# Modeling the Contribution of Offshore Wind to the Grid Mix and Air Quality Implications: U.S. National Approach

## Abstract

Offshore wind (OSW) is an established technology in Europe, but it has not yet gained market share in the United States (U.S.). There is, however, increasing interest in and action supporting OSW development from many coastal states, predominantly along the Atlantic coast. As OSW grows in the U.S., as seems likely, it will displace existing generation assets, and depending on which assets those are, the resulting emissions from the electric power sector. This research explores combinations of two energy sector drivers, OSW costs and carbon dioxide (CO2) mitigation, to measure the changes in the energy mix and quantify OSW’s impact on the resulting emissions.

For this analysis, an energy system modeling approach is used to generate and explore potential energy futures. The approach uses the Integrated MARKAL-EFOM System Energy System model (TIMES) and a database representation of the U.S. energy system called the EPAUS9rT, applying a nested parametric sensitivity analysis to represent potential futures. This sensitivity analysis allows us to explore the benefits of OSW as an energy source within the U.S. as it relates to air quality and GHG emissions reductions. The combinations of CO2 mitigation stringencies and OSW cost curves create vastly different energy futures with comparably different emissions profiles. We found that OSW buildout was affected more by cost than CO2 mitigation stringency, though both had a measurable positive impact. Buildout was more affected by CO2 mitigation stringency at higher prices and less at lower prices. Additionally, we found that while CO2 mitigation had a statistically significant negative effect on all five emissions investigated, OSW capacity only had a statistically significant negative effect on CO2 and PM2.5. We look at results both nationally and regionally, analyzing the differences in regional adoption of OSW and how access to this technology provides a broader range of emission reduction options for the power sector.

## Introduction and objectives

OSW is a renewable energy resource available over coastal and great lake waters. Its low variability and uncertainty paired with its proximity to large population centers makes it a prime candidate for electricity production. Offshore winds also blow relatively consistently and often peak in tandem with daily demands. In the U.S., approximately 40% of the population lives on the coast, and this population has grown 40% since 1970 [1-3]. This means electricity consumption is growing and there is less area available for development. More so, the area that is available is expensive due to availability constraints. OSW has an estimated 10,800 GW of resource potential, 2,058 GW of which are technically feasible for development in the U.S. [4]. Though the resources are vast, only 30 MW of this potential has been realized with the 5 turbine Block Island Wind Farm that began commercial operation as the first OSW farm in the U.S. in late 2016. It is, however, a relatively expensive technology. Many factors contribute to the high price, the most impactful being complex installation that requires highly-skilled instrumentation and labor at sea [5, 6]. Distance to shore and depth of water add further to these costs. Lastly, the electricity produced must make its way to shore through sea-worthy transmission lines [7].

Twenty-five coastal or great lakes states and Washington D.C. have instituted Renewable Portfolio Standards or Goals (RPS) and twenty have set greenhouse gas (GHG) emissions targets [8, 9]. Both types of policies incentivize the buildout of renewable and emissions-free generation resources, for which OSW qualifies. These policies have already begun to change the energy landscape. Policies paired with declining costs for terrestrial wind and solar led renewables to account for 17% of electricity generation in the U.S. in 2018, an increase of 5% from 2017 [10, 11]. It is unclear exactly how OSW will fit into this changing landscape, and what impact it will have.

With the growth of the OSW industry in the U.S. in mind, this research explores potential energy futures that include OSW and analyzes the resulting changes to the electric sector technology mix and associated emissions. Two drivers for OSW development are explored: (1) OSW costs and (2) CO2 mitigation stringency.

(1) OSW Costs: Supply chains are not yet developed in the U.S. for OSW and the development and transmission costs associated with sea-based projects are high. This results in a high cost for OSW as compared to other technologies. However, there is a great deal of potential for a declining cost curve for OSW. As capacity expansion in the power sector is highly sensitive to cost, this measure captures one of the main barriers to OSW deployment.

(2) Carbon Mitigation Stringency: Electricity generation produces several emissions, including but not limited to the criteria air pollutants sulfur dioxide (SO2), nitrogen oxides (NOX), fine particulate matter (PM2.5), methane (CH4), and carbon dioxide (CO2). These emissions vary in their environmental and health impacts, as well as their cost of mitigation. Federal programs already exist for the mitigation of SO2 and NOx from the power sector, but not for CO2. This measure accounts for air-quality and environmental health regulations that would favor non-emitting sources of power generation beyond what already exists. It also helps to encapsulate the upward trend in states with GHG emissions targets.

The 2019 Annual Energy Outlook produced by the U.S. Energy Information Administration (EIA) predicts that electric sector emissions will remain flat through 2050, assuming there are no significant changes to laws and regulation [12].Currently, the sector contributes approximately 69.4% of SO2 emissions, 32.9% of CO2 emissions, 14.1% of NOx emissions, and 3.4% of PM 2.5 emissions. Methane emissions in the U.S. have a wide variety of sources; 54% comes from gas production, 18% oil production, 16% transmission and storage, 6% distribution, and 6% processing. The electric sector contributes to many of these processes, most notably consuming 35.5% of natural gas [13, 14].

An energy system modeling approach is used to generate and explore these potential energy futures. The methodology developed in Loughlin et al. (2012) for assessing the breakthrough potential of emerging technologies for emissions mitigation was applied to OSW [15]. The Loughlin et al. methodology was designed to evaluate the potential of energy technology developments to yield a breakthrough in achieving GHG mitigation goals. It was applied more broadly in this research to evaluate the changes that OSW would elicit in the energy mix and grid emissions.

The approach involves a nested parametric sensitivity analysis using the TIMES energy system model with the EPAUS9rT, a database representation of the U.S. energy system. Combinations of carbon mitigation stringencies and OSW cost curves create vastly different energy futures with comparably different emissions profiles. The analysis allows us to analyze, given the uncertainty of any one “future” scenario, the factors associated with the implementation of OSW and the benefits to system emissions associated with an increase in OSW power.

