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Economies of scale, learning effects and offshore wind development costs

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ABSTRACT

This paper presents a model of overnight development costs for offshore wind projects and tests for the presence of economies of scale and learning effects. Both industry-wide and country-specific learning effects are analyzed. Recently, "pilot projects" have been proposed in states such as Maine and New Jersey with the hope of inducing cost savings in future larger utility scale projects. Therefore the impact of country-specific learning effects are of particular importance.

The dataset used in the analysis consists of forty-one European offshore wind projects. Research findings do not suggest that the costs exhibit economies of scale, nor do we find robust evidence of either industry-wide or country-specific learning effects.

1. Introduction

The world's first offshore windfarm (OSW), Vindeby, was completed in 1991 in Ravnsborg, Denmark. Vindeby has a total capacity of five Mega Watts (MWs) and is composed of eleven turbines. Since 1991, forty additional OSWs have been constructed in eight different European countries including Denmark, Sweden, the Netherlands, the United Kingdom, Germany, Ireland, Belgium and Finland. Recently, there has been interest in developing offshore wind in the United States, as there are currently nine OSW projects totaling over 2,300 MW of total capacity in the permitting and development process in the United States [15]. These projects are all located in the northeast, specifically concentrated primarily in New Jersey, Deleware, Rhode Island, and Massachusetts. In particular, some of these proposed projects are considered "pilot projects" with relatively expensive price tags, in hopes that the lessons learned from these projects will lead to a decrease in the cost of future large utility scale projects.

While a great deal of interest in offshore wind exists, there are currently no OSWs in operation in the United States as all of the current projects are still absorbed in the approval and financing stages. It is still uncertain if any of these projects will be completed. Two reasons are cited for this holdup; (1) relatively high cost of offshore wind compared to other forms of energy, and (2) difficulty in receiving permitting [15]. These two issues are interrelated, though, as relatively expensive projects are less likely to receive approval than relatively less expensive projects [14].

Currently, there is no consistent methodology available for comparing the cost of a proposed off-shore wind project to other similar off-shore wind projects around the world as this is not straightforward for a variety of reasons. First, different areas have different physical characteristics, and these heterogenous conditions can have a potentially large impact on costs. For instance, sites with deeper water or sites that are further from shore might be inherently more expensive to develop. If these physical characteristics impact the cost, then they need to be taken into account when comparing windfarm costs.

The second reason that comparing costs across OSWs is especially difficult is because economic environments in which existing OSWs were built are heterogeneous. The forty-one OSWs that are currently in operation were built in seven different countries over a twenty year period. Not only does a country face changing costs over time, but also different countries might have vastly different costs in the same time period. Furthermore, some of these OSWs were built in a few months while others were under construction for multiple years. This heterogeneity also needs to be taken into account when comparing projects.

This paper will combine three different literature. First the paper will calculate the cost of each OSW on an "apples to apples" basis. This will be referred to as the "overnight cost," or the estimated cost if the OSW were to be built overnight. This overnight cost is a function of the interest rate, inflation rate and construction

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Table 1
Windfarm information.

