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Modeling the National Potential for Offshore Wind

Preprint

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Modeling the National Potential for Offshore Wind

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1 Introduction

There is a national interest in the potential of offshore wind power due to the growing concern about climate change and the corresponding need for renewable energy. Offshore wind power is attractive due to the large and high-quality resource off the U.S. coasts as well as that offshore wind farms can be sited relatively close to load centers — over half the population of the U.S. lives within 50 miles of an ocean or Great Lake[1] — lowering transmission losses and expense. Additionally, wind farms off the coast of Europe have successfully demonstrated the technology. Offshore wind farms, however, have high up-front costs and are not seen as economical in the near term. There is interest, therefore, in examining under what economic, social, and technological conditions offshore wind becomes viable. This paper contributes to this examination.

To assess the potential penetration of offshore wind in the United States, the Wind Deployment System (WinDS) model was run under different technology development, cost, and policy scenarios. The methodology was to take a business-as-usual case and perturb it via three parameters:

- natural gas fuel price
- a restriction on the technologies that can be built to meet demand along highly populated, coastal areas of the country
- a national requirement that twenty percent of generation come from renewable sources by 2030

We ran the WinDS model for each of the eight scenarios (combinations of three conditions) to determine the effect of each condition, or set of conditions, on the penetration of offshore wind. This paper presents the results from those model runs.

2 WinDS Overview

The WinDS model was developed starting in 2000[2], to model the expansion of generation and transmission capacity in the U.S. electric sector. WinDS is a linear programming model that

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[*] NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by Midwest Research Institute & Battelle

[1] Crosset, Kristin; et al., *Population Trends Along the Coastal United States: 1980-2008.* NOAA, 2004.

[2] Short, Walter; et al., May 2003, *Modeling the Long-Term Penetration of Wind in the United States*, WindPower 2003 Proceedings, Austin, TX

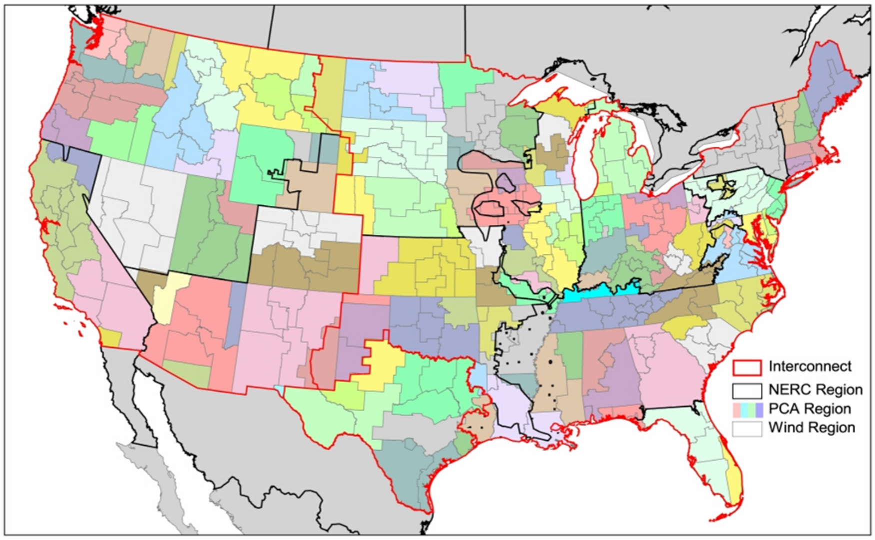


Figure 1: WinDS Regions

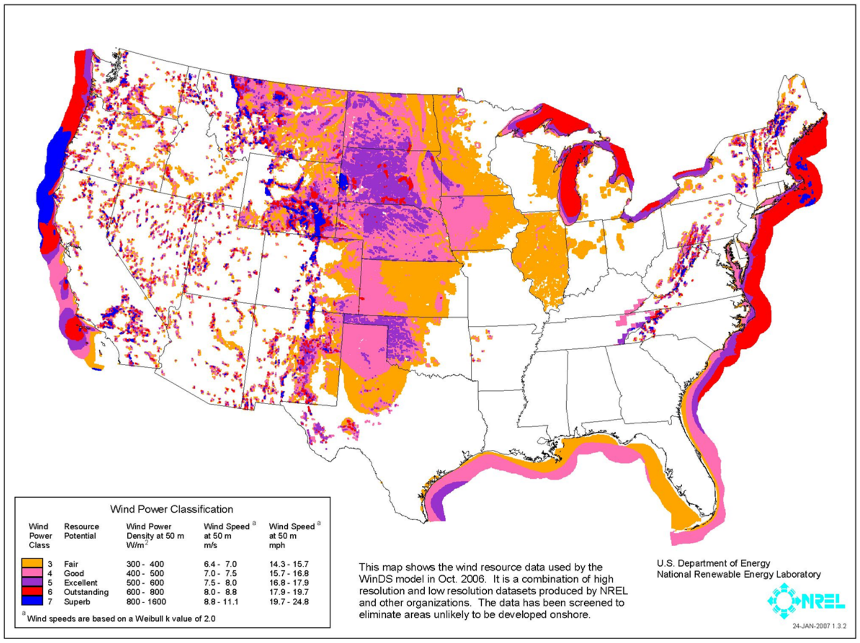
minimizes system-wide costs of meeting loads, reserve requirements, and emission constraints by building and operating power generators and transmission capacity in each of 26 two-year periods spanning 2000-2050. Although WinDS considers all major generation technologies, it was designed primarily to address the principal market issues related to the penetration of wind energy into the electric sector over the next several decades — specifically, wind resource variability and transmission requirements.

