# Contribution of Offshore Wind to the Power Grid: U.S. Air Quality Implications

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Cara – main suggestions are to 1) address model capabilities related to adequately representing VREs 2) add comparison of cost assumptions for key technologies (osw, wind, solar, and ng), align result figures to present the same scenarios throughout the paper 4) discuss sectoral results in a more systematic way 5) small edits to the visualizations \*\* find tipping points for terrestrial, solar, ng, and coal

## 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 and future generation assets. Depending on the energy resources used by those generators, emissions from the electric power sector will change. This research explores combinations of two energy sector drivers, OSW costs and carbon dioxide (CO2) mitigation stringency, 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 (TIMES) energy system model and a nine-region 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 was introduced at higher rates due to costs more than CO2 mitigation stringency, though both had a measurable positive impact. Buildout varied more by CO2 mitigation stringency at higher prices and less at lower prices. Cara – not disputing this, but I don’t recall this being included in the discussion section. Is this a conclusion you want to lead with? Additionally, we found that while CO2 mitigation led to a statistically significant reduction in all five emissions investigated, OSW capacity only led to a statistically significant reduction in CO2 and PM2.5. We look at results nationally, analyzing the differences in adoption of OSW and how access to this technology provides a broader range of emission reduction options for the power sector.

## Keywords

Offshore wind energy; energy system scenarios; cost optimization; carbon dioxide mitigation; air quality

## Highlights

* Offshore wind capacity is modeled for the U.S. based on cost and CO2 cap scenarios
* Natural gas and coal generation are most displaced by offshore wind
* PM2.5 and CO2 emissions are reduced most significantly by offshore wind additions
* Cost is the chief barrier to achieving these emissions reductions

## 1. Introduction and objectives

Offshore wind (OSW) is a renewable energy resource available over coastal and great lake waters. Its low variability and low uncertainty paired with its proximity to large population centers makes it a prime candidate for electricity production. Offshore winds 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 coastal population has increased by 40% since 1970 [1, 2]. While electricity consumption per capita has declined with energy efficiency improvements and adoption, total consumption continues to grow as there is less coastal area available for development. What is available is expensive due to these availability constraints. Jacky – Not sure you need this paragraph … It seems to be just another thing but not something that impacts the rest of the results…

OSW in the U.S. has an estimated 10,800 GW of resource potential, 2,058 GW of which are technically feasible for development [3]. Though the resources are vast, only 30 MW of this potential has been realized with the first and only operating OSW farm in the U.S., the 5-turbine Block Island Wind Farm located off the coast of Rhode Island, that came online in late 2016. It is, however, a relatively expensive technology. Many factors contribute to the high cost, the most impactful being complex installation that requires highly-skilled instrumentation and labor at sea [4, 5]. 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 and costly transmission lines [6].

Twenty-four coastal and Great Lakes states and Washington D.C. have instituted Renewable Portfolio Standards (RPS) and twenty have set greenhouse gas (GHG) emissions targets [7, 8]. 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 [9, 10]. It is unclear exactly how OSW will fit into this changing landscape, and what impact it will have – Jacky recommends taking this out.

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: 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 declining costs 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 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, NOx, and PM from the power sector, such as the Acid Rain Program and Cross-State Air Pollution Rule, but not yet 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 and the stringency of those targets.

The 2019 Annual Energy Outlook produced by the U.S. Energy Information Administration (EIA) projects that electric sector emissions will remain flat through 2050, assuming there are no significant changes to laws and regulation [11]. Currently, the sector contributes approximately 69% of SO2 emissions, 33% of CO2 emissions, 14% of NOx emissions, and 3% of PM 2.5 emissions. Methane emissions in the U.S. occur primarily through natural gas and oil production, transmission, storage, distribution, and processing. These sources feed into the electric sector as it consumes approximately 36% of natural gas used in the U.S. [12, 13].

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 [14]. 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 study 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.

## 2. Background

Cara – If your intent was to compare the success with Eorope with that of the US, then you should quantify the quality of the resource between the two regions and then later in the next paragraph explain why high VRE penetration isn’t an issue in Europe etc… \*\* could just skip the sentence with “several reasons why deployment has not taken off in the U.S…” and go straight to “significant research…” then list research areas

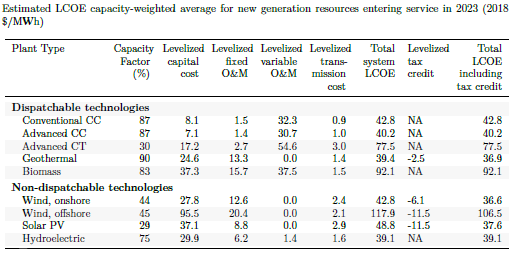
Despite the success of OSW in Europe, with over 18.9 GW of installed capacity, there are several reasons why deployment has not taken off in the U.S. and globally. It has reached cost competitiveness with many other technologies, though terrestrial wind and solar photovoltaic (PV) still remain less expensive than OSW [15]. OSW is a renewable technology that requires wind as a natural resource for electricity production. Though this resource varies across time and between regions, the U.S. has substantial resource availability [3]. Significant research has been conducted to investigate the feasibility of harnessing U.S. resources, specifically accounting for technological limits, land availability, risk factors, and economics [16-18]. A recent approach developed by Dupont et al. works to include Energy Return on Investment (EROI), incorporating more robust econometric measures into the assessment [19]. The U.S. Department of Energy has done a 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 interconnecting large amounts of OSW energy to the U.S. grid, however realizing this potential will be both complex and difficult [20].

