Locational Variance in Nuclear Micro-Reactor Performance Under Microgrid Conditions

Ryan Dailey,* Ben Lindley

*University of Wisconsin-Madison, 1500 Engineering Dr., Madison, WI, 53706, rdailey@wisc.edu

INTRODUCTION

With climate change and energy independence becoming an increasingly prevalent discussion in public discourse, federal and local governments alongside electrical utilities have been investigating methods to reduce their carbon footprint while ensuring a stable and resilient power supply for their critical loads or total electricity demand in several locations. Low carbon hybrid energy systems are being investigated with renewable energy technologies (solar and wind) integrated with energy storage systems (e.g., lithium-ion batteries) to cover for renewable intermittency during certain times of the year.

To improve reliability and reduce overall system cost, it has been proposed to integrate a micro-scale nuclear reactor into these hybrid systems to provide for a baseload power supply and grid stabilization. A mixture of nuclear, renewable, and storage grid assets coupled via a microgrid has the potential to compensate for the individual weaknesses of each technology while providing a low-carbon solution.

Microreactors are expected to have significant capital costs but provide the opportunity to have a relatively constant power supply in situations where solely relying on the main grid is undesirable. The semi-constant power output of the microreactor unit would then be supported by intermittent renewable resources and storage to potentially provide a cheaper microgrid energy solution. Through the use of a microgrid optimization package (HOMER Pro), it is possible to determine the optimal grid configuration[1].

In these grid-independent (“islanded”) scenarios, the cost efficiency of the microreactor unit is thought to depend on the degree of renewable resource availability in the area. Higher renewable resource availability (either solar or wind, typically) and storage capacity can reduce or eliminate the need for a constantly dispatchable power supply. Conversely, lower renewable availability (or higher intermittency) would make a constantly available power supply more desirable.

Previous studies have investigated the effect of microreactors and small modular reactors on macro-scale grids or at specific micro-grid locations [2]. These studies investigate site-specific load and weather profiles to determine specific hybrid micro-grid solutions for their site. In this work, a uniform, islanded micro-grid layout will be compared across several different locations (with correspondingly varied weather profiles). To allow for a consistent representation of various environments, the Köppen Climate Classification (KCC) system will be used.

The Köppen Climate Classification seeks to assign a classification to locations that share similar environmental conditions, such as average temperature and precipitation values [3]. Since environmental conditions can have impacts on the performance of renewable energy assets, the KCC could provide useful insights into predicting microreactor financial performance under microgrid scenarios.

Several different cost-performance profiles will be used for the microreactor models, as there exists significant uncertainty in the final design from most microreactor vendors. Should nuclear prove highly competitive in most cases, additional cases will be tested to discover the limits of microreactor cost-effectiveness (i.e., at what cost does a microreactor become non-competitive).

METHODOLOGY

HOMER Pro to Simulate the Integrated Energy System

To model economic performance of various microgrid configurations, HOMER Pro (HOMER) was used. HOMER combines a flexible microgrid modeling tool with the ability to import various solar/wind parameters to estimate the cost of a microgrid solution.

A characteristic microgrid for optimization contains varying amounts of installed microreactor capacity (1 MWe increments), generic 1500 kW wind turbine(s), generic 1 kW photo-voltaic solar PV panels, and generic 1kWh Li-Ion batteries. Data from the original UW Study was updated with data from Lazard’s Cost of Energy 2021 and NREL’s Annual Technology Baseline for 2021 [4], [5]. Figure 1 shows HOMER’s representation of the microgrid configuration for a case containing a microreactor. The modeled grid has a peak demand of ~6.3MWe, a minimum demand of 2.6 Mwe, and an average demand of 4MWe which matches the Green Site analysis scenario from the study performed by UW-Madison [2]. The maximum allowable annual unmet capacity is 0.01%.

