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Identifying Best Performance Scenarios For Micro Nuclear Reactors During Grid Disruption

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Abstract

Micro Nuclear Reactors (MNRs) are an emerging innovation in nuclear technology as small, portable, and self-sufficient reactor units in the size of a standard 40-foot shipping container. An MNR functions as a “nuclear battery,” where each unit can power load capacities from 500 kilowatts (kW) to 5 megawatts (MW) over the lifetime of 1–10 years. This technology may deploy by the end of the 2020 decade, so private and government organizations have prepared for potential operational use for energy resilience. This research develops an emergency grid disruption timeline with MNR deployments to respond and recover grids after severe weather events. This response integrates a series of models for transportation networks, power distribution, and decision strategies that utilize MNR capabilities while using real-world disruption events within the past decade for scenarios. The study then seeks to analyze the performance of MNRs when using different deployment strategies for emergency grid disruption response. First, this research investigates the trade-offs between time and cost in the emergency grid disruption timeline when integrating MNRs. This research also explores the conditions of disruption scenarios that contribute to the best MNR performance in grid recovery.

Keywords: micro nuclear reactors, disaster response, disaster recovery, microgrid

1 Introduction

Micro Nuclear Reactors (MNRs) represent the newest generation of advanced nuclear technology as small, portable, and self-sufficient reactor units in the size of a standard 40-foot shipping container. Characteristically, an MNR functions as a “nuclear battery,” where each unit can power load capacities from 500 kilowatts (kWs) to 20 megawatts (MWs) over their lifetime of 1 to 10 years. This technology may deploy by the end of the 2020 decade, so private and government organizations have prepared for potential operational use for energy resilience. In addition to the growing number of grid disruption events from severe weather events, cyber and physical threats potentially challenge dependence on the traditional above-ground grid infrastructure. This new generation of reactor technology has piqued the interest of nuclear industry companies and government organizations alike. U.S. Department of Energy (DoE) facilities have released numerous reports highlighting the potential capabilities and specifications of MNR technology (Hernandez et al., 2019; Sterbentz et al., 2017). Los Alamos National Laboratory (LANL) has partnered with the Westinghouse Electric Company to develop the eVinci Micro Reactor, which will potentially be the earliest introduction to the use of this technology (Arafat and Van Wyk, 2019).

The prospect of critical load-sustaining power sources with truck-load shipment capabilities has garnered academia, industry, and government's attention to determine their applications. The Nuclear Energy Institute (NEI) prepared a roadmap report in 2018 focusing on the actions needed to support the development and deployment of MNRs in domestic U.S. Department of Defense (DoD) installations (Nichol, 2018). This report emphasizes an essential question about MNR technology coming to fruition in the near future: How can MNRs be most effectively used upon their initial deployment? Although many situations could warrant the use of MNRs, effective immediate use for MNR capabilities would be a distributed generation response system to grid disruption scenarios.

Eaton (2017) reports that the number of customers affected by grid disruptions doubled to 36 million from 2016 to 2017 and that the duration of outages increased to an average of 8 hours per disruption. Most of these disruptions arise from weather-related incidents, but other cases involve errors in planned outage procedures.

This research evaluates the conditions, resources, and demand requirements in which MNRs would perform optimally during emergency grid disruptions.

2 Literature Review

2.1 Micro Nuclear Reactors

Recent evidence shows that the nuclear power industry is abandoning its large-scale, Light Water Reactor (LWR) dominant infrastructures that produced 20% of the U.S. electricity in 2019 and directing their next generation development towards smaller, cheaper, and safer designs. Specifically, ten reactors have been decommissioned since 2013, with twenty more reactors currently in the process (Department of Energy, 2019). Comparatively, the U.S. Department of Energy has invested $60 million in cost-shared research and development funding for projects in the research area of modular nuclear reactors (Department of Energy, 2019). These reactors, also known as small modular reactors (SMRs), are reactor unit designs with outputs of less than 300 MW and take advantage of factory fabrication and series production. Although SMR units would only require a third of the land area used in traditional nuclear power plants, continuing innovation in small nuclear technology introduced the potential for 30 MW output MNR units with mobile capabilities (Arafat and Van Wyk, 2019). There is limited literature on the applications MNRs due to their early phase in development. However, high-level analyses from Nichol and Desai (2019) and Lee (2020a) describe their specifications and implications for future markets.

