rates higher during that period to disincentivize electricity use. These rates make sense in the context of electricity production. For example, periods of “peak demand” in the summer are generally associated with the highest production costs. If E-Values were to follow a similar daily pattern, smart policy design could compensate DERs for the hours of the day in which they generate the most benefits to society. For example, if the E-Value was consistently greatest in the early morning, retail rates encouraging the use of DERs in the morning would generate more benefits to society than a policy that ignores daily patterns in the E-Value.

However, the results show that even though the hourly E-Value can vary significantly throughout the day - as the marginal electricity generator, marginal emissions, and associated health benefits change – there is no general and consistent daily pattern of E-Values across all subregions. This means that even granular E-Value compensation policies that try to capture hourly variation could be ineffective unless they are based on real-time marginal emissions factors. Accordingly, policymakers that wish to accurately compensate DERs for the E-Value must conduct modeling specific to the location and DER technology under consideration. Blanket policies based on conventional wisdom might incorrectly compensate distributed energy resources the most when they are actually generating the least amount of environmental value.

DER Policies Should Monetize Avoided Climate Damages and Public Health Benefits

Finally, policymakers should ensure that they overlook neither the climate nor the public health aspects of the E-Value. The effects of greenhouse gases and local pollutants vary geographically, so although the greenhouse gas component of the E-Value is significant in some regions, it is outweighed by the public health component in others. Figure 5 shows that damages from CO₂ make up about half of the total E-Value on average. Internalizing the negative public health externalities from local air pollutants is necessary for properly valuing DERs, but it is not sufficient: excluding the negative environmental (i.e. climate) externalities would lead to a serious underestimate of the E-Value in some places. In addition, climate damages themselves reflect public health consequences that are not attributable to local air pollutants, like increased mortality from extreme weather events, so the picture of public health effects is not complete without them.

Luckily, there is a readily available tool that policymakers can use to monetize the benefits from avoiding a marginal ton of CO₂ emissions, the IWG’s Social Cost of Carbon.³³ The Social Cost of Carbon should be used anytime a decision will affect greenhouse gas emissions, as is the case with many policies that affect DER deployment. In fact, because

DERs are often targeted by greenhouse gas reduction policies, using the Social Cost of Carbon in the E-Value makes the effectiveness of these policies more apparent.

In densely populated urban areas, it's possible the public health benefits of avoided local air pollution exceed the climate benefits of avoided greenhouse gas emissions. This is because the harms of local air pollutants, like particulate matter, increase in proportion to the number of people exposed to pollution. Monetizing the benefits of avoided greenhouse gas emissions is necessary for the reasons outlined above, but it is also not sufficient. DER policies must monetize both sets of benefits to ensure DERs are deployed at a scale that is economically efficient and provide the greatest possible benefit to society.

Conclusion

Policymakers looking to achieve efficient deployment of DERs in their jurisdiction must accurately compensate DERs for all of their benefits, including the E-Value. If they fail to do so, DERs are likely to be misemployed, meaning society misses out on important and cost-effective benefits of reduced air pollution. In practice, quantifying a DER's E-Value is difficult to do without specifically modeling or observing which electricity generators are displaced by DERs in any given hour and using a public-health model or other tool to monetize the benefits of avoided air pollution.

This report presents the average E-Value of DERs for 19 subregions in the United States using historical data from 2018. The results show that the E-Values are large relative to the benefits of avoided production costs, the public health benefits alone, and what hourly average pollution emissions would suggest. The most important factor in determining the E-Value of DERs is location. DERs in the Great Lakes and Mid-Atlantic region can provide benefits almost twice what they can in California. Finally, there is no general pattern of the E-Value of DERs throughout the day, suggesting policies that try to capture hour-to-hour benefits of DERs require real-time data on pollution from the electric power sector or modeling results specific to the region under consideration.

