Better estimates of LCOE from audited accounts – a new methodology with examples from United Kingdom offshore wind and CCGT

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Abstract

Around the world, government policies to support new renewable energy technologies rely on accurate estimates of Levelised Cost of Energy (LCOE). This paper reveals that such estimates are based on "public domain" data which may be unreliable. A new approach and methodology has been developed which uses United Kingdom (UK) "audited" data, published in company accounts that has been obtained from Companies House, to determine more accurate LCOE estimates. The methodology is applicable to projects configured within Special Purpose Vehicle (SPV) companies. The methodology is then applied to a number of UK offshore wind farms and one Combined Cycle Gas Turbine (CCGT) project, with cost data then compared to that presently in the public domain. The analysis reveals that recent offshore wind projects show a slightly declining LCOE and that public domain cost estimates are unreliable. But of most concern is that offshore wind farm costs are still much higher than those implied by recent bids for UK government financial support via Contracts for Difference (CfDs). The paper concludes by addressing further the question of how offshore wind projects can achieve the degree of LCOE reductions required by recent CfD bids.

1. Introduction

Offshore wind is expected to become an important component in the global future energy mix[1], including in the United Kingdom [2], Germany, Denmark, Japan, India and the United States of America[1,3]. The focus of this paper is on the United Kingdom (UK).

At present, offshore wind projects around the world are not directly cost-competitive with other forms of electricity generation [4]. In the UK, offshore wind projects are supported by government-mandated Contracts for Difference (CfDs). To secure financial support, developers are now bidding very aggressively, to the extent that the strike prices have fallen dramatically from around £150/MWh to £57.50/MWh between the first awards and the most recent auction rounds [5]. The capital and operating cost reductions implied by these bids are large, and are not supported by the overall trend of offshore wind farm costs for those projects already in operation.

Accurate evaluations of Levelised Cost of Energy (LCOE) are critical to policy choices and investment appraisal for offshore wind farms: the aim of this paper is to establish a new methodology to provide better information for policy and decision-making. This approach is based on calculating the LCOE applicable to energy projects undertaken through Special Purpose Vehicle companies (SPVs). The methodology is applied to a range of UK offshore wind farms in particular.

There is a considerable literature on costs and learning rates for offshore wind [4,6-14]. The literature on wind farm costs ranges from simple assessments of the comparative cost of electricity generation alternatives [4,6,7], through development of cost breakdown structures [8] and probabilistic assessments [9,10] to detailed evaluation of learning rates [11-13] and meta-analyses of learning rates [14].

The literature relies heavily on estimates of capital and operating costs from public domain sources. Ederer [15] has observed that cost data for offshore wind farms gathered from press reports or commercial databases can be unreliable, as “it is difficult to detect whether the figures were massaged”. In the case of online databases and reports from consulting companies, “where the original source is often not disclosed”…“it is not clear how the data were processed” [15]. In our own review of the literature we found that extant sources generally used for cost information are precisely those whose accuracy Ederer’s observations have thrown into doubt [15]. It is against this backdrop that this paper provides a new and robust approach to sourcing cost data which we believe should be more relevant, reliable and consistent than that currently in the public domain. It considers whether and why such data might be distorted, and compares data sourced using this approach to the publicly available data most commonly used in the literature.

The paper is divided into 8 sections. Section 1 introduces the paper. Section 2 reviews the relevant literature in the area of cost estimation with particular reference to offshore wind, and summarises the main sources of cost data and the uses to which it is put. Section 3 discusses the validity, robustness and potential for distortion of various data sources, while Section 4 sets out the new methodology used for gathering and working with audited data to provide the accurate capital and operating costs required to develop informed levelised cost of energy (“LCOE”) calculations.

Section 5 comprises the main conclusions for UK offshore wind farms, although the method is equally applicable in other countries with significant offshore wind development (such as Germany and Denmark) and to other technologies (an example is provided for a Combined Cycle Gas Turbine - CCGT - power project). It includes sensitivity calculations on discount rate – a key factor in LCOE calculation. Section 6 compares the new results with data derived from other public domain sources commonly used by other researchers and shows that these public domain sources can be significantly different to cost data derived from accounts. Section 7 explores the implications for cost reduction targets for new wind projects in the context of recent CfD bids.

Section 8 discusses the new methodology and draws important conclusions.

2. Literature review

Cost comparisons of alternative electricity generation technologies are essential in informing policy choices. In a world transitioning from carbon-emitting thermal power generating technologies (such as gas and coal-fired power stations) to carbon-neutral and renewable choices (including offshore wind), a well-informed understanding of comparative costs must lie at the foundation of informed policy decisions.

The literature is rich with examples of cost comparisons and evaluation of cost trends in specific technologies. It is immediately obvious that where underlying cost data is of poor quality, any conclusions may be in doubt. This brief review considers some of this literature, setting out some of the uses to which cost data is put and examines the sources of cost data used in these examples.

2.1. Cost comparisons

The simplest application of cost data is to provide comparisons of the costs of energy alternatives. Such comparisons are widely used by Governments (e.g. the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) [6] and by commercial consultants such as Lazard, Ernst & Young and Arup [7,16,17].

BEIS expresses costs in terms of Levelised Cost of Energy (LCOE). LCOE is "the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh" [6].

The formula for LCOE used by BEIS is set out in Equation 1:

$$LCOE = \frac{NPV_{Costs}}{NPE} = \sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t} \Bigg/ \sum_{t=1}^{n} \frac{E_t}{(1+d)^t} \tag{1}$$

Where t is the period ranging from year 1 to year n, C_t the capital cost in period t (including decommissioning), O_t the fixed operating cost in period t, V_t the variable operating cost in period t (including fuel cost, and sometimes taxes, carbon costs etc), E_t the energy generated in period t, d, the discount rate, and n the final year of operation including decommissioning. A theoretical justification for LCOE was recently set out by Aldersey-Williams and Rubert [18].

BEIS calculates LCOE for renewable energy technologies (RETs) based on a report by Arup [17] which included updated "cost and technical assumptions for projects reaching FID (Final Investment Decision) between 2015 and 2030". Arup's report [17] outlines the data collection approach as involving a "broad mix of public, internal and stakeholder sources" and involving "manufacturers, projects developers and utility companies". However, it is clear that such data can be susceptible to manipulation by participants, who might be expected to be concerned to shape policymakers' opinions in favour of future projects.

Other commercial consultants, such as Lazard and Ernst & Young are even less specific about their data gathering approaches. Lazard's analysis of LCOE is based on "Lazard estimates" [7], while Ernst & Young state that they rely on "validated sources and use average input data". Ernst & Young add that their study is "based on publicly available information sources and average input data" [16]. Again, there is limited opportunity to confirm the validity of these data, which, if derived from public statements, may again be vulnerable to "massaging" or selective presentation by developers.

