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A sensitivity analysis to determine technical and economic feasibility of energy storage systems implementation: A flow battery case study

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ABSTRACT

An economical and technical feasibility method was developed to determine the best implementation opportunities for a novel energy storage system (ESS). The ESS considered is a Zinc-Air flow battery in which energy storage may be scaled independently of the power output, and it can provide continuous power output of 5 kW during 8 h. Although the application field is vast, we have chosen three applicable scenarios where the new technology can be used: mining deployment, telecommunication tower, and a remote island. All three cases differ in load variability and load size, and we also considered three locations with their specific solar and wind resource. Three different power sources were also considered for this study: Diesel generator (DG), solar photovoltaic (PV), and wind turbine (WT). The best business opportunity for the new technology implementation was found to be in the mining industry. Power delivery from the ESS replaces the operation of DG during low demand periods in the case of variable load, as opposed to constant load, where the DG is permanently running. Fuel consumption reductions up to 75% can be achieved if the ESS is combined with renewable sources. However, the novel system alone represents approximate savings up to 33% in fuel consumption, when added to a conventional power generation system (diesel generator). Furthermore, the presented method aims to identify the main factors that affect the implementation feasibility of the ESS, and to provide a general approach that can be extended to different storage capabilities and fields of application.

1. Introduction

Renewable energy penetration into the global energy market is increasing at unprecedented rates in both on-grid and off-grid power systems. Renewable energy is emerging as an attractive alternative to conventional power generation systems as a result of reduced environmental impact, the introduction of investment tax credits and decreasing production costs. These factors are enabling renewable energy to compete in an energy market that is driven largely by environment and economic policy. In 2013 the average cost of electricity for on-grid energy markets in the United States was $0.1222 USD per kWh delivered to residential consumers and $0.0684 USD per kWh delivered to industrial consumers [1]. Canadian on-grid electricity prices have wide variations, since weather is a main factor to significantly impact the energy market. Prices in Alberta and Ontario were $0.0417 USD per kWh and $0.0617 USD per kWh, respectively [2]. Meanwhile, remote off-grid energy markets suffer from inflated electricity prices; according to Arriaga et al. [3], remote communities in Northern Canada have an average cost of $1.30 USD per kWh delivered. Traditionally, power generation in off-grid power systems is performed with diesel generators requiring fuel and inefficient operation. Electricity delivery to remote locations poses challenges that increase price, primarily due to the distance that this fuel has to be transported to reach its final destination. This has been shown to increase the cost of electricity by up to ten times its cost in urban areas [4]. Fuel transportation costs may be removed entirely by introducing renewable power generation to remote off-grid power systems.

The implementation of renewable power generation for remote off-grid power systems has the advantage of dramatically decreasing dependency on conventional fossil fuels, meanwhile introducing its own technical challenges, namely, delivering

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constant power supply. The intermittent nature of power delivery from renewable sources such as wind and solar requires the use of energy storage systems (ESS) to achieve constant power output. This need becomes especially important when such deployments are targeted for remote applications where renewable sources could be the only power source. As these renewable sources experience periods of inactivity, energy storage is required in remote communities to satisfy the demand during these periods.

Remote applications have the main characteristic of increased energy costs and the need for energy storage, due to the variability and intermittency of renewable power sources. Many cases are found in literature where remote energy applications are targeted as an important opportunity to introduce hybrid technologies for power generation [3,5–12] and to reduce costs in fuel transportation. We have addressed three case scenarios that conglomerate characteristics of remoteness, variability, intermittency, and variable demand to assess the economic advantages of a novel flow battery. We prioritize the Net Present Cost (NPC), environmental impact, and power reliability to define what is the best opportunity of implementation. Furthermore, we have considered these specific three cases because of their range of applicability in the power demand (5–200 kW) and type of sector (industrial, commercial, and domestic). Our industrial partners have stated that the three cases are located at potential sites of the ESS implementation. The first case considers a mining deployment located in British Columbia, Canada; the second case considers a telecommunication tower located in California, United States; and the third case consists of an island located in Baja California Sur, Mexico, with a population of 350 inhabitants, approximately.