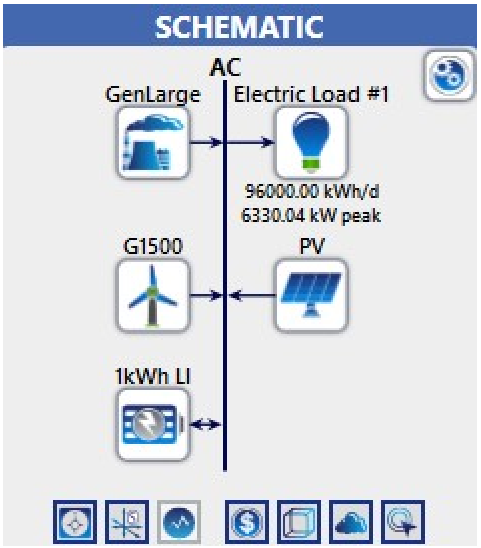

Fig. 1. HOMER Pro schematic of hybrid microgrid system, with a “best-case” microreactor

To properly analyze the variability of microreactor deployment based on location, multiple cost and performance cases were developed. Case 1 represents a purely renewable energy grid without the introduction of a microreactor and serves as the base case for analysis. Cases 2, 3, and 4 represent different microreactor financial performance cases, with case 2 being the least expensive microreactor and case 4 being the most expensive microreactor.

Characteristic Microgrid Location(s)

To construct a thorough comparison of microreactor economic performance throughout various locations, several locations throughout the United States will be modeled in HOMER Pro. Each site for the initial analysis will have a distinct Köppen Climate Classification. Figure 2 shows a KCC map of the United States west coast from Oregon State University. Candidate locations will display benefits from operating with main-grid independence, such as environments near defense installations or other federal entities.

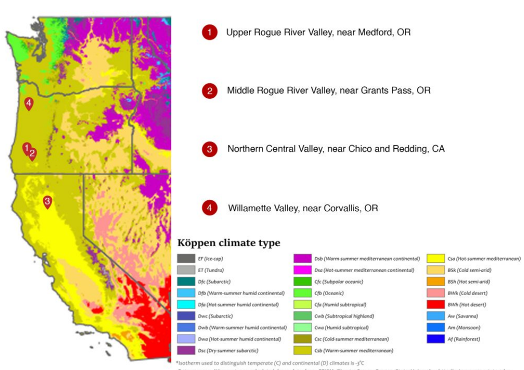

Fig. 2. Köppen Climate Classification for the western United States [6].

Local community acceptance and state policy will have a major impact on the microreactor site selection process. This study does not account for these factors, as it seeks to develop a generalized economic model for the cost/benefit analysis of site selection. If particularly favorable climates for microreactors are identified, it would then be prudent to consider which sites may not be viable due to lack of acceptance or lack of state support. It is noted that many of the KCCs found within the United States currently house nuclear generation.

A microreactor study performed by the University of Wisconsin-Madison provides a template for analyzing a microgrid, which will be expanded upon for this analysis [2]. In the UW’s study, Madison, Wisconsin’s weather data was used to as the basis for its study.

Solar data was acquired through the National Renewable Energy Laboratory’s solar irradiance database [7]. HOMER’s wind data is utilized.

Microreactor Modeling in HOMER

HOMER does not innately support microreactor modeling; only fossil generators are supported in various capacities. Previous works describe how a microreactor model was constructed for HOMER using custom generator input [8].These microreactor models originally constructed with public microreactor information available from potential microreactor vendors.

Table 1 provides sample microreactor input parameters, assembled from potential microreactor vendors and a microreactor study performed by the University of Wisconsin-Madison [2]. The UW study was then updated with more recent predictions for microreactor performance.

Table 1. Sample HOMER Simulation Data

TABLE I. Sample HOMER Data for a Microreactor

Quantity of Interest	**Value [Units]**
Reactor Size Increment	1 [MWe/unit]
Reactor Capital Cost	$4-20[$million/unit]
Discharge Burnup	Variable [MWd/kg]
Thermal Efficiency	37 [%]
Reactor Fuel Cost	3.55M [$/unit/cycle]
Reactor O&M Costs	400,000 [$/yr/unit]
Core Lifetime	5-20 [yrs.]
Reactor System Lifetime	60 [yrs.]*
Minimum Load Ratio	25 [%]

*Reactor system lifetime is tied to financial case. All cases assume a 60 year system lifetime.