In recent literature, Partridge [4] compared thermal and renewable costs and emphasised the importance of reliable cost inputs, including capital and operating costs, and costs of finance, in building up the overall LCOE comparison. His focus was "to examine the issues that can confound generation cost calculations rather than to produce definitive cost estimates". In attempting to develop industry-wide LCOE calculations, he relied on public domain information and industry samples, rather than project specific and verifiable information and admitted that "even for "official" data, we should question the validity of cost estimates" [4].

2.2. Cost breakdown structures

Gonzalez-Rodriguez [8] sought to improve the quality of LCOE estimates by developing cost estimates for each significant cost area of offshore wind development. He obtained aggregated cost data from the 4C Offshore website [19] and component cost data from a range of technical, engineering and commercial sources, in order to develop expected costs for new offshore wind farm developments. In the light of Ederer's [15] and Partridge's [4] identification of the potential limitations of public databases, relying on the 4C Offshore dataset could leave Gonzalez-Rodriguez's analysis of past costs open to challenge, due to possible errors in this data and/or manipulation by developers' choices in data presentation. As will be shown in Section 6 – especially in the cases of the Dudgeon and West of Duddon Sands wind farms - the 4C Offshore data can be materially different to that from accounts data.

2.3. Probabilistic evaluation

Heck et al. [9] and Cartelle Barros et al. [10] both advocate probabilistic methods in LCOE estimation. These methods explicitly incorporate uncertainty in input data, and aim to provide insight into probable ranges of LCOE for different technologies, based on ranges of input data.

Cartelle Barros et al.'s data were "based on an extensive literature review of scientific articles, sector reports, real cases with published data and various interviews with an expert who has more than 40 years in the energy sector in the international arena" [10] while Heck et al. "carefully collected cost and operational data from a variety of sources" and compared their probabilistic results "with other LCOE studies" [9].

2.4. Learning rates

The learning rates achieved by onshore wind, and potentially to be expected by offshore wind, are of great interest to both developers and policymakers, as offshore wind is expected to be an important part of the decarbonised energy mix [2].

Evaluation of learning rates relies on high quality cost information and much work has been done in this area. Williams et al. [14] provides a meta-analysis of learning rates for wind power (including on- and offshore), drawn in large part from earlier work by Rubin et al. [20] and Lindman and Soderholm [21]. Unfortunately both of these earlier studies note that, as Lindman and Soderholm say "learning curve studies on offshore wind power are very few".

Other workers have undertaken more sophisticated work in relation to learning curves for wind: van der Zwaan et al. [11] took account of the variability of some of the exogenous variables (such as costs of steel and copper), which affect the cost trajectory. Their underlying data was drawn from 4C Offshore and other public domain sources.

MacGillivray et al. [13] assessed the learning rates required for marine renewables technologies (wave and tidal stream) to become competitive with "the benchmark technology" of offshore wind. Again, MacGillivray et al. employed offshore wind cost data from 4C Offshore [19].

2.5. Political and public argument

Not all observers of offshore wind costs are supportive – the Global Warming Policy Foundation's 2017 paper "Offshore Strike Prices" [5] analysed offshore wind costs to explore whether the anticipated cost reductions are supported by past cost trends. The Foundation expressed a concern that developers face little penalty if they fail to deliver the projects awarded CfDs, and this could lead to a shortfall in national power generation if these costs cannot in practice be achieved.

The Global Warming Policy Foundation used a number of data sources. It states that “the first is an EU-funded study by the FOWIND consortium (Facilitating Offshore Wind in India)” which covers various European sites. This report [3] recognises the difficulty of obtaining robust data, stating that “publically available information on the cost of offshore wind is challenging to obtain, with developers only ever quoting expected Capex figures (at financial close) in the public domain”. Expected costs necessarily exclude cost overruns, which can add materially to project costs. The report also notes that there is no consistent basis on which figures are put into the public domain, with different sources including different aspects of wind farm costs (the example given is port upgrade costs to support wind farm activities).

The GWPF’s other sources were “a set of UK-specific figures obtained by one of the present authors, Capell Aris, through careful gleaning of press stories and press releases” and the 4C Offshore database [5].

It is clear that publicly available cost data is widely relied upon as the foundation for a range of analyses. This paper focuses on a method for developing more reliable cost data than that currently in the public domain, allowing these analyses to be developed with better accuracy in future. It appears that existing public domain data is potentially inaccurate, inconsistent and possibly susceptible to “massaging” in support of a political or commercial agenda. These findings should be of significant concern to policy-makers and taxpayers.

3. Data sources – robustness and risks of distortion

This paper uses audited accounting data from wind farm SPV companies, which are considered to be a more reliable source of actual expenditure information than information put into the public domain by wind farm developers. This view is worthy of investigation.

3.1. Why might developers distort data?

Developers might wish to distort cost data available in the public domain for a number of reasons. These might include the desire to minimise tax, to present costs which would be considered acceptable to external commentators (to positively influence the wider debate on the acceptability and role of offshore wind), to influence policy (specifically in relation to policy support measures) or to mislead potential competitors in a competitive environment.

3.2. Public domain vs. audited accounts data

Public domain data, which is not subject to audit or investigation by the tax authorities, is clearly easier to distort than audited accounting information. In addition, third parties gathering and publishing cost information may have a particular agenda in relation to climate change (in either direction).

We believe that there are a number of factors which lead us to expect that cost data from audited accounts would less liable to distortion than other data.

3.2.1. Accounting standards and audit requirement

Accounting standards exist to help ensure that like for like comparisons are meaningful, and the accounts provide a “true and fair view” of the financial status of a business. While there is always scope for some flexibility within the standards, they do provide some boundaries.

Additionally, the requirement for audit confirms that the accounts for each SPV present a “true and fair view” and adhere to the accounting standards, providing some comfort that they should be substantially undistorted. It must be accepted that the audit process is not infallible.

3.2.2. Tax investigation

Another factor which is likely to encourage developers to keep their audited SPV accounts within reasonable bounds is the risk of a tax investigation. A public investigation of financial misreporting or distortion for reasons of tax optimisation would be likely to be both embarrassing and detrimental to future CfD applications.

3.2.3. Multi-ownership

SPVs are used to manage the risk of large and costly project developments, and frequently have multiple shareholders. This offers perhaps the best reason to consider SPV accounts as acceptably reliable - because the commercial interests and tolerance of the risk of making the distortion would have to align across all of the shareholders if the costs within the SPVs were to be distorted,.

An analysis of how different participants in London Array account for capital costs (shown in Figure 1) shows that while there are timing differences in recognition of capital spend between participants in the London Array project, the total spend is closely matched between participants. This close match provides some reassurance that the audited accounts for wind farm SPVs accurately reflect the actual underlying costs.