## Background

OSW in Europe accounts for over 80% of worldwide OSW with over 18.9 GW of installed capacity and has reached cost competitiveness with many other technologies, though terrestrial wind and solar PV still remain less expensive [16]. While the technology is well established in Europe, there are many concepts that do not apply in the U.S. Most notably, OSW is a renewable technology that requires wind as a natural resource for energy production, and this resource varies between regions. Significant research has been conducted to assess OSW resources in the U.S., allowing for more robust investigation of its applicability to this location, specifically accounting for technological limits, land availability, risk factors, and economics [17-19]. A recent approach developed by Dupont et al. works to include Energy Return on Investment (EROI), incorporating more robust econometric measures [20].

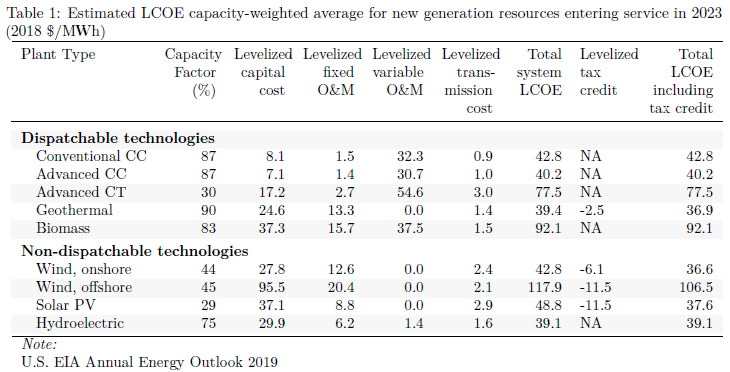
Of even more complexity is adding high penetration of variables renewable resources to the grid. Huang et al. developed control strategies for grid operators for highly OSW penetrated systems [21] which can be paired with research by Bernd Moller to harness spatial modeling for later-stage planning [22]. Finally, there remains the issue of transmission of the 

Table . AEO 2018 LCOE [12]

OSW-generated electricity to shore, where the U.S. resources vary greatly by region in sea floor depth and distance to shore. This makes economic and location-based analysis difficult given the highly variable cost and requirements for transmission. Models for configuration and cost optimization of OSW transmission systems have been modeled by multiple research teams, showing promising solutions for the vast technical solutions [23-25]. The U.S. Department of Energy has done preliminary assessment of interconnection for OSW and concluded that the U.S. (1) has sufficient OSW resources to build out a considerable amount of generation and (2) appropriate technologies exist for interconnection large amounts of OSW energy to the U.S. grid, however realizing this potential will be both complex and difficult [26]. \*\* maybe add cable routing optimization for offshore wind power plants via wind scenarios considering power loss cost model paper \*\*

Technologically speaking, OSW is still at a relatively early stage of development, even in Europe, and prices are expected to fall further as the technology advances [27]. In 2017, the National Renewable Energy Laboratory (NREL) published a study assessing the economic potential of OSW in the U.S. that projected a decline of approximately 50% in the levelized cost of electricity (LCOE) of OSW, both shallow and deep, by 2030 [17]. Supply chain and infrastructure advancement are key to these price declines, but the largest contributor has been the growth in the capacity of turbines. In 2016 the Block Island Wind Farm installed 6 MW turbines, standing at a height of 590 ft. In 2019, the newest and largest turbine design, the GE Halide X, has a doubled to a 12 MW capacity. It stands at 863 ft and has a 63% capacity factor, which is five to seven percent higher than the industry standard [28].

Steep LCOE decline has precedent in the U.S. Since 2009 the LCOE of solar PV and terrestrial wind have declined 88% and 69%, respectively [29]. These declines reflect both technological advancement and economies of scale for these technologies. OSW expects to benefit from these factors, enhanced by industry and state government interest in investing in the technology. Daniel et al. projects that research and development will help reduce initial capital investment for OSW due to industry advancements in these areas [26]. However, OSW still stands as one of the most expensive generation resources available in the U.S., as seen in Table 1. While LCOE is a generalized measure used to compare technologies, it does not account for regional differences in fuel or natural resource availability, load curves, or dispatchability. Additionally, uncertainty and unpredictability in the assessment of wind resources can change the LCOE, as quantified by Mora et al. [30].

Despite the high price of OSW in the U.S., many states are taking steps towards incentivizing and implementing the technology. Recent state advancements in supporting OSW projects and supply chain include the following [31]:

* California: 2019 memorandum of understanding between Castle Wind and Monterey Bay Community Power outlining intent to enter a long-term power purchase agreement for 1 GW of OSW [32]
* Connecticut: 2018 Connecticut Department of Energy and Environmental Protection generation-based RFP for renewable energy, including OSW; $15 million investment to revitalize a shipping pier; 2019 law outlining target to develop up to 2,000 MW of OSW by 2030 [33]
* Maine: 2019 Maine Offshore Wind Initiative and floating offshore turbine demonstration project announced by the Governor
* Maryland: 2013 Offshore Wind Energy Act developed Offshore Wind Renewable Energy Credits (ORECs), which can be applied to the state’s RPS; 2017 first OSW solicitation of 389 MW; 2019 1,200 MW OSW mandate by 2030 [34]
* Massachusetts: 2016 law requiring procurement of 1,600 MW of OSW by 2027, updated to 3,200 MW in 2019 [35]; 2018 selected Vineyard Wind project as first OSW project for 800 MW; 2018 BOEM held auctions for three lease areas with 32 rounds of bidding; 2019 second solicitation for 400-800 MW projects
* New Jersey: 2018 law outlining target to develop 3,500 MW of OSW by 2030, the first 1,1000 MW of which have just been won by Ørsted [36]
* New York: 2017 Governor commitment to develop up to 2.4 GW of OSW by 2030; 2018 solicitation of at least 800 MW in two RFPs; $15 million investment to train for OSW jobs and develop port infrastructure; 2019 OSW mandate updated to 9 GW by 2035 and procurement solidified July 2019 for 1,700 MW between two projects [37]
* Rhode Island: 2018 competitive procurement for 400 MW of OSW, in collaboration with Massachusetts
* Virginia: 2018 Governor released Virginia Energy Plan, calling for 2,000 MW OSW by 2028; 12 MW Coastal Virginia Offshore Wind Project is the first fully-permitted OSW project in Federal waters with an order from Siemens Gamesa for two 6-MW turbines and BOEM permits; 2019 Dominion Energy proposes largest OSW project in U.S. of 2.6 GW from 220 turbines by 2026 [38]

