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Fort Phantom Power System Analysis—Case Studies for Notional Power Resource Mixes and Energy Storage

Results Produced Using the Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) Computational Model

Jessica J. Nicholson, Matthew T. Gross, Camryn T. Anderson, and Thomas A. Bozada

December 2025

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Final Report

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Abstract

Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) is a computational model that provides quantitative results to installations and remote communities that inform them of the objectives they can achieve. Results provided by this model lead to reliable intermittent power resource implementation, optimize the set of resources within a power system, and improve reliability and resiliency outcomes. This technical report provides an example of the analysis results AMPeRRe can produce to quantify the expected benefits and trade-offs of incorporating different power resources and energy storage in a power system. Fort Phantom, a notional installation, was used as the testbed to produce these results. The AMPeRRe model forecasts outcomes such as the power availability, fuel consumption, duty cycle, and excess energy of different power resource investment scenarios. The results produced by this model are based on notional stages of development for the Fort Phantom Consolidated Maintenance Activity (CMA) power system. This technical report also provides an expanded set of results and comparison of outcomes from different quantities of incorporated power resources. These results can aid business case development for power systems and enable efficient, informed development.

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Preface

This study was conducted for the US Army Corps of Engineers under Program Element 0603119A, Project Number B03.

The work was performed by the Emergency and Operational Support Branch of the Operational Science and Engineering Division, Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Ms. Ellen Hartman was branch chief, Dr. George Calfas was division chief, and Mr. Jim Allen was the technical director for Operational Science and Engineering. The deputy director of ERDC-CERL was Ms. Michelle Hanson, and the director was Dr. Andrew Nelson.

Section 1 reproduces with modifications portions of Jessica J. Nicholson, Matthew T. Gross, Camryn T. Anderson, and Thomas A. Bozada, *Camp Ripley Training Center Microgrid Analysis—Incorporation of Solar Array and Energy Storage: Results Produced Using the Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) Computational Model*, ERDC/CERL TR-25-14 (Construction Engineering Research Laboratory, 2025). *This is a controlled report that is unavailable to the public. The reprinted material does not include the controlled unclassified information from the report.*

LTC Joshua M. Haynes was commander of ERDC, and Dr. Beth C. Fleming was the director.

1 Introduction

Energy demand continues to grow on a global scale. Because of this, implementing reliable and resilient energy solutions while transitioning away from costly fuel-based sources is becoming increasingly critical. The long-term reliability and resiliency of power grids in global communities and installations depends on the ability to make strategic investments that optimize cost and resources. While intermittent energy sources such as photovoltaic (PV) solar and wind pose challenges for energy generation that must be managed, these energy resources can offset the costs and logistics such as transportation and maintenance associated with fuel-based power sources when paired with energy storage and placed in a microgrid. Computational modeling is essential to designing power systems that make more effective use of power-grid assets, manage variability, ensure continuous power service, achieve operational objectives, and accommodate for the loss of utility power.

1.1 Background

The Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) computational model forecasts the power availability, fuel consumption, specific resilience factors, and excess energy production of planned power systems that include various power resources and energy storage (Nicholson 2024). It quantifies the value of proposed advancements to baseline power systems or the addition of new energy resources by comparing the baseline system performance to the performance outcomes that the model forecasts, given the added resources. If the proposed power systems are forecasted to lose power availability, users can apply this model to find which resources are needed to achieve a predicted 100% power availability by optimizing resource quantities for ideal performance outcomes. AMPeRRe informs the critical resource investment decisions needed to yield improved long-term reliability and resiliency outcomes.

There are three variations of the AMPeRRe model. One variation evaluates islanded microgrids, while two variations evaluate utility-connected grids. The *primary* utility-connected variation designates the utility as a primary power source. This variation assumes either that the on-site microgrid resources will only provide power support in the event of a utility outage or that intentional limits are placed on utility power. The *integrated* utility variation, on the other hand, treats the utility as a source that is integrated with the microgrid. Any on-site intermittent, harvestable energy and energy storage systems take priority in supplying power to the load during blue-sky conditions. The utility is counted as a tertiary support, only prioritized over on-site fuel-based dispatchable, power resources. Resource prioritization for each of the three variations is summarized below and shown in Figure 1.

Islanded microgrid power supply:

1. Harvestable energy (solar and wind for Fort Phantom)
   a. Harvestable energy supplies power directly to load.
   b. Surplus harvestable power charges the battery.
2. Energy storage (lithium-ion battery)
   a. Battery storage charges during any surplus of harvestable power and discharges to load during a shortage.
3. Liquid fuel (diesel generators)
   a. Liquid fuel supplies power to the load during a shortage to maintain a reserve level of stored energy.

Utility-connected power supply for a supporting microgrid:

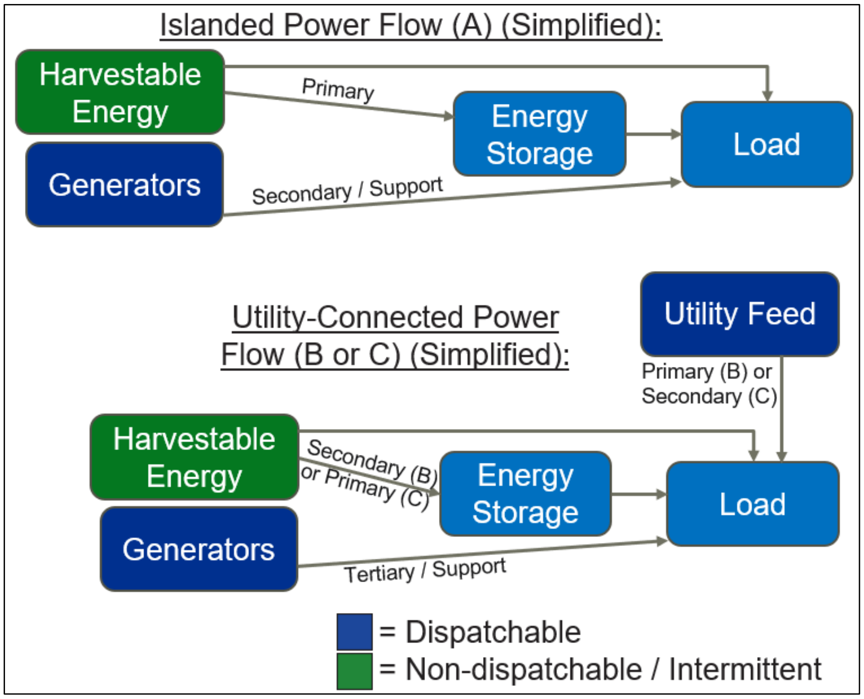
1. Utility power
   a. On-site microgrid resources only contribute when a limit is placed on utility power.
2. Harvestable energy
3. Energy storage
4. Liquid fuel

Utility-connected power supply for an integrated microgrid:

1. Harvestable energy
2. Energy storage
3. Utility power
   a. Harvestable energy and energy storage shortages prompt the utility to supply power to the load.
4. Liquid fuel

a. If limits are placed on utility power and it becomes insufficient to fully account for shortages, liquid fuels provide power.

Figure 1. Simplified power flow for each Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) variation.



1.2 Objectives

The objective is to use AMPeRRe to evaluate Fort Phantom, a digitally modeled, notional installation with electrical infrastructure and facilities. Fort Phantom's Consolidated Maintenance Activity (CMA) was the focus of this analysis. Fort Phantom was assumed to be connected to a utility with backup diesel generators on base. For the purposes of this study, the Fort Phantom CMA was assumed to have five diesel generators at the point of use that were dispatched during islanding. This is the baseline scenario from which comparative calculations were made. The AMPeRRe results in this report account for a microgrid at Fort Phantom, which enables the notional integration of a PV solar array, wind turbines, and supporting battery energy storage. These results include forecasted outcomes such as fuel savings, excess energy, and a utility peak-shaving capability that would result from incorporating different quantities of solar, wind, and energy storage at the installation. The AMPeRRe model also compares these outcomes for operation in a utility-connected state versus an islanded state and for different power resource control schemes.

Assumptions are used in this AMPeRRe analysis across each model variation that are specific to the Fort Phantom case study.

- AMPeRRe models a microgrid system with five generators that power the Fort Phantom CMA as the baseline case. Two generators are rated for 50 kW, two are rated for 25 kW, and one is rated for 75 kW.* All calculations of fuel savings for subsequent cases are based on the expected fuel consumption of the subsequent cases relative to this baseline case.
- The dispatch of each diesel generator is based on a set priority. Generators are dispatched in a determined order based on the load on the generator set at each time step. For this case, the priority is as follows: 50 kW, 50 kW, 25 kW, 25 kW, 75 kW.
- These results are produced under the assumption that Fort Phantom has a microgrid at the CMA with a control system that allows it to be utility connected or islanded during blue-sky conditions. The microgrid is adaptable and can scale to include solar, wind, and battery energy storage along with the diesel generators.
- The islanded outcomes shown in the comparative results section assume that on-site power resources at the Fort Phantom CMA supply power to its load rather than to a utility source. The utility-connected results all consider a limit condition placed on utility power draw for peak shaving.
- Fort Phantom has 50 L of diesel fuel storage at the CMA. The calculated number of days between fuel resupply assumes that resupply occurs when the stored fuel reaches 20% of capacity. In sealed storage, diesel fuel has an approximate shelf life of six months, or 182 days. This becomes a limiting factor if the calculated number of days between fuel resupply is greater than 182 days.
- For integrated utility-connected cases, the default threshold of stored energy at which utility power supports the load is a user-definable value. For this case, AMPeRRe assumes that the utility contributes during shortages of intermittent power when the stored energy is below a threshold of 22.5 kWh. This threshold is high enough to ensure a constant energy supply in the event of outages, but it is not set to capacity to allow for the battery to capture surplus energy from intermittent resources.

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

- Backup diesel generators support the load once the stored energy drops below a second, lower, user-defined threshold. This allows for AM-PeRRe to treat the generators as a lower-priority power source than the utility in utility-connected cases.

1.3 Approach

To apply AMPeRRe in the evaluation of a power system, users must define and input the following parameters and characteristics (Nicholson 2024):

- Solar array parameters
  a. Rated power
  b. Temperature coefficient
  c. Nominal operating cell temperature

- Wind turbine parameters
  a. Manufacturer
  b. Power curve (power output versus wind speed)
  c. Blade radius
  d. Altitude
  e. Air density associated with altitude

- Inverter parameters
  a. Size and rated power
  b. Efficiency
  c. Ramp-up rate limit
  d. Ramp-down rate limit

- Energy storage system parameters
  a. Manufacturer
  b. Energy storage capacity
  c. Maximum charge and discharge rate
  d. Round-trip or charge and discharge efficiency
  e. Average parasitic load (if not included in full load profile)

- Fuel-based dispatchable source parameters
  a. Number of systems
  b. Rated power
  c. Power acceptance rate
  d. Fuel consumption curves

- Chronological load data
    a. Time-step length
    b. Collective power load data from the location of interest
- Location-based, chronological natural resource data
    a. Direct, normal solar irradiance
    b. Wind speed
    c. Ambient temperature

AMPeRRe produces results that forecast the following measurable outcomes. It also allows the user to choose the grid configuration, or power resource mix, that achieves reliability and resiliency goals by optimizing one or more of the following outcomes.

- **Power availability—maximize:** Power availability is the percentage of time that a power grid meets demand during its period of operation. A system that provides continuous power supply to the load has a power availability of 100%. The primary objective of a power grid is to provide continuous service, so a proposed power grid's availability must be validated as 100%. If high load or low power generation are forecasted to cause loss of power supply, AMPeRRe will calculate power availability as a value below 100%. The power availability required from a power grid depends on the system it supports. The more critical the system, the higher the power availability standard it must adhere to. Many power-availability standards fall within the range of 99.99% to 99.9999%.
- **Utility energy contribution—minimize:** Utility power can be costly and incorporate fossil fuels. Reducing the contribution of utility energy to an installation load can reduce the overall costs. Reducing the utility contribution can also lower the installation's overall fuel consumption if this utility power loss is offset by non-fuel-based energy generation.
- **Intermittent energy contribution—maximize:** Maximizing the solar and wind energy contribution can reduce costs, as these sources do not require fuel. Despite their intermittency, it is possible to supply a significant amount of load using these resources and reach their maximum possible contribution while retaining power availability.
- **Generator energy contribution—minimize:** Generators are costly to operate due to their fuel consumption, so minimizing

generator involvement while maintaining power availability is cost-effective and minimizes logistical considerations.

- **Generator duty cycle—minimize:** AMPeRRe monitors the time steps that dispatchable sources operate and forecasts the duty cycle of these sources within the system. Similar to fuel consumption, the duty cycle of fuel-based sources within a system will decrease if greater quantities of intermittent energy sources are included in the grid. The more these energy sources are included in the grid, the less frequently fuel-based sources must operate to support the grid. This is reflected in a lower forecast of duty cycles. The lower the duty cycles of the generators, the longer their life span is expected to be and the lower the costs associated with maintenance and replacement.
- **Liquid fuel consumption—minimize:** The rate of fuel consumption from a fuel-based dispatchable energy source is dependent on its power output at any given time. In a power system with generators, for example, this means that the rate of fuel consumption from each generator will vary depending on the power demanded from the generator. When a power grid has one or multiple fuel-based power sources, AMPeRRe calculates the system's total fuel consumption over a period of time. The higher the quantity of intermittent energy sources within a grid, the less power is required of the fuel-based sources on average and the less fuel they will consume. The less fuel consumed, the more effectively the power grid can reach self-sufficiency objectives.
- **Excess energy—minimize:** If a power grid is producing more energy than it can capture, this excess energy must be managed. This is a necessity when the battery charge is nearing capacity and cannot capture additional energy surplus. If the power surplus is greater than the battery charge rate, the grid must also manage excess power. Excess energy may be curtailed, sold to a connected utility, or filtered out of the grid. Curtailment occurs when a microgrid controller intentionally halts power generation from specific power sources to prevent the grid from being overloaded. Energy filtered out would be lost to the surroundings, but if the grid is connected to a utility, energy could instead be redirected back to the utility. Many factors inform the decision to curtail power. These factors include limits on transmission line power flow and voltage, as well as the need to maintain stability. If power grids can minimize excess energy production, this energy can instead be used productively toward serving the load. Doing so can make the grid more cost-effective and minimize the need for fuel-based support.

- **Survival time—maximize:** In the event of a utility or power resource failure, survival time is the measured duration of time from the start of the failure to the loss of power service. AMPeRRe's survival time output shows a user how long their power grid would continue to provide service once failure occurs. Users can model any failure among the power sources within the power grid, as well as the start and end time of the failure. The longer the survival time forecasted by AMPeRRe, the more resilient the power grid is to the specified failure mode.
- **Magnitude and duration of power shortages—minimize:** The greater the intermittence of power generation or variability of the load, the more likely the load will exceed generated power. If the load exceeds generated power for a significant amount of time, there is a greater chance that stored energy reserves will fully deplete and cause a loss of service. Power grids often incorporate oversized intermittent power sources compared to the load to compensate for this intermittence. The greater the variability in the system, the larger the power grid must be relative to the load to maintain power availability. This is a cost-intensive solution, however. The preferable alternative is to design a grid with intermittent power generation patterns that align as well as possible with common load profile patterns. The better the grid's collective power generation pattern matches needs, the less frequently shortages will occur and the smaller these shortages will be. The less severe the power shortages, the more likely a system is to have continuous power availability and high survival times.

