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Contribution of pumped hydro storage to integration of wind power in Kenya: An optimal control approach

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ABSTRACT

This paper investigates the benefit of optimally integrating wind power in Kenya with pumped hydro storage. The approach includes development of an optimal control strategy to deploy paired wind and pumped hydro storage resources, for the Lake Turkana Wind Power project. The stochastic model, which maximizes expected revenue over the planning horizon, is developed taking into the consideration the structure and running of the Kenya electricity market. The 300 MW Lake Turkana Wind Power wind farm is simulated using wind speed data from Marsabit, which is in close proximity to the Lake Turkana region. From the simulation of the wind farm, we find that the daily pattern exhibited by the wind speeds, does not match the average daily load pattern. Pumped hydro storage reduces the systems total power output shortage by 46%. This approach to operation could alleviate the significant economic burden of the take-or-pay purchase agreement that led to the removal of financial backing of the project by the World Bank. The use of pumped hydro storage in conjunction with the wind farm is also found to increase the expected daily revenue of the wind farm by over ten thousand dollars.

1. Introduction

Many African countries rely heavily on renewable energy resources to generate power [1], with hydropower domination in Sub-Saharan African countries. A hydropower-dominated power system is vulnerable to large variations in rainfall and climate change resulting in power shortfalls [2] leading to increased use of diesel generators to meet the shortfalls. In Kenya hydropower constitutes approximately 50% of the total generation installed capacity, and has had reduced power generation, due to failure of long rains. The country also suffers from frequent intermittent outages, low electricity access rate for the country's population and high power system losses [3]. The burden of power outages on the economy is estimated to be as high as two percent of GDP [4]. Over the last couple of years there has been a considerable increase in the demand for electricity and with reduced generation of hydropower, there has been an increase in the use of diesel thermal plants. This has come at a high cost to the environment and to the consumer as well, due to the increase in crude oil prices [5]. As a result the government is turning its interests to the production of wind power [6].

In Kenya, the total installed capacity in 2011 was approximately 1400 MW [7] with wind power accounting for less than 1% of this value, 5.45 MW [5]. With incentives such as Feed-in Tariff policy, providing a fixed tariff structure, and priority purchase of renewable energy sources [8] there is keen interest in the development of wind resources to generate power. There are specific locations within the country that pose relatively strong and persistent wind speeds throughout the year [9]. It is estimated that wind farms producing up to a total of 610 MW of wind power are to be developed [5]. The first large wind farm to take advantage of the countries wind power potential is the Lake Turkana Wind Power Project (LTWP), which is currently under development, with a total installed capacity of 300 MW consisting of 365 Vesta V52 850 kW turbines [10]. Wind power in 2015 is expected to consist of approximately 17% of the total installed capacity [7]. The large increase in wind energy penetration in a country previously with little to no wind energy production, introduce new challenges for the entire power system. In addition the market structure and specifics of the LTWP power purchase contract will also pose challenges to the system.

In the Kenyan electricity market, power is bought from the generators on the basis of negotiated Power Purchase Agreements (PPA), which are long-term contracts of approximately 15–20 years [5]. The terms in the agreements stipulate, among others, that the value of each unit of power generated, capacity charges, and value of penalties charged. The terms agreed upon in the PPA's vary for

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different generation sources. The LTWP PPA, like most wind power PPAs, is on take-or-pay terms, meaning that payment for every kWh of energy delivered is made on the amount of energy available and not on how much is actually used. The take-or-pay clause coupled with the fact that renewable power generators are guaranteed priority purchase, transmission and distribution [8] could potentially pose a challenge in the power system operations and economics [11]. Based on these concerns, World Bank withdrew its backing for the LTWP project stating that the take-or-pay provisions in the PPA, would expose Kenya Power (system operator) to unacceptably large financial risk due to possible curtailment and defeats the project's primary purpose of reducing the cost of power in Kenya [12]. Due to these reasons, we consider the combined operation of wind power for the Lake Turkana Wind Power wind farm with pumped hydro storage.

Pumped hydro storage is a form of electricity storage and is the preferred storage system for Kenya because of the country's long standing use of hydro resources. Electricity storage offers a technological solution that can maximize the use of variable renewable energy production without the need of additional reserve or curtailment while also reducing chances of grid congestion and improving system reliability [13]. Energy storage could enhance wind energy by allowing limited control of dispatch from a wind farm and smoothing fluctuations in wind generation [14]. By optimally integrating a pumped hydro system with the LTWP wind farm the generator would be able to store energy during low consumption periods and generate power during the low wind and high consumption hours reducing the need for curtailment.