Windfarm	Country	Year Completed	Capacity (MW)	Depth (m)	Distance to shore (km)
Vindeby	Denmark	1991	5	3.5	1.8
Lely	Netherlands	1994	2	7.5	0.8
Tuno Knob	Denmark	1995	5	4	5.5
Irene Vorrink	Netherlands	1996	17	2.5	0
Bockstigen	Sweden	1998	3	6	4
Utgunden	Sweden	2000	10	8.6	4.2
Blyth	United Kingdom	2000	4	8.5	1
Middlegruden	Denmark	2001	40	6	2
Yttre Stengrund	Sweden	2001	10	8	2
Horns Rev	Denmark	2002	160	10	14
Nysted	Denmark	2003	158	7.75	10
Samso	Denmark	2003	23	20	3.5
Arklow	Ireland	2004	25.2		11.7
North Hoyle	United Kingdom	2004	60	12	7
Scoby Sands	United Kingdom	2004	60	16.5	2.5
Kentish Flats	United Kingdom	2005	90	5	10
Barow	United Kingdom	2006	90	17.5	7.5
Kemi Ajos Phase I	Finland	2007	15	6	5
Egmond aan Zee	Netherlands	2007	108	18	10
Lillgrund	Sweden	2007	110	7	10
Beatrice	United Kingdom	2007	10	45	22
Burbo Bank	United Kingdom	2007	90	5	6.5
Prinses Amaliawindpark	Netherlands	2008	120	21.5	23
Lynn/Inner Downsing	United Kingdom	2008	97	9.5	5
Thronton Bank	Belgium	2009	30		28
Horns Rev 2	Denmark	2009	209	13	31.7
Rhyl Flats	United Kingdom	2009	90	7.5	10.7
Robin Rigg	United Kingdom	2009	180	5	9
Belwind Phase 1	Belgium	2010	165	22.5	46
Rodsand II	Denmark	2010	207	10	9
Alpha Ventus	Germany	2010	60	45	56
Gunfleet Sands	United Kingdom	2010	173	6.5	7
Thanet	United Kingdom	2010	300	18.5	12
Avedore Holme	Denmark	2011	10.8	2	0.4
EnBW Baltic I	Germany	2011	48	17.5	16
Greater Gabbard	United Kingdom	2011	504	20.5	36
Walney Phase 1	United Kingdom	2011	184	21	14
Bard	Germany	2012	400	40	111.9
Global Tech I	Germany	2012	400	41	109.4
Lincs	United Kingdom	2012	270	15	9.1
London Array	United Kingdom	2012	630	25	27.5
Mean			126.2	14.5	17.1
Min			2	2	0
Max			630	45	11.9
Std. Dev.			144.9	11.5	24.8

time. Once the overnight cost is calculated, it will be used as the dependent variable to test whether two economic principles apply to the offshore wind market; economies of scale and learning effects.[1] We will test for the presence of both industry-wide and country-specific learning effects. Such economic principles will be important when considering whether or not to approve the construction of an OSW. If economies of scale exist, then regulators might be interested in larger OSWs to decrease average costs. If industry-wide learning effects are present in the offshore wind market, then newly proposed projects should be more efficient, and therefore less costly per MW, than past projects. Conversely, if country-specific learning effects are present, then countries might be inclined to built an initial, more expensive, project in hopes to bring down costs of future projects. In fact, states like New Jersey and Maine are currently proposing such "pilot projects" citing these learning effects as justification.

[1] There are a variety of different terms used to describe learning effects in the literature. Some of these include "learning curves," "learning by doing," and "progress functions."

2. Model

2.1. Economies of scale

For well over half a century, economists have empirically tested for the presence of economies of scale in a variety of industries [12]. Economies of scale in electric power generation specifically has also been studied extensively both in the United States [2] as well in other countries around the world [4,5]. USDOE (2011) [15] discusses economies of scale in the on-shore wind market within the United States and finds that economies of scale are present in relatively small windfarms (less than 20MW), but economies of scale attenuate substantially after the 20 MW threshold is met.

There has, though, been very little empirical research on economies of scale in off-shore wind. Junginger et al. [8], for instance, find that for orders of over 100 turbines, there is approximately a 30 percent reduction in the list price. But this is based on a "bottoms-up" approach in which individual components of OSWs are analyzed. They provide no empirical evidence that economies of scale have actually been realized in OSWs to date. Snyder and Kaiser [13] find a positive relationship between total cost and total

