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Improved framework for techno-economical optimization of wind energy production

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ABSTRACT

This paper presents an improved framework for the techno-economical optimization and analysis of wind energy production. The main objectives are the maximization of the wind energy production and the minimization of the Levelized Cost of Energy (LCOE). The energy production maximization is achieved through optimal site matching of wind turbine generators. Comparative and improved analyses of various models for the optimal matching process and its associated performance indicators are presented. In addition, an improved model for estimating the wind energy production is adopted. Numerical demonstrations are presented considering a set of selected sites in Egypt. These sites cover all the Battelle-Pacific Northwest Laboratory (PNL) classes of wind resources. In addition, careful inspection of the PNL classification discrepancies is presented. Based on energy production, the best site matching index is determined for various wind resources. In addition, the LCOE is estimated considering various indicators, financial, and technical inputs. Measures for reducing the LCOE are determined based on a sensitivity analysis. The external costs of energy have been considered in estimating the LCOE and evaluating the grid parity. In addition, a grid parity analysis is presented considering various load sectors and debt ratios. The main outcomes are summarized in the conclusions' section.

Introduction

There are many adverse impacts associated with the widespread use the non-renewable fuels in the electric energy production. These adverse impacts include ecological degradation and economical problems. In addition, the worldwide reserve of fossil fuels is diminishing. Therefore, the world tends to replace the non-renewable fossil fuels by renewable energy resources for electrical energy production [1]. Renewable energy technologies (RETs) offer electricity production with insignificant amounts of the emissions of carbon oxides as well as other pollutant gases and discharges [2–4]; however, the high investments associated with RETs are one of the major barriers to the widespread use of RETs. Therefore, minimization of the lifetime costs of renewable energy projects is expected to significantly promote the grid-integration of renewable energy sources. Other barriers include the intense variability and intermittency of variable renewable resources such as wind and solar energies [5,6]; however, the geographical diversity of resources and technologies as well as advances in the energy storage technologies such as hydrogen are expected to overcome the variability and other operational challenge [6–9].

The Levelized Cost of Energy (LCOE) is the ratio between the discounted lifetime costs and discounted lifetime energy production [4]. Therefore, the minimization of the lifetime costs and/or maximization of the energy production are the ultimate way for LCOE reduction. In [4], the proper selection of photovoltaic (PV) modules and sun tracking systems are shown to have significant impact on the energy production and the costs associated with PV power plants. Generally, proper or optimized selection of RETs for a given renewable energy resource is expected to improve the overall techno-economic feasibility of renewable energy projects.

Wind energy is among the major renewable energy resources. The costs associated with wind energy are low in comparison with other renewable energy production projects; however, wind energy projects have some ecological drawbacks such as noise, bird migration routes blockage, and landscape view debate [10]. The bird migration problem can be adequately solved by proper selection of the hub heights of the wind turbines. In this paper, the optimal site matching of wind turbine generators (WTGs) is adopted for selecting of the wind turbines for a given wind resource characteristics. The main target is the maximization of the wind energy production and consequently the minimization of the LCOE.

The LCOE associated with fossil resources are generally high in

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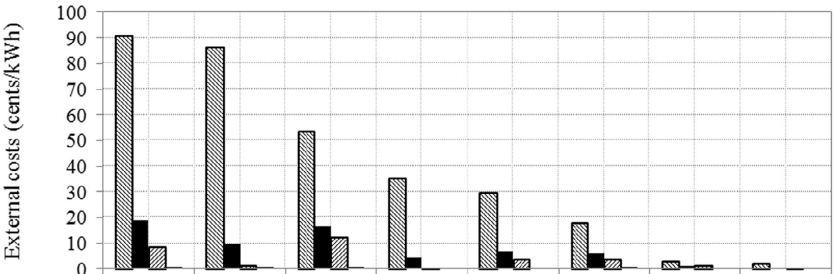

	Coal	Nuclear	Oil	Hydro	Biomass	Natural Gas	Solar	Wind
Max	90.61	86.23	53.43	35.14	29.56	17.69	2.94	1.81
Average	18.75	9.53	16.48	4.5	6.62	6.17	1.12	0.41
Median	8.54	1.08	12.19	0.43	3.59	3.51	1.02	0.43
Min	0.01	0.01	0.04	0	0	0.01	0	0

Generation source

Fig. 1. External costs of popular power generation technologies.

