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ELECTRICITY POLICY INSIGHTS

Valuing Pollution Reductions

How to Monetize Greenhouse Gas and Local Air Pollutant Reductions from Distributed Energy Resources

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Executive Summary

Distributed energy resources (DERs)—grid-connected, small-scale electric generators such as rooftop solar installations, micro-turbines, combined heat and power systems, customer backup generators, and distributed energy storage systems—are a growing component of the U.S. electric system. As DERs have become more prominent, state electric utility regulators have begun efforts to more accurately compensate DERs by paying for each of the benefits that they provide.

One such benefit is the avoidance of environmental and public health damages from air pollution (including local air pollution and greenhouse gas emissions) that would have been caused by generation resources that have been displaced by the DERs. This report lays out a practical methodology for calculating this environmental and public health value. It identifies existing tools that states can use, with varying degrees of specificity, accuracy, and complexity, to monetize these pollution reductions. State utility regulators can use the steps outlined here, weighing tradeoffs between accuracy and administrability, to implement their own program to compensate DER for environmental and public health benefits. Regulators can monetize air pollution reductions that DERs provide by using a five-step method:

> **Step 1** determines what generation will be displaced by DERs. The most accurate methods for determining displaced generation require working with grid operators and, potentially, local distribution utilities, to obtain needed data on which bulk system generators would have operated in the absence of DERs. If sufficient data is not available, utility regulators can use electricity system simulation models to estimate which resources would have operated in the absence of DERs.
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> **Step 2** quantifies the emissions rates for displaced generators. Emissions rates of existing resources vary widely, and therefore, the magnitude of the environmental and public health benefits of DERs will as well. Emissions rates depend on a generator's attributes, including fuel type (for example, coal, oil, natural gas, or renewable), electricity generation technology (for example, inefficient steam boilers or efficient combined-cycle technology), pollution control equipment, and operational practices like capacity factor.
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> Emission rates of existing generators can be determined based on those generators' historical, measured emissions rates, or can be estimated using engineering analyses, given known information about fuel type, generation technology, pollution control equipment, and operational practices. Databases of historical emissions rates for specific plants and of emission factors broken out by generator attribute (such as fuel type, generation technology, and pollution control equipment) are also available.
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> **Step 3** calculates the monetary value of the damages from emissions identified in Step 2. Air pollutants cause damage to human health, impair ecosystems, harm crops, and make it harder for workers to be productive. Given knowledge of the emissions rate for a power generator, utility regulators can calculate those damages as a function of:
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> - The type of the pollutant. Particulate matter, especially fine and ultra-fine particulates, cause severe health damages, including death. Oxides like SO_2 and NOx break down into particulate matter and combine with other pollutants to form asthma-causing ozone pollution. Toxic heavy metals like

mercury and lead cause rapid health deterioration even at low concentrations. Greenhouse gases lead to climate change. Researchers have developed monetized damages estimates per unit of emissions for each of these pollutants.

- The location of emissions. Each unit of a pollutant emitted in population-dense areas or in areas with highly vulnerable populations will cause more damage. Emissions also interact with environmental conditions such as prevailing winds to carry pollutants away from the point of emissions. Damage estimates can be modified to account for these concerns.
- The timing of emissions. Some pollutants, such as ozone, only form when precursors are exposed to direct sunlight. Therefore, emissions that occur at night or in winter may cause less damage than those during the day or in the summer. Granular damage estimates account for these timing issues.

A method that accounts for all of these factors would lead to the most accurate calculations of damage per unit of emissions. However, data constraints and ease of use might make alternative, less granular methods more desirable. There are multiple tools produced by various researchers as well as EPA that provide estimates of pollution damages at the county level, and many of these tools allow for partial customization to meet specific needs of regulators.

Step 4 uses the emissions rates from Step 2 and damage estimate per unit of emissions from Step 3 to monetize the value of avoided emissions from displaced generation. Adjustments are needed if existing policies already put a price on emissions of some or all of the pollutants covered in Steps 1-3.

Step 5 takes into account any emissions produced by the DER itself. DERs such as diesel generators or combined heat and power generators emit pollutants. To arrive at an accurate environmental and public health value, those emissions and the damage they cause must also be taken into account. If damage per unit of generation from the DER is high enough, then the net environmental and public health value of the DER could be negative.

Distributed energy resources can provide substantial value to a state by reducing air pollution from conventional electric generators and the resulting environmental and public health damages. DERs can be particularly valuable to the extent that they avoid local air pollution imposed on vulnerable populations. As state utility regulators implement new compensation policies for these resources, those policies should include payment for DERs' environmental and public health value.

This report presents a straightforward five-step methodology that can be used to calculate this value in a technology-neutral manner while relying on existing, readily accessible tools. The methodology outlined in this report is flexible enough to accommodate a variety of data and resource constraints. State regulators can weigh the tradeoffs between accuracy and administrability of different methods to calculating environmental value, pick the tools that are most accurate given the tradeoffs, and then update their methodology when feasible.

While more comprehensive reforms such as an economy-wide tax on greenhouse gases and local air pollutants are needed to fully value the environmental and public health benefits of all DERs, this methodology would allow utility regulators to implement a DER compensation scheme that incentivizes DERs when and where they are most beneficial to the society.

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Introduction

The electric grid is quickly evolving from its traditional structure, where electricity is generated by large power plants located far from end-users, into a multi-dimensional platform. The modern grid allows a variety of new distributed resources that are located near end-users, such as solar panels, energy storage, and demand response, to provide a multiplicity of electricity services. With rapid innovation and declines in costs, these "distributed energy resources" (DERs) are becoming an integral part of the modern grid, and thus, creating new challenges for regulators.[1]

As technology is transforming the grid, policymakers around the nation are working to reform utility regulation in order to harness the full benefits that these technological changes offer. A number of states have initiated proceedings to implement compensation schemes for electricity generated from DERs, or a subset of DERs, that reflect all of the benefits that those resources provide.[2]

DERs help reduce the need for generation from large-scale generators interconnected to the transmission system ("bulk system generators") such as fossil-fuel-fired power plants, which are often costly to build and highly polluting. Depending on the type of DER, they do so in two ways: by reducing customer demand at a given time, or by actually generating electricity. DERs such as demand response and energy efficiency reduce customer demand for electricity at a particular time. Other DERs, such as distributed solar, generate electricity, which can then be used by consumers to offset grid purchases and/or can be exported to the grid. Energy storage can provide benefits by shifting consumer demand, by charging and discharging at different times.

By avoiding the need for generation from the bulk system, DERs can provide many benefits to grid such as avoided energy costs, avoided or deferred capacity costs, and reduced line losses.[3] This report, however, focuses on one regularly overlooked category in utility regulation: environmental and public health benefits.

Bulk system generators often burn fossil fuels—coal, natural gas, and petroleum—or biogenic fuels—agricultural and wood waste, municipal solid waste, animal waste, and landfill gas—and in doing so, they emit air pollutants. When DERs avoid the need for such bulk system generation, they can help reduce air pollution, benefiting society at large. Currently, however, these benefits are not explicitly valued.

Air pollutants emitted by power plants

Combustion of fossil fuels and biogenic fuels results in the emission of air pollutants, which fall into several categories. Air pollutants that affect human health and are dispersed in the ambient air are referred to under the federal Clean Air Act as "**criteria pollutants**." These include particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO). These pollutants also combine in the atmosphere with each other and with volatile organic compounds (VOCs) to make other "secondary" criteria pollutants, including $PM_{2.5}$ and ozone.

In addition, combustion releases **greenhouse gases**—including carbon dioxide (CO_2) and nitrous oxide (N_2O)—that alter the climate and so cause a wide range of disruptive health, social welfare, and environmental effects.

Finally, combustion of some fuels results in emission of **hazardous air pollutants** (HAPs), also referred to as "air toxics," which cause significant damage even in small amounts. This category includes mercury and ammonia.

Air pollution is a textbook example of what economists call an "externality." Externalities are costs or benefits of market transactions that are incurred by parties other than the market participants, and thus are not taken into account by market participants. When externalities are present, market prices do not reflect the external costs and benefits of production or consumption, and therefore fail to provide an economically efficient signal for the true social value of the particular good or service, leading to an inefficient outcome. For example, because fossil-fuel-fired power plants are not paying for the environmental and public health damages their electricity generation causes, we get more air pollution than is socially desirable.

When negative externalities are present, social welfare can be increased by imposing a tax on the source of the externality—in this case, the emission of air pollutants—based on the amount of external damage caused. In the absence of efficient pollution taxes, alternative policies can help improve the efficiency of market outcomes.

One such policy approach is to pay generating resources that reduce air pollution. DERs provide environmental and public health benefits by displacing generation from other resources that would have emitted more air pollution.[4] Therefore, utility regulators can improve social welfare by ensuring that low and zero-emitting DERs are paid for the environmental and public health benefits they produce by displacing higher-emitting generation.

Appropriately valuing these benefits involves identifying the extent to which air pollution is avoided due to DERs, and then monetizing the economic, health, and climate damages those emissions would have caused. This report lays out a practical, technology-neutral methodology for identifying those values. Utility regulators can incorporate this methodology into proceedings aimed at establishing compensation structures for DERs.

It is important to note that, ideally, the same framework would be used to compensate all types of DERs for all the value they provide. However, because the price signals for load reductions manifest as avoided electricity purchases (at the retail electricity rate that customers pay), such comprehensive compensation would require complementary retail rate reforms in order to internalize the externalities.[5] Addressing this is beyond the scope of this report.

The methodology outlined in this report, therefore, is appropriate for compensating energy supplied to the grid by DERs. This limitation likely leads to an underestimation of the environmental and public health benefits of DERs that reduce on-site electricity consumption. However, despite the limitation of the methodology outlined here, compensating even just injections to the grid for the environmental and health benefits DERs provide would significantly improve social welfare.

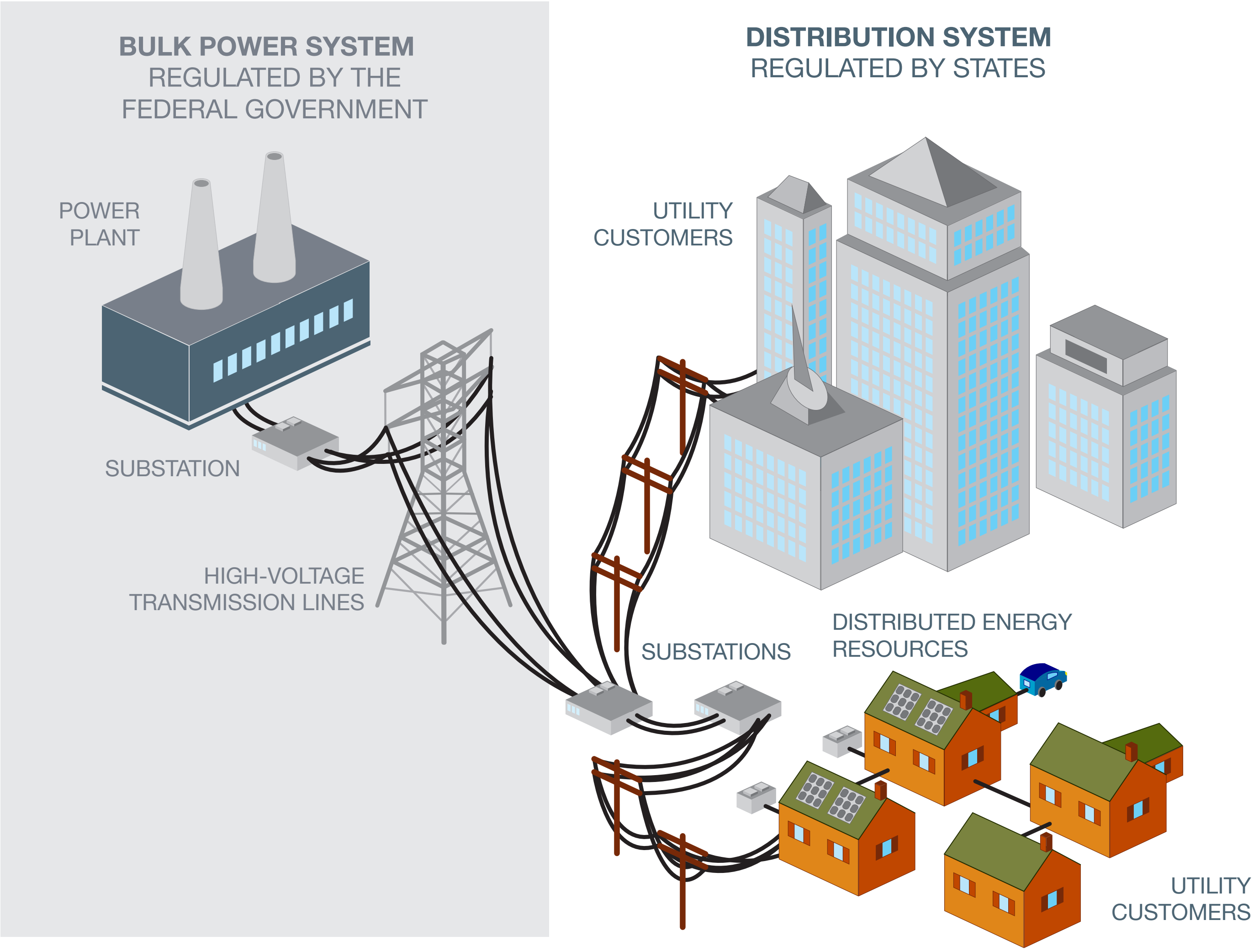
A brief overview of distributed resources, utility regulators, and grid operators

The regulation of electricity is divided between the federal government and the states.[6] Federal regulators have primary responsibility over interstate transmission and wholesale electricity, or the bulk power system, and state regulators have primary responsibility over the distribution system.