2 Case-Specific AMPeRRe Results for the Fort Phantom Consolidated Maintenance Activity (CMA)

Table 1 shares AMPeRRe results for the Fort Phantom CMA power system. These results are selected from the full set of AMPeRRe results as notional power system developments. Row 1 shows the forecasted outcomes associated with the assumed current power system at the Fort Phantom CMA, while each subsequent row showcases the forecasted outcomes for stages of power system development.

Table 1. Selected results from AMPeRRe's Fort Phantom Consolidated Maintenance Activity (CMA) results that show outcomes for notional developments.

CMA Power System Case	Power Availability (%)	Utility Energy (kWh/ year)	Harvested Energy (kWh/ year)	Generated Energy (MWh/ year)	Generated Duty Cycle (%)	Activations Per Year	Fuel Use (Liters/ year)	Fuel Savings (%)	Days Fuel Resupply	Excess Energy (kWh/ year)
1	100	0	0	501.35	100	1,686	286.6	0	63.7	0
2	100	218.83	0	282.5	98.3	939	195.2	31.9	93.45	0
3	100	344.53	0	156.8	27.2	765	84.5	70.5	215.85	0
4	100	0	622.73	359.55	59.6	1,785	208.4	27.3	87.55	451
5	100	0	706.69	316.44	56.7	1,521	182.3	36.4	100.1	490.5
6	100	0	706.69	265.64	35.8	1,467	152.6	46.7	119.55	409.7
7	100	218.83	706.69	148.63	19.5	986	81.7	71.5	223.4	516.9
8	100	344.53	706.69	86.77	15.2	623	46	83.9	396.85	582
9	100	144.41	706.69	122.85	22.9	623	66.7	76.8	273.95	412

2.1 Case 1: Baseline Case

Case 1 reflects a power supply to the Fort Phantom CMA from an islanded microgrid consisting of generators and 50 kWh of battery energy storage. This case assumes that diesel generators provide power to the CMA as an islanded system and that there are five generators of differing sizes at the point of use. Row 1 in Table 1 shows the prospective outcomes of this baseline case. While this case results in the maximum fuel consumption, there is no utility involvement and no utility costs. Data provided on the expected hourly load profile of Fort Phantom's CMA have enabled AMPeRRe modeling of this baseline case.

2.2 Case 2: Add Utility Involvement—25 kW Peak

Most installations rely on utility power as a primary resource, and peak shaving can minimize utility costs. Case 2 in Table 1 considers a Fort Phantom CMA that relies on utility power as a primary resource with a peak of 25 kW. This means that the power the CMA receives from the utility is limited to 25 kW and that on-site power resources must supply the remainder of the power when the demand is greater than 25 kW. CMA power demand regularly exceeds 25 kW, so this level of peak shaving leads to regular time steps in which the on-site generators provide supplemental power.

2.3 Case 3: Add Utility Involvement—50 kW Peak

This case is similar to Case 2, but the utility peak is 50 kW instead of 25 kW. The utility is treated as a primary resource and contributes more power to the CMA at each time step than Case 2. Additional utility involvement offsets the generator involvement needed to maintain the power supply, which can be seen by the lower fuel consumption and significantly lower generator set duty cycle in Case 3.

2.4 Case 4: Return to Islanded System and Add 500 kW Solar Array

If Fort Phantom places a solar array at the CMA, the solar array would offset the need for some of the generator power and contribute to lower fuel consumption. When the generators are called on to provide power, a solar array and existing battery energy storage would instead take priority in providing power before the generators contribute. Case 4 in Table 1 shows the outcomes of incorporating a 500 kW solar array. The expanded set of AMPeRRe results (Sections 3 and 4) shows the forecasted fuel savings associated with incorporating solar arrays of different sizes with supporting energy storage.

2.5 Case 5: Add a 910 kW Wind Turbine

A 910 kW wind turbine at the Fort Phantom CMA would add to the set of intermittent power resources. While intermittent power sources require supporting resources to ensure full power availability, strategically pairing different types of intermittent resources can make the power output profile less intermittent. Solar arrays produce power intermittently during the day with peak power production around midday, while wind turbines can produce power at all hours of the day. Pairing these resources can minimize the impact of a solar power deficit during the night. Case 5 in Table 1 shows how the added 910 kW turbine further reduces generator involvement and fuel consumption. The expanded set of AMPeRRe results shows the outcomes of incorporating a turbine of this size given different resource combinations and utility involvement conditions (Section 3.2).

2.6 Case 6: Increase Battery Energy Storage Capacity to 200 kWh

Case 6 increases the storage capacity of the lithium-ion battery energy system to capture and store more intermittent energy from the solar and wind resources. A 200 kWh battery will capture more surplus energy than the 50 kWh battery, and it can discharge more energy during periods of intermittent power shortage. Greater value is drawn from intermittent power resources when an energy storage system can capture more of their output. The battery energy storage can also enable utility peak shaving and capture excess generator power to allow the generator to output the power aligned with its peak efficiency. This case in Table 1 considers adding 200 kWh of battery energy storage capacity, while the expanded set of AMPeRRe results shows the outcomes of implementing various energy storage capacities (Section 3.3). The backup generators contribute once the stored energy drops below a specified threshold, which the AMPeRRe model shows happens less frequently given greater battery capacity. This leads to fewer generator duty cycles and less fuel consumption compared to the baseline case.

2.7 Case 7: Add Utility Involvement with Power Resources—25 kW Peak

While Case 2 considers utility involvement for the CMA given that its power system consists only of diesel generators, this case considers utility involvement for a CMA power system that includes solar, wind, and additional battery energy storage at the point of use. The utility is treated as a primary power resource. The output of the intermittent power resources remains the same, so utility involvement offsets generator involvement. Case 7 in Table 1 shows a significant decrease in generator duty cycles and fuel consumption.

2.8 Case 8: Add Utility Involvement with Power Resources—50 kW Peak

Case 8 is similar to Case 7, but the utility peak is 50 kW instead of 25 kW. The utility is treated as a primary resource and contributes more power to the CMA at each time step than Case 7. Additional utility involvement offsets the generator involvement needed to maintain power supply, which can be seen by the lower fuel consumption and significantly lower generator-set duty cycles in Case 8.

2.9 Case 9: Add Microgrid Controller and Integrated Utility Involvement

When Fort Phantom relies on utility power under a peak-shaving condition, the utility power is treated as a primary resource. The utility provides power to fulfill the power demand up to its specified peak, and any remaining power demand becomes demand on the on-site power resources. More power produced by the intermittent on-site power resources becomes in excess of the remaining power demand, creating more wasted energy that shows limited benefit. If Fort Phantom adds a microgrid controller and the proper agreements are in place, the Fort Phantom CMA could instead use the solar array and wind turbine as the primary power resources. The solar array, wind turbine, and battery energy storage system would take priority over the utility in this case, while utility power would only contribute during periods of intermittent power shortage and low collective battery charge. AMPeRRe's integrated-utility-involvement variation models this provisional scenario. Case 9 in Table 1 shows that if Fort Phantom were to apply this control system, generator involvement would increase, but the energy contribution of the utility would significantly drop and less of the power produced by the intermittent resource would become excess, wasted power. This would make more optimal use of the intermittent power resources, reduce the overall power drawn from the utility, and allow for more peak shaving that would lower utility costs.

3 Numerical and Plotted AMPeRRe Results

This section shares the results generated by AMPeRRe that cover the Fort Phantom CMA power system in utility-connected versus islanded operation. Each section provides plotted results to supplement the numerical results for select cases from Table 1. Figure 2, Figure 6, and Figure 9 show the input load profile representing demand on the CMA power system, the power output of each source, stored energy, and other plotted output results for each select case. These plots are used to visualize how the intermittent power production, dispatchable power, and state of stored energy are expected to change throughout the measured time period. The results include frequency-domain plots, including the frequency at which the collective stored energy is at different states. The higher the average state of collective stored energy, the more likely the power system is to be prepared and maintain availability during adverse events when energy resources fail. AMPeRRe also plots the frequency for which fuel-based sources operate at different rates of fuel consumption. One histogram in each case shows the duty cycle, or the proportion of time that any number of on-site generators are running.

Given primary utility involvement, the on-site power resources act as supporting sources during any peak shaving or utility outages. The on-site backup generators are sufficient to support Fort Phantom's CMA, so power availability is calculated as 100% for every Fort Phantom case with the generators and every case with additional resources. AMPeRRe provides results that show the benefits and trade-offs of planned power investments. For example, one of AMPeRRe's results for Fort Phantom shows that adding a 500 kW solar array, 910 kW wind turbine, and 200 kWh of energy storage capacity at the CMA as primary power resources would lead to 47% fuel savings. Fort Phantom is assumed to have 50 L of fuel storage capacity at the CMA to account for outages, which is enough to accommodate the fuel use of the baseline scenario and subsequent scenarios with minimal fuel resupply. The AMPeRRe-calculated number of days between fuel resupply exceeds the sealed shelf life of diesel in several cases, so the shelf life is the limiting factor rather than the fuel storage capacity.

3.1 Case 1: Baseline

For the purposes of this analysis, Fort Phantom's notional power system for their CMA is a set of five diesel generators that can operate in islanded mode. This is treated as the baseline case from which developments to the power system can occur. Since the CMA power demand relies entirely on this set of generators, Figure 2 shows that the rate of fuel consumption and number of generators operating change over time in alignment with changes to the CMA's power demand. Figure 3 shows the duty cycle of each generator in terms of the proportion of time for which a given number of generators are operating. One generator operates for the majority of the time steps, but power demand on the generator set occasionally causes several generators to operate to meet demand. Figure 4 shows that the battery stays at a constant state of charge, as this baseline case is a blue-sky scenario in which the generators are consistently available and sufficient to provide power up to peak demand. The energy storage also does not need to capture any power from intermittent resources.

Figure 2. Input Consolidated Maintenance Activity (CMA) load profile and plotted time-domain results.

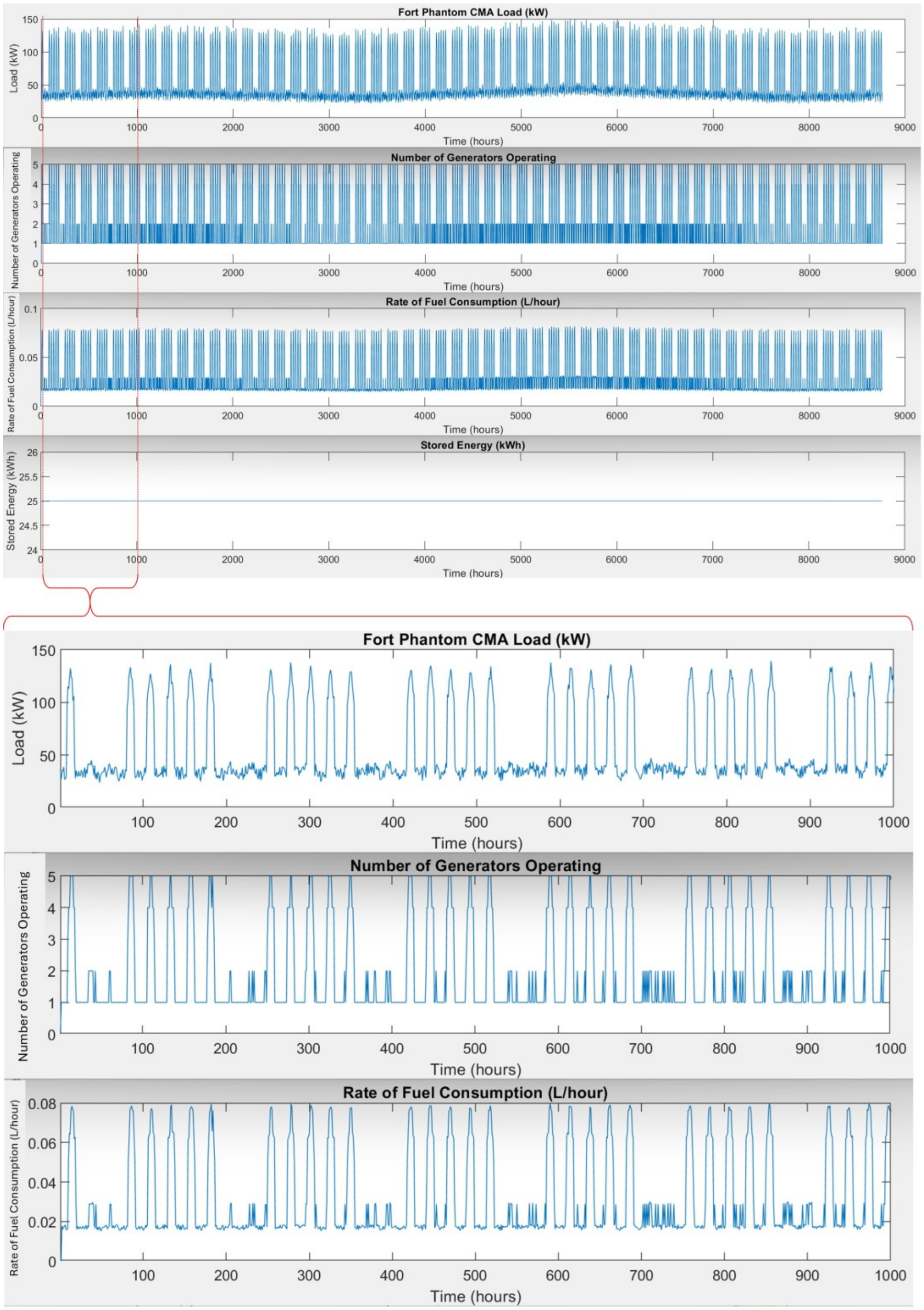


Figure 3. *Top,* duty cycle for each on-site diesel generator; *bottom,* frequency of operation at different rates of fuel consumption.

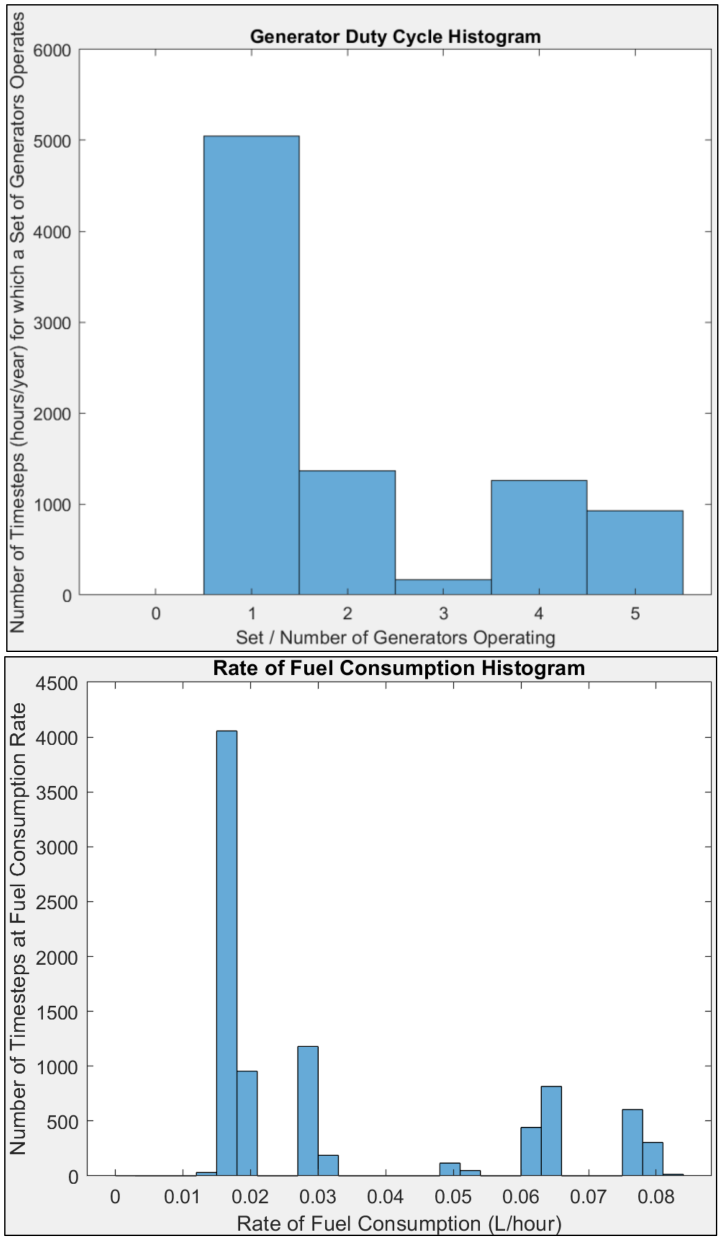
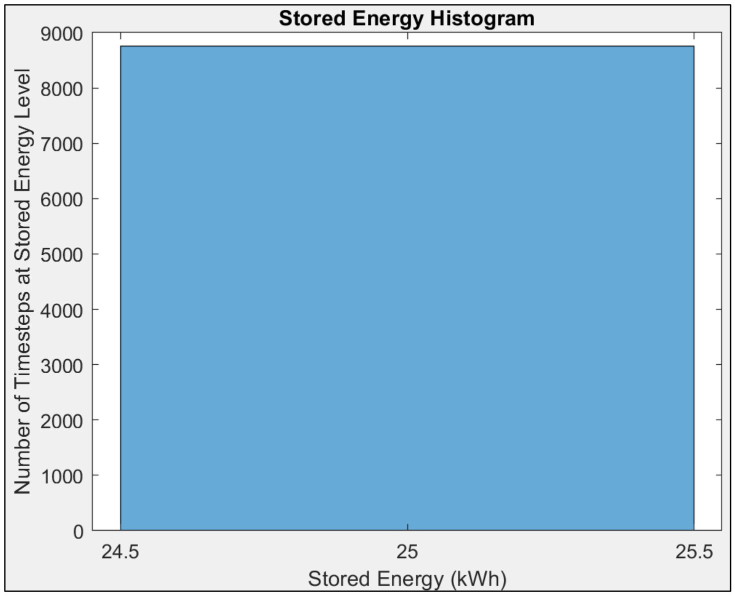


Figure 4. Frequency of stored-energy state-of-charge levels.

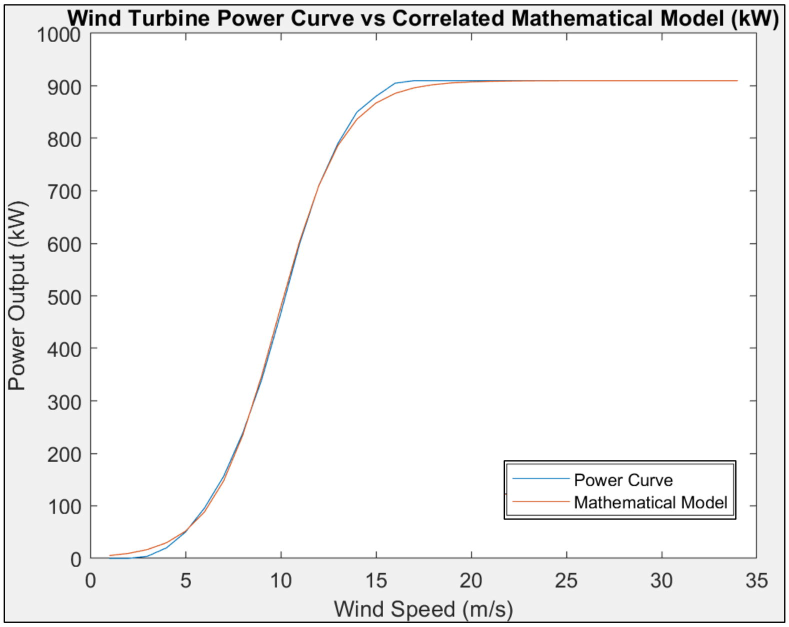


3.2 Case 5: Added 500 kW Solar and 910 kW Wind

In this islanded scenario, a 500 kW solar array and 910 kW wind turbine are incorporated into the CMA power system to act as primary power resources. The set of five generators at the CMA become tertiary resources that account for intermittent power shortages and low stored energy. As shown in Table 1, the fuel savings associated with the addition of these resources would be approximately 36%. Excess energy is produced due to insufficient battery capacity at time steps for which energy storage is at full capacity. To increase fuel savings, Fort Phantom can incorporate more non-fuel-based power resources and energy storage to maximize the use of intermittent power resources. The 50 L fuel capacity is sufficient for fuel resupply to be infrequent, and resupply would only be necessary approximately every 100 days.

Wind turbine power output is calculated using manufacturer power curves. AMPeRRe accepts a power curve dataset input, and it applies an optimization algorithm to choose the coefficients in a mathematical model designed to fit turbine power curves. These coefficients are factored into the mathematical model to maximize the correlation coefficient between the power curve and the model. Figure 5 shows the mathematical model closely matched to the power curve of the 910 kW turbine, which is used to calculate the power output of the turbine at every time step.

Figure 5. Wind turbine model correlation with power curve.



The addition of the solar and wind intermittent power resources causes AMPeRRe to output a time-based profile of intermittent power. This profile is matched to the power demand to determine whether the collective power output of the intermittent resources is in surplus or shortage of the demand at each time step, producing a surplus and shortage map as in the "Surplus Power from Intermittent Power Resources" plot in Figure 6. AMPeRRe assumes that surplus power is managed by diverting to energy storage, and energy storage and generators provide power during time steps of power shortage. The plotted generator power contribution and duty cycle histogram in Figure 7 still show significant generator involvement, although generator involvement is reduced due to the additional resources taking priority. Stored energy is shown in the "Stored Energy" plot in Figure 6, which experiences frequent charge and discharge cycles due to the involvement of the intermittent resources. Stored energy never drops below 25 kWh as this is the threshold for generator involvement (Figure 8).

Figure 6. Input CMA load profile and plotted time-domain results.

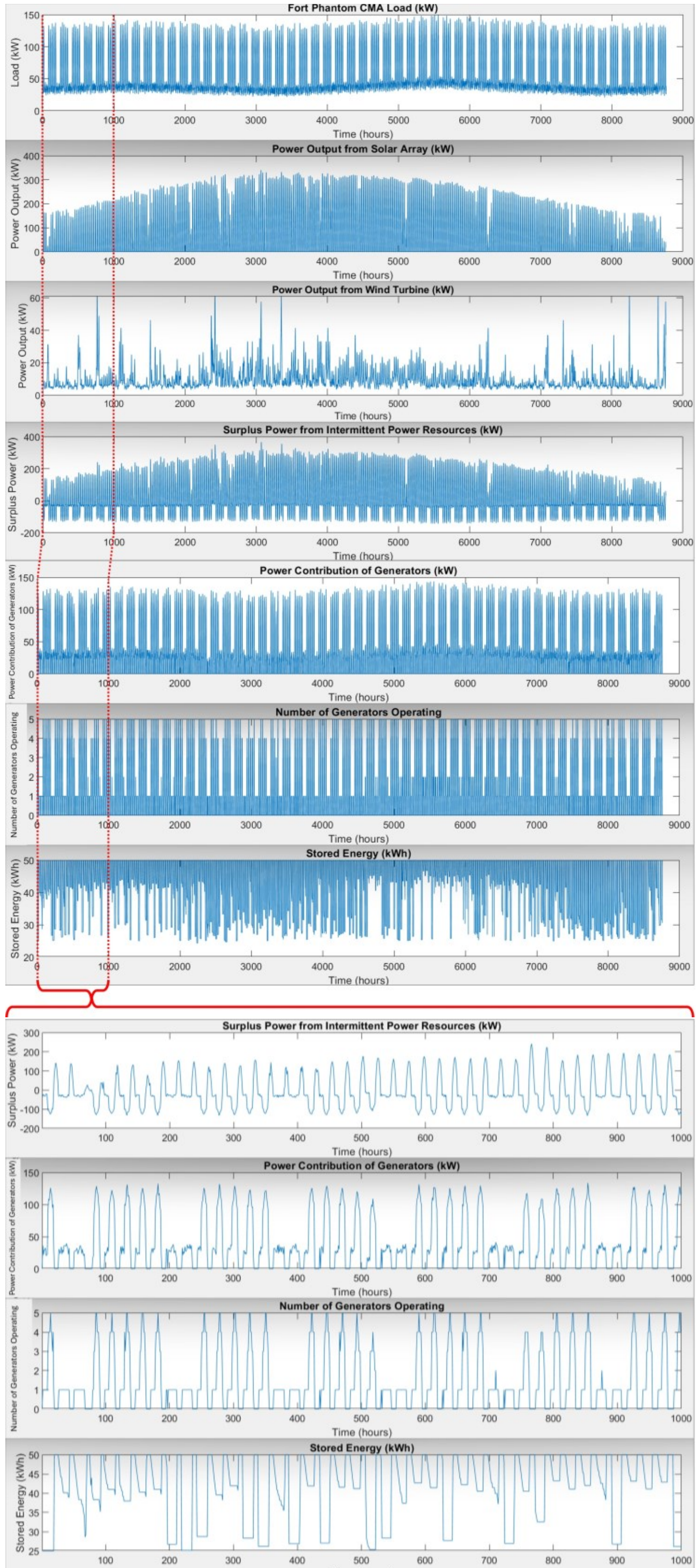


Figure 7. *Top,* calculated duty cycle for each on-site diesel generator; *bottom,* frequency of operation at different fuel consumption rates.

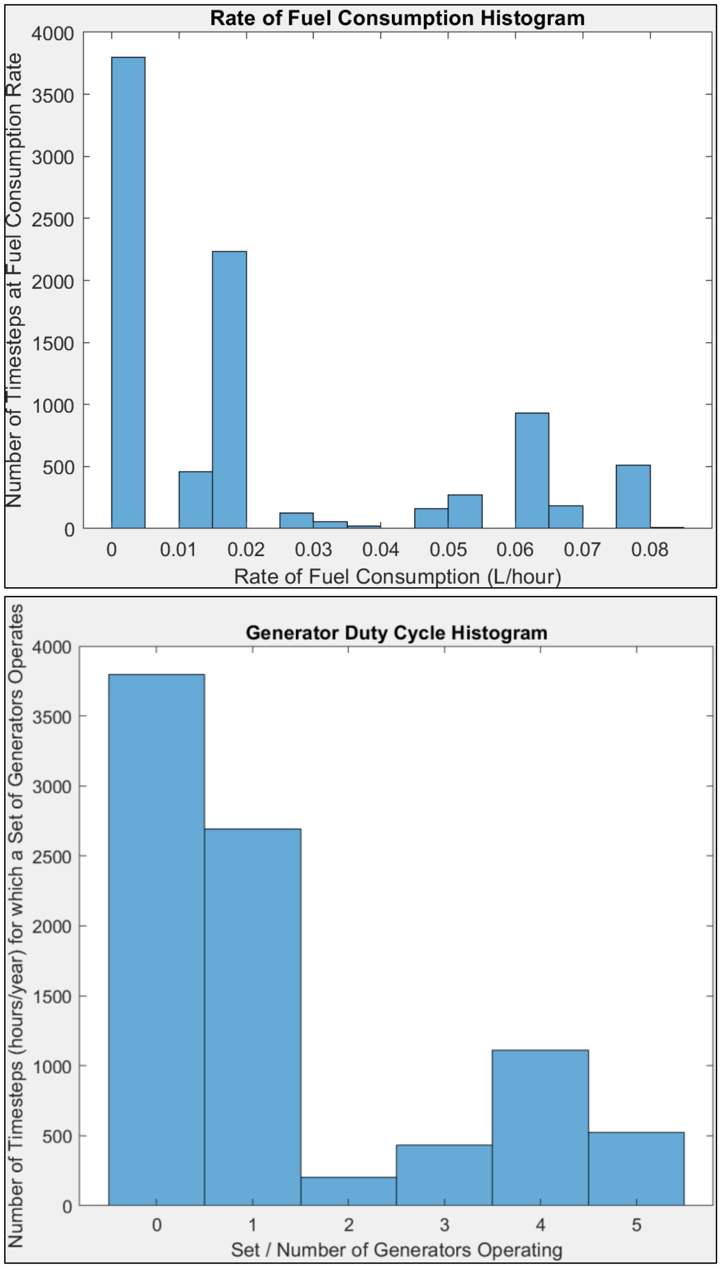
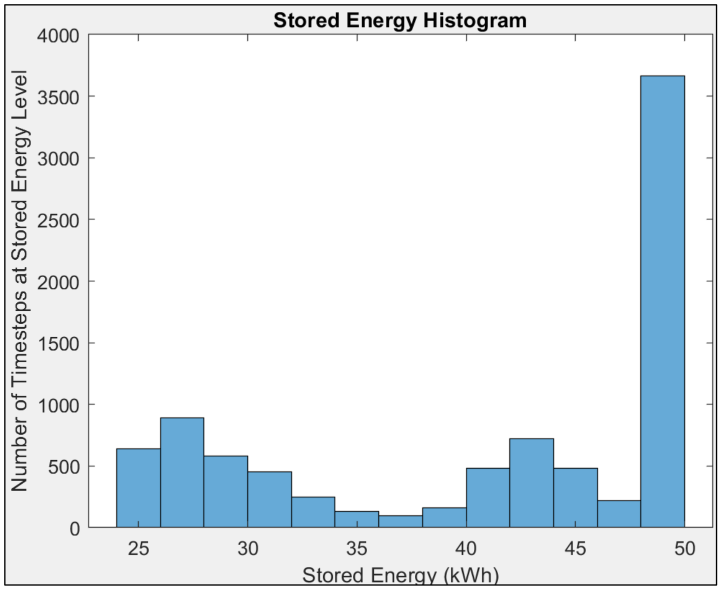


Figure 8. Frequency of stored-energy state-of-charge levels.