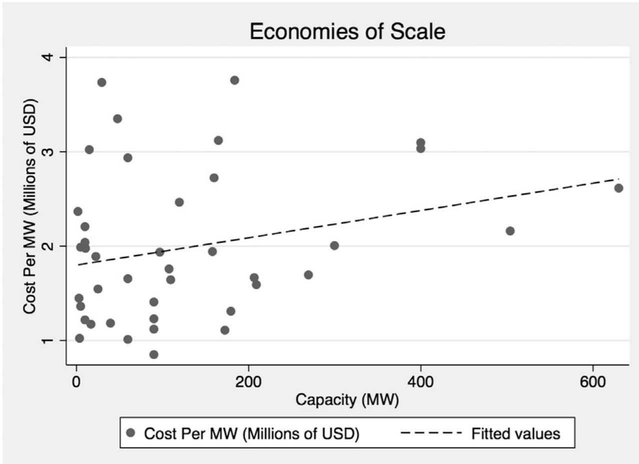

Fig. 1. Economics of scale: relationship between cost per MW and windfarm capacity.

capacity, but do not empirically test for the presence of economies of scale in their specification.

The current paper will build an econometric model in order to empirically test for whether economies of scale have been observed in European OSWs.

2.1.1. *Mathematical definition*

Economies of scale exist when the percent increase in output is greater than the percent increase in costs needed to achieve the increase in output. Or mathematically[2]:

$$E_{Cq} = \frac{\Delta C/C}{\Delta q/q} < 1 \quad (1)$$

where E_{Cq} is the "cost-output elasticity," C is the cost associated with the initial construction of the windfarm and q is quantity. In this particular application, q is the installed capacity of an OSW and C is the overnight cost of an OSW. If $E_C = 1$ then doubling of the input, C, will lead to doubling of the output, q. If economies of scale are present, though, then the cost-output elasticity will be *less than one*, and therefore doubling the cost will *more than double* the output. We will empirically test whether or not economies of scale exist in the off-shore wind market.

2.2. *Learning curves*

Learning curves were first researched by Wright [16] in studying the production of airplanes. Since then, economists have also been interested in the potential presence of learning curves both in theory [1] and in practice [10]. Learning curves have been empirically estimated for electricity generation [6,17], but very little research on the presence of learning curves in offshore wind has been conducted. Junginger et al. [7] empirically analyze "experience curves" in windfarms worldwide and find significant learning effects, but limit their analysis to on-shore wind. Wiser and Bolinger [15], on the other hand, find no evidence of a learning curve in on-shore wind in the United States.

Snyder and Kaiser [13] test for the change in cost of off-shore windfarms over time holding other factors such as distance to shore, turbine size, capacity, and water depth constant, but do not find a decline in cost over time. No research thus far has conducted specific empirical tests for industry-wide or country-specific learning curves in off-shore wind.

2.2.1. *Mathematical definition*

Learning effects exist when cumulative past output is negatively related to the cost of producing the next unit. In other words, more "experience" in past production allows for future production to occur more efficiently. Mathematically, learning curves can be described as follows[3]:

$$E_{CQ} = \frac{\Delta C/C}{\Delta Q/Q} < 0 \quad (2)$$

where E_{CQ} is the "cost-cumulative output elasticity," C is the cost and Q is the cumulative quantity produced. In this application, C is the cost associated with the initial construction of an OSW and Q is the cumulative capacity of all previous off-shore windfarms. We will test for the presence of learning effects for both the industry as a whole as well as country-specific learning curves within countries.

If the learning effects in the off-shore wind market are substantial, then this provides a potentially compelling argument for subsidies on off-shore wind, as investment in energy today will decrease the cost of future production. This argument has been widely used in support of subsidies for renewable energy.

3. Overnight costs

In order to test for economies of scale and learning effects, it is imperative to get an "apples-to-apples" comparison of costs associated with the construction of each windfarm.[4] If the estimated costs of the projects being compared are not consistently calculated, then any results will be problematic. Table 1 shows all of the windfarms being analyzed. As can be seen, they were built over a twenty year period in eight countries that have different exchange rates, interest rates, and inflation rates over time. Furthermore, some of these windfarms were constructed quickly, in just a few months, while others were under construction for almost three years. All of these factors need to be taken into account before testing for economies of scale and learning curves.