Although informative, these results paint only part of the picture. The E-Value presented in the report does not monetize the benefits of avoided primary PM_{2.5} pollution due to DERs. Incorporating these benefits of DERs can only increase the E-Value, possibly by a significant amount. In addition, modeling limitations prevent a more thorough analysis that considers how DERs might displace non-fossil resources like nuclear electricity generators or hydroelectric storage. Finally, as the grid transitions towards more utility-scale renewable generation and less pollution-intensive thermal resources, the E-Value of DERs is likely to change considerably. This suggests there are real benefits to updating E-Values used in policy making on a regular basis.

Appendix A: Reduced-Order Dispatch Model

This report uses an open-source reduced-order dispatch model to quantify the historical hourly marginal emission of electricity generation in a pre-specified region. This model uses publicly available data on historical fuel costs and electricity production to simulate which combination of electricity generators can generate the same electricity as was historically produced, for every hour, while minimizing production costs and respecting historical downtime requirements of thermal generators.

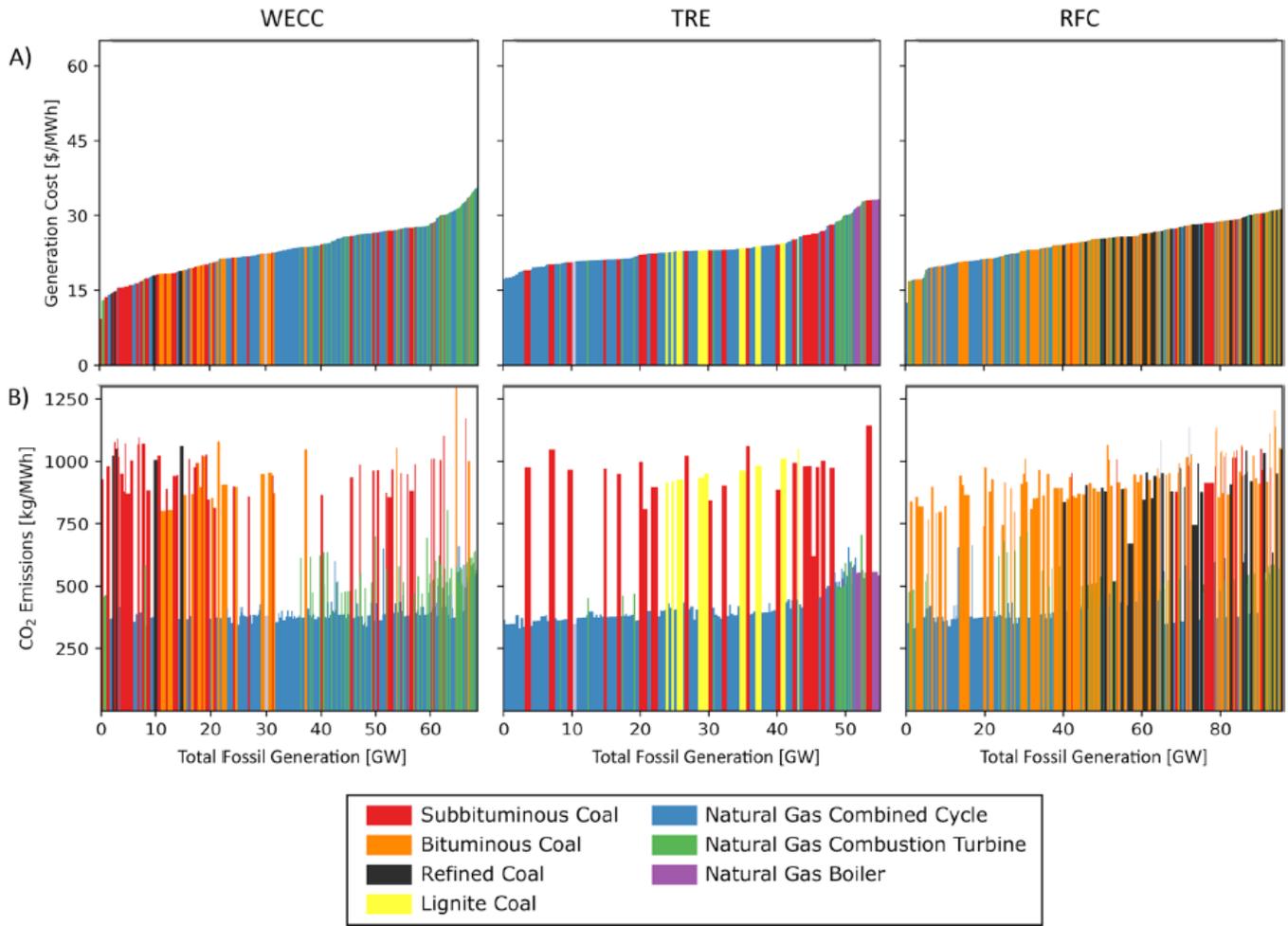
The model accomplishes this by constructing a “bid-stack” for every week on the sample year which ranks large fossil-fuel electricity generators according to their cost to produce electricity.³⁴ A separate set of bid-stacks are created for each subregion. This bid-stack varies week-to-week according to publicly available fuel prices and observed plant-specific efficiency rates. An electricity generator's costs includes fuel costs specific to the power plant when available, as well as general variable operations and maintenance costs based on the fuel type and power plant age. Figure 7 presents example “bid-stacks” for three regions for the first week in August of 2017 from Deetjen & Azevedo (2019). This figure also shows the weekly marginal emissions of CO₂ (per MWh) for each electricity generator in the bid-stack.