WinDS is better able to model transmission and wind resource variability, primarily by using a much higher level of geographic disaggregation than other models — 358 distinct regions in the continental United States, as illustrated in Figure 1. Many of the data inputs to WinDS are tied to these regions and derived from a detailed GIS model/database of the wind resource, transmission grid, and existing plant data. The geographic disaggregation of wind resources allows WinDS to calculate transmission distances (and charge appropriately), as well as account for the benefits of dispersed wind farms supplying power to a demand center. This geographic resolution is also critical for the analysis reported on here which examines the availability of offshore wind to limited coastal areas.

WinDS considers the availability of capacity on existing transmission lines, the cost of accessing and using those lines, and the cost of building new transmission lines dedicated to wind generation when existing lines are not available. These costs are made to reflect current electricity transmission pricing as realistically as possible.

WinDS disaggregates the wind resource into five classes ranging from Class 3 (5.4 meters/second at 10 meters above ground) to Class 7 (> 7.0 m/s). WinDS also includes offshore wind resources and distinguishes between shallow and deep offshore wind turbines. Shallow-water turbines are assumed to have lower initial costs, because they employ a solid tower with an ocean-bottom pier; while deep-water turbines are assumed to be mounted on floating platforms tethered to the ocean floor. Figure 2 displays the resource data used in WinDS.

Each class and type of wind has different cost and performance characteristics. Often, the higher wind-class sites are more desirable, though additional expenses for transmission, terrain, and population considerations can make, for example, an otherwise high quality, mountaintop class-7 resource much more expensive than a more conveniently located class-5 site. The result then is a mix of classes built at any given time — a mix that changes over time — depending on which class is the cheapest in that particular region at that time, as illustrated in Figure 3.



This map shows the wind resource data used by the WinDS model in Oct. 2006. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data has been screened to eliminate areas unlikely to be developed onshore.

Figure 2: Wind Resources in WinDS

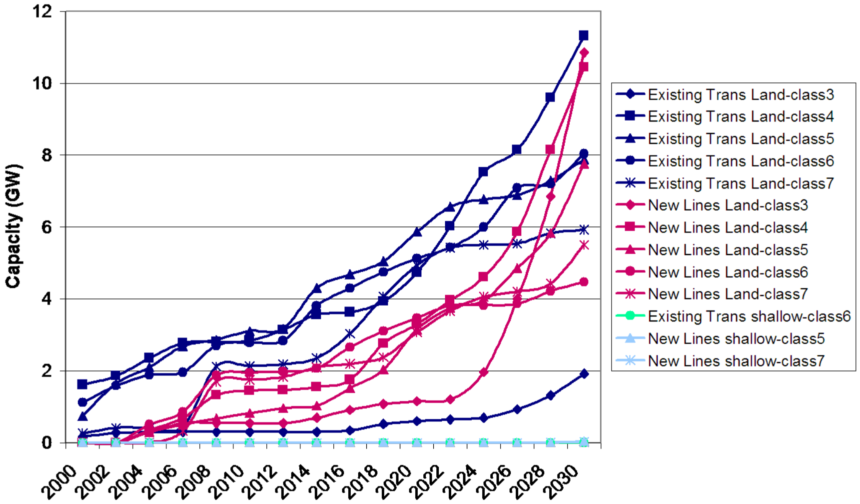


Figure 3: Business-as-Usual Scenario Wind Installations by Wind Class and Transmission Type

