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Offshore Wind Power Examined: Effects, Benefits, and Costs of Offshore Wind Farms Along the US Atlantic and Gulf Coasts

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Abbreviations

ATB Annual Technology Baseline

CCS carbon capture and storage

CCUS carbon capture, use, and sequestration

CES clean electricity standard

CO_2e carbon dioxide equivalent

GHG greenhouse gas

GoM Gulf of Mexico

GW gigawatts

InMAP Intervention Model for Air Pollution

MMT million metric tons

MW megawatts

MWh megawatt-hours

NO_x nitrogen oxides

OREC Offshore Wind Renewable Energy Certificate

OSW offshore wind

$PM_{2.5}$ fine airborne particulate matter

PPA power purchase agreement

RGGI Regional Greenhouse Gas Initiative

RPS renewable portfolio standard

RTO regional transmission organization

SO_2 sulfur dioxide

WEA wind energy area

Executive Summary

Electricity from offshore wind is considered important for reducing energy-related emissions because of its ability to serve coastal areas and complement other nonemitting electricity sources. However, there are open questions about the degree to which it will replace emitting versus other nonemitting generation, improve public health, and affect the total cost of the electricity supply. In the face of recent input cost increases and project cancellations, governments are deciding how strongly to support offshore wind development. To help with such decisions, we project and evaluate several effects of a set of 32 planned or proposed offshore wind farms along the Atlantic and Gulf coasts of the United States, which would produce approximately 2.5 percent of US and Canadian electricity generation. We examine how those offshore wind farms would affect other electricity generation capacity, generation, emissions, health, costs for electricity and natural gas customers, profits of the electricity and natural gas supply industries, and net government revenues, in the year 2035. We include capital expenditure recovery and financing among the costs.

In our modeling results, from a detailed power sector capacity expansion and dispatch model, the offshore wind farms' estimated net benefits are positive, with an estimated benefit-to-cost ratio of 14 to 1. Generation from the offshore wind farms disproportionately reduces natural gas and coal-fueled generation, causing large emissions reductions. Further, the emissions reductions tend to be upwind of densely populated areas. Consequently, the offshore wind farms reduce annual estimated US premature deaths from airborne particulate matter and ground-level ozone by 520 per year. Black, Hispanic, and low-income Americans account for a disproportionately large share of the premature deaths avoided, as do residents of the New York City area. The offshore wind farms reduce worldwide projected future deaths from climate change by 1,600 per year of their operation. The offshore wind farms increase the overall nonenvironmental costs of the electricity supply but reduce customer electricity and natural gas bills. Though our study is relatively comprehensive, it, like others, does not include all benefits and costs. Notably, it does not include estimates of the likely downward effect of the 32 offshore wind farms on the cost of subsequent offshore wind development or the benefits of the increased future development that is likely to result.

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1. Introduction

Globally, there are more than 290 offshore wind farms, totaling over 59 gigawatts (GW) of capacity (Musial et al. 2023), with generation equal to the consumption of approximately 20 million average US homes. Along the US coasts, three offshore wind farms are currently in operation, and dozens more are in various stages of development. Offshore wind has a temporal pattern that differs from those of sunlight and land-based wind, increasing the consistency of the overall wind and solar energy supply and allowing for greater reliance on renewable energy. It therefore has the potential to significantly reduce emissions and is well suited for supplying power to densely populated coastal areas that are home to a large portion of the population and are costly to serve with other nonemitting generation types, such as land-based wind, solar, and nuclear.

As a relatively new technology, offshore wind farms in the United States have needed state government support and might continue to need it for years to come. Several coastal states include offshore wind as part of their overall decarbonization plans and are soliciting such projects to enter into power purchase or offshore renewable energy credit agreements. More than 20 offshore wind farms have already entered into such agreements, but state governments must revisit their decisions where recent cost increases have prompted the cancellation or renegotiation of agreements. They have to decide how many additional offshore wind farms to support as well.

Federal government decisions are also important for the extent of development of offshore wind farms. The federal government sets the level of federal tax credits for offshore wind, sells ocean-area leases, incentivizes the development of installation infrastructure, funds research and development, oversees most US electricity transmission expansion, and more.

While the anticipated costs of offshore wind development have increased somewhat since 2020, so have the anticipated costs of power generation from most fossil sources, partly as a result of new emissions regulations. This makes it difficult to determine whether the anticipated costs of offshore wind farms relative to the alternatives are higher or lower than they were in 2020.

This study can help inform these state and national decisions. It presents the results from an analysis of the effects of the addition of a set of 32 planned or proposed offshore wind farms off the Atlantic coast of the United States, from Massachusetts to North Carolina, and off the Gulf coast states of Louisiana and Texas (see Table 1 and Figure 1). We report the combined effects of this set, with a projected capacity of 35 GW, in the year 2035. Many of these projects have offtake agreements, eight others had agreements that have been canceled by the developer or state, and some have been proposed by a developer or the US Bureau of Ocean Energy Management but do not yet have agreements. For those sites with canceled offtake agreements,

Figure 1. Capacity and Location of Modeled Offshore Wind Projects

Note: The markers on the map are much larger than the footprints of the offshore wind farms will be.

comparable projects are likely to be built under future agreements.[1] Some of the remaining agreements are currently subject to requests for renegotiation. Despite the uncertainty around canceled and new projects and existing agreements, this set of probable future sites is useful for producing estimates of the effects of offshore wind farms, particularly those along the US Atlantic and Gulf coasts, on the emissions, health impacts, and costs associated with the US power supply.

The emissions, health, and cost effects of adding an offshore wind farm depend greatly on how it affects the retirement and construction of other generators. For example, the less an offshore wind farm reduces the amount of solar and land-based wind capacity built, and the more emitting capacity it causes to retire, the more it will tend to reduce emissions. Projecting the effects of offshore wind farms on emissions therefore calls for a realistic power sector model that can project the effects of offshore wind on the construction, retirement, and operation of other generators. We use the E4ST power sector model (described in Section 2), an unusually realistic model that captures the complex interactions between costs, policies, and technical requirements.

1 Eight of the projects, Ocean Wind 1 and 2, Empire Wind 2, New England Wind 1 and 2, Attentive Energy 1, Community Wind, and Excelsior Wind, which account for 9.5 of the 35 GW of offshore wind modeled, canceled contracts in late 2023 and early 2024. However, it is likely that these projects will still be developed under future contracts because they are in locations deemed well suited for offshore wind development, and developers have purchased leases and have done some of the other work necessary for developing wind farms here.

Table 1. Set of Offshore Wind Farms in This Analysis

Project name	Capacity (MW)	Offtake contract	Lease location	Proposed cable landing
Atlantic Shores	1510	NJ	NJ WEA	Atlantic City and/or Sea Girt, NJ
Attentive Energy 1	1314	NY*	NY Bight WEA	Queens, NY
Attentive Energy 2	1324	NJ	NY Bight WEA	Sea Girt, NJ
Beacon Wind 1	1230	NY	MA WEA	Queens, NY
Carolina Long Bay Wind	1000	NC	NC WEA	—
Coastal Virginia Offshore Wind	2600	VA	VA WEA	Virginia Beach, VA
Community Wind	1404	NY*	NY Bight WEA	Brooklyn, NY
Duke Energy Renewables Wind	1600	NC	NC WEA	—
Empire Wind 1	816	NY	NY WEA	Brooklyn and/or Oceanside, NY
Empire Wind 2	1260	NY*	NY WEA	Brooklyn and/or Oceanside, NY
Excelsior Wind	1314	NY*	NY Bight WEA	Uniondale, NY
Galveston, TX (four leases)	3420	—	GoM	—
Kitty Hawk North Wind	2500	NC	NC WEA	—
Lake Charles, LA (one lease)	1244	—	GoM	—
Leading Light Wind	2400	NJ	NY Bight WEA	—
Marwin	248	MD	MD WEA	Rehoboth Beach or Dagsboro, DE
Momentum Wind	809	MD	MD WEA	Rehoboth Beach or Dagsboro, DE
New England Wind 1 (formerly Park City Wind)	804	CT*	MA WEA	Barnstable, MA
New England Wind 2 (formerly Commonwealth Wind)	1232	MA*	MA WEA	Barnstable, MA

Ocean Wind 1	1100	NJ*	NJ WEA	Seaside Park, Ocean City, and/or Forked River, NJ
Ocean Wind 2	1148	NJ*	NJ WEA	Seaside Park, Ocean City, and/or Forked River, NJ
Revolution Wind (CT contract)	300	CT	RI/MA WEA	North Kingstown, RI
Revolution Wind (RI contract)	400	RI	RI/MA WEA	North Kingstown, RI
Skipjack Wind 1	120	MD	DE WEA	Rehoboth / Bethany Beach area or Dagsboro, DE
Skipjack Wind 2	846	MD	DE WEA	Rehoboth / Bethany Beach area or Dagsboro, DE
South Coast Wind (formerly Mayflower Wind)	1200	MA	MA WEA	Somerse or Falmouth MA
South Fork Wind	132	NY	RI/MA WEA	East Hampton, NY
Sunrise Wind	924	NY	RI/MA WEA	Brookhaven, NY
Vineyard Wind 1	800	MA	MA WEA	Barnstable, MA

* Offtake agreement canceled since analysis began, but project still likely under a future agreement.

1.1. Determinants of Emissions Reductions and Health Benefits from Offshore Wind Investments

Ex ante, we do not know how large the emissions reductions and health benefits caused by the offshore wind farms will be. The average per-megawatt-hour (MWh) emissions rate of generation in nearby states is a useful benchmark against which to compare the emissions effects of building offshore wind farms. The emissions prevented by the offshore wind farms, per MWh of their generation, might be smaller or larger than the per-MWh emissions in nearby states for various reasons. One of the main functions of this study is to test which is the case.[2]

There are four main reasons the prevented emissions per MWh might be smaller than the average in the nearby states. First, many of the states sponsoring the offshore wind farms in this study have clean energy percentage requirements. Unless clean

2 In this study, we assume the states do not increase their clean energy requirements in response to the construction of the offshore wind farms. If they did, it would be likely to increase the emissions reduction benefits of the offshore wind farms.

generation is sufficiently cost-competitive that it exceeds those requirements (i.e., makes the requirements "slack"), they are increased in response to the decision to build the offshore wind farms, or they are not met without the offshore wind farms, the requirements will cause the offshore wind farms to entirely or mainly prevent other clean generation rather than emitting generation. This is presumably not a surprise to most policymakers. In states that have clean energy requirements, policymakers are arranging for a portion of these requirements to be satisfied by the offshore wind farms they sponsor instead of by other clean sources. Second, offshore wind has a slight tendency to be strong at the same times as wind over land (for example, these have a correlation coefficient of approximately 0.2 in the PJM region, according to PJM 2022), which could possibly cause the offshore wind farms to disproportionately reduce the construction of land-based wind farms.

Third, offshore wind farms are unlikely to cause the retirement of much emitting generation capacity in light of local system operators' current assessments of the capacity value of offshore wind, and hence of those operators' ability to reduce emitting capacity in response to the presence of the offshore wind. We assume based on current and prospective credit values calculated by the nearby system operators that in 2035, the offshore wind farms would receive 0.2 credits per megawatt (MW) of offshore wind capacity in a capacity market, while emitting capacity would receive an average of approximately 0.9 credits per MW.[3] Fourth, generators that do not yet exist may tend to be more affected by offshore wind farms than generators that already exist, because the generators that do not yet exist commonly have a smaller expected margin of revenues over going-forward costs, which could be rendered negative by the offshore wind farms. Preventing new capacity from being built could disproportionately prevent clean generation. In the results of our 2035 simulation without the offshore wind farms, in the areas adjacent to the offshore wind farms, there is approximately twice as much generation from new nonemitting generators as from new emitting generators (those built between 2024 and 2035).

There are also four main reasons the emissions prevented per MWh could be more than the average per-MWh emissions rates of generation in the nearby states. First, electricity consumption near the coast tends to be more dependent on fossil-fueled generation. Because of the high population density near the coast, it is very costly and legally and politically difficult to build large amounts of land-based wind, solar, nuclear, and transmission capacity to serve the electricity demand there. Generators powered by fossil fuels, mainly natural gas, tend to be easier to place in such areas, and many already exist there. The 19 offshore wind farms in this study connect to the grid near densely populated areas. Second, wind over the ocean in the study area is slightly negatively correlated with sunlight (for example, these have a correlation coefficient of approximately –0.14 in the PJM region, according to PJM (2022). This reduces the propensity of offshore wind to prevent new solar generation capacity.

3 This capacity credit value for offshore wind is near the average of actual or projected values of 39 percent for PJM (Glazer and Lu 2023), 13 percent for New England (Ibanez 2022), and 20–49 percent for New York (Ibanez and Bringolf 2022).

Third, hydropower, wind, and solar—all of which are nonemitting—are the types of existing capacity that are least likely to retire earlier or generate less due to offshore wind farms, because their variable costs are low and their going-forward costs tend to be relatively small compared with those of fossil-fueled or new generators.[4] Fourth, offshore wind farms could reduce coal-fueled generation by a larger percentage than they reduce natural gas–fueled generation. Offshore wind farms may reduce the capacity factors (i.e., average hourly generation per MW of capacity) of fossil generators, and reduced capacity factors could reduce the profits of existing coal generators more than those of existing gas generators, since the coal generators tend to have a higher ratio of fixed to variable costs than do existing natural gas generators. As a result, new offshore wind capacity could reduce existing coal-fueled capacity by a larger percentage than it reduces existing gas-fueled capacity. All coal-fueled capacity in our model is existing, while gas capacity is a mix of existing and endogenously built in the simulation, but this effect still could be great enough to reduce coal-fueled generation by a larger percentage than total gas-fueled generation.

For harmful emissions other than greenhouse gas (GHG) emissions, such as $PM_{2.5}$, nitrogen oxides, and sulfur dioxide, the health effects of offshore wind farms are determined by their effects not just on emissions quantities but also on emissions locations. The majority of the offshore wind farms in this study are near the most densely populated part of the United States, the coastal area from Maryland to Massachusetts. Consequently, the emissions reductions from displaced generation might be more beneficial than similar emissions reductions would be at average US power plant locations. On the other hand, the wind usually blows toward the northeast or east in this part of the world, so sometimes the emissions are carried out over the Atlantic Ocean before having spent much time over land, reducing their harm. The air pollution model we use includes these phenomena in its estimation of the air quality and health effects of the offshore wind farms.

1.2. Determinants of Cost

We also do not know in advance how much more costly the offshore wind farms will be than the generation for which they substitute, in terms of nonenvironmental costs. Offshore wind is projected to continue to have a higher cost per MWh than land-based wind and solar through 2035 (Mirletz et al. 2023), but it can serve population-dense coastal areas that are costly to serve, and it can make overall solar plus wind generation more consistent. Those two attributes increase the offsetting savings from relying on offshore wind, thereby reducing the net cost of offshore wind. Our analysis represents the effects of the offshore wind farms, including the effects of these two attributes. This study projects not just the emissions and health effects of the offshore wind farms but also the net costs.