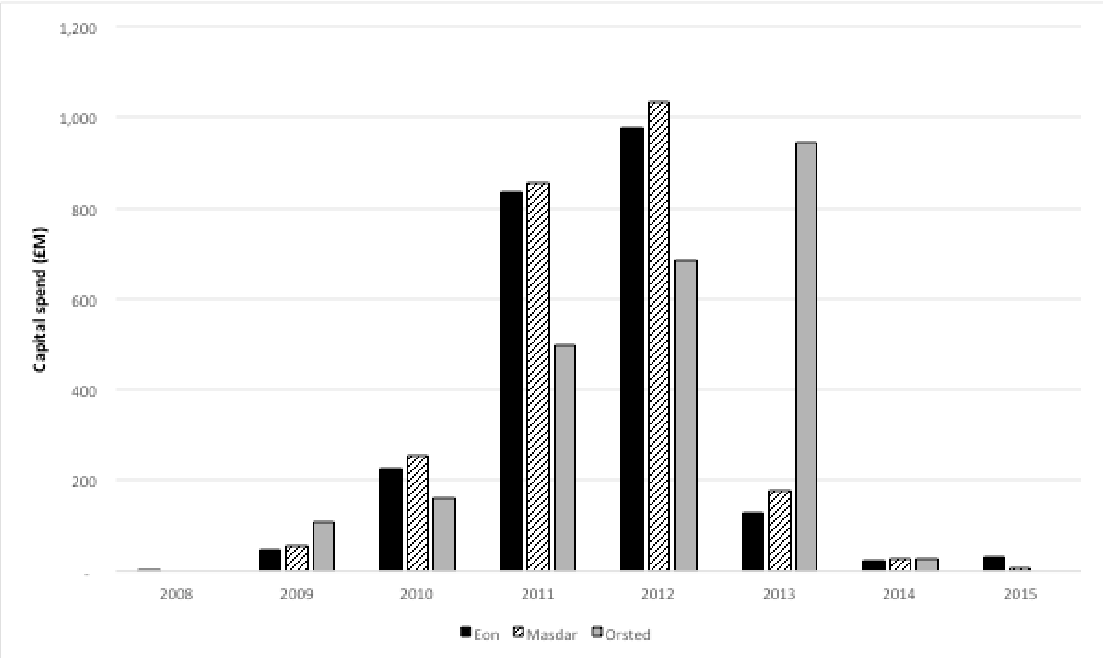

Figure 1 Timing differences in capital spend recognition - London Array (authors' analysis)

3.3. High or low?

The potential advantages to a developer of presenting the costs of offshore wind development as "higher than actual" or "lower than actual" are set out in Table 1.

Stakeholder	Higher than actual	Lower than actual
Tax position	Reduces local tax liability, shifts tax	Increases local tax liability, reduces tax

	liability to other (potentially lower rate) regime	liability in other (potentially higher rate) regime
Competitor impact	Distorts competitor perspective of cost base potentially encouraging competitor to accept higher costs	Distorts competitor perspective of cost base potentially driving competitor to attempt excessively low costs
Policy effect	Helps to make case for higher subsidy levels, but damages overall perception of technology viability	Helps make case to Government that technology is on viable trajectory but potentially impacts subsidy support
Public perception	Damages perception of technology as on viable trajectory	Enhances perception of technology as on viable trajectory

Table 1: Impacts of cost distortion (authors' analysis)

To summarise, it appears that there are various safeguards which suggest that while data in annual accounts may not subject from manipulation, it should nonetheless be more reliable than other data in the public domain.

4. Methodology

Ederer has pointed out that most offshore wind farm developments are undertaken through Special Purpose Vehicle (SPV) companies [15]. The use of SPVs allows parent company developers to insulate themselves from any liabilities potentially arising within the wind farm developments, and also makes asset sales easier, as shares in SPVs can easily be bought and sold as required.

However, a perhaps-unintended consequence of the commercial decision to isolate risks within SPVs is that detailed cost information is available in the public domain. As SPVs are legally constituted companies, they are required to submit audited accounts to the appropriate authorities. In the UK this is Companies House, which has recently made accounts for all UK companies publicly available at no cost. The methodology presented here exploits this data source to extract cost data from these published reports to build detailed assessments of actual LCOE.

This accounting information has some limitations: (1) accounting standards are not absolute, and offer some flexibility in presenting information; (2) accounts must be submitted within 9 months of the year end, so there can be a small time lag in data; (3) accounts may relate to a fractional interest in the underlying wind farm, and different participants may adopt different accounting treatments; (4) accounts contain very limited information on wind farm operational performance; and, (5) there are a number of stages of technical analysis which must be undertaken to extract the required information. These are detailed in Sections 4.8 and 4.9.

4.1. Source of Data

The operational offshore wind farms in the UK, and the related SPVs, are listed in Table 2. A database of the relevant SPV accounts has been compiled and analysed to extract cost information according to the methodology which follows.

In most cases, a single SPV accounts for all of the spend on a specific wind farm. In a limited number of cases, such as Gwynt y Mor and London Array, where multiple SPVs have interests in the underlying unincorporated joint venture, further analysis is required to identify total expenditures.

In Gwynt y Mor, where UK Green Investment GYM Participant Limited has held a constant 10% in the wind farm, it is a simple matter to gross up figures to provide total costs. At London Array, where ownership changes have complicated the picture, figures from Orsted Energy London Array Limited, Orsted Energy London Array II Limited, E.On Climate and Renewables UK London Array Limited and Masdar Energy (UK) Limited have been combined to allow compilation of an aggregated picture.

Some SPV names, and the interest they control in the underlying wind farm, have changed over time. Table 1 shows the current SPV names, and (where less than 100%) their current interest in the wind farm, as well as the dates for which accounts are available, and when the project transferred transmission assets to the Offshore Transmission Operator if applicable (see Sections 4.8 and 4.9).

Wind farm	**SPV Company(ies)** (Current names and current percentage interest)	**Accounts available**	**OFTO transfer date**
Barrow	Barrow Offshore Wind Limited	2001-2017	2011
Burbo Bank	Orsted Energy (Burbo) Limited	2002-2017	Not under

			OFTO
Burbo Extension	Burbo Extension Limited	2011-2017	2018
Dudgeon	Dudgeon Offshore Wind Limited	2003-2017	2018
Gunfleet Sands I	Gunfleet Sands Limited	2001-2017	2011
Greater Gabbard	Greater Gabbard Offshore Winds Limited	2004-2017	2014
Gunfleet Sands II	Gunfleet Sands II Limited	2007-2017	2011
Gwynt y Mor	UK Green Investment GYM Participant Limited (10%), Innogy GyM 2 Limited (10%), Innogy GyM 3 Limited (10%), Innogy GyM 4 Limited (30%), GyM Renewables One Limited (10%), GyM Offshore One Limited (15%), GyM Offshore Two Limited (10%), GyM Offshore Three Limited (5%)	2010-2017	2015
Humber Gateway	E.On Climate & Renewables UK Humber Wind Limited	2008-2017	2015
Inner Dowsing	Inner Dowsing Wind Farm Limited	2004-2017	Not under OFTO
Kentish Flats	Kentish Flats Limited	2001-2017	Not under OFTO
Kentish Flats Extension	Vattenfall Europe Windkraft GmbH (German company)	Not reviewed	Not reviewed
Lincs	Lincs Wind Farm Limited	2001-2017	2014
London Array	Orsted Energy London Array Limited (0%) (formerly CORE Energy Limited), Orsted Energy London Array II Limited (25%), E.On Climate and Renewables UK London Array Limited (30%), Masdar Energy UK Limited (20%), Boreas	2003-2017	2013