Similar cost-comparison problems have arisen when analyzing nuclear plants [9]. We will borrow the methodology used in this literature in order to calculate the "overnight cost" for off-shore windfarms.

3.1. *Mathematical definition*

The first step in calculating the overnight cost is to make an assumption about the distribution of expenditures over the construction period of a project. The following distribution of expenditures is common in the overnight literature.

$$\text{Cumulative Percent}_t = \left[1 - \cos\left(\frac{t - s_i}{f_i - s_i} \times \frac{\pi}{2}\right)^{\alpha}\right]^{\beta} \quad (3)$$

where t is the current time period, f_i is the time period in which windfarm i was completed and s_i is the time period when construction began (i.e. "start" to "finish"). For this particular analysis, the time period is monthly. α is assumed to be 4.082 and β is 3.25, which is consistent with previous literature [3]. Changing these

[2] This notation was borrowed from [11].

[3] This notation was borrowed from [11].

[4] The costs analyzed in this paper include construction costs, i.e. the "installed cost" of each project.

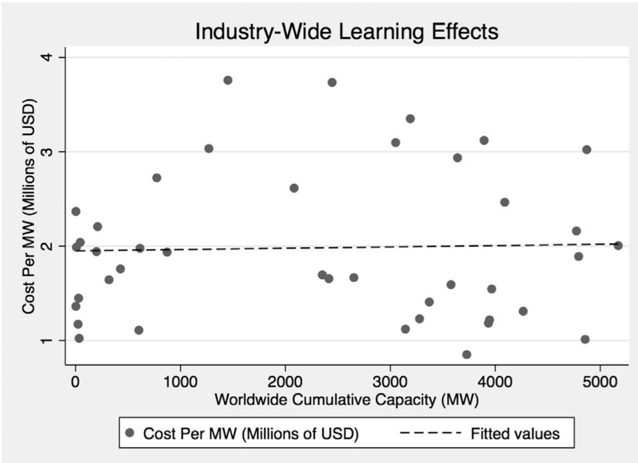

Fig. 2. Industry-wide learning effects: relationship between cost per MW and industry-wide cumulative capacity.

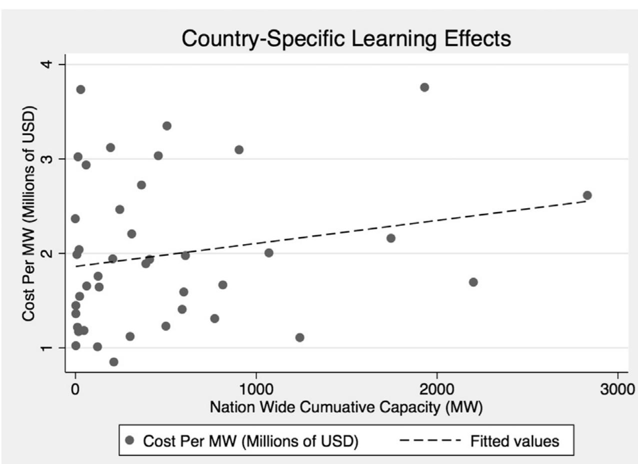

Fig. 3. Country-specific learning effects: relationship between cost per MW and country-specific cumulative capacity.

parameters will change the distribution of when the dollars are spent during the time of the project.