2.1.1 Markets and Competitiveness

Lee (2020a) evaluates the market opportunities for MNRs based on their current design specifications and capabilities. Their lower production capacity address off-grid and remote markets and could provide these markets with an estimated three GW by 2030. MNRs also have opportunities in urban areas because of growth in microgrid markets. Micro-grid markets operated 3.2 GW in the U.S. in 2017, with an annual growth of 14.1% per year since (Lee, 2020a). MNRs have the potential to contribute to this growing microgrid capacity depending on their capital and operation cost. The capital cost of energy generation plants and sources is different because the energy generation cost over their entire lifetimes can change. The cost of power production, usually $ per kWh, decreases over the plant lifetime due to the "learning curve" of operations (Energy Information Administration, 2013). Since capital cost has such a significant influence on total delivered cost, some methods estimate plant lifetime costs before construction. The "Overnight Capital Cost" concept combines capital, generation setup, installation, and construction interest cost into one value as if an electricity plant was built overnight (Koomey and Hultman, 2007). Although estimations can vary with large-scale plants, the overnight capital cost may be more accurate for MNRs with manufacturable specifications. Nichol and Desai (2019) estimates the overnight capital cost of MNRs for their study, analyzing their cost competitiveness against diesel DGs and find the production cost of production MNRs can be lower in specific markets.

For MNRs to realize their potential in the market and compete with other emission-free energy resources, the developing industries must fulfill their nuclear safety and security assurance. The socio-economic concern determines the level of use and distribution, especially for nuclear technology (Lee, 2020b). Radiation safety is described as protecting people and the environment from radioactive dispersion and effects. Radiation security is the protection of nuclear materials and sources from people that desire malicious acts (Anderson, 2016). These aspects are evaluated by the U.S. Nuclear Regulatory Commission (NRC) when conducting the initial safety and security evaluations of the reactor unit designs when determining license specifications.

2.1.2 Deployment State

The state of MNR development has a high impact on policy planning for licensing, market applications, and deployment timeline. The most consistent design aspect from MNRs developers, such as LANL and DoE, is in the fuel type planned for use. The Idaho National Lab (INL) conducted a phenomena identification and ranking table (PIRT) assessment on LANL's 2017 2 MW "special purpose reactor" design (Sterbentz et al., 2017). The specifications show that MNRs would use uranium oxide fuel form with enrichment at 19.75%. This categorizes the fuel as high-assay low-enriched uranium (HALEU) being between 5–20%. HALEU fuel provides high enough enrichment for small unit reactors by increasing power production per volume (Holland, 2019). HALEU also contributes to longer core life and more efficient fuel burn-up before the entire unit cores decommission. Although the NRC will evaluate every aspect of MNRs designs upon completion, preliminary reports in the Nuclear Regulatory Commission (2019) Interim Staff Guidance state they will modify policy originally dedicated to large-scale LWRs. It mentions that with designs showing "low potential for transients and accidents, low potential for radioactive releases, low potential consequences from radiological release," there is the need for scaling when working with advanced reactors with small MW output. Based on NRC's current policy, MNR deployments would require certain safety exemptions since its target application would place them in DGs application areas. Information about MNR development is continuously updating, so their current specification modeling could change in the future.

2.2 Distributed Generation

The concept of low capacity generation and small volume customers is not novel in power distribution. Pepermans et al. (2005) explains that the interest in the DG market returns to the original methods of energy distribution. Generation plants originally supplied power directly to local customers through direct current (DC) short-distance grids. The rise of alternating current (AC) technology opened the doors to long-distance transmission, higher capacity generation plants, and the current grid infrastructure.