	(Investments) Limited (25%)		
Lynn	Lynn Wind Farm Limited	2001-2017	Not under OFTO
North Hoyle	NWP Offshore Limited	2002 -2017	Not under OFTO
Ormonde	Ormonde Energy Limited	2004-2017	2012
Race Bank	Race Bank Wind Farm Limited	2004-2017	2018
Rhyl Flats	Rhyl Flats Wind Farm Limited	2005-2017	Not under OFTO
Robin Rigg East	E.On Climate and Renewables UK Robin Rigg East Limited	2006-2017	2011
Robin Rigg West	E.On Climate and Renewables UK Robin Rigg East Limited	2002-2017	2011
Scroby Sands	E.On Climate and Renewables UK Offshore Wind Limited	2003-2017	Not under OFTO
Sheringham Shoal	Scira Offshore Energy Limited	2004-2017	2013
Teesside	Teesside Windfarm Limited	2009-2017	Not under OFTO
Thanet	Thanet Offshore Wind Limited	2004-2017	2014
Walney	Walney (UK) Offshore Windfarms Limited	2005-2017	2011/12
Walney Extension	Orsted Energy Walney Extension (UK) Limited	2011-2017	2016
West of Duddon	Orsted Energy West of Duddon Sands (UK) Limited	2008-2017	2015
Westermost Rough	Westermost Rough Limited	2007-2017	2016

Table 2: Wind farms and SPVs (authors' analysis)

4.2. Capital costs

Capital costs for each wind farm have been derived from the database for each year and for each wind farm. In order to identify capital costs, the additions to Fixed Assets have been extracted, and additions to Fixed Assets which do not represent cash expenditure (such as additions to the provision for decommissioning) are then removed. Capitalised interest, which is often treated as a fixed asset, is included in these costs, as it represents actual cash costs which are borne by the wind farm developer in completing the development.

For those wind farms which sold their transmission assets under the Offshore Transmission Operator Regulations (OFTO projects), the costs of these assets has been captured separately, to allow analysis of the OFTO impact on LCOE. This is discussed further in Section 4.9.

4.3. Operating costs

In order to evaluate LCOE, the cash operating costs are required. In accounting terms, both costs of sales and administrative expenses (which we define as total operating costs) are relevant costs in calculating the LCOE of the wind farm, so it is appropriate to derive the total operating costs by subtracting depreciation from the sum of costs of sales and administrative expenses.

For OFTO projects, these cash costs include OFTO charges from the date on which the OFTO transfer took place. This is discussed further in Section 4.9.

4.4. Grants

Some of the early projects were in receipt of capital grants. In some cases, grant receipts were shown as a credit to expenses (e.g. Burbo Bank, Kentish Flats, North Hoyle, Scroby Sands). Where this was the treatment, these amounts have been added back to yield accurate operating costs. In some other cases they were shown as interest income (e.g. Inner Dowsing, Lynn), or as other income (e.g. Barrow) and no correction is necessary. The corrections for grant income ensure that the operating cost figures used are accurate.

4.5. Inflation adjustment

The database comprises costs for each wind farm SPV for each year of development or operation. In order to compare each wind farm’s costs on a comparable basis, it is necessary to normalize for inflation effects. A general European inflation factor[1] has been applied to correct all figures to 2012 terms. 2012 has been chosen as it is the base year for strike prices under the UK Contracts for Difference arrangements, so it seems the most appropriate base year for this correction.

4.6. Energy production

Details of the month by month energy production from wind farms accredited under the Renewables Obligation (RO) is available from OFGEM's Renewables and CHP Register[22], albeit with a delay of around 4 months. This data has been downloaded and analysed. The ROC Register does not present project by project data before April 2006, and for the very limited number of offshore wind projects which were producing prior to this date, data has been extracted from the Renewable Energy Foundation website (which provides historic project by project ROC data before 2006) [23].

Wind farms operating under CfDs are not eligible for ROCs, but they are issued with Renewable Energy Guarantees of Origin (REGOs) which confirm the renewable origin of the electricity generated by these projects. OFGEM's Renewables and CHP Register [22] provides data on issued REGOs, allowing the same derivation of production performance as the ROC register.

For wind farms with limited production history data on the ROC or REGO registers, estimates of typical capacity factor can be derived from the performance of nearby offshore wind farms with longer production histories. If no nearby wind farms are available, typical average capacity factor can be used.

4.7. Projections

Offshore wind farms are typically expected to have an operating life of 20-25 years, and the earliest in this study began production only 15 years ago. It is therefore necessary to develop projections of costs and energy production over the full life of each project to establish a full life LCOE.

In this analysis, a base case has been defined, in which real operating costs and production are kept constant at the average level achieved by the wind farm since commissioning. In the case of OFTO projects, operating costs are projected from the average operating cost for years after the OFTO transfer to ensure inclusion of OFTO charges.

[1] The European index has been chosen as the single largest cost element, wind turbines, are generally produced in Denmark or Germany, making the European index appropriate.

Production projections have been based on average production levels from years of full production, defined as years in which production is greater than 60% of average production over the farm's productive life (to compensate for low production in the year of commissioning). For those wind farms which have only recently begun production, and there is only a very short production history, an average capacity factor of 48% based on BEIS assumptions [6] has been used. Of course, the performance of offshore wind farms can vary from year to year in response to the wind climate, but it is considered that using the average-to-date (where a meaningful time series is available) is a fair estimate over the full project life.

4.8. OFTO regime

Burges Salmon partner James Phillips, writing in Modern Power Systems, set out the basis for the Offshore Transmission regime and the principles of its operation [24].

He explained that under the "Third Package" of legislation on the liberalisation of energy markets, electricity generation and transmission assets were required to be "unbundled" – that is, not owned by the same entities. Accordingly, under powers in the Energy Act 2004, the Secretary of State implemented the Electricity (Competitive Tenders for Offshore Transmission Licences) Regulations 2009.

Under these regulations, wind farm operators which exported at 132 kV or more were required to sell their transmission assets to third parties (who were known as Offshore Transmission Network Owners, or OFTOs), who were empowered to earn a regulated return from these investments.

Accordingly, many of the offshore wind farms under development at that stage were required to dispose of their transmission assets. These wind farm developers/operators received a capital sum for the assets, and were then contractually bound to pay operating charges to the OFTOs for up to 20 years. This had the effect of converting capital and operating costs of building and operating these assets into purely operating costs [24].

A report by KPMG [25] suggested that OFTO investors were typically seeking and receiving returns of 200 basis points over LIBOR, or around 3%, on their investments. A review by the Competition and Markets Authority [26] suggested that costs of capital for utilities engaged in generation activities might be in the range from 8-10%. The OFTO regime therefore makes lower cost capital available for funding a significant part of the wind farm generation and transmission system, thereby reducing the costs of financing (and therefore the discount rate to be used in the LCOE calculation).