Renewable energy has grown significantly in the U.S. as states have adopted RPS and emissions reductions goals, especially as costs have declined. It is uncertain, however, how OSW will play into the current grid mix. A multitude of factors elicit greater amounts of specific technologies in different regions depending on natural resource availability, demand growth, age of existing generation assets, and many more factors. Little research exists for the impact of OSW to the grid mix in the U.S., but many other countries are taking initiative to assess how OSW fits in. These efforts have been focused primarily on European countries and China, as they were the first and most prolific adopters of renewable technologies. For example, many researchers have begun assessing the opportunities in China for OSW to offset carbon-intensive generation [39-41] as well as more wholistic investigation into OSW planning for emissions reductions goals [42, 43]. Similarly, research has sought to quantify the ability of renewable technologies to contribute to emissions goals [44-46], and wind specifically [47]. Research has shown a direct correlation between adoption of renewable technologies and emissions reductions, accounting for demand and population growth.

Electric sector emissions reductions contribute to benefits for the environment, human health, and climate, often referred to as “co-benefits”. Analyses have been done to quantify the positive human health co-benefits from sectoral emissions reductions [48, 49] and more general climate mitigation efforts [50, 51]. Additional research has quantified the environmental and climate co-benefits of low carbon technologies [52-54].

\*\* think about adding info from northwestern Europe turbine greenhouse gas payback paper and china offshore wind displacing coal fired power plants and co2 savings paper \*\* 🡪 both papers from ES&T, so might want to think about that for citing too much from the same journal you’re applying to?

U.S-specific research has estimated the environmental co-benefits of low-carbon pathways [55, 56], and has begun to investigate wind specifically [57, 58]. In 2017, BOEM issued a report evaluating electricity system, environmental, and socioeconomic benefits offered by OSW [59], modeling a novel approach to quantifying more than costs and impacts when assessing new technologies. The U.S., while adopting very little OSW, has installed nearly 98 GW of terrestrial wind power [60], allowing for real-time analysis of emissions mitigation potential and the resulting impacts on and benefits for environmental, human health, and climate [61, 62]. As interest in OSW has grown, so has investigation into the co-benefits that the technology can bring to localities. Two studies focused on the state of Michigan showed that both terrestrial and offshore wind could bring environmental, air quality, and quality of life benefits to the counties that would host or border the turbines [63, 64]. They found that emissions reduction benefits varied across pollutant and locality, but that overall reductions were likely across all pollutants. A similar study focused on Mid-Atlantic states found direct human health and climate benefits from OSW specifically, citing the greatest differences in benefits coming from locality and facility generation capacity [65]. It must be noted that OSW does not produce emissions from generation, however materials production, construction, and operation of OSW have their own emissions footprints, which are quantified in life-cycle analyses [66-68], and there are emissions consequences when variable renewable resources must be paired with dispatchable, fossil-fuel generators to meet demand when renewable generation drops [69]. These contextual emissions have not yet been worked into a larger systems-approach to emissions mitigation, nor are they accounted for in our study.

These studies demonstrate the direct affects and benefits of wind technologies to their surroundings, but do not quantify the nation-wide impact that OSW would have on emissions. The large market in the U.S. is at a tipping point, with a project pipeline of 25,600 MW of OSW energy as of July 2019. Specific projects account for 4,864 MW of that capacity and the remaining 20,736 MW are comprised of undeveloped lease area. Of the project-based capacity, 4,831 MW is expected to be built and online by 2024 [31]. The U.S. Bureau of Ocean Energy Management (BOEM), the agency responsible for OSW leasing areas, announced in June of 2019 that it would publish a “request for competitive interest” to build a transmission line for OSW off the coasts of New York and New Jersey [70]. A planned transmission system for OSW would promote long-term success and interest in the OSW market, and likely increase the chances of the U.S. market accelerating OSW development.

## Materials and Methods

The TIMES model and EPAUS9rT energy system database, together, provide a comprehensive look at the U.S. energy system. The EPA’s Office of Research and Development has worked to develop the TIMES-EPAUS9rT model to investigate energy system futures that optimize for lowest cost over all economic sectors [71]. This allows the use of one model for all sectors instead of a piecemeal approach.

The TIMES model is developed by the Energy Technology Systems Analysis Program (ETSAP), one of the longest running programs at the International Energy Agency (IEA) [72]. The TIMES model is a Long-term energy system optimization model (ESOM) and is used for investment and operation decision support. It uses a bottom up approach with multi-year temporal resolution and user defined time slices to model for long time-horizons [3]. The TIMES model includes a wide range of commodity-related variables such as total production, total consumption, and process flows. Additionally, TIMES can allocate costs across investment timelines.

The TIMES model is a Linear Program formulated using the modeling language GAMS that maximizes system surplus by minimizing system costs. This formulation is called the *total system cost*

Where:

* *NPV* is the net present value of the total cost for all regions (the TIMES objective function);
* *ANNCOST(r,y)* is the total annual cost in region *r* and year *y*;
* *dr,y* is the general discount rate;
* *REFYR* is the reference year for discounting;
* *YEARS* is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if the costs have been defined for past investments, plus a number of years after EOH where some investments and dismantling costs are still being incurred, as well as the Salvage Value; and
* *R* is the set of regions in the area of study.

The TIMES objective is to minimize the total *cost* of the system, augmented by the *cost* of lost demand. All cost elements are discounted to a user-selected year [72]. The current EPAUS9rT database and its TIMES implementation uses 2010 as the base year and is calibrated to the present year.

The EPAUS9rT database represents the U.S. by census regions, as can be seen in Figure 5. OSW’s representation in this model is at this region-level and accounts for the geographic and economic variability of the resource. The OSW resources within the model span every census region except for Region 8 (Mountain West), due to no offshore resources being directly accessible from this territory. For each of the remaining 8 regions, the model represents technologies for OSW spanning the following characteristics: water depth (shallow and deep), wind class, and cost class. A discount rate for new capacity of 0.10 was applied for all OSW technologies. Capacity factor varies by time of day, season, technology, and region. For each OSW installation, a lifetime of 30 years was assumed. The model sets a capacity bound for type of OSW in each region based on technical feasibility. What is not considered in the model is the practical timeframe in which all the available OSW development area will become available. BOEM, an agency within the U.S. Department of the Interior, must assess outer continental shelf areas for leasing potential before they may be developed. Additionally, the model does not account for political feasibility of building OSW, which has proven to be a contentious technology in the U.S.