Adefarati and Bansal (2019) describe the multiple applications of DGs today and their growing integration with renewable energy resources. The most common application for new DGs today is the need for an emergency energy supply. Backup diesel generators fit this profile of emergency supply most commonly for customers. They temporarily provide power to smaller loads like individual homes or larger loads like hospitals, focusing on supplying critical loads. DGs also offer efficiency when used for peak shaving, generating independent power when demand is at its highest. This technique can reduce cost since electricity charges $ per kW hour, and electricity is most expensive at peak times. Extra capacity generation at these peak demand hours reduces cost from the utility.

The potential for renewable energy sources in DGs primarily exists in solar/photovoltaic (PV), or wind turbines (Adefarati and Bansal, 2019). The World Energy Council expects natural resources to provide 34% of power worldwide by 2030 based on the 23% usage in 2010 (Salvatore, 2013). PV systems have the option of being standalone or grid-connected and have energy storage capacity or are coupled with other energy sources (Adefarati and Bansal, 2019). The flexibility combined with low operation and maintenance cost shows PV's advantages as it grows. However, PV plans should consider the disadvantages of low efficiency, environment dependence, and high land area. Similarly, wind turbines have an optimal placement that ensures each unit is taking advantage of wind speeds and flow patterns. Multiple configurations (horizontal or vertical axes) also provide options for wind power collection. It has similar disadvantages of PV in the large land requirements and intermittent production (Adefarati and Bansal, 2019).

2.2.1 Micro-grids

Krishnamurthy and Kwasinski (2019) emphasize DGs as only one of the three micro-grid resilience characteristics. The other elements are energy storage units that help support island operations and the lifeline resources of what supplies the DGs. The most common lifelines are diesel fuel sources, which require a continuous supply over time to be sustainable. For renewable sources, this could entail solar energy availability for photovoltaic cells to absorb or wind flow to provide aerodynamic force to turbines. Although energy storage can temporarily compensate for disruptions in the lifeline behavior, uncertainty in its supply drastically reduces micro-grid resilience.

2.2.2 Power Distribution Evaluation

There is an overwhelming variety of power distribution studies conducted in the fields of electrical and systems engineering. The literature in this research focuses directly on power distribution studies that fit the ideal model's characteristics of optimizing limited DGs resources for critical loads. First, Krishnamurthy and Kwasinski (2019) discuss discrete event model of fuel-dependent DGs during a disruption in supply. With the methodology of a Markov chain model due to repeated refueling states, the model evaluates resiliency probabilistically given the chance of disruption.

Krishnamurthy and Kwasinski (2019) evaluate the distribution systematically instead of using optimization in other electrical engineering methods. Georgilakis and Hatziargyriou (2015) emphasize these methods as having single objective functions that could minimize a variety of net present cost values in the problem. The constraints introduce power flow equality, bus voltage limits, feeder capacity limits, or transformer specifications, which call for various optimization methods. Haffner et al. (2008) is a numerical method example that used mixed-integer linear programming (MILP) to minimize the installation cost of new feeders and substations. Numerical methods like this provide an advantage in evaluation speed and efficiency, but nonlinear methods such as mixed-integer nonlinear programs (MINLP) provide far more accuracy due to nonlinear constraints. Heuristic methods also model and evaluate power distribution, such as in the study by Falaghi et al. (2011) to expand distribution networks with DGs. Specifically, a combined genetic algorithm and optimal power flow (OPF) equation minimize annual cost over a planning phase and then an operational horizon of a year. Heuristic methods require more computational effort to design the model but provide solutions that do not require conversion of solutions.

Specific tools in power systems allow users to experiment with the many controls and capture the dynamic and transient behavior of power grids in a less challenging way. Simscape, a MATLAB/Simulink-based program, provides specialized power system libraries that construct models with generation, controls, and grid equipment (Delavari et al., 2018). Designs can scale from simple DC connections to loads that emulate the Western North American Power System (Delavari et al., 2018). Studies using these MATLAB/Simulink tools (MathWorks, 2024) have started to integrate more renewable energy sources as DGs, clustering them in a micro-grid infrastructure. Boudoudouh and Maâroufi (2018) present a model that manages DGs from photovoltaic and wind turbine sources while supported by energy storage. These tools allow for the photovoltaic and wind DGs to have characteristic functions and outputs, making this multi-agent design comparable to transient behavior that could appear in an actual grid. The Simscape power system library in MATLAB/Simulink contains numerous more components and equipment, allowing the closest possible simulations and dynamic power grids studies.

