Renewable Energy 160 (2020) 876–885

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Levelised cost of energy, A challenge for offshore wind

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ARTICLE INFO

Article history:
Received 30 December 2019
Received in revised form
28 May 2020
Accepted 4 June 2020
Available online 7 June 2020

Keywords:
Offshore wind energy costs
Policy development
Electricity market
Renewable energy
Levelised cost of energy

ABSTRACT

Long-term economic viability of offshore wind power is not only reliant on reducing installation, commissioning, and operations and maintenance costs, but also on the elimination of subsidies and grants. Current economic analyses use historical price and cost data to predict the levelised cost, net present value, payback period and internal rate of return from offshore wind. These analyses use parameters such as water depth at site, number and size of turbines, grid connection costs, equipment costs, revenue from the wholesale market price of electricity, operations and maintenance costs, revenue from subsidies and the cost of finance amongst others to build a model to determine the viability of the array. Here we review the challenges of accurately estimating levelised cost of energy (LCOE) for offshore wind outlining differing approaches to calculating LCOE, the factors influencing this, and the impact of variation in LCOE calculation. Current costs for the production of offshore wind energy are summarised based on publicly available datasets.

1. Introduction

In comparison with electricity generation from fossil fuels, offshore wind is still a relatively immature power source, it has however grown rapidly over the last fifteen years. Power generation from onshore wind is much more developed, but significant constraints on further development exist including opposition to site developments, noise pollution, visual changes to the landscape, and threats to avian species [1]. Offshore wind has the potential to eliminate some of these concerns, but is associated with enhanced technical and logistical issues leading to higher costs [2,3].

Offshore wind development is hampered by the complexity and expense of setting up a new site. Water depth, which determines the type of foundations required, and the distance from the shore, which adds to commissioning complexity are two of the substantial number of elements that contribute to the difficulties for development of an offshore wind array [2]. Individually, each of these variables can have a significant impact on installation and/or the running costs of an offshore wind array and thereby, on the economic feasibility. These variables therefore need to be fully understood and accurately costed to determine site viability [4].

Beyond the costs for installing and running an offshore wind array, contract structures, differing government incentives and long-term wholesale electricity price need to be considered in economic analyses. Offshore wind allocation auctions are analysed by Welisch & Poudineh [5] where concerns are raised about the possibility of Contract for Differences (CfDs) leading to speculative bidding in capacity auctions. Considering the complexity and the rapid development of the offshore wind energy industry, a flexible and complete costing metric with sufficient fluidity to cope with these variables, is required.

Despite some annual fluctuation, investment in renewable energy over the past decade has increased significantly. However, investment in wind has dropped from a high in 2015, this slowdown likely results from the saturation of onshore wind, while scaling has not fully started with offshore wind [6]. Electrical power generation from onshore wind turbines reached installed capacity of approximately 568 GW in 2018. Installation costs for onshore wind can be as low as £0.5 million/MW [1]. Despite higher installation costs ranging from £1.5 million/MW (when infrastructure such as sea cabling and substations already exists) to £6 million/MW (for undeveloped sites) and as high as £8 million/MW (for initial use of new technologies) [7], offshore wind has the potential to minimize some of the constraints seen with onshore wind power.

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https://doi.org/10.1016/j.renene.2020.06.030
0960-1481/

Nomenclature

Abbreviations

CAPEX	Capital Expenditure
CfD	Contract for Difference
EPA	Environmental Protection Agency
GE	General Electric
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCCC	Low Carbon Contracts Company
LCOE	Levelised Cost of Energy
NREL	National Renewable Energy Agency
NPV	Net Present Value
O&M	Operations and Maintenance
PPA	Power Purchase Agreement
ROC	Renewables Obligation Certificate
SPV	Special Purpose Vehicle
TSO	Transmission System Operator
UK	United Kingdom
USA	United States of America
WACC	Weighted Average Cost of Capital

Units

€/MW	euro per megawatt
$/MWh	dollar per megawatt hour
£/MWh	pound per megawatt hour
€/MWH	euro per megawatt hour
Ct/kWh	cent per kilowatt hour
CO_2	carbon dioxide
GW	gigawatt
Kr	krone
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
RPM	revolutions per minute
tCO_2/MWh	tonnes carbon dioxide per megawatt hour

Installation costs for offshore wind have been non-linear, with reductions seen as technologies develop in components such as monopile foundations. Reductions are also seen in the cost of turbines. However, the rapid introduction of new technologies such as floating foundations mean these reductions can get lost in the overall cost [8]. Increased installation costs can be offset by greater wind speeds, larger turbines and the potential to locate near demand centres. Indeed, recent work has shown that the market value of offshore wind typically exceeds that of onshore wind [9]. Installed capacity for offshore wind was approximately 23 GW in 2018, equating to approximately 4% of the total wind power capacity globally. This has grown significantly in the past decade from approximately 1% of the total wind power installed capacity in 2008 [10].

Decommissioning and recycling strategies for offshore wind turbines are variable. Options for end of life include repowering, where existing foundations and towers are used with the installation of a new nacelle and rotor, replacement of complete turbine and all support structures on an existing site, or removal and shut down of site [11]. Each of these options incur differing costs and the cost of removing turbines is subject to geographic and weather conditions and fluctuations in the value of recovered materials [12]. Additionally the composite construction techniques used for blade manufacture mean that despite ongoing work and progress being made, composite blades and nacelles are currently difficult to recycle [13].

Offshore wind auction prices have reduced significantly over the last 2 years in the UK, in the most recent round of capacity auctions, strike prices for offshore are around £40/MWh [14] from initial values of £150/MWh [15]. Similar reductions have been observed in Germany and Denmark, with multiple zero bids being accepted at German offshore wind auctions [16]. In countries with a more developed offshore wind energy sector, costs have levelled out [17]. However, the next step in ensuring long-term viability and sustainability globally involves the removal of subsidies and renewable energy incentives from the overall business case.

The spread of auction prices demonstrates the differing views on both the long-term production costs from offshore wind and wholesale costs of electricity. Offshore wind farm developers require an accurate way of determining returns on investment to attract more investors to the sector. The approach used by most is the levelised cost of energy (or levelised cost of electricity when relating to the electricity market specifically) (LCOE), which is a function of the total lifecycle costs relative to the amount of energy produced [18].

Lifecycle costs are normally split into different components comprising the initial non-recurring costs and recurring operational costs. Non-recurring costs include setup, planning and development, build, commission, decommission costs etc. In the case of offshore wind farms, also called arrays development costs are significant and include feasibility studies, permits, legal and all other costs associated with establishing an offshore wind farm.

Recurring costs include fuel and maintenance. Levelised cost of electricity constitutes the average cost per unit that the generator needs to receive to break even over the lifetime of the site [19]. These life cycle costs estimates become more stable and accurate as an industry matures and gathers real world data for modelling. An alternative novel approach for LCOE estimation has been proposed by Aldersey-Williams and colleagues, who use audited account information from Special Purpose Vehicles (SPV's) operating offshore wind farms to estimate operational costs [15].