Cost curves for OSW were constructed to linearly decline from 2015 to 2035 by a percentage of current costs. Capital expenditure (CAPEX) was back-calculated from LCOE’s presented in the Energy Information Administration’s (EIA) Annual Energy Outlook 2018 (AEO). The baseline cost reduction scenario assumes a 20% cost decrease, as is expected through normal technological advancement and “learning”. Five additional cost curves were constructed at 10% intervals, spanning from a 30% to an 80% reduction in the cost of OSW by 2035.

CO2 mitigation scenarios were constructed to linearly reduce emissions from 2010 to 2050 by percentage of 2010 electric sector CO2 emissions. The 2010 emissions were calculated endogenously, using the TIMES model and EPAUS9rT database. Each emissions reduction scenario instituted a constraint that held electric sector emissions to a cap, as represented by figure below. The baseline emissions reduction scenario assumed no carbon mitigation requirement. Each subsequent scenario increased the required carbon mitigation percentage by 10%, until an 80% carbon reduction is achieved by 2050.

All scenarios constructed and evaluated in the TIMES model ran from 2010 to 2050.

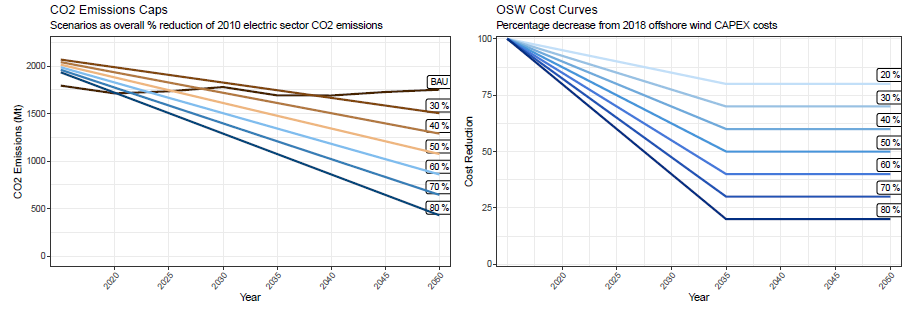


Figure 1. CO2 Cap and OSW Cost Curve Scenario Construction

## Results and Discussion

A total of 49 scenarios were created, representing the combination of all seven cost curves and emissions caps. The model results showed that OSW was not built out in all cases, as represented in Figure 2. Until the cost of OSW was reduced by 50%, it was not economically viable, even in the most stringent carbon mitigation scenario. At a 50% cost reduction 17 GW of OSW is built by 2050 in the 80% carbon mitigation scenario, though only 1.8 GW is built in the 60% carbon mitigation scenario. At a 60% cost reduction, OSW is built in all carbon mitigation scenarios, with the largest buildout coming at the highest cost reduction across all carbon mitigation scenarios. Over all scenarios, the largest market share that OSW achieves is 37% in the lowest cost and highest carbon mitigation stringency scenario.

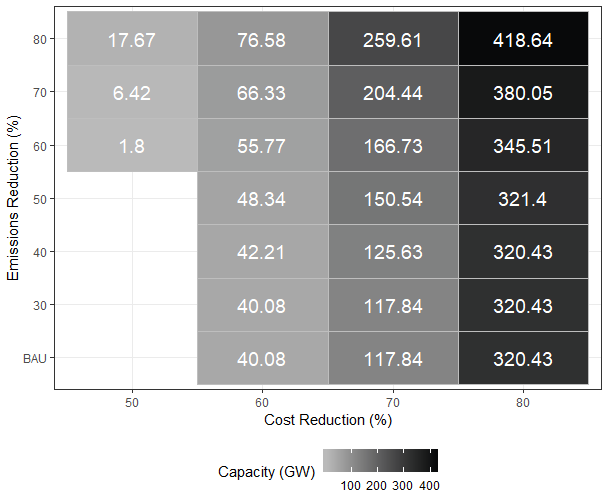


Figure 2. Total OSW Capacity in 2050

OSW’s sensitivity to carbon mitigation stringency is well defined across all technology costs. More stringent carbon mitigation incentivizes the buildout of OSW sooner, and at larger capacities, at a 50% cost reduction, however only affects the total capacity at higher cost reductions (Figure 3). The cheaper OSW becomes, the more capacity is built out each time period, regardless of carbon mitigation stringency. We see in all scenarios, however, that OSW is built out in high and relatively level once it enters the market.

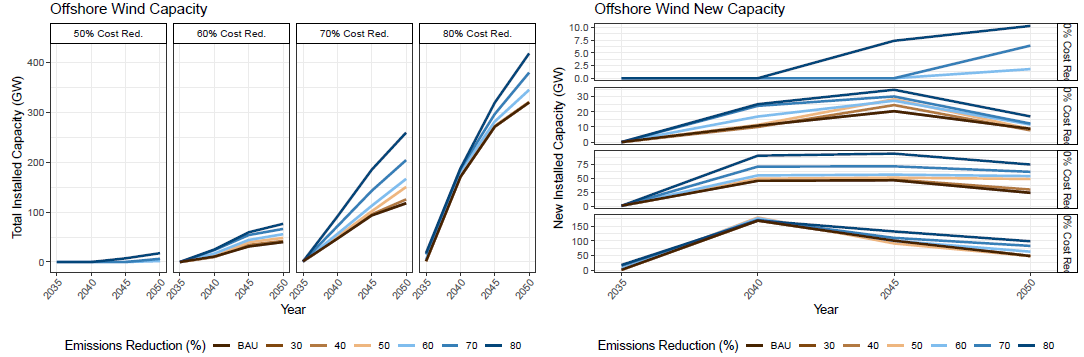


Figure 3. Total and New OSW Capacity by Scenario

Overall buildout of OSW varied across regions. OSW was not built out in either Region 4 or Region 6. Of the regions where OSW was built, Region 5 elicited the largest buildout and Region 7 the smallest (Figure 4).