Adding a high penetration of variable renewable resources to the grid is a major complexity due to their non-dispatchability. Huang et al. developed control strategies for grid operators for highly OSW penetrated systems [21] that can be paired with research by Moller et al to harness spatial modeling for later-stage planning [22]. Also, there remains the issue of transmission of the 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 developed by multiple research teams, showing promising solutions for the vast technical difficulties [23-25].

OSW is still at a relatively early stage of technology development, even in Europe, and prices are expected to fall further as the technology advances [26]. 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 [16]. Supply chain and infrastructure advancements are key to these price declines, but the largest contributor is 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 doubled to a 12 MW capacity and is 863 ft tall, increasing its capacity factor by five to seven percent above the current industry standard [27].

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 [28]. 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 [20]. 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. [29].

Table 1. AEO 2018 LCOE [11]



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 work in California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, and Virginia [30-37]. The U.S. market 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 [30].

Renewable energy has grown significantly in the U.S. as states have adopted RPS and emissions reductions goals, especially as costs have declined. Cara – I don’t think its necessarily fair to attribute the growth of renewables in the US to state policies. Manufacturing efficiencies overseas and federal incentives played a significant role. \*\* “renewable energy … but is still uncertain how OSW will play a role” 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, incentive policies, 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 OSW within their own contexts. These efforts have focused primarily on European countries and China, as they were the first and most prolific adopters of renewable technologies. Many researchers have begun assessing the opportunities in China for OSW to offset carbon-intensive generation [38-40] as well as more wholistic investigation into OSW planning for emissions reductions goals [41, 42]. Similarly, research has sought to quantify the ability of renewable technologies to contribute to emissions goals [43-45], and wind specifically [46]. This 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 [47, 48] and more general climate mitigation efforts [49, 50]. Additional research has quantified the environmental and climate co-benefits of low carbon technologies [51-53].

U.S.-specific research has estimated the environmental co-benefits of low-carbon pathways [54, 55], and has begun to investigate wind specifically [56, 57]. In 2017, BOEM issued a report evaluating electricity system, environmental, and socioeconomic benefits offered by OSW [58], 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 [59], allowing for real-time analysis of emissions mitigation potential and the resulting impacts on and benefits for environmental, human health, and climate [60, 61]. As interest in OSW has grown, so has investigation into the co-benefits that the technology can bring at the local level. Two studies 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 [62, 63]. 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 [64]. 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 [65-67], and there are emissions consequences when variable renewable resources must be paired with dispatchable, fossil-fuel generators to meet demand when renewable generation drops [68]. These contextual emissions have not yet been worked into a larger systems-approach to emissions mitigation, nor are they accounted for in this study.

These studies demonstrate the direct effects and benefits of wind technologies to their surroundings, but do not quantify the national impact that OSW would have on emissions. 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 [69]. 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. The growing state and federal interests in OSW require a more robust analysis of this technology within the broader system.

Jacky – This background is HUGE. You need to decide on key issues, give background ONLY on those issues, and give results and conclusions only on those issues. There is far too much verbiage for one manuscript. If there are this many points, it may do well to break into two papers. There is also lots of repetition here – make this background concise … it should not take up more than 1 page.

## 3. Materials and Methods

3.1 Model and Database

Cara – when modeling high VRE penetration scenarios, model specs like spatial and temporal resolution become more important. This section lacks a discussion of the model’s capabilities, its strength and weaknesses and in turn, how those impact the model results. I think the paper would be much stronger if you took this head on. Describe the spatial/temporal resolution, how capacity credit for VREs is estimated, how curtailments are calculated, and any other critical model components. For guidance/background look at the [IRENA](https://www.irena.org/publications/2017/Jan/Planning-for-the-renewable-future-Long-term-modelling-and-tools-to-expand-variable-renewable-power) long term modeling paper and [NREL](https://www.nrel.gov/docs/fy18osti/70528.pdf) variable renewable energy in long-term planning models paper \*\* discuss about availability factors and time slices and how the model decides how much capacity to build. All available capacity isn’t used, but all generated elc is used

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 modeling system to investigate energy system futures that optimize for lowest cost over all economic sectors [70]. This allows the use of one model for all sectors instead of a piecemeal approach, showing the interplay and tradeoffs between sectors as scenarios change. Cara – I think the greatest value of the TIMES model is this element you highlight here, but the discussion only touched this in a couple of tangential points. Could you possibly tease out more insights related to the energy-economy impacts, otherwise why wouldn’t we just do this analysis in a power-sector model that has greater temporal/spatial resolution \*\* leave this in here and then specify in the results that there were negligible changes in the other sectors

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) [71]. 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 Cara – include time segment assumptions to model for long time-horizons [72]. 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 GAMS modeling language that maximizes system surplus and minimizing system costs. This formulation is called the *total system cost* [71].

Equation 1: TIMES Objective Function

Where:

* *NPV* is the net present value of total cost for all regions;
* *ANNCOST(r,y)* is the total annual cost in region *r* and year *y*;
* *dr,y* is the overall discount rate;
* *REFYR* is discounting reference year;
* *YEARS* is the number of years for which the results will be modeled; and
* *R* is the group of regions in the 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 [71]. 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 4. Cara – this spatial resolution is not that great considering the type of analysis you are trying to conduct. See previous comment [NREL](https://www.nrel.gov/docs/fy16osti/66002.pdf) – evaluating the value of high spatial resolution in notational capacity expansion models using reeds 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 eight (8) regions, the model represents technologies for OSW spanning the following characteristics: water depth (shallow and deep), wind class, and cost class. Capacity factors vary 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.