State regulators, commonly called “public utility commissions” or “public service commissions,” are responsible for regulating local distribution utilities and setting retail rates, as well as deciding on other state-level policies such as DER compensation, renewable portfolio standards, and energy efficiency programs.

In much of the country, the bulk power system, consisting of most generators and large transmission lines, is regulated by the Federal Energy Regulatory Commission and operated by grid operators called “independent system operators” (“ISOs”) or “regional transmission organizations (“RTOs”). ISOs/RTOs ensure that supply and demand of the bulk power system are constantly balanced using complex algorithms that take into account the location of both generators and demand, the costs of generation, and congestion on the transmission system. Grid operators dispatch resources from least expensive to most expensive (taking into account the congestion on the transmission system), until demand has been met.

Figure 1: Regulatory Domains of the Electric Grid



Valuing Environmental Benefits of Distributed Energy Resources – An Overview

Public Utility Commissions can calculate the environmental and public health value of DERs based on emissions avoided by the DER and the monetary value of the damage that those emissions would have caused. These two values will depend on the location of the DER and the avoided emissions, the time of day and year when emissions are avoided, and the type of pollutants avoided.[7]

DERs in different locations or generating at different times will displace different sources of generation, with various levels of emissions. Because different generators use a variety of fuel types, electricity generation technologies, control equipment, and operation practices that result in a wide range of air pollutant emissions rates, the type of generators displaced is an important driver of the value. DERs are worth more to society when they offset generation from higher-emitting sources.[8]

DERs are also more valuable when they reduce air pollution in areas with high population density and more vulnerable populations. The time of year also matters because NOx and VOC emitted in the summer carry greater health consequences, due to their role in the formation of ozone in the presence of sunlight. Therefore, DERs that can reduces pollutants in such areas and times are more valuable.

Finally, different pollutants cause different levels of public health and climate damage. If a DER offsets a generator that emits more damaging pollutants, it should receive a higher payment to reflect its environmental and public health value.

Any approach should take into account not only the generation displaced by a DER but also the emissions created by the distributed resource. For example, behind-the-meter DER generators include oil, gas/coal combined heating and power, and storage systems charged by fossil-fuel-fired generation resources. For emitting DERs, payment should be reduced based on their emissions and could potentially be negative if the negative impact of emissions from the DER is higher than the value of emissions avoided by that DER.

Key Terms

Emissions rate

The emissions rate is the amount of pollution emitted by a generator per unit of generation. If a generator emits 1 metric ton of SO_2 and generates 1 megawatt-hour (MWh) of electricity, then its emission rate of SO_2 is 1 metric ton/MWh, or 1 kilogram (kg)/kWh. The emissions rate can be affected by, among other things, installation of pollution control equipment, changes in the efficiency of the generator, or use of different fuels by generators that have fuel flexibility.

Damage per unit of avoided emissions

The damage per unit of avoided emissions is the monetized value of the harm that the pollution would have done had it been emitted. For instance, each kilogram of SO_2 released by a generator causes roughly \$50 of damage. Therefore, if a DER avoids the emission of one kilogram of SO_2 by displacing generation of a fossil fuel power plant, then it would avoid \$50 of damage.

Environmental value of displaced generation

The value of displaced generation is the dollar value of damages avoided, per unit of displaced generation. It is the product of the emissions rate and the damage per unit of avoided emissions.

Harnessing all the benefits DERs can provide requires compensating them for their environmental and public health value in a technology-neutral way that can take into account these different factors, while balancing accuracy and administrability. To achieve this goal, regulators must first identify the generation that is displaced by DERs, determine the emissions avoided by this displacement based on the emissions rates of the displaced resources, calculate the monetary damages per unit of avoided emissions, and then calculate the monetary value of the net damages avoided by DERs.

Below, we outline the necessary steps and then explain each step in detail.

Methodology Outline for Valuing the Environmental Benefits of DERs:

1. Identify the generation that is displaced by a DER
2. Calculate emissions rates (kg/kWh) of the displaced resource
3. Calculate the damage per unit ($/kg) of avoided emissions
4. Monetize the value of avoided damage from displaced generation ($/kWh)
5. Subtract any damages from the DER itself from the displaced generators' damages, to calculate *net* avoided damages

Step 1: Identify Displaced Generation

Distributed energy resources produce environmental and public health benefits by displacing generation from emitting power generators. The first step in calculating the value of those benefits, then, is to identify what generation will be displaced by a DER.

If sufficient grid operation and market information is available, it is possible to identify, with a reasonable degree of precision, the specific generator or generators that would have operated in the absence of DERs. If such data is not available, there are techniques that can be used to approximate which generators were displaced by DERs.

This section outlines three techniques for identifying displaced generation: (1) using counterfactual dispatch scenarios, (2) identifying the marginal generator, and (3) using electric market simulation models. These options are explained in order of decreasing levels of precision and decreasing information requirements.

All of these methodologies will identify those generators that have been displaced by DER resources *in the short run*. That is, these methodologies identify which of the *existing* resources would have generated in the absence of the DERs. They do not account for the potential effect that DERs have on the longer-term entry and exit incentives for emitting resources. Installation of DER capacity may contribute to the retirement of an existing fossil fuel-fired generator or may avoid the need for a new fossil fuel-fired generator. Therefore, methodologies presented in this section likely understate the extent to which DERs reduce emissions. Complex methodologies have been developed to account for these emissions effects; however, incorporating these effects into a DER valuation methodology is beyond the scope of this report.[9]

Running Counterfactual Dispatch Scenarios

Overview. It is possible for market operators to identify all of the generating resources that would have operated in the absence of DERs with precision and confidence. A market operator can run a counterfactual dispatch scenario in which the operator runs its regular dispatch algorithm while assuming no DERs. The generators that would have operated in this counterfactual dispatch scenario but were not actually dispatched are the generators that were displaced by DERs. These identified resources can be used in Steps 2-3 to calculate the avoided damages attributable to DERs.[10]

Advantages. The primary advantages of this approach are that it is accurate, granular, and flexible. Because it relies on actual grid operations and market data used to make dispatch decisions, this method can accurately capture which resources would have operated in the absence of DERs. Because this approach can identify the specific generators that have been displaced, it will also provide specific information on the location of displaced emissions, which is useful for calculating accurate public health damages in Step 3.

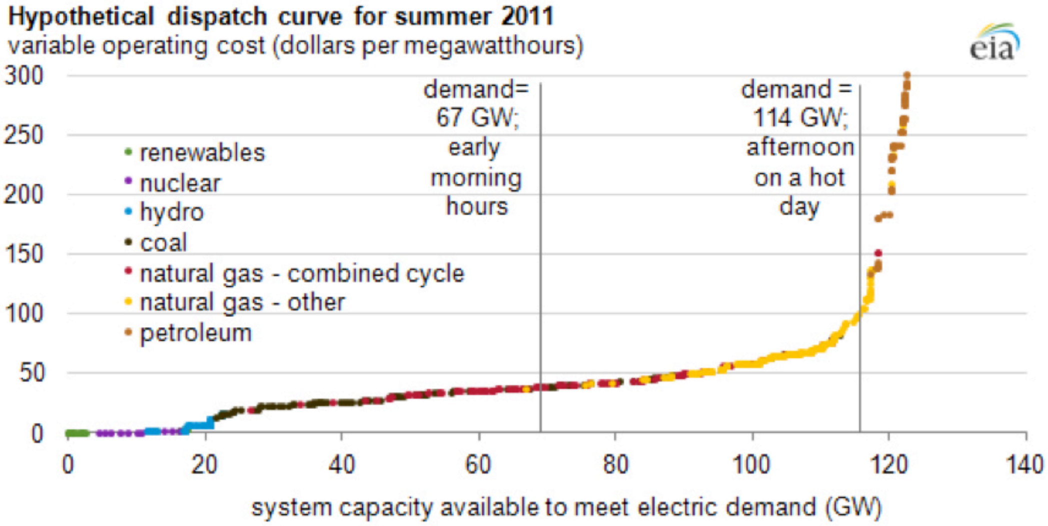
Counterfactual dispatch scenarios could be run as often as the grid operator reruns its dispatch algorithm. However, this approach is also flexible and can be updated less frequently if the administrative costs of frequently identifying counterfactual dispatch outweigh the benefits. For example, if there is limited variability in which resources are displaced over short intervals, grid operators could run counterfactual dispatch scenarios once per hour; during key parts of the day (such as during periods that typically have high electric demand and periods with low electric demand, or periods with high DER injections and periods with low DER injections); or during key times over each season of the year.

Limitations. The primary limitation of this approach is its significant data requirement. Regulators will have to work with distribution utilities to obtain the information—location, timing, and magnitude of DER penetration—needed for counterfactual dispatch scenarios, and then work with grid operators to produce counterfactual dispatch scenarios.

Identifying the Marginal Generator

Overview. An alternative approach to identifying displaced generation is to use information from the grid operators on marginal generators. Grid operators usually dispatch generators based on their cost of operation, as well as technical constraints of the system, until the total generation is high enough to meet the demand. The "marginal generator" for a given interval is the last generator that is needed to satisfy demand at that interval. Additional DERs at this time will reduce the need for generation from the marginal generator, and therefore avoid emissions from the marginal generator. States can work with grid operators to identify the generator on the margin at the time of DER operation, which can provide an accurate up-to-date estimate of which generators DERs are displacing.

Figure 2: Illustrative Market Supply Curve[11]



Source: Energy Information Administration (2012)

Figure 2 is an illustrative market supply curve, which shows available generators in ascending order of marginal cost from left to right. Different levels of demand are illustrated by the vertical lines. The marginal generator for a given level of demand is the generator at the intersection of the vertical line and the supply curve. Based on this curve, when load is at its minimum, a gas generator with a relatively low bid will be on the margin. Any DER at this time will reduce the need for generation from that gas generator. When load is at its maximum, the marginal generator may be an oil-fired generator. DER will replace generation from the oil-fired generator.

Because the transmission system can be congested, the marginal generator will often be location dependent. If transmission lines are congested, electricity cannot be transmitted from distant locations even if there are available cheap generators, and therefore grid operators must rely on more expensive local resources. Take, for example, the New York Independent System Operator. When there is no congestion, a DER in New York City can indeed displace a system-wide marginal generator, which can be located anywhere in the state. However, the transmission lines going in and out of New York City are often congested. During periods of such congestion near New York City, the marginal generator displaced by a DER in New York City will likely be local and different from the marginal generator displaced by a DER located in other parts of the state. States should therefore identify marginal generators at a level of geographic granularity appropriate given the level and location of congestion on the system.

