Wind Farm Capital Cost Regression Model for Accurate Life Cycle Cost Estimation

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Abstract— **Various studies over the last decade have attempted to forecast capital cost of wind power. The main assumption underpinning these models is that cost reductions will accrue indefinitely from technological learning over time. In this paper a regression model is proposed for wind farm capital cost which is based on commodities price and water depth rather than technological learning. With greater simplicity and certainty in the theoretical foundations of such a model, it is possible to gain realistic estimates of wind turbine capital cost. Such pragmatic and well-reasoned output is needed so that wind farm developers can understand their future risk exposure to price fluctuations in capital cost of plant.**

Keywords- Wind Turbine; Capital cost; Regression Model; wind farm; CAPEX. (key words)

I. INTRODUCTION

This paper proposes that the key driver for wind farm capital expenditure (CAPEX) has not been captured in existing models. Several authors propose application of technological learning models, which we will demonstrate as being inappropriate for the current level of technical development of wind, particularly offshore wind. Instead we propose a model based on coupling capital cost with metals commodities indexation and water depth. This model makes intuitive sense due to the well known influence of water depth on cost, and the amount of metal utilised in wind turbine construction. This pertinent to offshore wind due to high metallic content of foundations and inter-array cabling. Furthermore, the simplicity of this model means it can be applied transparently to cost data in the future.

II. PREVIOUS WORK

Several authors have proposed use of a technological learning model to capture wind farm or wind turbine capital costs. The papers by Junginger et al. [1, 2] are cases in point. The authors first reviewed the work of several other authors in fitting theoretical experience curves for prediction of wind turbine cost. They took UK data from 1991 – 2001 and used it to fit an experience curve, resulting in a progress ratio of 81%. This means that with each doubling of worldwide capacity, the per-unit cost should reduce by 19%. The authors used their model to extrapolate results out to a time horizon of 2020. Their UK data showed a turnkey installation price of approximately €1200/MW in 2001 at which point the global installed capacity of wind was approximately 20GW. By 2008 global capacity was around 120GW [3] implying that prices should have reduced significantly (since the capacity has been doubled twice since 2001), however current onshore projects are typically running at more than the €1200/MW figure used in 2001. According to the learning rate model, the cost should have dropped to around (0.812x1200) €790/MW. In the UK a recent low end estimate of capital cost is €1500/MW [4]. One can conclude that the global experience curve does not apply to this phase of wind turbine development, since the actual cost and the model-generated cost trend in opposite directions. This seems like a classic case of unjustified extrapolation on the part of authors utilizing such methodologies. These limitations are discussed by Greenacre et al. [5] however there is little transparency in their proposed alternative approach.

A. Data

Bilgili et al. [6] show capital cost data for a set of offshore wind farms installed from 2001 – 2007. Table 1 is produced by taking their data from this period and adding new projects for the period 2008 – 2011. Table 1 also contains water depth data. From overall CAPEX it is possible to deduce turbine and foundation cost by assuming this to be 52% of the overall project capital cost [7]. Table 1 shows generally increasing capital cost, directly at odds with models assuming technological learning is the prime mover of capital cost. Therefore the technological learning model should be replaced with an adequate model.

The main starting assumption adopted in this paper is that commodities pricing (particularly metal) and water depth, are instead the main drivers of wind turbine capital cost. The reason for these assumptions is that:

- Water depth is a good proxy for project complexity
- There is a significant amount of metal in wind turbines [8], and international competition for resources is forcing prices upwards.

TABLE I. CAPITAL COST FOR OFFSHORE WIND PROJECTS. BILGILI ET AL. [6] AND ADDITIONAL SOURCES INDICATED.

Project	area	commissioned	wind farm CAPEX €/MW	water depth m	mean water depth m
Middelgrunden	DK	2001	1.2	3-8 [9]	5.5
Horns Rev	DK	2002	1.7	2-9 [10]	5.5
Samsø	DK	2003	1.3	12-18 [11]	15
North Hoyle	UK	2003	2	5-12 [12]	8.5
Nysted	DK	2003	1.5	6-9 [13]	7.5
Scroby Sabds	UK	2004	2	2-10 [12]	6
Kentish Flats	UK	2005	1.8	5 [12]	5
Barrow	UK	2006	1.59 [14]	15-20 [14]	17.5
Egmond aan See	NL	2006	1.85 [15]	18 [16]	18
Burbo Bank	UK	2007	2	2-8 [17]	5
Lillgrunden	S	2007	1.8	4-13 [18]	8.5
Lynn & Inner Downsig	UK	2008	1.76 [19]	6.3-11.2 [20]	8.75
Alpha Ventus	DL	2008	3.00 [21]	30-40 [21]	35
Horns Rev II	DK	2009	2.14 [22]	9-17 [23]	13
Rhyl Flats	UK	2009	2.40 [24]	6.5-12.5 [25]	9.5
Thanet	UK	2010	2.96 [26]	20-25 [26]	22.5
Robin Rigg	UK	2010	2.78 [27]	0.5-17 [28]	8.75
Gunfleet Sands	UK	2010	2.77 [29]	8 [30]	8
Nysted II	DK	2010	1.93 [31]	6-12 [32]	9
Baltic 1	DL	2010	4.14 [33]	16-19 [33]	17.5
Walney 1 (not inc. grid conn.)	UK	2011	3.10 [34]	19-28 [34]	23.5

Data for metals commodity pricing was obtained for the period 1999-2011 [35]. The data takes the form of a commodity metals price index (CMPI) produced by the International Monetary Fund, which is broadly representative of iron, steel and copper as used in wind turbine manufacture. Figure 1 is a plot of the index for the period 1999-2011. The index has roughly trebled in value since 2001. Furthermore, it can be seen that the index had recovered to pre-2008 financial crisis levels as of end 2010.

