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Levelised Cost of Energy assessment for offshore wind farms – an examination of different methodologies, input variables and uncertainty

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Abstract
Levelised Cost of Energy (LCoE) is the most common metric used in renewable energy assessments. However, this can be a very complex calculation with numerous methodologies depending on the perspective taken. Inputs including costs, energy production are generally forecasts and predictions based on publicly available information; therefore they are key areas of uncertainty. Elements of the calculation are site or region specific such as the tax rate or inclusion of grid connection costs. The business case and financial assumptions applied will be very project specific e.g. the discount rate applied. These numerous variables and uncertainties must be fully understood in order to effectively apply the metric or review and compare LCoEs. Therefore, this paper provides a comprehensive set of LCoE methodologies that provide a reference basis for researchers. A case study demonstrates the application of these methods and the variation in results illustrates the importance of correctly selecting the discount rate and cash flow based on the perspective and motivation of the user. Sensitivity studies further investigates the potential impact of key variables and areas of uncertainty on results. Analysis indicates that the energy production and discount rate applied will have the most significant impact on LCoE, followed by CAPEX costs. While the key areas of uncertainties cannot necessarily be solved, this paper promotes consistency in the application and understanding of the metric, which can help overcome its limitations.

Introduction
Europe aims to become climate neutral by 2050 (the European Green Deal). This will require the decarbonisation of the energy system with a significant increase in renewable energy generation. It is expected that wind (onshore and offshore) will provide at last half of the EU electricity demand [1]. The EU foresee that the installed capacity for wind will be between 900-1,100 GW by 2050 [1], including 450GW for offshore wind [2]. Fixed offshore wind has seen dramatic reductions in cost over the last 10 years with Vattenfall's 2016 price bid for the Kriegers Flak project setting a record Levelised Cost of Energy (LCoE) forecast of €40/MWh [3], exceeding 2020 targets set by the industry of €100/MWh. Looking to the future, [4] predict ranges of €56.7-100.7/MWh by 2035. The goal is now to deploy larger turbines >10MW in new sites, often further offshore and in deeper waters utilising floating platform technologies. These sites often have a higher wind resource but more dynamic conditions also pose additional challenges, for example, accessing the site to complete maintenance. The development of new sites must be done while keeping costs down and finding further potential savings. Therefore, the estimated LCoE will remain closely watched, but how reliable is it? The wide range of LCoEs is indicative of the significant differences in how LCoE may be calculated e.g. what is included or excluded; variations in inputs between projects and across regions; and uncertainties in the assumptions that are generally based on forecasts and predictions.

LCoE works in fixed payment structure markets as a metric and is the most common Key Performance Indicator (KPI) used in energy cost assessments. It represents the present value of the total cost of electricity/energy over a project lifetime and is expressed as a single figure in terms of a cost per kWh or MWh. LCoE is used to determine the price required for a project to break even, recovering capital costs, and is a relatively simple way to assess a single project or compare multiple projects and technologies. It is widely used by academia and industry, often feeding into investment and policy

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decisions. [5] provide an overview of the different potential uses from cost comparisons of different technologies, time-series analysis of a specific technology, the determination of feed-in-tariffs, integration assessment modelling and grid-parity analysis. Specifically for offshore wind energy, [6] document key LCoE assessments that have been carried out by industry, governments, consultancy, and academic researchers in recent years. These have primarily focused on comparing technologies; financial assessment methodologies; cost reduction scenarios; or country-specific studies with site-specific constraints. There have also been several global-scale analyses by international organisations such as the IEA, IRENA and EWEA, which survey and analyse the cost differences between regions and technological developments. However, the use of LCoE as a comprehensive metric to address such a wide range of different perspectives is problematic. It must be implemented with an understanding of the potential issues and uncertainties in order to accurately calculate and use it effectively.

A number of studies have highlighted the limitations of using LCoE. [7] stress that LCoE values are highly location-specific, both because of regional cost differences as well as the varying strength of the resource, which affects energy output. [8] provide an overview of LCoE methodologies including a critical assessment and identifying key weaknesses of the metric including the discount rates applied; the treatment of inflation; and dealing with uncertainty in future costs. They also note that LCoE generally does not take into account system level effects, e.g. investment required in transmission and distribution grids. [6] highlights that most studies fail to explicitly deal with the cost of finance, which they demonstrate, has a significant impact on LCoE. [5] identify the limitations of using LCOE to determine if grid parity is achieved i.e. if it is marketable and no longer needs subsidies. They identify where studies have sought to extend traditional LCoE calculations to consider energy price rises and the impact of power purchase agreements to overcome these limitations e.g. [9] and [10]. [11] also identify some alternative methods to the traditional LCoE calculation to overcome different weaknesses but note that these are not much used. [12] provide a critique of the challenges including an overview of the different LCoE calculation approaches as well as some of the models currently available to calculate LCoE. [13] stress the demand to go "Beyond LCOE" and a one-size fits all metric but highlight the difficulty of achieving this considering the scope is large. Instead they advocate developing a toolset of standard and transparent metrics. This is a challenging task and this paper would argue that the first step is to fully de-mystify the LCoE calculation.

While many different formulas and critiques of the LCoE metric exist, there is not comprehensive documentation and demonstration of the different methods, identifying the potential pit-fills that can lead to errors and key areas of uncertainty that must be understood when reviewing results. This paper consolidates and expands on the existing literature, presenting a comprehensive set of LCoE methodologies considering the multiple possible perspectives and motivations for calculating the LCoE. It addresses the key variables and elements of uncertainty that must be understood to fully understand and accurately use this metric. These include the uncertainty of forecasted lifecycle costs and energy production; elements that may be site or region specific such as the tax rate or grid connection costs; and the financial assumptions applied such as the discount rate, loan repayment schedule etc. The paper presents a case study to demonstrate the different calculation options and undertakes sensitivity analysis to determine the impact of variations in key assumptions. A key objective is for this paper to serve as a reference document for future research to aid consistency in the calculation and interpretation of LCoE, particularly for those new to LCoE analysis.

Methods

Input variables and uncertainties

LCoE is generally used to forecast the viability of a project or compare multiple projects. However, estimating the costs and energy production required to determine the LCoE is a complex task requiring a large amount of data to produce a single figure. Figure 1 provides an overview of the key cost and revenues for an offshore wind farm across the lifecycle. This is not an exhaustive list and different LCoE estimates may include/exclude different elements. More extensive taxonomies and lists of potential costs

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can be found in [14], [15], [16] and [17] . It is essential to compare like-with-like when reviewing LCoE values, therefore; it is important to always interrogate what elements have been considered.