3.2 Scenarios

CO2 mitigation scenarios were constructed to linearly reduce emissions from 2010 to 2050 by percentage of 2010 electric sector CO2 emissions and were implemented as an electric sector CO2 upper bound (CO2 cap) (Figure 1a). The 2010 emissions were calculated endogenously, using the TIMES model and EPAUS9rT database. The baseline emissions reduction scenario assumed no carbon mitigation requirement and reaches approximately a 25% CO2 reduction by 2050. This case will be referred to as the business as usual (BAU) emissions case. Each subsequent scenario increased the required carbon mitigation percentage by 10%, until an 80% carbon reduction is achieved by 2050.

Cost curves for OSW were constructed to linearly decline from 2015 to 2035 by a percentage of current costs and hold steady until 2050 (Figure 1b). Capital expenditure (CAPEX) was calculated using base overnight costs presented in the Energy Information Administration’s (EIA) Annual Energy Outlook 2019 (AEO) [11]. The baseline cost reduction scenario assumes a 20% cost decrease, as is expected through normal technological advancement and “learning”. Cara – shouldn’t there be a shared learning effect with onshore wind? Would there ever really be a scenario where offshore capex is less than onshore? They are the same technology, except one requires additional costs for cabling and a platform. What are your cost assumptions for onshore wind and in which scenarios does the cost fall below onshore? The discussion section was fairly vague on this point \*\* check to see when osw becomes cheaper than solar and terrestrial wind – then address it. Can reword to say “learning” because its an entirely new tech. solar and wind have already gone through that. Five additional cost curves were constructed at 10% intervals, spanning from a 30% to an 80% reduction in the cost of OSW by 2035.

The reference case for this study is represented with the BAU CO2 cap and 20% OSW cost reduction scenarios.

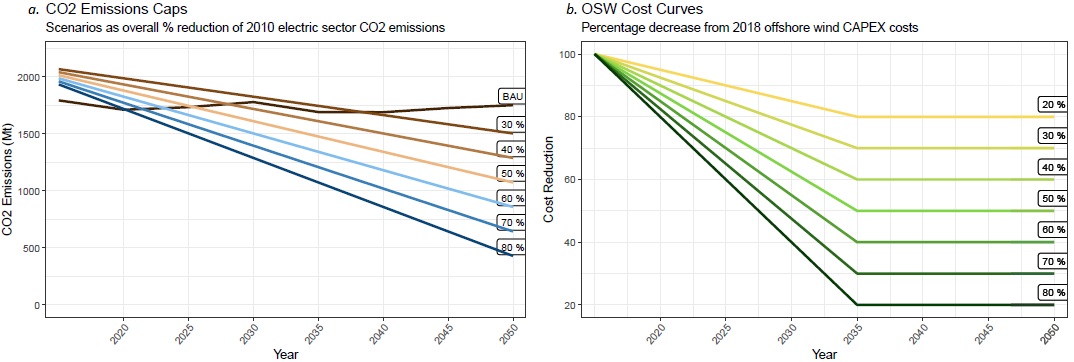


Figure 1. a. CO2 Cap and b. OSW Cost Curve Scenario Construction

Update with new graphs with 2015 added to the axis

## Results and Discussion

Cara – The depiction of the results across all of your figures was hard to follow at times. I think that you should show the same set of information consistently. I would like to propose showing the following combinations only:

CO2 Cap: BAU, 40%, 60%, 80%

Cost Reduction: BAU (20%), 40%, 60%, 80%

That would mean modifying figures 2,3,5,7,8,9 and Table 2. That’s a lot but I think it would be a huge improvement on the readability of the results

A total of 49 scenarios were created, representing the combination of all cost curves and CO2 caps. The model results show that OSW was not built out in all cases, as represented in Figure 2. Until the cost of OSW is reduced by 40%, it is not economically viable, and at 40% cost reductions it is only built in the most stringent carbon mitigation scenario. At a 50% cost reduction 21 GW of OSW is built by 2050 in the 80% carbon mitigation scenario, though only 11 GW is built in the 70% carbon mitigation scenario. At a 60% cost reduction and above, OSW is built in all carbon mitigation scenarios, with the largest capacity coming at the highest cost reduction across all carbon mitigation scenarios.

Cara – Many of the results presented in your paper are of 2050. Do you know how end-year effects are managed in your model? It may not be a concern, but something you should be aware of. It doesn’t necessarily need to be included in the paper \*\* Figure out what the end-year effects are and address them when I first introduce 2050 results