Most microreactor performance parameters have uncertainty in their final values which makes it difficult to build a vendor-specific model. Instead, a generalized model is used which pulls from a variety of data sources (NEI, UW-Study, and various vendors). Using a range of anticipated discharge burnup, core mass values, estimates of capital costs, and expected core lifetimes it is possible to construct a generic microreactor model in HOMER.

Following previous microreactor modeling work in HOMER, a capital cost focused method is used with fixed fuel costs [8].

RESULTS AND OBSERVATIONS

Results

LCOE predictions for six different U.S. climate classifications over four separate cost/grid profiles are shown on Figure 3. In most cases, the introduction of a microreactor reduces the cost of the islanded microgrid. The highest cost nuclear cases contain the most variation in deployed nuclear capacity. The various regions included in this study have significantly different solar and wind resources. In the optimistic (Low Nuclear) scenario, which assumes microreactor costs consistent with N'th-of-a-Kind (NOAK) construction, a well-developed fuel cycle, and experienced operators, the introduction of a microreactor significantly reduces the levelized cost of electricity (LCOE). Contrasting this, the High Nuclear case which is based on First-of-a-kind (FOAK) costs and inexperienced operators, shows the microreactor experiencing strong competition from the renewable grid elements. Locations that build low amounts or no nuclear are expected to have high solar irradiance, a strong wind resource, or a combination of the two.

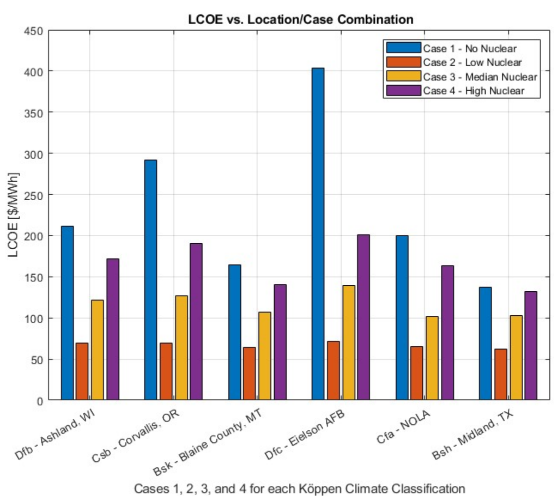

Fig. 3. Levelized cost of electricity vs. location for various cost profiles.

As expected, areas with high renewable energy availability (Texas) have lower LCOEs in each case when compared against those with lower renewable energy availability (Eielson).

Figure 4 shows the installed microreactor capacity for each case. In these cases, the viability of a microreactor demonstrates increasing locational variance as the financial cases became less favorable for the microreactor.

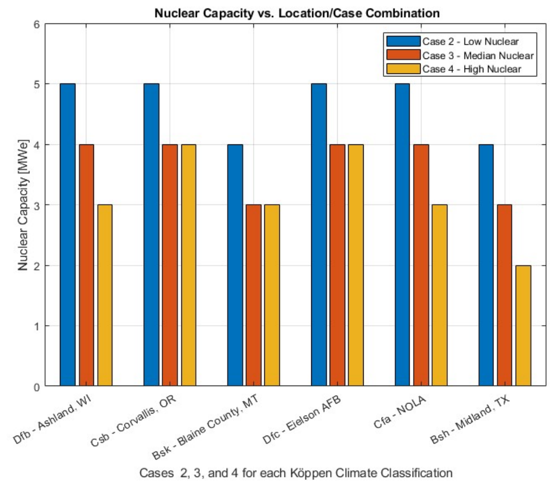

Fig. 4. Installed nuclear capacity vs. location for various cost profiles.

Installed solar capacity is shown as Figure 5. Solar is installed in every analysis case, likely due to a low sizing increment and relatively favorable solar resource availability.