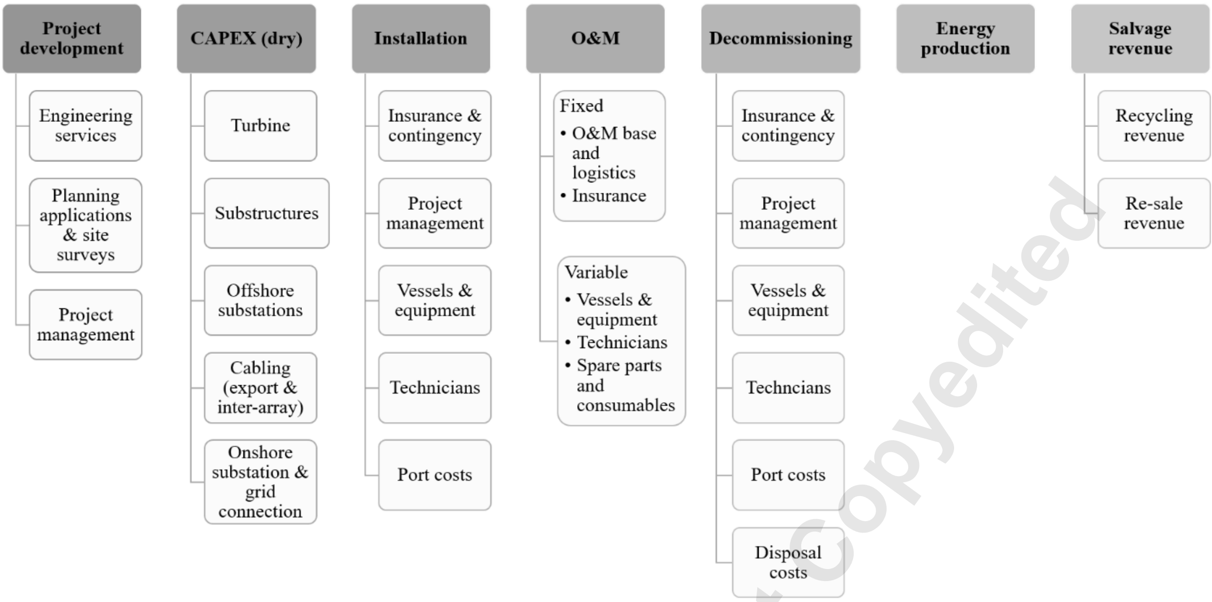

Figure 1 Breakdown of key costs and revenues for an offshore wind farm

The accuracy of an LCoE estimate will depend on the quality of the data available and whether it is based on real life information or forecast estimates. The IEA Wind TCP Task 26 has comprehensively covered country-specific costs of offshore wind energy and calculating resulting LCoEs [18] [19] [20]. However, [21] stress the difficulties of finding reliable data in each country due to its commercial value and sensitivity so costs are often estimated. Accurately estimating costs is a significant challenge particularly for academic researchers who will have limited access to information or ability to validate their assumptions or models used to calculated the LCoE. Even for industry, who will have insight into actual figures and data from existing sites, it will still be a challenge to forecast costs for a new site or new technology such as floating platforms. This is true even when a project is based on existing farms with the same distance from shore, water depth, technology etc. because costs are very project and site specific. Each site will have unique geotechnical requirements, determining the foundation type selected and/or their individual designs, which could vary within a single farm e.g. turbine tower lengths, impacting costs. Fluctuating costs of materials e.g. steel and labour are also difficult to predict. Costs are likely to fall as technologies mature over time and some studies may apply learning rates to account for this [6] [5]; however these are very difficult to predict and therefore add an additional level of uncertainty. Metocean conditions (particularly wave height and wind speed) will determine accessibility, impacting logistics and the associated costs of installing and maintaining the farm. Decommissioning costs are particularly uncertain given the lack of practical experience to date and uncertainty surrounding the recycling and disposal strategies for different materials [12]. Beyond the costs for installing and running an offshore wind farms, developers will have specific agreements with manufacturers and suppliers as well as different port, installation and O&M contracts etc., which could significantly impact costs. For example, they may receive a reduction in price based on the volume of turbines/foundations ordered from a manufacturer. [22] identify four principal methods developed to characterize future costs from wind power: expert elicitation; analysis and extrapolation of historical trends or learning rates; bottom-up engineering analysis; and analysis or replication of auction bids. However, they note that each of these methods has advantages and limitations that may influence the accuracy of cost projections.

The IEA task's international comparative analysis of offshore wind costs found that the anticipated energy production was the largest LCoE impact from country to country [23]. Each will depend on the

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inherent wind regime, site selection, technology used etc. [6] also stress the significant impact energy production predictions will have on LCoE. Generally, efficiency is determined based on an estimated capacity factor, the ratio of the expected energy output versus the maximum potential output over a given period of time. This may be calculated based on experience from other projects in similar sites or using historical Metocean data. [12] note that energy production estimations of wind energy production are heavily reliant on wind energy potential models used and that many do not adequately consider operational efficiencies e.g. downtime due to failures and maintenance. This can lead to overestimating energy yields, impacting LCoE estimates. In addition, energy yield usually changes over time due to degradation or deterioration of the assets [5]. Different studies will also consider different losses e.g. due to electrical array systems, [6]which would impact energy production estimates. However, determining the rate of degradation or transmission losses is an inherently uncertain factor which would rely on the availability of information and previous experience for accuracy.

The uncertainties in cost and energy production can be addressed to an extent by applying ranges rather than single figures [24]. Generally, LCoE analysis utilises deterministic models where costs and energy production are single inputs. These may range from high-level LCoE calculations to complex financial analysis cash flow spreadsheets e.g. model developed by the Energy Research Centre of the Netherlands (ECN), which has been used and adapted by the IEA task for their analysis [20]. [8], [11] and [25] advocate using probabilistic analysis to better account for the stochastic and/or uncertain nature of factors such as costs and energy. They propose applying the Monte Carlo simulation method, which generates random values and using probability distributions for factors with inherent variability. Considering a large sample of iterations e.g. 1,000-10,000, this method can produce a confidence interval or range of results rather than a single solution. The Monte Carlo simulation method is regularly used in models that focus on simulating operations and logistics of an offshore wind farm in detail over a Metocean time series to determine the power production and costs of O&M. However, few models also consider the installation and decommissioning phases in such detail or are integrated into a full lifecycle financial model that calculates LCoE. [12] provide an overview of existing models specific to Offshore Wind and [26] present the most comprehensive financial model in the existing literature developed by University College Cork and SINTEF Energy. This uses of a detailed discrete-event time-series Monte Carlo simulation methodology for the analysis of all three lifecycle phases (installation, O&M and decommissioning) and integrates the average results into a full financial assessment cash flow model that can calculate the LCoE, IRR and NPV of a project. This is used to determine figures for the case study presented in this paper.

In addition to uncertain in costs and energy production, which are site specific, other regional differences could significantly impact figures such as the tax system, policies and regulations; auction schemes and government incentives; and ownership of the seabed. For example, the exclusion of transmission costs in the Netherlands, Germany, Belgium and Denmark removes a substantial element of LCoE compared to the UK [27]. This is because the responsibility for grid connection in the UK lies with the developer whereas costs reside with the Transmission System Operator in other regions creating variations in cost estimates [12]. This difference is illustrated in the UK weighted average Contract for Difference (CfD) auction strike price of £62.14/MWh (€70.88/ MWh) for projects commencing in 2021/22, and £57.50/MWh (€65.59/MWh) for projects commencing in 2022/23 versus the lower Danish and Dutch wind farms prices of €63.90/MWh and €54.50/MWh, respectively [6]. Where offshore grid connection costs are included, it should be noted that these are often uncertain and difficult to predict [21].

