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Vanadium redox flow batteries to reach greenhouse gas emissions targets in an off-grid configuration

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HIGHLIGHTS

- We assess energy storage role in reaching emissions targets in an off-grid model.
- The energy storage technology is vanadium redox flow battery (VRFB).
- We evaluate life cycle GHG emissions and total cost of delivered electricity.
- Generation mixes are optimized to meet emissions targets at the minimum cost.
- For this model, integrating VRFB is economical to reach very low emissions targets.

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ABSTRACT

Energy storage may serve as a solution to the integration challenges of high penetrations of wind, helping to reduce curtailment, provide system balancing services, and reduce emissions. This study determines the minimum cost configuration of vanadium redox flow batteries (VRFB), wind turbines, and natural gas reciprocating engines in an off-grid model. A life cycle assessment (LCA) model is developed to determine the system configuration needed to achieve a variety of CO_2-eq emissions targets. The relationship between total system costs and life cycle emissions are used to optimize the generation mixes to achieve emissions targets at the least cost and determine when VRFBs are preferable over wind curtailment. Different greenhouse gas (GHG) emissions targets are defined for the off-grid system and the minimum cost resource configuration is determined to meet those targets. This approach determines when the use of VRFBs is more cost effective than wind curtailment in reaching GHG emissions targets. The research demonstrates that while incorporating energy storage consistently reduces life cycle carbon emissions, it is not cost effective to reduce curtailment except under very low emission targets (190 g of CO2-eq/kW h and less for the examined system). This suggests that "overbuilding" wind is a more viable option to reduce life cycle emissions for all but the most ambitious carbon mitigation targets. The findings show that adding VRFB as energy storage could be economically preferable only when wind curtailment exceeds 66% for the examined system. The results were most sensitive to VRFB costs, natural gas upstream emissions (e.g. methane leakage), and wind capital cost.

1. Introduction

The development of renewable energy sources, such as wind and solar, is considered an important strategy to decrease both environmental impacts and energy price volatility. With 38% of US carbon dioxide emissions coming from burning fossil fuels for electricity generation in 2012 [1], wind power is an appealing option to decrease the carbon intensity of power generation. Despite these sustainability opportunities, large-scale integration of variable renewables into the electrical grid poses critical challenges that may be overcome through the use of energy storage systems. When the objective is to integrate variable renewables such as wind and solar, energy storage must compete with other solutions such as increased flexibility of firm generation or simply allowing some wind or solar curtailment. Understanding the total environmental impacts of using grid-scale energy storage requires the integration of LCA and energy systems analysis, as is done in this study.

Many studies have assessed the role of energy storage in increasing the penetration of renewable energy. A major study by Electric Power Research Institute (EPRI) examined the applications of different energy storage systems for grid connected wind

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generation [2]. Denholm and Margolis considered energy storage to alleviate the challenges of introducing variable solar energy [3]. Denholm and Hand examined Electric Reliability Council of Texas (ERCOT) market and found that storage equal to one day of average demand could increase the wind and solar penetration up to 80% [4]. Zahedi reviewed the challenges in large-scale integration of solar photovoltaic (PV) systems and the utilization of economically and technically viable energy storage systems to solve these challenges [5].

While energy storage holds the promise of integrating high penetrations of variable renewables, its adoption is limited by high costs. Several studies have optimized an isolated hybrid system consisting of renewable energy, energy storage, and other sources of electricity generation to achieve the minimum cost. For example, Merei et al. optimized a stand-alone hybrid system comprising of PV panels and wind turbines as renewable sources of energy, diesel generator as back-up generation and batteries as energy storage to minimize the overall costs. Their results showed that the integration of batteries with renewables was economical and environmentally preferable. Also their optimization results showed that using redox flow batteries in combination with renewables and diesel was the best option in comparison to lead–acid and lithium-ion batteries integration [6]. Ma et al. also evaluated the techno-economic feasibility of a stand-alone hybrid solar wind energy system integrated with battery storage system as an electricity supplier for a remote island to achieve an optimal cost-effective configuration [7]. On the other hand, Kaabeche et al. showed that a stand-alone hybrid configuration consisting of PV/wind/diesel/battery was more economically viable compared to a PV/wind/battery system and also a diesel generator (DG) only system [8]. Besides batteries, other studies optimized hybrid configurations integrated with other energy storage systems such as compressed air or pumped storage systems [9–12].