If real-time information is not available from grid operators, regulators could identify marginal generators by matching load levels with generators on representative dispatch curves, such as the one outlined in Figure 2 above.[12] Such use of historical dispatch curves rather than actual dispatch curves for a given interval reduces the accuracy of this measure but it can be done with less involvement of the grid operator. These curves can be constructed using grid operator data, based on historical information on generator operation and energy bids. To most accurately reflect the generation mix available at a particular time, regulators should use historical dispatch curves applicable for times of day and seasons to reflect variations in renewable energy and seasonal outages.

Advantages. While identifying the marginal generator will require working with the grid operator, this approach requires significantly less involvement and data from the grid operator. This approach also will not require specific information from distribution utilities on the location, timing, and magnitude of DER load and generation profiles.

Limitations. This approach assumes that the magnitude of DERs is not large enough to change the marginal resource. Currently the level of DER penetration is small enough to meet this requirement in most contexts. In addition, especially during high-demand times when a small generator is on the margin, the next resource that would be marginal if that small generator is displaced may have quite similar emission characteristics. However, as DER penetration increases, it is possible that DERs will begin to change which generators are on the margin. This will reduce the accuracy of this approach as compared to the counterfactual dispatch scenario approach.

Electric Grid Dispatch Modeling

Overview. A number of sophisticated models of the electric grid have been developed that can be used to simulate the dispatch of generators under a variety of conditions.[13] These models generally incorporate databases of generators (including the location, size, fuel type, and other operational characteristics) and transmission, assumptions about fuel and other operational costs of generation, and assumptions about electric demand to simulate operation of a given electric grid. Regulators can use these dispatch models to identify the resources that have been displaced by DERs, similar to how a grid operator would identify displaced generation through counterfactual dispatch scenarios. The electric model would be run both with and without DERs to identify the resources that have been displaced.

Regulators should perform model runs under a variety of assumed operating conditions (e.g., varying levels of electric demand, transmission congestion, and DER availability). They can then use the simulation that best matches the appropriate real-world circumstance.

Advantages. The primary advantage of this approach is that it can be used without involvement of the ISO/RTO or distribution utility. While the relevant models are complex and require expertise to use, Public Utility Commissions can develop this expertise rather than having to rely on outside entities for ongoing data requirements.

Limitations. Because these models rely on assumptions, rather than realized outcomes, they are not likely to be as accurate as the first two approaches outlined. In addition, this approach will be even less likely to incorporate any sectoral changes over time including generator entry and exit and generator outages, unless the model used is updated to reflect these changes.

An Approach to Avoid: Grid-Average Generators and Grid-Average Emissions rates

While there are many acceptable options to identify generators that will be displaced by DERs, regulators should *not* assume that DERs displace all generators in equal amount (either numerically or generation-weighted). Similarly, regulators should not use grid average emission factors when determining the avoided emissions attributable to DERs. Assuming DERs displace all resources equally or using *average* emissions rates will incorrectly include substantial zero-emission generators that are unlikely to be affected by DERs. Use of averages will also miss significant temporal and locational variation in the amount of air pollution displaced by DERs. Research has shown that using average emissions rates significantly misstates emission impacts of new resources.[14] While this approach is computationally easy, and therefore appealing, using grid averages will not lead to accurate estimates.

Step 2: Identify Emissions Rates of the Displaced Generation

Once the resources that are displaced by DERs have been identified, the next step is to determine the emissions rates of those displaced resources. These emissions rates are necessary to determine the economic benefits of avoiding emissions from each kWh of the displaced emitting generation. Table 1 presents average emissions rates of select criteria and greenhouse gas pollutants by fuel burned.

Table 1: Average Emissions Rates of Select Pollutants for Generators in 2016[15]

Fuel Type	NOx (kg/MWh)	SO_2 (kg/MWh)	CO_2 (kg/MWh)
Oil	2.92	2.86	862.80
Coal	0.75	1.08	1003.38
Biomass	1.58	0.67	211.06
Gas	0.16	0.00	405.94

Generator Features Affecting Emissions rates

Emissions rates are a function of (1) the type of fuel combusted, (2) the combustion and electric generation technology, (3) any pollution control equipment, and (4) environmental and operational considerations.

Fuel Type

The type and amount of pollutants emitted by electricity generators is primarily a function of the type of fuel used. Some plants are designed to burn only one type of fuel. Others, called "dual fuel" plants, are able to switch between fuels depending on fuel availability and price. Dual fuel plants generally can burn either natural gas or oil-based fuel (e.g., diesel fuel).

Uncontrolled combustion of coal, oil and wood biomass emits relatively large quantities of most criteria pollutants, HAPs, and greenhouse gases.[16] Combustion of gas, including natural gas and landfill gas, primarily emits NOx, CO, VOCs, and CO_2, with little to no direct emissions of PM, SO_2 and HAPs.[17] On the other end of the spectrum, nuclear, hydroelectric, solar, and wind generation do not emit any air pollution.

Generation Technology

For a given fuel type, the primary determinant of the emissions rate is the efficiency by which a combustion technology converts fuel into electricity, called the generator's "heat rate".

Key Term

Heat rate is a measure of power plant efficiency. It is a measure of the amount of energy, embedded in the combusted fuel, measured in British Thermal Units, that it takes to generate a kWh of electricity.[18] The higher the heat rate, the *less* efficient the plant.

Steam boilers generate electricity by combusting fuel to produce heat, which warms water to produce steam that turns an electric turbine. Steam boilers generally have high heat rates.[19] In other words, they are not efficient. Steam boilers primarily use coal (and almost all coal plants use steam boilers), but they can also combust natural gas, fuel oil, or biomass.[20]

Stationary internal combustion engines (ICE), which generally burn fuel oil, have similar heat rates to steam boilers and are most often used as "peaker plants" when demand is particularly high, for backup power, or as distributed generation.[21]

Combustion turbines use heat produced from fuel combustion to turn a turbine that generates electricity. They use liquid or gaseous fuel, including natural gas, fuel oil and biogenic fuels (e.g., landfill gas).[22] Combustion turbines can range in efficiency and often function as peaker plants.

Finally, highly efficient combined-cycle plants combine the technologies to produce more electricity for the same amount of fuel.[23] In a combined-cycle plant, a combustion turbine produces electricity and heat, while the excess heat produces steam that generates more electricity. These plants primarily use natural gas (and much less often fuel oil).

Pollution Control Equipment

Emissions rates can also vary significantly depending on whether a plant has installed air pollution control technology. Almost all plants can implement some pollution control equipment, but there is significant variation in the type and effectiveness of installed equipment. For instance, flue gas desulfurization technology can reduce SO_2 concentrations of coal plant emissions by 98%, while catalytic reactions reduce NOx pollution by 80%.[24] Pollution control equipment can also negatively affect the efficiency of power plants.[25]

Operational and Environmental Considerations

A variety of environmental and operational considerations affect emissions rates. These include:

- **The age of the plant.** Plant efficiency generally declines with age.
- **The utilization of the plant.** Power plants that are operating below full capacity are generally less efficient and so have higher emissions rates.
- **Ambient weather conditions.** Ambient weather conditions including temperature, humidity, and pressure can affect the efficiency of a power plant.[26]

These operational and environmental considerations vary over time, while other features like fuel type, generation technology, and pollution control equipment are relatively static. Therefore, it is not possible to know a particular generator's emissions rate without measuring, in real time, its emissions and generation. Even though such data is rarely available, there are a number of existing or easy-to-develop tools that states can use to determine reasonably accurate emissions rates for generators.

Methods for Determining Emissions rates

States can use one of two primary options for determining reasonably accurate emissions rates: (1) historical, measured emissions rates of the generator, and (2) engineering estimates of a generator's emissions rates based on design characteristics and operational assumptions.

Historical Emissions Rates

Historical emissions rates calculate a given generator's emissions rate for each pollutant based on measured historical emissions and measured historical generation.

Historical Emissions. Generators above a specific size threshold are required to directly measure and report the volume of emissions for some pollutants to state environmental agencies and/or the U.S. EPA Clean Air Markets Division (CAMD). Continuous emission monitors are used to measure and report NOx, SO_2, and CO_2 emissions from generators subject to certain federal environmental program requirements.[27] For pollutants where continuous emission measurement is not feasible or is particularly expensive (such as for PM), generators calculate and report emissions through monitoring of parameters that have a known relationship with emissions, such as operational characteristics of plant systems (temperature, pressure, liquid flow rate, pH), through periodic emissions testing, or based on quantities of fuel consumed and the technology used to generate electricity.[28]

Historical Electric Generation. Generators are required to measure and regularly report various characteristics and operational performance of their plants to the U.S. Department of Energy's Energy Information Agency (EIA).

Dividing historic emissions by historic generation yields historic emissions rates. This calculation should be done with as high degree of granularity as possible in order to yield representative emissions rates for a generator's operational performance. For example, for a dual fuel generator, dividing annual total emissions of SO_2 by annual generation will not yield an accurate SO_2 emissions rate because SO_2 is only emitted in the hours that the generator burns fuel oil. Significant emissions rate changes for a generator can be captured by more daily or hourly emissions rate calculations.

Engineering Estimates

Engineering estimates of emissions rates are based on assumptions about known characteristics of generators. Accurate engineering estimates use the considerations identified above (fuel type, heat rate of generating technology, emission control technology, and environmental and operational considerations) to develop emissions rates that can be applied to generators with similar characteristics. Because of this, engineering estimates are sometimes referred to as "emission factors."

Selecting Between Historical Emissions and Engineering Estimates

Short of real-time continuous measurements, historical measured emissions rates are generally the best measure of a particular generator's emissions rate. Therefore, they should be used when available.

However, measured historical emissions rates are not always available for all sources. Existing databases are limited to those generators that exceed certain size and operational thresholds. Smaller generators, newer generators, or generators that did not operate over the historical period used to set emissions rates are not included in certain databases. In addition, because it is difficult to directly measure certain pollutants such as PM and air toxics, historical emissions rates for all pollutants may not be known for a given generator.

Finally, lack of temporal granularity of may produce misleading emissions rate estimates. In particular, the use yearly-average emissions rates may be problematic for generators that do not operate consistently over the course of a year, such as dual fuel peaking plants that may burn oil instead of natural gas when natural gas is unavailable or particularly expensive.

Where historical emissions rates are not available at all, or lack sufficient granularity, engineering estimates should be used.

Existing Tools and Databases

There are a number of existing databases that regulators can use to determine emissions rates. Different tools may be appropriate for different pollutants or for different desired levels of granularity.

This section outlines tools that fall into a number of categories: (1) Databases of generator-specific historical measured emissions; (2) databases of generator-specific historical measured generation, which, together, can be used by a state to develop generator-specific historical emissions rates; (3) databases of engineering estimates of emission factors; and (4) integrated databases that combine data from other sources to produce readily available emissions rates.

Table 2: Databases for Calculating Emission Rates

Tool	Data type	Pollutants covered	Covered sources	Data source	Update Frequency (last data year)
Historical Emissions Databases					
EPA CAMD	Generator-specific hourly emissions (can be aggregated)	NOx, SO_2, CO_2	Boilers > 25MW; combustion turbines, combined-cycle plants, & ICE online after 1990	Mandatory source-level reporting based on continuous monitoring	Monthly (Sept. 2017)
National Emissions Inventory	Unit-specific annual emissions	SO_2, NOx, PM_{10}, $PM_{2.5}$, CO, VOC, NH_3, Hg, HCl	Power plants with criteria pollutant emissions over certain thresholds	State environment office reporting, supplemented by EPA CAMD data and emission factors	3 years (2014)
Historical Electric Generation Databases					
EIA Form 923	Unit-specific monthly electric generation and fuel consumption	n/a	Sources > 1 MW	Operator-level reporting	Monthly (Oct. 2017)
Engineering Estimate Databases					
EPA AP-42	Engineering-based estimates by fuel and technology type	SO_2, NOx, PM_{10}, $PM_{2.5}$, CO, VOC, CO_2, CH_4	Boilers, combustion turbines, and ICE using coal, natural gas, fuel oil, and biomass	EPA tests of representative technology	Infrequent (1998-2008)
National Energy Technology Lab	Engineering estimates	CO_2, SO_2	Modern highly-efficient natural gas combined-cycle plants	Department of Energy engineering analysis of modern plants	Infrequent (2010)
Integrated Databases					
eGrid	Unit-specific annual emissions and electric generation	NOx, SO_2, CO_2	Electric generating units that report electric generation data on EIA-923	Emissions: EPA CAMD and AP-42 Generation: EIA-923	Sporadic, generally 1-4 years (2016)
Argonne National Labs GREET	Attribute-based emission factors using statistical analysis of historic emissions rates and open literature review	CO_2, CH_4, NOx, SO_2, CO, VOC, PM_{10}, $PM_{2.5}$	Boilers, combustion turbines, combined-cycle plants, ICE burning coal, nat. gas, fuel oil, and biomass, with various pollution control equip.	EPA eGRID, AP-42, open literature	Sporadic (2012 for full update, 2017 for limited update)

Generator-Specific Historical Emissions Databases

EPA maintains a number of databases of power plant emissions. However, no single database contains information on all important pollutants. Combining datasets is necessary to get a full picture of generator emissions.

