Analyzing the Deployment of Large Amounts of Offshore Wind to Design an Offshore Transmission Grid in the United States

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Analyzing the Deployment of Large Amounts of Offshore Wind to Design an Offshore Transmission Grid in the United States

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***Abstract*—This paper revisits the results from the U.S. Department of Energy's report *20% Wind Energy by 2030*, which envisioned that 54 GW of offshore wind would be installed by said year. The analysis was conducted using the Regional Energy Deployment System (ReEDS), a capacity expansion model developed by the National Renewable Energy Laboratory. The model was used to optimize the deployment of the 54 GW of wind capacity along the coasts and lakes of the United States. The graphical representation of the results through maps will be used to provide a qualitative description for planning and designing an offshore grid. ReEDS takes into account many factors in the process of siting offshore wind capacity, such as the quality of the resource, capital and operation and maintenance (O&M) costs, interconnection costs, and variability metrics (wind capacity value, forecast error, expected curtailment). The effect of these metrics in the deployment of offshore wind will be analyzed through examples in the results.**

Keywords-capacity expansion; long-term planning; offshore wind power; power systems; transmission planning; transmission systems; variability

I. Introduction

There has recently been increased interest to investigate how the installation of offshore transmission grids can enhance the appeal of offshore wind energy. Offshore wind has already been deployed in Europe, but no offshore farms currently exist in the United States. It is believed that the design of an offshore transmission grid would accelerate the deployment of offshore wind in the States.

In 2011, the U.S. Department of Energy (DOE) funded the National Offshore Wind Energy Grid Interconnection Study (NOWEGIS), among other projects, with the aim of addressing DOE's two critical objectives in overcoming offshore wind barriers: to reduce the cost of energy and to reduce deployment timelines. NOWEGIS is currently underway, led by ABB with participation of Duke Energy, AWS Truepower, the University of Pittsburgh, and the National Renewable Energy Laboratory (NREL). The study is analyzing the process of planning and designing an offshore transmission layout that would accommodate the levels of deployment envisioned in DOE's report *20% Wind Energy by 2030* [1] and its benefits. However, such a layout is highly dependent on the forecast for timing and location of offshore wind capacity coming online.

Thus, the first task in the study—and subject matter of this paper—is the determination of the location and timing for the development of the 54 GW of offshore wind capacity determined in [1]. The deployment was determined using the Regional Energy Deployment System (ReEDS) model developed by NREL [2]. This paper presents draft offshore wind deployment results produced for the NOWEGIS project.

The remainder of the paper is organized as follows: Section II introduces ReEDS and the principles behind its design; Section III summarizes the assumptions used; Section IV analyzes the results; and Section V concludes.

II. Regional Energy Deployment System

Modeling future renewable energy scenarios requires tools that can accommodate the diversity of the various renewable energy technologies and applications, the location-dependent quality of many of these resources, and the inherent variability and uncertainty of wind and solar generation. Although no modeling tool can meet all needs simultaneously, ReEDS is the analytical backbone of many NREL studies that involve capacity expansion, such as the aforementioned DOE study [1][1], *Renewable Electricity Futures* [3], and the *Sunshot Vision Study* [4].

ReEDS is a generation and transmission capacity expansion model of the electricity system of the contiguous United States. ReEDS is unique among nationwide and long-term capacity expansion models for its highly discretized regional structure and statistical treatment of the impact of variability of wind and solar resources on capacity planning and dispatch.

More specifically, ReEDS is a linear program that minimizes overall electric system costs subject to a large number of constraints. The major constraints include meeting electricity demand within specific regions, regional resource supply limitations, planning and operating reserve deployment location of these technologies. Additionally, because of its detailed regional and temporal representation, ReEDS can estimate the costs of transmission expansion and operational integration and has limited representation of transmission power flow. Even though ReEDS does not explicitly examine all reliability criteria, it can be linked to other models with higher fidelity, such as GridView [5].

[1] ReEDS was referred to as the Wind Deployment System (WindDS) model in the *20% Wind Energy by 2030* wind study.