Manchester et al. proposed a regenerative air energy storage system for remote micro-grids that increases the system's payback period, but brings diesel savings up to 30,000 L per year [4]. Different energy storage systems have been reported in literature, but batteries are currently one of the better options due to their advanced technology and widespread use in the energy market. However, their lifetime is significantly reduced when they have to respond to severe fluctuations in the power demand. For this reason, Ma et al. proposed a hybrid battery-supercapacitor energy storage system that accounts for this type of fluctuations [9]. ESS become a feasible solution for renewable sources intermittency in remote communities, mainly because they can significantly reduce the cost of electricity (COE) compared to that of the diesel generators. Richardson and Harvey [13] developed a method to balance power output delivery from renewable sources, energy demand, and energy storage to determine the lowest cost in each case scenario. In the aforementioned study, developed for Ontario, Canada, three cases were considered: substitution of conventional fuels, substitution of a nuclear plant, and vehicle fleet electrification. In all these cases, wind energy generation was the technology with better results offered, while energy storage capacity was slightly higher than the minimum requirements. This consideration reduces the significance in large grid-connected systems, which is not the case for remote scenarios, where energy storage not only optimizes power generation, but also reduces the impact of intermittency on the microgrid. Lamy et al. [10] developed a study that accounts for the marginal costs of energy storage in remote sites in Midwest USA that makes it a viable way to integrate wind technologies in the energy market. They found that energy storage becomes the optimal solution when its cost presents a maximum of $100/kWh, while the minimum cost of transmission is $600/MW-km. A more recent study of renewable integration in remote islands was carried out by Enevoldsen and Sovacool [14], especially considering hydrogen energy storage to be used in fuel cells. The remote islands studied by these authors currently run with diesel generators, and the study makes a survey of the benefits and challenges of integrating renewable power sources into the islands' generation agenda. The most important outcome, and the main point of agreement with the present study, is that renewable power sources and energy storage are more economically attractive when they are integrated, rather than one of these elements in combination with a conventional power source.

Hybrid technologies have been also proposed as a valuable element to increase the penetration of renewable sources in the energy market [15]. Furthermore, it has been mentioned that hybrid systems are, sometimes, the only solution due to the lack of reliability when power is delivered by only one source [16]. Regarding energy storage for remote applications, Omer et al. [8] reported a study where two hybrid systems PV/Fuel Cell and PV/Batteries were compared, using HOMER software. The first option doubled the capital cost of the second choice, concluding that fuel cells were not competitive at the time of the study. Cao and Alanne assessed the technical feasibility for a zero-energy building with hydrogen production and consumption through a hydrogen vehicle [17]. They used TRNSYS software to simulate the parameters of the building, using the surplus of renewable electricity to produce hydrogen, which would be used in a fuel cell powered vehicle. The authors concluded that a 14 kW wind turbine and a 19.2 kW PV array, the zero/energy condition would be achieved, with an energy surplus to produce hydrogen from an electrolyser, and the capacity to use the same fuel for domestic heating purposes.

Hybrid power generation systems that combine energy storage with renewable power sources represent a niche of opportunity in remote off-grid areas, where many mining deployments are located. The wide range of electric load in a mine makes this industry a feasible candidate to introduce hybrid power generation, reducing their overall costs of energy production. Regarding the mining industry, Levesque et al. [18] calculated that 15% and 19% of the production costs for metals and non-metals, respectively, are entitled to energy costs. Moreover, mining extraction represents 60% of the total energy consumption in this sector [19]. Renewable sources penetration in the mining market has been proved to be economically and technically feasible, as illustrated by Escalante et al. [20]. In the mentioned paper, the authors estimated savings of more than $403 MM USD in a 23 MW processing plant if a wind farm is targeted to supply most of the mining plant's power needs during 10 years of operation.

On the other hand, renewable power penetration in the energy market requires extensive analysis on the consequences of the renewable sources variability and intermittency. A study developed by Krakowski et al. [21] indicated that further research should be focused on low-cost energy storage technology, since their results indicated positive scenarios when a sensitivity analysis considered a reduction in energy storage costs. The authors concluded that high levels of renewable energy penetration could require additional storage capacity, bringing additional costs to the power generation system. The purpose of this to assess three different scenarios where our novel storage system would alleviate energy storage costs, while taking advantage of the energy surplus in a hybrid system.

In the present study, specific case studies are considered likewise other methods found in the literature. However, flow batteries are not widely studied in techno-economic feasibility studies. ESS lifetime and power delivery are two main issues to consider this technology in hybrid renewable energy systems. For this reason, we address this gap using a new flow battery with a reduced cost and increased lifetime in a sensitivity analysis to assess its implementation in different scenarios. Additionally, the method developed in this research study can be extended to compare our results with different energy storage technology.