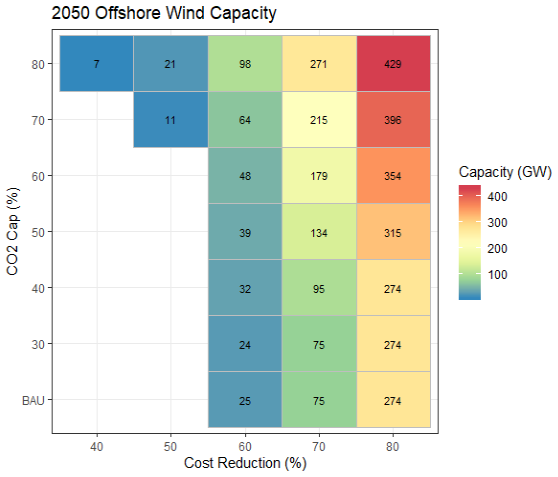


Figure 2. Total OSW Capacity in 2050

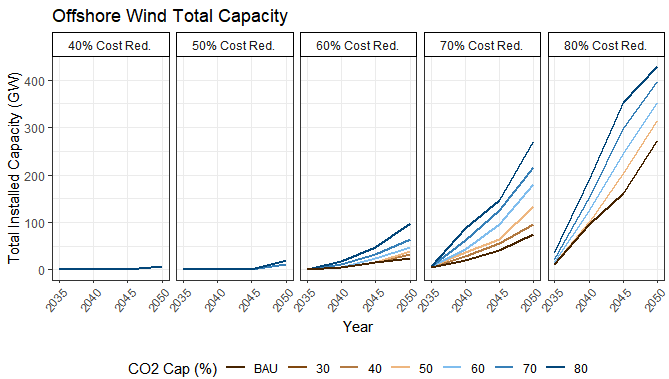


Figure 3. Total OSW Capacity by Scenario

OSW’s sensitivity to carbon mitigation stringency is well defined across all technology costs. More stringent carbon caps elicit the buildout of OSW sooner, and at larger capacities (Figure 3). Additionally, the less expensive OSW becomes, the more capacity is built out each time period, regardless of carbon mitigation stringency.

Overall buildout of OSW varied across regions, with no capacity added in Regions 4 and 6 due to minimal resource availability and comparably higher costs and Region 8 due to no resource availability (Figure 4). The EPAUS9rT database does not have OSW availability for Region 8 because there is no coastline, and Regions 4 and 6 have very little resource availability. Of the regions where OSW was built, Region 5 elicited the largest buildout and Region 7 the smallest, though the differences also varied between scenarios.

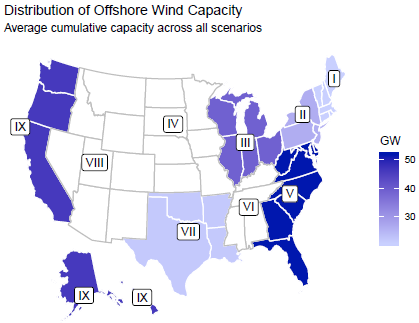


Figure 4. Average OSW capacity per region across scenarios

Cara – in 2050? Please add to the figure title. Don’t know if its appropriate to average results across scenarios. You should show the regional results for just one scenario, like your median or your most extreme results. Please add census region boarders to your map. Earlier in the paper you reference this figure to illustrate your regional assumptions, but I cant see the division between regions IV and VIII \*\* Pick 60 or 70% case and use paint to add in black dividers between regions

OSW, as a new technology, can be built to replace existing generation or to add capacity as electricity demand grows. All scenarios show electricity demand growth over time, but the degree of the growth varies between scenarios. Cara – I had a hard time reading this sentence, consider swapping the order of the phrases: “By 2050, as CO2 caps become tighter, they limit the increase in total electricity generation, showing…” CO2 caps limit the increase in total electricity generated as they become tighter, showing that the carbon constraint affects demand and electricity end uses (Figure 5). As OSW gets less expensive, however, total electricity production grows, compensating for and even increasing the total output over the reference case. When OSW is the least expensive and there is no carbon cap, total electricity production is 9% greater than when it is most expensive with a stringent carbon cap. Cara – are these values calculated off of the BAU or the 40%? The text implies that it is the BAU, but the calculations align with the 40% and the BAU values arent shown. \*\* Specify which cases are being used Across the tightest carbon cap scenarios, OSW is still able to elicit a 5% increase in total electricity production when it is least expensive. Cara – See comment later on in the industrial sector results. I think you should move that up here and have a more complete discussion on demand changes by sector \*\* move up here and talk about the switch. Then just reference the emissions effects later on

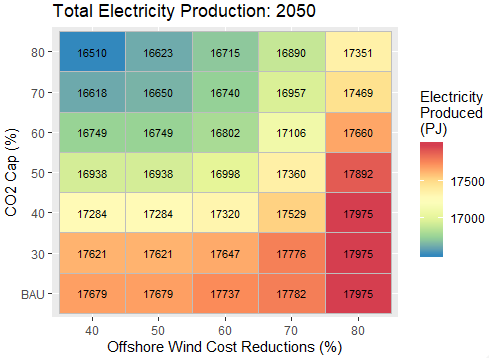


Figure 5. Total electric sector electricity production in 2050

Cara – If the results are showing electricity generation, then the units should be in MWh not EJ. I would recommend presenting the results in these units. When you’re discussing energy in EJ or BTU the value reported is typically primary energy, which include conversion losses. If this is the case, conversion assumptions become important and you should explain your assumptions, especially for renewables since there isn’t consensus on reporting (e.g. fossil fuel equivalency v incident approach). She lists three papers to refer to \*\* think about converting results to MWh instead of PJ

In most cases, the deployment of OSW displaces coal, natural gas, terrestrial wind, and solar PV (Figure 7), though the technologies displaced vary between scenarios. Figure 7 shows the differences in electricity production between the indicated cases and the reference case (Figure 6), with net increases above the dotted red line and net decreases below the red line. When OSW cost reductions are only 50%, little OSW is built. In order to meet the increasingly stringent CO2 caps, solar, terrestrial wind, and coal carbon capture and storage (Coal CCS) are built and displace the existing coal and new natural gas built in the reference case. At a 60% cost reduction, more OSW is built, displacing what would have otherwise been new solar, terrestrial wind, or coal CCS. As costs decrease to 70% and 80%, almost all added capacity is OSW, as it becomes less expensive than other carbon-free electric generation resources.