Here the challenges of accurately estimating LCOE for offshore wind outlining differing approaches to calculating LCOE, the factors influencing this, and the impact of variation in LCOE calculation are reviewed. Current costs for the production of offshore wind energy are summarised based on publicly available datasets. In section 2, LCOE with particular focus on offshore wind is described, section 3 details a number of approaches to LCOE calculation, section 4 examines the issues with LCOE uncertainty, section 5 discusses the findings and section 6 concludes.

Identifying and managing financial risk is essential in planning any infrastructure project. This risk is amplified for large complex projects such as offshore wind farms. Economic forecasts are often presented as metrics or measures to assess the viability and future investment performance. However, these forecasts have pitfalls, especially in large infrastructure projects. It is therefore vital to understand any limitations and potential inconsistencies when using them to avoid underestimation or over estimation of returns on investments. Furthermore, the blanket use of them across energy technologies needs to be undertaken with caution. This work focuses on this aspect of LCOE considering offshore wind investment and highlights several reasons behind differing LCOE calculations and auctions results in different regions.

2. Levelised cost of electricity

In the energy sector, LCOE is the most common way of calculating and discussing the cost of electricity. At the most basic level this can be expressed by Equation (1),

$$LCOE = \frac{\sum_o^n C}{\sum_0^n E} \quad (1)$$

where C is the total lifetime costs expressed in selected currency (usually either £, $ or €) and E is the total electrical energy produced in kWh or MWh from initiation (year 0) to end of life (year n). LCOE is expressed as currency/kWh or MWh. A summary of LCOE values for offshore wind is presented in Table 1. These values are converted to 2016 US$/kWh and show a decrease in LOCE between 2010 and 2020.

Table 1 outlines average global values. However, by way of comparison the 2018 LCOE for German offshore wind is estimated at between €0.07 & 0.13/kWh by Fraunhofer ISE [20], whereas Baringa Partners forecast a LCOE for Irish offshore wind at €0.14/kWh in 2020 dropping further to €0.13/kWh by 2030 [21]. Values of between £0.09 and 0.1/kWh are forecast for the UK offshore wind LCOE by BVG associates for projects commissioned in 2021, falling to £0.08/kWh for projects after 2026 [22].

Levelised cost of electricity is applied when comparing costs across differing technologies, determining price trends in single technologies, feed-in tariff requirements and calculating the viability of an energy producing technology [23]. Therefore, Formula (1) is overly simplified. A non-exhaustive, qualitative overview of LCOE inputs and market interactions is shown in Fig. 1.

Given the complexity of LCOE inputs, the large investment sums, and relatively long lifecycle of offshore wind arrays, an important consideration for LCOE is the influence of monetary inflation over time. Therefore, a more detailed and complete equation for renewable LCOE is as follows (taken from IRENA [24])

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (2)$$

where LCOE is the average lifetime levelised cost of electricity generation, I_t is the investment in year t, M_t is the operations and maintenance expenditures in the year t, F_t is the fuel expenditures in the year t, E_t electricity generation in the year t in kWh or MWh, r is the discount rate as %, and n is the life of the system in years. The result is expressed as a currency/kWh or MWh, for example in £/kWh.

2.1. Non-recurring costs

Non-recurring costs influencing LCOE encompass all costs related to the development of an offshore wind site. This includes feasibility and planning, physical infrastructure and installation costs. Additionally, contract structures, subsidies with consideration to duration and operational costs such as capacity factors need to be considered and costed [25]. Importantly however, inputs differ for non-recurring costs from one country to another. For example, grid connection costs are a substantial component of offshore wind farm costs in the UK but they are not included in the calculation in many other regions including Germany, Belgium and Holland [26]. This is because the responsibility and costs for grid connection infrastructure in the UK lie with the developer. In the other regions these costs reside with the Transmission System Operator (TSO) [26]. Inconsistencies like this can create artificial regional variances in the LCOE values [16,26].

A breakdown of build costs is available from the UK government, the analysis presents an allocation by % of the total build cost to individual elements of the array. For example, the report allocates 33% of the total build cost to the turbine, the analysis then looks in more detail and splits the turbine into the rotor and nacelle, allocating 11 and 22% to these components respectively. Using these values and taking a mid-range total installation cost of £4 million/MW as a reference, Table 2 estimates costs for various components in an offshore wind array.

The International Renewable Energy Association (IRENA) has identified five primary drivers in installation costs for developing a wind array. Firstly, turbine costs (consisting of rotor blades, gearbox, generator, nacelle, power converter, transformer and tower) are typically 30–50% of total installation costs. This estimate is in line with the UK government values shown in Table 2, where the turbine (inclusive of the tower costs) are 39% of the total. Secondly, structural costs to include all construction works required for the site and tower foundations. Thirdly, foundation costs, which vary widely, depending on water depth. Fourthly, grid connection costs consisting of transformers, substations and connection to the local distribution or transmission network. Finally, planning and project costs, including the cost of land.

The approaches to managing these costs vary across different countries [6] and is often informed by regional differences in geographical features, regulatory frameworks and ownership of sea beds [27,28]. In Belgium, the sea bed is controlled by the federal government, who allocate zones for offshore wind development including development of offshore substations [29,30]. The approach in Denmark is to manage infrastructure delivery via a not for profit company owned by the Danish Energy and Climate Agency. By taking this approach, the Danish government can promote offshore wind through a transparent tendering process where all data is made public [29].

In the UK, the seabed is owned and operated by the Crown Estate areas of seabed are released in phases for wind array development after consultations between industry and the Crown Estate. The consultations define requirements and suitability of various sites. Phases 1, 2 and 3 have already been released and auctions have taken place. Phase 4 is planned for release for tender in 2021 [31,32]. This means that similarly to Belgium and Denmark, there is a single entity to control sea bed allocation for offshore wind development.

2.2. Recurring costs

Operations and maintenance (O&M) costs are recognised as a substantial component of LCOE for offshore wind turbines. However, data is not readily available, costs associated with O&M are therefore not well defined with significant variance in the values quoted. Approximately 20–25% of the total lifecycle costs are attributed to O&M costs [33,34]. Using this value, it is possible to estimate lower and upper values for the lifetime O&M costs.

Table 1
LCOE trends since 2010, source data from IRENA.

