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A decision support tool to assist with lifetime extension of wind turbines

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ABSTRACT

This paper is aimed at analysing the levelised cost of energy (LCOE) of onshore wind turbine generators (WTGs) that are in operation beyond their design lifetime. In order to do so, the LCOE approach is introduced and input parameters are discussed for a UK deployment. In addition, a methodology is presented to support economic lifetime extension and investment decision making at the end of an asset's design lifetime. As part of a case study, a wind farm consisting of six 900 kW WTGs is subjected to different combinations of i) lifetime extension (5–15 years), ii) input assumptions (pessimistic, central, optimistic), and iii) reinvestment types (retrofits). Results indicate that in the central lifetime extension scenario, LCOE estimates of 22.40 £/MWh are achievable.
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1. Introduction

Lifetime extension of wind turbines is an industry area that is receiving more and more attention as depicted by standards, recommendations, and academic papers [1–10]. This is mainly because the European wind fleet is ageing [11] as exemplified in Fig. 1 for the UK and the more competitive allocation of governmental subsidies as identified by Rubert et al. [7]. In addition, recent results of a global survey on the development of levelised cost of energy (LCOE) with 166 participants reveal that within an optimistic economic scenario an onshore lifetime extension of 25% is expected, based on an average operational lifetime of 20.7 years [12]. Note that for the offshore fleet, these figures are +25% and 20.3 years, respectively. Based on the industrial attention and the overall observable reduction in onshore subsidies for new investments and repowering, lifetime extension is expected to become an essential part of the wind industry in the future. However, lifetime extendibility is dependent on an asset's unique technical and economic circumstances and thus requires due diligence in both areas.

Although, there are already significant numbers of wind turbines reaching their end of lifetime [11,13], at present there are no papers analysing the economics of lifetime extension and decision making at the end of lifetime. Consequently, in this paper we present the economic metric of LCOE and discuss input variables in Section 2 alongside a proposed application methodology to assist economic lifetime extension decision making. This is followed by a lifetime extension case study presented in Section 3 based on a wind farm with a capacity of 5.4 MW, consisting of six 900 kW rated wind turbine generators (WTGs). Section 4 presents the case study's results while in Section 5 this paper's validation is presented. In Section 6 limitations and future work are discussed and finally in Section 7, findings are concluded.

2. Levelised cost of energy

Levelised cost of energy is an economic metric that enables to compare different competing energy technologies such as gas, coal, nuclear, solar, hydro, and wind. It can also be applied to compare and contrast different investment scenarios. Contrary to other economic metrics such as return of investment (ROI) and internal rate of return (IRR) that take the financial revenue streams into consideration, LCOE determines the cost of energy produced rather than the potential profit of an investment. While there are different and modified LCOE calculation approaches [14–18], this paper's adapted approach is as follows. The net present value (NPV) of lifetime costs accrued of capital and operational expenditure

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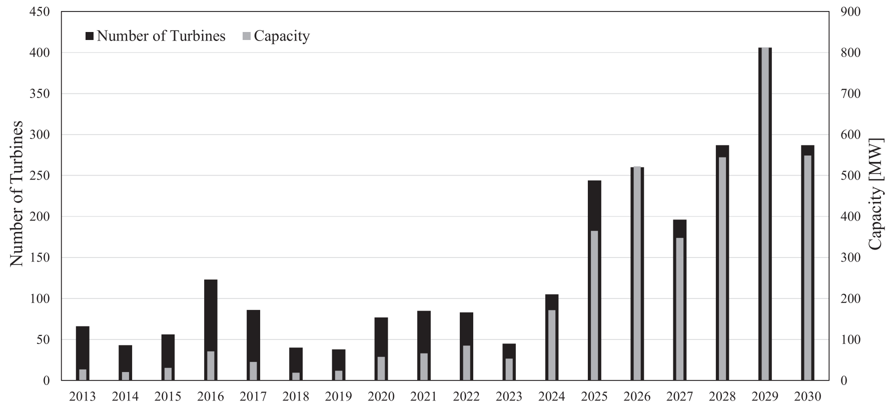

Fig. 1. Onshore capacity reaching end of design lifetime in the UK (20 years) [13].