It should be noted that while the LCoE calculation is an important consideration for determining the strike price, they are not the same. The LCoE is the amount the generator must earn for each megawatt hour produced over the full life of the assets, to cover its capital and operating costs and its cost of capital [27]. The strike price is the revenue sought by the developer for a period of time (for example 15-20 years) depending on the auction scheme. After this, revenue comes from the open market. Therefore, the price is based on future market price predictions and the bidder's approach to risk and competition [14]. It may be tempting to derive one from the other [21], this can be dangerous as strike prices may be significantly lower than LCoE. They are set by experienced industry players, assuming future prices and optimisation in technology and processes. They are also dependent on auction

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specifications, local regulations etc. [21] caution if the industry is going through a shakeout period, investors may bid below cost to deter new entrants from providing competition, accepting short-term losses in return for gaining market share and higher long-term profits. [28] assert that the design of CFD auctions may increase the probability of speculative bidding. However, although it may be misleading to derive one from the other, the strike prices and LCoE estimates may often impact each other. [29] provides a comprehensive analysis of the effects auctions may have on the financing conditions for renewable energy projects. They demonstrate how the impacts on financing conditions could be either positive or negative e.g. competitive pressure may force project owners/equity investors to accept lower profit margins but auction procedures can also result in higher risks and increase premiums. Finance costs are a significant portion of the LCoE [19]; therefore, the financing conditions created by different auction designs will impact LCoE estimates. [12] and [30] provide further examination of the different auction and subsidy schemes and their impact on LCoE estimates and strike price bids.

LCoE calculation methods

Existing studies utilise a wide range of LCoE methodologies. [31] summarise the different calculations that may or may not include e.g. actual cash flow analysis or formulas adapted to consider cash flow calculations; physical depreciation or the use of tax depreciation; policy incentives; and the detailed financial structure of a project. [23] note the potential impact the perspective taken may have on the LCoE calculation method selected. For example, a simplified high-level planning approach to facilitate comparison amongst technologies versus a more sophisticated discounted cash flow approach taken by a private investor. [22] also stress the important impact the perspective taken when making the calculation will have on the method selected. Therefore, it is important to understand the motivation and consequently, what has been included or excluded in the final LCoE figure. This section aims to provide an overview of LCoE calculations most commonly considered in order to present a comprehensive, consistent methodology that can be replicated for LCoE analysis. These equations have been derived from those most commonly found in the existing literature including [20], [18], [23] [11], [6], [8], [12], [22]. Table 1 provides a list of the abbreviations used in equations 1-8.

Table 1 Equation abbreviations

d	year in post-project decommissioning	**E**	Energy produced
f	post-project duration i.e. decommissioning	**ETR**	Effective Tax Rate
k	year in project lifetime	**I**	Investment costs
n	project lifetime	**INT**	Interest payment
r	discount rate	**IRR**	Internal Rate of Return
rNominal	Nominal discount rates	**LCoE**	Levelised Cost of Energy
rReal	Real discount rate	**LP**	Loan Payment
A	Annual costs	**NPV**	Net Present Value
C	Cash flow	**R**	Revenue
CF	Capital allowances Factor	**S**	Salvage revenue
CoD	Cost of Debt	**TP**	Taxable Profit
CoE	Cost of Equity	**TR**	Tax Rate
D	Decommissioning costs	**WACC**	Weighted Average Cost of Capital
DR	Degradation Rate		

The simplest LCoE calculation may be represented as follows:

Equation 1

$$LCoE = \frac{\sum_{k=1}^{n} \frac{I^k + A^k}{(1+r)^k}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}}$$

Equation 1 is the most common method used and essentially considers the total lifetime costs (using a pre-tax project cash flow) divided by the total energy produced. These are discounted to determine the Net Present Value (NPV) by a discount rate. The rate is selected by the user based on a number of

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criteria that will discussed in the next section. [18] notes that decommissioning costs may be neglected or, to the extent that funds are set aside at project initiation, included in the initial capital investment. Some LCoE estimates may include this under the Investment costs (I) or Annual costs (A) variable, and then not explicitly state whether or how decommissioning has been taken into account, allowing for uncertainty as to what is included in the final result. For greater transparency, Equation 2 includes decommissioning costs, offset by salvage revenue following the conclusion of the project.

Equation 2

$$LCoE = \frac{I + \sum_{k=1}^{n} \frac{A^k}{(1+r)^k} + \sum_{d=n+1}^{f} \frac{(D^d - S^d)}{(1+r)^d}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}}$$

The above simple LCoE methods may be useful to compare different technologies from a high-level perspective, but they do not provide insight into the financial structure of a project. More detail is required for investors to more accurately consider a project's viability [24]. To achieve this, LCoE could consider an equity cash flow. This includes project financing in terms of how much of the initial investment comes from equity and debt, resulting in the inclusion of loan and interest repayments in the LCoE calculation (equation 3).

Equation 3

$$LCoE = \frac{I + \sum_{k=1}^{n} \frac{LP}{(1+r)^k} + \sum_{k=1}^{n} \frac{INT}{(1+r)^k}) + \sum_{k=1}^{n} \frac{A^k}{(1+r)^k} + \sum_{d=n+1}^{f} \frac{(D^d - S^d)}{(1+r)^d}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}}$$

Some LCoE may include tax. In this case they would usually also consider a capital allowance or depreciation rate since depreciation on a capital investment is tax deductible [18]. A company can claim capital allowances on certain types of capital expenditure such as business assets. This essentially allows companies to write off qualifying expenditure against its profits over a certain period, reducing tax. Equation 4 summarises how the Taxable Profit (TP) is determined, implementing this calculation in equation 4.1, which demonstrates a post-tax scenario using the project cash flow from equation 2.

Equation 4

$$TP = \sum_{k=1}^{n} \frac{R^k - A^k - CF^k}{(1+r)^k}$$

Equation 4.1

$$LCoE = \frac{I + \sum_{k=1}^{n} \frac{A^k}{(1+r)^k} + (\sum_{k=1}^{n} TP * TR) + \sum_{d=n+1}^{f} \frac{(D^d - S^d)}{(1+r)^d}}{\sum_{k=1}^{n} \frac{E^k}{(1+r)^k}}$$

Different tax regimes may also include other elements e.g. tax credits for renewable sources e.g. the US Investment Tax Credit (ITC) and Production Tax Credit (PTC). These reflect a dollar-for-dollar subsidy that is deducted from the income taxes otherwise owed by the investor. [32] have introduced a tax factor into their LCoE calculation method to account for these additional parameters.

It should be noted that where losses rather than profits occur, these may be fully utilised essentially as a tax credit in a given period or accumulated and utilised in future tax periods during the project (tax losses carried forward). They can also be offset against other projects in a portfolio or limited to a single project. This means that the tax paid may vary between projects depending on when/how the project owner utilises their losses. This could be modelled considering an Effective Tax Rate (ETR) determined

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based on project utilisation of losses across the post-tax project cash flow. This represents the actual tax percentage paid on taxable profit versus the marginal rate. This is represented in equation 4.2.

Equation 4.2

$$ETR = 1 - \left(\frac{Post - tax\ IRR}{Pre - tax\ IRR}\right)$$

Equation 5 illustrates a post-tax scenario where project financing is considered (e.g. equation 3 equity cash flow) resulting in the inclusion of loan and interest repayments. It should be noted that interest repayments are deductible from the taxable income.