4.9. OFTO correction

Accounts for OFTO-governed projects typically include the build costs of the OFTO assets as additions to fixed assets (prior to their transfer to the OFTO operator) and the OFTO charges paid by the wind farm operator as part of the operating costs. If both of these costs are left in the LCOE calculation, the costs of the OFTO are effectively counted twice.

The capital costs of the OFTO assets are deducted from the wind farm total build costs, while the OFTO charges are left included within operating costs. This approach describes the economic situation for wind farm operators as it prevails under the OFTO regime.

Wind farm accounts generally show a reduction in fixed assets when the OFTO assets are transferred to the OFTO operator. The Fixed Assets note to the accounts generally shows the cost of the OFTO asset which had been borne by the wind farm up to that point, and this sum can be subtracted from the total capital costs derived from Fixed Asset additions. Care is taken to ensure that the undepreciated cost is subtracted from the total fixed asset additions, to ensure that the full cost is removed from the capital costs in the LCOE calculation.

Where there is a gain or loss on sale, this is included within the operating costs for that year, so the analysis correctly shows the cash effects for the developer (although it is not included in the average calculation of operating costs, to ensure that these reflect true costs of operation).

4.10. Discount rate

The discount used in the LCOE calculation has a significant effect on the outcome. Discount rates used by investors should reflect the risk implicit in the project, and it would be reasonable to expect the discount rate applying to CfD projects, on which the revenue risk is much lower than for ROC projects, to be lower. Aldersey-Williams and Rubert [18] found that reducing the discount rate from the 8.9% currently applied by BEIS for offshore wind projects to the 7.8% it uses for CCGT projects resulted in a reduction in LCOE of 6%. Section 5.5 evaluates the impact of using a lower discount rate in the CfD projects.

4.11. LCOE calculation

These actual and projected figures are combined into the LCOE calculation, as defined by BEIS and shown in equation 1. A discount rate of 8.9% (in line with BEIS's discount rate choice [6]) has been applied, and some sensitivities undertaken (see Section 5.5).

The LCOE in these calculations includes the costs of the wind farm including its connection to the National Grid (either as a direct cost for non-OFTO projects or through OFTO fees for OFTO projects). The next section sets out the results of calculating LCOE for the UK's operational wind farms using this approach.

5. Results

5.1. Overview of results

The LCOE has been calculated for all UK projects which had reported production before the end of 2017, set out in order of commissioning year, as shown in Table 2. In addition, the real capital cost per MW installed is evaluated, as this is a basis on which these data may be compared with public domain sources.

5.1.1. LCOE results – all projects

The summary results for all projects are shown in Table 2 and the overall trend of costs in Figure 2, which shows the LCOE for projects arranged in chronological order of commissioning.

Wind farm	**OFTO status**	**First production**	**LCOE (£/MWh)**
North Hoyle	Non OFTO	2003	77.35

Kentish Flats	Non OFTO	2006	66.43
Scroby Sands	Non OFTO	2006	104.83
Barrow	OFTO	2006	87.15
Burbo Bank	Non OFTO	2007	86.89
Inner Dowsing	Non OFTO	2008	96.59
Lynn	Non OFTO	2008	101.54
Rhyl Flats	Non OFTO	2009	125.62
Gunfleet Sands I and II	OFTO	2009	121.67
Robin Rigg	OFTO	2010	135.49
Thanet	OFTO	2010	158.69
Greater Gabbard	OFTO	2011	136.62
Ormonde	OFTO	2011	149.08
Walney	OFTO	2011	120.37
London Array	OFTO	2012	139.89
Sheringham Shoal	OFTO	2012	150.34
Teesside	Non OFTO	2013	235.96
Lincs	OFTO	2013	166.053
Gwynt y Mor	OFTO	2014	179.18
Westermost Rough	OFTO	2014	120.82
West of Duddon	OFTO	2014	72.11
Humber Gateway	OFTO	2015	147.13
Burbo Bank Extension[1]	OFTO	2016	146.95
Dudgeon[1]	OFTO	2017	104.07
Galloper[1]	OFTO	2017	133.89
Race Bank[1]	OFTO	2017	118.09
Walney Extension[1]	OFTO	2017	100.24

Table 3: LCOE (all projects, authors' analysis)

[1] due to short production histories for these wind farms, some assumptions are required. A typical modern offshore wind farm capacity factor of 48% has been applied in line with BEIS assumptions[6];

an average operating cost of 37/MWh has been applied based on the average post-OFTO operating costs found in this analysis and OFTO capital costs have been taken from the most recent accounts. These figures should be treated with some caution.

The same data is presented graphically in Figure 2.

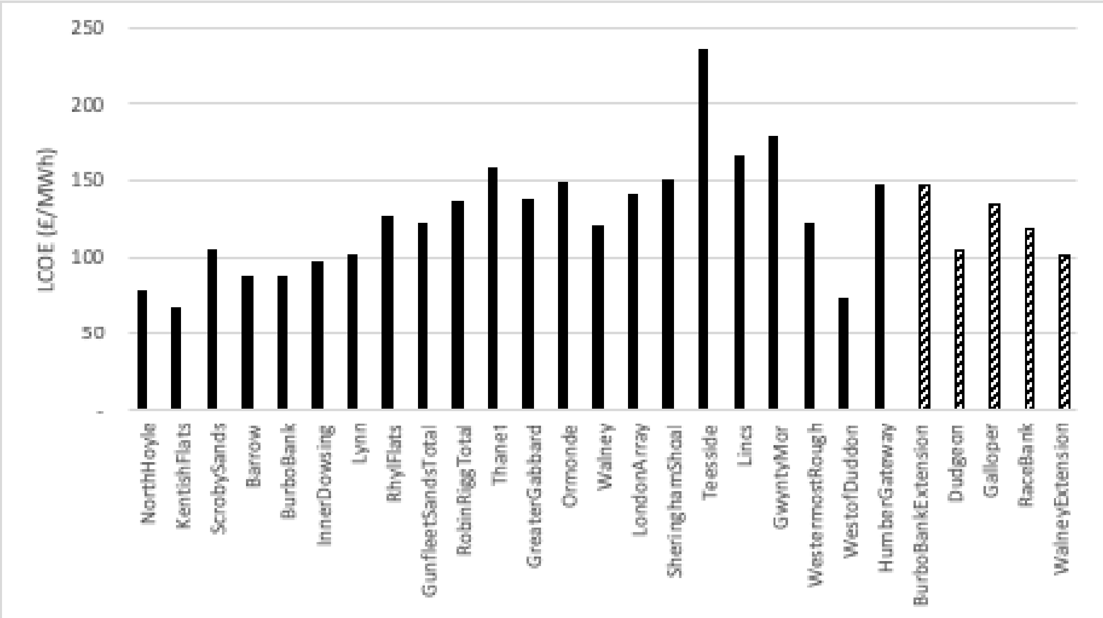

Figure 2: LCOE for all projects, chronological order by commissioning (authors' analysis). (NB solid bars show data for wind farms with full accounts-based and historic production data, striped where assumptions are used on capacity factor, OFTO transfer and operating costs)

5.2. LCOE Outliers

The Teesside project immediately stands out as having an anomalously high LCOE, while West of Duddon Sands appears low.