TABLE II. GENERATION, STORAGE, AND DEMAND TECHNOLOGIES CONSIDERED IN REEDS

Category	Technologies
Conventional Generation	Pulverized coal Natural gas combined cycle [a] Natural gas combustion turbine Nuclear Integrated gasification combined cycle [a]
Renewable Generation	Onshore wind Offshore wind CSP with and without thermal storage [b] Utility-scale and distributed rooftop PV [c] Dedicated and co-fired biomass Geothermal Hydropower Ocean
Storage	Pumped storage hydropower Compressed air energy storage Batteries
Demand-Side Technologies	Thermal energy storage in buildings Interruptible load Utility-controlled PEV charging [d]

a. Carbon capture and storage version of these technologies are also implemented in ReEDS
b. CSP is Concentrated Solar Power
c. PV is photovoltaic
d. PEV is Plug-in Electric Vehicle

The capacity expansion and dispatch decision making of ReEDS considers the net present value cost of adding new generation capacity and operating it (considering transmission and operational integration) over an assumed financial lifetime (20 years). This cost-minimization routine was applied for each 2-year investment period from 2010 until 2050. As a cost-optimization model, ReEDS does not attempt to capture noneconomic (e.g., behavioral, social, institutional) considerations in its investment and dispatch decision-making routine. These noneconomic factors can be significant, particularly regionally, and further work is necessary to quantify their impacts.

ReEDS represents the contiguous United States using 356 wind and concentrating solar power (CSP) resource regions. These 356 resource supply regions are grouped into four levels of larger regional groupings: balancing areas (BAs), reserve-sharing groups, North American Electric Reliability Council (NERC) regions [6], and interconnects. This level of geographic detail, depicted in Fig. 1, enables the model to account for geospatial differences in resource quality, transmission needs, electrical (grid-related) boundaries, political and jurisdictional boundaries, and demographic distributions. In ReEDS, BAs are the regional areas within which demand requirements must be satisfied. Although existing BA authority boundaries were considered in the design of the BAs, the BA boundaries are often not aligned with the boundaries of real BA authorities to accommodate other aforementioned boundaries (e.g., political boundaries).

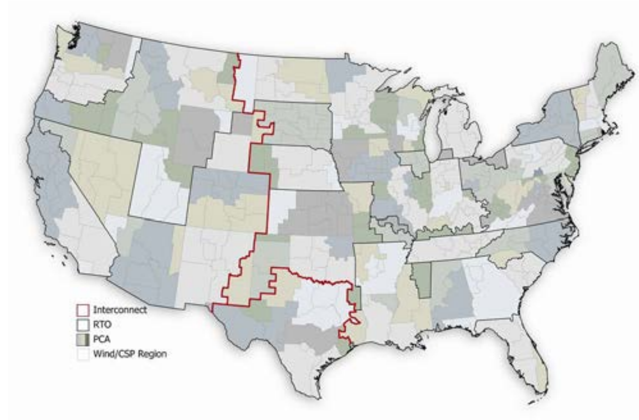

Figure 1. ReEDS regions showing the different aggregation levels.

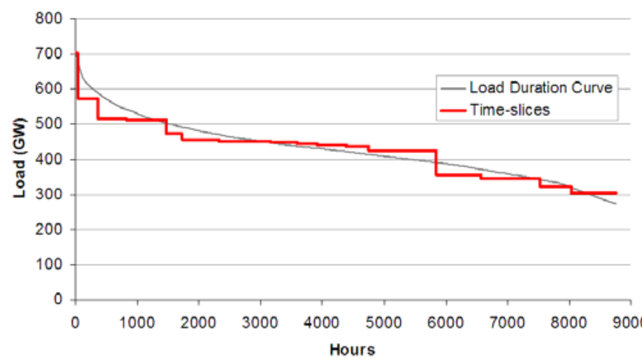

Figure 2. Discretization of the load duration curve utilizing the 17 time slices defined in ReEDS.

ReEDS dispatches generation within 17 different time slices (four time slices for each season representing morning, afternoon, evening, and nighttime, with an additional summer-peak time slice). This level of temporal detail—though not as sophisticated as that of an hourly chronological dispatch model—enables ReEDS to consider seasonal and diurnal changes in demand and resource availability. Fig. 2 compares a typical load duration curve and the discretized version based on the 17 time slices. Moreover, because significant demand and resource variations can occur within each time slice, ReEDS uses statistical calculations to estimate the capacity value, forecast error reserves, and curtailment of wind and solar resources; these calculations also consider the correlations of output profiles between projects of the same type in different locations, between projects that rely on different resource types, and between different regional demand profiles.

