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Levelised cost of energy – A theoretical justification and critical assessment

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ABSTRACT

Although widely accepted as a measure of the comparative lifetime costs of electricity generation alternatives, levelised cost of energy (LCOE) lacks a theoretical foundation in the academic literature and encompasses a number of areas where caution is important. Therefore, this paper seeks to provide a theoretical foundation by comparing the metric with alternative cost of energy metrics and by undertaking a brief literature review to describe its strengths and weaknesses. In comparison with other potential measures of unit cost of energy, LCOE is found to be the preferred choice, in large part because of its widespread adoption. The weaknesses of the LCOE are found to centre on discount rate, inflation effects and the sensitivity of results to uncertainty in future commodity costs. These weaknesses are explored in the context of comparing combined cycle gas fired generation and offshore wind in the UK, based on publicly available cost measures. It is found that with variability of future fuel gas prices, and a Monte Carlo approach to modelling LCOE, the range of LCOE for CCGT is much broader in comparison to the LCOE of offshore wind. It is urged that explicit account be taken of the areas of weakness in future use of LCOE.

1. Introduction

Levelised cost of energy (LCOE) is widely used as a comparative measure between alternative sources of energy. It is relied on by Governments (HM Government Department for Business, 2016) and Inter-Government agencies (OECD/IEA, 2015) for evaluating policy decisions in relation to differential support between carbon-based and renewable electricity generation. Data on LCOE is produced by a range of highly reputable non-government commentators such as Lazard (2016), Mott McDonald (2010), Arup (2016), and Ernst and Young (2012) as well as by academics (Astariz et al., 2015; Allan et al., 2011; Myhr et al., 2014; Ouyang and Lin, 2014). Over recent years, the difference between costs of thermal (e.g. combined cycle gas turbine, also known as CCGT) and renewable (e.g. offshore wind) power generation has fallen very considerably, as a result of technological and commercial innovation and changes in revenue support mechanisms enabling lower cost project financing. The decline in wind costs is expected to continue (Williams et al., 2017), making the importance of comparative metrics and their appropriate application ever more important.

As an influential comparative metric, it is important that the use of LCOE and the results it delivers are clearly understood. Therefore, this paper addresses a long-standing gap in the academic literature by providing a theoretical footing for use of LCOE as a comparative measure of the cost of energy. It goes on to apply the metric by taking into account identified key factors which have not necessarily been appropriately applied in the past. Following, the analysis explores the impact of varying discount and inflation rates and applies a probabilistic approach to understand the range of possible LCOE. It is found that these refinements to the application of LCOE show that offshore wind may already be cost competitive with CCGT. Partridge has recently suggested a scenario-based approach to the application of LCOE (Partridge, 2018) and has found cases where wind energy is cheaper than thermal alternatives. This paper adopts a Monte Carlo approach to explore the same question.

This paper is divided into eight sections. Section 2 reviews the literature on the definition and use of LCOE and provides a theoretical footing for one formulation of the metric. Section 3 proposes several possible alternative lifetime cost of energy metrics while Section 4 identifies the strengths and weaknesses of LCOE against these alternatives. Section 5 details the input data used in this review and Section 6 sets out the results obtained in this analysis. Finally, Section 7 discusses the results and their implications followed by a conclusion in Section 8.

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2. Overview of LCOE approaches

The calculation of the unit cost of energy can provide a useful comparative measure between projects and technologies. However, it is important that users take a consistent approach to the costs included within any calculation, and that the implicit weaknesses of any such calculation are taken into account.

The LCOE metric provides an indication of the unit energy cost over the full life of a project, including capital, operating and financing costs. In general terms, the metric sums the lifetime costs of the energy system under consideration (such as a wind farm, or CCGT power plant), and divides by the lifetime energy production to deliver an output in cost per unit energy. Conventionally, LCOE includes only "plant-level costs" (OECD/IEA, 2015) and does not take account of "effects at the system level in the sense that specific technologies demand additional investments in transmission and distribution grids or demand specific additional reconfigurations of the electricity systems" (OECD/IEA, 2015).

Two main methods for calculating LCOE are in use; one suggested by the Department for Business, Energy and Industrial Strategy (BEIS) and one suggested by the Department of Energy's National Renewable Energy Laboratory (NREL). Both methodologies are presented in depth in Sections 2.1 and 2.2, respectively.

2.1. LCOE (Department for Business, Energy & Industrial Strategy definition)

The definition for the LCOE metric which dominates in the UK defines levelised cost of energy as "the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in £/MWh" (HM Government Department for Business, 2016). The UK Government department which first produced information on LCOE was the Department of Energy and Climate Change (DECC). In 2016, DECC was merged into the Department for Business, Innovation and Skills to form a new department for Business, Energy and Industrial Strategy. The formula for LCOE used by BEIS is set out in Eq. (1):

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

where t is the period ranging from year 1 to year n, C_t the capital cost in period t (including decommissioning), O_t the fixed operating cost in period t, V_t the variable operating cost in period t (including fuel cost, carbon costs, and sometimes taxes, etc.), E_t the energy generated in period t, d the discount rate, and n the final year of operation. As defined in Eq. (1), this method takes account of costs over the life of a project, and thereby derives a lifetime cost of energy. To the best knowledge of the authors, there is no published theoretical justification for the $LCOE_{BEIS}$ methodology found in the literature. For completion, the derivation is as follows.

$LCOE_{BEIS}$ divides the discounted sum of costs by the discounted sum of energy production. For convenience, the discounted sum of energy generated can be defined as net present energy (NPE) as illustrated in the denominator of Eq. (1). By definition, when the NPV of a project is zero, the project's internal rate of return (IRR) equals its discount rate (Brealey et al., 2006). In equation form:

$$NPV_{project} = NPV_{revenues} - NPV_{costs} = 0. \tag{2}$$

When the project IRR is equal to the discount rate ($NPV_{costs} = NPV_{revenues}$), it is possible to substitute NPV_{costs} with $NPV_{revenues}$ and thus derive Eq. (3):

$$LCOE = \frac{NPV_{revenues}}{NPE}. \tag{3}$$

As this result is expressed in terms of revenue per unit energy figure, it is natural to interpret this figure as an energy price. As the analysis above shows, the $LCOE_{BEIS}$ result is equal to the constant energy price in real terms required for the revenues generated from the project to be sufficient to return the IRR for the project equal to the discount rate.

Although BEIS states that LCOE "should not be seen as a guide to potential future strike prices" (HM Government Department for Business, 2016), it is in fact apparent that the $LCOE_{BEIS}$ does reflect a minimum required real price for a project.

The foregoing analysis is based on the costs in the model being expressed in real terms. A parallel analysis finds that if nominal costs with constant inflation factors are used as inputs, and the discount rate scaled up by the nominal inflation rate, the formula returns the average through-life nominal price required for the project to achieve an IRR equal to the nominal discount rate. When used with real costs, the metric returns a value which equates to the minimum constant real price required for a project to achieve a target return. When using nominal figures, and a nominal discount rate, the formula returns the average nominal price required through the project's life to generate the required nominal return. $LCOE_{BEIS}$ therefore has a clear, theoretically justified, and commercially-useful meaning.