4 This can be restated in economic parlance: Emitting generation tends to be on the short-run margin, but as explained at the end of the preceding paragraph, nonemitting generation tends to be on the long-run margin. It is not clear ex ante which will be replaced more by offshore wind farms.

2. Methods and Inputs

To estimate the effects of the offshore wind farms listed in Table 1, we simulate two possible futures for the US electricity system in the year 2035, one with this set of 32 offshore wind farms and one with no offshore wind farms.[5] This allows us to estimate the effects of the offshore wind farms in that year compared with a scenario in the same year with the same model and inputs but without the offshore wind farms. We use the Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST; RFF 2022), a simultaneous capacity expansion and optimal power flow model that allows for unusually realistic simulations of the US and Canadian electric power sector. E4ST projects the effects on capacity expansion and generator operation and estimates the benefits and costs of policies, infrastructure investments, and other changes to the grid. It uses detailed representations of existing generating units, with location- and hour-specific wind and solar data for each current and potential wind farm and solar array site, as well as a model of the transmission system with all the high-voltage (over 200 kilovolt) lines and a modified Ward reduction representation of the lower-voltage lines (Shi et al. 2012). E4ST uses a standard linear approximation of the physics of how power distributes itself across the many lines to realistically represent the effects of power flow limits and transmission congestion. We assume that the capacity of all transmission lines is expanded in proportion to system-wide electricity consumption growth.

In both scenarios with and without the offshore wind farms, our model projects the retirement and construction of generators between 2024 and 2035. Consequently, our analysis includes the projected effects of the offshore wind farms on other generation capacity.

As a possible average of the costs of the 32 offshore wind farms, which are generally slated to be completed between 2024 and 2035, we use the 2030 cost projection from the National Renewable Energy Laboratory's 2023 Annual Technology Baseline (ATB; Mirletz et al. 2023).[6] The offshore wind farm cost projections in the 2023 ATB are higher than those in earlier ATBs, reflecting increased costs of inputs. We present three versions of our net benefits analysis based on the ATB's three sets of cost assumptions: advanced (low cost), moderate (mid cost), and conservative (high cost). The cost projections we use, in levelized form, are \$53/MWh (low), \$59/MWh (mid), and \$71/MWh (high). These are approximately \$5 higher per MWh than the ATB costs, due to a combination of longer transmission links, regional cost multipliers, and conservative assumptions.[7] Some of our

5 We omit the three offshore wind farms that are in operation as of August 2024 from the scenario without offshore wind farms for simplicity and because they are small, with a combined capacity of 174 MW. We include the largest of the three, South Fork, which began operation in 2024, in the set of 32 offshore wind farms.

6 For newly built generators of all types in this study, we use costs from the 2023 ATB. For offshore wind farms, we use the costs for those in class 4 as defined in the ATB.

7 We assume that all the offshore wind farms use direct-current transmission to connect to the existing grid, which raises their average costs. Also, the ATB costs seem to be based on offshore wind farms that are smaller than the average size of those in our study, potentially making the costs large for our purposes. Appendixes I and E further describe our cost inputs.

analysis uses just the mid-cost case. All dollar values in this study are in 2020 US dollars except where otherwise noted.

Most of the modeled offshore wind projects included in this analysis have signed power purchase agreements (PPAs) or negotiated Offshore Wind Renewable Energy Certificate (OREC) price agreements, which, if implemented, will play a large role in determining the prices that electricity customers will pay for offshore wind generation. Beiter et al. (2019) is the richest source we have found about the terms of the PPAs and OREC price agreements of the offshore wind farms in our study, but we do not have complete information about these terms, as up-to-date versions are not publicly available for all projects, the effective real prices depend in part on unspecified assumptions, and some of the agreements are being renegotiated. Also, the prices might include above- or below-normal profit for the developers, which would be a benefit or cost that we would not know about or be able to include if we used a cost estimate based on the information we have about agreement prices.[8] For these reasons, we use the ATB cost projections instead of PPA or OREC prices as the costs of these offshore wind farms to the grid and ultimately to electricity consumers. Our estimate of the average expected levelized total revenue per MWh of the offshore wind farms whose agreements were still in force in January 2024 is $61/MWh in 2020$, which is very close to the $59 average levelized cost of the mid-cost projections we use in this study.

Our model includes regional natural gas supply and demand curves for consumption outside the electricity sector. Appendix I explains our representation of the natural gas sector.

The policies we assume in our modeling include the Inflation Reduction Act, the new US power plant GHG emissions regulations announced in 2024 (EPA 2024b), a scaled-back version of the Good Neighbor Plan for power plant nitrogen oxide emissions from 22 US states announced in 2023 (EPA 2024a), state clean electricity standards (CESs) and renewable portfolio standards (RPSs), the Regional Greenhouse Gas Initiative (RGGI), and other influential power sector policies. Detailed descriptions of our policy and technology assumptions can be found in Appendixes H and I.

The 2024 GHG regulations (EPA 2024b) require the end of conventional coal-fueled generation by 2035. They increase the retirement of coal-fueled generation and call for the remainder to retrofit with either carbon capture, use, and sequestration (CCUS) or coal-gas cofiring, in which 40 percent of the heat input is from natural gas and the rest is still from coal. These effects are reflected in both of our scenarios and reduce the emissions that can be prevented by offshore wind farms.[9]

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8 Price could be higher than developers' cost expectations because of a successful effort to obtain greater-than-normal expected profits or lower because of a desire to gain a foothold in the emerging US offshore wind market or because the winning bidders were overly optimistic about costs (a documented phenomenon known as "the winner's curse," as summarized in Holt and Sherman 2014).

9 The 2024 greenhouse gas regulations and 2023 Good Neighbor Plan regulations could be overturned or weakened. In Appendix D, we summarize the projected results of the offshore wind farms in the absence of these regulations using an alternative scenario.

To estimate the benefits to people from GHG emissions reductions, we use the 2023 EPA estimates of the damages per ton of CO_2 and methane, which are based on the research literature (EPA 2023c) and guided by the recommendations of an expert panel convened by the National Academies of Sciences, Engineering, and Medicine (NASEM 2017). We use the Intervention Model for Air Pollution (InMAP) (Tessum et al. 2017) to estimate the effects of power plant sulfur dioxide (SO_2), nitrogen oxide (NO_x), and fine particulate matter ($PM_{2.5}$) emissions on the concentration of $PM_{2.5}$ in the air that people breathe; the effects of those concentrations on mortality and illnesses; and the dollar value of those health effects. InMAP uses 1 × 1 km grid cells in densely populated areas, and we have demographic information about all the grid cells, so we are able to estimate the average demographic composition of the people whose lives would be saved by the $PM_{2.5}$ concentration reductions caused by the offshore wind farms. A longer description of our method for valuing the damage caused by $PM_{2.5}$ is included in Appendix G.

To estimate the effects of the NO_x emissions reductions on deaths and illness from ground-level ozone, and the dollar value of those health changes, we use the national average estimated marginal effects per ton of ozone-season NO_x emitted by electricity generating units. This is conservative because the estimated effects per ton are higher, up to 50 percent higher, for NO_x emissions in the states near the offshore wind farms (EPA 2023a).[10] Also, to represent the fact that relatively little ground-level ozone forms outside the summer months, we assume that only 45 percent of the NO_x emissions reductions produce this benefit and conservatively assume that the other 55 percent do not reduce ground-level ozone at all.[11]

10 The estimated NO_x ozone damage by emitting state is in the incidence files accompanying the report.

11 This is based on the fact that approximately 45 percent of power sector NO_x emissions historically occur in the official "ozone season," May 1 through September 30 (EPA 2022b).

3. Results

Our model projects the effects of the offshore wind farms on emissions, health, emitting capacity, generation mix, costs for electricity and natural gas customers, profits of the electricity and natural gas supply industries, net government revenues (net of expenditures), monetized estimated value of environmental effects, and total estimated societal net benefits. This section details those results grid-wide. We also focus on results in what we term the "adjacent areas," the areas that connect to or have offtake agreements for offshore wind projects: Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, and North Carolina, as well as the area of Texas and Louisiana with the 16 percent of those states' generation that is closest to the Gulf of Mexico offshore wind farms in our simulation.[12]

In the scenario in which they are present, the offshore wind farms produce 15 percent of electricity generation in the adjacent areas and 2.5 percent of total US and Canadian generation. Overall, we find that the offshore wind farms disproportionately reduce fossil-fueled generation, and do so to a remarkable degree: fossil generation constitutes 55 percent of the net other generation prevented by the offshore wind farms even though it is only 27 percent of the projected 2035 generation in the adjacent areas.[13] This disproportionately large replacement of emitting generation results in large emissions reductions, and occurs despite almost no net effect on the total amount of fossil-fueled capacity. These emissions reductions prevent an estimated 520 premature deaths per year in the United States from reduced airborne particulate matter and ozone pollution, reduce climate change, and are worth an estimated $80 per MWh of offshore wind generation. The main effect on land-based renewable energy is a slight reduction of the rapid rate of construction of new solar farms.

In the mid offshore wind cost case, our model predicts that the offshore wind farms will increase the total nonenvironmental costs of the electricity supply by $6/MWh of offshore wind generation, taking into account the effects on other capacity, other generation, benefits for gas users, and profit losses for gas producers. This results in an estimated benefit-to-cost ratio of 14 to 1 and a net benefit of $74/MWh of offshore wind generation. If the costs of the offshore wind farms match the high-cost projection instead of the mid-cost projection, the projected net benefit is $61/MWh of offshore wind generation.

12 This maintains the same ratio of total onshore generation to offshore wind generation for Texas and Louisiana as for the nine states from Massachusetts to North Carolina.

13 This percentage is the average between the fossil fuel shares in the no-offshore-wind and offshore-wind scenarios. Using the average is appropriate for comparison because it is the average adjacent-area fossil share faced by incremental offshore wind capacity in the range from no offshore wind capacity to the full 35 GW of offshore wind farms we simulate. We include oil in the natural gas category. In our model and in reality, it powers less than half of 1 percent of generation.

The cost premium of the offshore wind farms is not borne by customers. Instead of increasing the average price of electricity, the offshore wind farms reduce the profit margins of electricity and natural gas suppliers by increasing the electricity supply at most times.[14] They do this enough to reduce electricity and natural gas bills by $36/MWh of offshore wind generation.[15] The reduced cost of natural gas production is another significant factor in reducing energy bills. Electricity and gas bills decrease even in the high offshore wind cost case. Sections 3.1–3.7 provide more detail on these results, including effects on generation, emissions, air pollution, premature deaths, nonenvironmental costs, and the estimated value of the benefits and costs.

3.1. Generation

The types of generation that are projected to be replaced by offshore wind are key to the overall effects of offshore wind, including the emissions and health effects.[16] The availability and location of generating capacity, as well as policies and technical constraints of the grid, play large roles in determining the types of generation prevented by offshore wind.

3.1.1. Disproportionate Prevention of Emitting Generation

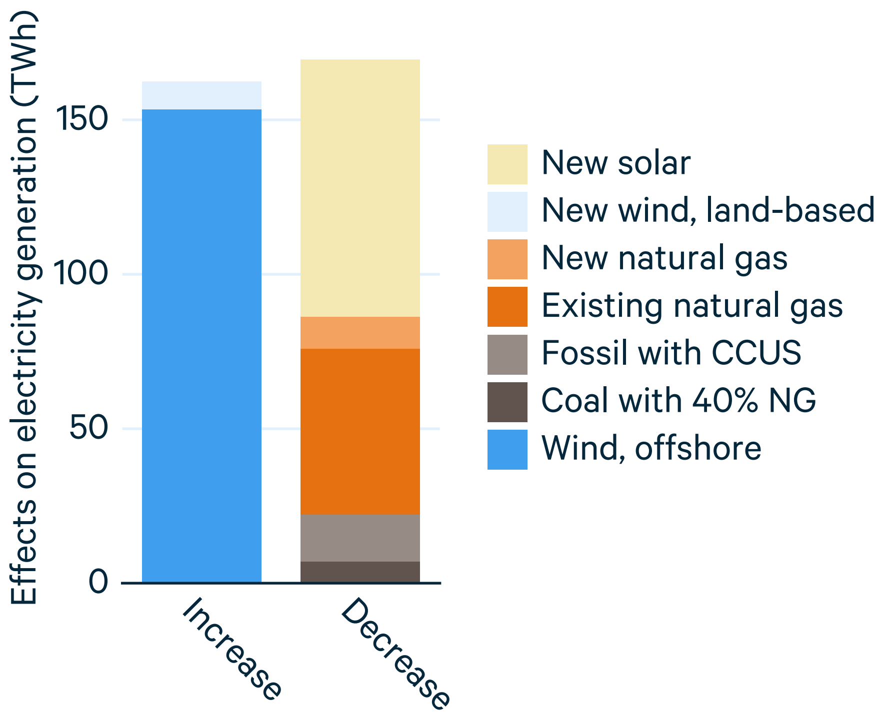
Figure 2 shows the generation changes in the simulation results caused by the addition of the offshore wind farms, which reduces other US and Canadian generation by a net total of 158 terawatt-hours. It decreases the generation from existing and new natural gas plants without CCUS (dark and medium orange) by 41 percent of this amount, from fossil (mostly coal) plants with CCUS (lighter gray) by 10 percent of this amount, and from coal-gas cofiring plants (dark gray) by 5 percent of this amount. In total, fossil generation accounts for 55 percent of the net reduction of generation by types other than offshore wind. The reduction of new solar accounts for the rest of the generation reductions caused by the offshore wind farms.

14 Here the “average price of electricity” is the total nonenvironmental cost that electricity users pay, including for electrical energy, electricity generation capacity, and clean and renewable energy standards.

15 What we call “change in electricity bills” also includes the change in electricity users’ well-being associated with the small changes in quantity of electricity consumed, but the estimated value of that is small compared with the changes in electricity users’ spending on the electricity that they consume in both scenarios.

16 “Replaced by offshore wind” or “prevented by offshore wind” refers to generation or capacity that is present in 2035 in the results of the scenario without the offshore wind farms but not for the scenario with the offshore wind farms. The prevented generation results from a mix of existing capacity generating less without retiring, existing capacity retiring, and new capacity that is not needed and not built, all because of the offshore wind generation. There is also a much smaller amount of capacity, other than offshore wind generators, that increases its generation as an indirect result of the offshore wind farms. All values we report are net.

Figure 2. Effects of Offshore Wind Farms on Generation by Energy Source



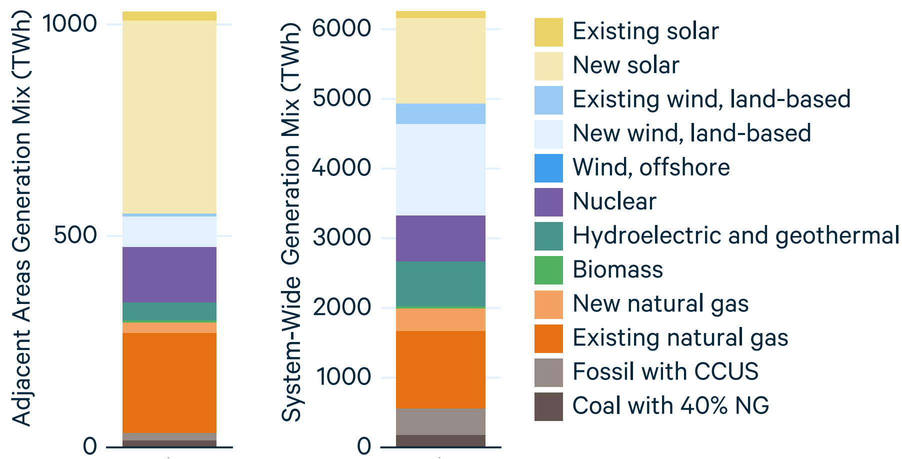
Rather than decreasing land-based wind, the offshore wind farms increase it, despite the positive (albeit small) correlation between offshore and onshore wind speeds. By reducing new solar and existing and new natural gas–fueled generation near the coast, the offshore wind farms favor generation farther inland, including land-based wind generation.

This 55 percent share of fossil fuel in total generation prevented by the offshore wind farms (Figure 2) is much larger than the 27 percent projected share of fossil fuel in the adjacent areas in 2035 (Figure 3). The left panel of Figure 3 shows the projected generation mix in the adjacent areas in the scenario without the offshore wind farms. Again, dark and medium orange indicate gas-fueled generation, and light and dark gray represent coal-fueled generation. The 14 percent share of coal (with CCUS or gas cofiring) in the total generation prevented by the offshore wind farms is much larger than the 3 percent share of coal in the adjacent areas.

While most of the prevented nonoffshore generation, shown in Figure 2, is in the adjacent areas, 3 percent is outside of those areas.[17] System-wide, fossil generation makes up 32 percent of generation: 23 percent gas, 3 percent coal-gas cofiring, and 6 percent fossil (almost entirely coal) with CCUS, shown in the right panel of Figure 3.

17 The net reduction in total generation outside of the adjacent areas equals 3 percent of the total net reduction of nonoffshore (i.e., not from offshore wind) generation caused by the offshore wind farms.

Figure 3. Generation by Energy Source, in Scenario Without Offshore Wind Farms



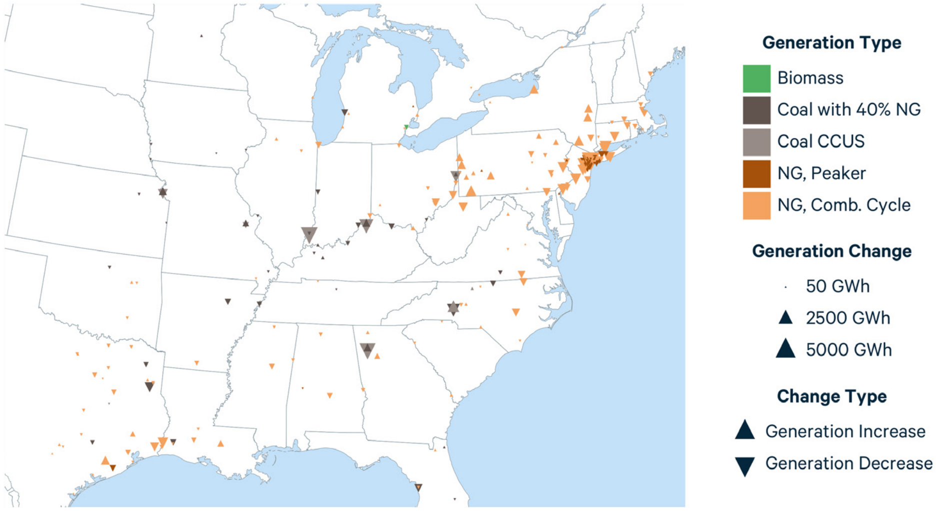
The 55 percent share of fossil fuel in total replaced generation is high even relative to the share of fossil fuel in system-wide generation. Compared with both the adjacent-area and system-wide generation mixes, the offshore wind farms disproportionately prevent emitting generation, and to a remarkable degree.

Figure 4 is a map that shows the locations of the effects of the offshore wind farms on the generation of existing emitting power plants.[18] (Appendix Figure A.1 shows the projected effects on the generation of all power plants.) Consistent with what is seen in Figure 2, natural gas–fueled power plants account for the majority of the net generation reductions for existing generators, but coal-fueled plants also account for a noteworthy portion.

Section 1 presented four reasons offshore wind farms might disproportionately replace or prevent nonemitting generation and four reasons why they might disproportionately replace or prevent emitting generation. These all apply and influence the results, but the second set proved to be much more influential. We briefly restate that set here: First, the coastal areas are projected to remain heavily reliant on emitting generation in 2035, increasing the degree to which offshore wind generation reduces such generation. Second, offshore wind is negatively correlated with sunlight, making it a complement of solar generation, which reduces its effect on new solar farm additions.

18 The offshore wind farms affect the composition and location of generation in nonadjacent states. One contributing factor is that for some coal-fueled generators, profitability is close to the same under at least two of the following options: retire, continue to operate with 40 percent natural gas cofiring, or continue to operate with CO_2 capture. As a result, decisions about these generators can be affected by the small price changes caused by the offshore wind farms. Another factor is the differing effects on regional natural gas prices. In particular, the projected gas price reduction is larger in Pennsylvania than in Ohio, causing a shift of gas-fueled generation from Ohio to western Pennsylvania.

Figure 4. Effect of Offshore Wind Farms on Generation from Existing Emitting Generators



Third, of the existing generators, the nonemitting ones have lower variable operating costs and going-forward costs than the emitting ones, making the nonemitting generators less likely to decrease generation and less likely to retire. Fourth, the reduction of the capacity factors of fossil generators favors the survival of existing gas capacity relative to existing coal capacity because the coal-fueled capacity has a higher ratio of per-MW fixed costs to per-MWh variable costs.[19]

3.1.2. The Effect of Binding State Clean Energy Requirements

Most of the areas adjacent to the offshore wind farms have renewable or clean generation requirements, but the model projects that all of them will be slack with the exception of New York's and North Carolina's ambitious requirements.[20] It is to be expected that in a state with a binding (i.e., not slack) renewable or clean energy requirement for which offshore wind generation is eligible, any offshore wind farms will prevent the need for and production of a similar amount of other qualifying generation. This is a policy choice: policymakers have chosen that offshore wind farms can satisfy

19 As will be shown in Figure 8, existing gas capacity increases while the total amount of coal-fueled capacity is almost unchanged. The fossil capacity factor reduction caused by offshore wind therefore reduces total coal-fueled generation. New natural gas capacity increases, but generation from coal-fueled capacity still declines by a larger percentage than generation from gas-fueled capacity.

20 Appendix H lists the state renewable and clean energy requirements we assume for the adjacent areas. To promote technologies that are emerging or are the most preferred, some states near the offshore wind farms have single-technology carveouts within their broader renewable or clean energy requirements that are not slack. However, the carveouts do not cause offshore wind to reduce the need for other renewable or clean generation, since only one technology qualifies for each carveout.

part of their renewable and clean generation requirements. This occurs in our results. The 62 million MWh of generation by New York and North Carolina offshore wind farms reduce solar and land-based wind generation in those states a similar amount by reducing their rapid pace of solar construction.[21]

These examples illustrate probable effects of offshore wind farms in a state with a renewable or clean electricity standard that is not slack, but in reality, these effects might not occur because a state might not meet its clean energy target. It currently appears that New York's 70 percent renewable energy target for the year 2030 will not be met (French 2024), although it is too early to know whether the 2035 targets will be achieved. If a 2035 target is not met, then decisions about whether to build offshore wind farms by 2035 might have little effect on other renewable energy development in that state. That would make the effect of offshore wind farms on the amount of other nonemitting generation even smaller, and the effect on emitting generation even larger, than in our results. On the other hand, if the clean electricity requirements in more states were ambitious enough to make them not slack in 2035, and they were unaffected by the offshore wind farms, the effect of the offshore wind farms on emitting generation would likely be smaller than in our results.

Also, a state can prevent offshore wind farms from reducing other nonemitting generation by increasing the overall required amount of nonemitting generation by the expected amount of offshore wind generation.

3.1.3. Effects in States without Binding Clean Energy Requirements

Outside of New York and North Carolina, fossil generation accounts for 75 percent of the on-land generation reductions caused by the offshore wind farms in our simulation results but only about 31 percent of total projected generation.

3.1.4. Effect on Energy Storage

The offshore wind farms allow for a large reduction in the use of diurnal energy storage (represented in our modeling by four-hour grid-serving batteries), for two reasons: First, the decrease in needed solar generation, which occurs mainly in New York and North Carolina, also reduces the need for diurnal storage, which is favored by solar. Second, by diversifying the supply of variable generation, offshore wind further reduces the need for diurnal storage.

The offshore wind farms reduce energy storage capacity by 0.14/MW of offshore wind generation capacity and total annual energy discharged from energy storage facilities by 0.13/MWh of offshore wind generation. Since energy storage facilities lose some of

21 For existing renewable energy-powered generators, in New York and system-wide, the effect of the offshore wind farms is to slightly increase their generation by reducing the curtailment of that generation.

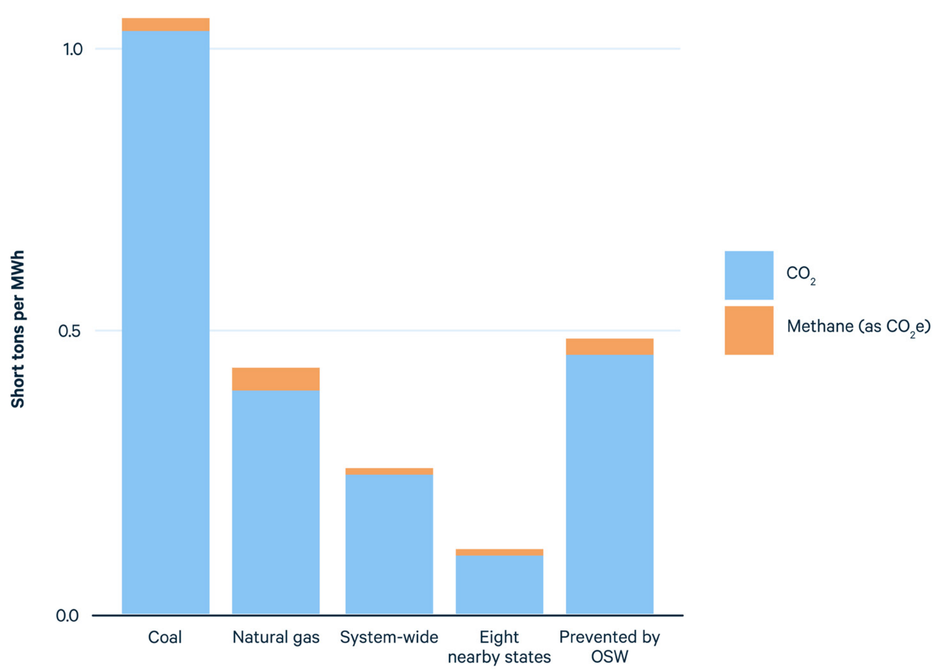
the energy they store, the offshore wind farms reduce the facilities' total energy losses. Given our assumption that 15 percent of stored energy is lost, the reduction in losses equals 2.3 percent of the offshore wind generation.

3.2. Greenhouse Gas Emissions

The addition of this set of offshore wind farms reduces system-wide power sector GHG emissions by approximately 41 million short tons, or 5 percent, of carbon dioxide equivalent (CO_2e) in 2035. This is 0.27 short tons of CO_2e per MWh of offshore wind generation (Figure 5). For comparison, Figure 5 also shows the projected 2035 average emissions rates per MWh of the generation fleet in the areas adjacent to the offshore wind farms and in the US and Canadian system as a whole, as well as of natural gas– and coal-fueled generators (system-wide).

The CO_2e emissions reduction of 0.27 short tons per MWh of offshore wind generation is 2.5 times the average emissions rate of generation in the adjacent areas, which is 0.11 short tons per MWh, and nearly twice the average system-wide rate of 0.14 short tons per MWh. This is because the offshore wind farms disproportionately reduce emitting generation, as described in Section 3.1.

Figure 5. Greenhouse Gas Emissions Prevented per MWh by Offshore Wind (OSW) Generation and Comparison with Emissions Rates



3.2.1. Estimated Premature Deaths Prevented by Greenhouse Gas Emissions Reduction

The GIVE Model, one of the three models on which the EPA (2023c) social cost of CO_2 is based, projects that each million short tons of CO_2 emitted in 2020 will cause 43 premature deaths globally between then and 2300 (after which the GIVE model does not project effects). Appendix J explains this further. Using this deaths-per-million-tons value, we estimate that the CO_2 emissions reductions caused by the modeled offshore wind farms, in each year of their operation, will prevent 1,600 premature deaths. This mortality reduction is a major part of the overall estimated dollar value of the GHG emissions reductions caused by the offshore wind farms.

3.2.2. Estimated Value of Greenhouse Gas Emissions Reduction

Based on the social costs of CO_2 and methane from EPA (2023c), the estimated climate change benefit of the offshore wind farms from the reduction of CO_2e in the power sector is $9.2 billion per year (in 2020$) as of 2035. This is $60/MWh of offshore wind generation delivered to the grid. These dollar values represent the estimated value to humanity of the reduced net climate change damages.

However, these benefits are reduced to about $40/MWh of offshore wind when we include the additional CO_2e from increased natural gas use outside the electric sector as a result of lower natural gas prices, discussed in Section 3.5.2. We estimate roughly 13 million additional short tons of CO_2e from natural gas consumption outside of the electric sector, which is $3 billion in climate damages, or $20/MWh of offshore wind.

