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Dynamic evaluation of the levelized cost of wind power generation ☆

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ABSTRACT

This paper discusses an alternative computation method of the levelized cost of energy of distributed wind power generators. Unlike in the conventional procedures, it includes time of commencement as an optimization variable. For that purpose, a methodology from Longstaff and Schwartz's dynamic program for pricing financial American options is derived, which provides the ability to find the optimum time and value while coping with uncertainty revenues from energy sales and variable capital costs. The results obtained from the analysis of wind records of 50 sites entail that the conventional levelized cost of energy can be broken down into an optimum, minimum (time-dependent) value and a penalty for early exercising, which can be employed to define investment strategies and support policies.

1. Introduction

The cost-effectiveness performance and improvement of an energy supply technology, when compared with other technologies and previous designs, can be easily assessed by the levelized cost of energy (LCoE). The LCoE—defined as the price at which each unit of produced energy must be sold, so that all generation costs are recovered—summarizes in one only figure a number of embedded features concerning a generation plant lifetime [1, Ch.6]. These features are specific to each technology and production site. But appropriately translated into a stream of financial revenues and costs—all actualized to the same present value—the LCoE makes it possible to conduct cross-sectional analyses between technologies or record sequential improvements over time.

The previous claims can be readily corroborated through the energy literature. Institutions such as the U.S. EIA [2] and the NREL [3], for instance, repeatedly make use of the LCoE as a benchmark tool. Researchers employ LCoE as a comparison between the performance of different technologies: see for example a comparison between 10 MW of wind and PV power in [4], or a comparison of non-renewable and renewable energies including CO_2 externalities in [5] to demonstrate the competitiveness of wind power plants compared with conventional generation. Studies like [6] for instance, make a thorough comparison of technologies precisely using the LCoE. In other instances indirectly as a measure of improvement, the LCoE is employed as the objective function of optimization problems concerning layouts or structural designs. In [7] individual turbines and wind farms are constructively optimized on the basis of reducing the final LCoE. Similarly in [8] the LCoE is employed as the objective function of a bi-level programming approach to also optimize the constructive layout.. And in the particular case of wind energy production—the subject of this paper—Farrell and colleagues' paper offers a thorough review of LCoE estimates existing in the literature [9].

A drawback of the LCoE as a tool for strategic evaluation is its static nature. Essentially it can be expressed as the ratio between lifetime costs and lifetime generation. But this simple relation entails that all the costs and generated energy must be discounted back to the year of interest. This can be the current year or a projection into the future, depending on the purpose of the computation. Indeed, the lifetime costs are inclusive not only of all the expenses incurred to produce the energy over the useful life of the generation plant, such as O&M and fuel costs, but also of the capital costs to build the plant; which in energy related literature are sometimes called "overnight" costs, meaning that the actual plant would be equivalent to a plant built in just one day (see for instance [6] where indicative figures of overnight costs for reactors are given, or [10] where a comparison between wind and other conventional thermal generation is given on this basis). For that reason, the LCoE is a static measure that needs as an input a year at which the installment will start.

It is argued in this paper, however, that the value of the LCoE can be revised by introducing the optimal time of investment as a supplement to the conventional analysis. In [11], Kahouli-Brahmi demonstrated that wind power generation—the scope of this paper—is still an evolving technology with declining

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capital costs. So it seems reasonable to think that depending on the expected future revenues and these declining capital costs, investors and policy makers might be willing to modify their decisions accordingly. Therefore, it would be preferable in such a case to have an LCoE that were inclusive not only of the present projected costs and revenues, but also of future values if the investment decision were delayed in an optimal sense. To this end, we shall demonstrate that a minimum, optimal value of the LCoE can be computed, which we shall call π_{RO}, and that the LCoE computed by conventional methods is but the sum of π_{RO} and a *penalty* for too early investment. The value π_{RO} will be the least expected cost, which will only be equal to the conventional LCoE—thus no penalty involved—when the immediate investment is actually attractive. In other cases, π_{RO} will be less than the LCoE, indicating the opportunity and advantages of waiting to a later date.

To proceed with the determination of the minimum, optimal value of the LCoE, this paper takes into account the managerial flexibility introduced through the use of Real Options theory. As in [12], Real Option analysis is recognized in this paper for its potential to increase the expected worth of projects by exploiting the value of flexibility within the investment decisions and designs. Particularly for computing the minimum cost of the energy, Section 3 provides a methodology derived from Longstaff and Schwartz's procedure for pricing American options under underlying uncertainty [13]. Unlike in the conventional computation of LCoE (see [10]), this methodology allows accounting for the uncertainty of future revenues and provides a valuation in which the starting time is an optimized variable. Thereafter in Section 4, the rationale and implications for strategic decisions and support policies of the calculated minimum cost of energy is discussed.