comparison with the LCOE of renewable resources; however, the consideration of the true costs of energy may reverse the situation or, at least, significantly reduces the LCOE of renewable energy [11,12]. The true costs of energy include all external costs. The external costs include the costs associated with health and environmental damages caused by emitting pollutions. The factors that affect the value of the true costs include the population density near a power plant, emitted pollutions, and sustainability. There are three main types of studies for estimating the true costs; the primary studies, benefits-transfer studies, and meta-studies [11]. Two approaches are available for estimating the true costs for each type of studies: the damage function approach, and the abatement cost approach. Details about various studies and approaches are available at Ref. [11]. Fig. 1 shows the minimum, median, average, and maximum values of the external costs of popular energy sources. As expected, it is clear from Fig. 1 that the minimum external costs are associated with wind and solar energy sources while highest costs are associated with conventional energy sources, especially coal, nuclear, and oil based energy sources.

The costs associated with wind energy projects are fixed and variable costs. The fixed (or capital) costs present about 80% of the total investment costs while variable costs present the rest of the investment [12–14]. The capital costs include the costs of wind turbines (64% of the capital costs), civil work (17%), grid connection (10%), and other costs (9%) such as development and engineering costs. The variable costs include operation and maintenance costs, land and substation rental, insurance, taxes, management, and administration costs.

This paper presents an improved framework for the techno-economical optimization and analysis of wind energy projects. Since the LCOE is among the main viability indicators of energy projects [4], then its minimization is the main objective of this paper. Randomly selected wind turbine generators (WTGs) regardless of the site-dependent stochastic characteristics of the wind resource can hinder the possible feasibility of wind energy projects. Therefore, in this paper the WTGs are optimally matched to the available wind energy resources in the project candidate sites. A wind resource is represented by the Weibull probability distribution function (PDF). In addition, the Weibull parameters and the average wind speeds are corrected for the selected hub-height of the proposed wind turbines. Based on the locations of the considered sites, the hub-heights of WTGs are determined considering various constraints. These constraints include bird migration routes, martial, and other site-specific constraints. Popular models of the output power curve of WTGs are considered and their performance is compared. In addition, various indices for WTG site-matching are considered and the consequent probable energy productions are assessed. These indices include capacity factor (*CF*) maximization, turbine performance index (*TPI*) maximization, and Normalized power (*PN*) maximization [15]. Based on energy production, the best site matching index is determined for various wind resources. In addition, the LCOE is estimated considering various indicators. Specific locations in Egypt are selected for the numerical demonstration of the presented framework. The selected sites cover all the classifications of wind energy resources as defined by the Battelle-Pacific Northwest Laboratory (PNL) [16,17]. Based on the actual utility retail energy prices in Egypt, the grid parity analysis is also presented for various sites and various load sectors.

Problem Statement and mathematical modeling

As previously stated, the main objectives of this paper are the construction of a framework for the maximization of the wind energy production and the minimization of the LCOE of wind power. In addition, the paper considers the estimation of the LCOE and grid parity analysis. The traditional evaluation of the LCOE is based on an unjustified selection of WTGs that do not consider the wind resource characteristics of the project location. Consequently, the estimated LCOE may be far from its minimum possible value. The minimum value of the LCOE is expected to be achieved if the WTGs are optimally matched with the wind resource, provided that the matching objective is the maximization of the energy production. This is the core concept of the presented framework. In addition, the assessments of the energy production of WTGs do not usually consider other meteorological conditions of the site, such as the temperature and atmospheric pressure as well as various losses. As a result, the estimated energy production is expected to be overestimated. Improved model for estimating the energy production is adopted in this paper. The adopted model considers various losses as well as represents the meteorological conditions impact on the energy production. The main structure of the framework is shown in the flowchart in Fig. 2.

This section provides the mathematical modelling needed for estimating the LCOE. In addition, this section presents various mathematical models for the output power curve of WTGs. The mathematical formulations and the solutions for the problem of the optimal site matching of WTGs are also presented. The nomenclature is listed in Appendix A1.

Modelling the LCOE

Generally, The LCOE captures capital costs, ongoing system-related costs and fuel costs – along with the amount of electricity produced – and converts them into a common metric; $/kWh [4]. The LCOE can be defined by Eq. (1) [4,18–20]. The total life cycle costs (*TLCC*) are ‘all costs that paid throughout the lifetime of the project discounted to the present year’. Therefore, TLCC is estimated using Eq. (2) [13]. In this equation, C_t is the net annual project costs at year *t*, *r* is the discount rate, and *n* is the project lifetime. The net annual costs of the project (C_t)