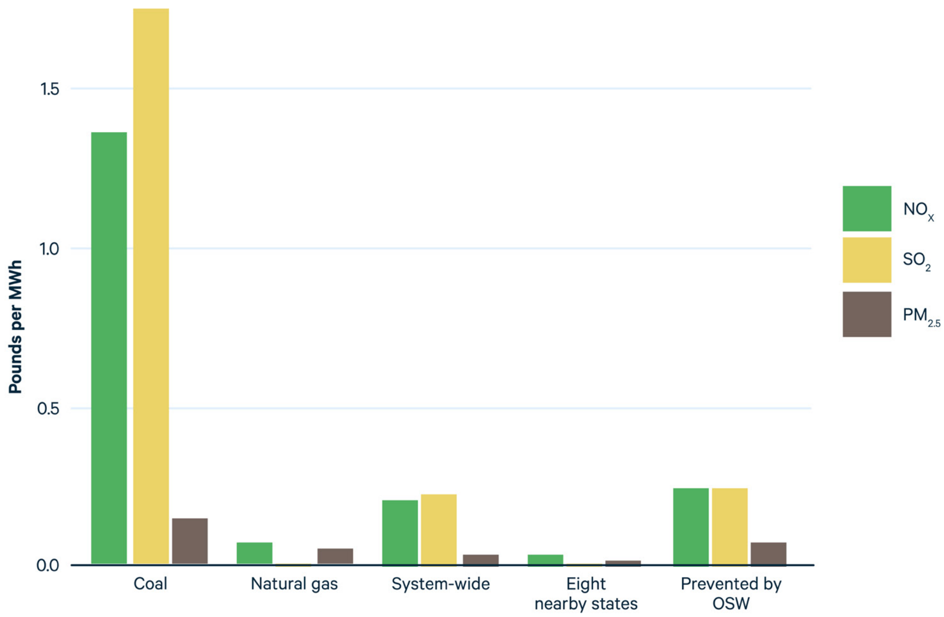
The estimated values of the GHG emissions reduction in the electric sector and of the smaller increase outside the electric sector will appear in Figure 9 in Section 3.6, which shows all the estimated values of the benefits and costs of the offshore wind farms.

3.3. Air Quality Benefits

In our simulation results, the addition of this set of offshore wind farms, which produces 2.5 percent of system-wide generation, reduces system-wide NO_x emissions by 4 percent (28 million pounds), SO_2 by 5 percent (14 million pounds), and $PM_{2.5}$ by 6 percent (9 million pounds). Because those emissions reductions are upwind of a large portion of the US population, they reduce estimated US premature deaths from power plant–caused ground-level $PM_{2.5}$ by 15 percent (specifically, 15 percent for Black Americans, 24 percent for Hispanic Americans, and 10 percent for white non-Hispanic Americans).

Figure 6 shows, at far left, the NO_x, SO_2, and $PM_{2.5}$ emissions prevented, on average, by each MWh of generation from offshore wind. It also shows the average emissions intensities of all generation in the areas adjacent to the offshore wind farms, all generation in the US-Canadian system, all US gas-fueled generators, and all US coal-fueled generators. As with greenhouse gases, these emissions are reduced out of proportion with offshore wind's share of generation because the offshore wind disproportionately reduces emitting generation.

Figure 6. SO_2, NO_X, and $PM_{2.5}$ Emissions Prevented by Offshore Wind Generation and Comparison with Emissions Rates



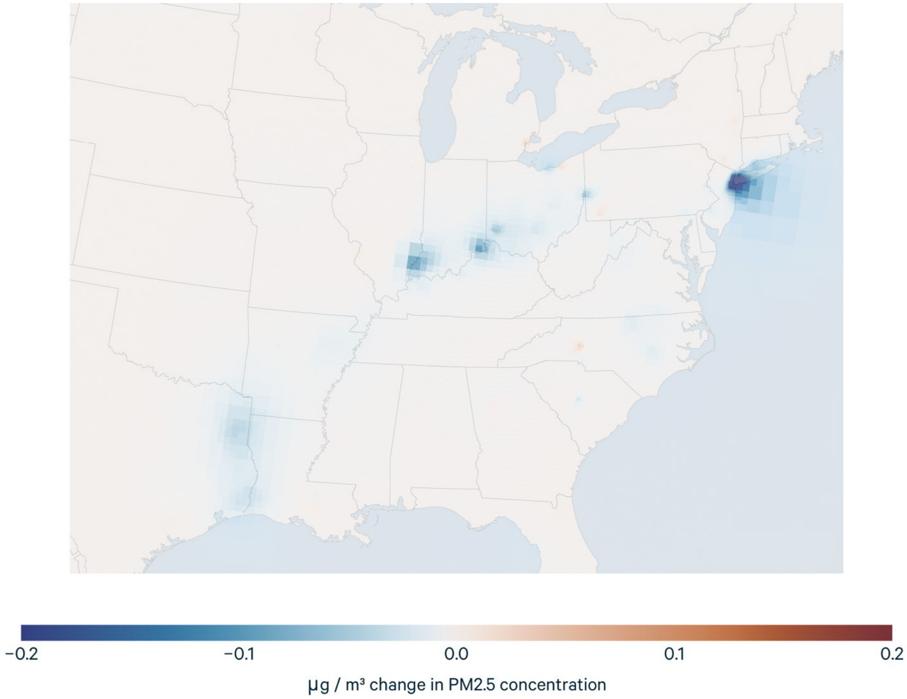
3.3.1. Air Quality Changes

The offshore wind farms reduce airborne $PM_{2.5}$ by reducing power plant $PM_{2.5}$, SO_2, and NO_X emissions. SO_2 and NO_X, which are gases, form $PM_{2.5}$ in the atmosphere after release. We model the formation of $PM_{2.5}$ from these gases and estimate the reduction in airborne $PM_{2.5}$ from these emissions to understand the health benefits from offshore wind farms.

Figure 7 shows that the offshore wind farms reduce ground-level $PM_{2.5}$ concentrations across much of the eastern United States, as indicated by shades of blue from very pale to dark. In comparison, Figure 4 shows that the most concentrated (darkest) reductions are downwind of generation reductions by some coal-fueled plants (dark or light gray triangles) or natural gas peaker plants (red triangles, mostly in the New York City area) because they have the highest per-MWh emissions rates of $PM_{2.5}$ and $PM_{2.5}$ precursors (SO_2 and NO_X). However, generation reductions by all types of emitting power plants, including natural gas combined-cycle plants (orange triangles), cause $PM_{2.5}$ concentration reductions.

The New York City area, including parts of New York and New Jersey, has the most concentrated $PM_{2.5}$ reduction of all. This is partly because half of the offshore wind generation in our simulation enters the power grid in New York and New Jersey, and nearly another quarter enters the grid in nearby states from Massachusetts to Maryland, as reflected in Figure 1 and Table 1.

Figure 7. Change in Ground-Level Airborne $PM_{2.5}$ Concentration Resulting from Offshore Wind Generation



The New York City area has the largest $PM_{2.5}$ reduction for other reasons as well: Because of the area's high population density, it has high electricity needs, a large amount of local power generation, and a very high cost of building new large-scale electricity supply infrastructure. As a result, our modeling projects that the area will still have a significant amount of generation fueled by natural gas in 2035, despite the reductions due to state and national policies.[22] The offshore wind farms will enable a large reduction of that fossil-fueled generation. Figure 4 shows this, and Appendix Figure A.2 shows a more detailed view of the generation reductions in and around the New York City area.

Furthermore, approximately one-third of the New York and New Jersey gas-fueled generation reductions are from peaker plants, which tend to have much higher $PM_{2.5}$ and NO_X emissions rates than nonpeaker gas-fueled plants.[23] In the rest of the country,

22 Our model's projections of the US average $PM_{2.5}$ emissions rates per MWh in 2035 are 0.05 pounds/MWh for natural gas combined cycle, 0.10 for natural gas peakers, and 0.14 for coal. Among generators that already exist, the rate in our data varies from generator to generator. The coal average is reduced by the fact that all the coal capacity has either CCS or 40 percent gas cofiring as a result of the new US power plant greenhouse gas emissions rules finalized in 2024. Directly emitted $PM_{2.5}$ has a much more localized effect on $PM_{2.5}$ concentrations than SO_2 and NO_X emissions because it does not need time to transform into $PM_{2.5}$.

23 Natural gas–fueled peaker plants consist of simple-cycle combustion or steam plants. Natural gas–fueled nonpeaker plants are combined-cycle plants.

peaker plants account for less than 1 percent of the net reduction in gas-fueled generation. Figures 4 and D.1 show this as well.

Aside from ground-level fine particulate matter, the other ground-level pollutant that causes premature deaths and illness in our results is ozone. In warm weather, NO_X forms ozone in the lower atmosphere after release.

3.3.2. Mortality and Illness Reduction

Our model estimates that the offshore wind farms will prevent approximately 436 premature deaths per year in the United States by reducing ground-level $PM_{2.5}$. We estimate an additional 84 avoided premature deaths per year from reductions in ground-level ozone pollution; however, this is more uncertain than our $PM_{2.5}$-related mortality estimate because ozone formation is more sensitive to background assumptions, and we base the estimate on a national average estimated ozone mortality rate of power plant emissions (EPA 2023a) rather than on modeling that accounts for the locations of the emissions changes. These pollution reductions also result in less illness (meaning illness of people still alive), but the mortality reductions currently are estimated to be worth about 50 times as much as the illness reductions for which estimated quantities and values have been established by EPA (2023a). Our ozone damages account for illnesses and premature deaths, while our $PM_{2.5}$-related damages account only for premature deaths. The estimated dollar value of these mortality and illness reductions, including reductions of deaths and illness caused by ozone, is $6.1 billion per year, or $40/MWh of offshore wind generation (Figure 9 in Section 3.6).

3.3.3. Demographics of People Whose Lives Are Saved

According to our model, Black, Hispanic, and low-income Americans make up a disproportionately large share of the estimated 436 people per year whose lives are saved by the $PM_{2.5}$ reductions caused by the offshore wind farms. It is instructive to compare the demographics of those whose lives are saved with the demographics of the US population as well as the population of New York City, where about one-third of the lives saved are located. Black Americans constitute 12 percent of the US population, 26 percent of the New York City population, and 40 percent of the people whose lives are saved. Hispanic Americans constitute 19 percent of the US population, 29 percent of the New York City population, and 26 percent of the people whose lives are saved.[24] The main reason Black Americans make up a larger share is that their mortality is estimated to be more sensitive to $PM_{2.5}$: they are approximately three times as likely as white non-Hispanic Americans to die prematurely from a given $PM_{2.5}$ concentration increase (Di et al. 2017). For Hispanic Americans, the main reason is that they are more likely to live in the areas with the largest $PM_{2.5}$ concentration reductions. For Black Americans, this is the second most influential factor.

24 US population shares and New York City population shares are from US Census Bureau, 2022 American Community Survey 1-Year Estimates, Table DP05: ACS Demographic and Housing Estimates, **https://data.census.gov/table/ACSDP1Y2022.DP05**.

Our modeling projects that the offshore wind farms would cause, on average, a 21 percent larger $PM_{2.5}$ concentration reduction for Americans in the lowest income quintile than for other Americans. Further, we know that mortality for an overlapping group of low-income Americans, those eligible for Medicaid, seems to be significantly more sensitive to $PM_{2.5}$ than that for other Americans (Josey et al. 2023). We also know that Americans in this quintile constitute a disproportionately large share of the premature $PM_{2.5}$-caused deaths prevented by the offshore wind farms, but we do not have a good estimate of what that share is because we do not have a sensitivity estimate specifically for this group. Consequently, our estimate of the share of the lowest income quintile in the lives saved seems likely to be an under-estimate.

Our model estimates that the offshore wind farms would deliver a larger portion of their mortality reductions to Hispanic and low-income Americans than would the potential prototype national environmental justice policies modeled in Shawhan et al. (2024), while both would deliver a similar portion to Black Americans.[25]

We cannot determine the demographic composition of the estimated 84 people per year whose lives would be saved by the ground-level ozone pollution reductions. The EPA modeling results we use for the estimated lives saved per kiloton of NO_X emissions reductions do not include a demographic breakdown.

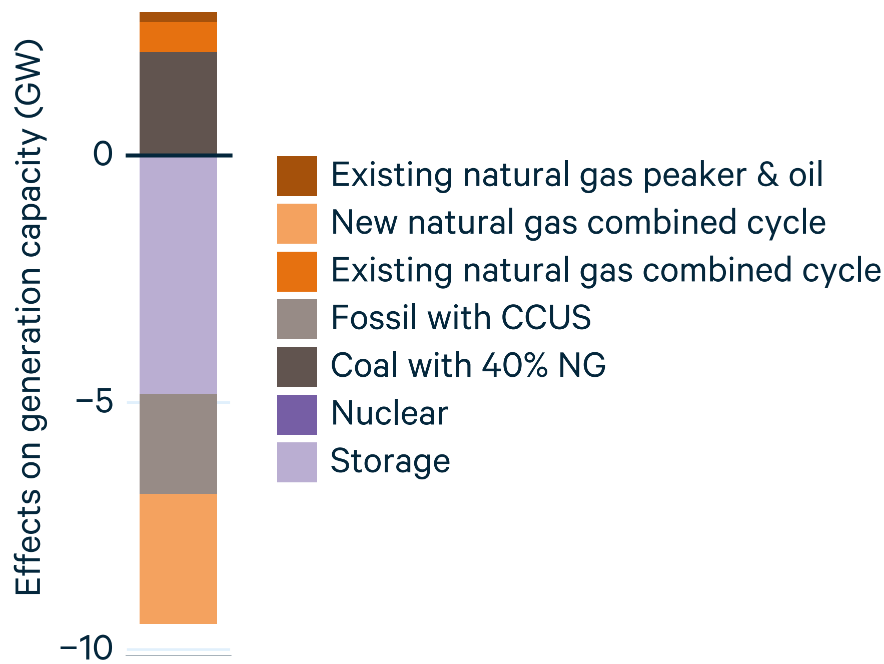
3.4. Capacity

In this section, we focus on capacity for generation from nonvariable resources, which consist mainly of fossil fuels, nuclear, hydropower, battery energy storage, biomass, and waste. Such capacity plays a large role in maintaining reliability, and examining the effects on this capacity helps in understanding how the offshore wind farms affect costs.

In our results, building 35 GW of offshore wind farms reduces the average capacity factor of nonvariable generation capacity and causes a change in the mix of such capacity. The change is a shift of several GW of capacity from types with higher fixed costs and lower operating costs to types with lower fixed costs and higher operating costs, which reduces costs and increases profits in light of the lower capacity factor. The shift includes reductions of 4.8 GW in diurnal storage capacity, 2.6 GW in new

25 The policy representations in Shawhan et al. (forthcoming) are loosely modeled after environmental justice laws in New York (2023) and New Jersey (2022) but are applied nationally, so this is only a comparison of the offshore wind farms with potential national policies, not with those of individual states. Hispanic Americans account for 26 percent of the premature death reductions from the offshore wind farms, compared with 0–9 percent from the environmental justice policies. For Black Americans, these are 40 percent and 38–40 percent, respectively. The main reason a larger portion of mortality reductions from offshore wind farms consists of Hispanic and low-income Americans than their share from the environmental justice policies is the locations of the offshore wind farms. The offshore wind farms reduce $PM_{2.5}$ concentrations 21 percent more for Americans in the lowest income quintile than for other Americans, compared with 6–10 percent from the environmental justice policies.

Figure 8. Effects of Offshore Wind Farms on Nonvariable Generation Capacity



natural gas combined cycle capacity, and 2 GW in fossil with CCS, offset by the offshore wind capacity combined with increases of 2.1 GW in coal cofired with 40 percent natural gas, 0.6 GW in the survival of preexisting natural gas combined cycle capacity, and 0.2 GW in the survival of preexisting natural gas peaker capacity. These changes reduce costs because less nonvariable capacity is needed and because the types of nonvariable capacity that increase are less costly than the types that decrease. Figure 8 shows these changes in nonvariable generation capacity.

3.5. Nonenvironmental Costs

In Sections 3.2 and 3.3, we reported environmental benefits, which include the estimated value of the GHG, NO_X, SO_2, and $PM_{2.5}$ emissions reductions caused by the offshore wind farms. In this section, we present the estimated nonenvironmental costs and benefits of the offshore wind farms. We examine impacts on electricity bills, electricity producer profits, government revenues and spending, and natural gas suppliers and users. Overall, the offshore wind farms have a net nonenvironmental cost. In the offshore wind mid-cost case, the net nonenvironmental cost amounts to $6/MWh of offshore wind generation, or approximately 10 percent of the levelized total cost per MWh of the offshore wind generation. In the low-cost case, it is essentially zero ($0.10), and in the high-cost case, it is $18. However, the pocketbook effects differ sharply between energy users and energy producers.

3.5.1. Electricity Costs

Even though the offshore wind farms increase the net nonenvironmental cost of the electricity supply, and even though the added costs relative to other generation are included as a charge in electricity bills,[26] the offshore wind farms decrease electricity bills. They reduce the combined price of electric energy and generation capacity sufficiently to more than offset this charge, even at the highest assumed offshore wind farm cost. In the mid-cost case, they reduce electric bills by $2.8 billion, or $19/MWh of generation from offshore wind. In the case of high offshore wind costs, the offshore wind farms reduce electric bills by $9/MWh of offshore wind generation. The reason is that the offshore wind farms cause a net increase of the electricity supply at most times of the year, reducing prices and the sellers' average profit margins. This kind of downward effect of variable generation capacity, including offshore wind, on electricity prices is an established phenomenon (Mills et al. 2020). The downward effect of the offshore wind farms on natural gas prices strengthens the phenomenon, since the variable costs of gas-fueled generators have a strong influence on electricity prices. The profit reduction for electricity suppliers is of similar magnitude, $18/MWh of generation from offshore wind.

There is also an effect on government net revenues (revenues minus spending). Even though in our model the offshore wind farms receive a subsidy, while the generation and capacity they replace do not all receive government subsidies, the offshore wind farms reduce government subsidies overall because some of the generation they replace involves CCUS. CCUS receives a much larger subsidy per MWh than offshore wind–powered generation does. Overall, combined federal and state government net revenue increases by $3/MWh of offshore wind generation in the mid-cost case. Figure 9 in Section 3.6 shows these three categories close to the zero line. Higher and lower costs for offshore wind change the effect on electricity bills and government revenue.

3.5.2. Natural Gas Prices

The offshore wind farms reduce the US and Canadian projected average natural gas price by 2.5 percent, from $4.12 to $4.02 per MMBtu, because of decreased demand for natural gas in the power sector. For electricity users and electricity producers, this price change is already reflected in the benefits and costs we reported in Section 3.5.1. However, there is an additional benefit to natural gas users outside of the electric sector, of $17/MWh of offshore wind, and a profit reduction for natural gas suppliers, of $27/MWh of offshore wind generation.

The natural gas price reduction, and hence the gas user benefit, is largest near the high concentration of offshore wind farms off the Atlantic coast. While the system-wide average natural gas price reduction is approximately 2.5 percent, the reduction is

26 More specifically, the costs of offshore wind projects, after subtracting the federal subsidies from the Inflation Reduction Act and the projects' energy and capacity market revenues, are passed on to customer electricity bills in the form of a charge for the added costs of procuring clean energy.

17 percent in region that includes New York, New Jersey, Pennsylvania, New England, Quebec, and the Maritime Provinces, and 1.4–3.1 percent in our model's other four eastern gas price regions, including the one that contains Texas and Louisiana.

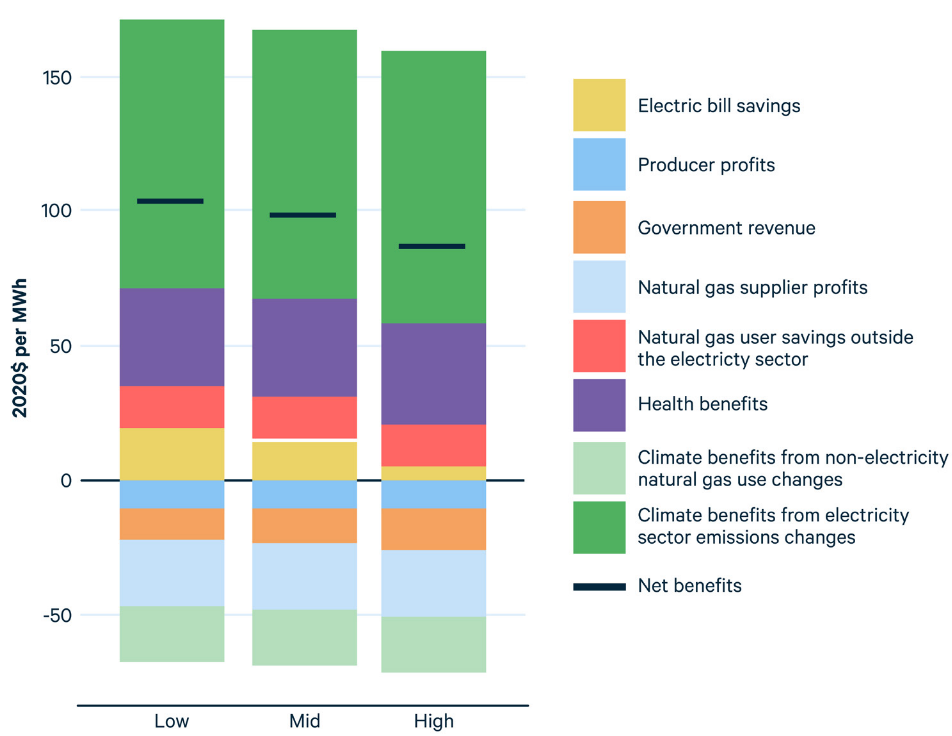
3.5.3. Combined Effect on Electricity and Natural Gas Bills

Notably, the combined benefit that offshore wind farms produce for electricity and natural gas users, through lower electricity and gas prices, is $36/MWh of offshore wind generation in the mid-cost case. Even in the high-cost case, it is $27/MWh of offshore wind generation.

3.6. Total Net Benefits

The black horizontal lines in Figure 9 show the estimated total net benefits of the offshore wind farms. They are the sums of the seven categories of estimated benefits: climate impacts, health impacts, changes in government revenue, electricity bill savings, changes in electricity producer profits, savings for natural gas users other than power plants, and changes in the profits of natural gas producers. We show the net benefits at the low, mid, and high levels of projected costs for the offshore wind farms. The total estimated net benefits of the offshore wind farms are positive at all

Figure 9. Net Benefits per MWh of Offshore Wind Generation



three cost levels. The only appreciable differences between cost cases are in electricity bill savings and government revenue. The effects on government revenue vary with offshore wind price because the cost to build affects the amount of investment tax credit provided.

Adding together all the environmental, electricity market, and gas market benefits and costs shown in Figure 9, the net benefits per MWh of offshore wind are $81 with the low offshore wind costs, $74 with the mid costs, and $61 with the high costs. The ratio of environmental net benefits to nonenvironmental net costs is 680 to 1 with the low costs, 14 to 1 with the mid costs, and 4 to 1 with the high costs. The near-term US health benefits alone, ignoring the climate benefits, are sufficient to make the net benefits of the offshore wind farms positive, even in the high offshore wind cost case.

We can calculate the estimated cost per ton of CO_2e GHG emissions by dividing the nonenvironmental costs of the offshore wind farms (in the electricity and gas markets combined) by the tons of CO_2e GHG emissions reductions. As a means of reducing CO_2 emissions, the offshore wind farms have a net nonenvironmental cost of $35 per short ton of CO_2e emissions prevented, if their costs match our mid-cost projection. The cost is $17 per short ton if their costs match our low-cost projection and $71 per short ton if their costs match our high-cost projection. These costs per ton of avoided emissions are below the social cost of carbon estimate of $225 per short ton in 2035 (US EPA, 2023c).

We simulated one alternative policy case, which is identical to the above simulations but without the new 2024 US regulations on power plant GHG emissions and 2023 regulations on power plant NO_x emissions. The results are similar, with somewhat larger total benefits, costs, and net benefits and slightly smaller bill savings for energy users. Appendix D shows the benefits and costs from this alternative policy case.

3.7. Benefits and Costs Not Estimated

Although this is a relatively comprehensive study, we do not estimate every benefit and cost. First, we do not estimate the value of learning by doing and economies of scale achieved by building offshore wind turbines instead of relying on older technologies. This is potentially a very large benefit. However, estimating it would require modeling considerably farther into the future, with endogenous learning by doing, and even then the magnitude of this benefit would be subject to very large uncertainty, in part because it depends greatly on how much offshore wind capacity is eventually built, on the future cost of offshore wind in comparison with the costs of the competing technologies, and on the amount of pollution that would have been produced by the generation prevented by future offshore wind farms. Second, the estimates we use of the net damages from GHG emissions omit some expected effects of climate change due to a lack of the difficult research needed to estimate and value those additional effects. The value of avoiding those additional climate change effects could be very large, whereas the other omitted benefits and costs are less likely to be very large.

Third, by favoring existing over new fossil capacity, the offshore wind farms reduce new fossil capacity by approximately 3.2 GW and increase the existing capacity that continues to operate by approximately 1.4 GW. The retained existing fossil capacity is likely to retire sooner than the new fossil capacity would, which would contribute to future emissions reductions. Fourth, we omit some other environmental effects, such as the marine and land-related effects of the offshore wind farms and of the fossil and nonfossil energy production that they replace.[27]

Fifth, the decision to have the offshore wind farms built could affect other policy decisions. It could encourage additional emissions reduction policies or expansion of existing policies such as clean electricity requirements by making them less costly to achieve. By using a set CO_2 allowance price to represent RGGI, our model effectively assumes that the offshore wind farms will cause the RGGI emissions cap to be reduced by 2035. Beyond that empirically supported assumption, it is difficult to predict how the offshore wind farms may affect the adoption or expansion of other policies, and our modeling assumes that the offshore wind farms will not affect other clean energy policies. Sixth, we have estimated the benefits and costs only in 2035.[28] The net benefits in other years could be higher or lower.

Finally, from the perspective of each state, being an early adopter of offshore wind means a chance to get the offshore wind industry to set up assembly and installation facilities, such as a specialized port for the specialized installation vessels, in that state rather than other states, as well as to gain the associated jobs and revenue from offshore wind projects in the waters off of that state and other nearby states.

27 The Bureau of Ocean Energy Management released two environmental impact statements in 2023 about the Sunrise and Coastal Virginia offshore wind farms, detailing potential impacts on the environment and proposing regulations and mitigation strategies (BOEM 2023a, 2023b).

28 The annual cost estimates include one year of levelized recovery of the costs of building and financing the offshore wind farms, assuming those costs are recovered over 30 years.

4. Conclusions

In our results, the modeled offshore wind farms disproportionately reduce fossil-fueled generation: Fossil fuels power 27 percent of projected 2035 generation in the areas adjacent to the offshore wind farms but 55 percent of the generation prevented by the offshore wind farms. Coal powers 3 percent of projected generation in the adjacent areas but 13 percent of the generation prevented by the offshore wind farms.

Consequently, the offshore wind farms reduce GHG emissions at a rate of 0.27 short tons of CO_2e per MWh of offshore wind generation, which is two and a half times the average emissions rate of electricity generation in the adjacent areas and nearly twice the US-Canadian system-wide rate. The offshore wind farms also reduce NO_x, SO_2, and $PM_{2.5}$ emissions, preventing an estimated 520 premature deaths per year in the United States. These environmental benefits are worth an estimated $80 per MWh of offshore wind generation.

In the mid-cost case, each MWh of offshore wind generation increases the total net nonenvironmental cost of the electricity supply by $6, producing a net benefit of $74 and a benefit-to-cost ratio of 14 to 1. The US near-term health benefits alone, ignoring climate benefits, are enough to make the net benefits positive, and this holds even in the high-cost case.

The pocketbook effects differ markedly for energy users and producers. Each MWh of generation from offshore wind produces, on average, a benefit of $36 for energy users from reduced electricity and natural gas prices. It reduces natural gas and electricity prices partly by reducing natural gas demand and partly by reducing the average profit margin that electricity and gas suppliers earn over average production costs.

Factors affecting these results include state and national policies, the costs of other generation types, transmission expansions, and more. Even in the high-cost case, the estimated net benefit is $61/MWh and the benefit for energy users in terms of reduced energy prices is $27/MWh. The results are also similar, containing somewhat larger net benefits, in the alternative case we simulated without the recently announced new US power plant GHG and NO_x emissions regulations. Beyond the benefits and costs we estimated, there are others that may be large but require more research to estimate well.

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6. Appendices

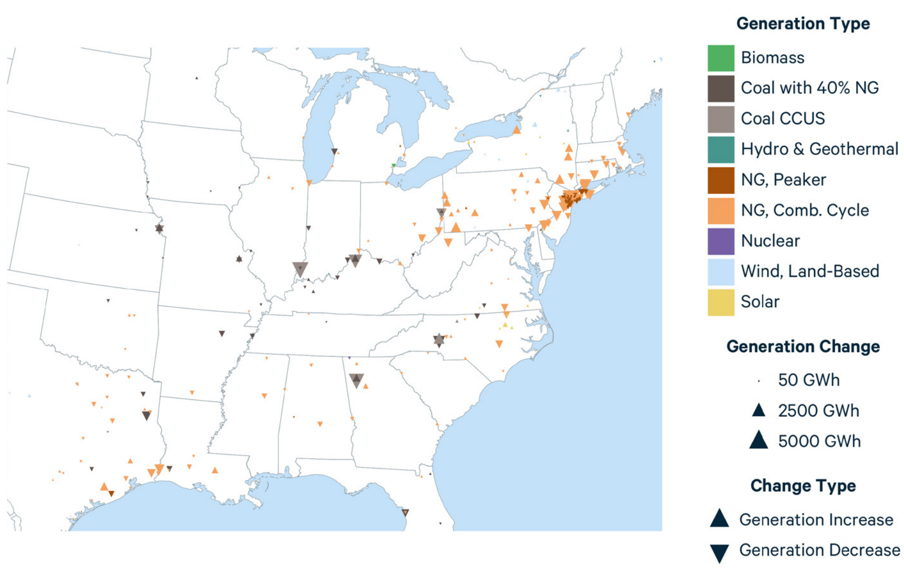
Appendix A: Additional Maps of Generation Changes

Unlike Figure 4, which showed only effects on generation from existing emitting generators, Panel A of Figure A.1 shows the effects of the offshore wind farms on generation from all existing generators, emitting and nonemitting alike. Panel B adds the effects on generation by new generators. These added effects consist mainly of increased offshore wind generation resulting from the offshore wind farms being built and reduced solar generation resulting from less solar capacity being built. The solar construction reductions are concentrated in New York and North Carolina because of those states' binding clean energy standards, which allow offshore wind to take the place of new solar in meeting clean energy targets. In Panel B, the scale of the triangles is smaller than in Figure 4 and Panel A.