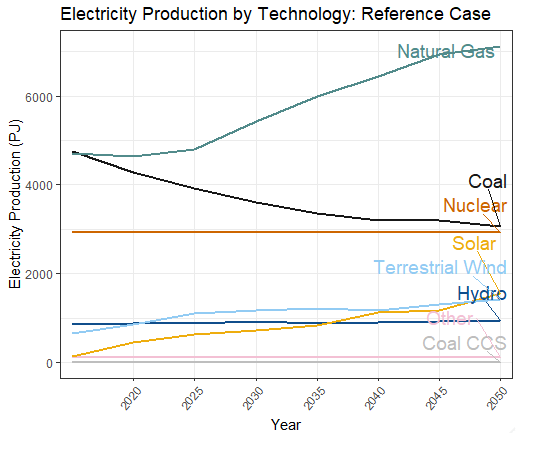


Figure 6. Reference case electricity production by technology

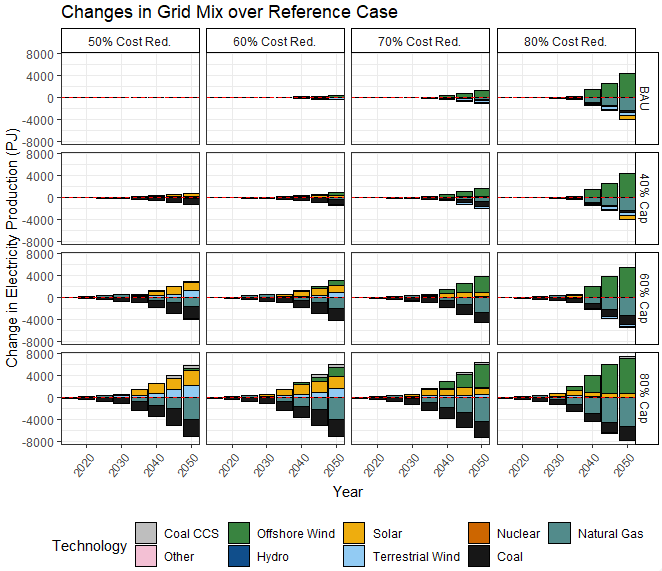


Figure 7. Capacity additions and retirements in relation to the reference case

Cara – I like the figure 6+7 combo but might I also suggest some alternatives? It would be nice to replicate figure 7 two more times. First, changes relative to the cost reduction BAU across cap scenarios. Second, the opposite, changes relative to the BAU CO2 emissions across cost reduction scenarios. These two figures would tie in nicely into illustrating your first regression analysis \*\* This figure shows all of that. I will explain better all of the data represented here. Explain the graph in the way she’d like to see it. Try a cumulative graph and put it next to this one and see if its worthwhile

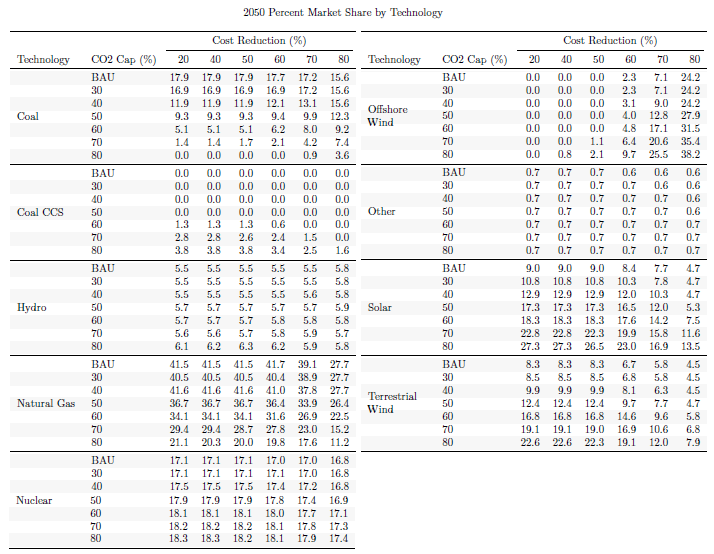
Cara – it might be nice to include a separate figure and discussion on how curtailments change across scenarios \*\* TIMES model as used for this analysis doesn’t include curtailments

In scenarios where OSW costs are low and new capacity is high, natural gas is the most displaced technology, whereas in higher OSW cost and low capacity scenarios more coal is retired. Natural gas makes up a large market share of the 2050 power grid in all scenarios regardless of OSW buildout (Table 2), but natural gas capacity additions are dramatically reduced as the cost of OSW falls. Coal sees a similar displacement when OSW is built out in low quantities, though as OSW costs decline and capacity increases coal retirements slow and more existing coal remains over time. This shows the tradeoff between building new carbon-free but non-dispatchable capacity and needing to meet demand at all times.

Over all scenarios, the largest market share that OSW achieves is 38% in the lowest cost and highest carbon mitigation stringency scenario. In all lowest cost reduction scenarios, OSW gains significant market share, but as costs increase that market share is more sensitive to the stringency of the CO2 cap.

Cara – in addition to the other recommendations of dropping the 30/50/70 results, drop the “other” table. Its not important and doesn’t change significantly over time. Since the story is about osw, have your renewables on the left side, starting with osw and non-re on the right.

Table 2. Percent market share by technology in 2050 (Technology PJ/Total electric sector PJ)



Additionally, as OSW becomes less expensive than solar and terrestrial wind, Cara – when does this happen? I feel like there have been a couple of instances in the paper where adding info on the cost assumptions across technologies would help with interpreting results \*\* figure out and add here and above these renewable technologies retain marginally less market share than they would have in the reference case. However, the total contribution of renewables increases as OSW costs decrease, across all CO2 cap scenarios since OSW capacity additions equal or surpass those of other renewable sources.