The statistical calculations in ReEDS are used in multiple reserve and load balancing constraints in the model. At the longest timescales, ReEDS enforces a planning reserve requirement that ensures there is sufficient generating capacity to exceed the annual forecasted peak demand hour by the requisite reserve margin, which ranges from 12.5% to 17.2%. At shorter hourly to sub-hourly timescales relevant to daily electric system operations, ReEDS requires sufficient supply- and demand-side technologies to satisfy operating reserve requirements. The operating reserves considered in ReEDS included wind and solar forecast error reserves, contingency reserves, and frequency regulation. Because contingency reserves and frequency regulation requirements were assumed to be established as a fraction of demand (6% for contingency and 1.5% for frequency regulation), they were independent of the amount of variable generation. In contrast, forecast error reserve requirements were estimated based on hourly persistence forecasts for wind and solar PV, and therefore increased as variable generation increased. ReEDS does not directly capture the wear-and-tear costs associated with operating the conventional thermal power plant fleet in a more flexible fashion. Additional research on these costs and their implications for renewable energy integration are warranted.

In ReEDS, planning and operating reserves were assumed to be maintained independently in 21 reserve sharing groups for all years of the study period, representing greater cooperation over larger areas than exists in the current grid. Existing regional transmission organizations and independent system operators (such as Midwest ISO, New England ISO, PJM, or California ISO) were used in the construction of some of the reserve sharing groups; where there was no existing regional transmission organization or independent system operator, a future reserve-sharing region was assumed. Some of these reserve-sharing groups were larger than those that currently operate under the assumption that additional market integration and transmission expansion over the next 40 years would expand current reserve-sharing regions.

For transmission, existing transmission infrastructure was assumed to continue to be operable throughout the study period, and existing line capacity was assumed to be usable by both conventional and renewable generation sources. The regional resolution of the ReEDS model allows it to roughly estimate new transmission expansion needs and their associated investment requirements. The ReEDS model's deployment decision-making algorithm was therefore able to compare the total costs, including costs of additional required transmission infrastructure, of distant but higher quality renewable resources with more local but lower quality resources, based on generation and transmission cost considerations. In addition to the expansion of long-distance transmission lines, interconnection costs for new generation and storage technologies were considered in ReEDS. For wind and CSP technologies, additional interconnection supply curves were applied to account for the strong location dependence of those resources, yielding total interconnection costs for these technologies that were generally greater than for other technologies. A detailed description of these supply curves and the transmission treatment in ReEDS is provided in [2]. Implicit in the ReEDS treatment of transmission is that new transmission can be built within and between regions to enable access to renewable resources and leverage geospatial, temporal, and technological diversity between resources.

These measures ensure that ReEDS results are as detailed geographically and temporally as computational constraints allow, while also being consistent with an electricity system that is able to maintain an overall balance between supply and demand. In sum, ReEDS provides a means of estimating the type and location of conventional and renewable resource development; the transmission infrastructure expansion requirements of those installations; and the composition and location of generation, storage, and demand-side technologies needed to maintain balance between supply and demand. Additional detail on ReEDS can be found in [2].

III. Modeling assumptions

This paper examines the deployment of large quantities of onshore and offshore energy. For the *20% Wind Energy by 2030* report, wind capacity deployment was not predetermined and neither was the mix of onshore versus offshore wind. As such, the model deployed the adequate capacity of both onshore and offshore in regions with sufficient resource quality (capacity factor) to reach the 20% target based on the assumed technology costs and performance data.

The resulting capacity build-out for onshore and offshore wind is represented in Fig. 3, which amounted to 304 GW in 2030. This schedule was used as an input to ReEDS—i.e., the cumulative installed onshore and offshore installed capacity installed was enforced in the model as a constraint. Fig. 4 summarizes the installed offshore wind capacity per year on a national basis. ReEDS then determined the location of that capacity.