Next, we calculate the percent of the expenditures incurred in each month over the course of the construction period. This can be done by taking the derivative of (3) with respect to time or, more simply, the discrete difference between Cumulative Percent_t and Cumulative Percent_{t-1}.

$$\text{Percent Expenditure}_{i,t} = \text{Cumulative Percent}_{i,t} - \text{Cumulative Percent}_{i,t-1} \quad (4)$$

Next, the discount factor is calculated.

$$\text{Discount Factor}_{i,t} = \text{Percent Cost}_{i,t}(1 + r_{i,t})\left(1 + \text{inflation}_{i,t}\right) \quad (5)$$

where $r_{i,t}$ is the interest rate of country i in time t and $\text{inflation}_{i,t}$ is the inflation rate in country i in time t. Finally, the overnight cost is calculated as follows.

$$\text{Overnight Cost}_i = \frac{\text{Total Cost}_i}{\sum_{t=1}^{T} \text{Discount factor}_{i,t}} \quad (6)$$

Previous research has used this methodology to calculate overnight costs of large industrial projects, but no standardized program has been developed to ensure consistency in these calculations. Furthermore, slightly different methodologies have been used for different studies [3,9]. For this reason, we have created a Stata program entitled *overnightcost* that can be used to assure a standardized calculation of overnight costs for future cost comparisons.[5]

4. Empirical specification

4.1. Economies of scale

In order to test for whether economies of scale are present in the off-shore wind market, the following specification will be used.

$$\ln(\text{Overnight Cost}_i) = \alpha + \beta \ln(\text{Capacity}_i) + X_i'\delta_k + \varepsilon_i \quad (7)$$

Overnight Cost is in 2012 U.S. Dollars. Capacity is the total capacity in MW of windfarm *i*. $\hat{\beta}$ is the estimated E_{Cq} in Equation (1). If β is estimated to be less than 1, then we will have evidence of economies of scale in off-shore windfarms. X_i' includes the following control variables.

1. Water Depth - the average water depth at the windfarm location measured in meters. It is hypothesized that as the water depth increases costs will also increase.
2. Distance to Shore - the distance from the shoreline to the windfarm measured in kilometers.
3. Country Fixed Effects - indicator variables for each country are used to capture any unobserved cross-country heterogeneity that might be present.

4.2. Learning curves

The following empirical specification will be used to test for learning curves in off-shore windfarms.

$$\ln(\text{Overnight Cost}_i) = \alpha + \gamma \ln(\text{Cumulative Capacity}_i) + \beta \ln(\text{Capacity}_i) + X_i'\delta_k + \varepsilon_i \quad (8)$$

$\hat{\gamma}$ is the estimated E_{CQ} from Equation (2) as γ represents the percent change in overnight cost associated with a percent change in cumulative capacity. We will test for both industry-wide and country-specific cumulative capacities' impact on overnight cost. If learning curves are present, then we expect $\gamma < 0$. X_i' includes the same list of control variables as seen above in the economies of scale specification.

5. Data

Currently, there are forty-one European OSWs located in eight different countries. These countries include Denmark, Sweden, the Netherlands, the U.K., Germany, Ireland, Belgium and Finland. As shown in Table 1, the average windfarm has a capacity of 126 MW (MW), values ranging from 2 MWs (Lely) to 630 MWs (London Array). Minimum and maximum water depth were averaged to get an average water depth for each OSW. The average water depth is about 15 m, with some OSWs in water as shallow as 2 m and others in waters as deep as 45 m. Data on capacity, water depth and distance to shore are from 4Coffshore. The overnight cost is calculated

[5] Please contact authors for this program and documentation.

Table 2
Economies of scale.

	Dependent Variable: ln(Overnight cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Capacity (MW))	1.051***	0.920***	0.944***	1.050***	0.989***	0.993***
	(0.0405)	(0.0485)	(0.0471)	(0.0385)	(0.0539)	(0.0503)
ln(Distance to shore (km))		0.225***	0.0718		0.111	−0.000228
		(0.0598)	(0.0870)		(0.0754)	(0.0848)
ln(Water depth(m))			0.195**			0.201**
			(0.0842)			(0.0858)
Country FE	No	No	No	Yes	Yes	Yes
Observations	41	40	40	41	40	40
R^2	0.945	0.960	0.966	0.970	0.973	0.978

Standard errors in parentheses. Country FE is shorthand for "country fixed effects."
$*p < 0.10$, $**p < 0.05$, $***p < 0.01$

Table 3
Industry-wide learning effects.