Equation 5

$$LCoE = \frac{I + \sum_{k=1}^{n}\frac{LP}{(1+r)^k} + \sum_{k=1}^{n}\frac{INT}{(1+r)^k}) + \sum_{k=1}^{n}\frac{A^k}{(1+r)^k} + (\sum_{k=1}^{n}\frac{R^k - A^k - CF^k - INT^k}{(1+r)^k} * TR) + \sum_{d=n+1}^{f}\frac{(D^d - S^d)}{(1+r)^d}}{\sum_{k=1}^{n}\frac{E^k}{(1+r)^k}}$$

The final LCoE example (equation 6) illustrates the use of a Degradation Rate (DR). This is used to represent the deterioration of an asset in terms of energy production as hardware degrades over time, thereby reducing efficiency.

Equation 6

$$LCoE = \frac{\sum_{k=1}^{n}\frac{I^k + A^k}{(1+r)^k}}{\sum_{k=1}^{n}\frac{E^k * DR^k}{(1+r)^k}}$$

The DR is calculated as E * (1-% annual degradation)$^{k-1}$ [5]. However, degradation may be implicitly considered when determining energy production, depending on the model used to calculate this figure. For example, an O&M simulation model may simulate increasing failure rates to factor in degradation over time. Therefore, it is important to know the full methodology used to find the values themselves as well as details of the elements included or excluded in the final LCoE equation.
It is vital that elements included and the calculation method applied are clearly stated when reviewing results, in order to determine the value of the LCoE estimate and/or to compare it with calculated values from other projects. This section is not an exhaustive list of LCoE equations that have been used; rather equations 1-6 provide a set of core methodologies that are fully documented that can be used as a reference for future research. The following case study demonstrates the application of these methodologies to facilitate replication. An Irish site has been selected as the offshore wind industry is in its infancy with just 1 farm operational to date (the Arklow Bank Wind Farm).

Financial assumptions

When reviewing LCoE values, it is important to acknowledge that the financial inputs can significantly impact the final result. Key factors include the discount rate; debt: equity ratios; loan duration and administration charges; tax rates and allowances. These elements are highly dependent on the project owners, the type of investors, and the level of risk they are willing to take in a project; prevailing market rates (e.g. debt rates); and on regional factors, which will determine elements such as tax regulations [22]. This section reviews the potential issues when selecting the business case and financial inputs for the LCoE calculation.

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The discount rate is applied to estimate the present value of future cash flows. [9] define it as the figure chosen to reflect the risk-adjusted opportunity-cost of capital and is considered the return on investment required. [8] note that the choice of an appropriate discount rate has long been contentious in many areas of financial analysis as it can have a significant impact on the LCoE result. The rate chosen is extremely dependant on a number of assumptions that are often subjective and audience dependant. [5] describe the discount rate as an individual value that usually differs from one investor to the other, depending on the level of risk they are willing to take.

The discount rate is generally selected based on the Weighted Average Cost of Capital (WACC) or the Internal Rate of Return (IRR). While these two elements may be similar, they serve different perspectives and involve different calculations. The WACC is the weighted average cost a company will pay to finance its assets including both debt and equity stakeholders. It is determined based on the Cost of Debt (CoD) and Cost of Equity (CoE) and the Debt:Equity ratio assumed for the project (Equation 7). The CoE represents the compensation required by shareholders for bearing the risk of owning the asset. The CoD is the rate a company pays on its debt e.g. interest rate.

Equation 7

$$\mathrm{WACC} = (\mathrm{CoD} * \%\ \text{of debt}) + (\mathrm{CoE} * \%\ \text{of equity})$$

The cost of debt and equity as well as the assumed ratio is very specific to each project as well as regional conditions and is often a very uncertain factor, particularly when considering unknown sites and technologies. [7] summarise key reasons why the WACC will vary widely between countries including elements such as scarcity of capital, governmental policies, lack of access to (cheap) capital, risk perceptions of financial institutions, macro-economic parameters such as the inflation rate and demand for credit. Given the complexity of the factors underlying this decision and where there is a lack of project-specific data, [7] suggest selecting a WACC representative of the relevant country based on the "Guidelines on the Assessment of Investment Analysis" developed by the Clean Development Mechanism's Executive Board.[1] Using this source, their paper details the cost of equity and debt capital, the weighted average cost of capital as well as residential electricity prices for solar energy for 143 countries. [19] provide an overview of the cost of debt and equity as well as the tax background for a range of countries specifically considering offshore wind technology based on 2017 figures. It should be noted that since the cost of financing is implicit in the WACC rate, this is simply applied as the discount rate to the project cash flow without considering project financing.

In general, the CoD is cheaper than the CoE, because the risk to shareholders is higher than for banks, since the repayment of debt is required by law. Therefore, the equity return required will be higher to ensure a project is worth the investment. This general results in projects with higher percentage CoD in the debt:equity ratio. However, debt will become more expensive or be more difficult to access at a higher proportion where projects utilise novel technologies; are located in countries where offshore wind is an emerging market; or in countries with less stable economies. These scenarios increase the risk to banks, resulting in higher interest rates and loan charges.

The IRR is the discount rate at which the project has an NPV of zero (equation 8). While the WACC may be considered in the IRR calculation, it represents the cost of financing. The IRR is generally used to make an investment decision and companies will want a higher IRR than the WACC. A simple project IRR may be used to determine the rate of return from the whole project, not including financing and irrespective of the debt:equity ratio. This is a type of yield rate expected from the project investment overall [11] and may be useful for a project developer with a central treasury function to prioritise the best opportunities in a portfolio. However, if the LCoE is to provide the basis for an investment an equity IRR should be utilised with an equity cash flow that considers project financing including loan repayments etc. This gives the rate of return earned by the equity shareholder on the money they invest.

[1] The Clean Development Mechanism Executive Board (CDM EB) supervises the Kyoto Protocol's clean development mechanism. Website: https://cdm.unfccc.int/.

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[11] describes equity IRR is the leveraged version of Project IRR and that shareholders give more weight to Equity IRR rather than Project IRR because it is related directly to the shareholders' profit.

Equation 8

$$0 = \sum_{k=0}^{n} \frac{C_k}{(1 + IRR)^k}$$

A key assumption that must be identified when reviewing any LCoE calculation is the treatment of inflation. LCoE can be expressed in real or nominal terms. [22] quote the NREL definition of real and nominal LCoE explaining that a real LCOE yields a constant dollar, inflation-adjusted value while nominal LCOE reflects a current dollar value. [33] explains that a real cost can be compared to things like the cost of your electricity bill per kWh or the cost of nature gas. Using a nominal LCoE, you are in a sense looking at the price in the middle of the project life. Therefore, you would be comparing your electric bill in 10 or 15 years. Generally, analysis favours looking at the real costs but it is important to determine whether you are looking at a real or nominal LCoE when reviewing and comparing estimates as they express different values and are used for different purposes. It should be noted that this paper quotes all figures in real terms i.e. already adjusted for inflation, unless otherwise specified.

[8] assert that the handling of inflation is a key weakness of the LCoE metric and the calculation methods is an area where mistakes could easily be made e.g. where it is not clear whether a discount rate is real or nominal and is applied to the incorrect cash flow. The methodologies can be summarised as follows:

1) Real LCoE is determined by applying an inflation-adjusted discount rate to a cash flow of real costs that do not contain the effects of inflation.
2) Nominal LCoE is determined by applying a nominal discount rate to an inflation adjusted cash flow.