2.2. LCOE (National Renewable Energy Laboratory definition)

In contrast, the US Department of Energy's National Renewable Energy Laboratory defines LCOE in terms of the annual cost of energy, where the capital costs include an annuity-based capital recovery factor (CRF) which addresses the costs of financing the capital for the project (National Renewable Energy Laboratory, 2018). Eq. (4) sets out the NREL definition for the simple levelised cost of energy, which it refers to as sLCOE and we call $LCOE_{NREL}$ (to differentiate it from the BEIS metric).

$$sLCOE = \quad LCOE_{NREL} = \frac{C_o{*}CRF + O}{8760{*}CF} + f{*}h + V \tag{4}$$

where Co is the overnight capital cost, O the fixed operating cost, CF the capacity factor, f the fuel cost, h the heat rate, and V the variable operation cost. Eq. (5) sets out the calculation of the capital recovery factor:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5}$$

where i is the interest rate, and n is the number of payments made to repay capital.

As such, NREL calculates total costs over an annual period and divides by the energy generated in the same period. Capital costs are expressed in terms of cost per kW installed, and modified by a capital recovery factor which calculates the equivalent annuity payment required to service the overnight capital over the term of the project's financing, and operating costs are expressed in terms of cost per kWh. NREL has published a more detailed formula for LCOE (Mone et al., 2015), allowing for more detailed analysis of costs. Both NREL formulae employ the same annualised basis for LCOE calculation, so the review in this paper applies equally to both.

NREL states that the LCOE returned by its formula is "the minimum price at which energy must be sold for an energy project to break even" (National Renewable Energy Laboratory, 2018). Put more clearly, the $LCOE_{NREL}$ is the energy price required for a project to exactly meet its operating costs in a year and the share of capital costs (including the costs of financing those costs) in that year.

Similarly, the BEIS-defined LCOE returns the constant real energy price required to generate the return equal to the discount rate used over the full life of the project.

It is worth noting that under certain simplifying assumptions, the BEIS and NREL metrics return exactly the same value. These simplifying assumptions are that the project has constant annual output and costs, that all construction spending occurs in year 1 and capital recovery starts immediately with a financing term equal to the project's operating life, and finally that there are no decommissioning costs. These requirements could be met in the case of a very simple project, such as a single wind turbine or small wind farm.

In conventional discounted cashflow-based investment appraisal, it is usual to apply discount factors to all revenues and costs, and the $LCOE_{BEIS}$ does this, making it more consistent with this approach.

Foster's thorough review of the details of alternative formulae (Foster et al., 2014) focusses mainly on which costs are included or excluded in various applications of the LCOE approach. While this is, of course important, the review in this paper focusses rather on the mechanics of the mathematical formulae in use, and what the results of these formulae mean in terms of required energy price. Neither BEIS's nor NREL's methodology is “right”, and both give an insight into the relative costs of energy, but their different characteristics mean that users must be consistent and thoughtful in which formula is selected. As this research is centred on the UK energy system, the BEIS approach has been adopted for further review.

3. Review of alternative metrics

In comparing alternative electricity generation technologies, it is useful to have a metric which indicates the lifetime unit cost of electricity generated. The $LCOE_{BEIS}$ has emerged as the standard measure in the UK, but it is only one of a family of potential measures of lifetime cost. Hence, this section compares the $LCOE_{BEIS}$ with other potential metrics in the “cost of energy” family; all of which take a total of costs and divide by the total energy generated. Two metrics are well established and are in wide usage - $LCOE_{BEIS}$ and $LCOE_{NREL}$ – and these were reviewed in Section 2.

In all of these metrics, it is critical to ensure that clear definitions of costs to be included and excluded have been made, and where discounting is applied, to have made informed choices about discount rates in the context of the cost of capital and project risk (OECD/IEA, 2015).

Three additional cost of energy metrics have been identified and defined. These are not, to the best of our knowledge, seen in the literature but offer alternative features to the LCOE metrics. They are undiscounted cost of energy (UCOE), discounted costs cost of energy (DCCOE), and total cost of energy (TCOE).

3.1. Undiscounted cost of energy

UCOE is simply the total capital and operational costs divided by the energy produced, as in Eq. (6).

$$UCOE = \frac{\sum_{t=1}^{n} C_t + O_t + V_t}{\sum_{t=1}^{n} E_t} \tag{6}$$

The UCOE measure provides a simple cost per unit energy measure, but offers no insight into the impact on value of the timing of cashflows or energy production. Whilst it might be informative in comparing projects with the same technology, it is not useful as a tool for comparison between technology types.

3.2. Discounted costs cost of energy

A possible new metric, discounted costs cost of energy, is defined by dividing the discounted sum of operational and capital costs by the sum of energy produced. It is defined in Eq. (7).

$$DCCOE = \sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t} / \sum_{t=1}^{n} E_t \tag{7}$$

DCCOE is comparable to the net present cost per barrel measure commonly used in the oil industry (Brealey et al., 2006), which also discounts the financial side of the equation but not the energy side. We believe that this measure was adopted as NPV is routinely determined in investment appraisal in the oil and gas industry, and it is a natural ranking approach to divide by the volumes of hydrocarbons relating to that NPV.

As the energy generation from all technologies is broadly constant year on year, the ratio of LCOE to DCCOE is expected to be broadly constant for each technology. Nevertheless, longer term projects will return a lower DCCOE than LCOE, as the late years production is not heavily discounted. Unlike the LCOE metric, which returns the minimum constant energy price, in real terms, required to deliver the return implicit in the discount rate, the DCCOE returns a figure which does not clearly relate to a price required for a project and this lack of apparent meaning makes it less useful as a metric.

3.3. Total cost of energy

Another new metric, total cost of energy is defined as the total project cost, including financing costs divided by the energy produced, as presented in Eq. (8).

$$TCOE = \frac{\sum_{t=1}^{n} C_t + O_t + V_t + F_t}{\sum_{t=1}^{n} E_t}. \tag{8}$$

The costs of financing incurred during each year, *Ft*, are calculated on an annuity formula, which assumes capital costs are financed on an annuity basis over a defined lifetime. Operating costs in the project are assumed to be paid from annual revenues and therefore do not incur financing costs. While this treatment of operating costs reflects the operating reality for most projects, it means that the TCOE metric is not consistent with conventional investment appraisal, in which all costs are discounted.

Eq. (8) returns a figure which describes the lifetime cost of energy, and, like $LCOE_{BEIS}$, includes financing costs, and it is worth exploring how its results differ from $LCOE_{BEIS}$.

TCOE is closely related to the $LCOE_{NREL}$ definition, as both build in the costs of a financial return with an annuity formula and only expect a return on the capital costs. They differ in that TCOE considers costs over the full project life, allowing for inter-year variability in costs, while $LCOE_{NREL}$ considers costs on an annual basis.

3.4. Summary of findings

Fig. 1 shows the breakdown of costs between technologies as presented by BEIS (HM Government Department for Business, 2016). It is clear that offshore wind is dominated by construction costs, while thermal projects, such as CCGT are dominated by fuel and variable operating costs.

A simplified Excel® model has been constructed to compare the results returned by each metric for notional CCGT and wind projects. The input data has been developed to ensure that the notional CCGT and wind projects return the same $LCOE_{BEIS}$. Fig. 2 shows the results.

TCOE returns the highest values, as it includes all costs (undiscounted) and divides by discounted energy. Conversely, DCCOE, which discounts costs but not energy, returns the lowest value for both technology families. ULCOE, which divides undiscounted capital and operating costs by undiscounted energy strongly differentiates between thermal and wind projects, as the different timing profiles and amounts of capital and operating spend is affected differently by the removal of discounting. The costs of thermal projects, with their long high operating cost profiles, are more reduced by the discounting process than those of wind projects, whose costs are much more front-end biased.

