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 country-specific and cross-country 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 especially importance.

The dataset used in the analysis consists of 35 internationally-developed offshore wind projects. Research findings do suggest that the costs do exhibit economies of scale, but neither country-specific or cross-country learning effects are observed. The research includes a unique Stata-based program that can be used calculate the overnight cost of any large scale renewable (or conventional) power generation project.

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, thirty-four additional OSWs have been constructed in seven different countries including Denmark, Sweden, the Netherlands, the United Kingdom, Germany, Ireland, and Belgium. 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 (USDOE 2011). 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 (USDOE 2011). These two issues are interrelated, though, as relatively expensive projects are less likely to receive approval than relatively less expensive projects. (Stone 2013)

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 have an impact on the cost, then they need to be taken into account when comparing wind farm 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 thirty-five OSWs that are currently in operation were built in six 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 literatures. 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 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 by doing.[1] We will test for the presence of both country-specific and cross-country 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 cross-learning effects describes 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 by doing in the literature. Some of these include "learning effects", "learning curves", 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 (Smith 1955). Economies of scale in electric power generation specifically have also been studied extensively both in the United States (Christensen & Greene 1976) as well in other countries around the world (Filippini 1996, Franquelli, Piacenza, & Vannoni 2004). USDOE (2011) 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 & Turkenburg (2005), 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 & Kaiser (2009) find a positive relationship between total cost and total 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 offshore windfarms built worldwide.

2.1.1 Mathematical Definition

Pindyck & Rubinfeld 2004 describe economies of scale as follows: “We say that a firm enjoys economies of scale when it can double its output for less than twice the cost.” Or mathematically:

$$E_{Cq} = \frac{\Delta C/C}{\Delta q/q} < 1 \tag{1}$$

Where E_{Cq} is the "cost-output elasticity", C is the cost 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 $E_C = 1$ the 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 exists in the off-shore wind market.

2.2 Learning Curves

Learning curves were first researched by Write (1936) in studying the production of airplanes. Since then, economists have also been interested in the potential presence of learning curves both in theory (Arrow 1962) and in practice (Mowery 1983). Learning curves have been empirically estimated for electricity generation (Jamsab 2007; Zimmerman 1982), but very little research on the presence of learning curves in offshore wind has been conducted. Junginger & Turkenburg (2005) empirically analyze experience curves in wind farms worldwide and find significant learning effects, but limit their analysis to on-shore wind. USDOE (2011), on the other hand, finds no evidence of a learning curve in on-shore wind in the United States.

Snyder & Kaiser (2009) 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 a specific empirical test for an industry wide learning curve in off-shore wind.

2.2.1 Mathematical Definition

Pindyck & Rubinfeld 2004 explain that a firm or industry can " [learn] over time as cumulative output increases." This act of "learning" with respect to cumulative capacity can be written mathematically as follows:

$$E_{CQ} = \frac{\Delta C / C}{\Delta Q / Q} < 0 \tag{2}$$

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 of an offshore wind farm and Q is the cumulative capacity of all previous off-shore wind farms. We will test for the presence of a learning curve for the worldwide offshore wind industry.

If the learning effects in the off-shore wind market are substantial, then this provides a 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 by doing, it is imperative to get an "apples-to-apples" comparison of costs. 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 wind farms being analyzed. As can be seen, they were built over a twenty year period in seven 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 (Ellis & Zimmerman 1980; Marshall & Navarro 1991). We will therefore borrow the methodology used in this literature in order to calculate the overnight cost for off-shore windfarms.

3.0.2 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.

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

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. 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 (EIA 1998). Changing these 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}.

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

Next, the discount factor is calculated.

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

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.

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

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 (Ellis & Zimmerman 1980, Marshall & Navaro 1991, and EIA 1998). 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. Appendix 1 shows specific instructions on how to install and use the *overnightcost* Stata program.

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.

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

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. Number of Turbines - this is the total number of turbines that makeup the windfarm. Some windfarms have many small turbines, while others have just a few larger turbines.

3. Distance to Shore - the distance from the shoreline to the windfarm measured in kilometers.

4. 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.

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

$\hat{\gamma}$ 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 country-specific and cross-country cumulative capacity's 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 thirty-five OSWs located in seven different countries worldwide. These countries include Denmark, Sweden, the Netherlands, the U.K., Germany, Ireland and Belgium. The average wind farm has a capacity of 107 Mega Watts (MW), values ranging from

2 MWs (Lely) to 504 MWs (Greater Gabbard). Minimum and maximum water depth were averaged to get an average water depth for each offshore wind farm. The average water depth is about 12.5 meters, with some OSWs in water as shallow as 2.5 meters and others in waters as deep as 45 meters. The average turbine size in the sample is 2.4 MWs.