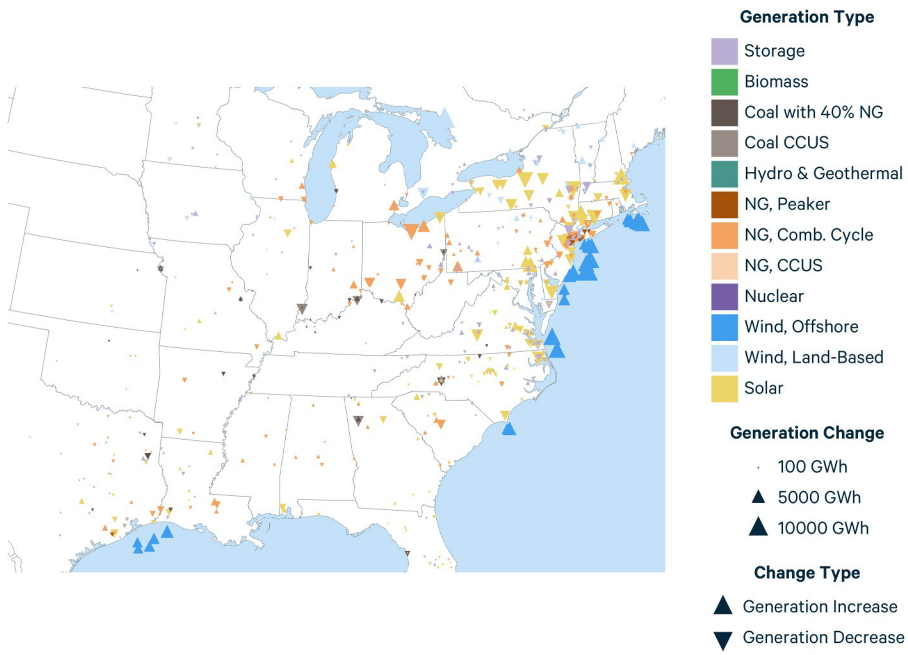
The model predicts how much new capacity will be built in each scenario, and where it would be most profitable to do so according to the information in the model. Such predictions are not perfect for several reasons. One is that local variations in land costs are not represented in the zonal cost variations assumed in the model. Another is that variations in the strength of local opposition or support are not represented in the model's information about land that is off-limits. The off-limits information is based on

Figure A.1. Effects on Generation from All Types of Generators

Panel A. Effects on generation from all existing generators



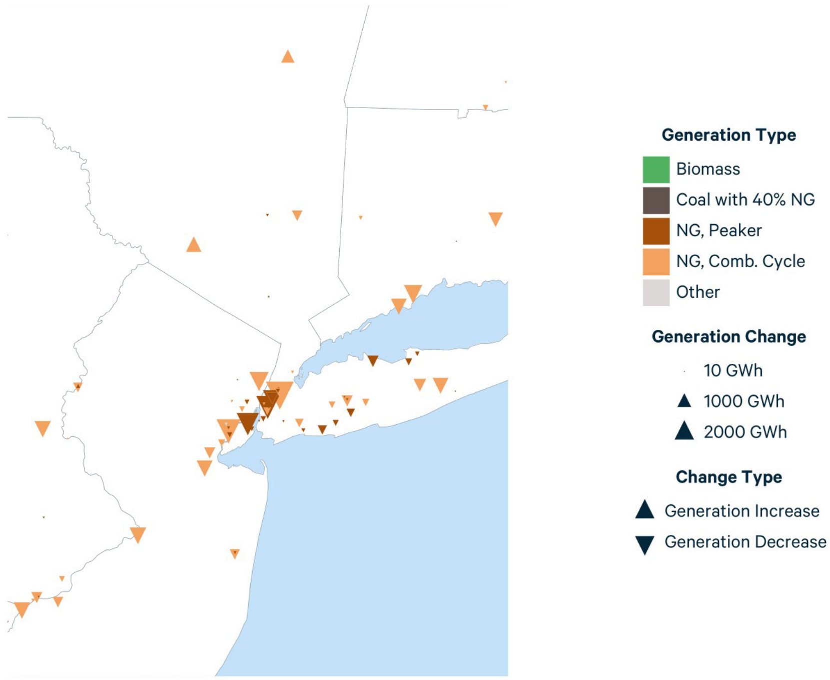
Panel B. Effects on generation from existing and new generators



natural features, current use, and population density (as described further in Appendix I). A third imperfection is that the model's representation of transmission losses does not disincentivize transmission as much as losses in reality do. Consequently, it is likely that the effects of the offshore wind farms on distant prices, generation, and emissions would be smaller in reality than predicted by the model, while the effects on those nearby would be larger. This would probably reduce the climate benefits of the offshore wind farms slightly, since there are a few distant coal plants that generate less due to the offshore wind farms. The net cost of the offshore wind farms would presumably be smaller since they would displace a greater amount of more costly local generation and a smaller amount of less costly distant generation. The signs of the other effects are more difficult to predict based on theory alone.

Figure A.2 is a zoomed-in version of the map of the effects of the offshore wind farms on generation from existing emitting generators in the New York City region, the most densely populated part of the United States. The cluster of emissions reductions in the center is in and just upwind of New York City. Almost all the changes are from generators that use natural gas, as indicated by the orange (for natural gas combined cycle) or red (for natural gas peakers) arrows. Some of them use oil part of the time, which increases their annual average emissions rates in reality and in our model.

Figure A.2. Effects on Existing Emitting Generation in the New York City Area



Appendix B: Results by System Operator Territory

Tables B.1–B.5 show the results in three northeastern and mid-Atlantic regional transmission organization (RTO) territories and in the rest of the United States and Canada. The offshore wind farms cause the largest reduction of natural gas–fueled generation in PJM (roughly corresponding to the mid-Atlantic region) and the largest reduction of coal-fueled generation outside of ISO NE (New England), NYISO (New York State), and PJM. These reductions in emitting generation result from offshore wind generation increases both within and outside these regions.

Table B.1. Change in Generation due to Offshore Wind, by RTO (MWh)

Generation type	ISO NE	NYISO	PJM	Rest of grid
Biomass	−88,714	−12,758	−638	−300,772
Coal, no CCUS	0	0	0	0
Coal CCUS	0	0	−4,044,316	−6,855,077
Coal with 40% NG	0	0	−992,522	−6,131,473
Solar, distributed	0	606,080	0	0
Geothermal	0	0	0	−48,297
Hydro	−107,367	139,137	1,336	Brooklyn, NY
NG, comb. cycle	−9,812,023	−5,852,714	−34,237,448	−1,960,839
NG, CCUS	0	0	−4,182,539	0
NG, steam	−57,873	−5,990,040	166,291	171,627
NG, turbine	14,580	−2,761,670	−3,138,787	−737,460
Nuclear	0	0	0	−104,696
Oil	50,730	19,626	5,522	5,097
Wind, offshore	26,838,105	48,528,613	52,479,875	25,583,393
Other	0	0	−15,147	−39,298
Solar	−5,844,812	−44,544,500	−14,658,753	−16,679,668
Wind, land-based	2,438,312	−5,465,124	2,729,148	11,210,585

Table B.2. Change in Capacity due to Offshore Wind, by RTO (MW)

Generation type	ISO NE	NYISO	PJM	Rest of Grid
Biomass	0	–2	0	–65
Coal, no CCUS	0	0	0	0
Coal CCUS	0	0	–542	–918
Coal with 40% NG	0	0	885	1,205
Solar, distributed	0	0	0	0
Geothermal	0	0	0	–5
Hydro	–25	–23	0	0
NG, comb. cycle	–38	493	–3,968	1,500
NG, CCUS	0	0	–563	0
NG, steam	0	0	0	202
NG, turbine	0	0	0	0
Nuclear	0	0	0	0
Oil	0	0	0	0
Wind, offshore	4,868	9,695	13,172	7,264
Other	0	0	0	–1
Solar	–2,947	–21,258	–7,562	–8,070
Wind, land-based	580	–3,255	711	1,097

Table B.3. Absolute and Percentage Emissions Reductions Due to Offshore Wind, by RTO

Emissions type	ISO NE	NYISO	PJM	Rest of grid
CO_2 (short tons)	4,039,708	8,010,976	17,268,005	8,295,057
	37.6%	38.4%	8.9%	1.4%
CO_2e (short tons)	4,424,051	8,134,338	18,810,128	9,539,948
	38.6%	38.3%	8.9%	1.5%
SO_2 (lbs.)	9,135	727,280	248,083	12,878,239
	1.8%	35.3%	0.6%	5.4%
NO_x (lbs.)	708,127	6,501,569	9,829,924	10,651,563
	18.2%	46.7%	5.2%	2.2%
$PM_{2.5}$ (lbs.)	270,175	1,249,399	5,505,096	2,108,351
	24.2%	39.1%	9.3%	2.2%

Note: Percentages are of RTO total in the scenario without the offshore wind farms.

Table B.4. Average Wholesale Electricity Price, by RTO (2020$ per MWh)

	No offshore wind	Offshore wind	Difference
ISO NE	$25.24	$20.88	–$4.37
NYISO	$34.26	$30.01	–$4.25
PJM	$37.18	$35.45	–$1.73
Remaining grid	$29.43	$29.18	–$0.25

Table B.5. Average Capacity Reserve Requirement Price, by RTO (2020$ per MW of available capacity per hour)

	No offshore wind	Offshore wind	Difference
ISO NE	$6.97	$7.39	$0.42
NYISO	$4.85	$9.63	$4.78
PJM	$10.17	$10.71	$0.54
Remaining grid	$8.83	$8.88	$0.06

Appendix C: Generation Mix and Capacity Mix

Figures C.1 and C.2 show the generation mix and capacity mix with and without the offshore wind farms.

Figure C.1. System-Wide Generation Mix With and Without Offshore Wind

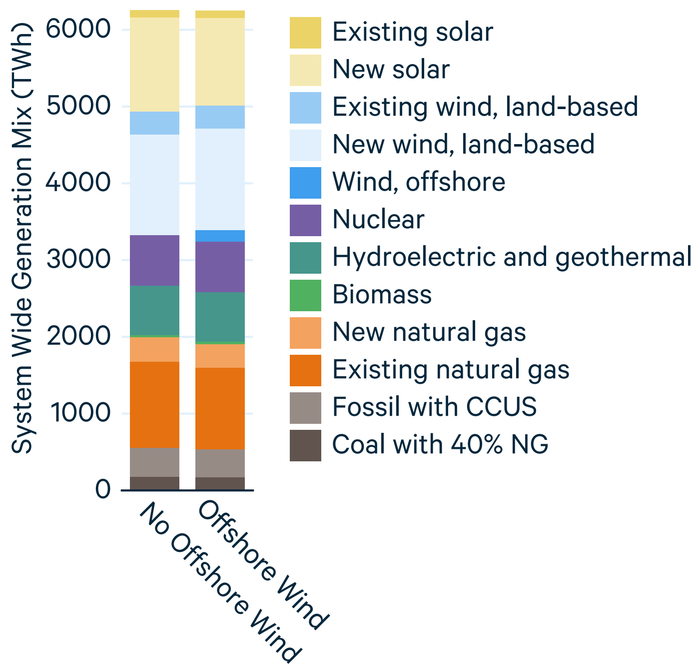
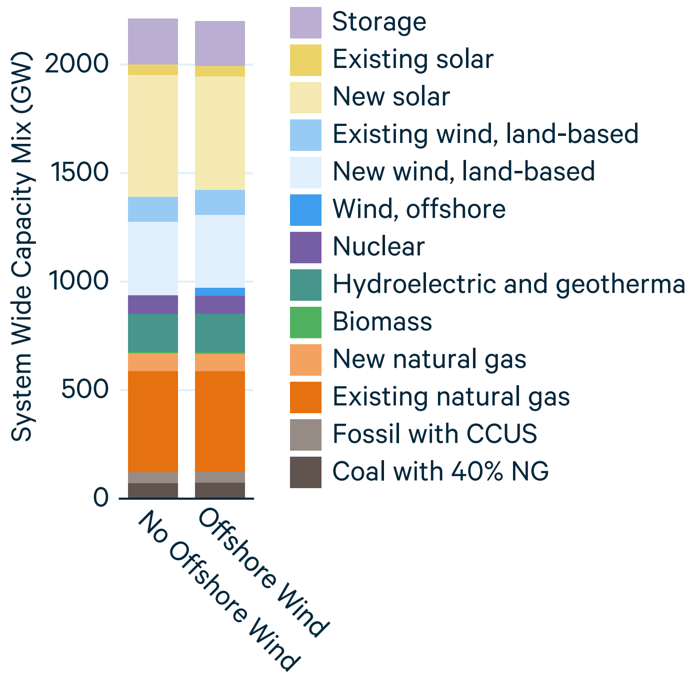


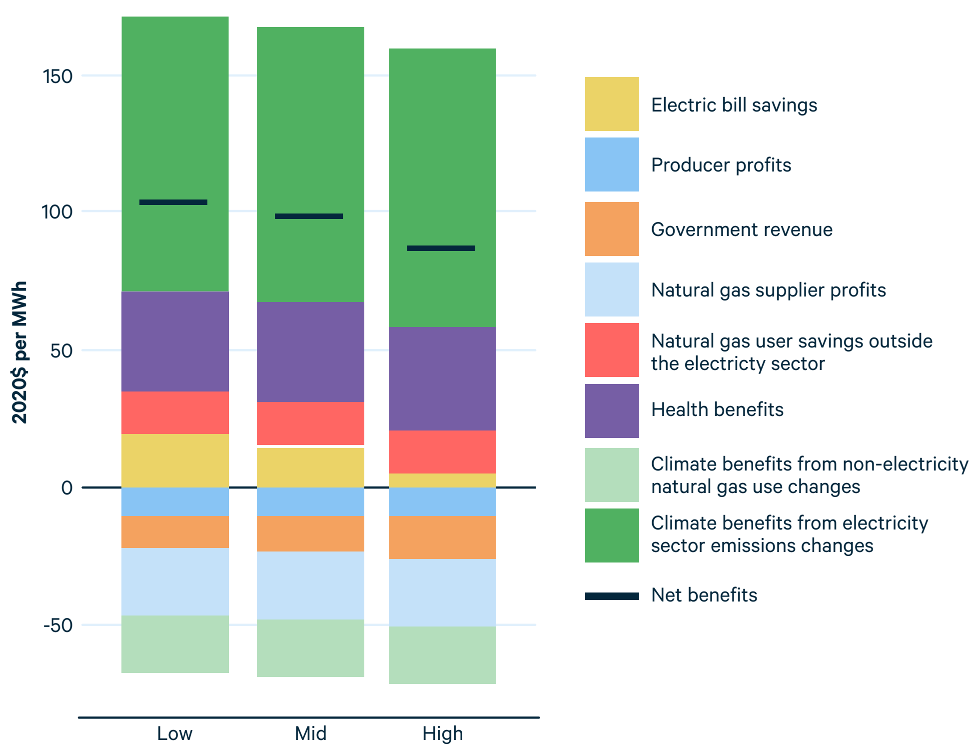
Figure C.2. System-Wide Capacity Mix With and Without Offshore Wind



Appendix D: Results Without the 2024 Power Plant Greenhouse Gas Emissions Regulations and 2023 Good Neighbor Plan for Power Plant NO_x Emissions

The 2024 power plant GHG emissions regulations and 2023 Good Neighbor Plan for power plant NO_x emissions might be overturned. Figure D.1, which can be compared with Figure 9, shows the net benefits of the offshore wind farms against a policy backdrop that lacks these two policies but is otherwise identical to the mid-cost case discussed in the body of this paper. The results are similar to the results with those two policies. The climate benefits are larger, health benefits slightly smaller, electricity bill savings smaller, and producer profit reductions slightly smaller. The other benefits and costs are similar, including the total net benefits. The combined electricity and natural gas bill savings are still positive, even in the high offshore wind cost case.