For every hour in the sample, the model determines which combination of resources could have produced the same quantity of electricity as historically produced by large fossil-fuel electricity generators, but at the lowest possible price by finding where the bid-stack intersects with the demand for electricity generated by large fossil-fuel electricity generators for that hour. In doing this, this model respects weekly limits on minimum and maximum output for each electricity generator, as well as required down time of larger fossil-fuel electricity generators. The last generator called upon to balance supply and demand for that hour is the marginal electricity generator, and the marginal emissions for that hour are based on the marginal emissions of that electricity generator.

Although the model is simple, it does a good job reconstructing the marginal electricity generator using historical data. Because it is a simulation, it allows for nuanced hourly emissions that might not be possible with regression-based estimates. In addition, it allows for counterfactual modeling exercises that can assess how pollution emissions would change if a carbon price were implemented in the electric power sector. The model could be improved upon, however, by incorporating non-fossil resources, transmission constraints, and the startup costs of electricity generators.

The Python code to run the reduced order dispatch model is publicly available.³⁵ For this report the code was modified to allow for more granular market definitions based on eGRID regions, as shown in Figure 1, and updated to more recent data from 2018. All the data required to run the model are publicly available, so the model can be updated in future years to reflect the changing electric power sector.

Figure 7 – Illustration of a Bid-stack and the Corresponding Marginal Emissions



The first figure from Deetjen & Azevedo (2019), *supra* note 1, showing example bid-stacks and the marginal emissions of each electricity generator in the bid-stack. Reprinted with permission from *Reduced-Order Dispatch Model for Simulating Marginal Emissions Factors for the United States Power Sector*, Thomas A. Deetjen and Inês L. Azevedo, *Environmental Science & Technology* 2019 53 (17), 10506-10513, DOI: 10.1021/acs.est.9b02500. Copyright 2019 American Chemical Society. Merit order – ascending in order of operation cost – for the first week of August for three NERC regions showing (A) generation cost and (B) CO₂ emissions rates. Note that (A) and (B) have the same ordering of power plants.