5.2.1. Teesside

The Teesside project employed 2.3MW turbines. These were outdated by its commissioning date of 2012, as the typical turbine size by this date was 3.6MW or larger.

This turbine choice, which obviously necessitated more foundations and installation work than a larger turbine size, along with significant delays in its consenting and development process, combined to push up the LCOE. Analysis of ROC data from the ROC Register [22] shows that Teesside also had a low capacity factor of 15-25% over its first years of operation, further increasing the LCOE. A sensitivity analysis in which it is assumed that the project can achieve a more realistic capacity factor of 35% for future years shows the LCOE reducing to £221.81/MWh. While this is slightly closer to the typical LCOE at that time, it suggests that the majority of the excess LCOE is due to capital cost and schedule overruns.

5.2.2. West of Duddon Sands

The LCOE for the West of Duddon Sands project appears to be exceptionally low. This project had a development timescale comparable to its neighbour at Walney and achieved a similar ramp up in production. The key differentiator was the low cost per MW installed relative to Walney. This is inferred to be due to improvements in installation process and costs, as both projects deployed Siemens 3.6MW turbines (although Walney used both 107m and 120m diameter variants).

5.3. LCOE trends

Figure 2 shows an upward trend in LCOE for offshore wind for projects developed up to and including Thanet, from less than £100/MWh to more than £150/MWh (excluding the Teesside project).

Many commentators, such as Greenacre et al., Heptonstall et al., Ioannou et al. and Voormolen et al. [2, 27-29] have linked the original increasing cost trajectory to the trend towards situating wind farms in deeper water, further from shore.

After excluding the apparent outlier of Teesside, it appears that LCOE increased gradually to a maximum of around £150/MWh in Thanet, after which it began a gradual decline, although project LCOEs vary widely.

A review of the trends would suggest that new wind farms are now achieving LCOE of around £100/MWh, which is still considerably above the level implied by the most recent CfD bids of £57.50/MWh.

5.4. LCOE sensitivities

The LCOE metric is sensitive to capital cost, production forecasting and discount rate. The methodology adopted in this paper addresses uncertainty in capital cost by using data from accounts, but the effect of uncertainty in production and choice of discount rate requires analysis.

5.4.1. Production forecasting

A recent study by Staffel and Green [30] used ROC data to evaluate trends in onshore wind farm performance with the "age" of turbines. They found that wind farm performance declined by 1.6%+/-0.2% per annum as turbines aged. Their dataset was limited to onshore wind farms, as they recognised that there was insufficient depth in the offshore fleet to provide a meaningful basis for analysis. This remains the case. However, it is recognised that the same factors which lead to performance degradation onshore are likely to be equally valid offshore. Accordingly, a sensitivity analysis has been undertaken to assess the impact on LCOE of an annual performance degradation of 1.6% in output.

The impact on LCOE for the offshore wind farms evaluated here is an increase of between 1% and 8%, depending on the date of commissioning date of the wind farm. The LCOE impact is greater for the most recently commissioned wind farms, as the older wind farms' LCOE is more heavily based on actual performance.

5.5. Sensitivity to discount rate

As discussed in section 4.10, the discount rate used in the LCOE calculation has a significant effect on the outcome. The introduction of Contracts for Difference has significantly changed the risk profile of offshore wind investment and it can be argued that the discount rate for CfD projects relative to ROC projects should be significantly lower. Aldersey-Williams and Rubert[18] found that current UK offshore wind projects were being financed with 75% debt/25% equity, with the debt secured at rates of 3.5%-4%. If an equity return of 15% is assumed, the resulting WACC is less than 7%. In this sensitivity, a discount rate of 7% has therefore been applied to the CfD-supported projects. Table 4 shows that this lower discount rate reduces the LCOE by around 10% for these projects.

	LCOE (£/MWh)	**LCOE (£/MWh)**

	Discount rate at 8.9%	Discount rate at 7%
Burbo Bank Extension	146.95	130.02
Dudgeon	104.07	92.71
Galloper	133.89	119.18
Race Bank	118.09	105.46
Walney Extension	100.24	90.74

Table 3: Impact of reduced discount rate for CfD wind farms LCOE (authors' analysis)

5.6. Capital cost per MW installed

The capital cost per MW installed is another widely used comparative metric. It is shown, in 2012 real terms, for each project in Figure 3. This shows a clear increase from £1.5-2 million/MW for the early projects, to £2-4 million/MW for more recent projects.

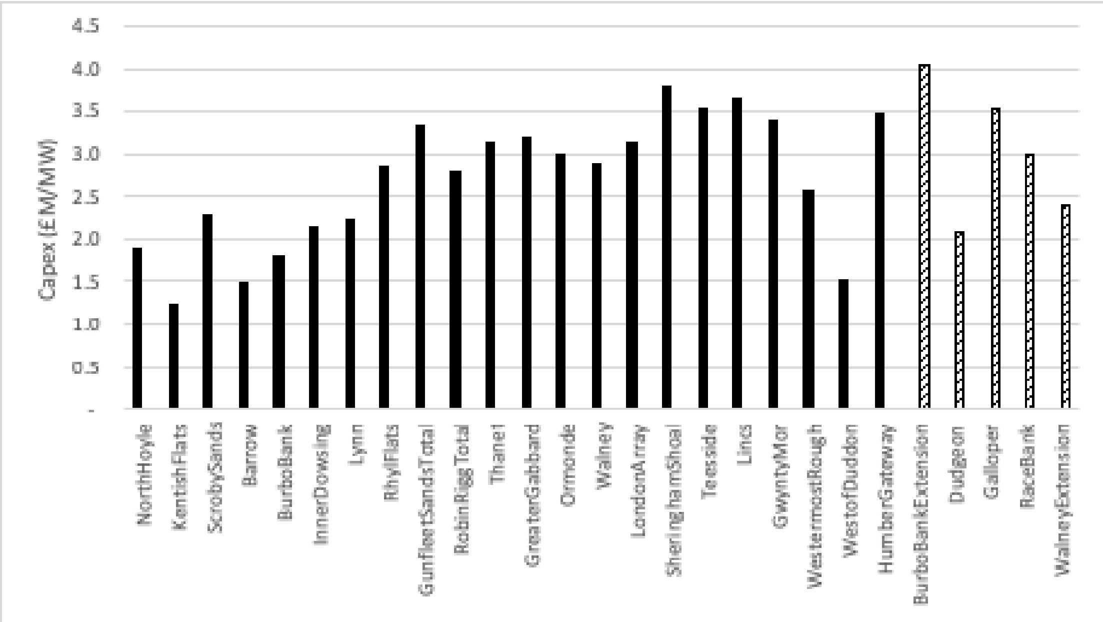

Figure 3: Capital cost per MW installed (2012 real terms), authors' analysis (NB solid bars show data for wind farms with full accounts-based and historic production data, striped where assumptions are used on capacity factor, OFTO transfer and operating costs)

The increase in LCOE in more recent projects is proportionately less than the increase in cost per MW, suggesting that production performance has increased, development timescales have been compressed or operating costs have been reduced, or a combination of these factors, over successive generations of wind farm development.