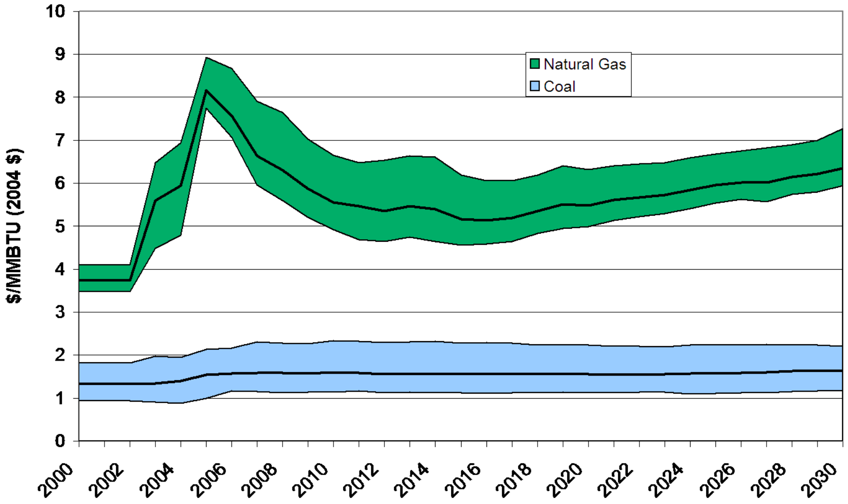


Figure 4: Business-as-Usual Scenario: U.S. Average Fuel Prices and Ranges over NERC Regions

WinDS is also disaggregated over time, not only with the 26 two-year periods between 2000 and 2050, but also within each year. Each year is divided into four seasons with each day of each season divided into four diurnal time slices. These 16 time slices during each year allow WinDS to capture the intricacies of meeting peak electric loads, with both conventional sources and wind generators. WinDS models the major conventional electricity generators, including:

- pulverized coal: modern and next generation
- integrated gasification combined-cycle coal (IGCC)
- existing coal boilers, both with and without SO_2 scrubbers
- natural gas combined cycle
- natural gas combustion turbines
- existing natural gas-fired boilers
- nuclear
- hydroelectricity: existing only, and energy limited due to water use limits

Fuel costs are specifed exogenously by NERC region (see Figure 4), as are the electric loads. In addition, WinDS has the capability to force the model to meet Renewable Portfolio Standards (requirements that a certain percentage or quantity of capacity or generation be derived from renewables) at state and national levels; as well as to meet emission caps for SO_2, NO_x, mercury, and carbon (or to have a tax on carbon). There are also options for financing of capital expenditures and tax credits for investment or production.

3 Business-As-Usual Scenario

Capital costs for new generation equipment changes over time in the model, according to input specifications, as do operations & maintenance costs, fuel prices, heat rates, and wind capacity factors. The business-as-usual case for this comparison trial uses fuel prices and load

Table 1: Onshore Wind Cost and Performance Data (2004 $)

Class	Year	Capital Cost k$/MW	Fixed O&M $/MW-year	Variable O&M $/MWh	Capacity Factor
3	2007	1523	10946	6.08	.338
	2020	1237	10946	4.41	.389
	2030	1237	10946	4.16	.408
4	2007	1523	10946	6.08	.377
	2020	1237	10946	4.41	.435
	2030	1237	10946	4.16	.447
5	2007	1523	10946	6.08	.414
	2020	1237	10946	4.41	.461
	2030	1237	10946	4.16	.469
6	2007	1523	10946	6.08	.450
	2020	1237	10946	4.41	.493
	2030	1237	10946	4.16	.499
7	2007	1523	10946	6.08	.488
	2020	1237	10946	4.41	.531
	2030	1237	10946	4.16	.537

Table 2: Shallow Offshore Wind Cost and Performance Data (2004 $)

Class	Year	Capital Cost k$/MW	Fixed O&M $/MW-year	Variable O&M $/MWh	Capacity Factor
3	2007	2208	14277	19.03	.354
	2020	1840	14277	13.37	.409
	2030	1713	14277	10.16	.417
4	2007	2208	14277	19.03	.396
	2020	1840	14277	13.37	.457
	2030	1713	14277	10.16	.466
5	2007	2208	14277	19.03	.435
	2020	1840	14277	13.37	.484
	2030	1713	14277	10.16	.489
6	2007	2208	14277	19.03	.472
	2020	1840	14277	13.37	.517
	2030	1713	14277	10.16	.521
7	2007	2208	14277	19.03	.512
	2020	1840	14277	13.37	.557
	2030	1713	14277	10.16	.561

forecasts from the Reference case of the EIA's *Annual Energy Outlook 2006*[3]. Conventional generation technology costs and wind data inputs are from Black & Veatch[4]. Tables 1-4 contain the technology cost and performance data used in the base case scenario. Other parameters are input according to current conditions: no national RPS, but state RPSs are enforced if currently enacted; the SO_2 cap follows current regulations; no carbon cap or tax is applied. Corporate financing and the consequent debt service coverage requirements are explicitly accounted for, as are federal tax credits and income tax deductions. A production tax credit of $18.5/MWh for wind power expires in 2008.

In the business-as-usual scenario, WinDS projects that — by 2030 — wind will provide 74

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[3] U.S. Department of Energy, Energy Information Administration. *Annual Energy Outlook 2006 with Projections to 2030.* DOE/EIA-0383, February 2006

[4] Personal communication with Ric O'Connell, Black & Veatch.