EPA Clean Air Markets Division

Overview. EPA's CAMD collects emission data from large air pollution sources, including power plants, in order to administer a number of federal environmental programs. Electric generators subject to reporting requirements include steam generators with at least 25 MW capacity, non-steam generators – gas turbines, combined cycles, internal combustion engines – that came on-line after 1990, and independent power producers/co-generators that sell over a specific amount of electricity.[29] These generators report hourly emissions of NOx, SO_2, and CO_2, collected from CEMs, to EPA on a quarterly basis. The hourly data can then be aggregated into daily, monthly, or seasonal data.

Advantages. Using hourly emission data would allow state utility regulators to calculate emissions rates that take into account environmental and operational characteristics. Because the data is collected from continuous monitoring, it is also more accurate than data collected through other means.

Limitations. The biggest limitation is that CAMD does not include historical data on a number of key pollutants, such as PM. CAMD only recently began collecting data on mercury, hydrogen chloride, from some coal and oil-fired steam generators.[30]

National Emissions Inventory

Overview. The National Emission Inventory (NEI) is a database of annual emissions for a wide variety of sources, including power plants with a potential to emit criteria pollutants above a 100 tons per year threshold.[31] NEI data includes generator-specific emissions of PM_{10}, $PM_{2.5}$, VOCs, CO, HAPs, SO_2 and NOx emissions.[32] Data is based primarily on data reported to EPA from state environmental agencies, supplemented and modified by data that EPA itself collects and other EPA assumptions.[33] New data is collected by EPA every three years, and released three years later after it goes through a substantial quality assurance process. The 2014 National Emissions Inventory was released in 2017.

Advantages. The primary advantage of NEI data is that it contains emissions of a wider variety of air pollutants than CAMD, including PM.

Limitations. Infrequent updating is the primary limitation of the NEI. The NEI is updated only every 3 years, on a 3-year delay. Therefore, accurate emissions rates will not be available for sources built or substantially modified after 2014. In addition, NEI contains only annual (and for NOx, summer season) emissions.[34] Therefore, emissions rates calculated using this data source will be limited to annual average emissions rates (and, for NOx, ozone season average emissions rates), and will have limited accuracy for plants whose emissions rates vary with operational changes, such as mid-year changes in fuel used.

Generator-Specific Historical Generation Databases

EIA-923

Overview. Operators of electric generators greater than 1 MW report net electric generation (as well as fuel consumption) to the Department of Energy's Energy Information Agency (EIA) on form EIA-923.[35] All generators report generation annually, and a large subset report generation on a monthly basis.[36] For generators that are not included as part of the sample, EIA imputes monthly generation data using statistical techniques.[37]

Advantages. EIA data is readily accessible online and practitioners consider it as the best source of widely available generation data.

Limitations. Emissions rates more granular than monthly averages are not available.

Engineering Estimate Databases

EPA AP-42

Overview: EPA has developed *AP-42 Compilation of Air Pollution Emission Factors* for a wide variety of pollutants and source categories. These factors are often used by EPA when measured data is not available and can be used by states to develop assumed emissions rates for sources where EPA data is not available.[38]

AP-42 provides emission factors for the following combustion technologies: steam boilers;[39] stationary combustion turbines;[40] and large stationary diesel and dual-fuel engines.[41] It generally includes emission factors for criteria pollutants and their precursors, HAPs, and greenhouse gases (including CO_2 and methane).

Advantages. AP-42 provides a standard set of widely used emissions factors. It is therefore easy to use when historical emissions data is not available.

Limitations. AP-42 emission factors have not been updated since the late 1990s and early 2000s. This is particularly an issue for generation technology that has seen significant advancements since the last AP-42 update, including natural gas combined-cycle combustion technology. In addition, recent analysis has shown that the factors do not capture the wide variety of emissions rates from actual facilities.[42]

NETL Natural Gas Combined-Cycle Analysis.

Overview: In 2010, the Department of Energy's National Energy Technology Laboratory (NETL) evaluated the cost and performance of representative fossil fuel-fired power plants, including new NGCC power plants. As part of this report, NETL developed air pollution emissions rate estimates for a standard NGCC plant.[43] These emission factors have been used by academic researchers studying the economic costs of air pollution externalities from power plants.[44] For relatively modern, large NGCC plants, states could use generic emissions rates based on this research.

Advantages. Up-to-date and widely used emission factors for modern NGCC technology.

Limitations. Limited to emission factors for a single generation technology type.

Integrated Emissions and Generation Database

There are two integrated databases that combine available emissions and generation data from the databases outlined above and other sources. These databases can help determine emissions rates with minimal additional work by utility regulators.

EPA eGrid Database

Overview. EPA maintains the eGrid database[45], which contains annual average emissions data and annual average generation data for most electric generators, compiled from a variety of data sources. The primary source for generation data is EIA form 923.[46] The primary source of EPA's emission data is EPA CAMD.[47] For generators that do not report to CAMD, EPA calculates annual emissions by multiplying emissions factors from AP-42 by the plant's heat rate (as reported to EIA).[48]

Advantages. The primary advantage of eGrid is that EPA has already done the work to compile and validate relevant data from CAMD, AP-42, and EIA.

Limitations. eGrid does not include data on key pollutants, such as PM and air toxics. Because eGrid provides *annual* emissions and generation data,[49] eGrid data does not take into account emissions rate changes that could result from variation in the fuel used by a plant throughout the course of a year, changes in capacity factor, or other operational and environmental characteristics.

Argonne National Laboratory GREET Emission Factor Database

Overview. Argonne National Laboratory (ANL) has developed a model for estimating lifecycle greenhouse gas and criteria pollutant emissions associated with various vehicle technologies: the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[50] In order to estimate lifecycle emissions of electric vehicles with this model, ANL has compiled a database of power sector emission factors broken out by relevant attributes such as fuel type, generation technology, and pollution control equipment.[51] The GREET emission factor database was developed using data from CAMD, EIA, AP-42 and the open literature.

Advantages. The GREET emission factor database includes emission factors for a wide variety of pollutants, including those not included in eGrid, such as $PM_{2.5}$. The database is broken out by many generator characteristics, so more accurate emissions rates can be identified, so long as relevant attributes of a given generator are known. It is updated more frequently than AP-42 (the last comprehensive update was in 2012, but limited updates were made in 2013 and 2017).[52] ANL conducted robust statistical analysis to arrive at emission factors.

Limitations. The GREET emission factor database includes general attribute-based emissions rates. Therefore, it is not as accurate as historical emissions rates for specific generators when such rates are available.

Estimating Displaced Emissions if Step 1 is Not Feasible

The methodologies described in Steps 1 and 2 of this report identify the emissions avoided by a DER by identifying specific generators that would be displaced and determining the emissions rate of those generators. However, when it is not possible to identify specific generators due to lack of data, it is possible to estimate the emissions displaced by DER by using econometric techniques.

Academic researchers have been using regression analysis to directly estimate the grid's marginal emissions rates.[53] This method requires high-frequency data on emissions of the pollutant of interest and the quantity of electricity demand – the load – for a particular electric grid. A linear regression of emissions on load will yield the relationship between changes in measured emissions from all generators on the grid and changes in electricity demand. The marginal emissions rates at a given time and location can then be estimated based on the level of electricity demand at that location and time.

The granularity of this method depends on the granularity of the underlying data. For example, if data are available on zonal level emissions and load, then marginal emissions can be calculated to the zonal level for each season or time of day.

Limitations: Because marginal emissions rates are estimated for a given area, assumptions are required about where specifically emissions will occur. This will limit the accuracy of damage estimates outlined in Steps 3-4 below. In addition, this approach will not be responsive to changes in the electric sector such as short-run changes caused by generator outages and medium-run changes in the composition of generators over time. Therefore, this approach should be used only to the extent that utility regulators are not able to obtain information from grid operators and cannot use electric market models.

Step 3: Calculate the Monetary Damages from Emissions

Air pollutants cause damage to human health, impair ecosystems, and harm crops and other production activities. The goal of this step is to find the monetary value of the damages from each unit of emissions identified in the previous step. Given knowledge of the emissions rate for a power generator, regulators can calculate damages as a function of the pollutants being emitted, the location where those emissions occur, the time of day and year when they occur, and ambient environmental conditions like weather and pollution concentrations. The most accurate calculation of damages would incorporate each of these elements.

Relevant Factors for Calculating Monetary Damages

The sections below discuss the factors needed for calculating monetary damages from emissions, as well as the motivation for incorporating these different elements and the key issues related to granularity versus ease of administration.

Pollutants Emitted

The previous section identified a number of pollutants emitted by fossil power generators. Each pollutant has its own relationship between exposure and impact, called the *dose-response function* or *damage function* in epidemiological and economic research. These different damage functions should be accounted for when calculating damage per unit of emissions for accurate assessment of the value of avoided emissions.

Toxic Heavy Metals

Toxic heavy metals like mercury or lead cause rapid health deterioration even for low concentrations and quickly become fatal. Heavy metals like mercury and lead can also decrease brain function, leading to marked reduction in IQ.[54] The harms also occur over long periods of time because heavy metals do not break down once they are released, leading to long-run harms as the public is exposed the pollutant over longs periods of time and permanent, negative health effects for individuals whose bodies cannot get rid of the toxins. Because the harm caused by these metals is so extreme, the damage per unit of emissions is correspondingly high.[55]

Sulfur Dioxide (SO_2)

Sulfur dioxide (SO_2) is a gas released during combustion of oil and coal that negatively affects the environment and human health. SO_2 irritates mucous membranes in the lungs, eyes, nose, and throat, exacerbating conditions like asthma.[56] SO_2 also breaks down into particulate matter. Fine particulates, especially those smaller than 2.5 micrometers, called $PM_{2.5}$, penetrate into the lungs, causing or exacerbating cardiovascular problems like asthma and heart disease. Fine particulate matter is also a primary contributor to haze and visibility reduction in much of the United States.[57] SO_2 is also a major contributor to acid rain.[58]

Nitrogen Oxides (NOx)

Nitrogen oxides are gases including nitrogen dioxide, nitrous acid, and nitric acid. Collectively, these gases are referred to as NOx.[59] Like SO_2, NOx breaks down into particulate matter, causing cardiovascular health effects and contributing to haze.[60] NOx, along with other pollutants like VOCs, react with sunlight to create ozone pollution, which is a respiratory irritant that aggravates conditions like asthma.[61]

Greenhouse Gases

Greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), lead to climate change.[62] Greenhouse gases exert a warming effect on the global climate. This warming is already having noticeable, damaging effects on the environment and the economy.[63] These damages are expected to increase in the future as further climate change occurs.[64]

Ambient Concentration

Ambient pollution concentrations affect the amount of damage that results from additional pollution emissions. Some pollutants cause severe health effects at low concentrations, so even small emissions of such pollutants can be dangerous, depending on ambient levels. One such pollutant is mercury. Even small concentrations of mercury can cause mortality, so an increase in emissions of mercury in an area with a high pre-existing concentration can cause severe health effects.[65] In contrast, an increase in emissions of a pollutant like particulate matter will cause declining marginal damage as the ambient concentration rises.[66]

Pollutants can also interact, exacerbating effects. For instance, ozone creation is more likely in the presence of both VOCs and NOx.[67] Pollutant interaction makes it potentially important to account for ambient concentration of other pollutants when calculating damages per unit of emissions. Such interaction effects might be challenging to quantify in a way that is also easy to administer, so a reasonable alternative would be to incorporate damages that vary by location depending on the average or usual concentration of important ambient pollutants.