As a cost-optimization model, ReEDS relies on technology cost and performance projections to make its capacity expansion and dispatch decisions. Detailed technology cost and performance assumptions and the broader economic impacts from the ReEDS scenarios were presented in Appendix A, Volume 2 of [3], and [7]. Because the deployment of onshore and offshore wind was predetermined, other assumptions in ReEDS (such as natural gas price projection, technology costs, demand projections, etc.) were not critical in this case.

ReEDS can also take into account Renewable Portfolio Standards (RPS) set by different states, e.g., by forcing a certain percentage of load to be met by renewables in a state by a given year. These RPSs have a moderate effect on the timing and distribution of the deployment of wind. The most recent published RPS requirements in effect [8] were used in ReEDS. Builds of other renewable sources (PV, CSP, geothermal, biopower, hydropower) were ignored for simplicity, given that the original 20% wind report did not include other renewables either.

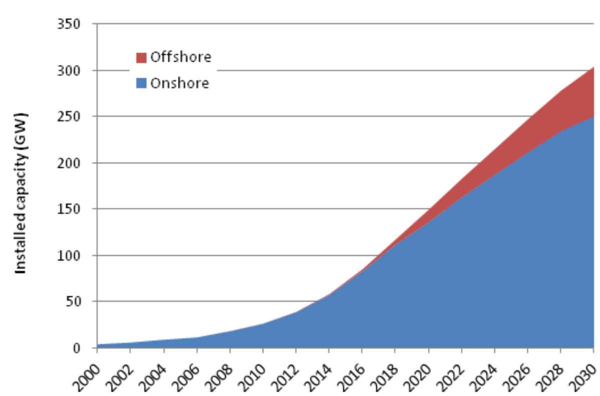

Figure 3. Onshore and offshore wind installed in the *20% Wind Energy by 2030* report.

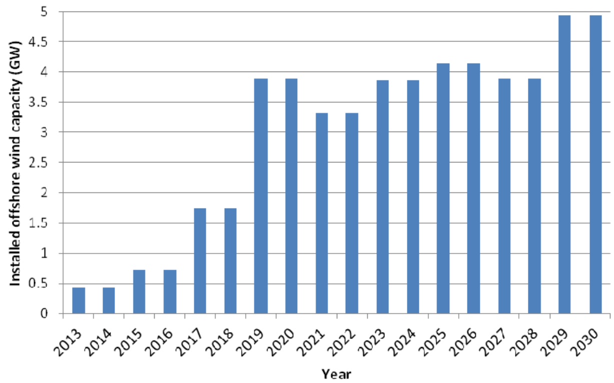

Figure 4. Installed offshore wind by year.

IV. ANALYSIS

A. *Deployment Results*

The model was solved utilizing the assumptions in the previous sections. Fig. 5 shows the evolution of installed capacity nationwide, and Fig. 6 represents the production of energy by generation type. In that figure, load represents bus-bar load. The difference between total production and served load represents transmission losses and energy curtailment.

Onshore and offshore wind schedules were successfully enforced. "Other renewables" included installed capacity (geothermal, biopower, landfill gas, CSP, PV) that existed in the system at the beginning of the simulation. As discussed in the previous section, no new capacity for these technologies was added. Existing coal and oil-, gas-, and steam-powered plants were gradually retired, although natural gas combined cycle and combustion turbine units were installed to increase system flexibility and accommodate the large penetration of wind energy.

Fig. 7 shows where the 304 GW of onshore and offshore wind were deployed. Onshore wind was heavily installed in the resource-rich Midwest (especially in northern and southeastern Texas, eastern Colorado, and Iowa), Great Lakes (Michigan), and to a lesser extend throughout the Western Interconnection, the Northeast, and Appalachia. Offshore wind deployment concentrated in the North and Mid-Atlantic, and marginally in the Gulf Coast, Great Lakes, and the northern California/southern Oregon area.

Just as important as the final build-out is the path to reach that point, because it will determine the possible stages to design and install an offshore transmission grid. Fig. 8 summarizes the installed capacity over time by state. Given that most of the capacity was concentrated in the East Coast, it made sense to focus the design effort around that area. New Jersey and New York were the epicenter of early capacity builds, which were later extended north (mainly Massachusetts) and south to Maryland, Virginia, and the Carolinas.