Appendix B: Environmental Value Reference Table

Table 1 – Average E-Value of DERs for 19 Subregions by Season and Time-of-Day

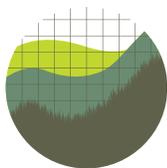
eGRID Region	Spring				Summer				Fall				Winter			
	Morning	Midday	Evening	Night	Morning	Midday	Evening	Night	Morning	Midday	Evening	Night	Morning	Midday	Evening	Night
AZNM	42.23	38.37	35.63	39.23	46.90	44.42	42.90	47.82	41.47	43.87	40.06	36.88	42.45	43.61	42.37	39.09
CAMX	32.00	30.32	26.05	27.26	25.69	27.20	26.82	25.92	22.91	22.34	24.04	22.57	28.00	31.70	25.52	26.62
ERCT	52.62	41.21	43.25	58.80	64.31	42.27	48.90	67.65	54.09	38.63	43.90	68.60	57.38	50.97	52.24	62.53
FRCC	46.25	39.96	43.80	46.74	55.59	46.03	49.09	52.91	47.75	33.21	36.20	47.61	43.85	31.33	34.20	47.04
MROE	70.74	67.79	70.60	66.08	68.24	65.44	69.40	64.93	59.99	60.35	60.98	57.45	66.25	63.74	68.59	64.77
MROW	74.92	74.39	78.24	74.67	73.33	71.83	72.95	70.23	76.03	77.25	78.13	73.86	74.94	71.23	75.52	75.26
NPCC*	57.10	39.55	45.25	60.38	69.06	59.21	61.52	72.05	66.63	47.06	54.83	66.47	63.80	53.94	54.71	63.14
NWPP	51.84	45.89	46.92	53.83	62.91	60.52	61.39	61.94	57.47	57.18	55.63	55.50	54.64	53.65	54.69	51.63
RFCE	66.70	41.41	46.86	77.81	69.36	32.53	41.29	71.94	48.95	34.72	37.30	56.17	60.46	58.76	54.83	80.76
RFCM	102.21	89.24	92.10	111.74	102.85	84.36	82.85	106.02	106.31	93.68	100.53	119.20	76.22	71.73	73.48	86.71
RFCW	80.31	79.88	82.16	76.87	82.34	78.40	80.72	86.78	79.12	78.20	79.41	82.32	77.31	73.41	77.66	76.83
RMPA	45.42	43.92	44.44	47.97	45.68	38.33	41.95	47.04	44.98	42.47	40.10	49.90	48.60	47.81	47.23	52.51
SPNO	56.62	53.13	53.65	57.07	56.96	47.76	50.89	58.48	59.29	55.14	57.05	58.45	59.55	55.49	58.06	61.74
SPSO	64.69	48.88	53.66	71.25	66.88	50.19	53.06	70.59	66.44	61.50	62.70	72.17	56.04	53.85	56.36	66.03
SRMV	53.15	38.39	41.98	69.20	66.78	44.94	51.74	73.21	30.37	28.30	26.11	35.75	52.17	50.34	50.94	54.14
SRMW	86.45	81.04	85.89	83.91	80.42	66.95	73.57	78.94	95.84	97.73	98.14	90.90	82.92	82.77	85.90	91.25
SRSO	37.57	42.83	42.20	35.89	48.63	51.97	52.08	44.56	47.61	47.32	49.03	47.61	36.22	33.23	34.00	33.97
SRTV	60.17	62.32	62.13	53.48	62.20	66.04	66.77	59.86	54.97	54.59	55.42	61.00	53.96	51.71	51.25	57.73
SRVC	42.57	45.42	49.40	40.97	39.13	50.91	51.30	37.00	53.03	51.21	51.17	50.77	41.57	40.64	41.59	41.78

E-Value of DERs (\$/MWh) for 19 subregions based on eGRID regions as defined in Figure 1. The cells in this table are shaded in proportion to E-Value for each time period and subregion. *Note “NPCC” represents an aggregation of the NYLL, NEW, NYUP, and NYCW eGRID regions in the Northeast as shown in Figure 1.