	Dependent Variable: ln(Overnight cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
ln(Cumulative capacity (MW))	−0.00432	−0.0223	−0.0355	−0.0425	−0.0476	−0.0529
	(0.0412)	(0.0366)	(0.0347)	(0.0384)	(0.0373)	(0.0345)
ln(Capacity (MW))	1.055***	0.938***	0.975***	1.087***	1.036***	1.046***
	(0.0549)	(0.0573)	(0.0557)	(0.0504)	(0.0648)	(0.0598)
ln(Distance to shore (km))		0.226***	0.0639		0.0975	−0.0194
		(0.0604)	(0.0873)		(0.0753)	(0.0839)
ln(Water depth (m))			0.208**			0.209**
			(0.0852)			(0.0840)
Country FE	No	No	No	Yes	Yes	Yes
Observations	41	40	40	41	40	40
R^2	0.945	0.961	0.967	0.971	0.975	0.979

Standard errors in parentheses. Cumulative capacity is industry-wide. Country FE is shorthand for "country fixed effects."
$*p < 0.10$, $**p < 0.05$, $***p < 0.01$

using the *overnightcost* Stata program that accompanies this paper. Interest rates and inflation rates from the World Bank are used.

Figs. 1–3 provide graphical representations of economies of scale and both industry-wide and country-specific learning effects. The best fit line shown in Fig. 1 illustrates a positive relationship between cost per MW and total capacity and thus does not provide evidence of economies of scale. In fact, this *positive* relationship between cost per MW and total capacity provides evidence of possible *diseconomies of scale*. Of course, this is before controlling for other factors such as the distance to shore and water depth that will likely impact costs. The best fit line in Fig. 2 shows a flat relationship between cost per MW and worldwide cumulative capacity, while the best fit line in Fig. 3 shows a positive relationship between country-specific cumulative capacity and costs. Thus, neither industry-wide nor nation-wide learning effects are observed in these figures. Of course, no conclusions can be reached from these graphs. In the next section, we will test for these relationships empirically.

6. Results

Table 2 shows empirical test results for economics of scale. Consistent with Fig. 1, the elasticity of cost with respect to capacity, not holding any other variables constant, is 1.051. This means that a 10 percent increase in capacity is associated with a 10.51 percent increase in costs, thus providing evidence of approximately constant returns to scale. Regressions 2 and 3 add control variables, including distance to shore and water depth. As can be seen, as both distance to shore and water depth increase, we estimate an increase in cost. This is consistent with our expectations. Notice though, that the coefficients for the elasticity of cost with respect to capacity are estimated to be approximately between 0.92 and 0.94 when these covariates are included. Therefore, we estimate that a 10 percent increase in capacity is associated with between a 9.2 and 9.4 increase in costs. When an F-test is conducted to test if these coefficients are statistically significantly different than 1, we cannot reject constant returns to scale. Regressions 4–6 are identical to regressions 1–3, with the addition country fixed effects. The results are very similar as the estimated coefficients vary from 0.99 to 1.05, and therefore the conclusion reached is the same; costs approximately exhibit constant returns to scale.

Table 3 presents results on the presence of industry-wide learning effects in the offshore wind market. Regression 1 estimates the elasticity of cost with respect to cumulative capacity holding the project size constant with no other covariates. The estimated coefficient on cumulative capacity is very close to zero and statistically insignificant. Therefore, this does not provide evidence of industry-wide learning effects. Regressions 2 and 3 add controls and while the point estimates are negative, ranging from −2.2 to −3.6 percent, these are not statistically significantly different than zero. Regressions 4–6 add country level fixed effects, and again we see consistently negative coefficients, but none are statistically significantly different than zero. Point estimates using country fixed effects, while not statistically significant, suggest that a 10 percent increase in cumulative capacity is associated with a 4.3 to 5.3 percent decrease in overnight construction costs. All point estimates presented in this empirical specification on the relationship between total capacity (MW) and costs are consistently clustered around one providing further evidence of constant returns to scale.