Figure D.1. Net Benefits per MWh of Offshore Wind Generation, without New EPA Power Plant Emissions Rules



Appendix E: Levelized Projected Revenue of Offshore Wind Projects

Table E.1 shows our calculations of the levelized projected revenue per MWh of the majority of the offshore wind projects that have had power purchase agreements (PPAs) or offshore renewable energy credit (OREC) agreements. We omitted those for which we have insufficient information about their PPA or OREC agreement terms. The levelized projected revenue per MWh is calculated using the PPA/OREC price set in the agreement for the duration of the period in which the agreement applies and estimated revenue from wholesale electricity and capacity markets for the remainder of the assumed 30-year economic lifetime. Projects connecting to some states receive revenue from the capacity market in addition to the agreement price, which we include for those projects in these calculations. We also calculate the levelized projected cost per MWh of offshore wind farms, using costs from the 2023 NREL Annual Technology Baseline (ATB) low-, mid-, and high-cost cases (Mirletz et al. 2023).

Table E.1. Levelized Projected Revenue of Planned Offshore Wind Projects for Which Offtake Agreement Price Data Were Available

Project name	Capacity	Levelized revenue per MWh
Beacon Wind 1	1230	$73
Empire Wind	816	$55
Empire Wind 2	1260	$68
Marwin	248	$93
Momentum Wind	809	$38
Revolution Wind (CT)	300	$66
Revolution Wind (RI)	400	$66
Skipjack Wind 1	120	$90
Skipjack Wind 2	846	$50
South Fork Wind	132	$103
Sunrise Wind	924	$55
Vineyard Wind 1	800	$57
Capacity weighted average actual		$61

Average Levelized Cost of Offshore Wind Generation in 2023 ATB Cost Projections, Using the Financial Assumptions of This Analysis	
ATB 2030 low	$48
ATB 2030 mid	$54
ATB 2030 high	$66

Our Average Levelized Cost of Offshore Wind Generation, Made by Modifying the 2023 ATB Cost Projections	
ATB 2030 low	$53
ATB 2030 mid	$59
ATB 2030 high	$71

The capacity-weighted average of these projects, per MWh, is $61. This average omits several projects, some of the projects we included are subject to renegotiation, and we do not have perfect information about the agreements and other revenues, so the actual average may be higher or lower. Also, the projected revenues for some of the projects (in the part of the ocean known as the New York Bight) must cover much higher lease payments than assumed in the ATB cost projections, and those lease payments are transfers from developers to governments, so they are unlikely to reflect net costs to society. If we were to adjust for that, it would reduce the average estimated cost across the actual projects.

The cost assumptions we use for the offshore wind farms are based on the ATB, but have three differences: we apply regional cost multipliers, the average distance to the existing grid is greater than in the ATB class 4 assumptions, and we assume the offshore wind farms will all use direct current connections to shore, which, on average, are more costly. These assumptions together raise the offshore wind costs to approximately $5/MWh above the raw ATB costs, when expressed on a levelized per MWh basis. The last part of Table E.1 shows these. This brings our mid-cost projection, $59/MWh, very close to the projected average levelized revenue of the offshore wind projects in the table, which again is $61/MWh. Despite the uncertainties about eventual costs, the cost projections that we use remain a plausible range for the eventual average cost per MWh of US Atlantic and Gulf coast offshore wind projects in operation by 2035.

Appendix F: Comparison with GridLab Study

We are aware of one other published study that projects the effects of offshore wind farms on the retirement and construction of other generators. The GridLab offshore wind study (Paliwal et al. 2023) projects their effects on the total cost of electricity production in 2035 in the presence of an emissions cap or fee that achieves a 90 percent reduction (compared with 2005) of economy-wide CO_2 emissions by that year. Our study complements the GridLab study by instead projecting the effects under policies closely resembling those currently on the books, which are less stringent, finding that those policies will achieve a 73 percent reduction (compared with 2005) of electricity sector CO_2 emissions in 2035.

The two studies complement each other in other ways as well. Ours uses different modeling tools and input data, uses higher projected offshore wind costs, and projects somewhat different types of outcomes. Both studies estimate the effects on other generation capacity, other generation, and total cost of electricity production. The GridLab study also projects offshore wind industry employment, supply chain developments, and more, while ours projects emissions effects, health effects, effects on electricity and natural gas bills, and effects on government net spending.

Appendix G: More about Models and Inputs Used

G.1. The Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST)

E4ST uses 16 representative days to represent the year. The days are chosen and weighted to represent the joint frequency distribution of electricity demand, wind, and sunshine well, with oversampling of the times with the greatest potential for generation scarcity in each region of the contiguous United States and Canada in the three years for which we have hourly site-by-site wind, solar, and electricity consumption data.[29] Eleven of the 16 representative days were carefully chosen and weighted to represent the types of days of extremely high potential for scarcity, based on combinations of high load, low wind, and low sun, in all regions of our model. The other five days, which have higher weights because they are more typical, were chosen to represent the rest of the days in the three-year period from which our data come.

We assume that electricity consumption in each representative hour matches the consumption in the historical hour on which it is based, with one type of exception: to represent demand response, we assume that electricity consumption is reduced as necessary to keep the wholesale price from exceeding $5000. In our simulations, as in reality, this occurs at few times and places.

Our analysis focuses on 2035, which we simulate with the projected circumstances in that year. We assume the retirement of the generating units that have announced that they will retire by 2035, as reported in the S&P Global (2021) generator dataset. We assume the construction of the generators that were planned for completion by the beginning of 2024 according to that same dataset. In the simulation, the model predicts what additional generators will retire or be built by 2035.

We first conducted a simulation of 2021, in which we started with the generators existing at the beginning of that year according to the S&P Global (2021) dataset. We assumed that generators retire if the model estimates that they cannot cover their going-forward costs. The purpose of this simulation was to eliminate excess capacity so that there would not be an excess of preexisting capacity in our simulation of 2035. Such an excess would tend to overstate the effects of the offshore wind farms on existing capacity and understate the effects on potential newly built capacity, leading to an overstatement of the emissions reductions and net pocketbook costs of the offshore wind farms. Before simulating 2035 and the endogenous generator construction and retirement that occur by then, we added new generators that had announced they would be online by 2024 and removed generators that had announced they would retire by 2035.

29 For this purpose, we use the Florida, Mid-Continent, Northeast, Mid-Atlantic, Southeast, Southwest, West, and ERCOT (Texas) regions, as defined by the North American Electric Reliability Corporation.

G.2. Model of Formation, Transport, and Fate of Airborne Particulate Pollution

We use the Intervention Model for Air Pollution (InMAP) (Tessum et al. 2017) to model the impacts of pollution from emitting generators in our results. Using pollution rates, predicted generation, and effective stack height data, InMAP predicts the downwind concentrations of SO_2, NO_X, and $PM_{2.5}$ from generators, and we calculate the impacts on human health. InMAP estimates the effects of emissions from over 50,000 source grid cells at three stack height layers across the United States and the resulting concentrations of $PM_{2.5}$ in those same grid cells. The grid cells vary in size based on the population density, using 1 × 1 km grid cells in areas with high population density for increased detail.

The E4ST team has mapped the air pollution to each census block group in the United States. Using race/ethnicity and income information from the American Community Survey (US Census Bureau 2020), we are able to estimate the changes in ambient $PM_{2.5}$ for the population in each race/ethnicity group for every block group. Combining that with the race/ethnicity-specific hazard ratios from Di et al. (2017) and group-specific county-level mortality information from the National Vital Statistics System (CDC 2020), we estimate the number of premature deaths in each race/ethnicity group caused by ambient $PM_{2.5}$ from power sector emissions. Finally, we use the 2035 value per life saved (often called value per statistical life or value of mortality risk reduction) estimate from EPA, which is approximately $12 million, to compute a dollar value for the health damages resulting from the $PM_{2.5}$ pollution caused by the power sector (EPA 2023a).

G.3. Valuation of Effects on Ground-Level Ozone Pollution

Aside from fine particulate matter, the other major ambient air pollution of concern is ground-level ozone. NO_X is the main power plant emissions type that contributes to ground-level ozone formation. The effect of emissions on ground-level ozone is more dependent on unpredictable conditions than is the effect of the SO_2, NO_X, and $PM_{2.5}$ emissions on ground-level $PM_{2.5}$, and we are not aware of a reduced-form model of the effect of NO_X emissions on ground-level ozone. Consequently, to estimate and value the effects of NO_X emissions reductions on ground-level ozone pollution, we use the estimated national average effect of ozone season (May 1–September 30) power plant NO_X emissions on illness and mortality, and the estimated value of those health effects, from an EPA study (2023a).[30] We assume that NO_X emissions during the rest of the year do not affect ground-level ozone, since there is little ground-level ozone formation from October through April.

Our methods can only estimate the lives saved by reductions in ground-level $PM_{2.5}$ and ozone in the United States, so our results omit lives saved in Canada. Additional modeling assumptions for E4ST and InMAP can be found in the E4ST documentation (RFF 2022).

30 The EPA study estimates the value of the health effects using both 3 percent and 7 percent real discount rates. We use the 3 percent value.

Appendix H: Policy Assumptions

One of the most influential policies in our model for this project is the Inflation Reduction Act, which became law in 2022 and provides incentives for clean electricity generation and electrification of current nonelectric energy uses. Its largest incentives, per MWh, are for coal-fueled generation with CCUS, followed by gas-fueled generation with CCUS. It also provides incentives for new offshore and land-based wind and solar generators, electricity storage facilities, and new and preexisting nuclear generators.

Another of the other most influential policies in our model for this project is the new GHG emissions limits for coal-fueled and new gas-fueled power plants, recently announced by EPA based on section 111 of the Clean Air Act (EPA 2024b). In our model, as in reality, by 2032, coal-fueled generators in the United States must retire, add 90 percent CCUS, or begin using natural gas for at least 40 percent of their energy input. Also by 2032, new natural gas–fueled power plants started after the rule was announced must either limit their capacity factor (utilization rate) to under 40 percent or add CCUS.

There is also a cap on power plant and industrial NO_x from May 1 to September 30 of each year in selected states that produce a disproportionate share of total US electric-sector NO_x emissions, and it has not been slack in recent years; it has had a nontrivial NO_x emissions allowance price. It was recently modified in an EPA policy revision known as the Good Neighbor Plan, under which the May–September NO_x cap will, by 2035, be largely determined by the amount of emitting generation capacity that is still operable at that time. The allowed emissions per MW of existing emitting capacity will be such that most, but probably not quite all, emitting capacity will need selective catalytic reduction as an emissions control type. This is a reason to use an estimate of the long-run marginal cost (or, equivalently, the levelized cost) of selective catalytic reduction as the projected May–September NO_x allowance price in the states that are subject to the ozone season power plant NO_x cap. Under the Good Neighbor Plan, there are now 22 such states.

We use the EPA (2023b) price estimate of $11,000/short ton (in 2016$, or $5.91/pound in 2020$). We reduce the per-MWh NO_x emissions rates of all US coal-fueled generators that choose CCUS by 40 percent and the per-MWh NO_x emissions rates of the rest of the surviving US coal-fueled generators, which must cofire with natural gas, by 70 percent. This is an approximate representation of the effects of the Good Neighbor Plan on emissions rates. It may understate the emissions reductions that will result if the plan survives, but the plan may not survive or may be modified in a way that reduces its effectiveness, which is the situation at the time of this writing in June 2024.

In addition, under the Cross-State Air Pollution Rule, there are annual SO_2 and NO_x tradable emissions caps in the eastern United States that have been slack for several years. We assume that these annual limits will be slack in 2035 as well, partly because the other policies contribute to the likelihood that they will continue to be slack.

The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade policy that applies to electricity sector CO_2 emissions in 12 northeastern states from Maine to Virginia, although Virginia's governor is attempting a contested departure. We assume that all those states except Virginia are in RGGI in 2035. Every few years, the state governments that manage RGGI have adjusted the number of allowances issued, largely in response to demand. This pattern is effectively similar to a policy of trying to achieve a target RGGI emissions allowance price. In addition, the program has a soft price ceiling, a soft price floor (the emissions containment reserve at a medium price), and a hard price floor (the floor at a low price), which further reduce the range of likely future prices. For both of these reasons, we represent RGGI as a price on power plant emissions within the RGGI states, rather than as an emissions cap or emissions allowance supply step function. Specifically, we assume that the allowance price will be at the cost containment trigger price, which, when adjusted with our inflation assumptions, will be equivalent to $19.45 in 2020$.

We model state renewable portfolio standards (RPSs), clean electricity standards (CESs), and technology carveouts included in Barbose (2023).[31] We assume that these states will have intermediate requirements, determined linearly, in each year between 2023 and the first announced requirement, and then between that and any later requirements. We assume that any requirements that end in current law, rather than being continued, will be continued at a flat percentage of the state's electricity consumption. In our results, most of the state renewable and clean electricity requirements are slack, so they do not have an effect, because the incentives in the Inflation Reduction Act induce more renewable and clean energy by 2035 than most of the state requirements call for by that year. However, the New York and North Carolina requirements are not slack, and this has a major influence on the effects of the offshore wind farms in our simulation results.

