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Evaluating the value of batteries in microgrid electricity systems using an improved Energy Systems Model

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ABSTRACT

A high-resolution model allowing for the comparison of different energy storage technologies in a variety of realistic microgrid settings has been developed. The Energy Systems Model (ESM) is similar to the popular microgrid software HOMER, but improves upon the battery models used in that program. ESM adds several important aspects of battery modeling, including temperature effects, rate-based variable efficiency, and operational modeling of capacity fade and we demonstrate that addition of these factors can significantly alter optimal system design, levelized cost of electricity (LCOE), and other factors. ESM is then used to compare the Aqueous Hybrid Ion (AHI) battery chemistry to lead acid (PbA) batteries in standalone microgrids. The model suggests that AHI-based diesel generator/photovoltaic (PV)/battery systems are often more cost-effective than PbA-based systems by an average of around 10%, even though the capital cost of AHI technology is higher. The difference in LCOE is greatest in scenarios that have lower discount rates, increased PV utilization, higher temperature, and more expensive diesel fuel. AHI appears to be a better complement to solar PV, and scenarios that favor the use of solar PV (low PV prices, low discount rates, and high diesel prices) tend to improve the LCOE advantage of AHI. However, scenarios that do not require constant cycling of the batteries strongly favor PbA. AHI is not a drop-in replacement for PbA. To minimize LCOE, microgrids using AHI batteries should be designed and operated differently than PbA microgrids.

1. Background

Microgrids are small self-reliant electricity grids that produce and distribute power across a limited area, such as a village or industrial complex. Microgrids can be grid-tied, where the system is able to connect with a larger traditional grid, or standalone systems where there is no outside electrical connection. The Energy Systems Model and this paper focus only on standalone systems.

Standalone microgrids have traditionally been a very niche market, appropriate only for applications where less expensive traditional grids could not operate [1,2]. But continual improvements in the performance and cost of microgrid technologies (ex. PV, small wind, and batteries) are making microgrids a more attractive option, particularly in developing or remote areas that have not yet invested in traditional grid infrastructure [1,3]. Microgrids have several advantages over traditional grids: they are scalable and do not require large capital investment, they are generally environmentally superior to traditional generation, and they can be tailored to the particular needs of a community [4–6]. But cost is always an important factor, and any serious discussion of microgrid technology must effectively address that issue.

Evaluating microgrid systems involves significant complexity and uncertainty. This complexity and uncertainty relates to both the design of the microgrid system (such as the scale of different energy sources and quantity of storage to purchase and install) and to the operation of an existing system (such as dispatch algorithms for storage and generation) [2]. Furthermore, the design and operation are somewhat interdependent: the optimal design depends on the way that the system will be operated and the optimal operation depends on the system design. This optimization is made more complex by uncertainty in actual load and renewable resource as well as price uncertainty for variable costs such as diesel fuel. Fortunately, the objective in microgrid design is normally very simple: to meet load with the lowest levelized cost

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of electricity (LCOE) or lowest net present cost (NPC) through the expected lifetime of the system. However, even this is complicated by questions of reliability: a lower LCOE can be attained if you are tolerant of more frequent power outages. For all of these reasons, one cannot expect to achieve the perfectly optimal microgrid system design or operation. Rather, several simplifying assumptions must be made and an acceptable compromise chosen from a more constrained set of options.

Due to both the growing importance of microgrids and the complexity of microgrid optimization, a significant quantity of academic research has been produced about microgrid operation, design, and economics. A large body of previous research has illustrated methods for optimizing the operation of existing microgrid resources, with a focus on microgrids with some form of energy storage [5–8]. Additionally, some researchers have investigated optimal system design for different types of microgrids in particular scenarios, such as grid-connected hospitals [9], standalone combined heat and power systems [10], as well as general formulations of standalone systems with multiple generators [11]. Much of the existing research in the field uses linear programming techniques to determine both the operation and design of the microgrid system, an approach that has both advantages and disadvantages. By using a linear programming approach, the truly optimal system design or operation can be determined. However, this approach normally accounts for neither the importance of uncertainty in load and variable renewable energy nor the risk aversion towards unserved load seen in the design of actual microgrids.