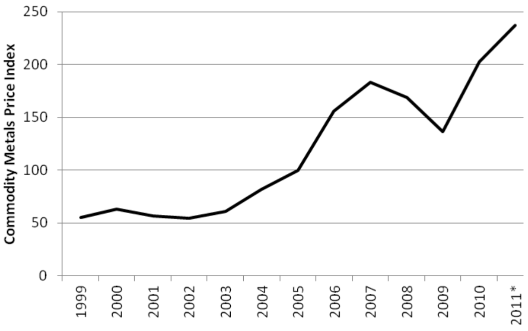

Figure 1. Metals price index [18]. *2011 figure based on Jan-Oct 2011

III. REGRESSION ANALYSIS

We follow a straightforward least squares linear regression as explained in Draper and Smith [36], where:

$$\text{Wind farm CAPEX } (€/MW) = y$$
$$\text{Water Depth } (m) = x_1$$
$$CMPI = x_2$$

It is assumed the relationship can be explained by the linear dependency:

$$y = b_0 + b_1 x_1 + \varepsilon \quad (1)$$

b_0 and b_1 are estimated using least squares (see Table II). After the water depth (x_1) regression is completed, the CMPI (x_2) is regressed on the residuals (ε) of (1). The model outputs are then added to yield a combined model.

TABLE II. MODEL PARAMETER ESTIMATION

model	b_1	b_0	σ
water depth only (x_1)	0.0481	1.5879	0.61152
CMPI model (x_2)	0.0037	-0.5701	0.6406

IV. RESULTS

The model performance is firstly tested by plotting against the cost data in Table 1.

A. Model Testing

Figure 2 shows the first stage of modelling, with the model regressed on water depth only. It can be seen that even a crude model based on water depth roughly captures the increasing cost seen in the data. This is in line with observations of similar recent studies [37]. To test the robustness of this conclusion, Baltic 1 was removed from the data set and the model was re-fitted. The regression line for both cases is presented in Figure 3. The effect of removing Baltic 1 is to reduce the gradient of the regression line from 0.0481 to 0.0400. While this does weaken the correlation between CAPEX and water depth, removal of the data point cannot be justified until more information is available regarding any unique aspect of Baltic 1 which increased the project CAPEX. Therefore the data point is retained for subsequent analysis.

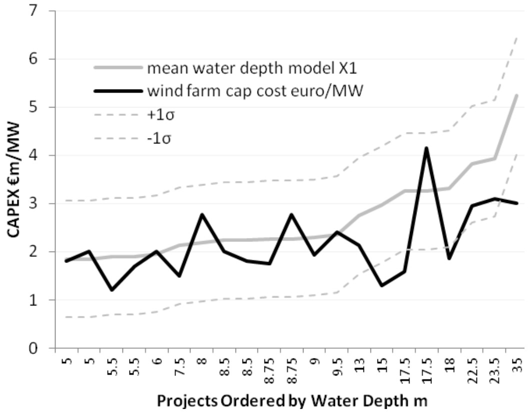

Figure 2. Regression model: water depth only (x_1)

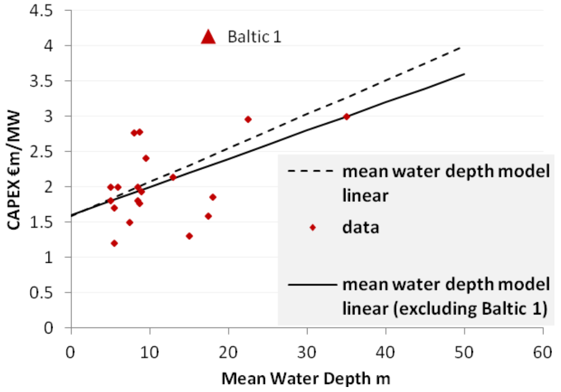

Figure 3. Regression line: water depth only (x_1), excluding Baltic 1

In the next stage, the CMPI data are used to fit a model to the residuals of the first model. Since the CMPI is an averaged value over a time scale of 1 year, the residuals have to be re-ordered according to the year of project commissioning (see Table 1). The results of this regression model are shown in Figure 4, and the regression line in Figure 5. As can be seen in Table II, the influence of CMPI is an order of magnitude less than water depth. Nevertheless, the CMPI regression is included in the model in order to observe its effect on estimating the CAPEX.

Figure 6 illustrates the performance of the 2 models (water depth only, and combined CMPI + water depth). Model output is plotted alongside the original data. Model performance is evaluated via measuring the error of the two models.