2.3 Emergency Response

Jiang and Yuan (2019) discuss large-scale emergency response logistics still being in the early stages of research for the operations research community. This study highlights work by Altay and Green III (2006) that states, "[t]he seeming randomness of impacts and problems and uniqueness of incidents demand dynamic, real-time, effective and cost-efficient solutions, thus making the topic very suitable for OR/MS research." Unlike humanitarian logistics, emergency response logistics manage the emergency resources and rescue services to minimize damage to life, property, and infrastructure. Jiang and Yuan (2019) summarize that current research in this area focuses on traditional logistics objectives (minimized distribution time, cost, or shortest path) instead of focusing on objectives that directly benefit the customer and aid in their recovery.

2.3.1 Utility and Government Response

The National Electricity Emergency Response Capabilities report for the DoE describes the organized structure of how government and utility provider entities respond to disruptions. Government organizations, starting from the local level, coordinate the response, gather/share information, and communicate with stakeholders and the public. They communicate with utility providers who physically repair damaged infrastructures and restore services. The severity of the disruption and availability of government and utility resources decide what echelon of coordinated response is required, with the highest level being a declared a national response event (Folga et al., 2016).

The timeline of disruption events is critical in reducing the number of customers affected and the amount of damage done to the current infrastructure. An expected disaster moves the grid operations from steady-state to preparation in the Pre-Event Phase, prioritizing resiliency. The grid operations then prioritize mitigation operations to minimize infrastructure damage. The Post-Disruption first involves a coordinated response, and recovery operations follow this to repair the damaged infrastructure (Folga et al., 2016).

2.4 Military Implications

This venture into MNRs is not the U.S. Military's first endeavor with this technology. The U.S. developed multiple small-megawatt output nuclear reactors under the Army Nuclear Power Program (ANPP) from 1954 to 1977 (Lee, 2020b). The U.S. military abandoned the program despite developing eight reactors due to a lack of application and suitability during its era. However, interest has renewed due to U.S. Congress setting a requirement for the DoD to prioritize energy security and resilience, as defined in Holland (2019). The 10 U.S. Code §101 describes energy security as the assured access to a reliable supply of energy and the ability to meet and deliver energy to meet mission requirements (US Code, 1956a). This code also describes energy resilience as the ability to prepare for, minimize, and adapt to anticipated/unanticipated disruptions while ensuring energy availability and reliability for readiness and mission assurance (US Code, 1956b).

There is no congressional requirement or established operational need for the DoD to pursue the integration of MNRs, so active planning by the individual branches has not begun. As mentioned in Section 2.1.2, the integration of MNRs depends on when designs completion, testing, and licensing. However, there is participation in research from the DoD and related organizations. The Strategic Capabilities Office (SCO), located in the Office of the Deputy Secretary of Defense, issued contracts and expects to invest nearly $400M for preliminary MNRs designs under "Project PELE" (Strogen and Cornell, 2020). These plans for 1 to 5MW(e) MNRs that use Tristructural Isotropic (TRISO) solid fuel instead of uranium oxide, which still contains HALEU enrichment but has more security concerns in mind (Edson et al., 2016). The Defense Science Board, a civilian advisory board to the DoD, produced a report that recommended that the Army be designated as the "executive agent" for the DoD being the first to integrate MNRs and demonstrate their operational use (Strogen and Cornell, 2020). Although the DoD's primary considers operational deployment of MNRs, MNR may be immediately suitable for domestic installation sustainment.

2.4.1 Current Installation Approach

The study by Marqusee et al. (2017) investigates over 30 domestic military bases' energy security infrastructure. DoD installations are the largest customers to their regional utility providers, but they use the same utility infrastructure to surround customers. Also, most installations operate fleets of standalone backup generators due to control and affordability. Reliance on decentralized backup generators reduces efficiency in operations and maintenance cost while also diminishes preparedness and security. An uncoordinated response to disruptions leaves gaps in both physical and cybersecurity.