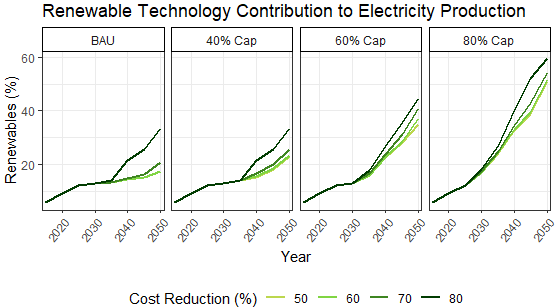


Figure 8. Percent of electric sector production from renewable technologies. Renewable technologies include solar, terrestrial wind, and OSW.

Cara – I don’t know about such high penetrations of VREs with only 16 time segments. What do the regional results look like? What are your transmission assumptions between regions? Are you building storage? \*\* add info about transmission representation in TIMES and that CAPEX includes transmission

Electric sector CO2 emissions constraints similarly constrain the other emissions investigated because they are cogenerated during fossil fuel combustion. The addition of OSW to the grid mix and the changes that it elicits vary the degree to which these emissions are reduced. As shown in Figure 9, all pollutants saw a significant reduction in emissions, with the greatest reduction in SO2. The dramatic decrease in SO2 emissions stems from the model’s representation of existing SO2 policies severly limit electric sector emissions and have realized benefits after the 2010 reference year. There is a clear trend showing greater reductions in all emissions as carbon mitigation stringency increases. For CO2, SO2, NOx, and CH4, tighter carbon constraints lead to emissions reductions surpassing the reference case beginning no later than 2030. This does not hold for PM2.5, however, as OSW costs cause more variation in the pace at which this emission is reduced Jacky – Why?. Due to the tradeoff between OSW and the slowing of coal retirements, PM2.5 emission reductions do not outpace the reference case when OSW is less expensive and gains larger market shares.

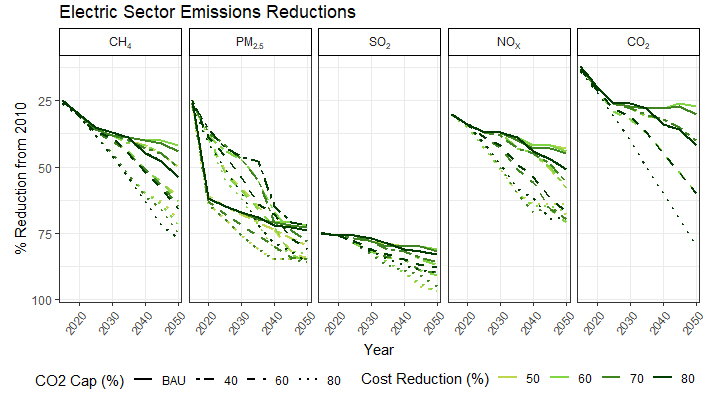


Figure 9. Electric sector emissions reductions

Cara – Using a start year of 2010 was an input assumption, but it doesn’t make sense to present the results in this way. You should present the change in emissions from 2015 or 2018. You can use actuals if model results have too much spread, but hopefully they don’t. Once you’ve addressed this, you’ll have to update your discussion above. Since your CO2 results are decreasing by sets of 10%, maybe change the y-axis tick marks and grid lines to be every 10% or 20% instead of every 12.5%. These figures are hard to read. A few suggestions on how this might be improved: Consider a set fo panel figures similar to figure 7, with pollutant as each column and co2 caps and each row and cost reduction as each series (or vis versa). Since CO2 results are an input assumption, do you even need to include it here? Maybe losing one panel and enlarging the others will help. Maybe it will be easier to read if you make the original change I siggest, in which case you can ignore this comment entirely \*\* try 2015 or 2018 as baseline from % reduction and see what they look like. Try emissions~emred facets

Another less obvious tradeoff occurs in the industrial sector. Cara – instead of making this paragraph a random something of note, I think structuring this to be a more systematic discussion around sectoral changes would be better. Then, you should move this up in your report. It should follow the paragraph discussing the overall change in electricity demand (production). For instance, you could start off in the changes in overall demand and then talk about the changes in each sector. This doesn’t have to be a huge addition, but more of a structural change. Another benefit to making this move would be that the discussion would flow better between the overall summary of emissions impacts above to the regression analysis on emission impacts below. The industrial sector both consumes electricity provided by the grid and produces its own using combined heat and power (CHP). The CO2 cap scenarios only apply to the electric sector and do not include emissions from industrial CHP. As the CO2 cap tightens, there is a small shift from industrial grid electricity use to CHP electricity production (Figure 10). While there is an increase in emissions from increased CHP, the increases are minimal in comparison to the much larger reductions seen in the electric sector as a whole.

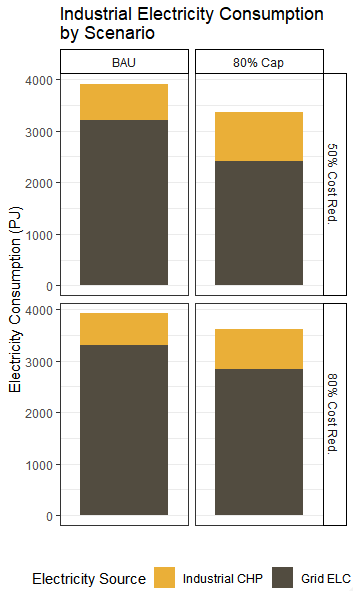
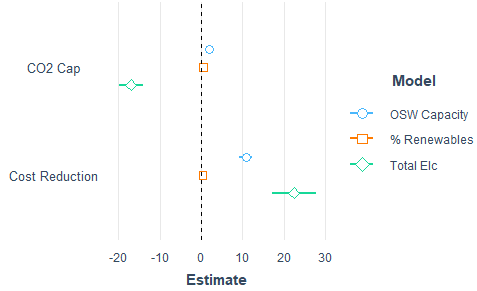


Figure 10. Industrial sector CHP and Grid electricity use

Cara – by 2050? I think you should switch these two series so that the industrial CHP is on the bottom. It would make the change easier to read \*\* will switch CHP to the bottom

Due to the fact that OSW displaces emissions-neutral and fossil fuel technologies differently between scenarios, it is difficult to qualitatively untangle the effects of OSW costs and carbon mitigation stringency on total emissions reductions. Investigating 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 8). Additionally, carbon mitigation stringency had a marked impact on total electricity production, reducing overall production in scenarios with high mitigation stringency (Figure 5).

Two sets of regression analyses were used to identify the strength of the study parameters’ effects on the electric sector and its emissions. All regression analyses use 2050 values for the independent variables and are applied across all model runs that had OSW buildout. Cara – this seems odd ot me. I’m not very familiar with people doing a stochastic analysis on deterministic results. Not saying this is wrong, but something I am less familiar with. Maybe you could cite a paper where people have applied this in the past? Maybe in the methods section or here. Are the relationships sufficiently linear enough to be doing this? \*\* add a paper or two with this type of regression analysis The first set of regressions looks at the impact of the scenario parameters, CO2 caps and OSW costs, on total OSW capacity, percentage of renewable generation, and total electricity production. Figure 11 shows the parameter coefficients, or strength of the parameter effects, for all three independent variables. All coefficients are statistically significant for both CO2 caps and OSW cost reduction. Cost reduction has a substantially greater positive influence on OSW capacity than carbon mitigation stringency, though both contribute to higher OSW capacity. Both parameters also have a positive effect on the market share of renewables, with CO2 caps playing a greater role increasing that share. Total electricity production is reduced by the CO2 caps but increased by OSW cost reductions. The increase achieved by OSW deployment outweighs the reductions caused by the caps, leading to a net increase in production as OSW costs decrease. Jacky – Error bars? Units? For both figures – also more descriptive title for these figures \*\* Most likely to take out the two graphs and just leave the regression tables



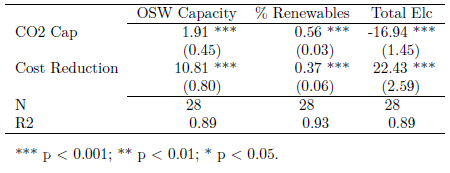
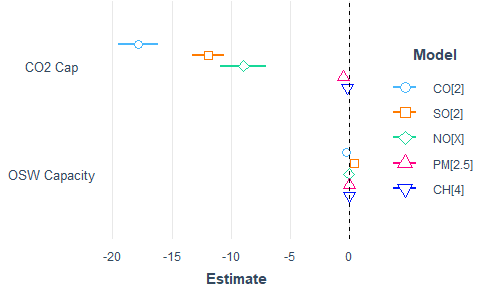


Figure 11. Electric sector regression analyses

Cara – I’m a big fan of having the zero axis either on the end or in the middle of a figure. Consider updating the scale of the x-axis to -30 to 30. This would illuminate your last point made in the previous paragraph. Is N=28 right? Figure 2 shows 24 instances (maybe 26 if you include BAU and 30% cost reductions not shown). I wonder if N is large enough? \*\* Need to better characterize results were chosen for any cost curve in which osw was built in any of the co2 cap scenarios, not only the specific scenarios where osw was built. Consider adding a table at the end with stats tests results to verify data is good for this analysis.

The second set of regressions looks at the impact of two parameters, CO2 caps and OSW capacity, on electric sector CO2, SO2, NOx, PM2,5, and CH4 emissions (Figure 12). Cara – absolute values? I ask because earlier your presented emissions results as a percent reduction \*\* change regression so that its on the % reduction in each emission, not absolute value. Make consistent with % reduction from the year chosen above (2010, 2015, or 2018). OSW capacity is used instead of OSW cost reductions in order to more closely align the direct effect of OSW on electric sector emissions. CO2 caps show statistically significant reduction effects on all five emissions. OSW capacity effects were only statistically significant for CO2, SO2, and PM2.5. OSW contributes to CO2 reductions, though to a much smaller degree than the CO2 caps, which is to be expected. SO2 increases as OSW capacity increases, though again, to a much smaller degree than the CO2 caps reduce SO2, leading to a net decrease in SO2 emissions for all OSW cost scenarios. PM2.5 is reduced as OSW capacity increases, though the reduction effect of the CO2 caps outweighs the effect of OSW capacity.



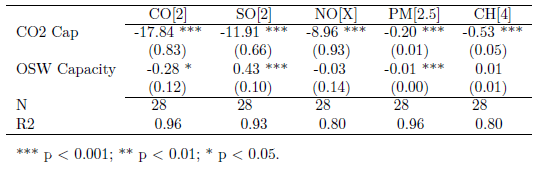


Figure 12. Emissions regression analyses

These regression results include all model runs that had OSW buildout, providing meaningful but broad insight into the emissions reduction potential of the two study parameters. In order to more acutely assess the potential for OSW to reduce emissions, we conducted a third set of regressions, one for each set of runs at a given CO2 cap. These regressions showed a much stronger potential for OSW to contribute to emissions reductions, with negative and statistically significant coefficients for OSW capacity for all five emissions in the BAU cases. All coefficients were negative, but not all were statistically significant with 30% CO2 cap. For all other carbon mitigation scenarios, OSW affected emissions more consistent with the regressions shown in Figure 12.