Pollution Transport

Pollution can be carried away from the area where it is created through a process called pollution transport. Wind and water carry pollutants away from the point of emission, potentially exposing populations far from the emission source.[68] Rain washes particulate matter out of the air and into bodies of water.[69] Pollution transport models are useful for understanding this movement of pollutants from source to final location. For instance, lighter pollutants like fine particulates can be carried farther than heavier pollutants like PM_{10}, making modelling of transport for fine particulates relatively more important for correct damage estimation.[70]

Secondary Pollutants

Related to pollution transport, pollutants break down and potentially create other, secondary pollutants as they travel through the atmosphere. As discussed above, SO_2 and NOx break down to create particulate matter. Ozone forms when sunlight reacts with oxides and organic compounds in the air.[71] Thus, ozone is less likely to form at night and is also less likely to form in the winter, making time of day and year important for damage from this pollutant.[72]

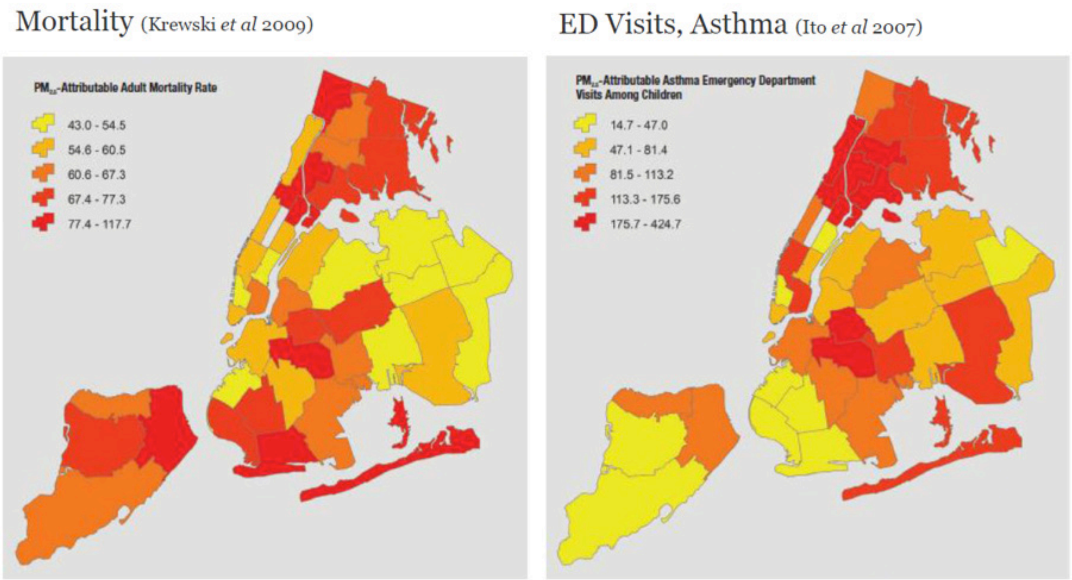
Exposed Population

Pollution causes damage when individuals are exposed to that pollution, so the size of the exposed population is one of the most important drivers of changes in damage from pollution. Densely populated areas experience more damage from a given amount of pollution simply because more people are exposed to that pollution. For instance, $PM_{2.5}$ released in the eastern region of the United States causes between $130,000 and $320,000 in damages per ton according to EPA estimates. A ton of $PM_{2.5}$ emitted in the western part of the United States, however, causes $24,000 to $60,000 in damage.[73] The difference in these estimates is primarily attributable to differences in population density.

Population Health

The healthiness of the exposed population also affects damage. Ozone created in an area with high asthma rates will cause more health damage than ozone released in an area with very few asthma sufferers. Overall health affects the vulnerability of individuals to mortality from pollutants. For example, Figure 3 shows that in New York City, $PM_{2.5}$-attributable mortality rate is higher in portions of Brooklyn than in southern Manhattan.[74]

Figure 3[75]



Mortality (Krewski *et al* 2009)

ED Visits, Asthma (Ito *et al* 2007)

2.7-fold variation by neighborhood
73% of deaths occur in ages 65 and above

30-fold variation by neighborhood

Source: NYC Department of Health and Mental Hygiene Bureau of Environmental Surveillance and Policy (2013).

The left panel shows the relationship between $PM_{2.5}$ and adult mortality for neighborhoods in New York City. The same quantity of $PM_{2.5}$ causes about twice as much mortality in a neighborhood colored red versus yellow. The right panel shows the relationship between $PM_{2.5}$ and child emergency room visits for asthma in New York neighborhoods. For asthma, the same quantity of $PM_{2.5}$ causes about ten times more emergency room visits in a neighborhood colored red versus yellow. Both panels show that the damage from air pollution usually depends on local characteristics like population health.

Methodologies for Calculating the Damage per Unit of Emissions for Pollutants that Depend on Time and Location

Accounting for all of the factors that affect damages using custom models would lead to the most accurate calculations of damage per unit of emissions. However, data constraints and ease of use might make alternative, less granular methods more desirable. Table 1 shows examples of different damage calculation methods that tradeoff between these two goals of accuracy and administrability. The most granular methods use high-resolution population data with time-varying pollution transport models. Less granular methods make stronger assumptions or use more aggregated data to reduce the complexity of calculation.

Custom Solutions

On the most granular side, policymakers could build a custom model that takes into account as many factors affecting damage per unit of emissions as possible. A recent example of such an approach is the Bay Area Clean Air Plan.[76] The Bay Area Air Quality Management District created a custom tool that translates emissions of multiple different pollutants into changes in pollution concentration throughout the Bay Area. The tool uses weather data to understand how pollutants are transported around the Bay Area, and it uses atmospheric chemistry models to understand how different primary pollutants cause secondary pollutants in the region. For instance, ozone is created by a complex interaction between different pollutants and sunlight, so the atmospheric chemistry models are important to understanding how ozone pollution can be addressed.

The model then uses population density to translate pollution concentration changes into human exposure. The exposure determines health effects according to the pollutant being considered and the health conditions of the exposed population.[77] The Bay Area Air Quality Management District focuses on PM, ozone, and greenhouse gas pollution, but in principle, any pollutants could be incorporated into a similar methodology.

One of the primary benefits of a custom method is the ability to incorporate variation in population density and population health. This ability is especially important for states that are characterized by a high degree of heterogeneity in population density. Pollutants emitted in areas near big urban cities would cause substantially higher exposure than the same pollutant emitted in more sparsely populated rural regions. This effect might be exacerbated if higher-emission power plants are located in the higher-population areas, leading to higher ambient pollution levels.[78] This correlated heterogeneity means that policymakers should avoid an approach that uses a state-wide average damage per unit of emissions, since such an approach would vastly understate damages in some areas of the state while overstating damages in others.

Estimating Air Pollution Social Impact Using Regression

Estimating Air Pollution Social Impact Using Regression (EASIUR) is a model of the damages from emission of primary $PM_{2.5}$, SO_2, NOx, and NH_3. The damage estimates are based on mortality due to secondary particulate matter.[79] One of the primary benefits of EASIUR is easy-to-use but accurate modeling of pollution transport. EASIUR was created by taking high-resolution, detailed pollution transport model output from the Comprehensive Air Quality Model with Extensions (CAMx)[80] to derive simple estimates of pollution transport on a 36 by 36-kilometer grid for the United States.[81] As a result, EASIUR provides relatively accurate estimates of air pollution damage based on the location of emissions without the cost of complex and time-consuming modeling of detailed pollution transport. EASIUR also provides estimates of damages for three different stack heights—ground level, 150m, and 300m.

BenMAP

BenMAP is a tool created by EPA to calculate and map damages from ozone and $PM_{2.5}$ in the United States. BenMAP does not include pollution transport modeling. Users specify the change in ambient concentration of pollution that they expect will occur due to a policy, and BenMAP monetizes the health impacts of that change based on population density and pollution damage functions derived from academic publications. It includes high-resolution population data (a 12 by 12-kilometer grid) and can be customized with user-defined population data, baseline health data, and pollution damage functions.[82]

Air Pollution Emission Experiments and Policy Analysis Model

Air Pollution Emission Experiments and Policy analysis models county-by-county marginal damage estimates for SO_2, NOx, $PM_{2.5}$, PM_{10}, NH_3, VOCs. This model allows specification of stack height. This is important in locations like New York City, where the combination of low stacks and large population combine to create high marginal damages for peak generators that often have relatively high emissions rates.[83]

Co-Benefits Risk Assessment

The Co-Benefits Risk Assessment (COBRA) tool from EPA uses a simple pollution source-receptor matrix and a subset of the BenMAP health damage functions to estimate county-level damages from the creation of secondary $PM_{2.5}$ from emissions of NOx, SO_2, NH_3, $PM_{2.5}$, and VOCs. Like BenMAP, COBRA can be modified with custom population, baseline health, and baseline emission data as well as custom damage functions. COBRA damages are based on mortality and morbidity due to nonfatal heart attacks and cardiovascular illness.[84]

Table 3: Tools to Calculate Damage per Unit of Emissions

Tool	Geographic Granularity	Additional Data Requirement	Pollutants Covered	Notes	Source
Custom model	Variable	High	ozone (NOx,VOC), $PM_{2.5}$ (directly emitted $PM_{2.5}$, NOx, VOC, SO_2), air toxics	Geographic-specific damage estimates based on: • Air transport • Ambient concentrations • Population • Comorbidity	Bay Area Air Quality Management District Multi-Pollutant Evaluation Method (2017)
BenMAP	High (default); Variable (custom)	Medium (default); Varies (custom)	ozone, $PM_{2.5}$	• Translates all pollutants into secondary PM & ozone • Driven primarily by mortality • Can input own data	U.S. EPA
EASIUR	36 km	Low	SO_2, NOx, NH_3, $PM_{2.5}$	• Detailed air transport model • Seasonal damages	Heo, Adams, and Gao (2016)
AP2	County	Low	SO_2, NOx, VOC, NH_3, $PM_{2.5}$, PM_{10}	• Accounts for air transport • Broader monetized damage categories	Muller, Mendelsohn, Nordhaus (2011)
COBRA	State or county	Low	$PM_{2.5}$ (directly emitted $PM_{2.5}$, NOx, VOC, SO_2)	• Recently updated (2017) • Previously used by NY PSC • Accounts for air transport • Driven primarily by mortality	U.S. EPA (2017)

Greenhouse Gases – Methodology for Calculating Damage per Unit of Emissions

Damages from greenhouse gases do not depend on the time or location of release, making the calculation of their damage per unit of emissions particularly straightforward.[85] The Interagency Working Group's Social Cost of Carbon is the best estimate of the damages caused by greenhouse gas emissions.[86]

The Social Cost of Carbon is the net-present value of damage caused by the emission of one metric ton of carbon dioxide today. The emissions of greenhouse gases like methane and nitrous oxide from electricity generation can be translated into carbon dioxide-equivalent units using methodologies developed by EPA.[87] The Social Cost of Carbon can then be used to calculate the damage per unit of emissions of all greenhouse gases.

The Interagency Working Group first developed the Social Cost of Carbon in 2010 and updated the estimate in 2013 and 2015.[88] In 2016 and 2017, the National Academies of Sciences issued two reports that recommended future improvements to the methodology.[89] In response to those reports, researchers at Resources for the Future and the Climate Impact Lab are working on further updates.[90]

The Interagency Working Group's estimate has been repeatedly endorsed by government reviewers, courts, and experts. In 2014, the U.S. Government Accountability Office reviewed the Interagency Working Group's methodology and concluded that it had followed a "consensus-based" approach, relied on peer-reviewed academic literature, disclosed relevant limitations, and adequately planned to incorporate new information through public comments and updated research.[91] In 2016, the U.S. Court of Appeals for the Seventh Circuit held that relying on the Interagency Working Group's estimate was reasonable.[92] And though the current Administration recently withdrew the Interagency Working Group's technical support documents,[93] experts continue to recommend that agencies rely on the Interagency Working Group's Social Cost of Carbon estimate as the best estimate for the external cost of greenhouse gases.[94]

Step 4: Monetize the Avoided Externality from Displaced Generation

Once the displaced resource has been identified and both the emissions rates and the damage per unit of emissions are known, these two values can be multiplied to get the monetary value of avoided damages per unit of generation.