The geographical resolution in ReEDS allowed for a detailed analysis of offshore deployment. The maps in Fig. 9 show the two-year increments for the East Coast, where an offshore grid would be most likely to benefit offshore wind deployment and integration. The first steps of the deployment would occur in the northern portion of the coast, between New Jersey and Massachusetts. It is in that area where the first phase of the grid could be laid out, possibly in the 2018 timeframe. In the next few years, deployment would then begin to be more present in Virginia, which could represent a second phase. Finally, Phase 3 would extend to North and South Carolina. Based on the level of deployment, the grid would not continue beyond this point, unless other economic or operational factors were taken into account.

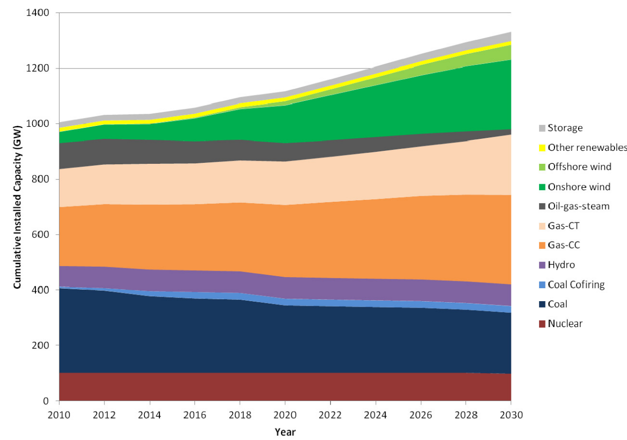

Figure 5. Cummulative installed capacity by year.

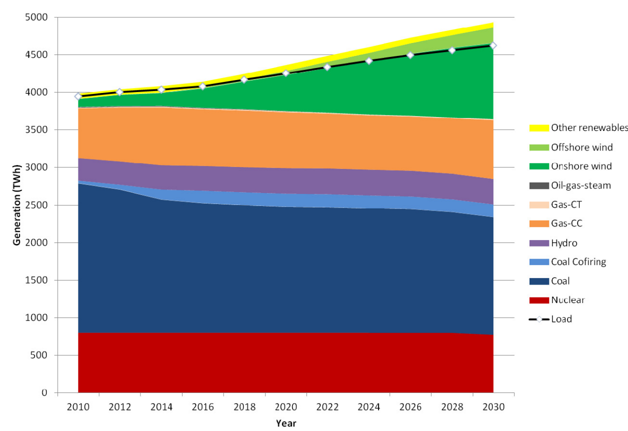

Figure 6. Generation by type.

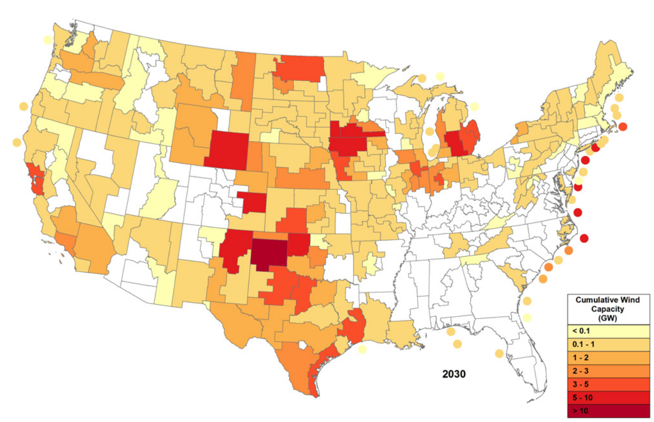

Figure 7. Onshore and offshore wind deployed in 2030.

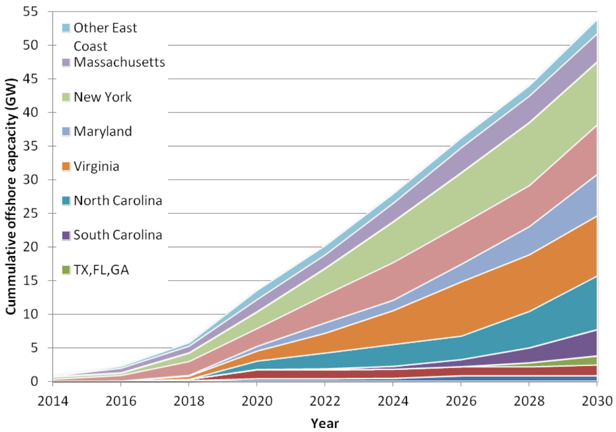

Figure 8. Installed wind capacity by state.