(CAPEX and OPEX) is estimated for each year, n and summed over the design lifetime as illustrated in Equation (1):

$$NPV_{TotalCost} = \sum\nolimits_{n=0}^{T} \frac{CAPEX_n + OPEX_n}{(1+i)^n} \tag{1}$$

where T is the design lifetime and i the discount factor. Generated electricity flow is a monetary metric, thus future energy delivery requires discounting as well. This might be counter-intuitive because a specified amount of energy delivered in the future is through discounting worth less quantity at present; however, based on the electricity supply a revenue stream is created and money exchanged. Hence discounting is necessary as illustrated in Equation (2):

$$NPV_{Yield} = \sum\nolimits_{n=1}^{T} \frac{AEP_n}{(1+i)^n} \tag{2}$$

where AEP_n is the annual energy production of year n.

LCOE is the cost to generate a defined amount of energy; i.e., [£/MWh], hence the NPV of lifetime generation costs defined in Equation (1) is divided by the NPV of the lifetime generated energy defined in Equation (2), thus:

$$LCOE = \frac{NPV_{TotalCost}}{NPV_{Yield}}. \tag{3}$$

Therefore, to determine LCOE for a project, it's lifetime expenditure as well as estimated yield requires evaluation. Within the wind energy industry, different organisations apply different LCOE models; i.e., model varieties originate from different design assumptions such as the CAPEX that can be dealt with as an overnight cost as suggested by the Department of Energy and Climate (DECC) [15], or alternatively as a constant annuity payment as suggested by the National Renewable Energy Laboratory (NREL) [17]. Furthermore, model differences can origin from the discount factor, selection of which requires caution and due diligence. In essence, the discount factor represents a project's risk and thus requires case specific evaluation that is dependent on several factors. For wind energy investments, this includes the investor and investment size, historical data, contracts in place, type of power purchase agreement, the subsidy scheme as well as assumptions in yield estimation and operations and maintenance (O&M) expenditure. Methodologies concerning the applied discount rate may deviate as well; i.e., NREL [17] takes a project's debt-equity ratio and corporate tax rate into consideration by application of the weighted average cost of capital (WACC). On the contrary, less complex models define a hurdle rate aimed at forming a specified project's return as applied by DECC that is set at 10%, although in form of a sensitivity analysis a rate of 7.5% is modelled as well [14,15,19].

Apart from a WTG's input, the output requires analysis as well in order to predict an asset's annual electricity production. If a turbine's physical parameters are known it's energy yield can be estimated by application of a Weibull distribution defined by the shape and scale factor as well as the mean recorded wind speed [20]. The Weibull distribution can thus be modified according to locally recorded environmental conditions. Once the yield for a given period is estimated or known based on a turbine's output, the capacity factor can be calculated. The latter that is defined as the ratio of the actual output of a turbine for a given period and the theoretical output at full capacity.

2.1. Model input parameters

In this Section the detailed LCOE methodology is presented, highlighting how parameters are obtained in order to allow reproduction of the findings presented in Section 4. As illustrated in Equation (3), a LCOE estimation requires two sets of input, a turbine's expected yield and the estimated expenditure over the asset's design lifetime. Within the wind energy sector, LCOE cost parameters are accessible from several sources such as DECC [15,19,21,22], WindEurope [23], Milborrow [24,25], NREL [17], and the International Renewable Energy Agency (IEA) [26], while Miller et al. [27] present a comparison for the US market; however, in agreement with the latter, input parameters deviate significantly (a comparison of OPEX is illustrated in Table 1). This presents challenges to select appropriate model parameters.

Further complexity arises from the time domain, as a wind farm that reaches its end of design life at present experiences current OPEX, while the asset's initial CAPEX was paid for in the past. This modelling challenge is addressed in the proposed lifetime extension methodology in Section 2.2.

2.1.1. Operational expenditure

Operational expenditure covers all occurring activities that are necessary to ensure a safe, reliable, and continuous operation. Costs include administration, land lease, insurance, service and spare parts, power from the grid, as well as miscellaneous items that can vary significantly with an example cost breakdown structure illustrated in Fig. 4 of the Appendix. To allow an impression on the variance in cost estimations, Table 1 presents the cumulated fixed and variable O&M expenditure of different published estimates for a 900 kW wind turbine over 20 years. Overall, a substantial expenditure range is observable which reveals the degree of uncertainty within LCOE calculations. In addition, in Germany there is

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