The integration of wind power with storage has been the basis of many studies [14–19]. The focus of the studies has been on the optimal integration of wind with storage to enable wind power to competitively participate in the electricity market while maximizing revenue. We seek to find the optimal operation of a wind farm with storage in the Kenyan electricity market to show the benefit of storage in the operation of a wind power farm. Many of the studies focus on countries in the west such as North America and Western Europe, where electricity markets operation and structure differ significantly from markets in developing countries. In this model we specifically take into consideration that the Kenyan electricity supply industry structure is of the single buyer model with all generators selling power in bulk to Kenya Power for dispatch and onward transmission and distribution to consumers [5], with no bidding in a day-ahead market.

There have been different approaches to the optimization of wind farms with storage units, broadly categorized into deterministic and stochastic approaches. For example Refs. [15,18] take a deterministic approach to solving the problem of the optimal dispatch schedule. In Ref. [15] the optimization is formulated as a linear programming problem and solved sequentially over various wind power scenarios and the average, maximum and minimum values are obtained and used to represent the proposed operation strategy. The authors in Ref. [18] assume that the forecasted wind velocity is equal to the mean historical wind speed for all the hours in the scheduling periods. Deterministic dynamic programming is employed to solve the problem. While deterministic models simplify the problem and achieve a solution faster than stochastic models, these models underestimate risk from the uncertainty of wind speed. The ability to make optimal decisions requires consideration of all possible states of wind power over time with their respective probabilities, through the use of a stochastic model. The authors in Refs. [16,17,14,19] take a stochastic approach to the optimization problem. In Ref. [16], a number of scenarios from a scenario tree are considered, each with an assigned probability in the optimization of the problem. The probabilities of each scenario are incorporated in the objective function. In Ref. [17], use the forecasted generated wind power from a uniform distribution to find the optimal policy that maximizes the expected cumulative revenue. This is solved by use of stochastic dynamic programming. Ref. [14] randomly samples wind generation values from an empirical probability density function to calculate the optimal dispatch schedule that maximizes hourly profits over the set time horizon. They also solve the optimization problem by use of stochastic dynamic programming. In Ref. [19], the forecast error of wind power are generated according to probability distribution and used to calculate the maximum profits of the combined wind and storage system. Hybrid genetic algorithm and neural network methods are applied to optimize the problem.

Our model is solved via stochastic dynamic programming similar to Refs. [17,14] but differs in the following ways: 1. We do not seek to compute the optimal dispatch policy or quantities, but instead seek to find the optimal control strategy for the different wind power generation scenarios to meet the committed dispatch. 2. We calculate probabilities of different wind power generation scenarios by use of a Markov transition probability matrix. 3. We simulate the wind farm from the given wind speeds. 4. Unlike Ref. [17] wind in this paper is not a small player in the market. 5. Unlike Ref. [14], the wind park operator signs a long-term contract to produce an agreed upon quantity of power. The model seeks to maximize the expected revenue of the operation horizon by reducing power deviation. Price inputs on the other hand are deterministic, which is characteristic of Kenyan electricity market. We investigate how best to operate the Lake Turkana Wind Power farm, coupled with pumped hydro storage so as to maximize revenue, and reduce variability hence ease scheduling, while considering the electricity sector and market conditions in Kenya. Showing the benefit of hydro storage to the Lake Turkana Wind Power farm and probably the need for storage for high wind power penetration in the country.

The rest of the paper is organized as follows: In Section 2, the electricity market structure used in the model, the inputs to the model and the mathematical formulation of the optimization model are discussed. In Section 3, the results are presented, followed by conclusion in Section 4.

2. Model

The mathematical model developed here, uses an optimal control approach to maximize expected revenue by minimizing power deviation and thereby enhance integration and operation of wind power into the Kenyan power system. Model inputs include hourly wind power scenarios, hourly scenario probabilities and storage parameters. The market price and penalty cost are set variables and are set to emulate the Kenyan electricity market prices as close as possible.

The model is developed based on three primary assumptions:

1. The amount of committed power per hour is constant, as determined at the signing of a power purchasing agreement
2. Wind farm operators are charged a penalty for under production of power
3. Penalty charges are charged on a per kW basis, and are time varying on a deterministic basis

2.1. Prices

Independent Power Producers (IPP's) operate under a PPA with the national utility for the sale of electricity generated. The price paid for each kWh generated is constant and does not vary