	Data Type	Cumulative Deployment (GW)	LCOE (2016 $US/kWh)
2010	Historical	3.1	0.17
2011	Historical	3.8	0.16
2012	Historical	5.4	0.14
2013	Historical	7.5	0.19
2014	Historical	8.6	0.15
2015	Historical	11.2	0.18
2016	Historical	14.0	0.15
2017	Estimate	17.1	0.14
2020	Estimate	30.5	0.08

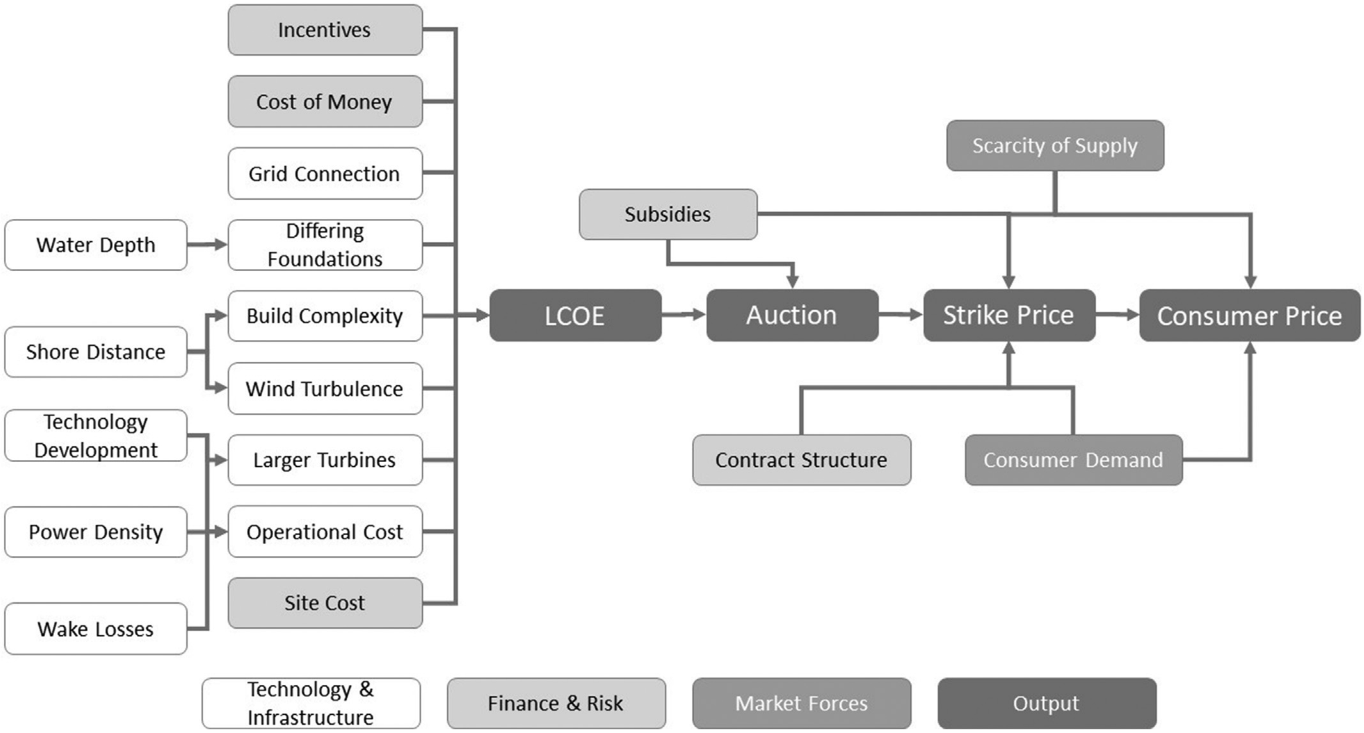

Fig. 1. Qualitative overview of market interactions.

Table 2
Non-recurring cost breakdown from UK Government.

Category	Cost %	Estimated £/MW installed	First Level Breakdown	Cost %	Estimated £/MW installed	Second Level Breakdown	Cost %	Estimated £/MW installed
Development & Consent	4.0	160,000	Environmental Survey	0.3	12,000	–		–
			Sea Bed Survey	0.6	24,000	–		–
			Met Mast	0.3	12,000	–		–
			Dev Services	2.8	112,000	–		–
Turbine	33.0	1,320,000	Rotor	11.0	440,000	Blade	7.0	280,000
						Hub	3.6	144,000
			Nacelle	22.0	880,000	Gearbox	9.0	360,000
						Electrical	8.0	320,000
						Other	4.6	184,000
Balance of Plant	37.0	1,480,000	Tower	6.0	240,000			
			Foundation	16.0	640,000			
			Cables	5.0	200,000	Inter Array	1.4	56,000
						Export	4.1	164,000
			Offshore Substation	7.0	280,000	Electrical	5.0	200,000
						Other	1.4	56,000
			Onshore Substation	2.7	108,000	Electrical	2.0	80,000
						Other	0.7	28,000
Installation & Commissioning	26.0	1,0,40,000	Foundation	7.0	280,000			
			Cables	9.0	360,000			
			Turbine		360,000			
			Offshore Substation		28,000			
Total	**100**	**4,000,000**		**99.4**	**3,976,000**			

As noted in Section 1, installation costs for offshore wind can range from £1.5 million/MW to £6 million/MW. Using the lower and the upper values from these ranges, O&M costs can range from £0.375 million/MW installed to £2 million/MW installed. Using the lower is unrealistic as this assumes a scenario where infrastructure is already in existence. However, the existing infrastructure will incur O&M costs, which will be omitted from the calculation. Similarly, the upper value is likely to be an overestimation. These estimations are approximately in line with values from the National Renewable Energy Laboratory (NREL) who suggest $86/kW/year. This assumes a 25 year life span and using current exchange rates, this value converts to £1.7 million/MW [7].

Potential sites for offshore wind arrays are identified in part by wind energy potential models. Therefore, wind variability is a major component of any economic case for an offshore wind array [35] and is subject to significant debate. Estimations of wind energy production are heavily reliant on wind energy potential models with variation in the results of these models cited as a potential risk for inaccurate estimates [36].

Variation in wind supply has been cited as a reason that LCOE is not a good metric when comparing wind and variable renewable energies in general, against traditional dispatchable energy generation. Many calculations of LCOE do not factor in operational efficiencies and ones that do have different assumptions about the amount of time across a year in which the turbines will be in operation and generating electricity [36]. This concept is developed further by Milligan et al. [37] who discuss the interaction between dispatchable and intermittent energy sources. In this report it is proposed the addition of the intermittent supply will improve the overall reliability of the system, which will allow the system operators to decrease the capacity of the dispatchable generators [37]. Technology development considering power curves and wind modelling techniques is reviewed by Østergaard et al. [38]. A key finding of this review notes that overestimation of energy yields has a significant detrimental impact on the economic case for wind energy. This is important in LCOE estimations. Similarly, this could be applied to other renewable energy technologies.

The reduction in operational output varies widely depending on the variability of the intermittent supply. Lamont et al. build on this concept and argue that an intermittent energy supply should only be introduced if the overall benefit outweighs the overall costs [39]. A theoretical model was developed by examining the effect of introducing variable energy sources at a higher penetration level in California by Mills and Wiser [28]. While it is noted that the model does have limitations and may only be applicable in the California region, they determine that increased use of renewable energy sources can reduce the requirement for natural gas combined cycle (in this instance) and combustion turbine power plants [28].

2.3. Technology development

Technology maturation generally leads to lower non-recurring and recurring costs. In offshore wind energy production, this is only likely to be true for some cost elements. While some suggest that the initial high costs associated with offshore wind will lead to more cost reduction opportunities in the future. Others state that the desire in offshore wind to go for deeper water, accessing more remote sites, the introduction of floating foundations, and the use of larger turbines, will likely increase costs at least in the medium term [17].