Data on capacity, water depth, turbine size, number of turbines, and distance to shore are from 4Coffshore. The overnight cost is calculated using the *overnightcost* Stata program that accompanies this paper. Interest rates and inflation rates from the World Bank are used.

Figures 1-3 provide a graphical representations of economies of scale and both worldwide and country-specific learning effects. There appears to be a small positive relationship between cost per MW and total capacity in Figure 1. Of course, this is before controlling for other factors such as the distance to shore and water depth that will likely impact costs. Nonetheless, this provides no evidence of economies of scale. Figure 2 shows a negative relationship between cost per MW and worldwide cumulative capacity, thus providing evidence of a worldwide learning curve, while Figure 3 shows a positive relationship between country specific cumulative capacity and costs. Of course, no conclusions can be reached from these graphs. In the next section, we will test for these effects empirically.

6 Results

Table 2 shows empirical tests for economics of scale. Consistent with Figure 1, the elasticity of cost with respect to capacity, not holding any other variables constant, is 1.039. This means that a 10 percent increase in cost is associated with a 10.39 percent increase in capacity, thus providing evidence of 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 .91 and .94 when these covariates are included. 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, and the conclusion reached is the same; while point estimates suggest that economies of scale are present, we find no statistically significant evidence of economies of scale in the offshore wind market.

Table 3 tests for the presence of cross-country (or 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. The estimated coefficient on cumulative capacity is slightly positive, but statistically insignificantly different than zero. Therefore, this provides no evidence of an industry-wide learning curve. Regressions 2 and 3 add controls and again, there is no evidence of an industry-wide learning curve. Regressions 4-6 add country level fixed effects, and the conclusions do not change. Table 3 presents no evidence of a cross-country learning effects in the offshore wind market.

Table 4 tests for the presence of country specific learning curves. 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, 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 have on average been more expensive than earlier projects.

Interestingly, in Tables 2-4, when appropriate covariates are used, point estimates consistently suggest economics of scale, as coefficients on capacity range from .643 to .967. This means that a 10 percent increase in capacity is associated with only an 6.4 to 9.7 percent increase in cost. If these point estimates are accurate, then there is evidence of economies of scale in the offshore wind market. Due to the inherently small sample size, it is not surprising that these confidence bounds are large and therefore formal statistical tests for economies of scale are rejected.

7 Conclusions

This paper presents an empirical test for economies of scale and both cross-country and country-specific learning effects in the offshore wind market using data from 35 offshore wind farms built in six different countries over a 20 year period. Due to the level of heterogeneity within our sample, we calculate the "overnight cost" of each offshore wind farm, a method that has been commonly used in other electrical production analysis, specifically nuclear, and then adjust for exchange rate differences. This allows for an "apples to apples" comparison of the cost of each of these wind farms.

While point estimates with the correct appropriate covariates suggest that economies of scale are present, these results are not statistically significant. We do not find evidence of either cross-country or country-specific learning effects in the offshore wind market. These results are robust after controlling for the distance of the wind farm from shore as well as the water depth where the wind farm is built. As expected, we find evidence that increases in distance to shore and increases in water depth are associated with higher total costs. When country level fixed effects are included into our regressions, these results are robust.

These results can potentially have substantial policy implications for the offshore wind market both in the United States and worldwide. Due to the lack of empirical evidence of an industry wide learning curve, there is no evidence to suggest that investing in more offshore wind will lead to a decrease in costs of future projects. Furthermore, these results do not provide evidence that "pilot projects" in a country will lead to decreased costs in future projects. While results on economies of scale are not robust, point estimates do suggest that larger projects appear to have lower average costs than smaller projects. For this reason, increasing capacity on the margin, will likely decrease the overall cost per capacity.

Simply because learning effects have not been observed in the offshore wind market to date, does not necessarily mean the these will not be observed in future projects. Our model simply shows that these have not been realized in previous projects and therefore a similar analysis should be conducted as more offshore wind projects are completed to see if these gains are realized in the future.