2. Conventional LCoE

Several formulations can be employed to compute the LCoE; see [14] and references therein. But essentially, the LCoE can be expressed as

$$\text{LCoE} = \frac{I_0 + \sum_{t=1}^{T} C_t e^{-rt}}{\sum_{t=1}^{T} E_t e^{-rt}}, \tag{1}$$

where

T is the lifetime of the project;
I_0 is the initial (capital) expenditures, the overnight costs, hereafter CAPEX;
C_t is the annualized cost of operation—inclusive of O&M and other expenditures—at year t, usually termed OPEX;
E_t is the energy produced at year t; and
e^{-rt} is the *discount factor* at an interest rate equal to r.

(Other more detailed formulations can be found in the literature, that account for taxes, loans, landowner remittance fees, or salvage values: see for instance [4], where insurance costs, taxes, and incentives are incorporated; [15] including the degradation of the technology and the salvage value; [16] including a detailed account of the land lease cost; or [17] for a thorough description of the numerator and denominator of (1). In this paper those factors have not been included into the analysis, mindful that its inclusion would unnecessary complicate and expand the discussion, without essentially modifying the proposed approach for LCoE computation. The inclusion of those factors is, notwithstanding, straightforward.)

The LCoE can be readily put in terms of the well-known Net Present Value (NPV), if the price of energy is introduced as a known value. Let π_t be the mean price for energy sale at time t. Then the NPV is

$$NPV = -I_0 + \sum_{t=1}^{T} e^{-rt}(\pi_t E_t - C_t). \tag{2}$$

If this price is let to be constant over the whole period of analysis—which is an assumption that permits establishing a constant FiT—Eq. (2) can be put as a simple function of that constant value, π, as follows:

$$\pi = \frac{NPV + I_0 + \sum_{t=1}^{T} C_t e^{-rt}}{\sum_{t=1}^{T} E_t e^{-rt}} \tag{3}$$

Hence by comparing (1) with (3) it can be concluded that the LCoE is but the price for energy sale that makes the NPV equal to zero.

Eq. (3) is a *static* estimate of the required price of energy to obtain a given NPV, with $NPV = 0$ if the LCoE is sought. It is static because it is defined at a given time. The decision maker decides when the plant is going to be built and thereafter proceeds with the estimation of the costs and revenues corresponding to years $t = 1, \ldots, T$. From the point of view of strategic investment in which it is of interest to know the time at which it would be more profitable the investment in a given site, the year 1 may be postponed to a later date and redo all the computations to evaluate the ensuing LCoE. However, the comparison of all this simulations would not be rigorously precise enough to determine the optimal time of investment and its value, as it is discussed next.

3. Proposed methodology

3.1. Real options approach

It is observed in (1) that the LCoE computation stems from an estimate of the wind power produced at a given site, which is confronted with the *current* CAPEX (plus the O&M costs). But the question posed in this paper is: What if the commencement is delayed in time, awaiting for better profits which would arise from a possible CAPEX reduction? Again, the same revenue estimation needs to be conducted; but additionally it should be investigated (i) if there is really an added value in waiting and, if so, (ii) how long.

The problem is not easy to solve, because the decision has to be taken in a stochastic framework. Particularly, a first straight attempt to solve it would be to provide a revenue estimate for each future time step (e.g. year) and proceed with the comparisons. If at any given time in the future the sum of expected revenues obtained from building a wind power plant exceeds the CAPEX, the decision would be positive in the sense to go ahead with the investment. This would be repeated for all the years in the planning horizon. Eventually by inspection of all the positive payoffs, it could be concluded that the optimal installment time would be that at which the expected payoff is maximum. This reasoning is incorrect, however, because it implies *perfect foresight*. It entails that at the optimal time the decision maker knows that it is better to stop and install at that point than to wait, because later payoffs will be lower. Obviously, in this way the decision maker would be foreseeing the future payoffs.

A similar problem has been faced by finance analysts in the realm of American options. In this case, an option holder has the right—not the obligation—to exercise at any time over the contract duration an option, which is to buy/sell an underlying asset by paying a previously agreed upon strike price. Also in this context, the investor seeks to maximize her/his payoff—eventually the value of the option—by exercising it at a time that she/he does not know. Hence the problem is similar if the underlying (a traded asset or