Suppliers for turbines are Siemens GAMESA, General Electric (GE), MHI Vestas and Repower (renamed Senvion in 2014). Senvion is a wholly own subsidiary of Suzlon. Wind turbines are now approximately five times larger than when they were first deployed. MHI Vestas announced in September 2018 that their first 10 MW turbine is available for order with deployment expected in 2021 [40] and now GE has developed a 12 MW offshore wind turbine with a blade diameter of 220m [41]. As turbines get larger (i.e. taller, larger rotor diameter and bigger drive), they are able to access more stable wind flows. This effect is amplified on offshore sites due to the lack of land features and contours, which cause turbulence in wind flow. This less turbulent airflow leads to higher full load hours, which significantly improves operational efficiency and increasing capacity factors [42,43]. Once planning and all the pre-installation work is complete, deployment and installation of wind turbines is relatively fast [42].

2.4. Market forces, pricing strategy and financing costs

Analysis of market forces and pricing strategy tends to vary from company to company and is driven by forces internal and external to the organisation. These strategies will impact both the cost that an electricity generator will accept for electricity and how much an electricity resellers or suppliers are willing to pay for electricity in the wholesale markets.

Across Europe, since the 1990's electricity markets have been opened to deregulation and levels of competition. For consumers this means that they are free to choose from different utility suppliers [44]. This trend was underpinned by the belief that more competition improves efficiency, leading to reduced costs for consumers, improved security of supply, higher levels of integration of renewables, and promotion of energy efficiency across the industry [45]. Since the introduction of competition and the opening of electricity markets there has not been a significant reduction in costs as originally predicted [46]. This lack of price reduction contrasts with the wholesale prices of electricity, which have declined between 2010 and 2016, and are substantially below highs seen in 2008 [47].

Since the 1990's there has been a substantial increase in the amount of energy generated from renewables as a whole and it is unclear whether this has been driven by competition in the market, consumer perceptions on the industry, or government incentives. Despite increased efficiencies and regional reductions on energy requirements, overall energy requirements remain level across Europe [46]. Consumer market demand was analysed in two parts by Cialani and Mortazavi [45]. Firstly, household demand and secondly, industrial demand. Using this split they went on to propose a framework identifying variables which can influence consumer demand for energy as a whole. For households these include energy availability, price, income levels, and external variables such as climate and weather. Industrial demand is driven by cost effectiveness [45].

Market forces are comprised of fluid variables including supply and demand, which can be influenced quickly and significantly by government policy or a shift in consumer requirements. Typical components of finance costs include debt interest and inflation, leading to estimates of the future value of money invested. Government incentives can also have a significant impact on the outcome of these calculations.

2.5. Financial incentives

Government incentives have provided funding and a degree of security for offshore wind energy with, for example the UK Offshore wind subsidy of £140/MWh, which is secured to 2019 [4]. Additionally, the UK government published their industrial strategy document in March 2019, which gives detail on an '*Offshore Wind Sector Deal*.' This strategy document sets out ambitions and scale for how they want the industry to grow. One of the headline targets is to grow offshore wind capacity by 1–2 GW per year to 30 GW by 2030 [48]. The UK government is providing support for research and development and subsidies, and is making up to £557M available for future CfD opportunities [48] to achieve these goals.

Germany and the UK have both introduced CfD schemes, which are allocated through a competitive tender process. CfD mechanisms are an agreement between the electricity generator and (usually) the energy regulator. These contracts set a price for electricity, which will be generated at a point in the future. Under these contracts, differences between the agreed 'strike' price and the wholesale value of electricity at the point of sale are calculated.

In the UK and German CfDs, differences between the agreed price and the wholesale prices, where the wholesale prices are below the agreed price, are paid to the generator by the regulator. In addition, under the UK system, differences between the wholesale price and the agreed price, where the wholesale price is higher than the agreed prices, are paid by the generator to the regulator. These are referred to as one way CfDs in the German system and two way CfDs in the UK system. This replaces feed-in tariffs and the renewables obligation certificate (ROC) scheme respectively [49].

Other countries who use CfDs have some fundamental differences in their implementation. For example, in the Netherlands and Denmark, developers bid on specific, already identified sites, thereby avoiding initial development and feasibility costs [50]. Strike prices in the Netherlands, Denmark and Germany are not indexed to inflation whereas in the UK they are. Other differences include the term for the subsidies, as an example, Demark limits subsidies to 50,000 full loads hours as opposed to other countries who set a term limit in years from installation [50,51].

When comparing strike prices from country to country, it is important to consider the impact of the CfD structure. If a developer were to win an auction with a zero bid, under the two way contract in the UK that is what they will receive irrespective of what happens in the wholesale market [52]. Conversely, if a developer were to win an auction with a zero bid under the one way contract, but the wholesale price at point of sale is €40/MWh for example, then they will receive €40/MWh [16]. From a generator's perspective this is important point of difference. If the, developer is confident that the wholesale price will be above the LCOE plus a profit margin at the point of sale, the strike price is of little relevance under a one way CfD. This is not the case in a two way CfD where the site will not be economically viable if the strike price is set too low.

Sweden and Norway have a joint electricity certificate market where producers are allocated a certificate for every MWh produced. Certain electricity customers through a compulsory purchase scheme then purchase these certificates. The requirement for purchases is determined by the electrical demand, which also determines the prices, resulting in a correlation between income and demand for the electricity producers [53]. Belgium has a tradable certificate system to support renewable energy supplies as a whole. With the exception of offshore wind and hydroelectric power, this is managed at a devolved level with some regional variance. Offshore wind and hydropower incentives are managed at a national level [54]. In addition to these incentives renewable electricity sources are given priority for connection to the electrical grid.

3. Current LCOE models and approaches in offshore wind

Viability of a given site can be estimated using different economic parameters. Economic comparative analyses on the viability of any array should be viewed in the context of the purpose of the analyses and not limited to simple payback periods, generalised LCOE approach, cost benefit analysis, total lifecycle costs, and net present value calculations, as each of these metrics have limitations.

Data sets for non-recurring and recurring costs are publicly available, this data is from specific sites that are already commissioned and in operation. A potential issue with many of published datasets available is that they originate from the early stages of the offshore wind industry when developers were on a learning trajectory. LCOE forecasts can be created using a range of software tools.

Agora Energiewende provide a downloadable MS Excel based calculation tool for calculation of LCOE. In this tool there is a table and graphic which allows comparison of five differing energy producing technologies. The formula in this sheet uses €/kW values for investment costs and €/kW/year for fixed O&M, but uses €/MWh for calculation of variable O&M. Other inputs include % for Weighted Average Cost of Capital (WACC), duration of plant lifetime in years, a variable for CO_2 emission costs using tCO_2/MWh, and full load hours to consider capacity factor. With these inputs, formulas in MS Excel are used to calculate annual values for Capital Expenditure (CAPEX), O&M, and fuel and CO_2 emission costs. From these values, a final value for LCOE is presented in ct/kWh. The tool allows for a best and worst case to be calculated and presented simultaneously, in a min/max bar chart [55].