Table 3: Deep Offshore Wind Cost and Performance Data (2004 $)

Class	Year	Capital Cost k$/MW	Fixed O&M $/MW-year	Variable O&M $/MWh	Capacity Factor
3	2007	3478	14277	25.58	.381
	2020	2633	14277	19.62	.409
	2030	2326	14277	13.44	.417
4	2007	3092	14277	25.58	.425
	2020	2824	14277	19.62	.457
	2030	2495	14277	13.44	.466
5	2007	3092	14277	25.58	.465
	2020	2824	14277	19.62	.484
	2030	2495	14277	13.44	.489
6	2007	3092	14277	25.58	.500
	2020	2824	14277	19.62	.517
	2030	2495	14277	13.44	.521
7	2007	2958	14277	25.58	.548
	2020	2824	14277	19.62	.557
	2030	2495	14277	13.44	.561

Table 4: Selected Conventional Cost and Performance Data (2004 $)

Technology	Year	Capital Cost k$/MW	Fixed O&M $/MW-year	Variable O&M $/MWh	Heat Rate MMBtu/MWh
Natural Gas	2007	585	6911	7.92	8.90
Combustion Turbine	2020	585	6281	2.67	8.90
	2030	585	6281	2.67	8.90
Natural Gas	2007	590	13706	2.86	6.87
Combined Cycle	2020	590	13706	2.86	6.87
	2030	590	13706	2.86	6.87
New	2007	1647	33600	1.618	9.47
Pulverized Coal	2020	1647	33600	1.618	9.47
	2030	1647	33600	1.618	9.47
Coal IGCC	2007	1884	36264	3.712	8.58
	2020	1720	36264	3.712	8.58
	2030	1558	36264	3.712	8.58
Nuclear	2007	2352	85663	.476	10.4
	2020	2198	85663	.476	10.4
	2030	2141	85663	.476	10.4

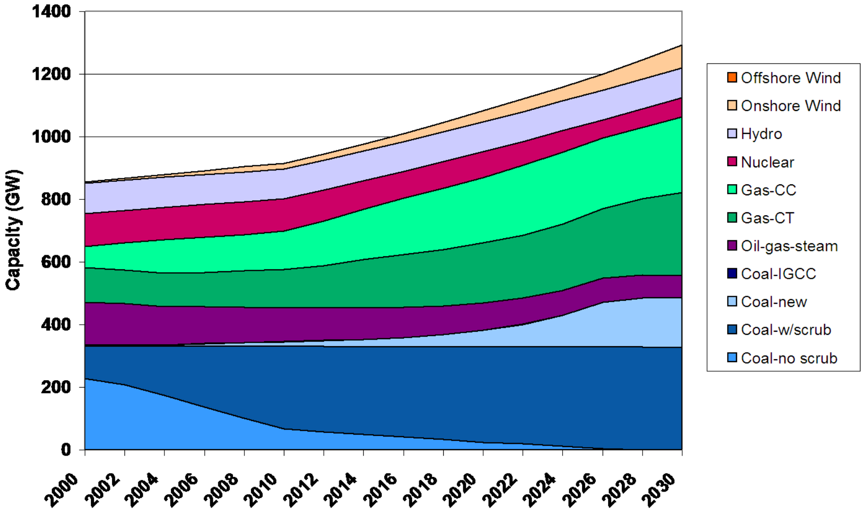

Figure 5: Business-as-Usual Scenario Cumulative Installed Capacity

GW of electric capacity to the grid (compared to 11.6 GW in 2006[5]). Of that 74 GW, only 0.07 GW is projected to come from offshore wind, all of it in shallow water off the coasts of California and Massachusetts. Since the scenario does not penalize or restrict carbon or fossil fuels, the buildout of wind power is in large part attributable to increasing competitiveness of wind farms with conventional power plants as technological cost and performance improvements reduce the relative costs of wind turbines. Natural gas costs do increase with time, and there are SO_2 emissions caps that restrict the use of older coal technologies. Offshore wind, as evidenced by the lack of installed capacity, simply remains too expensive to compete.

The vast majority of new generation capacity comes from either coal or gas, between which it is fairly evenly split. Existing coal plants steadily add SO_2 scrubbers until all unscrubbed coal plants are phased out in 2028. Retirements from the existing coal plants is minimal — of the 334 GW of coal capacity in 2000, 328 GW remain in 2030. Integrated Gasification Combined Cycle coal plants (IGCC) first appear in 2028 and only account for 1.23 GW of capacity in 2030.

While natural gas-fired capacity is roughly split between combustion turbines and combined cycle plants (Figure 5), the latter dominate generation. Combustion turbines are cheap to build due to simplicity but expensive to run on account of the resulting low efficiency, so they are used only for peaking power when instantaneous electricity can command higher rates.