The recommended approach to addressing this from Marqusee et al. (2017) introduces a micro-grid infrastructure to domestic DoD installations. In comparison to the numerous small capacity (1 to 5 MW) generators located at various sites, a smaller number of larger capacity (6 to 10 MW) generators would be stationed and interconnected with each other, high capacity batteries, and the utility grid. During a disruption of the utility grid, the micro-grid would switch the base to island mode and prioritize demand to critical loads with the energy stored from battery storage and diesel generators. As previously mentioned, these microgrids can hybridize with renewable energy sources, potentially even MNRs in the future. Marqusee et al. (2017)'s modeling study of a hypothetical 20 MW critical load installation across regions showed that even a diesel generator only micro-grid could reduce the cost of crucial load during a disruption from $85/kW to $31/kW in the Southeast and save at least $25/kW in other regions. Although nuclear energy is not considered renewable, Nichol and Desai (2019) discuss MNR's potential energy savings cost in this market. MNRs do not require a lifeline like renewable and diesel sources and can sustain loads for up to 5 years without refueling. These units provide a constant supply of energy that can address energy security and energy resilience concerns of the DoD.

3 Methodology

The general research methodology designs emergency grid disruption scenarios and requires critical decisions, logistics transportation, and power distribution to recover the disrupted grid. Scenarios are based on historical grid demand data of disruption events in the U.S. within the past six years. This setup permits modeling the real-time grid interaction between demand and generation in the face of recent disruptions. MNRs are then integrated into these scenarios to observe their performance as a primary DG resource during customer utility recovery. Figure 1 visualizes the series of models and shows how each process outputs contribute to scenario generation.

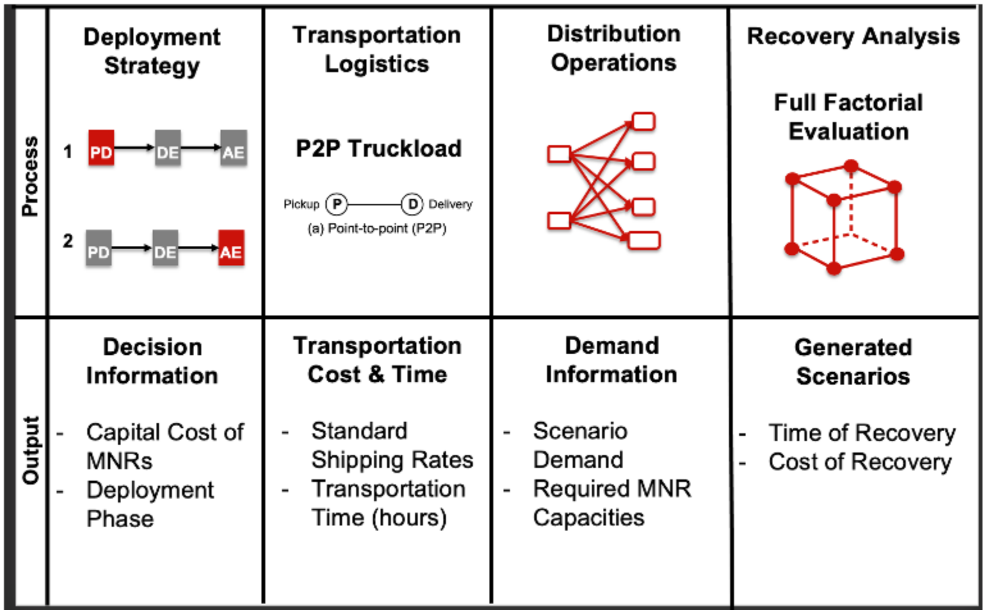

Figure 1: The methodology for the series of models in the research. Note: PD: Pre-Disruption; DE: Disruption Event; AE: After Disruption; P2P: Point-to-Point.

3.1 Assumptions

To support this series of models, we make a few assumptions.

Deployment Strategy

1. **Known Grid Demand:** The grid demand required for recovery in each scenario is known after the 24 hours of initial impact. This situation creates a horizon between the Pre-Disruption and Post-Disruption Phases of the disruption timeline and drives the model's trade-off of decision strategies.