Lazard present a financial analysis method for assessing rate of return on investments, specifically in the context of renewable energy sources. The output from the analysis is an Internal Rate of Return (IRR) value. One of the components of this tool is a calculation for LCOE. The difference with the approach Lazard propose is that O&M costs are calculated in parallel to LOCE, rather than being including in the calculation as is the case with many other LOCE calculations. The approach used by Lazard is to combine the LCOE and O&M costs to create a value or IRR. Therefore, the O&M is included in the IRR values but not LCOE [56]. While this approach will create an accurate reflection of the IRR of a project, the LCOE is likely to be significantly different to other methods where O&M is included in the LCOE value.

An additional spread sheet method for calculation of LCOE is available through the American Environmental Protection Agency (EPA) (an Optony branded MS Excel spread sheet is downloadable from the EPA website). While this tool is targeted for solar developers, the methodology is similar to other available tools in that this tool calculates LCOE over a 20 and 25 year time frame in parallel. It also includes fixed CAPEX subsidies and escalating O&M in the calculation. PPA subsidies are calculated outside of LCOE and presented in a separate section and because this tool is primarily for solar, an annual degradation factor is included, but a capacity factor is not included in the calculation [57].

The Danish Energy Agency worked with Ea Energy Analyses to produce an MS Excel and macro enabled spread sheet to calculate and present LCOE from multiple different technologies, including renewable and fossil fuel, and developed and emerging technologies. This sheet is a free download from the Danish Energy Agency website. The way in which LCOE is calculated is similar to other methods discussed here. However, the structure of the spread sheet allows for significantly more detailed information to be captured and analysed [58].

Exceedence provides software for tracking current and forecasting future renewable energy projects. Economic indicators such as LCOE, IRR, Net Present Value (NPV), Payback, and Cash flows are provided as part of the analysis. Exceedence also provides comparison features to allow users to compare financial performance of multiple projects in the software. The software is pitched at investors, developers, consultants and device developers, highlighting the LCOE feature and how this informs bid/auction prices. The cost as of July 2019 for access to this software ranges from €299 to €999 per month depending on the package [59].

The approach to calculating LCOE and the inputs used, vary from one organisation to another a selection of LCOE approaches and attributes considered is given in Table 3.

4. Impact of LCOE uncertainty

Some studies detail limitations with LCOE for renewable energy sources, including lack of sensitivity to fluctuations in power supply [23]. Furthermore, Bruck et al. propose the inclusion of power purchase agreements in LCOE calculations [68]. Whereas Elliston

Table 3
Attributes for differing approaches to LCOE calculations.

	Organisation Type	Discounted Investment	IRR	Fixed O&M	Variable O&M	Capacity Factor	Environmental Cost	Calculation Tool	Source
IRENA	Governmental	+	-	+	-	-	-	-	[24]
Fraunhofer	Research	+	-	+	-	-	-	-	[20]
Siemens	Industry	+	-	+	-	+	+	-	[60]
Lazard	Consultancy	+	+	+	+	+	-	+	[61]
Beiter	Governmental	+	-	+	-	+	-	-	[62]
NREL	Governmental	+	-	+	+	+	-	+	[63]
USE.I.S	Governmental	+	-	+	+	+	-	-	[64]
Danish Energy Agency	Governmental	+	-	+	+	+	+	+	[58]
Blix Consultancy BV & Part.	Consultancy	+	-	+	-	-	-	-	[65]
Black & Veatch	Consultancy	+	+	+	+	+	-	-	[66]
Stanford Grad School of Bus.	University	+	-	+	+	+	+	+	[67]

Attribute/feature available/considered +
Attribute/feature not available/considered -

and colleagues underline the need to include electricity pricing variation in the calculation [69]. Traditionally LCOE ignores variability and integration costs. However, Ueckerdt et al. propose a 'System LCOE' to incorporate these additional costs [19]. Other users of LCOE note the regional variances between the calculation inputs, for example connections charges are paid by wind farm developers, but in other part of Europe they are covered as national infrastructure projects so the costs lie elsewhere [16].

These variances in calculation inputs combined with different regional auction and contract structures partially explain variance in auction prices across different countries. A selection of auction results from across Europe is shown in Table 4. Site auction bids placed by developers are informed significantly by the results of LCOE calculations. This is of particular interest considering the number of zero bids placed recently by developers in Germany and the Netherlands. However, while the LCOE calculation is an important consideration for determining the strike price, it is important to note that LCOE and strike price are not the same, and that strike price is a composite number comprising LCOE, market forces and a number of other factors [25].

In the UK's CfD mechanism terms in the contract allow for increases to the agreed strike price under certain conditions. For example, the strike price can increase to compensate for inflation. The initial strike price and any alterations are published via the Low Carbon Contracts Company (LCCC) for renewable energy sources. These publications show an increase to the initial strike prices of 10–14% depending on the technology, with offshore wind showing a 15% increase on round one strike prices and 8% on round 2 results [14]. Over this timeframe, the impact of inflation is approximately 8.9% on round one and 3.3% on round two results [70], suggesting that there are other factors beyond inflation influencing this increase.

Since LCOE is expressed in varying currencies and as a cost per kWh or MWh, it can be difficult to accurately compare LCOE from one region to another. While conversion from kWh to MWh is straightforward, fluctuations in exchange rates mean that converting currencies can have a significant impact on the final value for LCOE.

Table 4
Auction price trends in Europe since 2016.

Date Declared	Country	Project	Location	Scale (MW)	Developer	Bid €/MWh	
Apr 2018	Germany	Borkum Riffgrund West 1	North Sea	420	Ørsted	0.00	
Apr 2017	Germany	Borkum Riffgrund West 2	North Sea	240	Ørsted	0.00	
Apr 2017	Germany	He Dreiht	North Sea	900	EnBW	0.00	
Apr 2017	Germany	OWP West	North Sea	240	Ørsted	0.00	
Mar 2018	Netherlands	Hollandse Kust Zuid	North Sea	750	Chinook C.V.	0.00	
Nov 2019	UK	Forthwind	North Sea	12	Forthwind Ltd.	45.81	[a]
Nov 2019	UK	Sofia OWF Ph 1,2,3	North Sea	1400	Sofia OWF Ltd.	45.81	[a]
Nov 2019	UK	Doggerbank Multiple Sites	North Sea	3600	Doggerbank Projco Ltd.	47.32†	[a]
Apr 2018	Germany	Kaskasi	North Sea	325	Innology SE	48.00	[b]
Nov 2019	UK	Seagreen Ph 1,2,3	North Sea	454	Seagreen Wind Energy Ltd.	48.08	[a]
Nov 2016	Denmark	Kreigers Flak	Baltic Sea	605	Vattenfall	49.90	
Dec 2016	Netherland	Borssele 3 & 4	North Sea	731	Blauwind II Const.	54.50	
Apr 2017	Germany	Gode Wind 3	North Sea	110	Ørsted	60.00	
Sep 2017	UK	Hornsea Project 2	North Sea	1386	Ørsted	63.30	[a]
Sep 2017	UK	Moray OWF East	North Sea	950	EDPR, ENGIE & China Three Gorges	63.30	[a]
Sep 2016	Denmark	Vesterhav	North Sea	350	Vattenfall	63.61	[c]
Apr 2018	Germany	Baltic Eagle	Baltic Sea	476	Iberdrola	65.00	
Jul 2016	Netherlands	Borssele 1 & 2	North Sea	752	Ørsted	72.70	
Sep 2017	UK	Triton Knoll OWF	North Sea	860	Innology, J. Pow. & Kansai Elec. Pow. Co	82.30	[a]
Apr 2017	Germany	Gode Wind 4	North Sea	132	Ørsted	98.30	
Apr 2018	Germany	Arcadis 1	Baltic Sea	247	KNK Wind	Not Av	