3.3 Case 6: Increase Battery Energy Storage Capacity to 200 kWh

Figure 9 shows time-based plots for Case 6. The baseline case considers 50 kWh of battery energy storage capacity. This case increases the capacity to 200 kW h, which allows for the battery energy storage system to capture a greater proportion of surplus energy from the intermittent power resources. With a 200 kWh battery supporting the intermittent energy resources, the fuel savings of the power system would be approximately 47%. The generator-duty-cycle histogram in Figure 10 shows that generators contribute less frequently. Excess energy is still produced when stored energy is at full capacity, but less is produced. Figure 11 shows the variability of the stored energy given a higher capacity.

AMPeRRe can model different user-input control conditions that increase the battery charge at which generators provide support. For this case, the threshold for generator support is a battery charge below 25 kWh. Increasing this threshold leads to more fuel consumption, but it is ideal for scenarios where adverse conditions may affect a microgrid, and the microgrid must be prepared to survive during component failure.

Figure 9. Input CMA load profile and plotted time-domain results.

Figure 10. *Top,* calculated duty cycle for each on-site diesel generator; *bottom*, frequency of operation at different fuel-consumption rates.

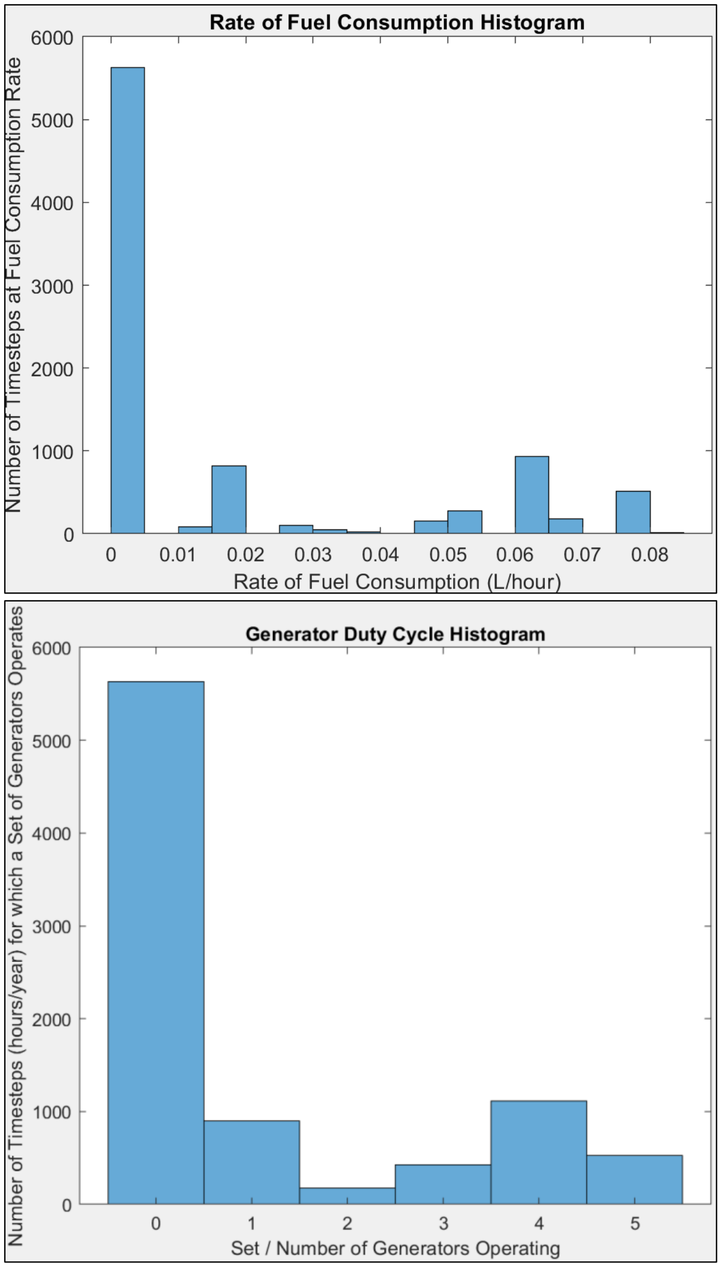
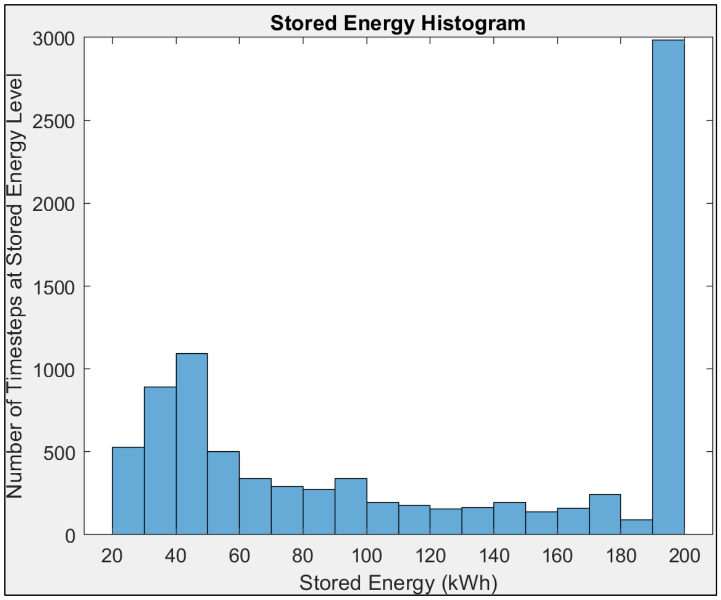


Figure 11. Frequency of stored-energy state-of-charge levels.



3.4 Case 8: Utility Involvement with 50 kW Peak

For the purposes of AMPeRRe, peak shaving is a limit placed on the amount of power that can be drawn from a utility at any given time. The more the utility peak is limited, the less overall energy is provided by the utility and the more energy the on-site resources must provide. If an installation's or facility's on-site power resources can meet enough of its power demand, a utility-reliant installation may peak shave to save utility costs. Given its on-site solar, wind, and generator power resources, Table 1 shows that the CMA would achieve a fuel savings of 84% from the baseline case if it were to rely primarily on utility power with a peak power draw of 50 kW. The "Power Contribution of Generators" plot in Figure 12 shows that, when the utility becomes involved, generators are less frequently needed to supply power during periods of solar power shortage and low stored energy. The duty-cycle histogram in Figure 13 shows that generators do not operate during most of the evaluated time period. Figure 14 shows that the energy storage remains closer to capacity on average due to the involvement of the utility.

Figure 12. Input CMA load profile and plotted time-domain results.

Figure 13. *Top*, calculated duty cycle for each on-site diesel generator; *bottom*, frequency of operation at different fuel consumption rates.

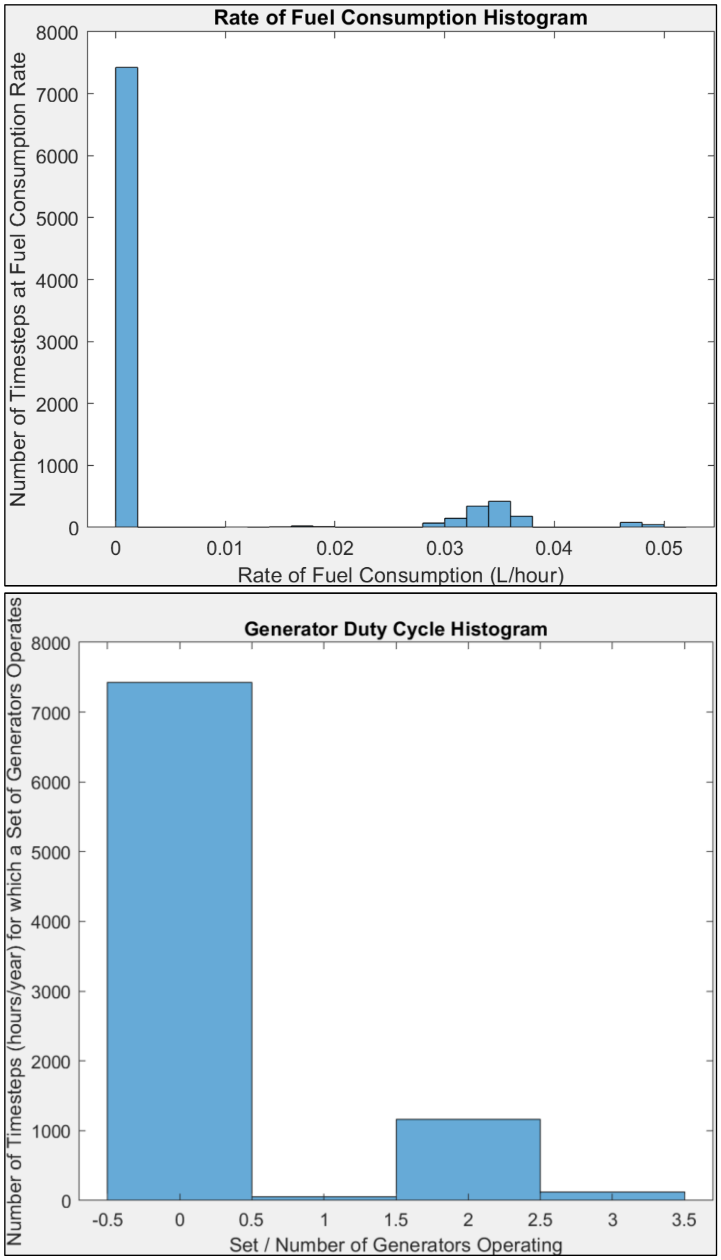
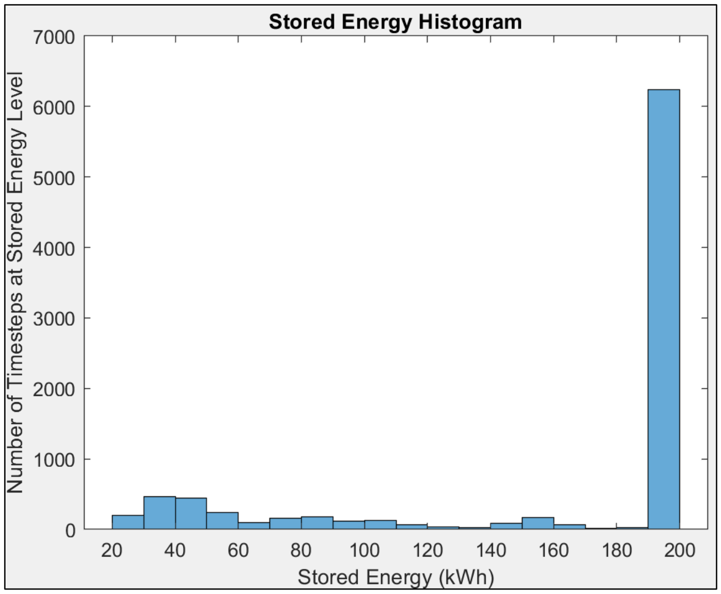


Figure 14. Frequency of stored-energy state-of-charge levels.



3.5 Case 9: Integrated Utility Involvement

If the Fort Phantom CMA implements a microgrid controller, its on-site solar, wind, and battery energy storage could provide primary power to the load in a utility-connected scenario. Rather than treat the utility as a primary source, the utility would support periods of intermittent energy shortage and low stored energy. Figure 15 shows that the power drawn from the utility is minimized in this case as the intermittent power resources and battery energy storage provide a greater proportion of the power demand. Figure 16 shows the generator involvement of this case, while Figure 17 shows the greater battery energy storage involvement. AMPeRRe sets the utility power to support the load only when the collective stored energy drops below a user-defined threshold. This minimizes the energy drawn from the utility and maximizes the power the system can capture from the intermittent resources, producing less excess energy. When the utility-power-support threshold is higher than the generator-power-support threshold, utility power takes priority over the on-site generators to support the power demand during intermittent power shortages and low stored energy. When the generator-power-support threshold is higher than the utility-power-support threshold, generators take priority. For this case, the utility-power-support threshold is set higher than the generator threshold to minimize involvement of the on-site generators and fuel consumption.

The control scheme of this case is integrated utility involvement. Comparative results in the next section distinguish between primary utility and integrated utility involvement. While the primary utility involvement in Case 8 results in approximately 345 kWh of utility energy use, this integrated utility involvement case results in approximately 144 kWh of utility energy use. This means that integrated utility control can lower energy-based utility costs. If the utility is predominantly fuel-based, this may also reduce the overall fuel consumption of the Fort Phantom CMA despite its on-site generators.

Figure 15. Input CMA load profile and plotted time-domain results.