Focussing on the LCOE measures, it is found that $LCOE_{BEIS}$ and $LCOE_{NREL}$ are broadly similar for the two technology families. In the case shown in Fig. 2, in which the Capital Recovery Factor is applied over the full operational life of 25 years, $LCOE_{NREL}$ is some 12% lower than $LCOE_{BEIS}$; if capital recovery is accelerated to a 15 year period, $LCOE_{NREL}$ is higher than $LCOE_{BEIS}$ by a similar factor. In the case of thermal projects, the $LCOE_{NREL}$ is less variable, as the lower fraction of

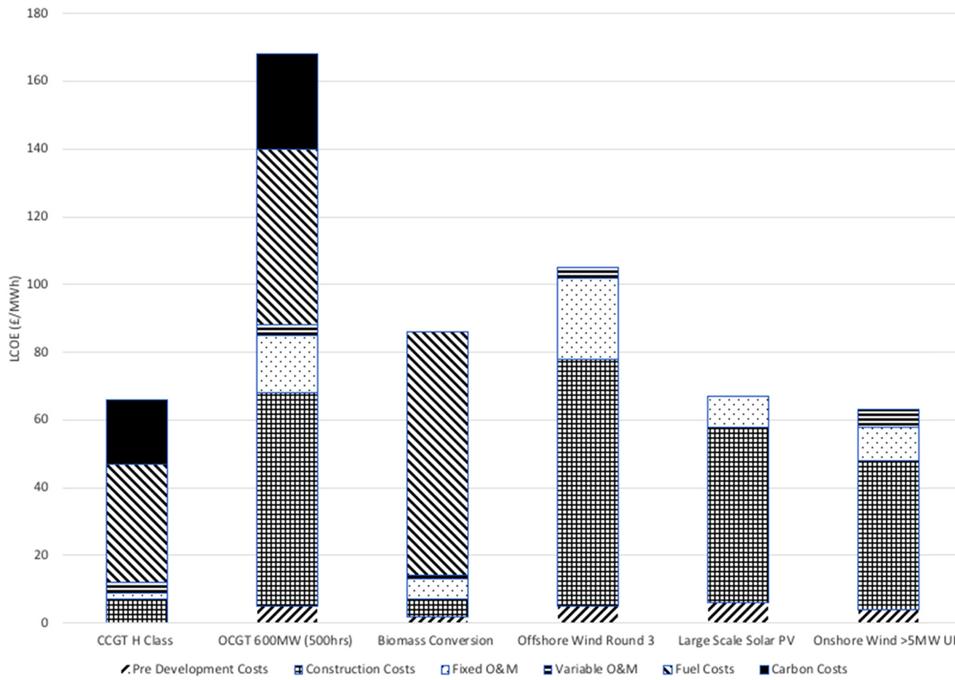

Fig. 1. Breakdown of levelised costs across technologies, data from (HM Government Department for Business, 2016).

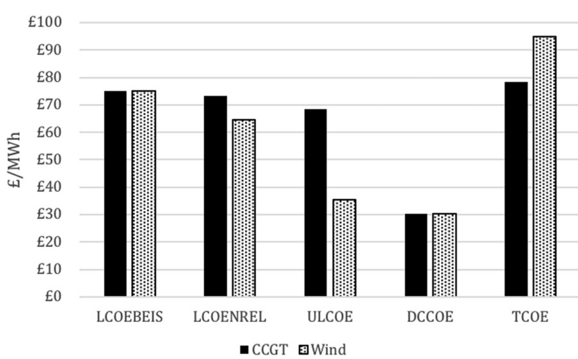

Fig. 2. Comparison of unit cost of energy metrics (authors' analysis).

costs attributable to capital make the sensitivity to CRF less.

Each metric's key features, their outcome and benefits as well as drawbacks are further summarised in Table 1.

The key strength of $LCOE_{BEIS}$ is that it generates a figure equal to the constant real energy price required by a project to return the rate of return on capital invested equivalent to the discount rate used in the formula, and therefore equivalent to the energy price required by the project in an inflation-free world.

3.5. Other measures

Other authors have recently proposed the extension of LCOE to provide additional information. These proposals include accounting for the costs of externalities (such as environmental damage, health and mortality effects) when comparing between technologies (Millstein et al., 2017); including the costs of carbon taxes or other carbon costs (Aquila et al., 2017); and seeking to evaluate the relative contribution to a local or national economy by considering the fraction of spend which contributes to local or national gross value added (GVA) (Roberts, 2017). All of these are interesting and relevant proposals, as the comparison of electricity generation technologies should take account of these wider factors, but they are not considered to be within the scope of this paper.

4. Strengths and weaknesses of LCOE relative to other cost of energy metrics

All measures of unit cost of energy must be considered as simple “rules of thumb” and are exposed to weaknesses relating to the choice of costs included and excluded. This review recognises that tax effects may impact calculations of unit cost of energy, particularly where targeted preferential tax treatment regimes are in place (for example in the United States where production tax credits may apply to renewable energy (US Department of Energy, 2018)), but has not explicitly addressed these. Wider costs, including environmental and other externalities might also legitimately affect choices between technologies, but these have also not been addressed in this paper.

4.1. Strengths

$LCOE_{BEIS}$ has been widely discussed in the literature (Astariz et al., 2015; Kammen and Pacca, 2004; Manzhos, 2013; Sklar-Chik et al., 2016) but the principal focus has been on the application of the metric, its weaknesses and potential improvements. A discussion of the strengths of the metric is long overdue, not least because of its widespread use and acceptance. The principal strengths of the $LCOE_{BEIS}$ metric are simplicity, sophistication, interpretation, and adoption.

$LCOE_{BEIS}$ reduces complex comparisons to a single number. This simplicity necessarily disregards some subtleties, even where these can lead to inappropriate conclusions in some cases. However, this simplicity offers the advantage of reducing a comparison to a single number, providing ease in explaining policy choices to an inexperienced public. By definition, all of the LCOE metrics proposed here share the strength of distilling a comparison into a single number.

The $LCOE_{BEIS}$ metric's sophistication allows it to take some account of capital and operating costs, operational performance and costs of finance in assessing a cost of energy. The metric therefore has a degree of sophistication, which helps to justify its use as a high level comparative tool. Other LCOE metrics, as proposed here, do not offer the same sophistication in fully considering intra-year variability in costs (particularly fuel costs) or costs of project financing.

$LCOE_{BEIS}$ is only one of a family of possible lifetime cost of energy calculations, each of which can claim to being a valid tool for cross-

Table 1
Comparison of lifecycle cost alternatives (authors' analysis).

Parameter	$LCOE_{BEIS}$	UCOE	DCCOE	TCOE	$LCOE_{NREL}$
Key features	Discounted total costs (excluding finance costs) divided by discounted total energy	Simple sum of costs (excluding finance costs) divided by simple sum of energy	Discounted total costs (excluding finance costs) divided by simple sum of energy	Total undiscounted costs including finance costs divided by total energy	Annual costs (including financing costs for capital) divided by annual energy
Outcome and meaning	Constant real price required to generate IRR equal to discount rate	Constant real price required for total costs to equal total revenue (i.e. zero return)	Net present cost per unit energy Informs on required net present value of revenue stream for project return	Average flat real price required to cover all costs and generate return on capital	Annual price required to cover operating costs and service finance costs
Benefits	Widely used in UK Returns meaningful metric equivalent to minimum economic price	Simple to calculate Easily understood	Net Present Cost per unit energy is clearly understood Indicates net present value required from revenue stream for return	Closely related to $LCOE_{NREL}$ but can include costs of financing operating costs	Widely used in US
Drawbacks	Sensitive to discount rate	Does not reflect time value of money; not in wide use	Difficult to explain; not in wide use	Not consistent with conventional project appraisal; not in wide use	Unable to address annual variable costs (e.g. fuel costs); not consistent with conventional project appraisal; does not take into account return of investment and time value of cash flows

technology comparison. It is in relation to meaning that $LCOE_{BEIS}$ has a critical advantage, and Section 2 of this paper sets out a theoretical backing for the preference of $LCOE_{BEIS}$ over other measures, by considering the meaning of the results returned by the methodology.

Notwithstanding the new theoretical justification offered here, perhaps the most compelling benefit of the $LCOE_{BEIS}$ metric is its wide adoption. It is used by BEIS (HM Government Department for Business, 2016) as a comparative tool, and employed by a range of commentators (Lazard, 2016; Mott McDonald, 2010; Arup, 2016; Ernst and Young, 2012) in considering the merits of renewable energy as compared with conventional thermal generation.

4.2. Weaknesses

A number of authors, including academic researchers (Manzhos, 2013; Sklar-Chik et al., 2016; Cartelle Barros et al., 2016) and other writers (Bronski, 2014; Bolton, 2016; Irons, 2016) interested in the comparative costs of energy sources have discussed the weaknesses of the LCOE metric. Memorably, Cartelle Barros described LCOE as "an abstraction from reality" (Cartelle Barros et al., 2016) but accepted that it is "used as a benchmarking or ranking tool to assess the cost-effectiveness of various energy generation technologies". Joskow expanded on this, pointing out that LCOE does not consider the impact of changes in the value of electricity through the day, or the difference in value between dispatchable and intermittent generation (Joskow, 2011). More recently, Laszlo Varro, the Chief Economist for the International Energy Agency (IEA), said that LCOE was becoming less relevant as a metric, as it failed to take into account wider system costs or to deal with variability and intermittency (Snieckus, 2017). This paper does not address the concerns relating to intermittency and wider system integration, but focusses on the weaknesses identified by Manzhos, Sklar-Chik et al., Cartelle Barros et al. and others (Manzhos, 2013; Sklar-Chik et al., 2016; Cartelle Barros et al., 2016) which are concentrated in three detailed areas: (i) discount rates, (ii) treatment of inflation, and (iii) dealing with uncertainty in future costs.

Choice of an appropriate discount rate has long been contentious in many areas of financial analysis (Frederick et al., 2002; Henderson and Bateman, 1995; Weitzman, 1998), and this is also true in the LCOE literature (Manzhos, 2013). As (Manzhos, 2013) points out, the choice of discount rate has a significant effect on the LCOE. He goes on to argue that the most appropriate rate to use in comparing technologies is the risk-free rate. In practice, different discount rates may be used for different technologies, in an attempt to account for different risk profiles (HM Government Department for Business, 2016). BEIS uses a "hurdle rate" which it defines as "the minimum project return that a plant owner would require over a project's lifetime on a pre-tax real basis" and is set to "reflect different financing costs for different technologies". These rates therefore reflect the weighted average cost of capital (WACC). This has the effect of raising the LCOE for technologies considered to be riskier, and potentially skews the metric in favour of apparently less risky technologies. As the discount rate reflects the project risk, it is also important to recognise that the appropriate discount rate to be applied can change through a project's life. Increasingly financial investors such as pension and insurance companies are investing in offshore wind projects. These companies generally have lower return expectations and appetites for risk than developers, and this trend is indicative of the perceived reduction in project risk as this technology matures. Section 6 explores the effect on $LCOE_{BEIS}$ of variations in discount rate.

The second key weakness in application of the LCOE metric is in the handling of inflation. Sklar-Chik et al. (2016) has said that the conventional application of the $LCOE_{BEIS}$ metric does not take into account cost inflation, and says that "it is possible to account for inflation, although this requires somewhat more intensive calculation". In this work, it has been found that the $LCOE_{BEIS}$ formula readily accommodates nominal costs (i.e. costs with inflation), as long as nominal

Table 2
Input data for deterministic assessment (HM Government Department for Business (2016) and authors' analysis).

Input parameter	CCGT	Unmodified Wind farm	Scaled wind farm
Capacity (MW)	1200	844	844
Availability / Capacity Factor (%)	93%	48%	48%
Prebuild costs (£/kW)	10	120	74
Construction (£/kW)	500	2300	1409
Infrastructure (£'000 s)	15,100	323,000	197,870
Fixed O&M (£/MW/yr)	12,200	47,300	28,976
Variable O&M (£/MWh/yr)	3	3	2
Fuel cost conversion factor (%) (converts fuel cost (p/therm) to annual variable cost (£/MWh)	110%	Zero fuel cost	Zero fuel cost
Insurance (£/MW/yr)	2100	3300	2022
Connection charges (£/MW/yr)	3300	48,900	29,956
Discount rate (%)	7.8%	8.9%	8.9%
Operating life (yrs)	25	25	25
LCOE (£/MWh)	47.00	103.88	57.50

discount rates are used, and it is understood that the result is an average nominal energy price required over the life of the project to deliver the nominal discount rate. Inflation is explicitly built into strike prices under UK contracts for difference (CfD) of renewable energy auctions (Low Carbon Contracts Company, 2018), making this aspect of the analysis relevant and important. The incorporation of inflation can generate divergent results between different technologies, as a result of their different temporal patterns of expenditure. This difference means that as cost inflation increases, the proportionate increase in $LCOE_{BEIS}$ for CCGT projects is greater than for offshore wind. This is explored further in Section 6.

This could have significant effects when the $LCOE_{BEIS}$ metric is used to compare between thermal and renewable technologies. Over a full life cycle, the costs of CCGT plants are dominated by operating and fuel costs, as shown in Fig. 1, while offshore wind costs are dominated by the capital costs, which are less susceptible to the effects of inflation, as they take place over a limited period (and can potentially be limited by contractual arrangements). While constant inflation, where nominal prices increase by a constant percentage each year, can be accommodated within the $LCOE_{BEIS}$ formula without stress, experience suggests that it is unreasonable to expect fuel gas prices to behave in this manner. This is further explored below.

The largest element of costs in a CCGT project is fuel costs. Conventionally in calculating $LCOE_{BEIS}$, a deterministic forecast of gas prices is employed to determine the "most likely" future costs (HM Government Department for Business, 2016). The BEIS report (HM Government Department for Business, 2016) includes some sensitivity analysis to examine the effect on LCOE of uncertainty in future gas prices, but this is relegated to a separate chart and does not form a key part of the conclusions. Over the past two decades, wholesale gas prices have varied widely, and it is not obvious why similar volatility should not be expected in the future. Probabilistic analysis, as pioneered in the calculation of LCOE by Cartelle Barros et al. (2016), Heck et al. (2016) offers an appropriate tool to understand the variability of LCOE for CCGT projects. Neither of these authors considered offshore wind in their analysis, and recent significant reductions in costs for this technology make this timely and important.

In summary, the $LCOE_{BEIS}$ metric is considered to be the most informative metric as to comparative economics of energy generation alternatives, as it generates the constant price in real terms required for the project to generate the return indicated by the discount rate and it is already in widespread use. Other measures, whilst informative in different ways, suffer from a lack of widespread adoption and/or a lack of apparent "meaning" to the results they return in terms of real world applicability. For these reasons, this paper now focusses on $LCOE_{BEIS}$ in considering the effect of variation in key input parameters.

Sections 5 and 6 explore the quantitative effects on $LCOE_{BEIS}$ of variation in each of these factors (discount rate, inflation and cost uncertainty) in turn and in combination, to evaluate realistic and current estimates for $LCOE_{BEIS}$ for CCGT and offshore wind.

5. Method and input data

A detailed Excel® model has been built to determine LCOE for an idealized CCGT project and an idealized offshore wind project. Costs have been taken from BEIS' report of UK electricity generation costs (HM Government Department for Business, 2016).

5.1. Deterministic method

In the case of CCGT, converting from wholesale gas price in pence per therm (1 therm = 1.0 MMBTU = 29.3 kWh) to annual fuel costs requires a conversion factor which has been used to ensure that the LCOE generated in our analysis for CCGT equates to £47/MWh. This ties the model outputs into the BEIS report, which states that the central case LCOE for CCGT is £66/MWh including carbon taxes of £19/MWh (HM Government Department for Business, 2016).

Costs for offshore wind have also been taken from the BEIS report (HM Government Department for Business, 2016). Based on the central case costs in the BEIS report, the LCOE is calculated as £103.88/MWh. In order to reflect currently anticipated changes in offshore wind costs, costs have been reduced by a scaling factor to produce a base case LCOE at £57.50/MWh (the initial strike price to be received under the recently-announced second round CfD). The implementation of the scaling factor is illustrated in Table 2.

It is recognised that LCOE and strike price do not necessarily equate, but as LCOE is a constant real price required to offer the required return (implied by the discount rate used) it is an appropriate starting point for this comparative analysis. In practice, since there is guaranteed inflation linkage in the strike price under the CfD arrangements (Low Carbon Contracts Company, 2018), the contractual price, and its built-in inflation factor, will likely generate higher revenues and therefore a return above the discount rate used by BEIS to calculate LCOE.

5.2. Deterministic input data

The input data used for the deterministic assessment is set out in Table 2. The BEIS analysis (HM Government Department for Business, 2016) includes carbon taxes in thermal generation costs. This analysis has ignored the potential effect of carbon taxes, as it is interested to see whether offshore wind costs, based on recent CfD auctions, are now legitimately competitive with CCGT.

With the model calibrated, it was then used to vary discount rates, inflation rates and to determine $LCOE_{BEIS}$ under each of these cases.

5.3. Probabilistic method and input data

The Monte Carlo method allows key variables in a calculation to vary within defined probability distributions over multiple calculation iterations to generate multiple outcomes which define the range of possible outcomes for the target metrics. A statistical analysis of this range is undertaken, to allow users to understand the likely range of outcomes, in terms of the median outcome (the "P50", or the value for which there is a 50% probability of exceedance) and the likely extremities of the range, which are typically presented as "P10" and "P90" values. There is a 90% chance of the LCOE being higher than the P90 value, and a 10% chance that it exceeds the P10.

For both offshore wind and CCGT, it has been assumed that capital and operating costs derived from BEIS' central cases (HM Government Department for Business, 2016) are varied within a distribution with bounds at ± 10% of the central case. While offshore wind technology is arguably less developed than CCGT, in practice operators ensure that their costs are very tightly constrained before bidding projects into the CfD process and proceeding to final investment decision, so similar ranges for these technologies are appropriate.

Fuel costs for CCGT are likely to be more variable, and have been modelled in two different ways. BEIS (HM Government, Department for Business, 2016.) provides a range of price forecasts from the present until 2035. In the first analysis, these have been used as the basis for future fuel gas prices, and to model variability, the selected gas price in any year has been selected randomly with equal probabilities between the central, high and low price cases. The second analysis adopts an approach in which future gas prices are based on a statistical review of past gas prices, on the basis that future volatility may be similar to that shown in the past. The fuel price for 2017 is taken from the BEIS central case forecast (HM Government, Department for Business, 2016.). The fuel gas price for each subsequent year is then derived from the previous year, with a percentage change derived from the statistical distribution of annual price change defined by past UK gas prices from the BP statistical review of world energy 2017 (BP Plc, 2017). These data points cover two decades, from 1996 to 2016. An analysis of this data shows that the mean annual change in gas price was 10.7% and the standard deviation 36.8%, meaning that the 95% confidence interval for annual gas price change was −62.9% to + 84.3%. This is considerably more variability than in the BEIS forecasts, and consequently it generates a much wider range of LCOE outcomes for the CCGT case. The recent variability of gas prices seems to be the more reasonable basis on which to model future variability, as it builds forecasts which respect the largely random price variability seen in the past.

Finally, capacity factors for offshore wind farms have been allowed to vary within a normal distribution, with a mean of 48% and standard deviation of 3%, based on our own analysis (in press).

The spreadsheet model employs Visual Basic to generate multiple outcomes, sampling the variability of operating costs, capital cost, fuel costs and wind farm output within the ranges defined. In this analysis, it was found that 20,000 iterations were sufficient to develop robust distributions of solutions. The input data used for the probabilistic assessment is set out in Table 3.

6. Results and commentary

6.1. Discount rate

BEIS applies a discount rate of 8.9% for offshore wind projects and 7.8% for CCGT projects (HM Government Department for Business, 2016); this is in agreement with the range for cost of capital recently estimated by the Competition and Markets Authority for integrated generation companies (Competition and Markets Authority, 2015).

With the introduction of CfDs for offshore wind (Onifade, 2016), the revenue risk for offshore wind has been drastically reduced. Revenue is the product of output and price, and with the constant price (guaranteed by a zero-risk Government-backed contract), the effect of CfDs is to remove a key revenue risk factor. Accordingly, as the revenue risk is much reduced, the projects can employ much higher levels of project finance than previous offshore wind projects at historically low rates, allowing operators to maintain equity returns at a lower WACC. It would therefore be appropriate to consider lower discount rates in considering LCOE for post-commissioning projects, and to undertake sensitivity work in assessing project LCOE.

It is reported (Chalons-Browne, 2015) that there is growing competition among lenders for early CfD projects, suggesting that debt returns will be very low, particularly as interest rates at the time of project financing were generally low. Linklaters, a law firm, recently announced that the Beatrice offshore wind farm has secured nearly 75% project finance (£1.9 billion debt on a £2.6 billion project) (Offshorewind.biz, 2016), and a number of recent reports on offshore wind financing indicate that 15 year project finance is currently priced at 250–300 basis points over base rates (Wind Europe, 2018; European Wind Energy Association, 2013), for a total debt rate of around 3.5–4% and gearing levels in excess of 70%. These reports suggest that developers and investors are using variable rate debt, although there may be conversion to fixed rate debt at a later date to protect lender returns. The equity return implied from the BEIS hurdle rate of 8.9% can be calculated from the WACC formula in Eq. (9).

$$\text{WACC} = r_{equity}.\,(1 - w_{debt}) + r_{debt}.\,w_{debt} \tag{9}$$

where r_{equity} and r_{debt} are the returns on equity and debt respectively, and w_{debt} is the percentage of debt in the capital base.