The specific plans for an actual design of the offshore grid was beyond the scope of this paper, but will be addressed in upcoming work in the NOWEGIS. The complex process involves a number of planning and design decisions, such as for technologies to be used, number and location of substations and ties to shore, number and capacity of lines, and timing.

B. Factors That Influence ReEDS Deployment Decisions

The following is a list of the main drivers that influence site selection in ReEDS. The run that was performed for this project forces all offshore resource to compete to be part of the 54 GW of installed offshore wind. This is done through a cost minimization of the system, so the ultimate reason of wind being deployed in a region is that it was economically advantageous compared with other regions. (A nationwide constraint of 54 GW of offshore wind capacity by 2030 was applied.)

- Resource quality: All potential resource in the country (after applying exclusions) is classified into five capacity factor groups. The average capacity factor for each group evolves over time to represent technology improvement.
- Capital and O&M costs: These are common for all offshore wind.
- Interconnection cost: All developable wind potential is assigned a connection cost to the grid, along with other cost adders that depend on factors such as population density, slope, etc. A supply curve is created through a GIS process and it becomes a static input to ReEDS.
- Transmission cost penalty: This represents the difficulty of developing new transmission lines in certain portions of the country, based on [9].
- Variability metrics: To better capture aggregate variability of the system, correlation statistics are calculated between the power outputs of geographically separated variable generation. In general, greater geographic distance between two wind plants leads to a lower degree of correlation between power outputs, which decreases the variability of their combined generation. These metrics include capacity value, forecast error, and curtailment.
- Proximity of wind resources to high load centers.

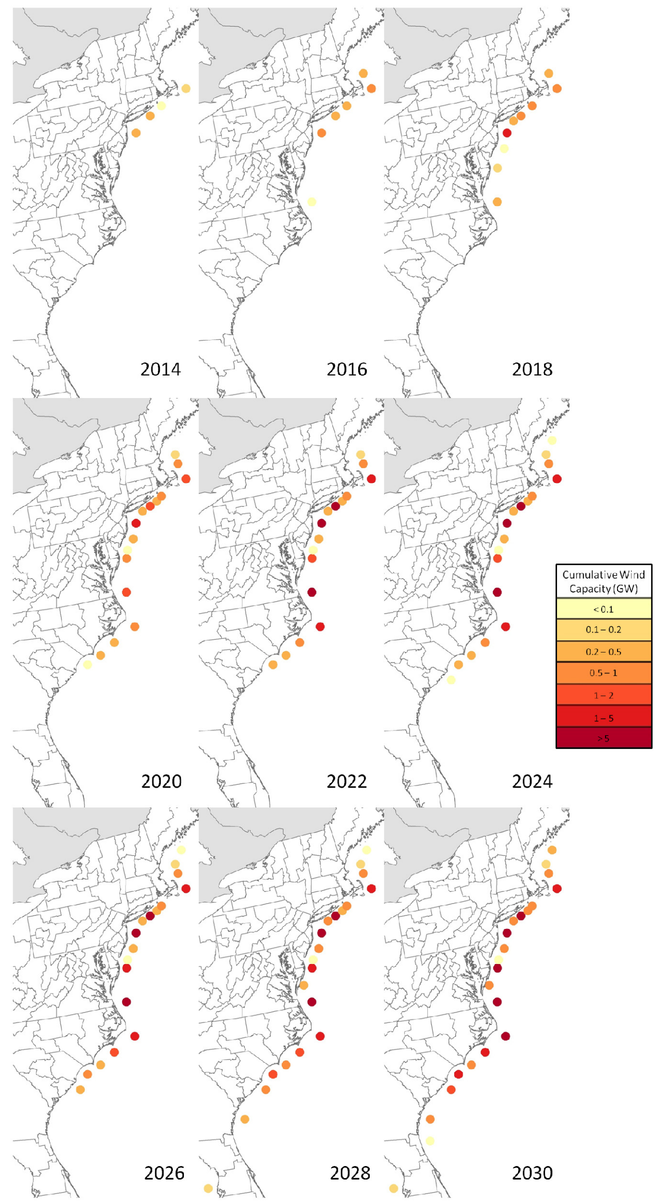

Figure 9. Offshore wind build-out for the East Coast.