If other existing policies already internalize externalities, such as a cap-and-trade program, an additional step to take these policies into account is necessary. Failing to take these policies into account could lead to double counting of the benefits generated by pollution reduction. To see this, consider a case where bulk system generators are subject to a policy that requires payment per ton of CO_2 emitted. The cost of operation for such emitting generators will be higher, and therefore they would submit higher bids to the wholesale electricity market. These higher bids would result in a higher equilibrium price in the market, so any resource that did not emit CO_2 (or emitted less CO_2 than the marginal resource) would receive the benefit of this higher price. In this way, zero or low emitting resources—like a clean DER—would be incentivized to produce more, and high emitting resources would be incentivized to either reduce their emissions or to produce less. If DERs also received direct payments for the full environmental and public health externality of emissions on top of this price increase, the result would be double payment for the same benefits.

If the existing policies do not fully internalize the externality from pollution, then DERs should receive payment that is sufficient to achieve full internalization. States participating in the Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade program run by nine states in the Northeast, provide a good example. Generators in these states that are larger than 25 megawatts must pay for emissions of CO_2 by purchasing emissions permits under RGGI.[95] If the generator displaced by a DER is a participant in RGGI, then the price in the wholesale market already incorporates a payment for CO_2 emissions, and the monetized value of avoided emissions should take that into account. Current and forecasted RGGI permit prices, however, are not sufficient to fully internalize the external damage from CO_2, so clean DERs should still receive a payment for CO_2 emissions that they avoid. The payment should be reduced to reflect the degree to which the CO_2 externality has been internalized by RGGI.

Numerically, consider a case where the displaced resource is a combined-cycle natural gas plant that emits one ton of CO_2 per MWh of generation.[96] If there were no policies that required the displaced generator to pay for carbon emissions, then the value of avoided damages from each kWh injection would be the emissions rate times the external damage per unit of emissions. The external damage caused by carbon dioxide, as discussed in the previous section, is given by the Social Cost of Carbon and the central estimate is currently around \$46 per metric ton in 2017 dollars.[97]

$$\textbf{External value of avoided } \mathbf{CO_2} = 1 \; \frac{kg\ CO_2}{kWh} \times 0.046 \; \frac{\$}{kg\ CO_2e} = 0.046 \; \frac{\$}{kWh}$$

Therefore, for every kWh of displaced generation, a zero-emitting DER would provide a benefit of roughly 5 cents by internalizing the externality from CO_2 emissions.

The payment for a concurrently existing cap-and-trade policy such as RGGI changes this calculation. The current RGGI price is around \$4 per metric ton of CO_2. If the displaced generator is paying for RGGI permits, then \$4 of the external cost of CO_2 has already been internalized, meaning that the uninternalized damage from CO_2 is \$46–\$4=\$42. The value of avoided damage from CO_2 in this case would be:

$$\textbf{External value of avoided } \mathbf{CO_2} \textbf{ with RGGI} = 1\ \frac{kg\ CO_2}{kWh} \times (0.046 - 0.004)\ \frac{\$}{kg\ CO_2} = 0.042\ \frac{\$}{kWh}$$

The value of avoided external damage falls to reflect the fact that some of the external damage from carbon has already been internalized.

As another example, consider an alternative policy that is being discussed in several jurisdictions: carbon pricing. If a carbon charge is levied on electricity sold in a state, the charge would raise the price that wholesale electricity generators pay for carbon emissions and hence help internalize the externality. If this charge is based on the Social Cost of Carbon, then the external value of avoided emissions of CO_2 would fall to zero since the externality would be fully internalized.

$$\textbf{External value of avoided } \mathbf{CO_2} \textbf{ with charge} = 1\ \frac{kg\ CO_2}{kWh} \times (0.046 - 0.046)\ \frac{\$}{kg\ CO_2} = 0.00\ \frac{\$}{kWh}$$

In practice, the benefits from implementing a carbon charge in the state would come from both the incentive it would provide to clean generation and the disincentive to emitting generation, leading to a higher likelihood of the displaced generator having a lower emissions rate as well.

When setting the level of payment for other pollutants, policies including the Cross-State Air Pollution Rule (CSAPR) for NOx and SO_2, the Mercury Air Toxics Standard (MATS), and other future policies should also be taken into account. In the case of a policy like the RGGI cap-and-trade program, discussed above, a positive permit price that results from a binding cap should be taken into account by reducing the payment to DERs in proportion to the amount of the environmental and public health externality that has been internalized. For other programs, like CSAPR, where the cap is currently not binding and the permit price has settled near \$0, no adjustment needs to be made.[98] If the cap binds in the future and prices rise above zero, then the payment to DERs would need to be adjusted.

The table below summarizes recent values of the damage per unit of generation from three different analyses done by different state and federal agencies. As the table shows, these different agencies come to similar conclusions regarding the value of avoiding these different pollutants.

Table 3: Examples of Dollar Value of Average Damage per MWh[99]

Pollutant	2016 EPA RIA	New York DPS	Bay Area Clean Air Plan
SO_2	\$76 to \$171 per MWh	\$52 to \$55 per MWh	\$77 per MWh
NOx	\$4 to \$12 per MWh	\$5 per MWh	\$3 per MWh
$PM_{2.5}$	\$7 to \$16 per MWh		\$22per MWh

Step 5: Monetize and Subtract DER Damages

The final step is to take into account any emissions generated by the DER itself. Distributed energy can come from non-emitting resources like solar panels or small wind turbines or it can come from emitting resources like combined heating and power generators, diesel generators, or small natural gas fuel cells. In fact, the Department of Energy estimates that the majority of DERs in the United States are emitting backup generators, and that in 2006, 42% of DER energy produced in the country came from combined heating and power.[100] If the DER emits pollutants, then those emissions and the damage they cause must be taken into account to accurately quantify the environmental and public health values of the resource. Damages from energy storage systems that are charged by emitting resources should be calculated similarly. In this case, damages from the DER's own emissions must be calculated and netted out from the value of emissions avoided by the DER. In cases where the DER does not emit, this additional step is not necessary, and the calculation of environmental value is simply the external value of avoided emissions calculated in the previous step.

Step 5A: Monetize the Externality from DER

If the DER emits pollutants, then the externality associated with emission of those pollutants must be accounted for, in the same way that the value of emissions from displaced generation was calculated in Steps 2, 3, and 4. First, policymakers need to know the DER's emissions rate for each pollutant. Lack of data on emissions rates presents a unique challenge for calculating damages from DERs. Resources like eGrid and the National Emissions Inventory do not record emissions or generation for very small generators. Instead, policymakers will likely need to rely on engineering estimates of emissions rates. As an alternative, policymakers could also use EPA emissions standards for non-road generators to estimate emissions.[101] Note that fossil-fuel-burning DERs generally produce higher emissions per unit of generation than otherwise comparable, large generators because the latter benefit from returns to scale in generator efficiency.[102]

Second, the policymaker must determine the damage per unit of emissions given the DER's location, time, and pollutants emitted. Damages per unit of emissions from DERs will also likely be different than from a similarly located large generator given that large generators generally have tall stacks that allow pollutants to disperse their over a larger area. Moreover, since DERs are generally located near load centers, they are also generally located nearer to areas of relatively high population density.[103] Proximity to higher population will raise the damage per unit of emissions from emitting DERs.

Using these numbers, the value of damage per unit of electricity generation can be calculated for the DER in the same way that the value is calculated for larger generators. In particular, the value per unit of generation will be the sum across all pollutants of the emissions rate times the damage per unit of emissions.

Step 5B: Subtract the Value of DER Emissions from the Value of Avoided Emissions

The last step for finding the environmental and public health value of DERs is to subtract the value of emissions from the DER calculated in Step 5A from the value of avoided emissions calculated in Step 4. Subtracting these two values must be the last step of the process. In other words, the dollar value of damages per unit of generation from the two resources should be calculated first, then the value of damage from the DER should be subtracted from the value of damage from the displaced resource. This procedure will correctly estimate the net environmental value of the DER by including differences in emissions rates and damage per unit of emissions discussed above. Incorrect calculations would net out either generation or emission before calculating the damages. Netting out generation first would not account for unique emissions by the two resources. Netting out emissions first would not account for the differences in location and exposed population between the two resources.

For instance, consider a case where the DER emits pollution in a high population area while the displaced resource would have emitted pollution in an area with lower population. The damage per unit of emissions is higher from the DER, but if the emissions are first subtracted from each other, then this difference between the two resources would be lost. In such a case, the DER would be erroneously incentivized to produce more electricity, increasing the damage experienced by the high population area.

If damage per unit of generation from the DER is high enough, then the net environmental value of the DER could be negative. This might be the case, for instance, if a diesel generator located in close proximity to a high-population area is displacing generation from a relatively clean natural gas plant located further from a populated area.[104] In these cases where the DER causes more environmental damage than it avoids, it should be penalized for that damage. In other words, the "compensation" for the environmental and public health value may be negative. Failing to do so would also fail to fully internalize the environmental externality associated with emissions.

Example Calculation

To illustrate the calculation of the value of DER using all of the above steps, consider an example of DERs in New York State. New York's current generation mix primarily includes hydropower, nuclear, natural gas, oil, and renewables.[105] Figure 2 shows a representative dispatch curve for New York. During periods of low electricity demand, a DER might offset hydro or nuclear generators, resulting in no avoided emissions. During these periods, the environmental and health value paid to the DER would be zero for a zero-emitting DER and would be negative for any DER like a diesel generator that produces emissions.

During periods with near-average load, the marginal fuel is natural gas. Typical natural gas generators in New York emit relatively low levels of NOx and PM, and moderate levels of CO_2. They do not emit SO_2. As demand rises during periods of particularly high load, oil becomes the marginal fuel and the emissions per unit of generation rise. Currently, New York does not produce any power from coal. A small amount of biomass production occurs in the state, but biomass has, historically, not been the marginal fuel in any region of the state.[106] During the course of a single day, the marginal generator might change from zero-emitting nuclear, to gas, and to oil and back again as load shifts. Table 4 summarizes the emissions rates for typical gas and oil generators in the state. These emissions rates provide the necessary data for Step 2 of the method described above.

Table 4: Average Emissions Rates for Fossil Fuel Generators in New York[107]

Fuel Type	SO_2 (kg/MWh)	NOx (kg/MWh)	CO_2 (kg/MWh)	$PM_{2.5}$ (kg/MWh)
Oil	2.10	2.62	1059.3	0.35
Biomass	0.16	2.71	481.7	0.02
Gas	0.00	0.12	397.3	0.02

The damages from emissions depend on both the location of the avoided emissions and the time of year. For this example, consider the damages from primary $PM_{2.5}$, SO_2, and NOx as given by EASIUR for two locations in the New York. These damages are shown in Table 5. Per unit of emissions, fine particulate matter is the most damaging of the three pollutants. In densely populated Queens County in New York City, damages per unit of particulate matter are much higher than damages in sparsely populated Franklin County. Moreover, pollution emitted in the two locations disperses to areas with much different populations. Emissions from a generator in Queens affect not only residents of Queens County, but other residents in New York City and Long Island. For these three pollutants, damages are higher in the spring and summer than in the winter or fall. In the EASIUR model, these different damages are largely a function of changes in pollution transport due to seasonal weather changes as well as seasonal differences in the rate at which primary pollutants become particulate matter.

The bottom of Table 5 shows the damages from emissions of CO_2.[108] As discussed above, damages from CO_2 do not depend on the time or location of the emissions. In this example, we have chosen the current Social Cost of Carbon minus a hypothetical $5 price for permits in the Regional Greenhouse Gas Initiative.