Figure 6 shows the 2030 distribution of wind capacity by region for this scenario. Although there is substantial regional variation, some trends are apparent, especially when compared with Figure 2: the mountainous West and the Appalachian regions both build a substantial quantity of wind — utilizing the high-quality mountain resource. In addition, the upper Midwest (*e.g.* Minnesota and the Dakotas) takes advantage of its broad-based flatland resource. The Southeast, lacking substantial wind resource, does not build wind capacity.

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[5] AWEA Wind Project Data Base. *Wind Energy Projects Throughout the United States of America.* March 31, 2007. http://www.awea.org/projects/.

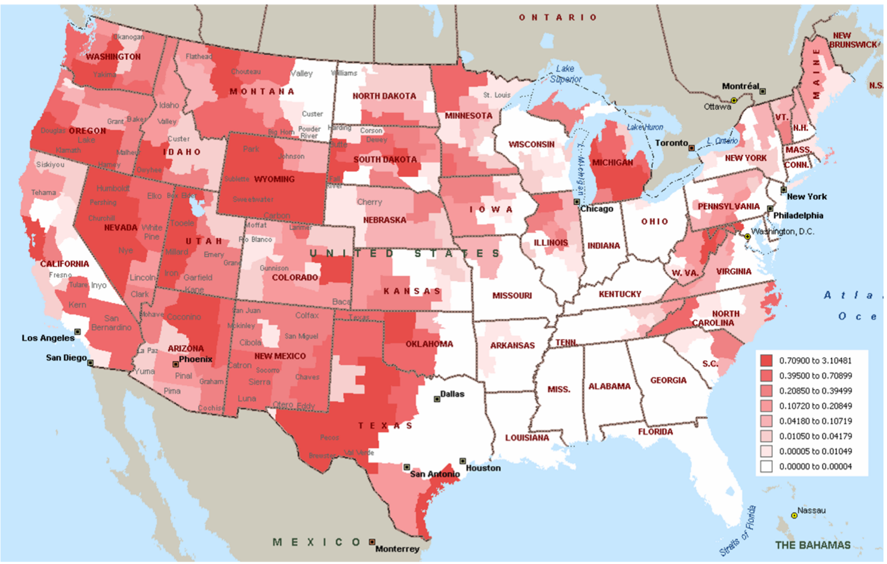

Figure 6: Business-as-Usual Scenario 2030 Wind Capacity by Region

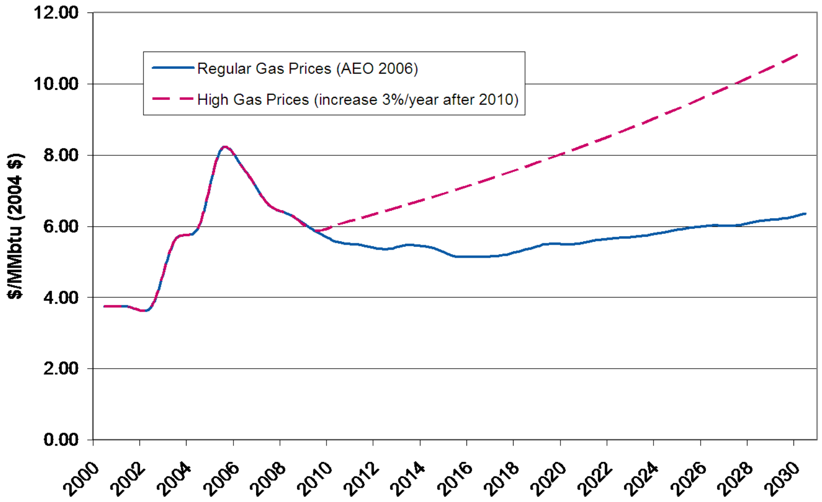

Figure 7: National Average Natural Gas Prices for Business-as-Usual- and 3% Growth Cases

4 Natural Gas Prices

To identify scenarios under which offshore wind becomes viable, we begin by altering natural gas prices. In the first sensitivity scenario we increase natural gas prices by a flat 3% per year after 2010 instead of following the Annual Energy Outlook 2006 projections[6] (see Figure 7). This increases the relative cost of all natural gas technologies compared to alternative options, such as coal, wind, or nuclear. However, this increased gas price trajectory does not have a large near-term impact. The present value of gas costs over a 20 year analysis period for a gas plant investment does not exceed that of a plant built in 2006 until after 2020. All other parameters remain consistent with the base case in this scenario.

Figure 8 shows the stacked capacity chart for the high gas price case. As expected, with higher natural gas prices the installed capacity of both combined cycle and combustion turbine natural gas decrease markedly. The bulk of the lost capacity is replaced by new coal plants (almost all modern pulverized coal; IGCC plants are still not built in significant quantities), though over the last few time periods some nuclear is built as coal construction lags. Wind experiences modest increases to 114 GW total capacity, and 5 GW of shallow offshore. In this scenario, the bulk of the offshore capacity is shared between New York and Massachusetts with Maine, New Jersey, Rhode Island, and California claiming the rest. Again, there is no deep offshore capacity.