2. **Capacity Reshipment:** In the scenario where the initial MNR capacity shipment does not meet grid demand, an additional MNR shipment initiates in the Post-Disruption Phase. This additional shipment is additive to the MNR capacity already present in the area.

Transportation Logistics

3. **Truckload Rates:** The model uses Producer Price Index (PPI) and Truckload (TL) revenue for 2004 to estimate the case study year's TL revenue. The U.S. Bureau of Labor Statistics provides the PPI database for each month and year (Bureau of Labor Statistics, 2020).

4. **Transport Charge:** The transportation model confirms the transport charge before deploying MNRs from the pickup point to the delivery point. One-time shipment structures utilize this strategy in accordance with Kay (2019) for freight logistics.

5. **Distance and Speed:** The transportation model uses a constant speed rounded to 55 miles per hour for freight truckload carriers as reported by the U.S. Department of Transportation (2010). The model uses Google Maps to find the exact road distance from the pickup point to the delivery point (Google, 2005).

6. **Pickup Point:** The pickup point in the point-to-point shipment model is in the city of the headquarters for Westinghouse Electric Company, Cranberry Township, Pennsylvania. The pickup and delivery points in the model only scale down to city limits.

7. **Hours-of-Service Regulations:** This model disregards the Federal Motor Carrier Safety Administration's Hours-of-Service (HOS) regulation that truck drivers drive no more than 11 hours in a 14-hour duty window (Kay, 2019).

Distribution Operations

8. **Case Study Demand:** The model uses demand during the first 24 hours of impact on the distribution model's daily demand.

9. **Individual MNR Units:** MNRs capacities range from 1 to 5 MW. Demand greater than 5 MW requires additional units that are additive towards total MNR capacity. Each unit requires a separate TL shipment.

10. **MNR Capital Cost:** Section 2.1.1 defines the total MNR capital cost as all costs required to build an electric power plant overnight. This research does not consider reducing generation cost over time from the learning curve of distribution operations.

3.2 Historical Demand As Case Studies

The National Electricity Emergency Response Capabilities report emphasizes the typical causes of disruption events are weather-related events (Folga et al., 2016). It states from 2000 to 2014, severe weather and natural disasters account for more than 50% of grid disruptions. The exploration of grid disruption data from the U.S. Energy Information Administration (EIA) confirms this was additionally true for the last six years (Woodward and Marcy, 2018). Therefore, the case study data for this research are for natural disruption events within the past decade. Specifically, they were hurricanes and tropical storms that impacted the eastern U.S. from 2016 to 2020, causing millions of customer outages and billions of dollars in recovery damage within the past decade. Table 1 depicts the details of the selected case studies.

To generate additional scenarios, we scale the energy demand data from the four storms by multiplying the data by the scalar $\kappa > 0$, where we select $\kappa \in \{0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2\}$.

Table 1: Case Study Details Selected for Scenario Generation. Note: H: Hurricane. Point-to-point (P2P) distance is measured from Westinghouse Electric Company headquarters.

Label	Event	Category	Year	P2P Distance (miles)	Grid Balancing Authority
1	H. Michael	5	2018	615	NC Duke Energy Progress East
2	H. Irma	5	2017	1157	FL Power and Light Co.
3	H. Matthew	5	2016	668	SC Public Service Authority
4	H. Isaias	1	2020	436	NY Independent System Operator

The case study data is retrieved from the EIA-930 U.S. Electric System Operating Database (Energy Information Administration, 2021), which collects hourly electricity input from all Balancing Authorities (BAs) of the lower 48 states. This system uses an Application Programming Interface (API) to easily allow users to access time-series data from each regional BA. The data includes the hourly demand, the amount of energy customers use, and the hourly net generation, which is the energy supply from all sources. The day-ahead demand forecast is a power planning tool that helps utilities schedule the generation capacity needed a day ahead to prepare the energy generation. The database provides energy measurements as megawatt-hours (MWh), which is later divided over the distribution model's 24-hour time horizon to convert to power units (MW).