This analysis is consistent with Ernst and Young's 2009 report [31], which noted that "average capital costs have doubled over the last five year to c. £3.2million/MW; the cost increase appears largely driven by supply chain constraints for components (e.g. wind turbine generators) and services (e.g. installation)". It is also consistent with anecdotal evidence from informal discussions with developers, who often claim that turbine prices increased after the introduction of ROC banding (and therefore the higher revenue expectations among developers). Rhyl Flats was among the first offshore wind farms to be built in the foreknowledge of higher support under the RO, and shows a cost per MW installed significantly higher than earlier projects.

5.7. International comparisons

International data [32] suggest that the overall cost trend of UK offshore wind is broadly in line with international cost trends in wind turbine costs. Figure 4 shows wind turbine prices in the US and globally [32] and shows a peak in around 2008 – when the Thanet project was procuring its turbines [19]. The data in Figure 4 comes from a range of sources, including “financial and regulatory filings, as well as press releases and news reports” [32] and is therefore considered to be meaningful. A better comparison would require accounts-based LCOE estimates for international projects, which lie beyond the scope of this paper, but would be an interesting direction for future research.

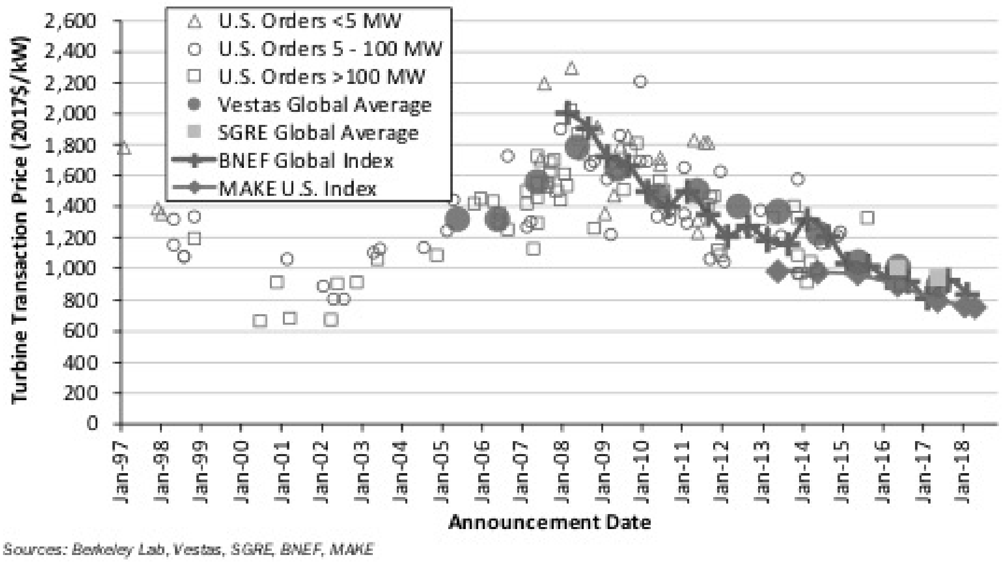

Figure 4: International turbine price trends (from [32])

While the overall cost trend in UK offshore wind is now downward, the degree of reduction is less than for turbine prices as noted in the US Department of Energy’s report. This is inferred to reflect the siting of UK wind farms in more distant offshore locations and deeper water, driving up installation and foundation costs.

5.8. CCGT example

The same methodology has been applied to the Coryton CCGT power station, which was built between 1999 and 2001 and began commercial operation in 2002. Coryton CCGT is operated through a SPV called Coryton Energy Company Limited which files accounts at Companies House. Analysis of the accounts shows a total real (2012) capital spend of £71 million, and annual operating costs varying between £75 million and £330 million with the variation driven very largely by fuel prices. An average of £110 million, based on the average real operating cost over the project's operating life to date has been applied for forecasting future opex.

Production data is not available for the full operating life of the project. Data is available for the period 2010-2014 (2015 forecast) [33] and this has been applied in the model. Where production data is not available, an average load factor of 34% has been used. This is the average load factor for CCGT for 2012-2016 reported in Digest of UK Energy Statistics, Table 5.1 [34] and is comparable to the average load factor of 32% for the period for which project data is available. A discount rate of 7.5% as applied by BEIS for this technology [6] has been used. The resulting LCOE (2012 real terms) is £62.63/MWh.

The methodology is demonstrated to be applicable to any project organized in a SPV where meaningful production data can be found.

6. Comparison with other work

As previously noted, researchers, analysts and other professional commentators on offshore wind costs have generally used data compiled from public domain sources [4, 6-14]. In general, their cost databases are not published, making comparison of costs developed from the approach detailed here with publicly gleaned information difficult. However, two full data sources are available for comparison.

The datasets are the 4C Offshore website [19], which we believe sets out nominal (money of the day) costs, and the Global Warming Policy Foundation's report [5] which makes corrections for inflation and reports in 2012 terms. Neither of these datasets evaluates LCOE but both allow for evaluation of the capital cost per installed MW.

These data are set out in Table 5 for the wind farms capable of analysis using the accounts-based method set out here.

Name	**This analysis (£ million**	**4C Offshore (£**	**GWPF (£ million**

	/MW)	million /MW)	/MW)
Barrow	1.49	1.37	1.53
Burbo Bank Extension	4.05	3.15	NA
Burbo Bank	1.79	1.53	1.10
Dudgeon	2.09	3.73	3.44
Greater Gabbard	3.21	3.28	2.98
Gwynt y Mor	3.41	3.33	3.33
Humber Gateway	3.48	3.36	3.23
Inner Dowsing	2.15	1.54	1.63
Kentish Flats	1.22	1.17	1.57
Lincs	3.66	3.70	3.63
London Array	3.13	3.23	2.80
Lynn	2.22	1.54	1.63
North Hoyle	1.88	1.35	1.63
Ormonde	3.00	2.98	3.68
Rhyl Flats	2.84	2.11	2.31
Robin Rigg	2.79	2.19	2.36
Scroby Sands	2.30	1.28	1.50
Sheringham Shoal	3.78	3.42	3.47
Teesside	3.53	3.22	3.16
Thanet	3.14	3.00	3.11
Walney	2.89	3.43	3.39
West of Duddon Sands	1.50	3.22	3.11
Westermost Rough	2.58	2.95	3.38

Table 5: Capital cost per MW; authors' analysis, [5,19].

It is clear that these estimates vary widely, with the main drivers of cost per MW being turbine costs, distance from shore, foundation type and installation strategy [35].