It is worth noting that gas combustion turbine construction continues, albeit at a reduced rate, in this scenario. Also, generation from gas plants is 27 TWh in 2030, far from its peak of over 400 TWh in 2010, but demonstrably nonzero.

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[6] U.S. Department of Energy, Energy Information Administration. *Annual Energy Outlook 2006 with Projections to 2030.* DOE/EIA-0383, February 2006

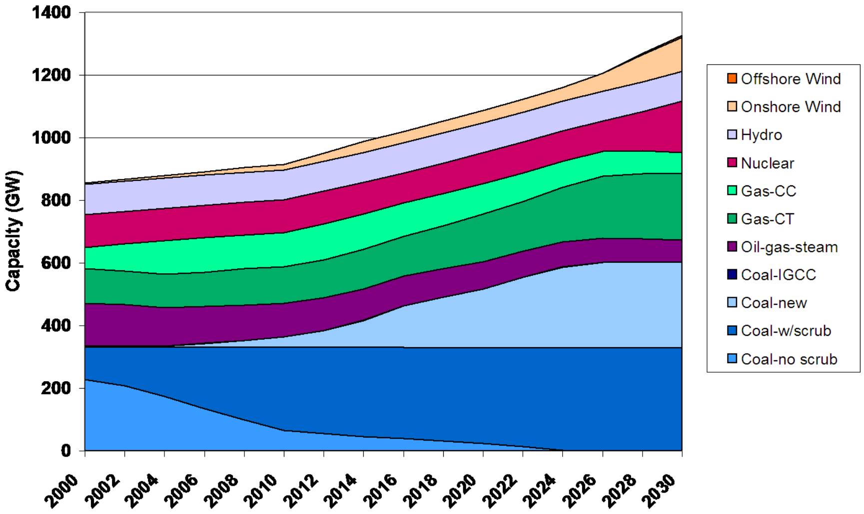

Figure 8: High Gas Price Cumulative Installed Capacity

Figure 9: Siting-Restricted Regions

5 Coastal Siting Restriction

In the second sensitivity scenario examined, a constraint is assumed on the technologies that can be built in populated coastal regions to meet the regions' load growth. The new restriction requires that all new demand in heavily-populated coastal regions (indicated in Figure 9) be met either by combined-cycle gas power plants or offshore wind farms and that there can be no new transmission into the regions in question. The rationale for the constraint is that congestion in these regions makes new major transmission capacity prohibitively expensive and that the populace would resist new construction of dirtier generation technologies (*e.g.* coal) or nuclear facilities.

The selected regions include the entire Pacific Coast and the northern Atlantic Coast. The southern Atlantic coast and the Gulf of Mexico are unrestricted except for Houston. Similarly, only Chicago is restricted around the Great Lakes. Arguments could be made to include some Rust-Belt or Gulf-Coast Cities such as Cleveland, Miami, or New Orleans, or to leave out some of the more sparsely populated Pacific coast regions. The decisions were not made by any specific metric, but rather by an estimation of where population density was sufficiently high over a large proportion of the WinDS region, as well as consideration for the environmental sensibilities of the region's inhabitants and the quantity and quality of the available wind resource. The results of the siting-restricted scenario would certainly shift some with a different set of constrained regions, but the overall picture would probably remain very similar.

Siting-restricted scenarios were run with both regular and high natural gas prices so that the two conditions could be cross-compared. Figure 11 compares the 2030 capacity for selected technologies among the four scenarios. Unsurprisingly, gas prices continue to have a strong effect on combined cycle gas installations. Most of the gas capacity lost due to increased gas prices is taken up by coal, though wind makes some gains. When the coastal restriction is implemented, some of the gas capacity returns, but not much since the 3% annual gas price increase continues to dominate investment decisions. It is interesting to note that total wind declines slightly when the siting restriction is applied in the regular gas price cases — due in part to some onshore wind in coastal regions being outlawed.

In the scenario with both high gas prices and the siting restriction on (Figure 12), offshore wind exhibits a sharp increase over the other three scenarios. Offshore wind is built in exactly

Figure 10: 2030 Offshore Wind Capacity: High Gas Price, Siting Restricted Scenario