Chinook C.V. is a wholly owned subsidiary of Nuon/Vattenfall.
Blauwind II Consortium consists of Shell, Van Oord, Eneco & Diamond Generating Group (Mitsubishi).
† weighted average value across all the phases.
[a] £ to € converted at the rate at the close of trading on the day of announcement.
[b] Not disclosed estimated value based on comments and analysis by NERA.
[c] Kr to € converted at the rate at the close of trading on the day of announcement.

5. Discussion

There is significant variability in how costs are calculated for offshore wind, which can be attributed to several key factors. The industry is still relatively immature meaning that existing and not insignificant unknowns are compounded by the rapid development and introduction of new technologies. Technology development is happening at a very fast pace with manufacturers bringing to market larger and more advanced turbines, affecting not just the initial costs but heavily influencing O&M costs. Differences in national policies contribute to cost variation. However, for the economic cases to be accurate, it is important to factor in these regional differences. This can create difficulties when comparing costs from one region to another. These differences lead to questions about the suitability and completeness of LCOE as an economic tool for variable renewable energy. This is an important issue to investigate as LCOE is often quoted when comparing different energy sources and is used for investment and policy decisions. The rapidly developing nature of this industry means it is essential that any economic models have a level of fluidity built into the model to keep pace with the technologies.

Strike price differences between the UK and other regions in Europe are likely to be influenced by a number of factors including differences in how feasible sites are identified, connection charges, differences in where the responsibility lies for elements of the infrastructure, and geographical differences including water depth and distance to shore. However, the difference in CfDs and how exposure to decreases in wholesale electricity prices is allocated in these arrangements explains how 0 €/MWh bids have been seen in Germany and Netherlands but the last round of auctions in the UK were around £40/MWh. The differences in CfDs does not explain the significant discrepancy between auction results and forecast values for LCOE. Values for LCOE by 2026 (as noted in Section 2) for offshore wind in the UK are predicted to be around £80/MWh, approximately twice current strike prices. This means that either the costs of installing and running an offshore wind farm have to decrease significantly by the time these sites come online or the agreed strike price will have to rise so that the sites are economically viable.

6. Conclusions

In this study, the challenges of accurately estimating LCOE for offshore wind are reviewed. The different approaches to calculating LCOE, the factors influencing this, and the impact of variation in LCOE calculation are examined. Current costs for the production of offshore wind energy are summarised based on publicly available datasets. This is an important exercise for the field and the sector as a whole as offshore wind power is set to grow globally to 228 GW by 2023 and potentially to 1000 GW by 2050 [71]. Financial risk management is essential in planning any infrastructure project, and as this study has shown, this risk is amplified for large complex projects such as offshore wind farms. Economic forecasts based on LCOE will be helpful, but the decision makers must understand any limitations and potential inconsistencies in LCOE when applying them in financial decision making. Blanket blind use of them across energy technologies also needs to be undertaken with caution and in this study aspects of LCOE considering offshore wind investment in different regions and auctions was discussed in this context.

It is important to highlight that caution is required when using LCOE for policy and/or investment decisions. For example, regions where offshore wind is being deployed include but are not limited to the UK, Ireland, Germany, and Denmark in the EU, Massachusetts, and California in the USA, China, Japan, and Korea. Each of these regions will have significant differences in geographical attributes such as water depth, wind resource, and distance to load centre, all of which impact the total costs substantially. In addition, there will be substantial variance in the economic viability due to regional incentives and contract frameworks. Public perception, ability and willingness to pay more for electricity from low CO_2 sources has a substantial impact on long term wholesale electricity prices. This is an essential consideration before deciding to install offshore wind capacity and will influence the future actions of energy regulators and governments. Perception and public opinion can be subject to dramatic and rapid changes particularly when in response to an event. A recent example is the Fukushima Daiichi nuclear disaster, whereby one earthquake impacted national policy and public perception across the globe. While this is an essential consideration, it is beyond the scope and does not factor into LCOE calculations.

This critical review highlights the issues and challenges of using LCOE in policy, regulatory and financial decision-making in the offshore wind industry. It shows that LCOE must be taken in context with the risk associated with any specific site and the unknown civil and environment engineering aspects (i.e. sunken or hidden costs). Thus the next part of this work will be to develop a decision making tool that will integrate the LCOE with future electricity prices to make better financial commitments.

In conclusion, LCOE is a useful indicator of potential economic performance, but should be used with caution when considering decisions around investments and subsidy schemes in offshore wind power as it has inherent limitations.

CRediT authorship contribution statement

Barry Johnston: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Aoife Foley:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **John Doran:** Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Timothy Littler:** Supervision.

Acknowledgements

The Bryden Centre project is supported by the European Union's INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB). This work was first presented as an oral presentation in a special session entitled "*Wind Power Sustainability*" at the 14th SDEWES conference in Dubrovnik, Croatia on 4th October 2019. The lead author would like to thank the Sustainable Development of Energy Water and Environment Systems (SDEWES) 2019 conference team for the opportunity to present this work. Finally, we are also grateful to Professor González Rodríguez at the Universidad de Jaén for access to datasets.

References

[1] B. Snyder, M.J. Kaiser, Ecological and economic cost-benefit analysis of offshore wind energy, Renew. Energy 34 (2009) 1567–1578.
[2] B. Möller, L. Hong, R. Lonsing, F. Hvelplund, Evaluation of offshore wind resources by scale of development, Energy 48 (1) (2012) 314–322.
[3] M. de Castro, S.G.-G.M. Salvador, X.C.D. Costoya, F.J. Sanz-Larruga, L. Gimeno, Europe, China and the United States: three different approaches to the development of offshore wind energy, Renew. Sustain. Energy Rev. 109 (2019) 55–70.
[4] P. Higgins, A. Foley, The evolution of offshore wind power in the United Kingdom, Renew. Sustain. Energy Rev. 37 (2014) 599–612.
[5] M. Welisch, R. Poudineh, Auctions for allocation of offshore wind contracts for difference in the UK, Renew. Energy 147 (2020) 1266–1274.
[6] International Renewable Energy Agency, Featured dashboard - finance,