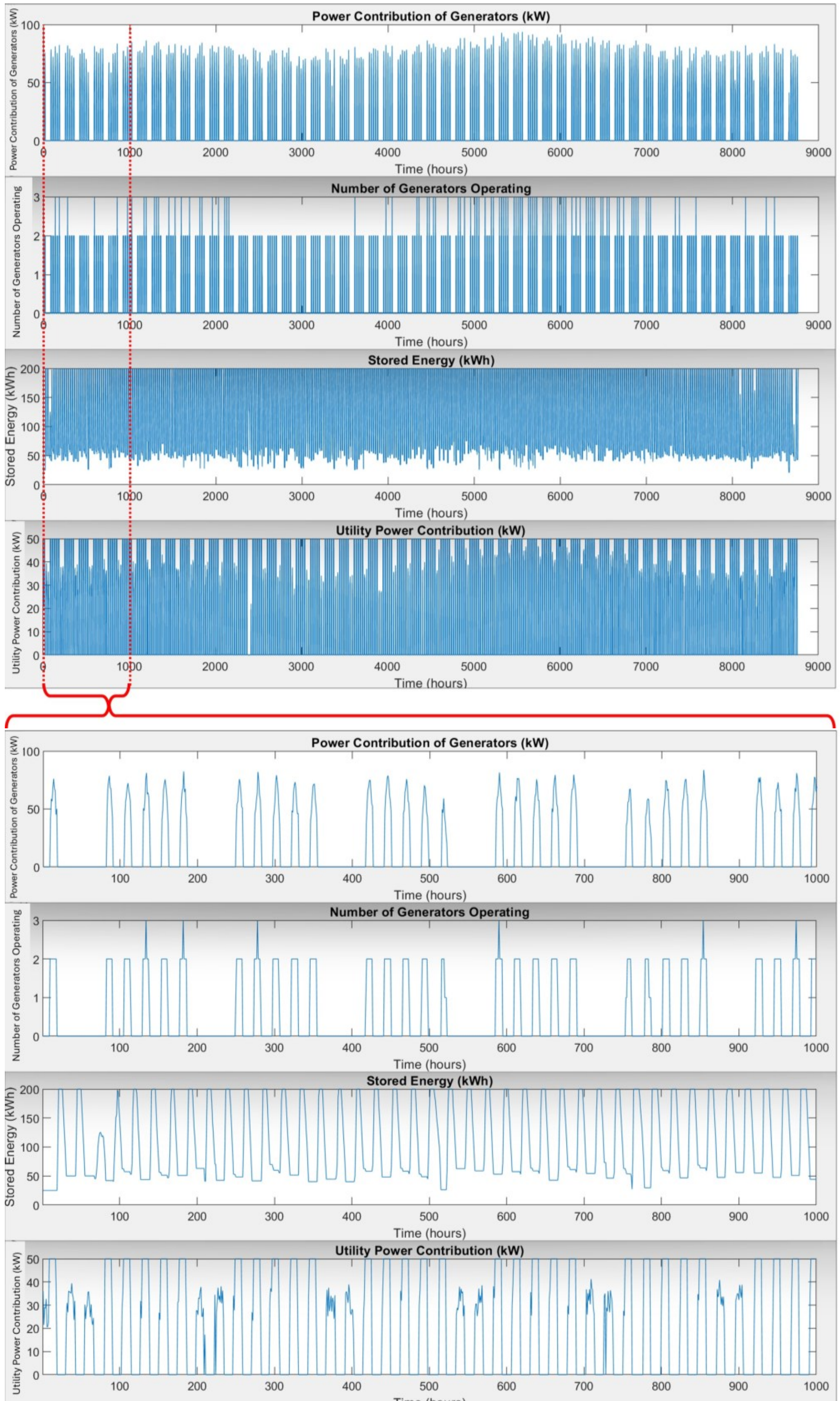


Figure 16. *Top*, calculated duty cycle for each on-site diesel generator; *bottom*, frequency of operation at different fuel consumption rates.

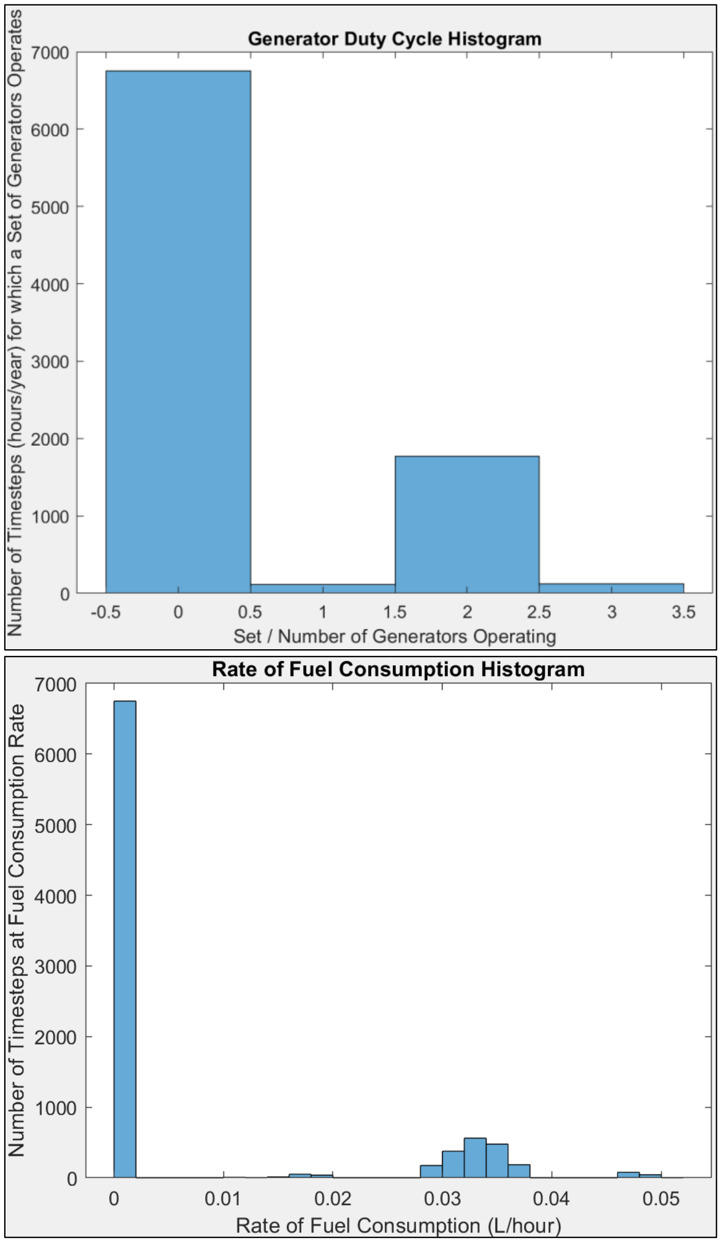
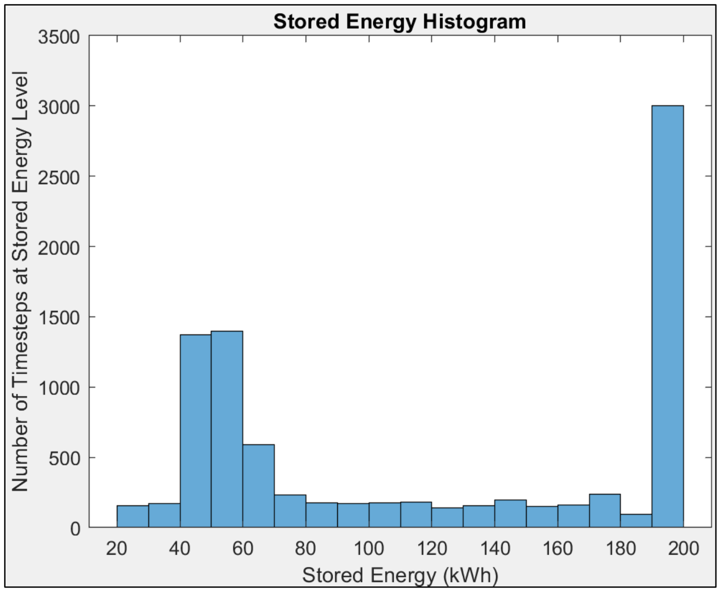


Figure 17. Frequency of stored-energy state-of-charge levels.



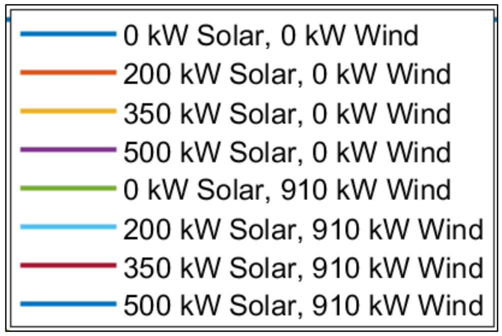
4 Comparative AMPeRRe Results for Fort Phantom CMA

The AMPeRRe results in this section expand on Table 1 to quantify how the addition of different solar array sizes, different sizes of energy storage, and different control conditions would affect the expected outcomes of the Fort Phantom CMA. These results cover several notional power grid resource configurations to determine the best quantity of energy storage to pair with the intermittent power resources and the benefits of utility peak shaving. While Table 1 shows results for a notional progression of iterative developments to the Fort Phantom CMA power system, this next set of results covers a greater range of potential resource investments and scenarios of utility involvement. Each figure in Section 4 focuses on one forecasted outcome and contains more than one plotted output series to account for different control and utility involvement scenarios. These plots are titled "islanded," "primary utility involvement," and "integrated utility involvement."

- **Islanded:** No utility power is involved, so only the on-site microgrid resources contribute to the load. The solar array, battery energy storage system, and backup diesel generators must fulfill all the loads on the installation.
- **Primary utility involvement:** The utility is treated as a primary power source, so the on-site microgrid resources only contribute during utility peak shaving or outages. A limit is placed on the amount of power that can be drawn from the utility (peak shaving). The utility power limits applied in this Fort Phantom case study are 25 kW and 50 kW.
- **Integrated utility involvement:** The solar array and energy storage system are treated as primary power resources, so the utility only contributes when the solar power production is in shortage and the battery charge is below a defined threshold. A limit is placed on the amount of power that can be drawn from the utility (peak shaving). The utility power limits applied in this Fort Phantom case study are 25 kW and 50 kW.

The *x*-axis in each plot represents varied energy storage, while the *y*-axis series shown in the legend below represent different quantities of rated intermittent power resources and utility peak shaving. The legend in Figure 18 applies to Figure 19 through Figure 36.

Figure 18. Legend for comparative result plots.



4.1 Generator Duty Cycle and Number of Activation Cycles

Generator duty cycle is calculated as the proportion of time that any of the generators within the system are operating. The desired outcome is the lowest duty cycle for the on-site generators. The lower the duty cycle of the generator system, the longer the operational life is expected to be. Duty cycle tends to decrease with an increase in solar energy, wind energy, or energy storage since each scenario reduces the need for generator operation. It tends to increase with greater levels of utility peak shaving and reaches its highest values when the system is islanded. Figure 19 shows the duty cycle of the generator system for an islanded system, Figure 20 shows this duty cycle for a system with primary utility involvement, and Figure 21 shows this duty cycle for a system with integrated utility involvement.

Figure 19. Generator-set duty cycle plots for an islanded system.

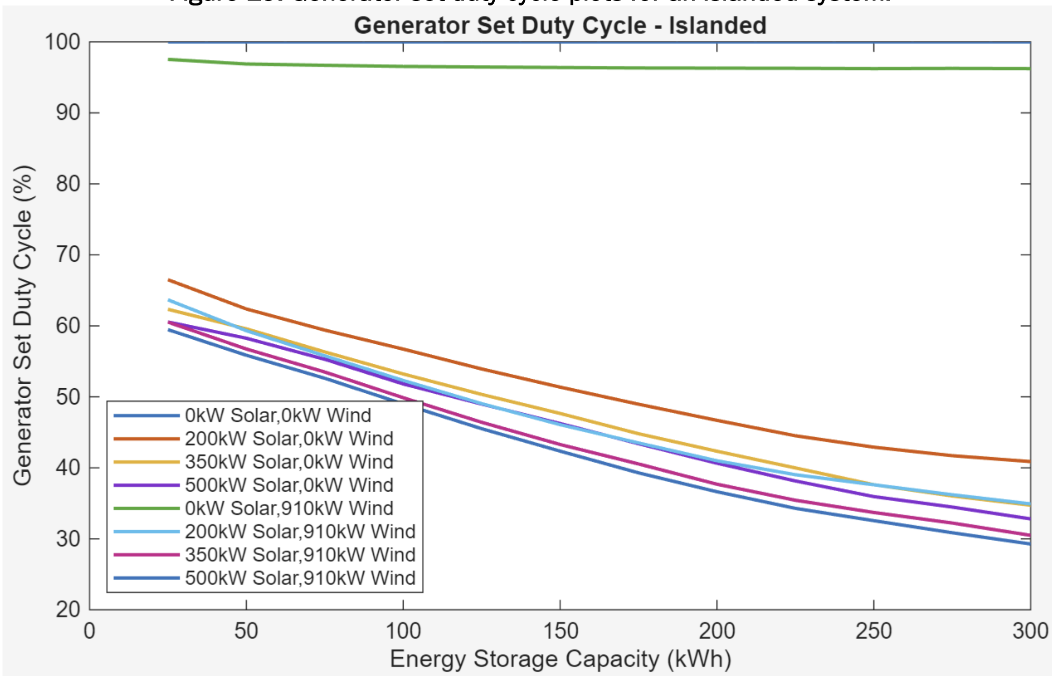


Figure 20. Generator-set duty cycle plots for primary utility involvement.

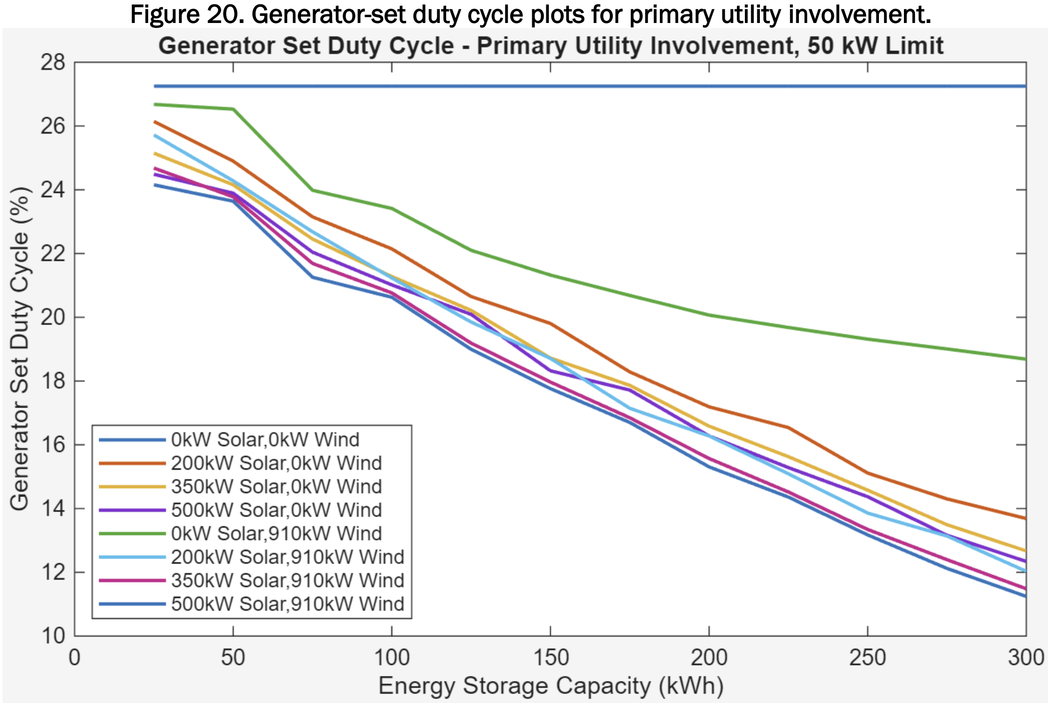
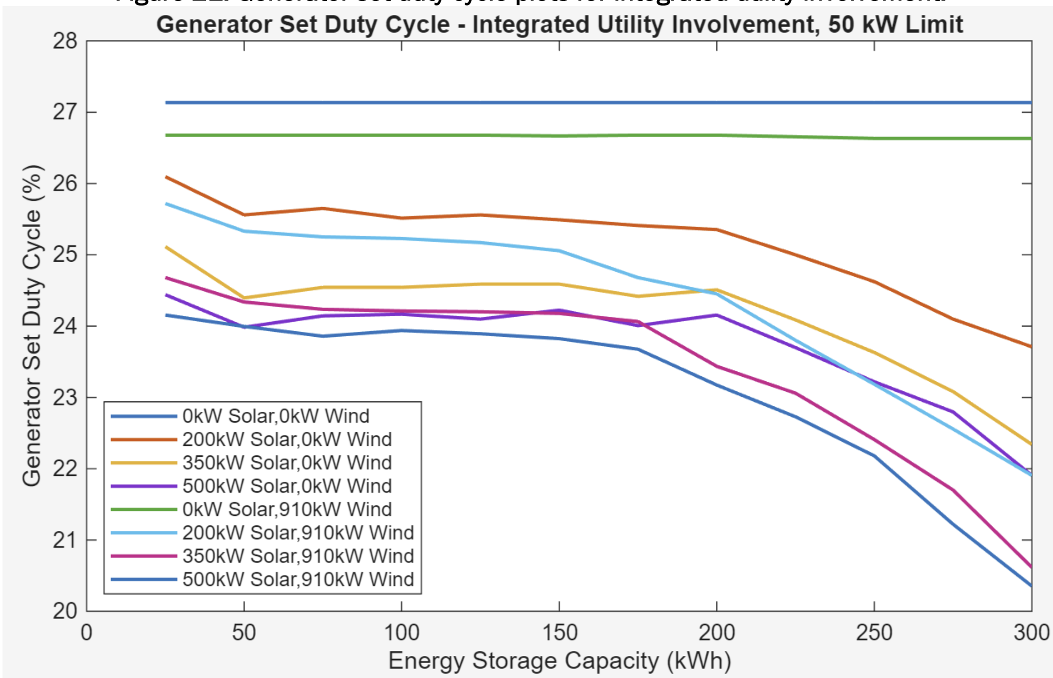


Figure 21. Generator-set duty cycle plots for integrated utility involvement.



For the following figures, the desired effect is a low frequency of generator activations. Frequent activation can wear out a set of generators over time. The less often a generator must go through its activation cycle, the longer its expected operational life. Figure 22 shows that the frequency of generator activation cycles at the Fort Phantom CMA would decrease in an islanded system with increased solar energy and energy storage. Figure 23 shows this trend for a system with primary utility involvement, while Figure 24 shows this trend for a system with integrated utility involvement.

Figure 22. Generator activation cycle plots for an islanded system.

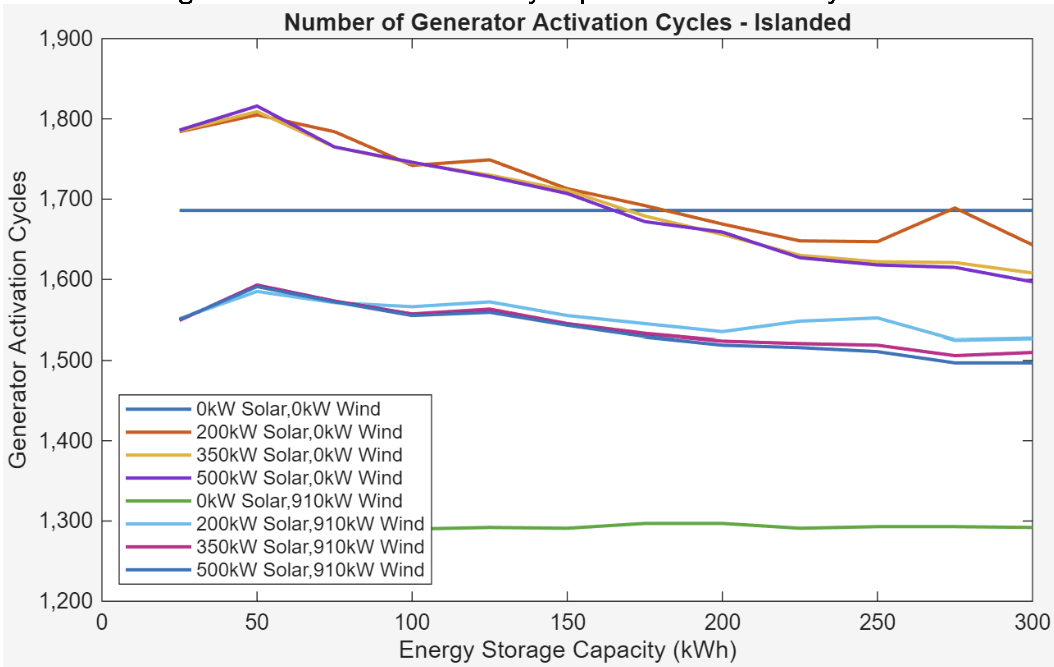


Figure 23. Generator activation cycle plots for primary utility involvement.

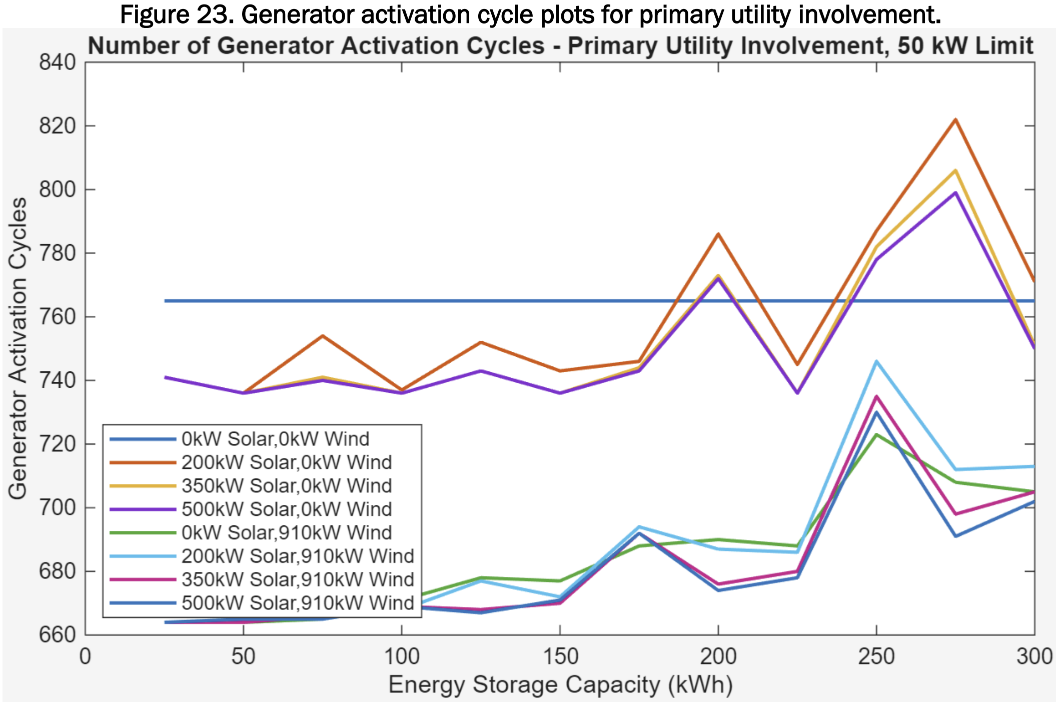
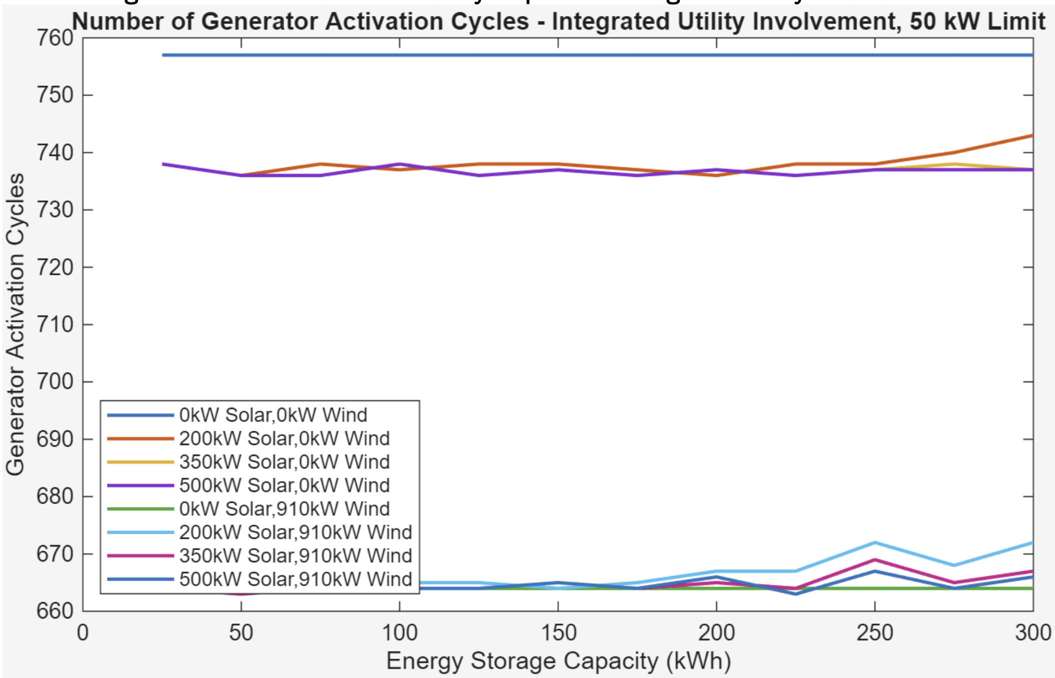


Figure 24. Generator activation cycle plots for integrated utility involvement.



4.2 Fuel Consumption and Fuel Savings from Power Resources and Energy Storage

For notional power resource investments, the desired outcome is to lower fuel consumption and maximize fuel savings. Figure 25, Figure 26, and Figure 27 compare the yearly fuel consumption of different Fort Phantom CMA scenarios. Higher quantities of intermittent power sources and energy storage would lower the fuel consumption of the CMA, as would shifting the control scheme from islanded to utility connected.

Figure 25. Yearly fuel consumption plots for an islanded system

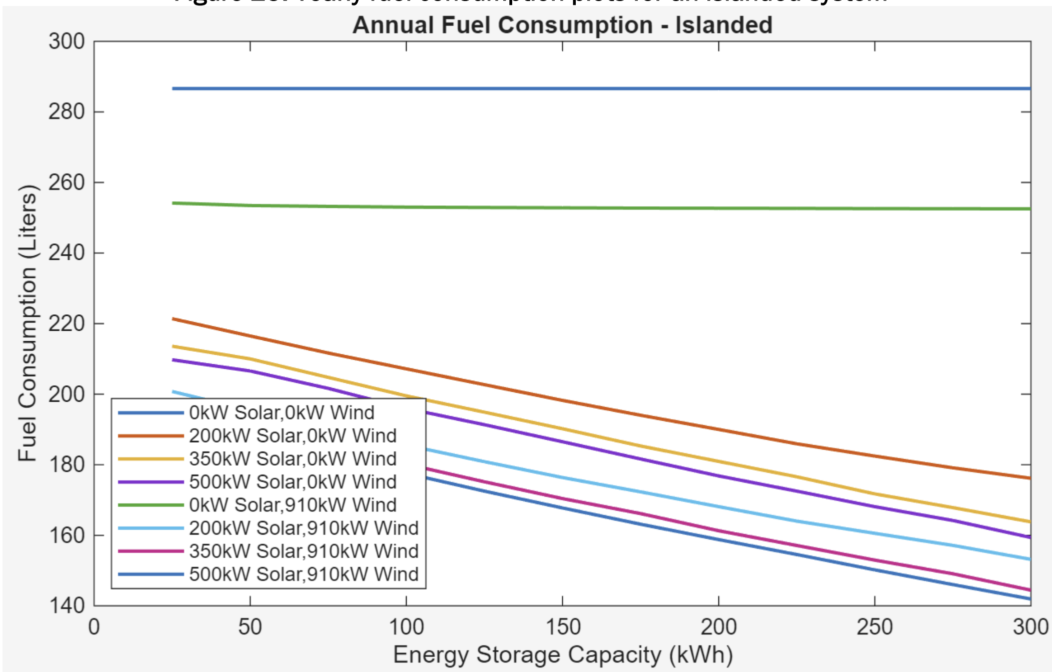


Figure 26. Yearly fuel consumption plots for primary utility involvement.

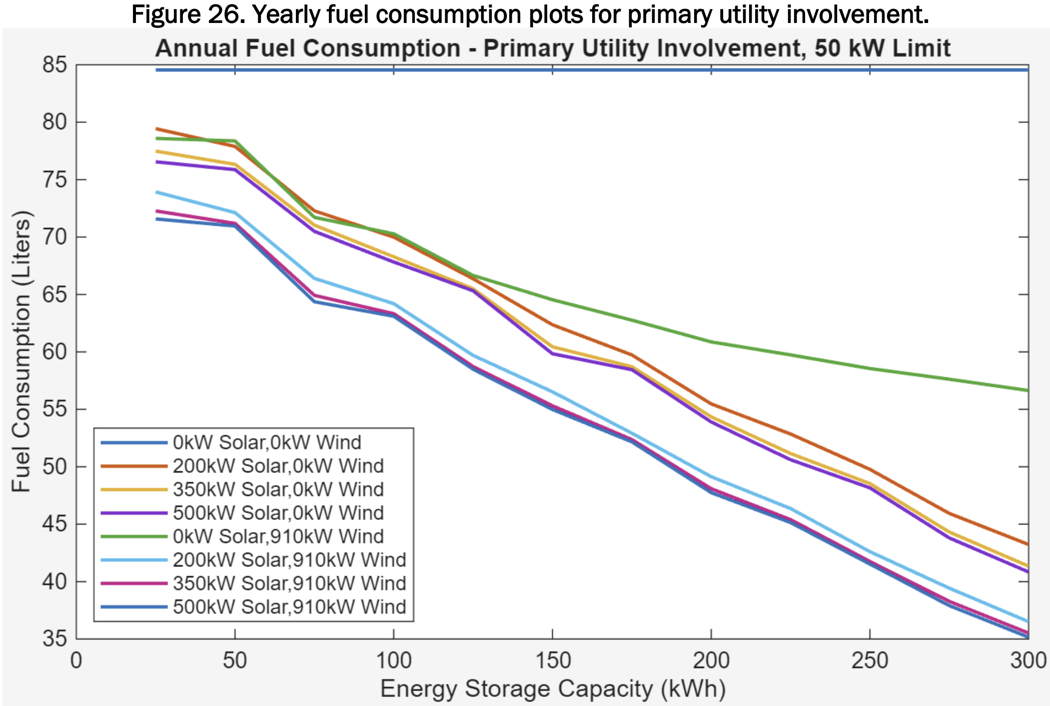


Figure 27. Yearly fuel consumption plots for integrated utility involvement.