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	.8
Tuno Knob	Denmark	1995	5	4	5.5
Bockstigen	Sweden	1998	3	6	4
Middlegruden	Denmark	2000	40	6	2
Utgunden	Sweden	2000	10	8.6	4.2
Blyth	UK	2000	4	8.5	1
Yttre Stengrund	Sweden	2001	10	8	2
Horns Rev	Denmark	2002	160	10	14
Nysted	Denmark	2003	158	7.75	10
Ronland	Denmark	2003	17.2	2	.1
Samso	Denmark	2003	23	20	3.5
Arklow	Ireland	2004	25.2		11.7
North Hoyle	UK	2004	60	12	7
Scoby Sands	UK	2004	60	16.5	2.5
Kentish Flats	UK	2005	90	5	10
Barow	UK	2006	90	17.5	7.5
Egmond aan Zee	Netherlands	2007	108	18	10
Irene Vorrink	Netherlands	2007	17	2.5	0
Lillgrund	Sweden	2007	110	7	10
Beatrice	UK	2007	10	45	22
Burbo Bank	UK	2007	90	5	6.5
Prinses Amaliawindpark	Netherlands	2008	120	21.5	23
Lynn/Inner Downsing	UK	2008	97	9.5	5
Thronton Bank	Belgium	2009	30		28
Horns Rev 2	Denmark	2009	209	13	31.7
Rhyl Flats	UK	2009	90	7.5	10.7
Robin Rigg	UK	2009	180	5	9
Belwind Phase 1	Belgium	2010	165	22.5	46
Gunfleet Sands	UK	2010	173	6.5	7
Thanet	UK	2010	300	18.5	12
EnBW Baltic I	Germany	2011	48	17.5	16
Greater Gabbard	UK	2011	504	20.5	36
Sheringham Shoal	UK	2011	317	18.5	23
Walney Phase 1	UK	2011	184	21	14

Table 2: Testing Economies of Scale in Offshore Windfarms

	Dependent Variable: Ln(Overnight Cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
Ln(MW)	1.039***	0.905***	0.941***	1.037***	0.916***	0.930***
	(0.0584)	(0.0668)	(0.0627)	(0.0685)	(0.0830)	(0.0744)
Ln(Dist.)		0.243***	0.0629		0.219**	0.0460
		(0.0794)	(0.0995)		(0.0996)	(0.110)
Ln(Depth)			0.341**			0.433**
			(0.129)			(0.161)
Country FE	No	No	No	Yes	Yes	Yes
Observations	35	34	34	35	34	34
R^2	0.906	0.928	0.941	0.916	0.931	0.947

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Testing For a Learning Curve in Offshore Windfarms

	Dependent Variable: Ln(Overnight Cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
Ln(Cum. MW)	0.0193	0.0376	-0.0276	-0.00274	0.0380	-0.0116
	(0.0631)	(0.0603)	(0.0610)	(0.0696)	(0.0752)	(0.0703)
Ln(MW)	1.025***	0.874***	0.967***	1.039***	0.877***	0.942***
	(0.0742)	(0.0835)	(0.0848)	(0.0858)	(0.114)	(0.105)
Ln(Dist.)		0.253***	0.0410		0.242**	0.0360
		(0.0818)	(0.112)		(0.111)	(0.128)
Ln(Depth)			0.368**			0.440**
			(0.144)			(0.170)
Country FE	No	No	No	Yes	Yes	Yes
Observations	35	34	34	35	34	34
R^2	0.906	0.928	0.942	0.916	0.932	0.947

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Testing Country Specific Learning Curves in Offshore Windfarms

	Dependent Variable: Ln(Overnight Cost) in 2012 U.S. Dollars					
	(1)	(2)	(3)	(4)	(5)	(6)
Ln(Cum. Cap by Nation)	0.110	0.170**	0.127	0.250**	0.257**	0.169
	(0.0902)	(0.0796)	(0.0774)	(0.104)	(0.0938)	(0.110)
Ln(MW)	0.911***	0.689***	0.775***	0.777***	0.643***	0.746***
	(0.119)	(0.119)	(0.119)	(0.125)	(0.124)	(0.140)
Ln(Dist.)		0.282***	0.121		0.230**	0.116
		(0.0774)	(0.103)		(0.0888)	(0.116)
Ln(Depth)			0.287**			0.275
			(0.130)			(0.187)
Country FE	No	No	No	Yes	Yes	Yes
Observations	35	34	34	35	34	34
R^2	0.910	0.937	0.946	0.932	0.947	0.952