International renewable energy agency, 2018 [Online]. Available, http://resourceirena.irena.org/gateway/dashboard/?topic=6&subTopic=11. (Accessed 10 July 2019).
[7] National Renewable Energy Laboratory, Cost of wind energy review, September 2018. [Online]. Available, https://www.nrel.gov/docs/fy18osti/72167.pdf, 2017 [Accessed 2019 July 14].
[8] M. Vieira, B. Snyder, E. Henriques, L. Reis, European offshore wind capital cost trends up to 2020, Energy Pol. 129 (2019) 1364–1371.
[9] N. Ederer, The market value and impact of offshore wind on the electricity spot market: evidence from Germany, Appl. Energy 154 (2015) 805–814.
[10] Global Wind Energy Council, GWEC global wind report 2018 [Online]. Available: https://gwec.net/wp-content/uploads/2019/04/GWEC-Global-Wind-Report-2018.pdf, , April 2019. (Accessed 21 November 2019).
[11] M. de Simón-Martín, Á. de la Puente-Gil, D. Borge-Diez, T. Ciria-Garcés, A. González-Martínez, Wind energy planning for a sustainable transistion to a decarbonized generation scenario based on the opportunity cost of the win energy: Spanish Iberian Penninsula as a case study, Energy Procedia 157 (2019) 1144–1163.
[12] E. Topham, D. McMillan, S. Bradley, E. Hart, Recycling offshore wind farms at decommissioning stage, Energy Pol. 129 (2019) 698–709.
[13] J.P. Jensen, K. Skelton, Wind turbine blade recycling: experiences, challenge and possibilities in a circular economy, Renew. Sustain. Energy Rev. 97 (2018) 165–176.
[14] Low Carbon Contracts Company, Download current and historical CFD Register data [Online]. Available, https://www.lowcarboncontracts.uk/download-current-and-historical-cfd-register-data, 2019 [Accessed 2019 July 15].
[15] J. Aldersey-Williams, I.D. Broadbent, P.A. Strachan, "Better estimates of LCOE from audited accounts – a new methodology with examples from United Kingdom offshore wind and CCGT, Energy Pol. 128 (2019) 25–35.
[16] NERA Economic Consulting, Renewable energy auctions: lessons from Germany, the UK and The Netherlands [Online]. Available, https://www.strommarkttreffen.org/2018-05_Huebler_Deutsche_und_britische_Erfahrungen_EE-Ausschreibungen.pdf, 4 May 2018. (Accessed 10 July 2019).
[17] J.A. Voormolen, H.M. Junginger, W. van Sark, Unraveling historical cost developments of offshore wind energy in Europe, Energy Pol. 88 (2016) 435–444.
[18] J. Bosch, I. Staffell, A.D. Hawkes, Global levelised cost of electricity from offshore wind, Energy 189 (2019) 116357.
[19] F. Ueckerdt, L. Hirth, G. Luderer, O. Edenhofer, System LCOE: what are the costs of variable renewables? Energy 63 (2013) 61–75.
[20] Fraunhofer ISE, Levelised cot of electricity renewable energy technologies [Online]. Available, https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf, March 2018. (Accessed 11 July 2019).
[21] Baringa Partners LLP, 70 by 30, A 70% renewable electricity vision for Ireland in 2030 [Online]. Available: https://www.iwea.com/images/Article_files/Final_Baringa_70by30_Report_web.pdf, , 20 September 2018. (Accessed 10 July 2019).
[22] BVG Assoiates, UK Offshore Wind: Less than Ten Years to "Subsidy-free", BVG Assoiates, March 2016 [Online]. Available: https://bvgassociates.com/uk-offshore-wind-less-ten-years-subsidy-free/. (Accessed 11 July 2019).
[23] U. Nissen, N. Harfst, Shortcomings of the traditional "Levelized Cost of Energy" [LCOE] for the determination of grid parity, Energy 171 (2019) 1009–1016.
[24] Inernational Renewable Energy Agency, Resource your source for renewable energy information data methodology [Online]. Available: http://dashboard.irena.org/download/Methodology.pdf, , 18 May 2015. (Accessed 11 July 2019).
[25] Department for Business, Energy and Industrial Strategy, "Electricity Generation Costs,", Department for Business, Energy and Industrial Strategy, 2016.
[26] IEA-Renewable Energy Technology Deployment, Comparative analysis of international offshore wind energy devlopment [Online]. Available: http://iea-retd.org/wp-content/uploads/2017/03/IEA-RETD-REWind-Offshore-report.pdf, , March 2017. (Accessed 10 July 2019).
[27] O. Fitch-Roy, An offshore wind union? Diversity and convergence in European offshore wind governance, Clim. Pol. 16 (2016) 586–605.
[28] Ernest Orlando Lawrence Berkeley National Laboratory, Changes in the economic value of variable generation at high penetration levels: a pilot case study of California [Online]. Available: https://emp.lbl.gov/sites/all/files/lbnl-5445e.pdf, , June 2012. (Accessed 21 November 2019).
[29] S. Rodrigues, C. Restrepob, E. Kontos, R. Teixeira Pinto, P. Bauer, Trends of offshore wind projects, Renew. Sustain. Energy Rev. 49 (2015) 114–1135.
[30] Ramboll Group A/S, Project Database Interface, Ramboll Group A/S, 2018 [Online]. Available: https://ramboll.com/projects. (Accessed 11 November 2019).
[31] The Crown Estate, "Our Assets Offshore Wind Energy," the Crown Estate, 8 July 2019 [Online]. Available: https://www.thecrownestate.co.uk/en-gb/our-places/asset-map/#tab-2. (Accessed 8 July 2019).
[32] Department for Business, Energy & Industrial Strategy, Contracts for difference [Online]. Available, https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference#the-fourth-cfd-allocation-round-ar4, 2 March 2020. (Accessed 15 May 2020).
[33] International Renewable Energy Agency, Renewable energy technologies: cost analysis series [Online]. Available: https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf, , June 2012. (Accessed 21 November 2019).
[34] Wind Europe, Economics, Wind Europe, 29 March 2019 [Online]. Available, https://windeurope.org/policy/topics/economics/. (Accessed 21 November 2019).
[35] G.R. Timilsinaa, G.C. van Kooten, P.A. Narbel, Global wind power development: economics and policies, Energy Pol. 61 (2013) 642.
[36] J. Bosch, I. Staffell, A.D. Hawkes, Temporally explicit and spatially resolved global offshore wind energy potentials, Energy 163 (2018) 766–781.
[37] National Renewable Energy Laboratory, California RPS integration study: phase 1 summery and results, in: 2004 Global WINDPOWER Conference, Chicago, 2004.
[38] P.A. Østergaard, N. Duic, Y. Noorollahi, Sustainable development using renewable energy technology, Renew. Energy 146 (2020) 2430–2437.
[39] A.D. Lamont, Assessing the long-term system value of intermittent electric generation technologies, Energy Econ. 30 (2008) 1208–1231.
[40] MHI Vestas, MHI Vestas Launches the First 10 MW Wind Turbine in History, MHI Vestas Offshore Wind, 25 Septemebr 2018 [Online]. Available: http://www.mhivestasoffshore.com/mhi-vestas-launches-the-first-10-mw-wind-turbine-in-history/. (Accessed 21 November 2019).
[41] General Electric, Haliade-X 12 MW Offshore Wind Turbine Platform, General Electric, 2019 [Online]. Available: https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine. (Accessed 21 November 2019).
[42] M. Bilgili, A. Yasar, E. Simsek, Offshore wind power development in Europe and its comparison with onshore counterpart, Renew. Sustain. Energy Rev. 15 (2011) 905–915.
[43] J.G. Dedecca, R.A. Hakvoort, J.R. Ortt, Market strategies for offshore wind in Europe: a development and diffusion perspective, Renew. Sustain. Energy Rev. 66 (2016) 286–296.
[44] S. Bahrami, V.W.S. Wong, J. Huang, Data center demand response in deregulated electricity markets, IEEE Trans. Smart Grid 10 (3) (2018) 2820–2832.
[45] C. Cialani, R. Mortazavi, Household and industrial electricity demand in Europe, energy policy, Energy Pol. 122 (2018) 592–600.
[46] Europa, Eurostat, Europa, [Online]. Available, https://ec.europa.eu/eurostat/web/main/home. (Accessed 11 July 2019).
[47] European Commission, Overall targets, European Commission, [Online]. Available: https://ec.europa.eu/info/energy-climate-change-environment/overall-targets_en. (Accessed 21 November 2019).
[48] United Kingdom Government, Press Release: Offshore Wind Energy Revolution to Provide a Third of All UK Electricity by 2030, Government Digital Service, 7 March 2019 [Online]. Available: https://www.gov.uk/government/news/offshore-wind-energy-revolution-to-provide-a-third-of-all-uk-electricity-by-2030. (Accessed 21 November 2019).
[49] M. Vieira, B. Snyder, E. Henriques, L. Reis, European offshore wind capital costs up to 2020, Energy Pol. 129 (2019) 1364–1371.
[50] NERA Economic Consulting, Offshore revolution? Decoding the UK offshore wind auctions and what the results mean for a "Zero-Subsidy" future [Online]. Available, https://www.nera.com/content/dam/nera/publications/2017/PUB_Offshore_Wind_A4_0917.pdf, 29 September 2017. (Accessed 14 July 2019).
[51] Council of European Energy Regulators, Status review if renewable support schemes in Europe for 2016 and 2017 [Online]. Available: https://www.ceer.eu/documents/104400/-/-/80ff3127-8328-52c3-4d01-0acbdb2d3bed, , 14 December 2018. (Accessed 14 July 2019).
[52] United Kingdom Government, Contracts for Difference (CfD) Allocation Round 3: Standard Terms and Conditions, United Kingdom Government, 1 May 2019 [Online]. Available: https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-3-standard-terms-and-conditions. (Accessed 28 November 2019).
[53] Norwegian Water Resources and Energy Directorate and the Swedish Energy Agency, The Norwegian-Swedish electricity certificate market [Online]. Available, Accessed, https://beta.nve.no/Media/4750/elcertifikat-2015-en_web.pdf, 2015. (Accessed 11 July 2019).
[54] RES Legal, Legal Sources on Renewable Energy, RES Legal, 2010 [Online]. Available, http://www.res-legal.eu. (Accessed 11 July 2019).
[55] Agora Energiewende, Calculator of levelized cost of electricity for power generation technologies [Online]. Available, https://www.agora-energiewende.de/en/publications/calculator-of-levelized-cost-of-electricity-for-power-generation-technologies/, Feburary 2014. (Accessed 24 June 2019).
[56] Lazard, Lazard's levelized cost of energy analysis - version 11.0 [Online]. Available, https://www.lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf, 2017 [Accessed June 2019].
[57] Optony, US envionmental protetion agency - solar PV project cost calculator, levelized cost of energy (LCOE) model [Online]. Available, https://www.epa.gov/sites/production/files/.../webinar_20140416_calculator_0.xlsx, 24 October 2013. (Accessed 25 June 2019).
[58] Danish Energy Agency, Levelized cost of energy (LCoE) calculator, 2018 [Online]. Available, https://ens.dk/en/our-responsibilities/global-cooperation/levelized-cost-energy-calculator. (Accessed 27 June 2019).
[59] Exceedence, Our software is a key tool for the Renewable Energy sector, Exceedence Ltd., [Online]. Available, https://exceedence.com/software/. (Accessed 20 July 2019).
[60] Siemens, What is the real coost of offshore [Online]. Available:, [Accessed March 2019], https://www.energy.siemens.com/br/pool/hq/power-generation/renewables/wind-power/SCOE/Infoblatt-what-is-the-real-cost-of-offshore.pdf.
[61] Lazard, Lazard's levelized cost of energy analysis – version 12.0, 2018 [Online]. Available: https://www.lazard.com/media/450784/lazards-levelized-