It is expected that the nominal discount rate and resulting LCoE will be higher than the real discount rate and resulting LCoE, although using the correct methods should result in the same NPV of the cash flow. A real discount rate can be derived from a nominal rate and vice versa using the following formula in equations 9 and 10:

Equation 9

$$\text{rReal} = [(1 + \text{rNominal})/(1 + \text{inflation rate})] - 1$$

Equation 10

$$\text{rNominal} = [(1 + \text{rReal}) * (1 + \text{inflation rate})] - 1$$

Applications of these formula can be found in [18] and [8] as well as in the case study section below.

Case study

This section details a case study was developed as part of the SFI funded EirWind project to assess the LCoE for fixed offshore wind farms in the Irish Sea. The core LCoE methodologies will be applied to this case study to demonstrate their application. The following section will undertake sensitivity analysis on key variables and uncertain elements within the inputs e.g. discount rate, loan repayment period and administration fees, tax rate and tax depreciation schedule, costs (CAPEX, OPEX and decommissioning), energy production and the treatment of inflation.

It should be noted that this study is theoretical and not based on any current or proposed wind farm. However, it is intended to be representative of potential offshore wind farms given the general characteristics at this location. The scenario comprises 41 12MW turbines with XL Monopile foundations. It was simulated using the LEANWIND Financial Model as outlined in [26] to determine power production and costs. Results were determined using a simple LCoE calculation method based on equation 2 of this paper and are labelled as CS1.0 in Table 2. This is detailed in [34].

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Table 2 Results

Case study reference	*Number*	1.0
Site	*Text*	Irish Sea
Turbine	*MW*	12
Substructure	*Text*	XL Monopile
Number of turbines	*Number*	41
Farm capacity	*MW*	492
Farm lifecycle	*Years*	25
Start	*Year*	2025
Discount rate	*%*	5
LCoE	*€/MWh*	**58.43**
DEVEX	€/MW	269,684
CAPEX (dry)	*€/MW*	*1,810,422*
Installation	*€/MW*	*473,391*
CAPEX (dry & installation)	*€/MW*	2,283,813
OPEX (undiscounted)	*€/MW/year*	94,888
Energy production	*MWh*	58,735,908
DECEX	*€/MW*	214,367
Salvage revenue	*€/MW*	58,615
Availability (energy-based)	*%*	96.94%
Net Capacity Factor	*%*	55%

It should be noted that the LCoE calculation does not consider debt and equity, loan repayments or tax. The discount rate of 5% was selected based on the pre-tax project IRR. This is in line with the estimated rate of 6.5% for fixed offshore wind in Ireland according to a 2017 Renewable Energy survey launched to gauge investors' perception of cost of capital [35]. The rate reduction (-1.5%) assumes there would be a decrease given increased market maturity by 2025 (project start date).
Based on the above case study costs and power production figures, this paper applies the range of LCoE methodologies outlined in equations 2-5. Where relevant, a corporate tax rate of 12.5% was applied with an accelerated capital allowance rate where 100% of capital expenditure is claimed the first year of use, in line with Irish regulations for renewable energy projects. The scenarios considered and their respective results are outlined in Table 3.

Analysis shows that the LCoE converged towards a similar result for the WACC and IRR calculations respectively. This is to be expected, provided the correct discount rate is applied to the cash flows and validates the LCoE methodologies presented in this paper. To explain this process in further detail, the discount rates were determined by firstly deriving the pre-tax WAAC. The WACC scenario (assuming a 70:30 debt equity ratio with a CoD and CoE of 2.6% and 6.4% respectively) was determined based on [7] and adjusted to a CoE of 6.97% based on additional equity IRR cash flow analysis outline below. A pre-tax WACC of 3.7% and a post-tax WACC of 3.54% was applied to the project cash flow without considering financing and resulted in LCoEs of €54.52/MWh and €54.77/MWh respectively.

As previously explained, an IRR will generally be higher than the WACC as this is generally used to make an investment decision and requiring something of a buffer in addition to covering the costs of financing. The WACC implies that the original EirWind case-study project IRR of 5% is a reasonable assumption and the LCoE of €58.43 results in an NPV of zero. The inclusion of tax along with the estimated revenue of €58.43 (LCoE based on the pre-tax IRR) in the cash flow resulted in a post-tax IRR of 4.61%. Pre and post-tax equity cash flows considered loan and interest repayments over a 15-year period and loan administration charges of 2.5%. These determined a pre and post-tax equity IRR of 6.97% and 6.48% respectively.

The case study indicates a significant difference between LCoE using a WACC discount rate versus where project and equity IRR are applied. The LCoE determined using the pre-tax WACC looks to be

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under-stated by 6.7% if you were assessing the project from an investor perspective. This demonstrates the importance of understanding and selecting the most appropriate method for a given purpose.

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Table 3 Case study LCoE methods and results

LCOE equation	Discount rate (%)	Discount rate method	Debt:Equity ratio	CoD (%)	CoE (%)	Loan administration charges	Repayment period (years)	Tax rate (%)	Capital allowance rate (%)	LCoE (€/MWh)
2	3.91	Pre-tax WACC	70:30	2.6	6.97					54.52
4.1	3.54	Post-tax WACC*	70:30	2.6	6.97			12.5	12.5	54.77
2	5	Pre-tax project IRR								58.43
4.1	4.61	Post-tax project IRR*						12.5	12.5	58.43
3	6.97	Pre-tax equity IRR	70:30	2.6		2.5	15			58.43
5	6.48	Post-tax equity IRR*	70:30	2.6		2.5	15	12.5	12.5	58.43

*In the current case study tax is assumed to be limited to the project and tax losses are carried forward resulting in an ETR of 7.01% for the Post-tax equity cash flow and 7.75% for the post-tax project cash flow. The ETR is calculated using equation 4.2.

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Sensitivity analysis

To remain concise, this section undertakes sensitivity analysis on key variables using the pre-tax WACC and post-tax equity IRR calculations as relevant, rather than applying them to all LCoE methods introduced.

Discount rate

It should be noted that the financial structure contains a number of assumptions that are based on previous case studies in the literature e.g. the debt-equity ratio applied in [27]. Other potential variations will be further examined in sensitivity analysis. This includes varying the cost of debt and equity % assumed in the WACC calculation and the impact of increasing and decreasing the discount rate on the LCoE. Results are presented in Table 4 and show the impact a higher WACC has on the LCoE.

Table 4 Sensitivity analysis – Cost of Debt and Equity

Debt:Equity ratio	**70:30**	**70:30**	**70:30**
Cost of equity	6.97%	10.0%	12.0%
Cost of debt	2.6%	3.0%	5.0%
Pre-tax WACC	**3.9%**	**5.1%**	**7.1%**
LCOE (€/MWh)	**54.52**	**58.81**	**66.61**
% Difference	Base case	**7.9%**	**22.2%**

Furthermore, the Debt:Equity ratio assumed will impact the discount rate and the resulting LCoE as illustrated in Table 5 using the pre-tax WACC as the base case scenario.