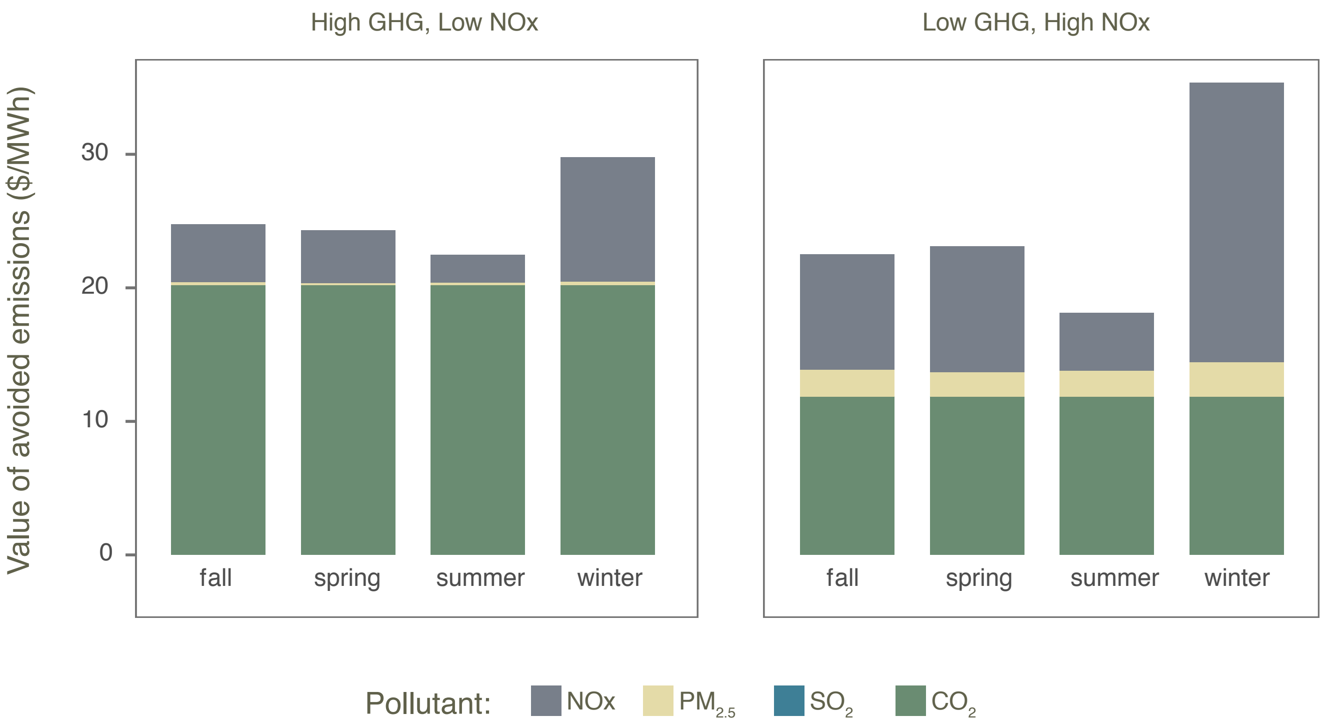
Table 5: Damage Per Unit of Emissions in Two Regions of New York[109]

<table>
<tr><th colspan="5">$PM_{2.5}$ ($/kg)</th></tr>
<tr><td>Population</td><td>Winter</td><td>Spring</td><td>Summer</td><td>Fall</td></tr>
<tr><td>High</td><td>355</td><td>872</td><td>712</td><td>316</td></tr>
<tr><td>Low</td><td>107</td><td>48</td><td>50</td><td>80</td></tr>
<tr><th colspan="5">NOx ($/kg)</th></tr>
<tr><td>Population</td><td>Winter</td><td>Spring</td><td>Summer</td><td>Fall</td></tr>
<tr><td>High</td><td>19</td><td>133</td><td>38</td><td>38</td></tr>
<tr><td>Low</td><td>21</td><td>4</td><td>2</td><td>4</td></tr>
<tr><th colspan="5">SO_2 ($/kg)</th></tr>
<tr><td>Population</td><td>Winter</td><td>Spring</td><td>Summer</td><td>Fall</td></tr>
<tr><td>High</td><td>12</td><td>102</td><td>71</td><td>21</td></tr>
<tr><td>Low</td><td>23</td><td>31</td><td>35</td><td>23</td></tr>
<tr><th colspan="5">CO_2 ($/kg)</th></tr>
<tr><td>Population</td><td>Winter</td><td>Spring</td><td>Summer</td><td>Fall</td></tr>
<tr><td>High</td><td colspan="4">0.04</td></tr>
<tr><td>Low</td><td colspan="4">0.04</td></tr>
</table>

Putting together the emissions rates from Table 4 and the damage per unit of emissions in Table 5, the environmental and health value for a zero-emitting DER can be calculated. For example, if a typical gas-powered generator was on the margin in the high-population, downstate region in the spring, then a zero-emitting DER would create roughly 5 cents of value per kWh of generation. In the lower-population upstate region, this value would be lower—around 2 cents per kWh. If higher-emitting fuels like oil were on the margin, then the value of DERs would be even higher. Previous publications show that oil heating and power generation lead to particularly high environmental and health damages in the New York City area.[110] In contrast, if a zero-emitting resource like hydro power were on the margin, then a zero-emitting DER would create zero additional environmental value.

Figure 4 shows how the environmental and health value varies even among similar generators. The generator in the left panel is relatively inefficient—emitting a larger amount of carbon dioxide per unit of electricity generation than a typical plant in the state—but it is located in a sparsely populated area where NOx and $PM_{2.5}$ emissions reach a smaller population. The generator in the right panel is relatively efficient, but its emissions of local air pollutants reach a larger population, increasing the value of avoiding those emissions.[111]

Figure 4: Value of Avoided Emissions from Two Natural Gas Plants



The figure shows the value of avoided emissions for natural gas generators in New York state. The generator in the left panel emits more pollution per unit of generation than the typical gas generator in New York, but it is located in a sparsely populated area where NOx and PM2.5 emissions reach a smaller population. The generator in the right panel is located in a heavily populated area, so despite being relatively low emitting, its emissions of local air pollutants cause more health damage, increasing the value of avoiding those emissions.

Conclusion

Distributed energy resources can provide substantial value to a state by reducing the need for large-scale bulk system generation, thereby reducing pollutant emissions. The environmental and public health damage from this pollution is often imposed on vulnerable populations. As state utility regulators implement new compensation policies for these distributed resources, a key component of those policies should include payment for that value.

A straightforward five-step methodology, relying on existing or readily accessible tools, can be used to calculate the environmental and public health value of DERs. These tools can allow utility regulators to implement a compensation scheme that rewards DERs when and where they most enhance social welfare.

The methodology presented here is flexible enough to accommodate a variety of data and resource constraints. State regulators should weigh the tradeoffs between accuracy and administrability of different methods to calculating environmental and health value, pick the tools that are as accurate as possible given the tradeoffs, and then update their method when feasible.

Endnotes

[1] Different states have implemented different definitions of DERs. *See* Staff Subcommittee on Rate Design, Nat'l Ass'n Regulatory Util. Comm'rs, Distributed Energy Resources Rate Design and Compensation 43 (2016), https://pubs.naruc.org/pub/19FDF48B-AA57-5160-DBA1-BE2E9C2F7EA0.

[2] *Id.* at 133-136, 142.

[3] Richard L. Revesz & Burcin Unel, *Managing the Future of the Electricity Grid: Distributed Generation and Net Metering*, 41 Harv. Envtl. L. Rev. 43, 78-91 (2017), http://policyintegrity.org/files/publications/Managing_the_Future_of_the_Electricity_Grid.pdf [hereafter Revesz & Unel, *Distributed Generation*]; Richard L. Revesz & Burcin Unel, *Managing the Future of the Electricity Grid: Energy Storage and Greenhouse Gas Emissions*, 42 Harv. Envtl. L. Rev. (2018), http://harvardelr.com/wp-content/uploads/2018/03/revesz_unel.pdf [hereafter Revesz & Unel, *Energy Storage*].

[4] In fact, every resource that avoids emissions—that is, any generating resource that emits less than the resource that would have generated instead—should be paid commensurate with the value of avoided health, climate, and economic damage. This report is specifically focused on DER because Public Utility Commissions in different states are presently focused on reforming the compensation structure of those resources. However, the methodology discussed could be applied more generally.

[5] Revesz & Unel, *Distributed Generation*, *supra* note 3, at 101-108.

[6] For more detail on the changing nature of federal-state divide over regulation of electricity, *see* Robert R. Nordhaus, *The Hazy "Bright Line": Defining Federal and State Regulation of Today's Electric Grid*, 36 Energy L.J. 203 (2015), http://felj.org/sites/default/files/docs/elj362/19-203-216-Nordhaus_FINAL%20%5B11.10%5D.pdf.

[7] Revesz & Unel, *Distributed Generation*, *supra* note 3, at 85-86; Revesz & Unel, *Energy Storage*, *supra* note 3.

[8] Revesz & Unel, *Distributed Generation*, *supra* note 3, at 85-86; Revesz & Unel, *Energy Storage*, *supra* note 3.

[9] *See* Derik Broekhoff et al., World Resources Institute, Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects (2005), http://www.ghgprotocol.org/sites/default/files/ghgp/standards_supporting/Guidelines%20for%20Grid-Connected%20Electricity%20Projects.pdf.

[10] To the extent that the counterfactual scenario identifies multiple generators that are offset by DERs, a generation-weighted average of displaced generators can be used in Steps 2-3.

[11] *Electric Generator Dispatch Depends on System Demand and the Relative Cost of Operation*, Energy Info. Agency: Today in Energy (Aug. 17, 2012), https://www.eia.gov/todayinenergy/detail.php?id=7590.

[12] *See* Broekhoff et al., *supra* note 9, at 63-65.

[13] *See* Erin Boyd, Dep't of Energy Office of Energy Policy & Sys. Analysis, Overview of Power System Modeling 17-19 (2016), https://energy.gov/sites/prod/files/2016/02/f29/EPSA_Power_Sector_Modeling_020416.pdf. The models particularly well suited to this type of analysis are "grid operation models" (otherwise known as "unit commitment and dispatch models" or "production cost models"). Models primarily designed for policy assessments, screening, and data analysis are not as well suited to this use. This includes EPA's AVoided Emissions and geneRation Tool (AVERT), a "high-level gross analysis" tool intended to estimate the emissions implications of new renewable capacity. *Id.* at 8. Nor are "capacity expansion models," such as IPM, NEMS, Haiku, ReEDS, and PLEXOS, which simulate generation and transmission *investment* decisions. *Id.* at 9, 11.

[14] Nathaniel Gilbraith & Susan E. Powers, *Residential Demand Response Reduces Air Pollutant Emissions on Peak Electricity Demand Days in New York City*, 59 Energy Policy 459, 461 (2013); Kyle Siler-Evans et al., *Regional Variations in the Health, Environmental, and Climate Benefits of Wind and Solar Generation*, 110 Proc. Nat'l Acad. Sci. 11768 (2012), www.pnas.org/cgi/doi/10.1073/pnas.1221978110.

[15] *Emissions & Generation Resource Integrated Database* (eGRID), U.S. Envtl. Prot. Agency (Feb. 15, 2016), https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid [hereafter eGrid (2016)].

[16] *See* Hao Cai et al., Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors and Their Probability Distribution Functions for Electric Generating Units (2012), https://greet.es.anl.gov/publication-updated-elec-emissions.

[17] *Id.*

[18] *Frequently Asked Questions: What is the Efficiency of Different Types of Power Plants?*, U.S. Energy Info. Agency (May 10, 2017), https://www.eia.gov/tools/faqs/faq.php?id=107&t=3 (defining "heat rate").

[19] U.S. Energy Info. Agency, Electric Power Annual 2016 169 (2018), https://www.eia.gov/electricity/annual/pdf/epa.pdf.

[20] U.S. Envtl. Prot. Agency, Compilation of Air Pollutant Emission Factors Vol. I [hereafter AP-42] at 1.0-1 (5th ed. 1995), *available at* https://www3.epa.gov/ttn/chief/ap42/ch01/final/c01s00.pdf.

[21] *Id.* at 3.4-1, *available at* https://www3.epa.gov/ttn/chief/ap42/ch03/final/c03s04.pdf.

[22] *Id.* at 3.1-1, *available at* https://www3.epa.gov/ttn/chief/ap42/ch03/final/c03s01.pdf.