Table 4 presents test results for the presence of country-specific learning effects. Interestingly, point estimates suggest that additional cumulative capacity within a country leads to an increase in the overnight cost, holding other factors such as capacity, distance,

Table 4
Country-specific learning effects.

	Dependent Variable: ln (Overnight cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
ln (Cumulative capacity (MW))	0.0140	0.0666	0.0481	0.129**	0.135**	0.109**
	(0.0622)	(0.0551)	(0.0533)	(0.0552)	(0.0519)	(0.0522)
ln (Capacity (MW))	1.035***	0.836***	0.882***	0.923***	0.848***	0.878***
	(0.0802)	(0.0850)	(0.0840)	(0.0655)	(0.0735)	(0.0729)
ln (Distance to shore (km))		0.245***	0.0966		0.126*	0.0397
		(0.0618)	(0.0915)		(0.0693)	(0.0826)
ln (Water depth (m))			0.182**			0.151*
			(0.0856)			(0.0846)
Country FE	No	No	No	Yes	Yes	Yes
Observations	41	40	40	41	40	40
R^2	0.945	0.962	0.966	0.974	0.978	0.981

Standard errors in parentheses. Cumulative capacity is specific to the country in which each OSW is located. Country FE is shorthand for "country fixed effects."
$*p<0.10$, $**p<0.05$, $***p<0.01$.

and water depth constant. These results oscillate between statistical significance and insignificance, but reject country-specific learning effects due to the positive coefficients. In fact, subsequent projects within a specific country have on average been more expensive than earlier projects.

In Tables 2–4 point estimates consistently do not suggest economies of scale, as coefficients on capacity range from 0.836 to 1.055. All of these point estimates are clustered around one and not a single coefficient is statistically significantly different than one. Therefore, in all specifications using a variety of controls, we find consistent evidence that costs increase at approximately the same rate as capacity, and therefore find no evidence of economies of scale. Furthermore, while point estimates suggest industry-wide learning effects in some specifications, none of these estimates are statistically significant. We find no evidence of country-specific learning effects; in fact we find evidence that costs increase within a country as more windfarms are built.

7. Conclusions

This paper presents empirical test results for economies of scale and both industry-wide and country-specific learning effects in the offshore wind market using data from forty-one offshore windfarms (OSWs) built in eight different countries over a twenty year period. Due to the level of heterogeneity within our sample, we calculate the "overnight cost" of each OSW, a method that has been used in other electrical production analysis, specifically nuclear. This allows for an "apples to apples" comparison of the cost of each of these windfarms.

Point estimates with a variety of covariates suggest that costs are unitarily elastic, and therefore consistent evidence of approximately constant returns to scale is found. We do not find statistically significant evidence of either industry-wide or country-specific learning effects in the offshore wind market. These results are robust after controlling for the distance of the windfarm from shore as well as the water depth where the windfarm is built. As expected, we find evidence that increases in distance to shore and increases in water depth are associated with higher total costs.

These results may have policy implications for future offshore wind development since potential "learning-by-dong" and "experience" effects are often used to justify government financial support for proposed offshore wind development. This research suggests that there are no learning-by-doing effects associated with the construction of offshore wind facilities and that any consideration of these learning-by-doing impacts should be secondary, if not eliminated, from the policy calculus of providing offshore wind financial support. These conclusions do not suggest that are no other rationales for providing government financial support for wind energy, only that learning-by-doing impacts, or even simple economies of scale in construction arguments, should not be used as rationales for that support. Additionally, this research is based upon findings to date and likely outcomes for the near future. Over time, these types of impacts need to be continuously observed, particularly if offshore wind becomes more commonplace, standardized, and prolific.

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