Table 5 Sensitivity analysis – Debt:Equity ratio

Debt:Equity ratio	**70:30**	**60:40**	**50:50**
Cost of equity	6.97%	6.97%	6.97%
Cost of debt	2.6%	2.6%	2.6%
Pre-tax WACC	**3.9%**	**4.1%**	**4.3%**
LCOE (€/MWh)	**54.52**	**55.33**	**56.02**
% difference	Base case	**1.5%**	**2.8%**

Loan repayment period and administration charges

Other key assumptions in the business case include the loan repayment period and administration charges. The loan repayment period assumed for the case study was 15 years. However, Table 6 illustrates the potential reduction in LCoE where this is extended to 20 years and the corresponding increase in LCoE where this is reduced to 10 years. This is due to the impact of discounting and the reduced value of the debt over a longer period.

Table 6 Sensitivity analysis – Loan repayment period

Repayment period	**15**	**20**	**10**
Post-tax equity IRR	6.48%	6.48%	6.48%
LCOE (€/MWh)	**58.43**	**56.72**	**60.43**
% difference	Base case	**-2.9%**	**3.4%**

However, the length of the loan period may also impact the discount rate assumed. [11] suggests that investors usually prefer a shorter period and reduced risk result in lower IRRs while longer ones induce higher risk and higher IRRs. This means that the reduction of loan period could increase profitability and reduce LCoE.

Loan administration charges are likely to vary less in magnitude, with 2.5% applied in the base case and a sensitivity study increasing this to 3.5%. Therefore, they will have a smaller impact (<1%) on the

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LCoE as illustrated in Table 7. However, the uncertainty of this assumption could still have an effect that should be considered when reviewing results and it is important to know whether this has or has not been included in the calculation.

Table 7 Sensitivity analysis – Loan administration charges

Loan admin charges	2.50%	3%	3.50%
Post-tax equity IRR	6.48%	6.48%	6.48%
LCOE (€/MWh)	**58.43**	**58.55**	**58.66**
% difference	Base case	0.3%	0.5%

Tax rate and tax depreciation period

It may be noted that corporate income taxes are generally higher in other countries ranging from 20% in the United Kingdom to 35% in the United States [27]. Therefore, sensitivity analysis was undertaken to examine the impact of a higher tax rate on LCoE. Results are presented in Table 8 and indicate the expected impact on the LCoE and ETR.

Table 8 Sensitivity analysis – Tax rate

Tax rate	12.50%	20%	35%
Post-tax equity IRR	6.48%	6.48%	6.48%
LCOE (€/MWh)	**58.43**	**58.96**	**60.03**
% difference	Base case	0.9%	2.7%
ETR	**7.01%**	**11.6%**	**21.7%**

In addition, the accelerated capital allowance schedule applied to the base case (100% in the first year) has also been varied to consider the standard capital allowance schedule in Ireland (12.5% for 8 years), to indicate the impact of this assumption on the LCoE and ETR. This in more in line with depreciation schedules in other countries e.g. the five-year Modified Accelerated Depreciation Schedule in the United States to the 16-year linear depreciation schedule in Germany [27]. Results presented in Table 9 demonstrate the advantage the Irish accelerated scheme may afford renewable energy projects and the impact country/regional specific tax regimes may have on the LCoE estimate.

Table 9 Sensitivity analysis – capital allowance rate and tax depreciation schedule

Tax rate	12.50%	12.5%
Capital allowance rate	**100.00%**	**12.5%**
Tax depreciation period	**1**	**8**
Post-tax equity IRR	6.48%	6.48%
LCOE (€/MWh)	**58.43**	**59.21**
% difference	Base case	1.3%
ETR %	**7.01%**	**13.6%**

Costs

Cost inputs are based on predictions and information available in the current literature. They will have a significant impact on the calculated LCoE as outlined by [19]. The magnitude of impact has been demonstrated for this case study using the pre-tax WACC rate (3.91%) and project cash flows, increasing and decreasing CAPEX, OPEX and decommissioning costs by 10%. Results are illustrated in Figure 2 and Table 10-Table 12.

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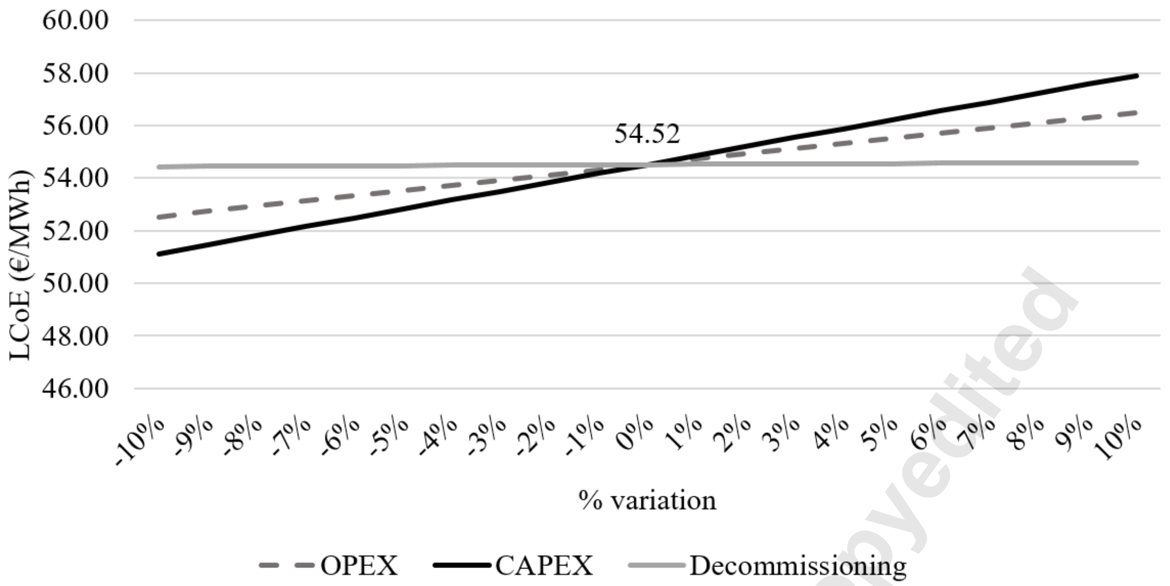

Figure 2 Impact of varying costs on LCoE (€/MWh)

Table 10 Impact of varying CAPEX cost on LCoE (€/MWh)

% variation in CAPEX cost	LCoE	% increase/decrease
-10%	51.13%	-6.22%
0%	**54.52**	0%
10%	57.91%	+6.21%

Table 11 Impact of varying OPEX cost on LCoE (€/MWh)

% variation in OPEX cost	LCoE	% increase/decrease
-10%	52.53	-3.64%
0%	**54.52**	0%
10%	56.50	+3.64%

Table 12 Impact of varying decommissioning cost on LCoE (€/MWh)

% variation in Decommissioning cost	LCoE	% increase/decrease
-10%	54.44	- 0.15%
0%	**54.52**	0%
10%	54.60	+ 0.14%

Results demonstrate that CAPEX costs will have the most significant impact although variations in OPEX are also meaningful. Decommissioning costs have quite a minor impact; however, it is important to note that very little is known about the actual costs of decommissioning so further validation of the figure assumed would increase confidence in this conclusion.