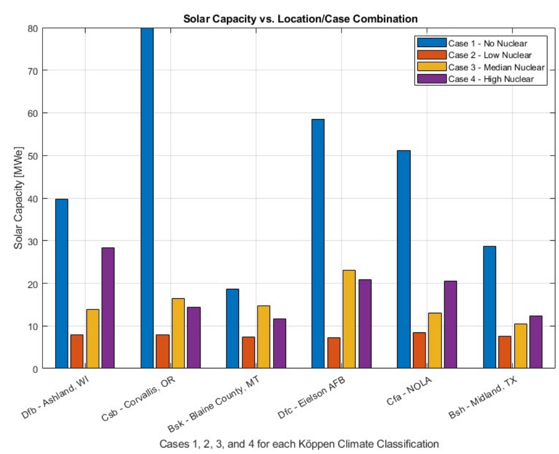

Fig. 5. Installed solar capacity vs. location for various cost profiles.

Installed wind capacity is shown as Figure 6. Wind is not installed in every analysis case, likely due to varying resource availability and a large unit size of 1.5 MWe. Smaller wind turbines could lead to a larger installed wind capacity. Usage of smaller wind turbines is inconsistent with industry trends, however [9].

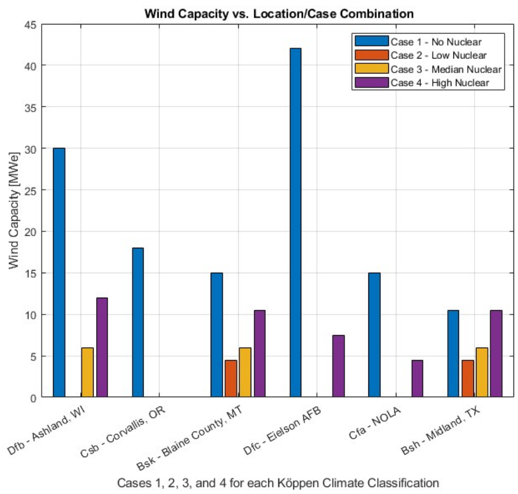

Fig. 6. Installed wind capacity vs. location for various cost profiles.

Installed battery capacity is shown as Figure 7. Consistent across all cases is the reduction in battery capacity with the installation of a microreactor.

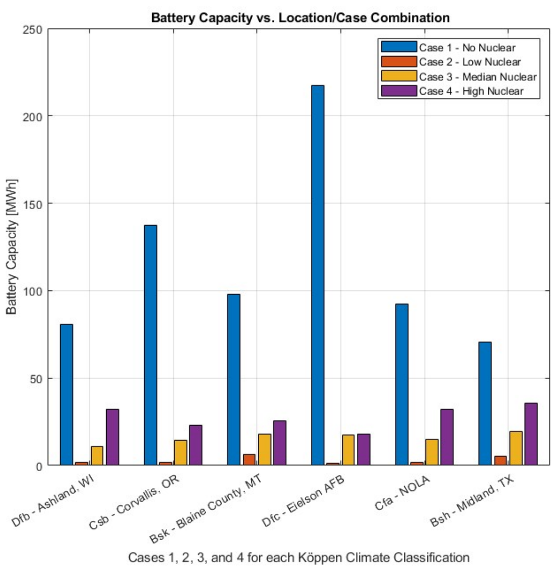

Fig. 7. Installed battery capacity vs. location for each cost profiles.

CONCLUSIONS

The results shown suggest that microreactor deployment is sensitive to cost assumptions and location. From the previous figures, at low assumed costs microreactors have the potential to be competitive across all locations. As microreactor costs increase, the grid penetration drops significantly, with variance based on location. Particularly remote and cold classifications such as Dfc (Eielson AFB) are simulated to realize significant cost savings even with poor microreactor cost performance. In high renewable availability climates, such as Bsh (Texas), the microreactor performance is much more sensitive to cost due to competition.

Current results suggest that the Köppen Climate Classification could be used as an initial performance predictor for microreactors, but further study is needed. To understand inter-classification variance, multiple locations within a KCC are under examination. This will allow for a better understanding of whether the KCC system accurately predicts microreactor performance, or if it only serves as a different method of expressing renewable energy availability.

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