In addition to economic issues, the life cycle environmental impacts of energy storage systems from cradle-to-grave will influence their overall sustainability performance. Denholm and Kulcinski analyzed the life cycle energy requirements and emissions from large-scale energy storage systems coupled with renewables. Their results showed that despite the added emissions and energy input, these systems offered lower emissions than fossil fuel based electricity [13]. Sioshansi evaluated the impact of adding wind and energy storage to a market based electric power system [14]. In an examination of environmental impacts of different batteries, McManus concluded that lithium ion batteries had the most significant contribution to greenhouse gases and metal depletion, but nickel metal hydride batteries had a more significant cumulative energy demand [15]. Galvez et al. optimized an autonomous hybrid system consisting wind turbines, solar panels and hydrogen storage with the objective of minimizing net present cost and net avoided emissions in the system life cycle [16]. Bondesson introduced a comparative LCA model on renewable solutions integrated with batteries for off-grid base stations [17].

Among various energy storage systems, vanadium redox flow batteries (VRFBs) offer high energy density and efficiency [18], suggesting the potential for cost competiveness in applications for variable renewable energy integration. Rydh compared VRFB and lead–acid batteries utilizing life cycle analysis and found that former had a lower environmental impact, greater net energy storage efficiency, and longer cycle-life [19]. Stiel and Skyllas-Kazacos also assessed the environmental and economic benefits of integrating vanadium redox battery with remote wind/diesel power systems using the HOMER model. Their results showed that the system comprised of wind, diesel and vanadium flow batteries had lower carbon emissions and net present cost compared to wind/diesel system [20]. Our current study differs from this work by examining natural gas generation (at a far lower cost), including all life cycle impacts of the system components, and optimizing to meet life cycle emissions targets. Joerissen et al. showed the ability of VRFBs for load leveling and seasonal energy storage in small grids and stand-alone PV systems [21]. Zhang et al. showed the importance of the vanadium to the overall capital costs of all-vanadium redox flow batteries in a sensitivity analysis [22]. While those studies have done economic and environmental analyses, there remains the need for further examination of the economic and environmental trade-offs between curtailment and energy storage.

1.1. Objectives and energy system assumptions

This paper examines the trade-offs between environmental and economic metrics when using energy storage to integrate wind energy and explores the role of energy storage in achieving very low emissions targets. In this study, optimal generation mixes comprised of VRFBs, wind turbines, and natural gas reciprocating engines are determined to minimize the delivered cost of electricity to an isolated load, while meeting progressively more challenging life cycle GHG emissions targets. This study is novel because it assesses the environmental emissions of integrating VRFB with wind energy through a full LCA of all system components and evaluates the total cost of the system. LCA methods are utilized to compare the GHG emissions associated with the system components, including upstream effects of fuel and material production and equipment manufacturing. The total cost of the off-grid system is calculated to determine when the value of large-scale energy storage outweighs the cost of wind curtailment, i.e. when energy storage is preferable over additional wind capacity. There are emissions associated with the production of batteries; this study examines if such emissions are compensated by the reduction in environmental impact due to less natural gas combustion.

The case study is intended to represent an island with the same size as "Grosse Ile", the largest island in the Detroit River, which has population of 10,894 [23]. Using MISO-wide per capita data, it is estimated that this system has annual demand of 10.6 MW h per capita, and annual peak and minimum demand of 22 MW and 8.7 MW respectively. The annual electrical load profile of State of Michigan is scaled down to create a load profile of the island. The distribution losses are assumed to be 3 percent and the load factor is 60%. The island system is an isolated grid and the generation options are assumed to be wind energy integrated with energy storage and natural gas. Planning for reliability is achieved by maintaining a reserve margin of 20 percent [24], assuming that the system does not have any grid connection.

In this model wind is treated as a must-take resource. Excess wind is stored in the battery (if available), and it is discharged when needed. If battery storage is not available, the excess wind is curtailed. Natural gas reciprocating engines are used to provide firm capacity, to meet the annual peak plus the reserve margin, and to meet all energy demand unmet by the wind and battery. Three scenarios are developed to assess the optimal system configurations to meet emission targets at minimum cost. The scenarios are described as follows:

- Natural gas generation without any wind generation and energy storage.
- Wind energy, natural gas generation.
- Wind energy, energy storage, and natural gas generation.

2. Methods

2.1. Life cycle assessment

In this analysis, a full LCA is developed for the off-grid system to evaluate total GHG emissions. Fig. 1 shows the system boundary