Energy

Sensitivity analysis was undertaken applying a degradation rate, calculated using equation 6, and varying the assumed capacity factor to consider the impact of these assumptions on energy production and the subsequent LCoE. As with the cost analysis, this uses the pre-tax real WACC rate (3.91%) on project cash flows. Results are summarised in Table 13 and Table 14 respectively.

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Table 13 Impact of implementing a degradation rate on energy production and LCoE.

Degradation rate	Energy production (GWh)	Discounted energy	% decrease in energy production	% decrease in discounted energy	LCoE (€/MWh)	% increase in LCoE
0%	58,776	37,078	0%	0%	€54.52	0%
0.10%	58,076	36,709	-1.19%	-1.00%	€55.07	1.01%
0.20%	57,387	36,344	-2.36%	-1.98%	€55.62	2.02%
0.30%	56,708	35,985	-3.52%	-2.95%	€56.18	3.04%
0.40%	56,040	35,631	-4.65%	-3.90%	€56.73	4.05%
0.50%	55,381	35,281	-5.78%	-4.85%	€57.30	5.10%

Table 14 Impact of varying Capacity Factor on LCoE

Variation in Capacity factor	Capacity factor	LCoE (€/MWh)	% increase/decrease in LCoE
-10%	49.06%	€ 60.58	11.11%
0%	54.51%	€ 54.52	0%
10%	59.96%	€ 49.56	-9.09%

Analysis demonstrates the significant impact considering a degradation rate could have on the assumed energy production and resulting LCoE but the most important consideration should be to determine an accurate capacity factor when modelling a project as an error of 10% results in a substantial increase and decrease in the LCoE.

Based on all the sensitivity analysis undertaken, energy production and the discount rate assumed appear to have the most significant impact on LCoE, followed by CAPEX costs. This conclusion is in line with conclusions from similar sensitivity analysis in the current literature including [6]. However, various other elements including variation of OPEX costs and loan repayment period are not inconsequential and combined, variations in all financial assumptions could produce a sizable difference in LCoE.

Due to their significant potential impact on results, these are the key variables and areas of uncertainty that require considered and validated inputs to ensure the most accurate LCoE estimate. In addition, analysis suggests that LCoE could be reduced by optimising energy production, reducing CAPEX and OPEX costs and determining the most efficient business case possible within regional and site-specific requirements. For example, wind farm operators should focus on improving availability, turbine reliability and optimising O&M strategies to maximise energy outputs.

Nominal LCoE

While this study as focused on calculating real LCoE it is also useful demonstrate the nominal calculation and review the potential impact of the inflation rate assumed. To this end, the Real pre and post-tax WACC rates were converted to nominal values using equation 10 assuming an inflation rate of 2%. This resulted in a pre and post-tax nominal WACC of 5.99% and 5.61%. These were applied to a nominal cash flow (real costs, adjusted for inflation at 2% per year). Results are summarised Table 15 and are in line with expectations previously discussed i.e. that the nominal LCoE will be higher than the real LCoE.

Table 15 Comparison of real and nominal LCoE

	WACC	LCoE (€/MWh)
Pre-tax real	3.91%	54.52
Post-tax real	3.54%	54.77
Pre-tax nominal	5.99%	66.69

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Post-tax nominal	5.61%	67.53

Using the pre-tax nominal WACC of 5.99%, the inflation rate was varied to consider the potential impact of uncertainty on results. Table 16 demonstrates that the impact would be substantial and therefore, the assumed inflation rate must be carefully considered.

Table 16 Impact of varying inflation rate on nominal LCoE

Inflation rate	Nominal LCoE (€/MWh)	% increase/decrease
3%	73.15	9.69%
2.80%	71.84	7.72%
2.60%	70.54	5.77%
2.40%	69.25	3.83%
2.20%	67.96	1.91%
2%	**66.69**	**0.00%**
1.80%	65.43	-1.90%
1.60%	64.17	-3.78%
1.40%	62.93	-5.64%
1.20%	61.69	-7.49%
1%	60.47	-9.33%

Conclusion

The LCoE can be a complicated calculation, depending on the level of detail involved; how clearly the inputs are defined; and for what/ by whom it is being calculated. There are a lot of uncertainties involved as inputs are generally based on forecast predictions including the costs, energy production and financial assumptions used to model the discount rate and financial structure of a project. Regional differences could significantly impact figures such as the tax system, policies and regulations; auction schemes and government incentives; and ownership of the seabed. LCoE is commonly used in preparing policy and investment decisions as well as comparing different projects (sites and technologies). Therefore, it is vital to ensure a clear and consistent calculation method is used to facilitate accurate estimates and realistic comparisons of like-with-like.

This paper provides a comprehensive overview of the potential variations and uncertainties in the LCoE calculation that must be understood in order to effectively use or review the metric. It then documents a series of LCoE calculation methodologies derived from the current literature, identifying what is included/excluded and their suitability in different circumstances. The paper further interrogates key financial assumptions, particularly the appropriate selection of the discount rate, as this will have a significant impact on all LCoE methods. A case study demonstrates the core methodologies, and provides a clear and transparent reference for replication and extension in future research.

The case study indicates there may be a significant difference between the LCoE determine using the WACC as the discount rate versus where the project and equity IRR are applied. This reinforces the importance of understanding and selecting the most appropriate method for a given purpose e.g. choosing a WACC to simply determine the cost of financing to assess and compare projects and technologies or whether a higher internal rate of return is needed to cover the cost of financing for an investment decision. The paper also shows the potential impact of key uncertain assumptions on results, applying sensitivity analysis to a number of elements including:

- the discount rate, varying the WACC based on different cost of debt and equity assumptions as well as a range of debt: equity ratios;
- the loan repayment period and administration charges;
- tax rates and depreciation schedules;
- cost assumptions including CAPEX, OPEX and decommissioning costs;
- the energy production calculated, applying a degradation rate and varying the capacity factor;

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- considering the treatment of inflation by demonstrating the difference between a real and nominal LCoE as well as varying the assumed inflation rate to consider its potential impact

Results indicate that the energy production and discount rate applied will have the most significant impact on LCoE, followed by CAPEX costs. However, various other elements including variation of OPEX costs and loan repayment period are not inconsequential and combined, variations in all financial assumptions could produce a sizable difference in LCoE. Therefore, these variables are key inputs that must be validated wherever possible to ensure an accurate estimate, and can be considered a focus for optimisation to reduce the LCoE.

This paper tackles the challenge of providing a comprehensive documentation and analysis to fully de-mystify the LCoE calculation to promote its correct and consistent use for the wide range of perspectives that can be taken and motivations. However, future work could focus on the demand to go “Beyond LCOE” outlined in [13], developing a toolset of standard and transparent metrics to address a wider range of issues and added value beyond the financial assessment of a project.

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References

[1] ETIP Wind, “Roadmap,” 2020.

[2] Wind Europe, “Our energy, our future,” 2019.

[3] WindEnergyUpdate, “Europe’s new record offshore LCOE forecast at 40 euros/MWh,” *WindEnergyUpdate,* 2016.

[4] Fraunhofer, “Levelised Cost of Energy - Renewable Energy Technologies,” Fraunhofer, Freiburg, 2018.

[5] U. Nissen and N. Harfst, “Shortcomings of the traditional “levelized cost of energy” [LCOE] for the determination of grid parity,” *Energy,* vol. 171, pp. 1009-1016, 2019.