The water depth model root mean squared error (RMSe) = 0.612 whereas the combined model RMSe = 0.530. The results obtained by the authors of [37] suggest that cost of metals are statistically significant in overall project cost, but less so compared with the influence of water depth. Figure 6 reinforces this conclusion.

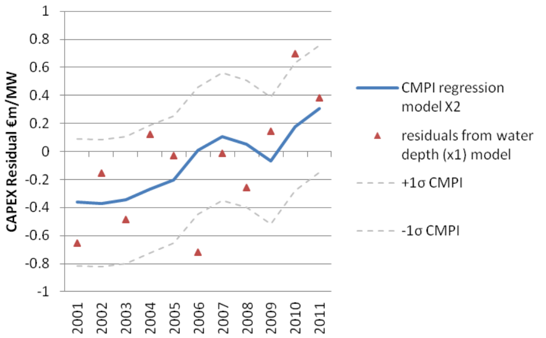

Figure 4. Regression model: CMPI (x_2)

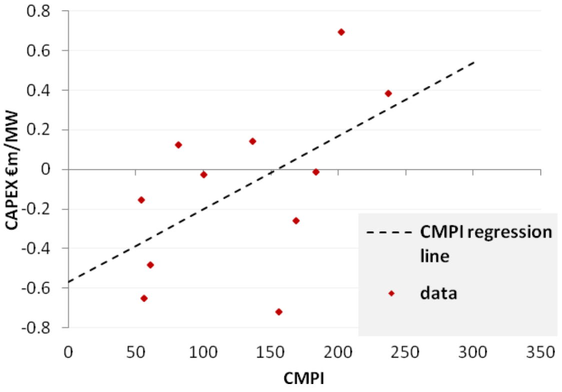

Figure 5. Regression model: CMPI (x_2)

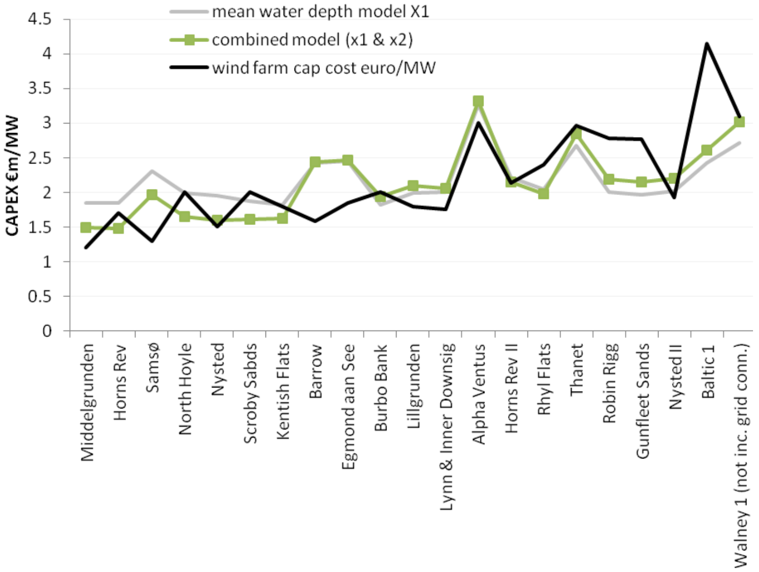

Figure 6. Combined regression model ($x_1 + x_2$)

B. *Forecasting*

The model can be used in predictive mode to estimate future costs. For near shore shallow water projects of water depth = 20m, we can evaluate the scenario of a collapse in commodity prices, using 2008 CMPI index levels. Using values from Table II, firstly the CMPI contribution is calculated:

$$y = b_0 + b_1 x_2 + \varepsilon = -0.5701 + 0.0037 * 169.01 + \varepsilon$$

$$= 0.053845757 + \varepsilon$$

This is added to the water depth model, resolved at 20m depth:

$$y = b_0 + b_1 x_1 + \varepsilon = 1.5879 + 0.0481 * 20 + (0.053845757 + \varepsilon)$$

$$= €2.60m/MW$$

Alternatively we can evaluate the project at the same water depth at current commodity cost levels:

$$y = b_0 + b_1 x_1 + \varepsilon = 1.5879 + 0.0481 * 20 + (0.305276716 + \varepsilon)$$

$$= €2.85m/MW$$

This is equivalent to a CAPEX rise of nearly 10%.

V. CONCLUSIONS

The research area of modelling and predicting wind farm capital cost has been dominated by technological learning models. These models do not explain the recent upwards cost trends seen in practice, which is a major flaw with such models. The parsimonious model presented here provides a highly intuitive approach which can be tested and used easily. The result is greater confidence in the model.

Clearly water depth and materials are not the only drivers in offshore wind farm capital cost. The other oft-cited factors are demand and supply bottlenecks. Manufacturing capacity data are not available in the public domain. However building annual demand into the model may result in a better fit.

Currency exchange rates are another possible source of CAPEX coupling. Furthermore, nonlinear regression methods may be more appropriate for future estimates of capital cost. These issues will be explored in a future paper.

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