## Conclusions

Jacky – These conclusions have too much repetition and are too scattered. They need to match up with the items laid out in your background/intro. Also need to be more concise – fewer paragraphs

In this research, we used a TIMES modeling framework to assess the potential for OSW capacity expansion and its sensitivity to CO2 mitigation stringency and OSW cost reductions. We also measured the impact that OSW capacity would have on the generation resource makeup of the grid and the resulting emissions implications.

This paper found that costs for OSW will need to decrease by at least 40% to compete on the market with other technologies, both renewable and fossil fuel. When costs are reduced by 50%, substantially more OSW is built, as with 60%, 70% and 80%. OSW reaches its highest modeled market share at 38% with cost reductions and CO2 mitigation both at 80%. At each price point, more OSW capacity is built as CO2 mitigation stringency increases. Both study parameters have a positive effect on capacity buildout as they increase, with costs having the greatest positive impact.

The pipeline for OSW development in the U.S. is growing and the research about the technical feasibility is robust, but we are missing the future-looking research to assess how this technology will fit in, what will be displaced and when, and how it might affect our air quality and emissions goals. This research characterizes OSW within this context to show how the grid’s generation mix will change. As carbon mitigation stringency increases, natural gas and coal are displaced at higher rates. When OSW is too expensive to compete in the market, solar and terrestrial wind capacity is added to meet demand and lower emissions to meet the cap. As OSW costs decrease, it is better able to compete with other renewable technologies, as well as new natural gas and existing coal. With lower OSW costs, there is a greater displacement of new natural gas and slower growth of solar and terrestrial wind. Despite slower solar and terrestrial wind growth, OSW capacity additions lead to an overall increase in renewable contributions ot the grid. It is to be noted, however, that the model does not account for political feasibility of building OSW, which has proven to be a contentious technology in the U.S.

Jacky – Combine next three paragraphs and make more concise

CO2 caps elicited statistically significant reductions in CO2, SO2, NOx, PM2,5, and CH4 emissions. OSW capacity elicited statistically significant reductions in CO2 and PM2.5, though these reductions are smaller than those from the CO2 caps. SO2 is statistically significantly increased by OSW capacity, though there is still a net reduction due to the CO2 caps reduction effects. Cara – NG is more dispatchable than coal. Why does coal stop retiring, why wouldn’t it just be replaced with NG? I had a coment in the discussion section earlier that touches on this. I just think this needs to be explained more \*\* table until further assessment Higher capacities of OSW, especially in the 80% cost reduction scenarios, require a greater capacity of dispatchable resources, slowing coal retirements by keeping them running longer than they would otherwise. Thus, this tradeoff impacts the potential for OSW to lower SO2 and PM2,5 emissions. OSW capacity elicits more pronounced and consistent reductions in all emissions at the least stringent CO2 caps as there is no forced tradeoff between OSW and coal.

Some of the emissions reductions in the electric sector are offset by gains due to end-use sector electricity production. Under tight CO2 caps, the industrial sector consumes less electricity from the grid, where the CO2 cap is applied, and increases its own electricity production with CHP. Despite the increase in industrial emissions, there is still a significant overall reduction across all emissions.

The benefits of systems approach, as is the case with the TIMES model and EPAUS9rT database, can be seen in the identification of these tradeoffs. OSW is a new technology to the U.S. and its potential energy system effects cannot be fully analyzed unless the system can be seen as a whole. With new emerging technologies, such as electric vehicles and hydrogen fuel, the electric sector and electric generation are less isolated than they have been in the past. In many ways, electricity operates more as a traditional fuel as the economy is electrificed and generation resources diversify. With this research we are able to characterize the role that OSW plays in this system, as well as the potential it holds to reduce emissions.

Jacky – too much info for future work – this is supposed to be conclusions about current work [take out last two paragraphs]

Further research might apply this methodology to a database that includes the OSW mandate policies of U.S. states and incorporates technology learning curves based on the current pipeline, assuming it comes to fruition. The technology landscape and cost reduction pathways are not yet realized, and state policies are likely to shape these as OSW begins to be built. Changes to emerging technology costs, and thus electricity costs, are likely to affect end-use electrification and cross-sector tradeoffs. Focusing research in this area could assess system-wide emissions outputs and sensitivities to the model parameters. Additionally, incorporating OSW live-cycle anlyses and emissions accouting could give a broader picture of the total emissions implications of adding OSW capacity.

The emissions reduction potential of OSW was analyzed at a national level in this study, but the TIMES-EPAUS9rT modeling system can provide results at the census region level. CO2 caps could instead be applied at the regional level to better mimic state RPS and emissions goals. Extending the study to quantify emissions reduction benefits for environmental and human health would provide additional assessment of OSW, or another emerging technology, at a national or regional level.

## Notes on Modeling

The TIMES model [71] was implemented using the VEDA FrontEnd and BackEnd software suite and the EPAUS9rT database. OSW representation was developed for the database using the National Renewable Energy Laboratory’s Regional Energy Deployment System (ReEDS) model and database. No additional transmission expansion or offshore transmission system was modeled. This version of the EPAUS9rT database can be made available upon request by contacting author Carol Lenox (lenox.carol@epa.gov).

## Disclaimer

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. The authors declare no special interests.

## Acknowledgments

The authors would like to thank Dr. Jacky Rosati and Ms. Cara Marcy for their valuable input during the administrative review of this manuscript.

## Data Availability

The EPAUS9rT database and its corresponding documentation can be found at

<https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=346478>.

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