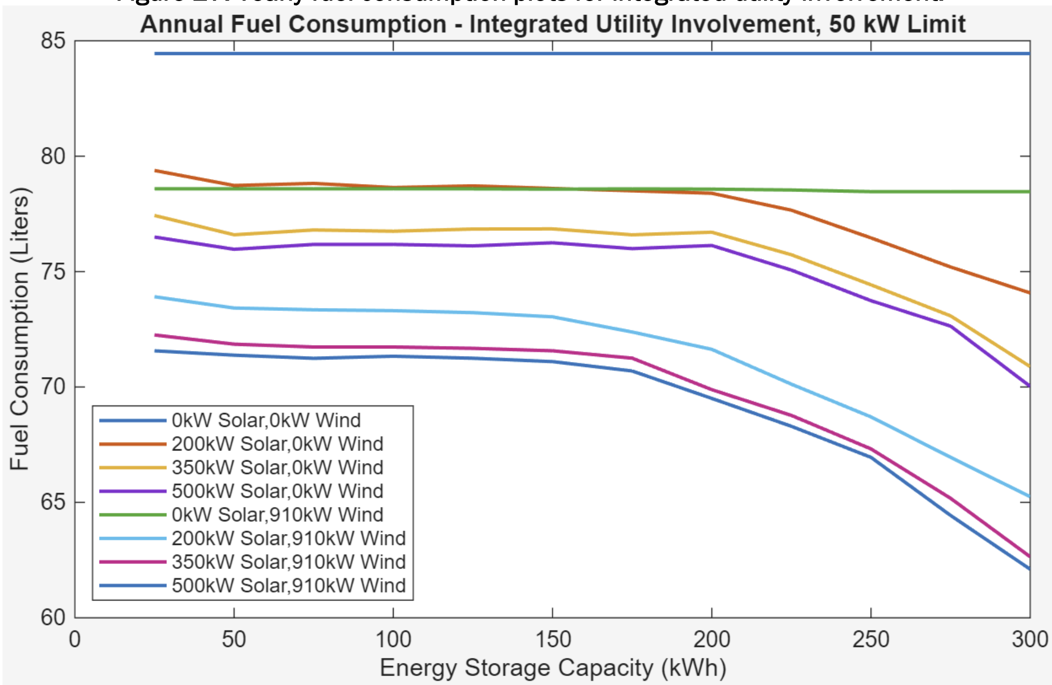


Figure 28, Figure 29, and Figure 30 show the expected fuel savings from the addition of different power resources, energy storage, and utility involvement in Fort Phantom's CMA when compared to the baseline case (Case 1) of islanded on-site generators. Greater quantities of intermittent power resources and energy storage increase fuel savings. Although peak shaving increases fuel consumption in a utility-connected case, it can save money over an extended period of time. Peak shaving is typically used to avoid paying high-demand penalty charges for short-duration high demands that are charged for an entire monthly bill. Given a case in which the on-site power resources fully account for peak shaving, the results show that the intermittent resources and energy storage achieve fuel savings that partially offset the increased fuel consumption.

Figure 28. Fuel-savings plots for an islanded system.

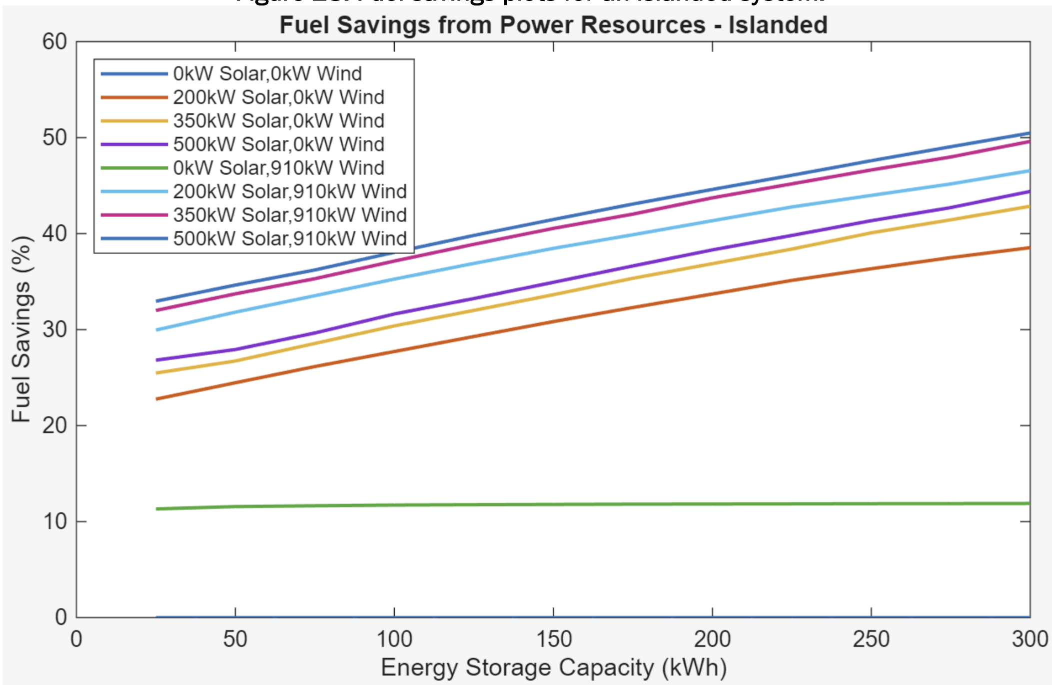


Figure 29. Fuel-savings plots for primary utility involvement.

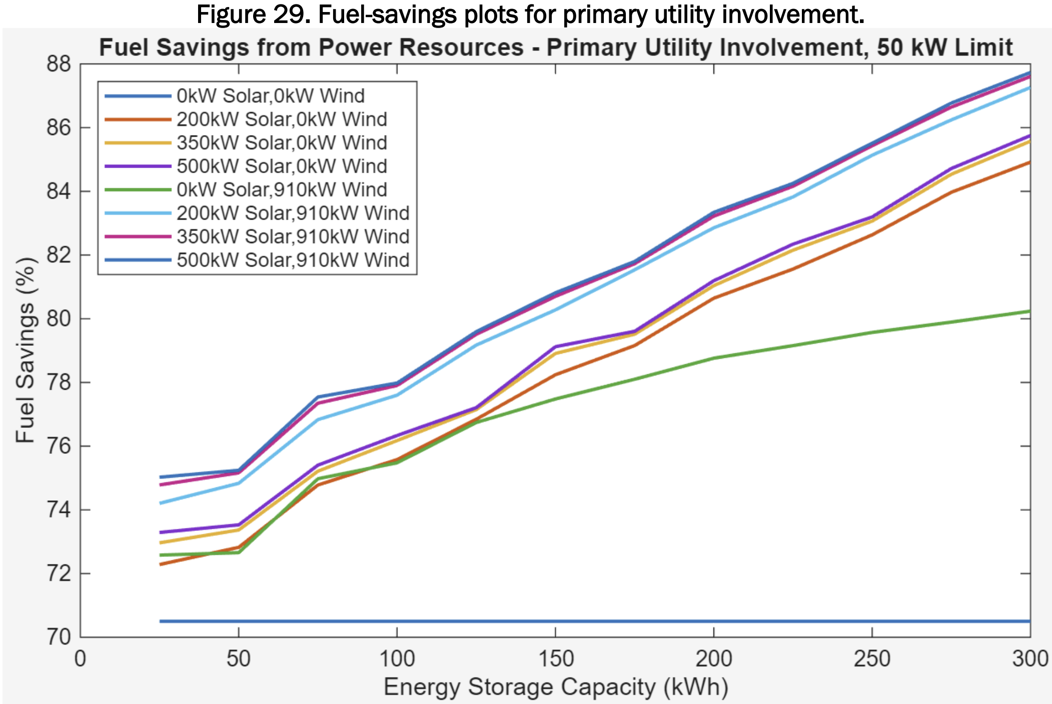
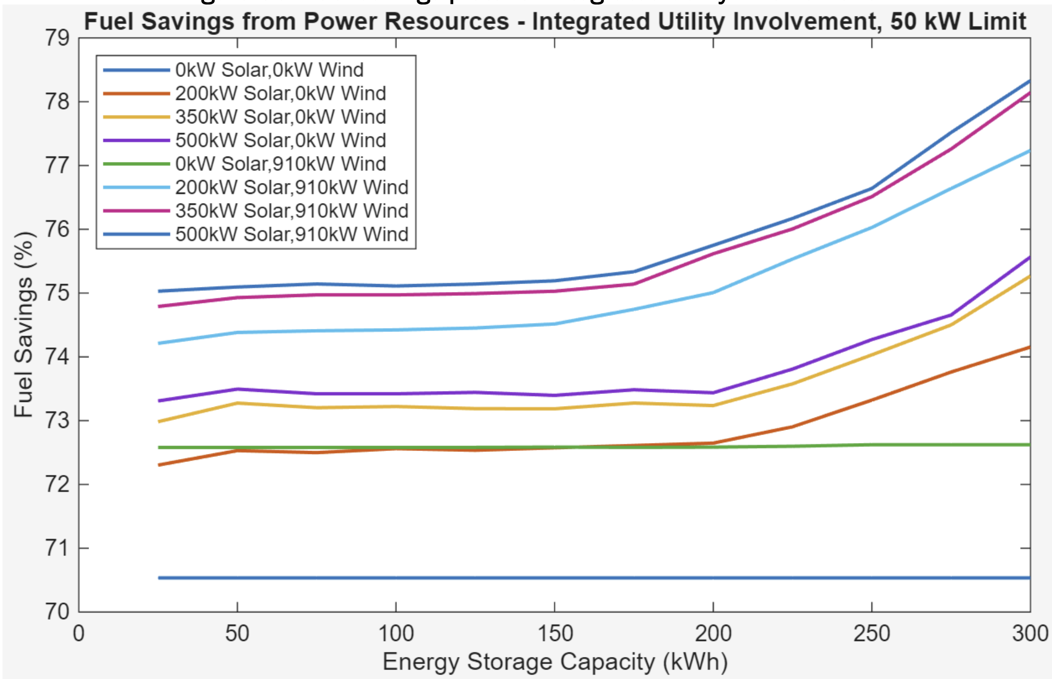


Figure 30. Fuel savings plots for integrated utility involvement.



4.3 Number of Days Between Fuel Resupply and Excess Energy

The desired outcome of producing the results shown in Figure 31, Figure 32, and Figure 33 is to find the set of power resources that results in the longest possible time between fuel resupplies while adhering to resource constraints. These figures show the number of days it takes to deplete a site's fuel supply or the average number of days between each fuel resupply needed to maintain fuel availability. This value is inversely related to the rate of fuel consumption; it increases as the rate of fuel consumption decreases. Assuming that the Fort Phantom CMA has 50 L of fuel storage capacity, Figures 31–33 show that the addition of intermittent power resources and energy storage increases the number of days needed between fuel resupply for all scenarios of utility involvement. Islanding the on-site resources significantly increases fuel use, so the days between fuel resupply are lower for the islanded cases. Each of these cases, however, indicate that an infrequent fuel supply is needed to maintain power availability due to a sufficient fuel storage capacity.

Figure 31. Days-between-fuel-resupply plots for an islanded system.

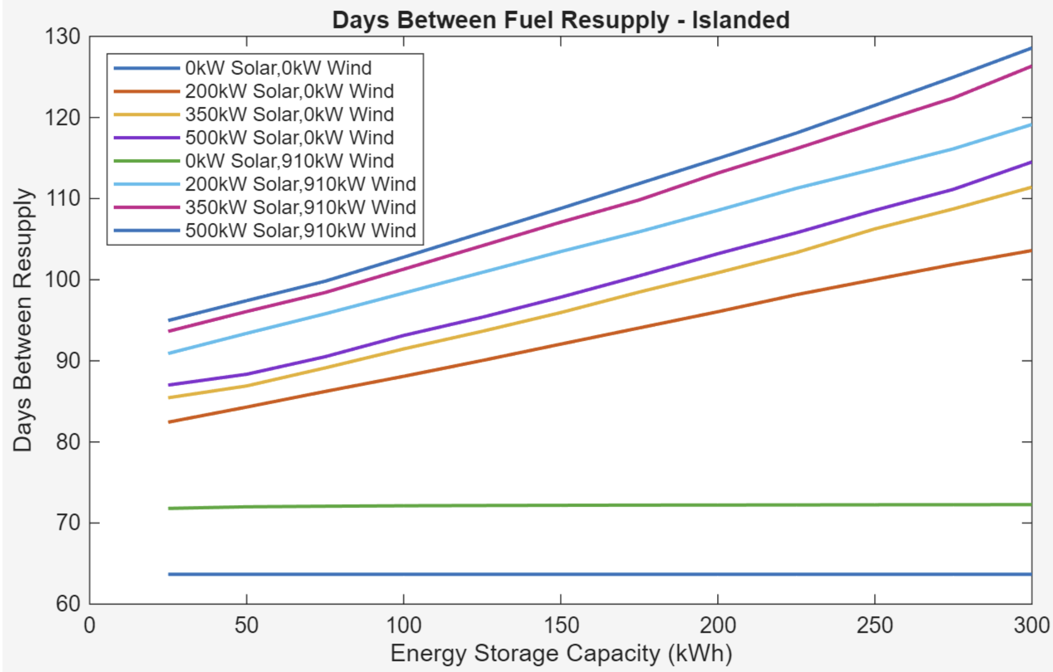


Figure 32. Days-between-fuel-resupply plots with primary utility involvement.