[6] J. Bosch, I. Staffell and A. D. Hawkes, “Global levelised cost of electricity from offshore wind,” *Energy,* vol. 189, no. 116357, 2019.

[7] J. Ondraczek, N. Komendantova and A. Pratt, “WACC the dog: The effect of financing costs on the levelized cost of solar PV power,” *Renewable Energy,* vol. 75, pp. 888-898, 2015.

[8] J. Aldersey-Williams and T.Rubert, “Levelised cost of energy – A theoretical justification and critical assessment,” *Energy Policy,* vol. 124, pp. 169-179, 2019.

[9] A. Levitt, W. Kempton, A. Smith, W. Musial and J. Firestone, “Pricing offshore wind power,” *Energy Policy,* vol. 39, p. 6408–21, 2011.

[10] M. Bruck, P. Sandborn and N. Goudarzi, “A levelized cost of energy (LCOE) model for wind farms that include power purchase agreements (PPAs),,” *Renewable Energy,* vol. 122, pp. 131-139, 2018.

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Accepted manuscript posted August 31, 2021. doi:10.1115/1.4052269

[11] S. Sung and W. Jung, “Economic Competitiveness Evaluation of the Energy Sources: Comparison between a Financial Model and Levelized Cost of Electricity Analysis,” *Energies,* vol. 12, p. 4101, 2019.

[12] B. Johnston, A. Foley, J. Doran and T. LIttler, “Levelised cost of energy, a challenge for offshore wind,” *Renewable Energy,* vol. 160, pp. 876-885, 2020.

[13] K. Dykes, L. Kitzing, M. Andersson, C. Pons-Seres de Brauwer and H. Canét, “Beyond LCOE: New assessment criteria for evaluating Wind Energy R&I,” SETWind, 2020.

[14] BVG Associates, “CATAPULT - Wind farm costs,” 2019. [Online]. Available: https://guidetoanoffshorewindfarm.com/wind-farm-costs. [Accessed 16 03 2020].

[15] IRENA, “Renewable Power Generation Costs 2019,” International Renewable Energy Agency, 2020.

[16] T. Stehly, P. Beiter and a. P. Duffy., “2019 Cost of Wind Energy Review,” NREL, 2020.

[17] IRPwind, “Comprehensive taxonomy supporting open data for wind energy,” 2021. [Online]. Available: https://www.irpwind.eu/knowledge-transfer/comprehensive-taxonomy-supporting-open-data-for-wind-energy.

[18] M. Hand (e.d), “IEA Wind TCP Task 26–Wind Technology, Cost, and Performance Trends in Denmark, Germany, Ireland, Norway, Sweden, the European Union, and the United States: 2008–2016.,” National Renewable Energy Laboratory, 2018.

[19] M. Noonan, T. Stehly, D. Mora, L. Kitzing, G. Smart, V. Berkhout and Y. Kikuchi., “IEA Wind TCP Task 26 – Offshore Wind International Comparative Analysis,” International Energy Agency Wind Technology Collaboration Programme., 2018.

[20] P. Schwabe, S. Lensink and M. Hand, “Multi-national Case Study of the Financial Cost of Wind Energy - Work Package 1,” IEA Task 26, 2011.

[21] M. Jansen, I. Staffell, L. Kitzing, S. Quoilin, E. Wiggelinkhuizen, B. Bulder, I. Riepin and F. Müsgens, “Offshore wind competitiveness in mature markets without subsidy,” *Nature Energy,* vol. 5, no. 8, pp. 614-622, 2020.

[22] P. Beiter, A. Cooperman, E. Lantz, T. Stehly, M. Shields, R. Wiser, T. Telsnig, L. Kitzing, V. Berkhout and Y. Kikuchi, “Wind power costs driven by innovation and experience with further reductions on the horizon,” Wiley, 2021.

[23] M. Noonan, T. Stehly, D. Mora, L. Kitzing, G. Smart, V. Berkhout and Y. Kikuchi, “ IEA Wind TCP Task 26 Offshore Wind International Comparative Analysis,” International Energy Agency Wind Technology Collaboration Programme, 2018.

[24] E. d. Visser and A. Held, “Methodologies for estimating Levelised Cost of Energy (LCoE) - Implementing the best practice LCoE methodology of the guidance,” ECOFYS, 2014.

[25] C.-Y. Lee and J. Ahn, “Stochastic Modeling of the Levelized Cost of Electrictiy for Solar PV,” *Energies,* vol. 13, no. 3017, 2020.

ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part B: Mechanical Engineering. Received October 30, 2020;
Accepted manuscript posted August 31, 2021. doi:10.1115/1.4052269

[26] F. Judge, F. D. McAuliffe, I. B. Sperstad, R. Chester, B. Flannery, K. Lynch and J. Murphy, "A lifecycle financial analysis model for offshore wind farms," *Renewable and Sustainable Energy Reviews,* vol. 103, pp. 370-383, 2019.

[27] G. Smart, "Offshore wind cost reduction - recent and future trends in the UK and Europe," 2016. [Online]. Available: https://ore.catapult.org.uk/app/uploads/2017/12/SP00007-Offshore-Wind-Cost-Reduction.pdf. [Accessed 16 03 2020].

[28] M. Welisch and R. Poudineh, "Auctions for allocation of offshore wind contracts for difference in the UK," *Renewable Energy,* vol. 147, pp. 1266-1274, 2020.

[29] M. Dukan, L. Kitzing, R. Brückmann, J. M. F. Wigand, I. Kielichowska, C. Klessmann and B. Breitschopf, "Effects of auctions on financing conditions for renewable energy: A mapping of auction designs and their effects on financing," DTU, 2019.

[30] A. Diallo and L. Kitzing, "Technology bias in technology-neutral renewable energy auctions: Scenario analysis conducted through LCOE simulation," DTU, 2020.

[31] A. C. Levitt, W. Kempton, A. P. Smith, W. Musial and J. Firestone, "Pricing offshore wind power," *Energy Policy,* vol. 39, p. 6408–6421, 2011.

[32] S. D. Comello, G. Glenk and S. Reichelstein, "Levelized Cost of Electricity Calculator: a user guide," Standford University, 2017.

[33] E. Bodmer, "Four Levelised Cost Methods," 2021. [Online]. Available: https://edbodmer.com/real-lcoe/. [Accessed 2021].

[34] Cummins, V. and E. McKeogh (ed.), "Blueprint for Offshore Wind in Ireland 2020-2050: A research synthesis," EirWind project, MaREI Centre, ERI, University College Cork, Ireland., 2020.

[35] Grant Thornton, "Renewable energy discount rate survey results - 2018," Grant Thornton, Online, 2019.

[36] C. Desmond, J. Murphy, L. Blonk and H. Wouter, "Description of an 8 MW reference wind turbine 753 092013," *Journal of Physics: Conference Series,* vol. 753, no. 9, 2016.

[37] Copernicus Climate Change C3S programme, 2020.

[38] ERA5-ECMWF, *Reanalysis dataset,* Online: ECMWF, Accessed 2020.

[39] Scaldis, "Rambiz," 2019. [Online]. Available: http://www.scaldis-smc.com/en-GB/rambiz/31/. [Accessed 12 11 2019].

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