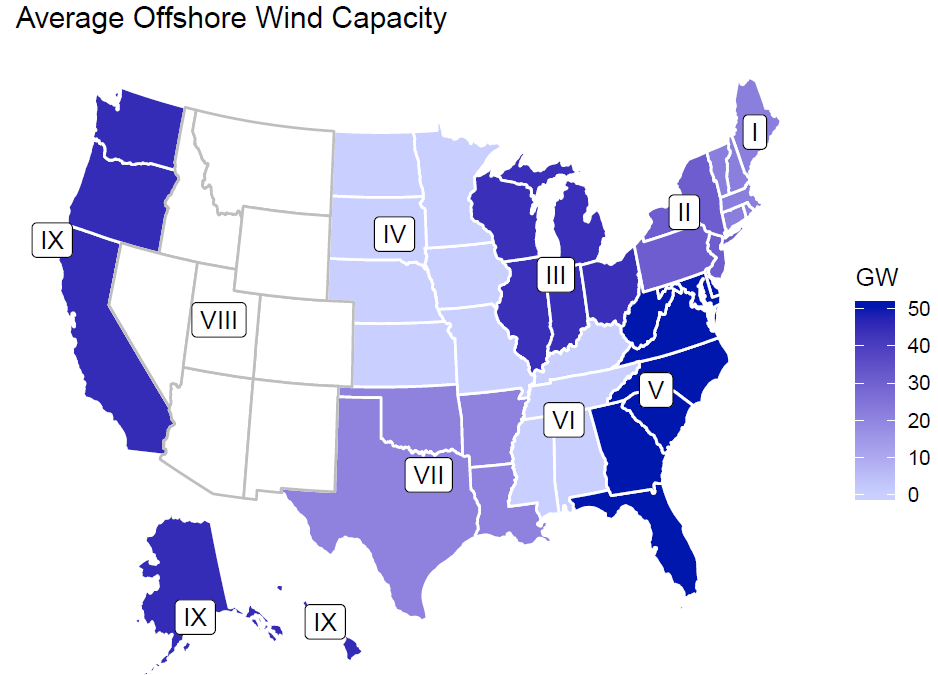


Figure 4. Average OSW capacity per region across scenarios

The deployment of OSW displaces coal, natural gas, terrestrial wind, and solar PV (Figures 5 & 6), though the technologies displaced vary between scenarios. Below we can see that in the cases where OSW is cheapest, the displaced technologies vary dramatically with carbon mitigation stringency. In the business as usual case for emissions, OSW primarily displaces wind and solar. Only as carbon mitigation stringency increases does OSW displace natural gas and coal at higher levels. In scenarios where the most OSW is built out, natural gas is the most impacted technology. Natural gas makes up the largest large market share of the 2050 grid in all scenarios regardless of OSW buildout, but the amount of natural gas is dramatically reduced when OSW is built out. Coal sees a similar displacement when OSW is built out. While the cost of OSW elicits a decline in the generation from fossil-fuel resources, we see that terrestrial wind and are also affected. All scenarios that impose a carbon cap elicit greater quantities of these technologies, however we can also see that as OSW becomes cheaper, the growth of these technologies is slower. The market share for all technologies in all scenarios is depicted in Table 4 (end of document).

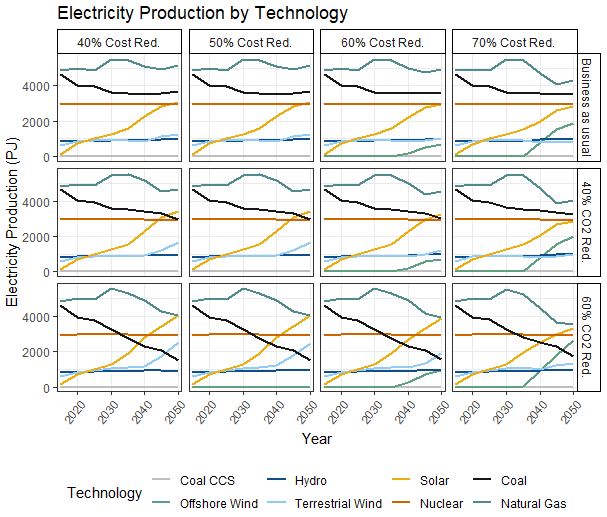
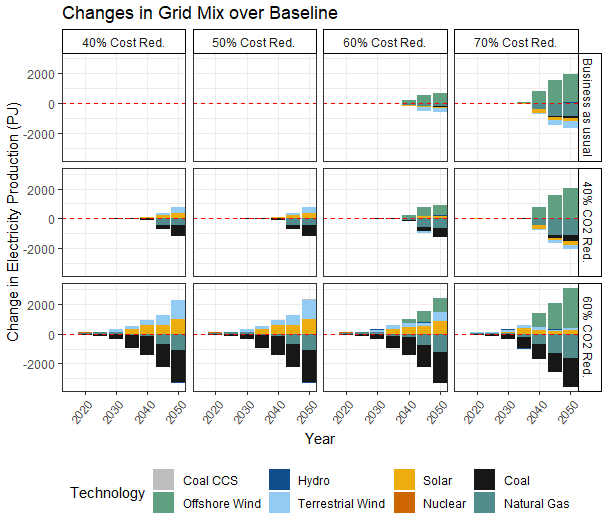
 

Figure 5. Grid Mix Changes over the Baseline Scenario Figure 6. Electricity production by technology

Due to the fact that OSW displaces other emissions-neutral technologies in some scenarios, it is harder to disentangle the affects of OSW costs and carbon mitigation stringency on total emissions. In order to tease out some of this complexity, we looked at some confounding factors. Carbon mitigation stringency elicited a higher percentage of renewables independent of OSW cost, though OSW cost did contribute to higher percentages in all scenarios (Figure 7). Additionally, carbon mitigation stringency had a marked impact on total electricity production, reducing overall production in scenarios with high mitigation stringency (Figure 8).