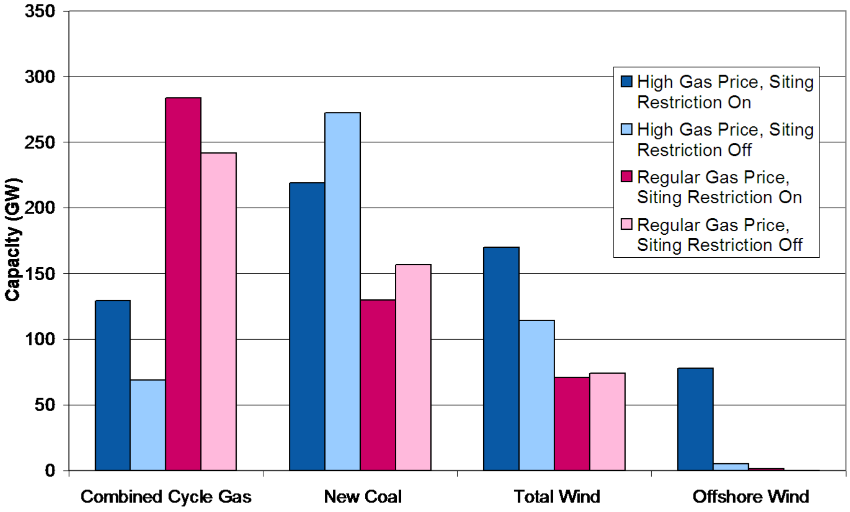

Figure 11: 2030 Capacity: Gas Price and Siting Restriction Comparison

the regions included in the coastal restriction (Figure 10), though to varying degrees from one region to the next. In this scenario, offshore wind needs to compete only with combined cycle gas, and when gas prices get too high, offshore becomes the more economical of the two.

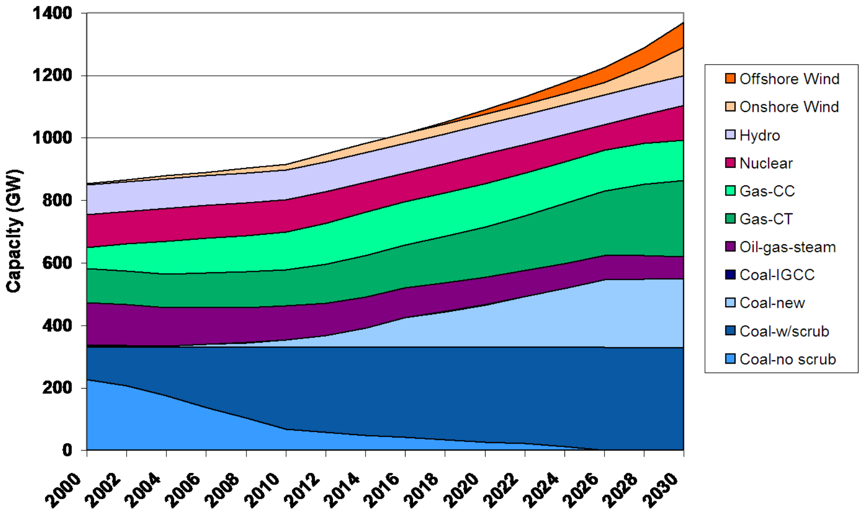

Figure 12: High Gas Price, Siting Restricted Cumulative Installed Capacity

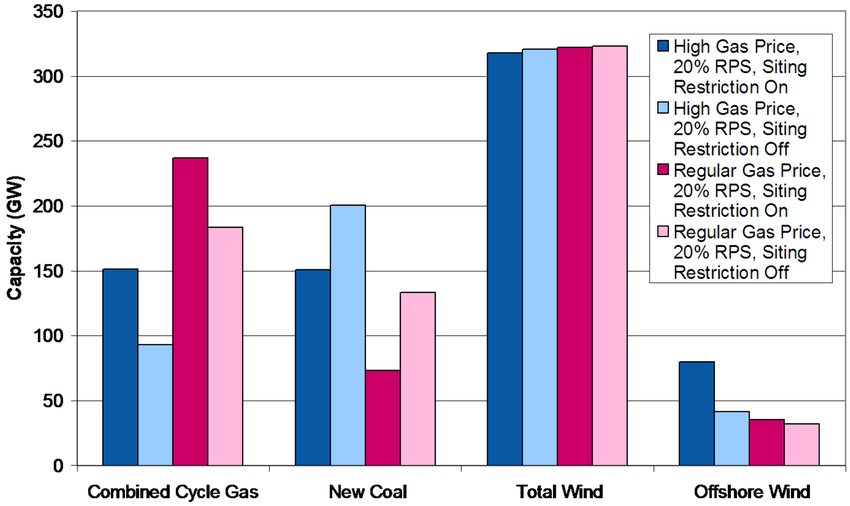

Figure 13: 2030 Capacity: 20% RPS, Gas Price and Siting Restriction Comparison

Table 5: 2030 Generation Comparison (TWh)

	Offshore	Onshore	Gas-CC
Regular Gas Prices, No RPS, No Siting Restriction	0.33	282	1227
High Gas Prices, No RPS, Siting Restriction On	329	353	338
High Gas Prices, 20% RPS, Siting Restriction On	378	846	400

6 20% National RPS

The third parameter adjusted for these scenarios is the institution of a 20% National Renewable Portfolio Standard (RPS) for wind — requiring at least 20% of U.S. electrical load to be met by wind power by 2030. The requirement ramps linearly from zero in 2007 to 20% in 2030. The four previous scenarios (high and regular gas prices, with and without the coastal restriction) are evaluated again, this time with the 20% RPS. The capacity comparison can be seen in Figure 13.