Endnote

- ¹ See Thomas A. Deetjen & Inês L. Azevedo, *Reduced-Order Dispatch Model for Simulating Marginal Emissions Factors for the United States Power Sector*, 53 ENVTL SCI. & TECH. 10506 (2019). Appendix A of this report describes the application of this model in detail.
- ² E.g., New Jersey’s Clean Energy Act of 2018 requires that “[t]he methodology, assumptions, and data used to perform the benefit-to-cost analysis [for energy efficiency programs] shall be based upon publicly available sources.” N.J.S.A. 48:3-87.9(d)(2)
- ³ Examples include distributed electricity generators (i.e. modular solar panels or other small-scale electricity generators), energy storage (e.g. batteries that charge and discharge electricity onsite or with the grid), demand response practices (i.e. a system that can use battery storage, ‘smart’ residential or commercial appliances, and other technologies to reduce demand for electricity when called upon), and energy efficiency investments (i.e. efficient appliances, weatherization, and other technologies that reduce energy consumption onsite).
- ⁴ Some DERs, like small diesel generators, do generate pollution. For others, the associated pollution is uncertain. For example, distributed battery storage can contribute to more pollution if the electricity generator charging the battery produces more pollution than the electricity generator the battery displaces when it is discharged. See Richard L. Revesz & Burcin Unel, *Managing the Future of the Electricity Grid: Energy Storage and Greenhouse Gas Emissions*, 42 HARV. ENV’T L. REV. 139 (2018). The E-Values in this report are still beneficial to policymakers so long as DERs are accountable for the pollution they induce (via electricity generation or otherwise).
- ⁵ See MASS. INST. OF TECH., *THE FUTURE OF THE ELECTRIC GRID* 110 (2011).
- ⁶ For example, without accounting for the E-Value of DERs it is possible that rooftop solar could end up displacing electricity generated from wind turbines, and areas with serious air pollution might not invest in energy efficiency or demand response programs at the scale that is best for society.
- ⁷ See JEFFREY SHRADER ET AL., *INST. FOR POL’Y INTEGRITY, VALUING POLLUTION REDUCTIONS: HOW TO MONETIZE GREENHOUSE GAS AND LOCAL AIR POLLUTANT REDUCTIONS FROM DISTRIBUTED ENERGY RESOURCES* (2018).
- ⁸ Marginal emissions are measured as a rate, in mass of pollution (e.g. tons) per unit change in electricity demand (e.g. megawatt-hours (MWh)).
- ⁹ See SHRADER ET AL., *supra* note 7 at 19-21; see also RICHARD L. REVESZ & JACK LIENKE, *STRUGGLING FOR AIR: POWER PLANTS AND THE “WAR ON COAL”* 11 (2016).
- ¹⁰ See SHRADER ET AL., *supra* note 7, at 12-13.
- ¹¹ For other available tools to determine marginal emissions, see SHRADER ET AL., *supra* note 7 at 14, Tbl. 2: Databases for Calculating Emission Rates.
- ¹² See SHRADER ET AL., *supra* note 7, at 22-25.
- ¹³ If the DER itself produces any emissions, the effects of those must be accounted for as well.
- ¹⁴ See Deetjen & Azevedo, *supra* note 1. In this setting, large fossil-fuel electricity generators are greater than 25 MW in capacity and regularly report to EPA’s CEMS.
- ¹⁵ In this report, the sample period is the year 2018. An electricity generator’s cost to produce electricity includes marginal fuel costs as well as variable operations and maintenance costs.
- ¹⁶ Ignoring non-fossil resources will not bias the marginal emissions estimates so long as non-fossil resources are not marginal. This is typically the case for nuclear and renewable resources but not for load-following hydro resources.
- ¹⁷ eGRID regions are defined by the EPA as partitions of more aggregate North American Electric Reliability Corporation (NERC) regions. Although there might be several market operators in a single eGRID region (e.g., NWPP) and perhaps a single market operator in multiple eGRID regions (both RFCW and RFCE are a part of the PJM RTO), eGRID regions are a fair approximation to granular market operators and transmission connections within the United States.
- ¹⁸ See Jinhyok Heo, Peter J. Adams, & H. Gao, *Reduced-Form Modeling of Public Health Impacts of Inorganic PM_{2.5} and Precursor Emissions*, 137 ATMOSPHERIC ENV’T 80 (2016); see also Richard Revesz et al., *Best Cost Estimate of Greenhouse Gases*, 357 SCI. 655, 655 (2017).
- ¹⁹ Kimberly M. Castle & Richard L. Revesz, *Environmental Standards, Thresholds, and the Next Battleground of Climate Change Regulations*, 103 MINN. L. REV. 1349, 1353 (2019).
- ²⁰ See U.S. ENVTL. PROT. AGENCY, *REGULATORY IMPACT ANALYSIS FOR THE CLEAN POWER PLAN FINAL RULE ES-6 n. 2* (2015), https://www3.epa.gov/ttn/ecas/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf [hereinafter “CPP RIA”] (noting that benefits from directly emitted PM_{2.5} accounted for approximately 10% of total monetized health co-benefits).
- ²¹ Castle & Revesz, *supra* note 19, at 1401.