cost-of-energy-version-120-vfinal.pdf, , November 2018 [Accessed 2019 November 2019].
[62] National Renewable Energy Labratory, A spatial economic cost reduction pathway analysis for US offshore wind energy development form 2015-2030 [Online]. Available, https://www.nrel.gov/docs/fy16osti/66579.pdf, September 2016. (Accessed 19 July 2019).
[63] National Renewable Energy Labratory, Levelised cost of energy calculator [Online]. Available: https://www.nrel.gov/analysis/tech-lcoe.html. (Accessed 14 July 2019).
[64] US Energy Information Administration, Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2019 [Online]. Available: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf, , Feburary 2019. (Accessed 15 July 2019).
[65] BLIX Consultancy BV & PArtners, Study into Levelised Cost of Energy of Variants for Wind Farms Site Boundaries of Hollandse Kust (West), Ten Noorden van de Waddeneilanden and IJmuiden Ver, 14 Novemeber 2018 [Online]. Available, https://www.rvo.nl/sites/default/files/2018/12/20181114_BLIX_RVO_LCOE_HKW_TNW_IJV_F.pdf. (Accessed 15 July 2019).
[66] Black & Veatch, Levelized cost of energy calculation [Online]. Available, http://csep.efchina.org/report/20112844913435.70772110666485.pdf/Levelized%20Cost%20of%20Energy%20Calculation_BV_EN.pdf. (Accessed 15 July 2019).
[67] G. S. o. S. Business, Levelised cost of electricity calculator: a user guide [Online]. Available, http://stanford.edu/dept/gsb_circle/cgi-bin/sustainableEnergy/GSB_LCOE_User%20Guide_0517.pdf, March 2017. (Accessed 21 November 2019).
[68] M. Bruck, P. Sandborn, N. Goudarzi, A levelized cost of energy (LCOE) model for wind farms that include power purchase agreements (PPAs), Renew. Energy 122 (2018) 131–139.
[69] B. Elliston, I. MacGill, M. Diesendorf, Grid parity: a potentially misleading concept?, in: 48th AuSES Annual Conference, Canberra, 2010.
[70] Bank of England, Inflation Calculator, Bank of England, 2019 [Online]. Available, https://www.bankofengland.co.uk/monetary-policy/inflation/inflation-calculator. (Accessed 27 November 2019).
[71] International Renewable Energy Agency, Future of wind [Online]. Available, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf, October 2019. (Accessed 15 May 2020).