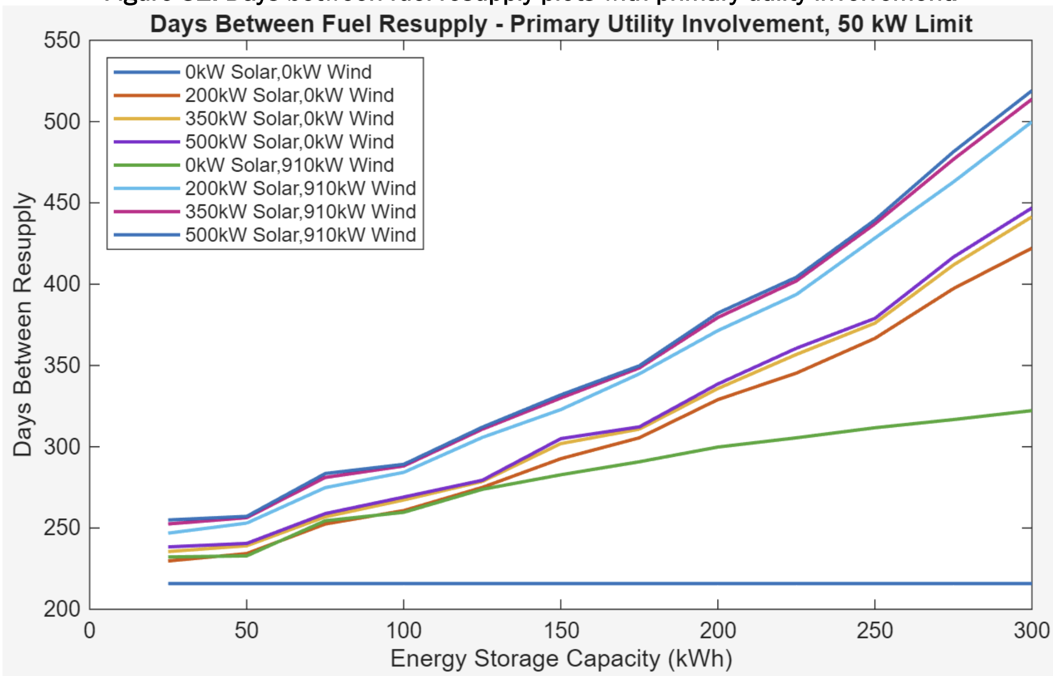
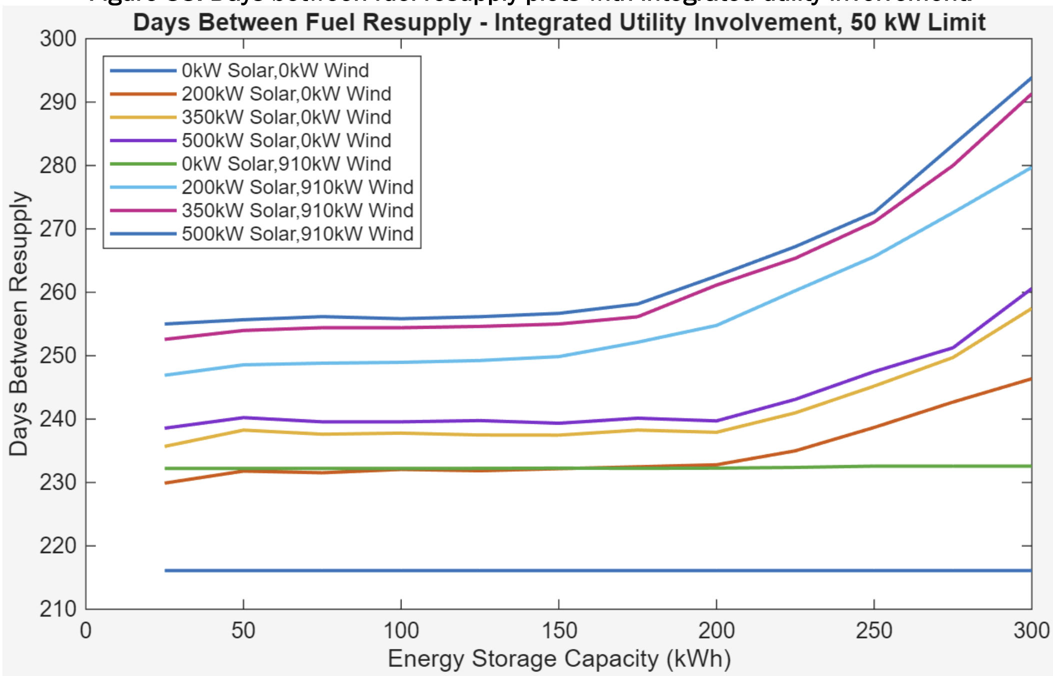


Figure 33. Days-between-fuel-resupply plots with integrated utility involvement.



This analysis calculates excess energy produced due to the intermittent power resources and insufficient energy storage capacity. Generally, the desired outcome is to minimize excess energy. Energy produced by intermittent power is typically routed to the power demand. When the power produced is higher than demand, the excess power is routed to energy storage. When the energy storage system does not have available capacity to capture this energy, this energy becomes excess. Excess energy can be considered wasted energy without a method to identify and manage it. AMPeRRe calculates the expected quantity of excess energy that a power system will produce. AMPeRRe's excess energy calculations inform the user how much energy is available for alternate uses. A common option for managing excess energy is automatic control that curtails the power production of intermittent sources; however, this is the least beneficial option. Better options include sizing energy storage to reduce excess energy or selling excess energy to the connected utility. The desired outcome is dependent on Fort Phantom's objectives for its CMA power system.

Figure 34, Figure 35, and Figure 36 show the comparative excess energy produced at Fort Phantom in several power resource mix scenarios. These plots show that, in every case, excess energy increases with an increased quantity of intermittent power resources and decreases with increased energy storage capacity. The plots also show that integrated utility control minimizes excess energy. This means that Fort Phantom would minimize excess energy by using the intermittent power resources and energy storage as primary power resources with the utility serving as a supporting resource. For this case, different levels of peak shaving have minimal effect on the amount of excess energy. If the utility remains a primary resource, lowering the peak power drawn from the utility—or increasing peak shaving—would lower the excess energy produced by the full power system. Either using integrated utility involvement or fully islanding the on-site microgrid would minimize excess energy production.

Figure 34. Yearly-excess-energy plots for an islanded system.

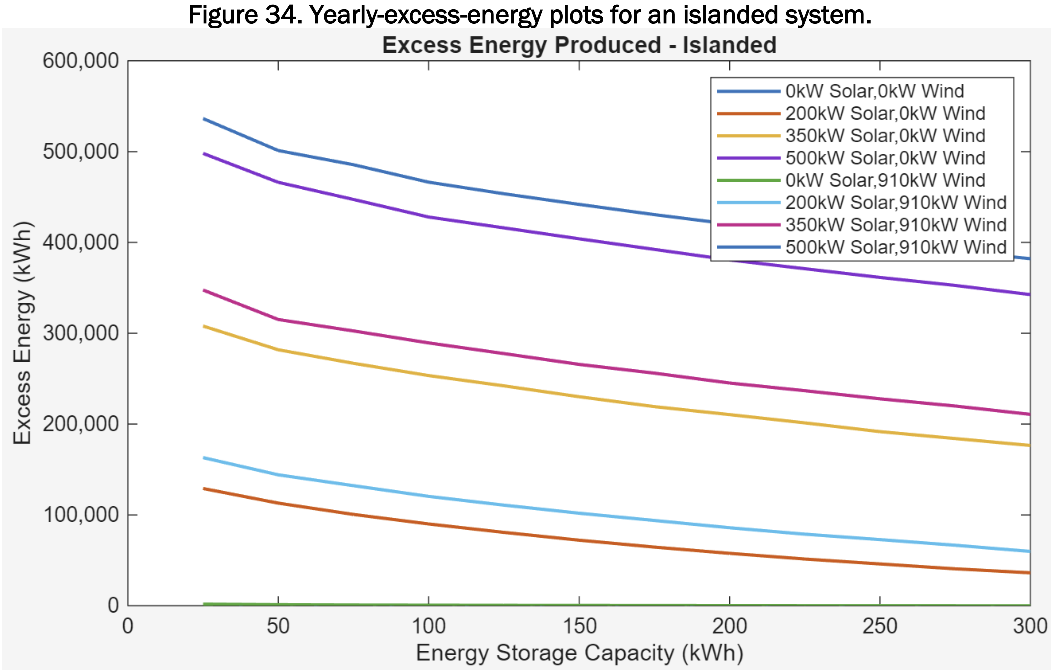


Figure 35. Yearly-excess-energy plots for primary utility involvement.

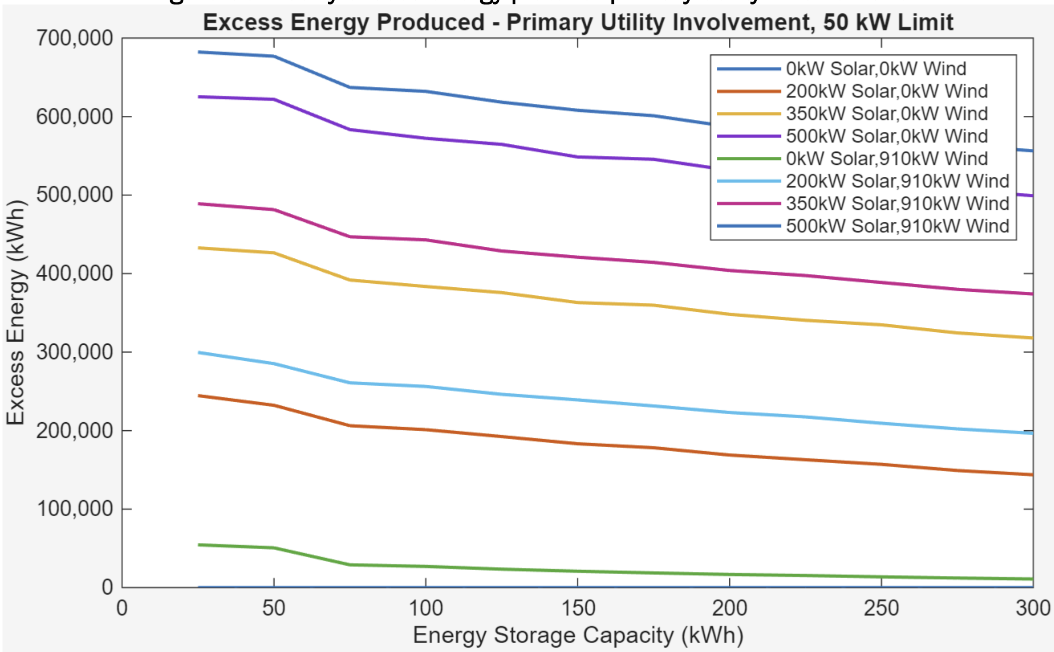
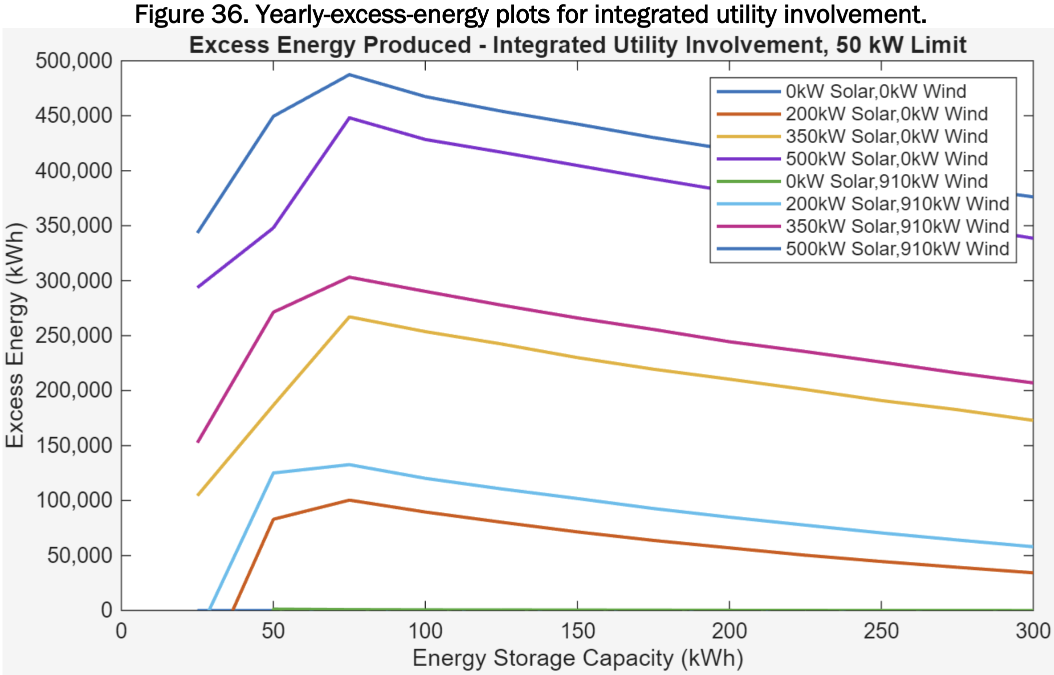


Figure 36. Yearly-excess-energy plots for integrated utility involvement.



5 Conclusion

Fort Phantom is a notional installation with facility loads based on real, historical data that can be used as a modeling and simulation testbed. Based on an assumed on-site power system at the Fort Phantom CMA that consists of islanded diesel generators, AMPeRRe was used to evaluate the outcomes of incorporating solar, wind, and additional battery energy storage. The incorporation of non-fuel-based, on-site power resources would lower the duty cycle of the on-site generators and fuel consumption. Additional benefits are possible through the incorporation of energy storage with the power resources. The greater the energy storage capacity, the more energy is captured from the intermittent power resources to offset generator involvement and costly fuel consumption. To understand the optimal resource mix to meet Fort Phantom's needs, AMPeRRe quantified the expected benefits and trade-offs of incorporating different energy resources and battery energy storage system sizes. One specific highlight is that the incorporation of an existing 500 kW solar array and 910 kW wind turbine with 200 kWh of energy storage will lower the Fort Phantom CMA's fuel consumption by approximately 47% in prolonged islanding.

If an installation such as Fort Phantom were to rely on utility power as a primary resource with a peak-shaving condition, AMPeRRe shows that the intermittent energy resources and battery energy storage will still reduce fuel consumption. The more intermittent power and battery energy storage in the system, the less fuel is needed and the longer any critical loads can operate in the event of an outage. AMPeRRe can also model systems for which a microgrid is incorporated with the control capabilities to allow intermittent power resources and energy storage to take priority over utility power. This minimizes the amount of power drawn from the utility, excess energy, and fuel consumption.

These example AMPeRRe results for Fort Phantom show that AMPeRRe can quantifiably compare the outcomes of different planned power-resource investments for power systems. These quantified trade-offs are used to determine which sets of resources will enable a power system to reach its unique performance objectives. The results of AMPeRRe studies such as this one can guide power-resource investment decisions for current power systems and future power systems, contributing to the development of business cases that justify proposed investments into certain power resources.

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Nicholson, Jessica, Matthew Gross, Daniel Herring, Thomas Bozada. 2024. *Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) Computational Model: Novel Analytical Model to Forecast the Outcomes of Installation Power Grids*. ERDC/CERL TR-24-13. Construction Engineering Research Laboratory. https://dx.doi.org/10.21079/11681/49485.

Abbreviations

AMPeRRe	Analysis of Microgrid Performance, Reliability, and Resilience
CMA	Consolidated Maintenance Activity
PV	Photovoltaic

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14. ABSTRACT

Analysis of Microgrid Performance, Reliability, and Resilience (AMPeRRe) is a computational model that provides quantitative results to installations and remote communities that inform them of the objectives they can achieve. Results provided by this model lead to reliable intermittent power resource implementation, optimize the set of resources within a power system, and improve reliability and resiliency outcomes. This technical report provides an example of the analysis results AMPeR-Re can produce to quantify the expected benefits and trade-offs of incorporating different power resources and energy storage in a power system. Fort Phantom, a notional installation, was used as the testbed to produce these results. The AMPeRRe model forecasts outcomes such as the power availability, fuel consumption, duty cycle, and excess energy of different power resource investment scenarios. The results produced by this model are based on notional stages of development for the Fort Phantom Consolidated Maintenance Activity (CMA) power system. This technical re-port also pro-vides an expanded set of results and comparison of outcomes from different quantities of incorporated power resources. These results can aid business case development for power systems and enable efficient, informed development.

15. SUBJECT TERMS

Computer simulation; Electric power; Electric power systems; Microgrids (Smart power grids); Military bases

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