Figure 5 shows the percentage difference between the figure for capital cost per MW from the analysis of accounts undertaken here and two relatively complete public sources - 4C Offshore [19] and the Global Warming Policy Foundation [5]. The close parallels between the 4C and GWPF data can be explained as the GWPF data is gathered, at least in part from 4C Offshore.

In many cases, the public domain cost figures are c. 20% lower than the capital costs from accounting data, although there are cases where the public domain data significantly higher, notably Burbo Bank, Kentish Flats, Ormonde, Walney, West of Duddon Sands and Westermost Rough.

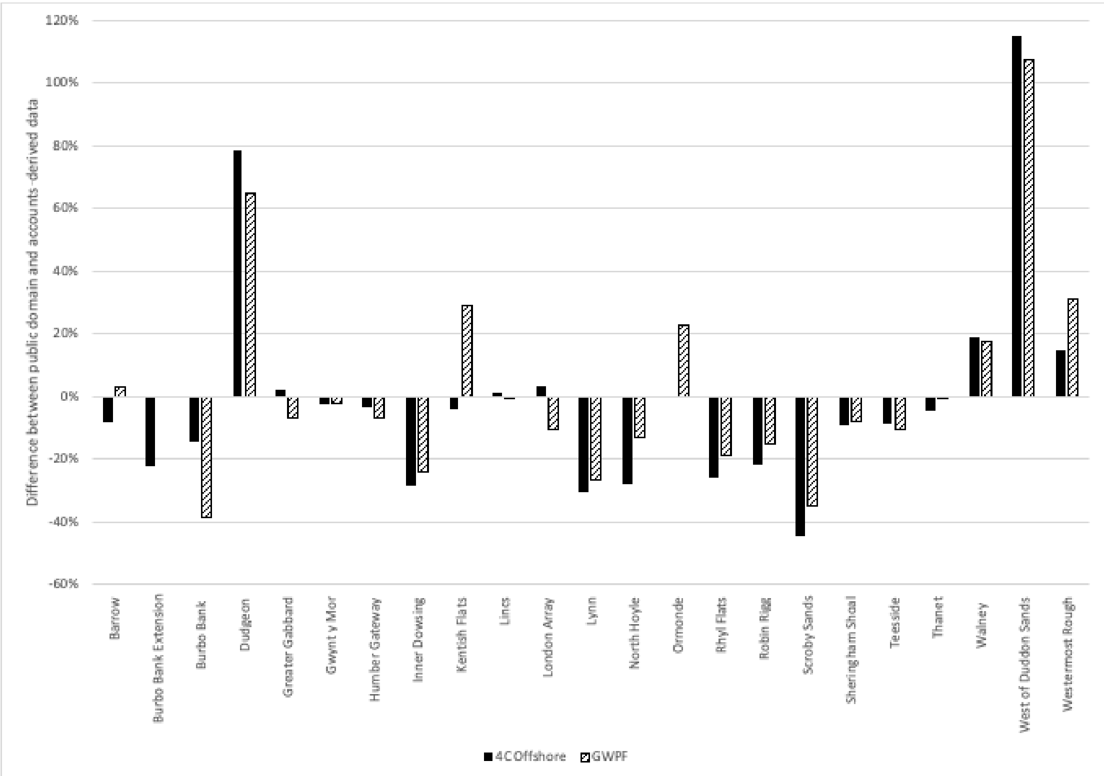

Figure 5: Percentage difference between public data and this analysis; authors' analysis and [5, 19].

As capital cost/MW is the most important factor in assessing the LCOE for offshore wind projects (as operating costs only typically contribute around a quarter of the LCOE, while Capex contributes the majority [6]), these discrepancies will have a significant effect on estimates of LCOE in the existing literature. These discrepancies further demonstrate that public domain data is not wholly to be relied on.

7. Required cost trends

This analysis has shown that there may be a gradual downward trend in LCOE for UK offshore wind farms since about 2010. It is interesting to consider the LCOE which offshore wind must achieve in order to offer commercial returns at the prices at which recent CfDs have been awarded.

The most recent CfDs were awarded at a price (in 2012 terms) of £57.50/MWh, while the analysis here shows that modern wind farms typically have a LCOE of c. £100/MWh. Although as Aldersey-Williams and Rubert make clear [18] the LCOE and strike price are only the same in a zero-inflation world, it is nonetheless clear that very significant reductions are required to wind farm costs to offer economic projects in the context of current strike prices.

One key area in which LCOE can be reduced is by reducing the discount rate used for the calculation. The discount rate reflects the investment risk in the project, and the introduction of CfDs significantly reduces the revenue risk for the developers. As noted in Sections 4.10 and 5.5, lower discount rates, reflecting the lower risk of CfDs, help to reduce wind farm LCOE.

8. Discussion and conclusion

This paper has presented a new methodology for determining LCOE in cases where reliable audited data is available. It is observed that much of the existing literature examining costs and trends in offshore wind is potentially compromised by inaccuracy, inconsistency or selective presentation by developers.

Application of this new methodology suggests that the LCOE for new wind farms is still significantly higher than the level of recent CfD strike price bids. There are some encouraging signs, however, as the recent West of Duddon Sands project has a LCOE of less than £100/MWh.

It is clear that continuing LCOE reduction will require continuing technological evolution, as well as more efficient operating practices and lower discount rates to reflect the reduced revenue risk under CfDs. Technological improvements are likely to be dominated by the continuing trend to increasing turbine capacity. This is exemplified by GE's recent announcement of a 12MW turbine [36]. Larger turbines allow more installed capacity per foundation, and therefore offer economies of scale in manufacture and installation. Fewer turbines also offer economies of scale in operational costs, as the costs of maintaining a turbine are largely determined by access costs, rather than by each turbine's rated capacity. Larger wind farms also make alternative operational strategies viable, as demonstrated by the emergence of Service Operations Vessels [37] - vessels based at sea within the wind farm, offering 24/7 service and higher reliability and production.

The LCOE result is also determined by the discount rate used, just as the economic returns of the wind farm are driven by its capital structure. The introduction of CfDs reduces the revenue risk for developers relative to wind farm projects supported under the RO. It is reported that this reduced risk can allow the use of a higher proportion of debt than RO projects [38, 39], thereby justifying the use of a lower discount rate and reducing the LCOE.

This paper has found that much of the analysis of offshore wind costs, and the trends they show, is based on public domain data which are shown to be inconsistent with cost data taken from audited accounts, which are considered to be more reliable. Significant discrepancies in capital cost per MW have been found, with public domain data found to be both higher and lower than data from accounts. As a result, policy choices based on these data may be flawed with important effects on the future energy mix.

More widely, the methodology is seen to be equally valid for any power project configured as a Special Purpose Vehicle and where production data is available or can be reasonably estimated.

In conclusion this paper has presented and applied a new methodology for developing LCOE data and applied it to a number of offshore wind farms and to one CCGT project. The new methodology, explained here in detail for the first time, offers a robust route to evaluation of key data and trends in power generation costs, to inform better policy choices, around the world.

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