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

8 Figures

Figure 1: Economies of Scale

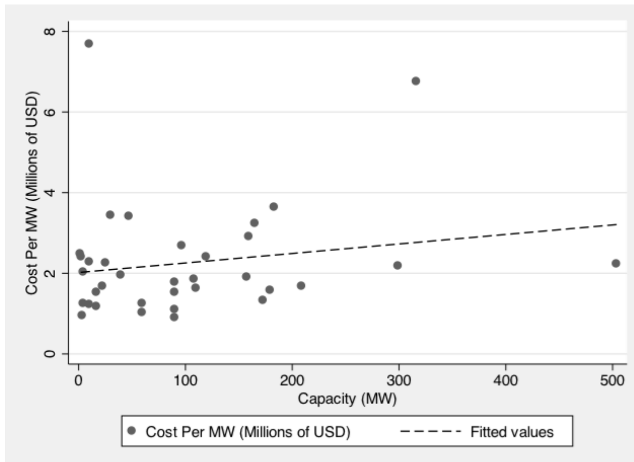


Figure 2: Worldwide Learning by Doing

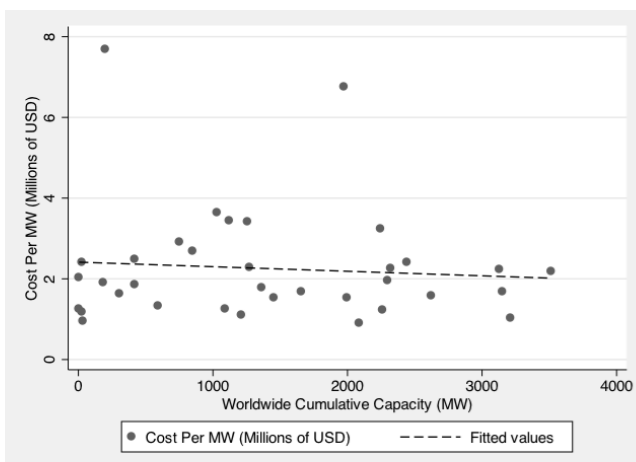
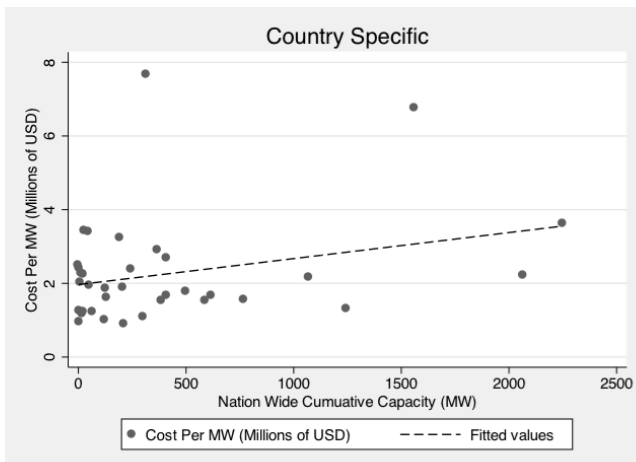


Figure 3: Nation-wide Learning by Doing



9 Appendix

In order to install the overnightcost program, Stata 11.2 or later is needed. Type the following into Stata:

net install overnightcost.pkg, from(`http://www.gregoryuptonjr.com/stata/`)

Stata will automatically install overnightcost and all supporting documentation.

1. Create a comma separated file with the following variable names: "month", "year", "interest_rate", "inflation_rate", "total_cost", and "project_name".

2. For the month variable, fill in the month number. January= 1, February= 2, etc.

3. For the year variable, simply put the year: 2001, 2002, etc.

4. For the interest rate and inflation rate, put the yearly rate observed in each month. For instance, 5% inflation rate is listed as .05, NOT 5.

5. For the total cost, put in the total cost for the project in nominal dollars at the time of construction. There cannot be commas or currency indicators included. For instance, if the project costs five million dollars, input 5000000. This cost only needs to be listed as the first observation, with all subsequent observations left blank.

6. Put the name of the project in the project name column. Notice, this can be anything (project identification numbers or string variables are fine).

7. Name the file in the following format: stub#. In my example (`www.gregoryuptonjr.com/overnightcost`), the stub is "project_". Therefore the projects are named "project_1", "project_2", etc.

8. Repeat steps 1 through 7 for each project.

9. Run the overnight cost program. It will save a file entitled *overnightcost.dta* in the folder where the input files are saved.

10. Please see the files listed at `www.gregoryuptonjr.com/overnightcost` for an example.

For additional help with *overnightcost* simply type help overnightcost into Stata after installation.

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