Table II shows some of the parameters listed above for different wind regions in ReEDS. The regions on the left had offshore wind deployed; the regions on the right did not. The table also includes a brief explanation of each row in the table and their net impact on making offshore wind more attractive. Based on these values and further exploration of the inputs and results, it was possible to explain the reason why some areas did not receive offshore wind although others did:

TABLE II. PARAMETERS THAT INFLUENCE DEPLOYMENT DECISIONS FOR AREAS WITH AND WITHOUT WIND INSTALLED IN 2030

	Offshore Wind Installed					No Offshore Wind Installed				
Wind Region [a]	219	256	270	294	330	174	234	318	320	333
State [a]	IN	TX	FL	NC	NJ	TX	OH	DE	PA	NY
Onshore Capacity (GW) [b]	0.12	3.03	0	0.48	0	3.66	0.45	0	0	1.95
Offshore Capacity (GW) [b]	0.29	0.06	0.29	5.02	6.82	0	0	0.03	0	0
Offshore installed in 2030 (GW) [b]	0.29	0.06	0.29	1.67	1.23	0	0	0	0	0
Capacity Factor (%) [c]	48.3	44.5	38.4	48.3	48.3	52.3	48.3	48.3	48.3	44.5
Connection Cost ($/kW) [d]	78.2	59.1	52.7	166.4	307.4	208.2	39.9	377.8	125.0	915.2
Transmission Penaly (multiplier) [e]	1	1	1	1	3.56	1	1.58	3.56	1.58	3.56
Capacity Value (%) [f]	16.7	17.2	17.2	21.8	22.2	15.8	16.7	22.2	22.2	27.2
Forecast Rrror (fraction) [g]	0.039	0.040	0.040	0.035	0.046	0.094	0.039	0.046	0.046	0.041
Curtailment (%) [h]	6.7	4.1	4.1	7.8	6.0	8.3	6.7	6.0	6.0	3.4

a. Wind region in ReEDS (see Fig. 1 and [2]) and region it belongs to.
b. Cumulative onshore and offshore wind capacity installed at the end of 2030, and offshore capacity installed in 2030.
c. Capacity factor for additional offshore capacity (higher is better).
d. Cost to connect to the grid for additional offshore capacity (lower is better).
e. Penalty applied as a multiplier to transmission cost for additional offshore capacity (lower is better).
f. Capacity value provided by additional offshore capacity (higher is better).
g. Parameter that determines the forecast error for additional offshore capacity, which increases the need for regulation in the system (lower is better).
h. Fraction of potential that is curtailed for additional offshore capacity (lower is better).

- Texas (Region 174): Connection costs and curtailment were high, although capacity value was low (compared to Region 256).
- Ohio (Region 234): A transmission cost penalty, low capacity value, and high curtailment were present.
- Delaware (Region 318): Connection costs were high. This was due to the fact that the best resource in Delaware is either excluded or is found several miles off the coast, as confirmed by a visual inspection of the resource map. The transmission penalty was high too.
- Pennsylvania (Region 320): A transmission cost penalty was present.
- New York (Region 333): There was a high connection cost and transmission penalty.

Based on the assumptions used in this model, the proposed build-out represented the least-cost option, but the process took into account important variability factors in the optimization. The regions with little or no installed capacity were simply less valuable to the system than those that were actually installed.

V. CONCLUSIONS

The objective of the work presented in this paper was to create a staging scenario of 54 GW of offshore wind capacity in the United States by 2030. The ReEDS model was utilized for its unique capabilities to represent renewable resources with geographic detail and their effect on power system operations. The assumptions used and the offshore build-out were presented, with a description of how an offshore grid could accommodate the resulting deployment. An analysis was performed on the different factors that affected decisions in ReEDS in this project, including resource quality, costs, transmission, and contribution to system variability. A rigorous design of the offshore grid will follow this work. Finally, the benefits of the grid will be estimated by comparing production cost simulation runs with a scenario for which offshore wind farms connect radially to shore.

ACKNOWLEDGMENT

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