Because of the fundamental uncertainties inherent in microgrid design and operation, researchers have created battery and microgrid models of varying levels of complexity, depending upon the purpose for which the model will be used. Tradeoffs must be made between the complexity of the component modeling and the ability to search for optimal systems and system operation. In Bortolini et al., which also includes a thorough literature review of different microgrid modeling efforts, operational and economic elements of a grid-connected PV/battery system are investigated [12]. In this system, load is met first from the PV, then batteries, and the grid is used as a backup source. Batteries are never charged from the grid. In Khatib and Elmenreich, a generator/PV/storage system is considered in which load is met first from available PV energy, then from battery energy, and the generator is only started when PV and battery are unable to serve load [13]. When the generator is running, it is also used to charge batteries if possible. This approach easily answers the questions of when to operate the generator and when to charge the batteries from the generator, but does not allow a system designer to search for systems that can produce electricity at lowest cost, as cost is not part of the formulation.

Other models have used different approaches, focusing on particular elements of system components or operation. Dufo-López et al. use genetic algorithm search to identify optimal control strategy in addition to system design [14,15]. This permits their Hybrid Optimization by Genetic Algorithms (HOGA) model to co-optimize operation and system design and to search in a multi-criteria space that attempts to balance LCOE with life-cycle system emissions. However, the modeling of system components, especially energy storage, is necessarily quite limited. Koohi-Kamali et al. use agent-based modeling to investigate the use of PbA batteries to provide smoothing and other support services in a PV/diesel generator/PbA battery system [16]. They model the electrical and mechanical characteristics of the system in great detail, including elements such as generator torque versus crank angle and system active and reactive power. This extensive system model is used to demonstrate the operational value of energy storage providing integrating services.

With the Energy Systems Model (ESM), we create a versatile engineering-economic model of microgrid operation. We use this model to demonstrate that more sophisticated battery modeling can result in very different LCOE and system design, by comparing ESM to the popular microgrid modeling tool HOMER. We then use the ESM to investigate the economics and system design of Aqueous Hybrid Ion (AHI)-based microgrids in comparison to PbA-based systems.

HOMER is an easy-to-use system modeling program that utilizes a time-series (not linear programming) approach to microgrid operation. Originally developed by the National Renewable Energy Laboratory, HOMER can rapidly evaluate a variety of potential microgrid options [17]. HOMER is chosen as a comparison because it is commonly used in microgrid research, education, consulting and industry. HOMER Energy, the company that distributes the software, reports over 100,000 users in 193 countries [16]. While many other researchers have improved upon various aspects of HOMER's microgrid modeling, we demonstrate that more sophisticated modeling can result in very different results.

While HOMER has a relatively sophisticated and realistic modeling approach for most system components, its battery models are more theoretical to maintain ease of calculation. As a result, HOMER underestimates or neglects several important issues relating to battery operation in microgrid systems, such as capacity fade, temperature effects, or rate-based battery efficiency. We believe that the battery modeling is the weakest part of this useful modeling tool, and can be improved with a more realistic battery model.

Because we are particularly interested in the value and operation of batteries, we have developed our own Energy Systems Model (ESM) to evaluate the operation and costs of different standalone microgrid energy systems. Much of the modeling approach for ESM is similar to that used in HOMER, with improvements made where the HOMER approach appeared to lack the necessary sophistication. The ESM does not allow as many system elements as HOMER, which permits multiple generators and several different renewable generation technologies. Similar to HOMER and unlike much of the literature in the field of microgrid optimization, ESM uses operational algorithms that are risk averse towards unserved load. We believe that this better reflects the design and operation of actual microgrid systems.

One of the major reasons for creating the ESM was to evaluate and compare PbA batteries with Aquion's Aqueous Hybrid Ion (AHI) batteries in microgrid applications. AHI is a novel battery chemistry that offers durability across environmental and operational regimes, has a very high cycle lifetime, and a moderate capital expense. This makes AHI a potential improvement over the incumbent PbA technology, which has cycle life and operational limitations but a lower upfront cost.

This paper is structured as follows. In Section 2, we describe the structure and assumptions used in ESM. In Section 3, we compare ESM to HOMER, discussing the differences between the two programs, and provide an example of the effect that these differences have on output. In Section 4, we use ESM to evaluate and compare the economics of PbA and AHI batteries for standalone microgrid systems. Section 5 is a discussion of the implications of the results in Sections 3 and 4, and we conclude in Section 6.

2. Model description

At its core, the ESM is an engineering-economic model that inputs a particular microgrid system configuration, electricity load time series, and solar resource time series, determines the time-series operation of each component, and calculates the LCOE and other relevant financial information for the system. In the current