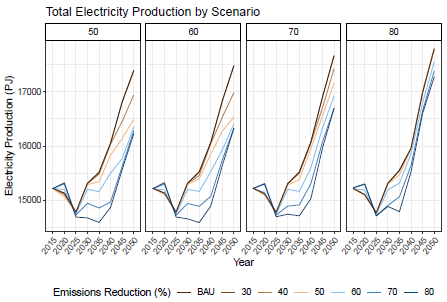
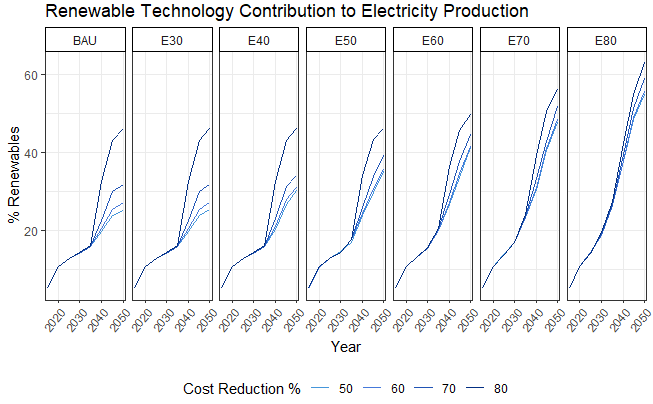


Figure 7. Total electricity production Figure 8. Percent renewable technology generation

The impact of these factors, as well as the impact of OSW buildout, contributed to an overall reduction in all emissions investigated in all scenarios over the baseline scenario. As shown in Figure 9, all pollutants saw a significant reduction in emissions, but the largest reduction was in SO2. The dramatic decrease in these emissions stems from the model’s representation of existing SO2 policies that require substantial shift away from sulfur-rich fuels.

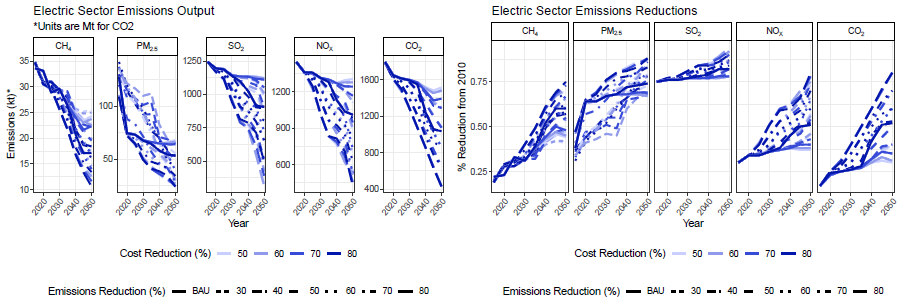


Figure 9. Emissions Output and Percent Reductions

In order to tease out the effects of these factors and the original sensitivity parameters on emissions, we looked at the correlations between all factors (Figure 10). Carbon mitigation stringency was highly negatively correlated with all emissions, while OSW capacity was only significantly negatively correlated with CO2 and CH4.

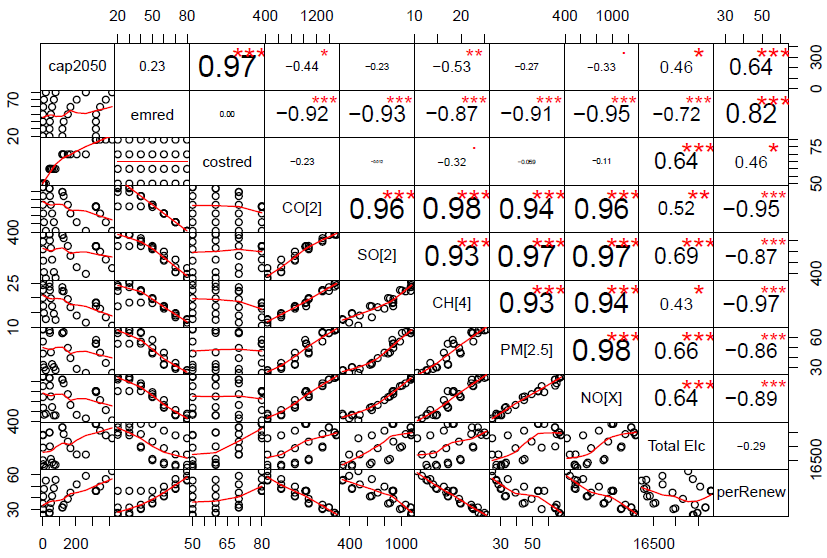


Figure 10. Correlations between parameters

Further statistical analysis was required to identify the strength of the effects of these parameters on emissions. Multiple linear regressions were constructed to analyze these factors. Table 2 shows the regression coefficients for three independent variables, OSW capacity, percentage renewables, and total electricity. All coefficients were statistically significant for both carbon mitigation stringency and OSW cost reduction. Cost reduction had a substantially greater positive influence on OSW capacity than carbon mitigation stringency, though both contribute to higher OSW capacity. Table 3 shows these factors as they elicit changes in emissions. All coefficients were statistically significant for carbon mitigation stringency but only CO2 and PM 2.5 were statistically significant for OSW capacity.

Table 2

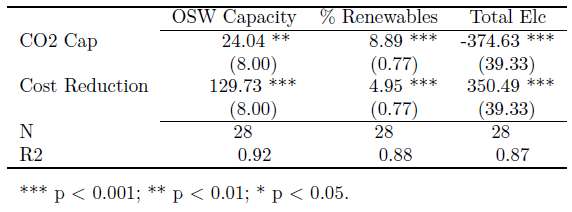


Table 3

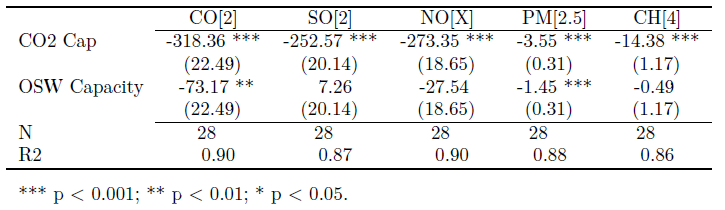
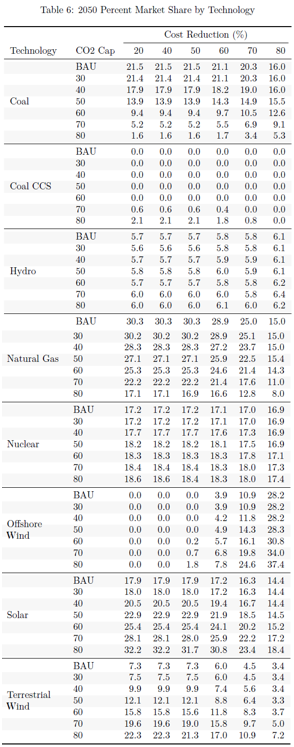


Table 4. Share of electricity production (%)



## Conclusions

## References

1. NOAA, *American Community Survey Five-Year Estimates [NOAA Office for Coastal Management, U.S. Census Bureau]*, NOAA, Editor. 2014.