Table H.1 contains examples of the 2030 and 2035 state targets for CESs and RPSs as we model them. Other states also have targets that are not in this table. The 2035 targets are the important ones for this analysis. Some are announced targets. For places without a target in 2035 but with targets before and after 2035, we linearly interpolate to predict the 2035 target. Each goal is a percentage of total load in the state. We combine those goals into "supplying regions" and allow generation from anywhere within a region to count toward the combined target of all states in that region. This approximates the real policies that allow supply from nearby states. The areas adjacent to the offshore wind farms fall into five supplying regions:

7. Northeast: Maine, New Hampshire, Massachusetts, Vermont, Rhode Island, Connecticut, Quebec, Newfoundland and Labrador, New Brunswick, Nova Scotia
8. PJM: New Jersey, Pennsylvania, Maryland, Delaware, District of Columbia, West Virginia, Virginia, Ohio, Indiana, Kentucky
9. New York State: New York
10. North Carolina: North Carolina
11. Texas: Texas

31 We do not model the Washington, DC, solar carveout, a local policy that is minor by national standards.

Table H.1. CES and RPS Targets in the Areas Adjacent to the Offshore Wind Farms

Supplying region	State	Policy type	2030	2035
Northeast	CT	CES	58%	79%
	CT	RPS	44%	44%
	MA	CES	58%	66%
	MA	RPS	41%	45%
	RI	CES	71%	99%
	RI	RPS	71%	99%
PJM	NJ	CES	70%	100%
	NJ	RPS	53%	51%
	VA	CES	44%	54%
	VA	RPS	23%	34%
	MD	CES	50%	50%
	MD	RPS	50%	50%
	DE	CES	20%	29%
	DE	RPS	20%	29%
New York	NY	CES	67%	84%
	NY	RPS	70%	70%
North Carolina	NC	CES	74%	81%
	NC	RPS	5%	5%
Texas	TX	RPS	4%	4%

Of the CESs and RPSs listed in Table H.1, the New York and North Carolina RPSs are binding (i.e., not slack) in our results. The Colorado CES is also binding but is far enough away from the offshore wind farm sites that it has little influence on their effects. There are binding solar carveouts in Delaware, Massachusetts, New Jersey, New Hampshire, and Illinois and a binding distributed generation carveout in Vermont.

The CESs in our model give full credit for wind, solar, water, nuclear, and geothermal generation. Biomass receives credit based on a benchmark emissions rate of 0.66 short tons per MWh. The RPSs in our model, which are mostly based on tier 1 of states with multiple RPS tiers, give credit only for solar, wind, and geothermal generation, except for the ambitious New York 70 percent RPS, which also gives credit for hydroelectric.

Appendix I: Technology Assumptions

For the costs of new technology, including offshore wind farms, we use future cost estimates from the 2023 ATB (Mirletz et al. 2023). The ATB offers multiple assumptions for cost of capital and economic lifetime. We assume a real weighted average cost of capital of 5.44 percent and an economic lifetime of 30 years for all generation technologies, except those with carbon capture, which we assume have a 12-year lifetime corresponding with the length of the Inflation Reduction Act 45Q tax credits, and battery energy storage, for which we assume a 20-year economic lifetime. We use the projected costs of projects completed in 2030 so that our results approximately reflect the average cost of facilities built between the present and 2035.

We use the costs for offshore wind farms of class 4 as defined in the 2023 Annual Technology Baseline (ATB). This is one of the fixed-bottom classes, which is appropriate since all the offshore wind projects we are modeling are fixed-bottom projects, rather than floating. We use costs from the advanced, moderate, and conservative development pathways in the ATB to get low, mid, and high cost estimates for offshore wind. The majority of our analysis uses the mid cost for offshore wind. For all new generation units, we use regional cost multipliers from the input assumptions for the 2021 Annual Energy Outlook (EIA 2021), which are the latest EIA multipliers that match our cost regions. In addition, the levelized annual cost of transmission from each offshore wind farm to its point of connection to the existing transmission grid is the ATB's assumed cost of an alternating current connection with zero length plus $13,000/MW plus $226,000/km per project. This represents the cost of using direct-current transmission to connect to the existing grid. In total, our average cost per MWh of offshore wind generation is approximately $5 more than in the ATB. This is true in the low-, mid-, and high-cost cases, as shown in Appendix E.

Since we completed the analysis and writing of this study, the 2024 ATB came out (NREL 2024, version 2). Its mid cost projection for class 4 offshore wind projects completed in 2030 is approximately 20 percent higher than the same projection in the 2023 ATB, after applying the same financial assumptions and dollar year to both, although the 2023 high cost projection is almost the same as (and in fact is slightly higher than) the mid cost projection in the 2024 ATB. The 2024 ATB projection might significantly overestimate costs because it is based on a new information source in which the costs are self-reported by project developers. In such reporting, the developers might greatly overstate costs to attempt to secure higher contract prices for future offshore wind projects. The cost projection we used for the high-cost case in this study is based on (and is about $5 higher per MWh than) the 2023 ATB high cost projection. Consequently, our high-cost case projects the effects if the costs turn out to be slightly higher than, but similar to, the central cost projection in the 2024 ATB.

Our site- and hour-specific offshore wind data are based on wind speeds from the NREL Wind Toolkit version 2 (NREL n.d.-a), which we convert to generation values (before any curtailment) using a 15-MW reference turbine (NREL n.d.-b) with a hub height of 136 meters. We assume 6.3% wake losses and 3.3% net other losses taking into account the practice of slightly overbuilding turbine capacity relative to balance of system.

Our site- and hour-specific over-land wind generation values (before any curtailment) come from directly from the NREL Wind Toolkit version 1 (NREL n.d.-a).

Our site- and hour-specific solar resource values come from NREL's National Solar Radiation Database (n.d.-c), and we convert them to generation values (before any curtailment) using the System Advisory Model (NREl n.d.-d).

We assume that utility-scale solar generation capacity can be built only in counties with population densities below 750/km^2. We assume that land-based wind farms can be built only in 2 × 2 km grid cells with population densities below 8/km2 as measured in an approximately 1 × 1 km grid cell that includes the center of the 2 × 2 km grid cell.

Another important assumption is the cost of natural gas. We model endogenous electric sector natural gas prices that respond to changes in the electric sector's natural gas consumption. Reducing the price of natural gas appears likely to be a significant benefit of offshore wind farms for energy customers. We employ the common assumption of perfect competition in the natural gas and electricity sectors. We generate separate supply curves for the 10 US census division regions used by the Assumptions to the Annual Energy Outlook 2023: Natural Gas Market Module (EIA 2023b). We include each Canadian province in the nearest US region. Specifically, these are the supply curves to the electric industry after accounting for the natural gas demand curve of all other sectors, so they are known as residual supply curves.

Constructing these residual supply curves involves three inputs. First, for own-price elasticity of natural gas supply, we assume a supply elasticity of 0.34, based on the model estimated by Prest et al. (2022) and an assumption that, on average, the information that allows suppliers to project expected future natural gas prices comes 10 years in advance. Second, for own-price non-electric-sector demand for natural gas, we assume a demand elasticity of –0.3, the middle of the range of –0.2 to –0.42 in the literature review by Prest et al. (2022). That range is demand elasticity of all natural gas users together, but it applies because the ratio of non-electric-sector elasticity to all-sector elasticity is approximately 0.95 based on the individual sector elasticities reported by Hausman and Kellogg (2015), the consumption-weighted average calculated by Metcalf (2018), and the approximately 40 percent share of the electricity sector in US natural gas consumption from EIA (2023 a). Third, as the anchor point to establish the position of each region's curve, we use the projected 2035 price and consumption of natural gas in each region from the reference scenario in EIA (2023 a). In each region that includes a Canadian province, we adjust for the additional consumption by applying a regional multiplier calculated from the relative natural gas consumption in the full region compared with the US portion only. These consumption values come from a baseline simulation in this project.

The Inflation Reduction Act has large incentives for carbon capture and sequestration. In the simulations, we allow coal-fueled power plants to be retrofitted with carbon capture and new natural gas–fueled power plants with carbon capture to be built, each with an assumed CO_2 capture rate of 90 percent. Like all buildable power plant types, the model builds them where it projects that they will be profitable. However, to represent the high marginal cost of rapidly developing and building the infrastructure for carbon capture, transport, and storage, we add a price of $44.68 per short ton of CO_2 captured. This price reduces power-sector CCUS to approximately 400 million metric tons (MMT) per year. That quantity is approximately equal to the upper limit on annual CO_2 sequestration (600 MMT) assumed by Jenkins et al. (2023) minus their projection of non-electric-sector CO_2 capture (261 MMT) in 2035. Their assumed upper limit predates the new EPA power plant GHG emissions regulations, which are based on emissions rates achievable through the use of CCUS. Those regulations might prompt actions that increase the upper limit of CO_2 use and sequestration.

Based on the anticipated emissions rate reductions of planned coal power plant CCUS retrofit projects reported by Purswani and Shawhan (2023), we assume that retrofitting with CCUS reduces emissions rates of coal-fueled plants (per unit of heat input) by 35 percent for NO_X and 98 percent for SO_2 and increases them by 3 percent for $PM_{2.5}$. We assume that cofiring a coal-fueled generator with 40 percent natural gas reduces the generator's emissions rates (per unit of heat input) by 70 percent for NO_X (Kim et al. 2021) and 40 percent for both SO_2 and $PM_{2.5}$ (Andover Technology Partners 2022).

Otherwise, for existing generators or generators to be built by 2024 according to the S&P Global (2021) generator dataset as of June 2021, we use each generator's recent or expected per-MWh emissions rates according to that dataset. For new generating units endogenously build in our model, we assume emissions rates based on the average emissions rates of recently built generators of the same types.

We also assume that the summertime NO_X emissions allowance price in the 22 states subject to the national summertime NO_X emissions regulations will be $11,000 per short ton, as explained in Appendix H. In reality, a generator can improve its NO_X emissions controls, so an $11,000 summertime price might result in more improvements and fewer retirements of generators with high NO_X emissions rates than in our simulation results. The overall influence of this on the emissions and cost effects of offshore wind farms is ambiguous and likely to be small relative to their overall benefits and costs.

The one type of generation capacity for which we do not use cost assumptions from the ATB is coal-fueled generators retrofitted with carbon capture, because the ATB does not include cost estimates for retrofits that depend on existing plant characteristics. Instead, we use coal plant retrofit cost and performance functions based on the cost and performance effect projections reported in the Integrated Planning Model Summer 2021 Reference Case (EPA 2021). Those projections are for nine combinations of generating unit preretrofit generation capacities and heat rates. For each cost or performance parameter, we fit a linear or quadratic function to the set of nine effect estimates, with generating unit capacity and heat rate as the input variables. These functions then enable us to estimate the cost and performance parameters for generating units with capacity and heat rate combinations other than the nine presented in the Integrated Planning Model documentation. This model is funded by EPA and updated by consulting firm ICF.

To determine the costs of transporting and sequestering CO_2, we use the CO_2 transportation and sequestration model from the Integrated Planning Model, which is drawn from the National Electric Energy Data System. CO_2 can be sequestered in saline aquifers or used for enhanced oil recovery. Use for enhanced oil recovery earns a smaller US government subsidy per ton, in our model as in reality. We assume that none of the CO_2 sequestered in a saline aquifer escapes, but that the net emissions effect of using CO_2 for enhanced oil recovery, including all upstream and downstream market effects of doing so, is equivalent to 23 percent leakage of the sequestered CO_2 (IEA 2015). To represent the demand for CO_2 storage from other sectors, we remove the cheapest CO_2 storage options adding up to 261 MMT of CO_2 stored, the estimated demand for CO_2 storage outside the power sector from Jenkins et al. (2023).

Electricity transmission capacity has an effect on the ability of offshore wind farms to prevent emitting generation and capacity. Regarding transmission expansion, we make the neutral assumption that the flow limit on every segment of every transmission line increases in proportion to US and Canadian electricity consumption. For example, if projected electricity consumption is 20 percent higher in 2035 than in the year our starting transmission system data represent, we expand the flow limit on every transmission line segment by 20 percent.

Appendix J: Methods of Quantifying and Valuing Damage Caused by Greenhouse Gas Emissions

In 2017, a panel convened by the National Academies of Sciences, Engineering, and Medicine of the United States prescribed a series of research tasks for improved estimates of the social costs of GHGs—that is, the value to people of the damage caused by GHG emissions. Three groups of researchers have now followed those steps and reported updated estimates: Rennert et al. (2022), Carleton and Greenstone (2022), and Azar et al. (2023). Based on the work of these researchers and others, EPA has produced new proposed estimates of the social costs of CO_2 and methane (2023c). These are likely to be underestimates because they rely on conservative assumptions and do not include all the expected effects of climate change. However, they are still useful as estimates of the value of emissions reductions. The social costs of carbon and methane emissions in 2030 are estimated to be \$225 and \$2570 per short ton, respectively (in 2020\$). At least two other studies in recent years have estimated the social costs of both CO_2 and methane. Prest et al. (2022) estimate \$222 for CO_2 and \$3167 (in 2020\$) for methane emissions in 2035, and Azar et al. (2023) estimate \$211 for CO_2 and \$4400 for methane emissions in 2020; their damage estimates would presumably be higher for emissions in 2035.

In Section 3, we reported not just the estimated dollar value of the CO_2 and methane emissions changes but also the number of premature deaths prevented by the CO2 emissions changes. Prest (email correspondence, June 11, 2024) provided the expected mortality effect of a 1 metric gigaton pulse of CO_2 in 2020, consistent with the model and central assumptions made by Rennert et al. (2022). Translated to mortality per short ton, it equates to 43 premature deaths per million short tons of CO_2 emitted. This projected mortality effect is just from the first 280 years after the CO_2 is emitted. Expected effect on premature mortality slowly increases for the first 90 years after the CO_2 is emitted, then slowly declines. In the 280th year, it is still two-thirds as large as in the years of maximum effect.

In addition to reporting quantities of CO_2, we report quantities of the greenhouse gases CO_2 and methane together. We combine CO_2 and methane into a single measure called CO_2 equivalent, or CO_2e. In doing so, we assume that each ton of CO_2 has a CO_2e of 1 and that each ton of methane has a CO_2e of 10.4. For this CO_2e value of methane, we are using the ratio of estimated damages per ton mentioned earlier in this appendix, from EPA (2023c). The ratio from Prest et al. (2022) is 12.9 and that from Azar et al. (2023) is 21. Most studies use a higher CO_2e for methane, such as a value of approximately 30 based on the estimated warming from methane compared with CO_2 over the first 100 years after release or a value of approximately 80 based on the estimated warming from methane compared with CO_2 over the first 20 years after release. However, using a ratio other than the damage ratio in an otherwise optimal policy analysis is likely to result in suboptimal policy choices, in terms of the net benefits that the choices would produce.

We assume a methane leak rate of 0.000434 short tons per million Btu of natural gas use and 0.000174 per million Btu of coal use. These estimates are from Lenox et al. (2013), whose natural gas leakage rate estimate has withstood the test of time. This rate of natural gas leakage is approximately 2.5 percent, which is consistent with the prevailing current estimate from Alvarez et al. (2018).