[23] *Id.*

[24] Coal plants can install selective catalytic reduction technology that reduces NO_x pollution by over 80%, flue gas desulfurization (aka "scrubbers") that can reduce SO_2 by up to 98%, and electrostatic precipitators and baghouse fabric filters that can drastically reduce PM emissions. Emanuele Massetti et al., ORNL/SPR-2016/772, Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice 24-27 (2017), https://energy.gov/sites/prod/files/2017/01/f34/Environment%20Baseline%20Vol.%202--Environmental%20Quality%20and%20the%20U.S.%20Power%20Sector--Air%20Quality%2C%20Water%20Quality%2C%20Land%20Use%2C%20and%20Environmental%20Justice.pdf. Combustion Turbines can utilize water injection, dry controls (varying the amount of air needed for combustion), and selective catalytic reduction technology. AP-42, *supra* note 22, at 3.1-7. For combined cycle plants and stationary ICE, there are not pollution control technologies that are in wide use, beyond technologies and operational practices to improve plant efficiency.

[25] Massett, *supra* note 25, at 110-111

[26] Felipe R. Ponce Arrieta & Electo E. Silva Lora, *Influence of Ambient Temperature on Combined-Cycle Power-Plant Performance*, 80 Applied Energy 261 (2004).

[27] *See* 40 C.F.R. part 75.

[28] *See* National Emission Standards for Hazardous Air Pollutants from Coal- and Oil-Fired Electric Utility Steam Generating Units, 77 Fed. Reg. 9,304, 9,370-72 (Feb. 16, 2012) (outlining compliance reporting options for the EPA Mercury and Air Toxics rule); *Stationary Source Emissions Monitoring*, , U.S. Envtl. Prot. Agency (last visited March 11, 2018), https://www.epa.gov/air-emissions-monitoring-knowledge-base/basic-information-about-air-emissions-monitoring#stationary.

[29] U.S. Envtl. Prot. Agency, The Emissions & Generation Resource Integrated Database Technical Support Document for eGRID with Year 2016 Data 18 (2018), https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_technicalsupportdocument_0.pdf [hereafter eGrid (2016) TSD].

[30] *See Air Markets Program Data*, U.S. Envtl. Prot. Agency (last visited March 11, 2018), https://ampd.epa.gov/ampd/.

[31] *2014 National Emissions Inventory (NEI) Data*, U.S. Envtl. Prot. Agency, https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data (last visited March 11, 2018) [hereafter NEI (2014)]; U.S. Envtl. Prot. Agency, 2014 National Emissions Inventory Version 1Technical Support Document at 1-1, 1-5, 3-1 (Dec. 2016), https://www.epa.gov/sites/production/files/2016-12/documents/nei2014v1_tsd.pdf [hereafter NEI TSD].

[32] *Id.*

[33] Where state data was not available, EPA supplements the NEI with emissions using data reported directly to EPA (from CAMD data) and by multiplying heat input data by predetermined emission factors (based on AP-42). EPA also performs some modifications to state-reported data, including PM emission data. NEI TSD, *supra* note 32, at 2-7.

[34] EPA defines the NO_x ozone season as the period between May 1 and October 1. During this period, NO_x emissions are more likely to lead to the formation of ozone. *See, e.g.* Finding of Significant Contribution and Rulemaking for Certain States in the Ozone Transport Assessment Group Region for Purposes of Reducing Regional Transport of Ozone, 63 Fed. Reg. 57,356 (Oct. 27, 1998).

[35] U.S. Energy Info. Agency, Form EIA-923 Power Plant Operations Report Instructions https://www.eia.gov/survey/form/eia_923/instructions.pdf [hereafter Form EIA-923 Instructions]. Power plant owners report additional facility-level information on EIA form 860, which can be used to supplement the generation information reported on EIA form 923. *Form EIA-860 Detailed Data*, U.S. Energy Info. Agency (Nov. 9, 2017), https://www.eia.gov/electricity/data/eia860/.

[36] Form EIA-923 Instructions, *supra* note 35.

[37] EIA form 923 is submitted monthly by a large sample of potential respondents and annually by all units. U.S. Energy Info. Agency, Electric Power Monthly Technical Notes 14-15 (Feb. 2018), https://www.eia.gov/electricity/monthly/pdf/technotes.pdf.

[38] Emission factors are provided as pounds of emission per unit of fuel input. Therefore, in order to develop emission rates denominated in kWh, states would have to use the unit's heat rate. This may be available from EIA or through engineering estimates provided by the unit's manufacturer.

[39] AP-42, *supra* note 21, at Chapter 1, https://www3.epa.gov/ttn/chief/ap42/ch01/index.html

[40] *Id.* at Section 3.1, at https://www3.epa.gov/ttn/chief/ap42/ch03/final/c03s01.pdf.

[41] *Id.* at Section 3.4, https://www3.epa.gov/ttn/chief/ap42/ch03/final/c03s04.pdf.

[42] Rachel Leven, *Bad Science Underlies EPA's Air Pollution Program*, Scientific American, (Jan 29, 2018), https://www.scientificamerican.com/article/bad-science-underlies-epa-rsquo-s-air-pollution-program.

[43] Nat'l Energy Tech. Lab., Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity 458 (Nov. 2010), https://www.nrc.gov/docs/ML1217/ML12170A423.pdf.

[44] Gilbraith & Powers, *supra* note 14.

[45] eGrid (2016), *supra* note 15.

[46] eGrid (2016) TSD, *supra* note 29, at 16.

[47] *Id.*

[48] *Id.* 17.

[49] The notable exception is the inclusion of both annual NO_x emissions and ozone season-specific NO_x emissions. *Id.*

[50] *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transpiration Model*, Argonne Nat'l Lab. (Oct. 9, 2017), https://greet.es.anl.gov/index.php.

[51] Hao Cai et al., *supra* note 16.

[52] Hao Cai et al., Updated Greenhouse Gas and Criteria Air Pollutant Emission Factors of the U.S. Electric Generating Units in 2010 (2013), https://greet.es.anl.gov/publication-electricity-13; Hao Cai et al., Update on Generation Efficiency and Criteria Pollutant Emissions of Integrated Coal Gasification Combined-Cycle Power Plant (2017), https://greet.es.anl.gov/publication-coal_igcc_2017.

[53] *See* Joshua Graff Zivin, Matthew Kotchen & Erin Mansur, *Spatial and Temporal Heterogeneity of Marginal Emissions*, 107 J. Econ. Behavior & Org. 248 (2014).

[54] Daniel A Axelrad et al., *Dose-Response Relationship of Prenatal Mercury Exposure and IQ: An Integrative Analysis of Epidemiologic Data.*, 115 Environ. Health Perspect. 609 (2007).

[55] Richard L. Revesz & Jack Lienke, Struggling for Air: Power Plants and the "War on Coal" 11 (2016).

[56] *Id.* at 10.

[57] *Particulate Matter (PM) Basics*, U.S. Envtl. Prot. Agency (last visited March 11, 2018), https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM; For a more detailed description of the health effects of $PM_{2.5}$ and ozone, *see* U.S. Envtl. Prot. Agency, Regulatory Impact Analysis for the Proposed Carbon Pollution Guidelines for Existing Power Plants at 4-16 to 4-24 (2014), https://www3.epa.gov/ttn/ecas/docs/ria/utilities_ria_proposed-carbon-poll-existing-egus_2014-06.pdf.

[58] Revesz & Lienke, *supra* note 55, at 11.

[59] *Id.*

[60] *Id.*

[61] Matthew MJ Neidell, *Information, Avoidance Behavior, and Health: The Effect of Ozone on Asthma Hospitalizations*, 44 J. Hum. Resources 450 (2009).

[62] Endangerment and Cause or Contributed Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act, 74 Fed. Reg. 66,495 (Dec. 15, 2009).

[63] D. B. Lobell, W. Schlenker & J. Costa-Roberts, *Climate Trends and Global Crop Production Since 1980*, 333 Science. 616 (2011).

[64] Intergovernmental Panel on Climate Change [IPCC], *Climate Change 2014 Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects*, 1132 (2014), http://www.ipcc.ch/report/ar5/wg2/.

[65] Axelrad et al., *supra* note 54.

[66] For instance, EPA, in their BenMAP tool for calculating the health effects of particulate matter exposure, estimate that the relationship between myocardial infarction and $PM_{2.5}$ follows the function (1-(1/((1-Incidence)*exp(b*(change in $PM_{2.5}$))+Incidence))), where "Incidence" is a measure of the baseline rate of myocardial infarction and b is a parameter derived from Annette Peters et al., *Increase Particulate Air Pollution and the Triggering of Myocardial Infarction*, 103 Circulation 2810–2815 (2001).

[67] Claire E. Reeves et al., *Potential for Photochemical Ozone Formation in the Troposphere Over the North Atlantic as Derived from Aircraft Observations During ACSOE*, 107 J. Geophys. Res. Atmos, no. D23, 2002, at ACH 14-1. Paola Michelozzi et al., *High Temperature and Hospitalizations for Cardiovascular and Respiratory Causes in 12 European Cities*, 179 Am. J. Respiratory Critical Care Med. 383 (2009).

[68] *See, e.g.*. Jerald L. Schnoor, Environmental Modeling: Fate and Transport of Pollutants in Water, Air, and Soil (1996).

[69] *Id.*

[70] Alex A. Karner, Douglas S. Eisinger & Deb A. Niemeier, *Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data*, 44 Envtl. Sci. Tech. 5334 (2010).

[71] Reeves *et. al.*, *supra* note 67.

[72] Revesz & Lienke, *supra* note 55, at 108.

[73] U.S. Envtl. Prot. Agency, Regulatory Impact Analysis for the Clean Power Plan Final Rule at 4-23 (2015), https://www3.epa.gov/ttn/ecas/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf.

[74] *See* N.Y.C. Department of Health and Mental Hygiene, Air Pollution and the Health of New Yorkers: The Impact of Fine Particles and Ozone at 16, 22 (2013), https://www1.nyc.gov/assets/doh/downloads/pdf/eode/eode-air-quality-impact.pdf.

[75] Iyad Kheirbek, N.Y.C. Department of Health and Mental Hygiene, Estimating Morbidity and Mortality Attributable to Air Pollution in New York City 10 (2013), https://www.epa.gov/sites/production/files/2014-10/documents/hia_for_benmap_webinar_8.7.13.pdf.

[76] Bay Area Air Quality Mgmt. District, Spare the Air Cool the Climate: Final 2017 Clean Air Plan (2017), http://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf.

[77] David Fairley & David Burch, Bay Area Air Quality Mgmt. District, Multi-Pollutant Evaluation Method Technical Document 2016 Update 7 (2016), http://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/mpem_nov_dec_2016-pdf.pdf.

[78] Aleksandr Rudkevich & Pablo A Ruiz, *Locational Carbon Footprint of the Power Industry: Implications for Operations, Planning and Policy Making*, in Handbook of CO_2 in Power Systems 148 (Qipeng P. Zheng et al. eds., 2012) (showing that the highest levels of carbon dioxide emissions occur in the southern part of the state). Kathryn Hansen, *New NASA Images Highlight U.S. Air Quality Improvement*, NASA (June 26, 2014), https://www.nasa.gov/content/goddard/new-nasa-images-highlight-us-air-quality-improvement/ (showing that this same area also experiences higher ambient levels of non-carbon dioxide air pollution).

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[99] Each column shows examples of the dollar value of damages from emissions of SO_2, NO_x, and $PM_{2.5}$ (direct) in 2016 dollars. U.S. Envtl. Prot. Agency, *supra* note 73, at 4-23; Proceeding on Motion of the Commission in Regard to Reforming the Energy Vision, Staff White Paper on Ratemaking and Utility Business Models, PSC Case No. 14-M-0101 (July 28, 2015), at C-9; and the Bay Area Air Quality Mgmt. District, *supra* note 76, at C/3.

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[107] Emissions rates are calculated based on data from eGrid (2016), *supra* note 15, and NEI (2014), *supra* note 31.

[108] The values are for CO_2e, or carbon dioxide equivalent. This includes carbon dioxide as well as other greenhouse gas emissions in CO_2 equivalent values.

[109] Damages from SO_2, NO_x, and $PM_{2.5}$ come from EASIUR, *supra* note 79. Damages from CO_2 come from the IWG (2016), *supra* note 97.

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