Substituting WACC = 8.90%, r_{debt} = 3.5%, w_{debt} = 70% allows calculation of the implied equity return of 21.5%. This is an extremely attractive equity return, and it would only be reduced to 17.8% if the WACC was reduced to 7.8% in line with CCGT projects.

Table 4 shows the impact of this potential change to the discount rate on $LCOE_{BEIS}$ from offshore wind projects and compares to CCGT values.

This analysis finds that if the discount rate for offshore wind is reduced to 7.8%, to match that for CCGT, the LCOE falls from £57.50/MWh to £54.11/MWh; a reduction of 6%.

It therefore appears from this analysis that if BEIS is using the discount rate as a surrogate for WACC, it should consider applying a lower discount rate to offshore wind projects. The appropriate discount rate for CCGT has not been addressed here, although the risk in CCGT projects is strongly related to gas prices, and it might be argued that a higher discount rate might be appropriate to reflect this cost risk and its associated impact on the potential scope for gearing of these projects at the same levels as offshore wind.

6.2. Inflation

The impact on $LCOE_{BEIS}$ of different inflation rates is shown in Table 5. This analysis retains the real discount rates (d_{real}) for the projects applied by BEIS. As a result, the nominal discount rates (d_{nom}) applicable at different inflation rates are calculated according to the formula in Eq. (10).

$$d_{nom} = [(1 + d_{real})*(1 + \text{inflation rate})]-1. \tag{10}$$

Comparison across each inflation rate is valid as the discount rate includes the risk premium implicit in the BEIS analysis.

Table 3
Input parameters for probabilistic analysis (authors' analysis).

Input parameter	CCGT	Scaled wind farm
Availability variation	No data available - output fixed at 93%	Capacity factor mean 48%, standard deviation 3%
Capital cost variation	+/- 10%	+/- 10%
Fixed operating cost variation	+/- 10%	+/- 10%
Variable operating cost variation	+/- 10%	+/- 10%
Fuel cost variation	Two cases: BEIS high/central/low cases and variation with probabilistic range	N/A

Table 4
Impact of discount rate on $LCOE_{BEIS}$ (authors' analysis).

$LCOE_{BEIS}$ at different discount rates	7.8% discount rate	8.9% discount rate
Offshore wind	£ 54.11/MWh	£ 57.50/MWh
CCGT	£ 47.00/MWh	£ 47.25/MWh

Table 5
Impact of inflation on $LCOE_{BEIS}$ (authors' analysis).

Inflation rate (%)	Nominal discount rate (%)	Wind farm LCOE £/MWh	Wind farm change relative to zero inflation	Nominal discount rate (%)	CCGT LCOE £/MWh	CCGT change relative to zero inflation
0%	8.9%	57.50	–	7.8%	47.00	–
1% pa	10.0%	64.20	11.7%	8.9%	53.01	12.8%
2% pa	11.1%	71.38	24.1%	10.0%	59.47	26.5%
5% pa	14.3%	95.86	66.7%	13.2%	81.62	73.7%

Table 5 shows that the impact of non-zero inflation on $LCOE_{BEIS}$ for CCGT projects is greater than for offshore wind projects. With each increase in inflation, the $LCOE_{BEIS}$ of CCGT projects increases by a larger factor than for offshore wind projects. Of course, in a financial project assessment, operators will make assumptions about both cost and price inflation, but only cost figures affect the LCOE, and these disproportionately impact CCGT and other thermal projects.

6.3. Uncertainty in future prices

BEIS (HM Government, Department for Business, 2016) sets out high, reference and low gas price forecasts for the period to 2035, as set out in Fig. 3.

Applying each of these cases in turn, with the gas price applied in each year derived from the BEIS data, the effect on $LCOE_{BEIS}$ for CCGT projects is set out in Table 6.

Use of the BEIS high and low gas prices cases shows that the $LCOE_{BEIS}$ from CCGT can vary within a considerable range, depending on the price of fuel. The variability critically depends on the range of fuel gas estimates, which are examined further in Section 6.5.

6.4. Combined deterministic output

Table 7 shows the nominal $LCOE_{BEIS}$ results in the case where the real discount rates for both CCGT and offshore wind projects are set at 7.8%, inflation is set at 2% and the cases are run for each of the gas price forecasts.

Recalling that the results of the nominal $LCOE_{BEIS}$ formula represent the average nominal price required to achieve a return equal to the nominal discount rate, it appears that in this deterministic analysis, the costs of offshore wind can be less than those for CCGT, if fuel gas prices are in the high case as illustrated in Fig. 3.

6.5. Probabilistic results

The sensitivity of CCGT $LCOE_{BEIS}$ to fuel gas prices suggests that a probabilistic approach would offer a richer analysis with which to compare technologies. All of the analysis has taken the same basic input data as the combined deterministic analysis above, with real discount rates at 7.8%. In addition, input parameters have been allowed to vary as defined in Table 4.

The first probabilistic analysis is based on fuel gas prices varying between the reference, low and high cases defined by BEIS. Fig. 4 shows a comparison of gas price forecasts presented by the UK Government in 2006 (HM Government, 2008), against actual gas prices which were actually experienced in the period for which the forecasts were

Table 6
Impact of gas price case on CCGT $LCOE_{BEIS}$ (authors' analysis).

Gas price case	$LCOE_{BEIS}$
Reference	£ 47.00/MWh
Low case	£ 34.10/MWh
High case	£ 56.17/MWh

Table 7
$LCOE_{BEIS}$ with gas price variability and 2% inflation (authors' analysis).

Scenario	Wind farm $LCOE_{BEIS}$	CCGT $LCOE_{BEIS}$
Nominal discount rate 10.0%, inflation 2%, reference gas price	£ 67.64/MWh	£ 59.47/MWh
Nominal discount rate 10.0%, inflation 2%, low gas price	£ 67.64/MWh	£ 43.15/MWh
Nominal discount rate 10.0%, inflation 2%, high gas price	£ 67.64/MWh	£ 71.08/MWh

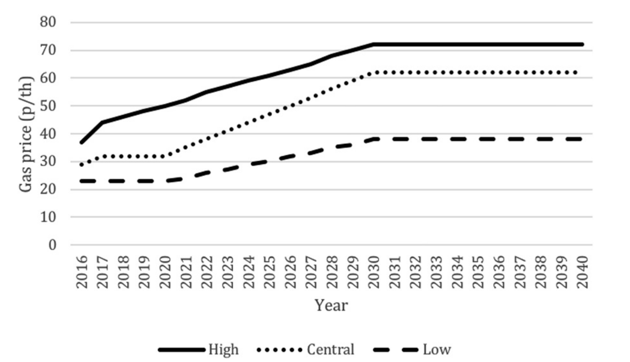

Fig. 3. BEIS gas price forecasts (HM Government, Department for Business, 2016).

presented. It is immediately apparent that actual prices were much more variable than the forecasts, and frequently ranged outside the minimum/maximum ranges in these forecasts.

Fig. 4 shows that it might be argued that short term (up to 3 year) trends can be observed in gas prices. Accordingly, the analysis allows for each three year period to apply a gas price case at random from the three BEIS gas price series.

This analysis is summarised in Fig. 5, which shows that the range of possible $LCOE_{BEIS}$ outcomes for CCGT is generally below that for offshore wind, with only minimal overlap.