2. NOAA, *National Coastal Population Report: Population Trends from 1970 to 2020*, in *NOAA's State of the Coast*. 2013.

3. Ringkjob, H.-K., P.M. Haugan, and I.M. Solbrekke, *A review of modelling tools for energy and electricity systems with large shares of variable renewables.* Renewable and Sustainable Energy Reviews, 2018. **96**: p. 440-459.

4. Musial, W., et al., *2016 Offshore Wind Energy Resource Assessment for the United States.* National Renewable Energy Laboratory, 2016(NREL/TP-5000-66599).

5. Green, R. and N. Vasilakos, *The economics of offshore wind.* Energy Policy, 2011. **39**: p. 496-502.

6. Myhr, A., et al., *Levelised cost of energy for offshore floating wind turbines in a life cycle perspective.* Renewable Energy, 2014. **66**: p. 714-728.

7. Stehly, T., et al., *2017 Cost of Wind Energy Review*. 2017, National Renewable Energy Laboratory.

8. NCCETC, *Renewable and Clean Energy Standards: Database of State Incentives for Renewables and Efficiency*, N.C.C.E.T. Center, Editor. 2019.

9. C2ES, *U.S. State Greenhouse Gas Emissions Targets*, C.f.C.a.E. Solutions, Editor. 2019.

10. U.S. EIA, *US electricity generation by energy source*, U.S.E.I. Administration, Editor. 2018.

11. U.S. EIA, *U.S. primary energy consumption by energy source, 2018*, U.S.E.I. Administration, Editor. 2018.

12. U.S. EIA, *Annual Energy Outlook 2019 - with projections to 2050*, U.S.E.I. Administration, Editor. 2019.

13. U.S. EPA, *National Emissions Inventory Report*, U.S.E.P. Agency, Editor. 2014.

14. U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017 Inventory Report*, U.S.E.P. Agency, Editor. 2017.

15. Loughlin, D.H., et al., *Methodology for examining potential technology breakthroughs for mitigating CO2 and application to centralized solar phovoltaics.* Clean Technologies and Environmental Policy, 2012. **15**(1): p. 9-20.

16. GWEC, *Global Wind Energy Council: Global Wind Report 2018*. 2019, Global Wind Energy Council.

17. Beiter, P., et al., *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030.* National Renewable Energy Laboratory, 2017(NREL/TP-6A20-67675).

18. Bosch, J., I. Staffel, and A.D. Hawkes, *Temporally explicity and spatially resolved global offshore wind energy potentials.* Energy, 2018. **163**: p. 766-781.

19. Staid, A. and S.D. Guikema, *Risk Analysis for U.S. Offshore Wind Farms: The Need for an Integrated Approach.* Risk Analysius, 2015. **35**(4): p. 587-593.

20. Dupont, E., R. Koppelaar, and H. Jeanmart, *Global available wind energy with physical and energy return on investment constraints.* Applied Energy, 2018. **209**: p. 322-338.

21. Huang, F., H. Wang, and B. Wen, *A grid-side reactive power control strategy for highly offshore wind power penetrated systems.* Renewable and Sustainable Energy Reviews, 2018. **10**.

22. Moller, B., *Continuous spatial modelling to analyse planning and economic consequences of offshore wind energy.* Energy Policy, 2011. **39**: p. 511-517.

23. Dedecca, J.G., R.A. Hakvoort, and P.M. Herder, *Transmission expansion simulation for the European Northern Seas offshore grid.* Energy, 2017. **125**: p. 805-824.

24. Houghton, T., K.R.W. Bell, and M. Doquet, *Offshore transmission for wind: Comparing the economic benefits of different offshore network configurations.* Renewable Energy, 2016. **94**: p. 268-279.

25. Jin, R., et al., *Cable routing optimization for offshore wind power plants via wind scenarios considering power loss cost model.* Applied Energy, 2019. **254**: p. 113719.

26. Daniel, J.P., et al., *National Offshore Wind Energy Grid Interconnection Summary.* U.S. Department of Energy, 2014.

27. St. John, J., *Offshore Wind Reaches Cost-Competitiveness withouth Subsidies*, in *Greentech Media*. 2017.

28. General Electric. *Haliade-X Offshore Wind Turbine*. 2019; Available from: <https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine>.

29. Lazard, *Lazard's Levelized Cost fo Energy Analysis - Version 12.0*. 2018.

30. Mora, E.B., et al., *The effects of mean wind speed uncertainty on project finance debt sizing for offshore wind farms.* Applied Energy, 2019. **252**: p. 113419.

31. AWEA, *U.S. Offshore Wind Industry Status Update*, A.W.E. Association, Editor. 2019.

32. Castle Wind, *Castle Wind and Monterey Bay Community Power Sign Agreement in Anticipation of Offshore Wind Project Off the Coast of Morro Bay*. 2019, Castle Wind.

33. *An Act Concerning the Procurement of Energy Derived from Offshore Wind*. 2019.

34. *An Act Concerning Clean Energy Jobs*. 2019.

35. *An Act to Advance Clean Energy*. 2018.

36. NJ Board of Public Utilities, *New Jersey Board of Public Utilities Awards Historic 1,100 MW Offshore Wind Soliciation to Orstead's Ocean Wind Project*, S.o.N.J.B.o.P. Utilities, Editor. 2019.