In all the RPS scenarios, WinDS is forced to build much more wind capacity than before — both onshore and offshore — as seen in Figure 13. Due to the RPS, total wind capacity is almost the same regardless of gas price and siting restrictions. However, wind capacity does decrease slightly with higher gas price and siting restrictions as more offshore wind is installed with higher capacity factors (less capacity required to reach 20% of generation). In all the RPS cases, more offshore wind is installed than in the non-RPS cases simply because some offshore is more cost effective than the remaining onshore wind options at these high levels of penetration. For example, in the case with regular gas prices and without the siting restriction, 32 GW of offshore wind is built by 2030, a significant amount — especially when compared to the .07 GW constructed in the RPS-free counterpart. On the other hand, the difference between the two high gas price, siting-restricted cases when the 20% RPS is applied is only an increase from 78 to 89 GW: a much less substantial adjustment.

Up to this point all the results have been presented in terms of capacity installations. Table 5 is a generation comparison among three of the scenarios: the business-as-usual case and the two high gas price, coastal restriction cases. Regardless of whether an RPS is implemented, the increased natural gas prices and siting constraint have a strong effect on offshore wind generation

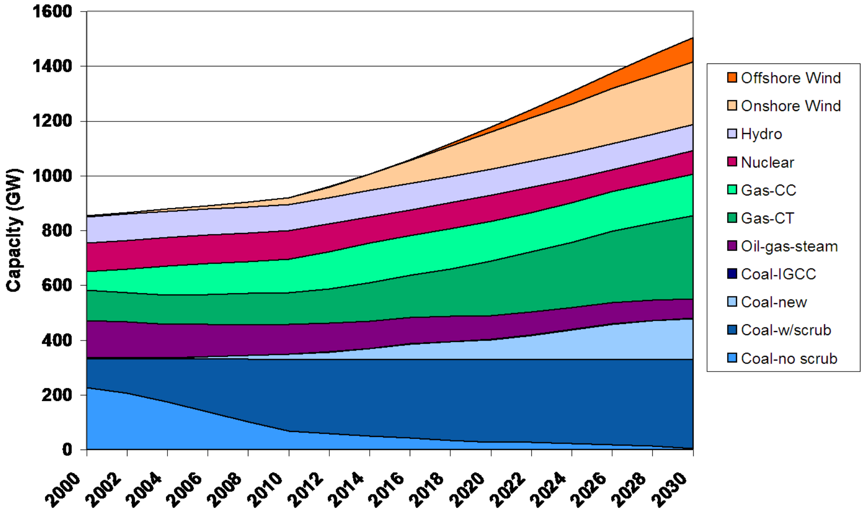

Figure 14: High Gas Price, 20% RPS, Siting-Restricted Cumulative Installed Capacity

and use of natural gas — instigating nearly a switch between the two (coal-fired generation also increases between these two scenarios). In contrast, applying the 20% RPS stimulates growth in onshore wind generation much more so than in offshore wind or combined cycle gas.

7 Summary and Conclusions

These scenarios testify that offshore wind could be used to meet new loads in locations where siting restrictions on new onshore power plants and transmission are severe, such as coastal metropolitan areas. In these locations, offshore wind could be competitive with combined cycle natural gas plants if gas prices increase significantly from current projections. If a 20% RPS is implemented, some offshore wind will be built simply because it is more cost effective than the remaining onshore at these high levels of penetration, *i.e.* at 20% penetration, there aren't as many good onshore wind sites left.

Deep-water offshore wind farms, being even more expensive than shallow-water farms, are only built in the two cases with high gas prices and the coastal siting restriction: 18 GW out of 89 GW total offshore in the 20% RPS case, 19 GW out of 78 GW in the no RPS case. Furthermore, in each of those cases over 14 GW of that is off the California coast where there is a large and high-quality wind resource, but nearly all of it in deep water. Those observations combine to assert that WinDS is very reluctant to build deep offshore wind farms.

There remain other scenarios to investigate that might spur offshore wind installations. Primary among these would be a climate change scenario with either carbon taxes or caps. NREL is modifying the WinDS model to be able to address such scenarios. In addition, NREL is planning and making general improvements to the WinDS model that will allow it to better capture the potential of offshore wind. Such improvements are anticipated to include an updated regional structure, an improved representation of transmission, siting considerations for fossil-fired power plants, and recent state restrictions on the siting of both new generating plants and transmission.

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The Wind Deployment System (WinDS) model was created to assess the potential penetration of offshore wind in the United States under different technology development, cost, and policy scenarios.

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