Table 8 shows the analysis of these results, in which the range of values for $LCOE_{BEIS}$ for CCGT is generally below that of offshore wind across the range of probabilities. In this case, there is a 1% chance that the $LCOE_{BEIS}$ for CCGT exceeds the P50 $LCOE_{BEIS}$ for wind (the area under the CCGT graph above £54.14/MWh is c. 1%).

However, this analysis is based on the range of BEIS gas price forecasts, and if these forecasts are wrong, the range of CCGT $LCOE_{BEIS}$ values may be significantly altered. Uncertainty in CCGT availability has also not been considered.

This analysis suggests that relying on the latest BEIS price forecasts to define the possible range of future fuel gas prices is likely to underestimate the possible range of $LCOE_{BEIS}$ for CCGT projects. Accordingly, building on the premise that the past can be a guide to the future, a probabilistic analysis has been undertaken within which gas prices are allowed to vary according to a statistical analysis of their variability over the past 20 years. BP (BP Plc, 2017) provides UK National Balancing Point (NBP) price data, in $/MMBTU. This has been

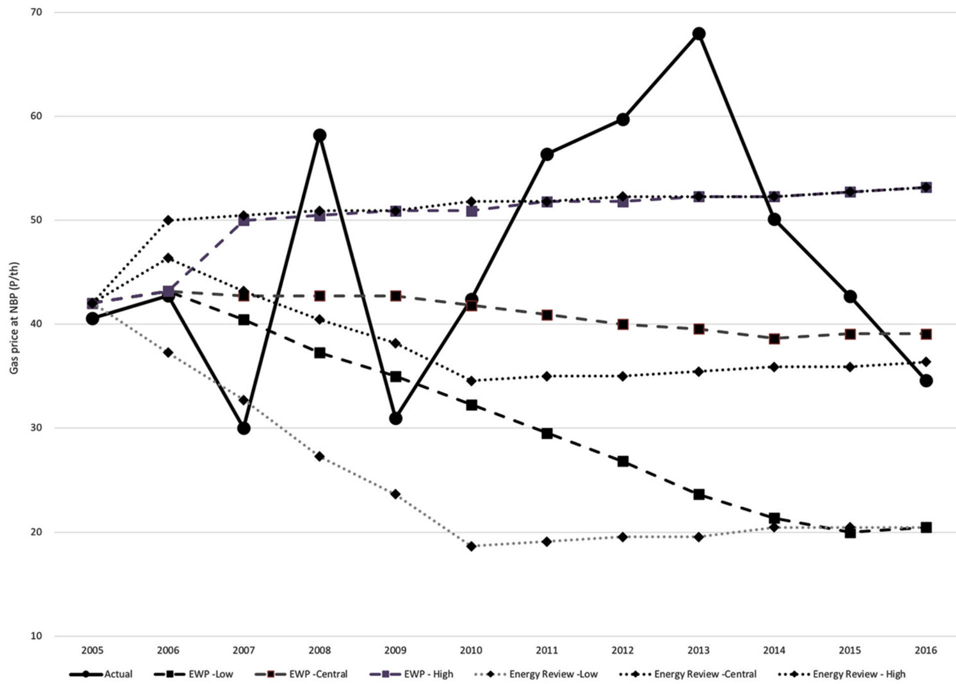

Fig. 4. Comparison of actual vs. forecast gas prices ((HM Government, 2008) and authors' analysis).

converted to UK Sterling values, and deflated by an inflation index to 2016 terms. The statistical distribution of year by year changes, in real 2016 terms, is derived.

It is found that the average (mean) change in gas price from year to year, in 2016 terms, was 0.84p/therm with a standard deviation of 14.9p/therm. Over a shorter period of a single decade, it is found that the variability is higher; the longer time series has been used as the basis for developing a statistical gas price forecast for the Monte Carlo

Table 8
Probabilistic results - BEIS gas price scenarios (authors' analysis).

Technology	P90	P50	P10
CCGT	£ 37.82/MWh	£ 45.76/MWh	£ 50.39/MWh
Offshore wind	£ 45.87/MWh	£ 54.14/MWh	£ 59.80/MWh

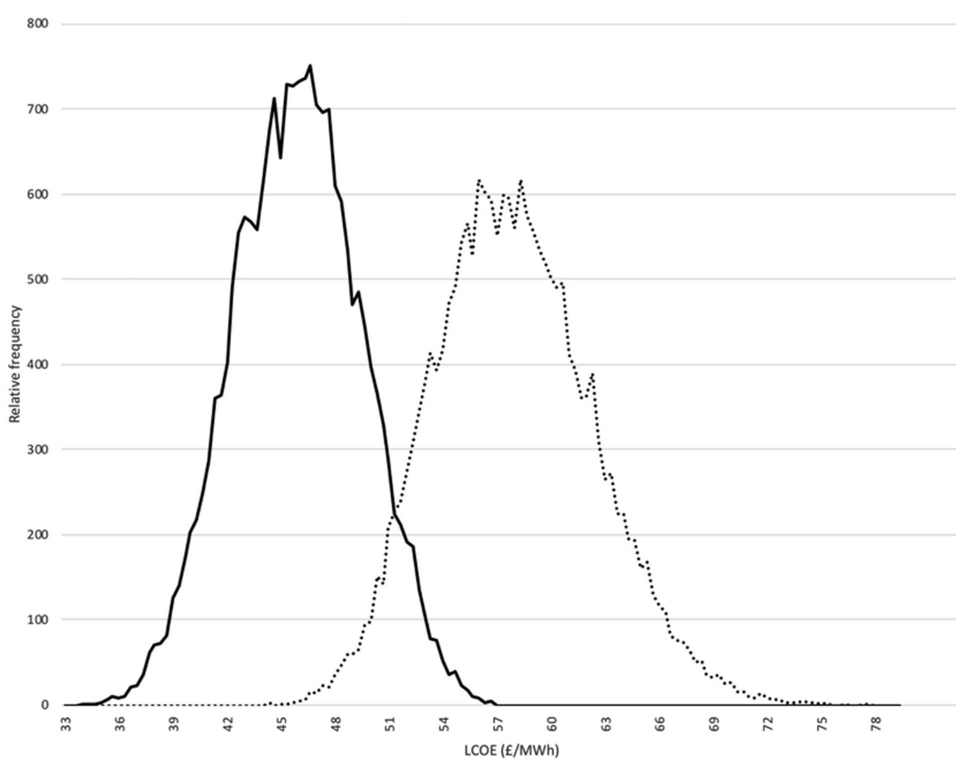

Fig. 5. $LCOE_{BEIS}$ ranges for CCGT and Offshore Wind (authors' analysis).

Table 9
Probabilistic results -statistical gas price scenarios (authors' analysis).

	P90	P50	P10
CCGT	£ 17.30/MWh	£ 45.59/MWh	£ 83.48/MWh
Offshore wind	£ 45.87/MWh	£ 54.14/MWh	£ 59.80/MWh

analysis.

The Monte Carlo model has been adjusted to allow the fuel gas price for CCGT to vary within the statistical distribution determined by past data (i.e. the change from year to year in real terms was set to have a mean of 0.84p/therm with a standard deviation of 14.9p/therm), and the initial results for this are shown in Table 9 and in Fig. 6.

This analysis shows that the range of variability of $LCOE_{BEIS}$ for CCGT is much higher than for offshore wind.

