Energy Conversion and Management 107 (2016) 22–33

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Technical, economic and uncertainty modelling of a wind farm project

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A R T I C L E I N F O

Keywords:
Wind farm
Financial modelling
Risk assessment
Monte Carlo simulation

A B S T R A C T

Wind is one of the fastest-growing renewable sources of electricity. As with most renewables, the economic viability relies on public subsidies. Even among renewables, the economic evaluation of wind projects is particularly challenging due to the unpredictability of the energy source, wind, and the high sensitivity of the project profitability to changes in a number of parameters. This makes the uncertainty analysis an important topic of research in the wind power sector.

This study presents a method of combining two uncertainty analysis methods, sensitivity study and the Monte Carlo method, together with a technical and economic model of a wind farm, in an effort to improve the understanding of the practical effects of the uncertainties, and how they affect the financial risks of wind projects.

1. Introduction

Among renewables wind power is one of the most popular sources of energy. The worldwide wind market grew by more than 25% annually during the last decade and future growth is expected to show a similar trend [1]. One of the main advantages of wind power is zero fuel cost and thereby independence from fuel price fluctuations and supply security concerns. However, at the same time the volatile and unpredictable nature of the wind also creates a considerable financial risk to the project and the economic environment carries its own risks as well.

Before investing in a wind farm project, an investor will want to be sure that the project is feasible and not unacceptably susceptible to risks. The aim of the paper is to create a technical and economic model of a wind farm and to incorporate a risk analysis to provide a tool for predicting the economic performance of a wind farm within a chosen uncertainty level.

Extensive manual by National Renewable Energy Laboratory (NREL) [2] gives a guideline for economic evaluation of the renewable energy technologies, providing a comparative analysis of the main economic metrics used in the industry: simple payback period (SPB), discounted payback period (DPB), benefit-to-cost ratios (B/C), net-present value (NPV), total life-cycle cost (TLCC), internal rate of return (IRR), cost of energy (COE), levelized cost of energy (LCOE), etc. Each of the metrics has advantages and drawbacks: it is important to be aware of the scope of the analysis to use right metric for right application.

Several authors have studied the economics of wind farm projects. Similarly to [2], work [3] also discusses the economic metrics listed above and some others, focusing particularly on the wind energy industry. Authors propose using several metrics for the economic evaluation of the project, as they can give different results. The predominant economic analysis techniques are COE [4–6], LCOE [7] and NPV [8]. The LCOE and NPV use net cash flows discounted to the present.

In this work the economics of the project are considered in terms of NPV obtained from the evaluation of investment costs, operation and maintenance costs and income from the sold electricity. NPV is considered as the most explicit and robust method for project financial analysis [3]. The results are validated against a period of plant data from an operating wind farm. The disadvantage of the NPV method is that it is based on forecasts of future costs, prices and interest rates that may not hold true for the lifetime of the project, and it does not consider uncertainties of these assumptions.

Common methods to consider uncertainty in the standard discounted cash flows (DCF) techniques are scenario and sensitivity analysis. These methods give some indication of the risk; however, they do not provide clear measure of project risk, as they do not produce an estimate about probable net profit. The Monte Carlo (MC) simulations enable presenting a better picture of the expected outcome and the related uncertainties. The MC method yields stochastic predictions, provided that information about the probability distributions of the uncertain variables is known. Most

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http://dx.doi.org/10.1016/j.enconman.2015.09.048
0196-8904/

Nomenclature

A	surface area (m^2)
AEP	annual energy (MW h)
C	cost (k€)
c	Weibull scale parameter (m/s)
c_T	thrust coefficient
D	diameter (m); direction (°)
f	probability density function
h	height (m)
I	income (k€)
k	Weibull shape parameter
NPV	net present value (k€)
P	power (MW)
p	interest rate
p	probability
T	time (h)
V	wind speed (m/s)

Greek symbols

α	wake decay constant
Γ	Gamma function
γ	wind shear
ε	error
κ	discount factor
ρ	density (kg/m^3)
σ	standard deviation

Subscripts and superscripts

COE	cost of energy
d	direction
eff	effective
hub	at the hub of the turbine
in	cut-in
inv	investment
LCOE	levelized cost of energy
O&M	operation and maintenance
op	operation
out	cut-out
overlap	overlapping
rated	rated by manufacturer
SI	sensitivity indicator
std	standard
SV	switching value
swept	swept by the wind turbine blades
t	time
VaR	value at risk
x	at position x

commonly the normal distribution is assumed, but a number of important uncertain parameters are in fact known to be not normally distributed. In wind farm research field uncertainties have been considered by some authors, using both sensitivity analysis [7,9] and MC simulations [10,11].

The work by International Energy Agency [7] recommends a procedure for the classification of wind projects by levelized production cost (LPC), summarising the input parameters and their uncertainties, and proposes simple methodology to estimate confidence interval of LPC. The parameters are assumed to be independent and have Gaussian distributions; the overall uncertainty is found using the expected values and variances of each input parameter.

According to report [8] wind resource, electricity price, future variable costs and discount rate are the main factors contributing to uncertainty in the profitability of the wind farm. The report investigates the influence of uncertainty in wind resource on the optimization of the wind farm layout. The presented model also incorporates a function describing the level of risk the investor is willing to accept, based on Utility theory. It uses different scenarios and their probability in long-term wind resource to find expected values of NPV and utility function. Naturally this model demonstrated that for risk averse investor the optimized layout is less sensitive to wind resource variability, but at the same time profitability is smaller compare to riskier investor.

In Ref. [10] a probabilistic cost model OWECOP (Offshore Wind Energy Costs and Potential) is implemented. For this model a wide range of relevant parameters was identified and their probability distributions were constructed based on measurements and experts' opinions. To name a few, average wind speed and vertical wind shear exponent were modelled using normal distribution, Weibull shape parameter was assumed to follow uniform distribution, and for wind farm availability and array efficiency PERT distribution was used.

In this paper to handle the disadvantages of the NPV method, both the sensitivity analysis and the MC method are included to account for uncertainties. MC simulations rely on the estimation of the uncertain parameters from historical data; this may not always be the most reliable way for estimating the future, however. For instance, electricity price trend may change due to changes in policies and market situation, and due to climate change wind resource at site can also change. It was therefore considered appropriate to accompany the MC method also with a sensitivity analysis of uncertain variables, to provide additional information about project economics under different conditions for better assessment of the project.

In this work the MC simulations are performed using input parameters whose distributions are known; wind resource parameters and power production of the wind turbine. For parameters that are uncertain, but distributions and degree of uncertainty itself is unknown, sensitivity analysis is applied.

2. Modelling

The framework structure used in this paper is shown in Fig. 1. To evaluate the performance of a wind farm, both the economic and technical aspects must be modelled. This is done separately within the framework. Data of wind turbines and economics are processed according to the wind farm design. The annual energy production (AEP) is determined using the wind speed distribution at the turbine locations, the power curve of the turbines and the operational time per year. Together with economic data, the AEP is the basis to calculate financial parameters in the economic model. The Monte Carlo sampling module takes uncertainties into account and is further explained in Section 3.

2.1. Economic model

The economic evaluation of the wind farm project is based on the NPV, which represents the sum of cash flows during the life time of the project discounted to the present. It is chosen as it gives a clear picture of the profitability of the investment, and is also one of the most commonly used economic evaluation methods. The NPV is calculated from the investment cost $C_{\mathrm{inv}\,t}$ operation and maintenance (O&M) cost $C_{\mathrm{O\&M}\ t}$ and income I_t: