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Techno-economic analysis of off-grid hydrokinetic-based hybrid energy systems for onshore/remote area in South Africa

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ABSTRACT

Hydrokinetic power generation is a relatively recent type of hydropower that generates electricity from kinetic energy of flowing water making the conversion process more competitive compared to traditional micro-hydropower. Few authors have already analyzed the use of standalone hydrokinetic systems for rural electrification, however, there is no available literatures investigating the possibility of using this technology in combination with other renewable energy sources or diesel generator. Therefore, the aim of this paper is to investigate the potential use of hydrokinetic-based hybrid systems for low cost and sustainable electrical energy supply to isolated load in rural South Africa where adequate water resource is available. Different hybrid system configurations are modeled and simulated using the Hybrid Optimization Model for Electric Renewable (HOMER) and the results are analyzed to select the best supply option based on the net present cost and the cost of energy produced. The simulation results from two different case studies show that hybrid systems with hydrokinetic modules incorporated in their architectures have lower net present costs as well as lower costs of energy compared to all other supply options where the hydrokinetic modules are not included.

1. Introduction

The estimated electrification rate in South Africa is around 75% in 2013 [1]. There is still 25% of the country which is not electrified through the grid due to uneconomical cost of extension lines or difficult terrain especially in rural areas. These remote areas are generally electrified by means of standalone diesel generators (DG) which emit pollutants in the environment [2]. However, worldwide rise in fuel price as well as high transport and delivery cost to these isolated areas make the cost of energy produced from the DG very expensive [3].

South Africa has a potential of solar energy ranging from 4.5 to 6.5 kWh/m^2 and wind speed reaching annual averages of 6 m/s that can be used to generate sustainable amount of renewable energy [4,5]. These huge potential of renewable resources that can be used for energy generation is poorly used [6]. The installed capacity of solar, wind and hydropower plants in 2012 are approximately 30 MW, 10.1 MW and 3730.3 MW, respectively [7–9]; representing less than 2% of South African electricity production capacity.

The use of renewable energy source is still low in South Africa. The reason is due to the higher cost of energy produced by renewable sources compared to the one from the currently used coal power plants [10]. Referring to the Department of Mineral and Energy's aim (DME), setting a target of 10,000 GWh of renewable energy production by 2013 [11], it is imperative to explore the local renewable resources to provide sustainable electricity to the rural areas.

The solar photovoltaic (PV) is one of the renewable energy generation system mostly used in South Africa. The wind energy system is also being developed mostly in the coastal region where the wind potential is very good. However, for inland areas where adequate water resource is available, micro-hydro is the best supply option compared to other renewable resources in terms of cost of energy produced [12]. Unlike conventional hydropower technology, hydrokinetic is a relatively recent type of hydropower system that generates electricity by extracting kinetic energy of flowing water instead of potential energy of falling water, this makes hydrokinetic far less site specific and more competitive in terms of building cost compared to traditional micro-hydropower [13].

However the main disadvantage of hydrokinetic systems as well as of other renewable energy technologies is their resource-dependent output powers and their strong reliance on weather and climatic conditions [14]. Therefore, they cannot always match the fluctuating load energy requirements each and every time.

Using hydrokinetic-based hybrid systems for electricity generation can increase the reliability and reduce the cost of energy compared to the single energy systems. Hybrid systems are

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well-suited solutions for supplying electricity to remote areas where the grid extension is not cost effective [15]; they can also decrease or eliminate the reliance on DGs in the remote areas [16].

Few feasibility studies have been conducted to develop stand-alone hydrokinetic power systems [17,18]; however currently there is no literature available showing the use of this technology operating in combination with other power generation systems [19]. Therefore, in this study the techno-economic analysis of hydrokinetic-based hybrid energy systems is done for two different loads located in two distinct South African remote areas and having different climatic conditions. HOMER (Hybrid Optimization Model for Electric Renewable) [20] is used as a simulation tool to build a computer model that optimizes the sizing and operation of different feasible hydrokinetic-based hybrid systems for the project's lifetime.

For this simulation, the main outputs to be analyzed are the hydrokinetic turbines (HKT), photovoltaic panels (PV), wind turbines (WT), DG and battery sizes (power ratings) with the intention of determining which hybrid system configuration or supply option is the best compared to the others based on the net present cost (NPC) and on the cost of energy produced (COE) selection criteria. For accurate results, all the resources, loads and system component data are actual data acquired in the specific studied locations.

2. Off-grid generation options

In this study, the supply options considered can be used alone or combined in hybrid systems configurations. Battery is incorporated as storage system and is also used to reduce the number of ON and OFF switching's of the backup DG in the hybrid systems simulated as suggested in Ref. [21]. The HKT, PV, WT and DG are the main supply options to be considered in this study which can be combined in deferent hybrid configurations. The energy model of each individual energy source is explained in the sections below. The emphasis will be on the hydrokinetic system which is a relatively new technology.

2.1. Hydrokinetic system

Hydrokinetic systems extract kinetic energy from moving water without the need for a dam, barrage or penstock. Hydrokinetic can generate power from low speed flowing water with almost zero environmental impact, over a much wider range of sites than those available for conventional hydropower generation [22].

In this study, the hydrokinetic system has been selected instead of the traditional micro-hydropower. Its operation principle is identical to the one of the wind turbine. Knowing that water is approximately 800 times denser than air [22], this means that the amount of energy produced by a hydrokinetic turbine is much greater than that produced by a wind turbine of equal diameter under equal water and wind speed. The other advantages of hydrokinetic system are that the water resource does not fluctuate unpredictably in a very short period of time as the wind speed, and the flow of water does not change in direction as the wind does.

The energy generated (E_{HKT}) by the hydrokinetic system is expressed as [23]:

$$E_{\mathrm{HKT}} = \frac{1}{2} \times \rho_{\mathrm{W}} \times A \times v^3 \times C_{p,\mathrm{H}} \times \eta_{\mathrm{HKT}} \times t \quad (1)$$

where ρ_{W} is the density of water (kg/m^3), $C_{p,\mathrm{H}}$ is the coefficient of the hydrokinetic turbine performance, η_{HKT} is the combined efficiency of the hydrokinetic turbine and the generator, A is the turbine area (m^2), v is the water current velocity (m/s), and t is the time (s).

2.2. PV system

The sunlight striking on the panels, i.e. irradiance is measured in units of watts per square meter (W/m^2). The output energy (E_{PV}) of the solar PV system can be expressed as follows [24]:

$$E_{\mathrm{PV}} = A \times \eta_{\mathrm{m}} \times P_{\mathrm{f}} \times \eta_{\mathrm{PC}} \times I \quad (2)$$

where A is the total area of the photovoltaic generator (m^2), η_{m} is the module efficiency, P_{f} is the packing factor, η_{PC} is the power conditioning efficiency and I is the hourly irradiance (kWh/m^2).

2.3. Wind energy system

The energy generated (E_{WT}) by wind system is expressed as [25]:

$$E_{\mathrm{WT}} = \frac{1}{2} \times \rho_{\mathrm{a}} \times A \times v^3 \times C_{\mathrm{p,w}} \times \eta_{\mathrm{WT}} \times t \quad (3)$$

where ρ_{a} is the density of air (kg/m^3), A is the turbine area (m^2), v is the wind velocity (m/s), η_{WT} is the combined efficiency of the wind turbine and the generator, $C_{p,\mathrm{w}}$ is the coefficient of the wind turbine performance, and t is the time (s).

2.4. Diesel generator

Diesel generators are normal diesel engines coupled to generator. To operate efficiently, most of DGs are designed in such a way that they always run between 80 and 100% of their kW rating while supplying the load.

The energy generated (E_{DG}) by a DG with rated power output (P_{DG}) is expressed as [26]:

$$E_{\mathrm{DG}} = P_{\mathrm{DG}} \times \eta_{\mathrm{DG}} \times t \quad (4)$$

where η_{DG} is the efficiency of the DG.

3. Simulation data

Two case studies are conducted on two different sites from which the environmental data, load energy profile and system component costs are acquired and used as input to HOMER. Sections 3.1 and 3.2 describe the loads and the different renewable resources available on the two sites, respectively. Section 3.3 highlights the assumptions made while modeling the different supply options able to adequately respond to the loads energy requirements.

3.1. Case 1: rural household

3.1.1. Load description

A 24-h load data is obtained from a typical household situated in the Kwazulu Natal province at 30.6 degrees latitude south and 29.4 degrees longitude east and the corresponding load profile is illustrated on Fig. 1. The load is 5.6 kW peak and 35 kWh per day. It is assumed that any of the selected supply option should provide electricity for low consumption electrical appliances such as lights, TV, radio, laptop, fridge, kettle, cell phone chargers, iron, toaster, etc. [27]. When scrutinizing this load profile, one can notice a general pattern arising from the daily activities of the users which might change depending on different seasons of the year.