- ²² For example, the EPA National Emission Inventory report provides annual estimates of particulate matter pollution from electricity generators. And the EPA AVOIDED EMISSIONS AND GENERATION TOOL (AVERT) directly models particulate matter pollution from electricity generation in each state or county.
- ²³ CPP RIA, *supra* note 20, at 4-23.
- ²⁴ Alternatively, policymakers could compensate a DER more if it reduced the demand for bulk-power electricity during the time of day when the E-Value is largest on average.
- ²⁵ For example, Mid-Atlantic represents the RFC NERC region that consists largely of the PJM RTO.
- ²⁶ See U.S. ENERGY INFO. ADMIN.. WHOLESALe ELECTRICITy AND NATURAL GAS MARKET DATA, <https://www.eia.gov/electricity/wholesale/>, (last visited on Aug. 28, 2020) (showing average hourly price across all nodes in 2018 was \$44/MWh).
- ²⁷ See U.S. ENVTL PROT. AGENCY, PUBLIC HEALTH BENEFITS PER kWh OF ENERGY EFFICIENCY AND RENEWABLE ENERGY IN THE UNITED STATES: A TECHNICAL REPORT 25 (2019). <https://www.epa.gov/sites/production/files/2019-07/documents/bpk-report-final-508.pdf>. (showing the average low estimate of 1.7 cents per kilowatt hour (\$17/MWh) and average high estimate of 4 cents per kilowatt hour (\$40/MWh) for the public health benefits of DERs.) For comparison, the hourly marginal emissions of NO_x and SO₂ from the reduced-order dispatch model described in this report correspond to public health benefits (not including GHG emissions) of \$17/MWh on average across all regions, with the highest public health benefits in Michigan (\$46/MWh on average).
- ²⁸ See JUSTIN GUNDLACH & BURCIN UNEL, INST. FOR POL'Y INTEGRITy, GETTING THE VALUE OF DISTRIBUTED RESOURCES RIGHT: USING A SOCIETAL VALUE STACK 11 (Dec. 2019), https://policyintegrity.org/files/publications/Getting_the_Value_of_Distributed_Energy_Resources_Right.pdf. (showing a more complete characterization of DERs' potential benefits.).
- ²⁹ For more details on the value stacking approach to compensating DERs see GUNDLACH & UNEL, *supra* note 28.
- ³⁰ See Revesz & Unel, *supra* note 4, at 163.
- ³¹ See NATALIE MIMS, TOM ECKMAN & CHARLES GOLDMAN, TIME-VARYING VALUE OF ELECTRIC ENERGY EFFICIENCY at ix fig. ES-1, 32-36 (2017) (quantifying value of carbon dioxide emissions reduction available from different forms of energy efficiency across different regions).
- ³² See U.S. ENERGY INFO. ADMIN., *supra* note 26.
- ³³ See ILIANA PAUL ET AL., INST. FOR POL'Y INTEGRITy, THE SOCIAL COST OF GREENHOUSE GASES AND STATE POLICY: A FREQUENTLY ASKED QUESTIONED GUIDE (2017), <https://policyintegrity.org/publications/detail/social-cost-of-ghgs-and-state-policy>.
- ³⁴ In this setting, large fossil-fuel electricity generators are greater than 25 MW in capacity and regularly report to EPA's CEMS.
- ³⁵ The entirety of the Python code is available here: https://github.com/tdeetjen/simple_dispatch.



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