In this case, it is clear that the possible range of CCGT varies widely between around £17/MWh and £120/MWh with the median (P50) at £45/MWh, while offshore wind remains well constrained around £45–60/MWh. Under these assumptions, there is a 38% chance that the $LCOE_{BEIS}$ for CCGT exceeds the P50 $LCOE_{BEIS}$ for wind. The much wider range in possible $LCOE_{BEIS}$ for CCGT is clearly attributable to the wider range in possible fuel gas prices used in this latter analysis.

Although further statistical analysis on the variability of fuel gas prices is required, it is clear that this factor is a powerful driver of the $LCOE_{BEIS}$ for CCGT projects. By extension, it is likely that the $LCOE_{BEIS}$ for coal and oil fired generation is also likely to be strongly driven by feedstock prices.

7. Discussion

There is a considerable literature in which the LCOE metric is used. Perhaps surprisingly, it is rare to find any discussion of theoretical basis for the metric in literature, which focusses instead on its application. It is as if the metric sprang rapidly into widespread use before there was any opportunity to consider whether it was genuinely the most suitable metric to use.

Its promotion by both NREL (National Renewable Energy Laboratory, 2018) and the UK Government BEIS (HM Government Department for Business, 2016) may well have led to its widespread adoption as the “standard” measure, and its use by well-respected commercial entities such as Lazard (2016), Mott McDonald (2010), Arup (2016) and Ernst and Young (2012) are likely to have added to its perceived gravitas.

Perhaps rather late in the day, a theoretical justification for $LCOE_{BEIS}$ has been offered here and its use justified in the context of other potential measures of lifetime costs of energy. The comparative review undertaken here suggests that $LCOE_{BEIS}$, particularly when used with real (rather than nominal) costs, does provide useful insight into the minimum price required for a project to achieve a target return. As Table 1 shows, $LCOE_{BEIS}$ is merely one of a family of potential metrics to evaluate the unit cost of energy. While other metrics are available, adoption of an alternative to $LCOE_{BEIS}$ would not offer such an increase in benefits that the abandonment of $LCOE_{BEIS}$ should be recommended.

It is critical however to note that $LCOE_{BEIS}$ and $LCOE_{NREL}$ are different measures, as the BEIS measure includes an allowance for the financing requirements of operating costs, while the NREL measure does not. Users should be clear which metric they are using, and why. It is noted that both benefit from the credibility of being called LCOE, despite their differences.

Many authors use the LCOE without any explicit reference to the importance of appropriate choice of discount rates or to the impact of inflation or uncertainty in future costs, and this can give rise to misleading or even unhelpful results, as this analysis has determined.

This analysis has found that selection of appropriate discount rate, inflation rate and probabilistic modelling of future costs can radically change the perception of the relative merits of energy generation alternatives. In particular, the variability in future fuel prices for CCGT (and by extension, other thermal technologies) can significantly alter the possible range of LCOE. Fig. 6 shows that the possible range of

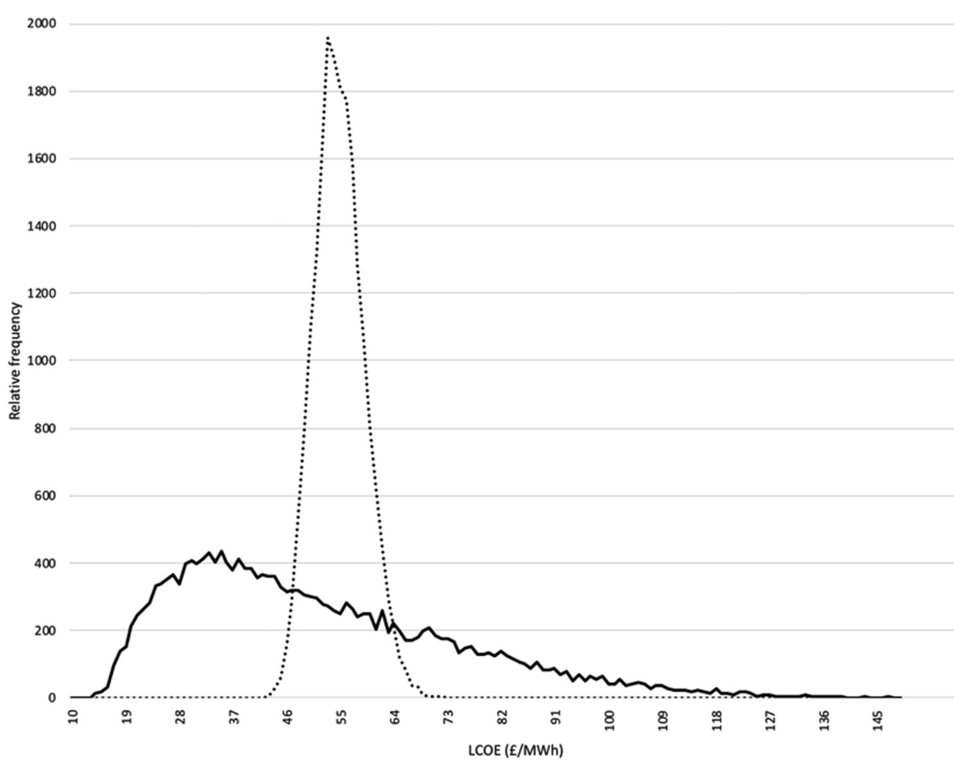

Fig. 6. $LCOE_{BEIS}$ for CCGT and Offshore wind, with statistical fuel gas prices (authors' analysis).

$LCOE_{BEIS}$ for CCGT, from £17/MWh to £120/MWh might be so great as to make the choice for offshore wind (range from £45/MWh to £60/MWh) a less risky choice. In the light of historic variability of gas prices, attempting to make meaningful deterministic forecasts of fuel prices seems doomed to inaccuracy. While scenario-based approaches might give some sense of the range of possible LCOEs, it can be hard to resist the temptation to pick a preferred scenario and rely on its deterministic result. This can lead to poor decision-making, and it is therefore strongly urged that a probabilistic approach be taken in the application of the $LCOE_{BEIS}$ metric, to provide richer information on the relative merits of alternatives.

The metric still has weaknesses: on one side, the impact on a national electricity distribution system of the intermittency of renewables, as compared with the dispatchable nature of thermal generation (explored by Joskow (2011)) is not directly addressed; conversely, application of the $LCOE_{BEIS}$ metric rarely includes any attempt to value the carbon impact of thermal technologies or other externalities. With offshore wind and CCGT technologies now apparently approaching comparability on the basis of LCOE, it may be time for application of the metric to address these sophistications.

As overall project costs for offshore wind reduce over time, and become more directly competitive with thermal electricity generation, it will become more and more important to apply comparative evaluation tools in the full knowledge of their subtleties.

8. Conclusion

The $LCOE_{BEIS}$ metric is well established but lacks a clear theoretical justification. This paper provides one. It analyses and compares different cost of energy metrics by scrutinising their working principles and concludes that $LCOE_{BEIS}$ offers a useful metric, albeit with shortcomings and subtleties. While deterministic assessments of LCOE for CCGT power plants can be lower than those for offshore wind, when discount rates, inflation factors, and most critically, variability in feedstock prices are taken into account, the variability in LCOE for CCGT projects can complicate the picture. The authors urge the thoughtful use of this metric and the widespread adoption of Monte Carlo techniques in its calculation.

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