37. *Climate Leadership and Community Protection Act*. 2019.

38. Dominion Energy, *Dominion Energy Announces Largest Offshore Wind Project in US*. 2019: <https://www.virginiamercury.com/2019/09/24/four-things-to-know-about-dominions-massive-wind-farm-proposal/>.

39. Liu, J., et al., *Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China.* Environment International, 2019. **125**: p. 236-244.

40. Guan, D., et al., *Structural decline in China’s CO2 emissions through transitions in industry and energy systems.* Nature Geoscience, 2018. **11**(8): p. 551-555.

41. Lu, X., et al., *Opportunity for Offshore Wind to Reduce Future Demand for Coal-Fired Power Plants in China with Consequent Savings in Emissions of CO2.* Environmental Science and Technology, 2014. **48**: p. 14764-14771.

42. Zeng, J., et al., *The impacts of China's provincial energy policies on major air pollutants: A spatial econometric analysis.* Energy Policy, 2019. **132**: p. 392-403.

43. Lu, X., et al., *Optimal integration of offshore wind power for a steadier, environmentally friendlier, supply of electricity in China.* Energy Policy, 2013. **62**: p. 131-138.

44. Cali, U., et al., *Techno-economic analysis of high potential offshore wind farm locations in Turkey.* Energy Strategy Reviews, 2018.

45. Clancy, J.M., et al., *Fossil fuel and CO2 emissions savings on a high renewable electricity system - A single year case study for Ireland.* Energy Policy, 2015. **83**: p. 151-164.

46. Lu, X., et al., *Challenges faced by China compared with the US in developing wind power.* Nature Energy, 2016. **1**(6): p. 16061.

47. Holttinen, H. and S. Tuhkanen, *The effect of wind power of CO2 abatement in the Nordic Countries.* Energy Policy, 2004. **32**: p. 1639-1652.

48. Zhang, S., et al., *Modeling energy efficiency to improve air quality and health effects of China's cement industry.* Applied Energy, 2016.

49. Peng, W., et al., *Substantial air quality and climate co-benefits achievable now with sectoral mitigation strategies in China.* Science of the Total Environment, 2017. **598**: p. 1076-1084.

50. Xie, Y., et al., *Co-benefits of climate mitigation on air quality and human health in Asian countries.* Environment International, 2018. **119**: p. 309-318.

51. Peng, W., et al., *Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China.* Applied Energy, 2018. **218**: p. 511-519.

52. Yang, J., D. Song, and F. Wu, *Regional variations of environmental co-benefits of wind power generation in China.* Applied Energy, 2017. **206**: p. 1267-1281.

53. Yang, J., *Environmental and Climate Change Co-Benefits Analysis of Wind Power Generation in China.* Energy Procedia, 2016. **88**: p. 76-81.

54. Yuan, J., Z. Yuan, and X. Ou, *Modeling of environmental benefit evaluation of energy transition to multi-energy complementary system.* Energy Procedia, 2019. **158**: p. 4882-4888.

55. Ou, Y., et al., *Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution.* Applied Energy, 2018. **216**: p. 482-493.

56. Dimanchev, E.G., et al., *Health co-benefits of sub-national renewable energy policy in the US.* Environmental Research Letters, 2019. **14**.

57. Novan, K., *Valuing the Wind: Renewable Energy Policies and Air Pollution Avoided.* American Economic Journal: Economic Policy, 2015. **7**(3): p. 291-326.

58. Millstein, D., et al., *The climate and air-quality benefits of wind and solar power in the United States.* Nature Energy, 2017. **2**: p. 17134.

59. U.S. Department of the Interior and Bureau of Ocean Energy Management, *Evaluating Benefits of Offshore Wind Energy Projects in NEPA*. Headquarters,

Sterling VA,.

60. AWEA, *U.S. Wind Industry Annual Market Report, Year Ending 2018*. 2018.

61. Greene, J.S. and M. Morrissey, *Estimated Pollution Reduction from Wind Farms in Oklahoma and Associated Economic and Human Health Benefits.* Journal of Renewable Energy, 2012. **2013**.

62. Lu, X., M.B. McElroy, and N.A. Sluzas, *Costs for Integrating Wind into the Future ERCOT System with Related Costs for Savings in CO2 Emissions.* Environmental Science and Technology, 2011. **45**: p. 3160-3166.

63. Nordman, E., et al., *An Integrated Assessment for Wind Energy in Lake Michigan Coastal Counties.* Integrated Environmental Assessment and Management, 2014. **11**(2): p. 287-297.

64. Chiang, A.C., et al., *Emissions reduction benefits of siting an offshore wind farm: A temporal and spatial analysis of Lake Michigan.* Ecological Economics, 2016. **130**: p. 263-276.

65. Buonocore, J.J., et al., *Health and climate benefits of offshore wind facilities in the Mid-Atlantic United States.* Environmental Research Letters, 2016. **11**(7).

66. Reimers, B., B. Ozdirik, and M. Kaltschmitt, *Greenhouse gas emissions from electricity generated by offshore wind farms.* Renewable Energy, 2014. **72**: p. 428-438.

67. Huque, J.C.V.S.V.B.H.D.R.R.K.Z., *Life Cycle Environmental Impact of Onshore and Offshore Wind Farms in Texas.* Sustainability, 2018. **10**: p. 2022-2039.

68. Kaldellis, J.K. and D. Apostolou, *Life cycle energy and carbon footprint of offshore wind energy. Compariosn with onshore counterpart.* Renewable Energy, 2017. **108**: p. 72-84.

69. Apt, W.K.J., *Air Emissions Due to Wind and Solar Power.* Environmental Science and Technology, 2008. **43**: p. 253-258.

70. Bureau of Ocean Energy Management, *BOEM Announces Next Steps for Proposed New York - New Jersey Wind Energy Transmission Line: Includes Opportunity for Expressions of Competitive Interest and Public Comments*. 2019.

71. Lenox, C., *EPAUS9rT database for use with the TIMES modeling platform*. 2019: U.S. Environmental Protection Agency, Washington, DC.

72. Loulou, R., et al., *Documentation for the TIMES model. .* Tech. Rep. Energy Technology Systems Analysis Programme (ETSAP), 2005.