As previously mentioned, the case studies require observations of the difference between grid demand and net generation of energy during the disruption event, the unfulfilled demand. DoE's Office of Cybersecurity, Energy Security, and Emergency Response provides this information through real-time situation reports of disruption timelines (Department of Energy, 2018). These federal reports provide timelines of the updated disruption event status, interactions of grid infrastructures and affected areas, and estimates of the number of customers with outages. The situation reports for potential case studies were closely examined and compared with the hourly demand and generation of the local grid through the EIA database (Energy Information Administration, 2021). A disruption event is selected when a significant change between the day-ahead demand forecast and the actual demand occurs during their timeline. This change indicates an unexpected change in the grid capabilities due to the disruption event, and the case data should be extracted for further study.

3.3 Decision Strategies

The decision strategies drive the initial timeline for MNR use in the model.

3.3.1 Pre-Disruption Deployment

The Pre-Disruption phase starts when a disruption event is expected and ends once the disruption event occurs. The key aspect of deploying an MNR in the Pre-Disruption phase is that the necessary capacity to fulfill the disrupted grid is unknown. Therefore, the Pre-Disruption Deployment decision has two different decision pathways that impact the subsequent recovery timeline differently.

Strategy 1(-) deploys MNRs in the Pre-Disruption phase without information known about the disruption event's exact impact on the grid. This introduces the possibility of underestimating the MNR capacity required for recovery. The lack of demand fulfillment occurs after the initial 24 hours of MNR support to the disrupted grid. This triggers am additional shipment of MNR capacity in the Post-Disruption phase that is additive to the initial MNR capacity shipped. This scenario incurs additional capital and transportation costs but delivers the necessary MNR capacity to fulfill grid demand.

Strategy 1(+) also deploys MNRs in the Pre-Disruption phase when the grid's effect is unknown but permits overestimating or matching the demand required for recovery. Because the first shipment fulfills grid demand, there is no requirement to ship additional MNR capacity. The unknown demand in this deployment phase creates a cost horizon for the overestimated MNR capacity. Just as in Strategy 1(-), this strategy has the MNR established at the local grid before the disruption occurs.

3.3.2 Post-Disruption Deployment

The Post-Disruption Phase begins after the initial 24 hours of the grid disruption event. At this point, the required grid demand is known after the duration of the initial disruption period. This scenario allows for guaranteed fulfillment of known grid demand before selecting MNR specifications. Therefore, **Strategy 2** deploys MNRs in the Post-Disruption phase with the necessary capacity to support the grid demand, but delays MNR arrival slightly.

3.4 MNR Cost Structure

There are limited studies that provide cost estimates for MNRs since they are still in development so the model uses interpolated data from Nichol and Desai (2019). Current studies on MNRs estimate the highest capacity of a single unit to be 5 MW (Sterbentz et al., 2017), so additional MNR units must be shipped to accommodate higher demand. The upper bound is set for four shipments of the highest capacity MNR (20 MW), and the lower bound is one shipment of the lowest capacity MNR (1 MW). Detailed cost information available from Ivey (2021, pp. 15–16).

3.5 Transportation Logistics

In the proposed emergency response timeline, the primary objective is to take advantage of truckload (TL) transport capabilities to deploy MNRs quickly. The MNR dimensions (2496 ft^3) and weight (17.85 tons) specifications from Arafat and Van Wyk (2019) meet TL requirements (3500 ft^3, 50 tons) Arafat and Van Wyk (2019). The load size (ft^3), value ($\$/\text{ft}^3$), and distance to travel determine the transport cost and transport mode (Kay, 2019). Given the TL revenue per loaded truck-mile (\$/mi),

$$r = \frac{PPI_{TL}}{102.7} \times \$2.00/\text{mi}, \tag{1}$$

this model returns two outputs: transportation time based on average truck speed and the TL transportation charge,

$$C_{\text{TL}} = \left\lceil \frac{q}{q_{\max}} \right\rceil rd, \tag{2}$$

with

C_{TL}	Transportation charge (\$),
r	TL revenue per loaded truck-mile (\$/mi),
PPI_{TL}	Producer Price Index for current year (Bureau of Labor Statistics, 2020),
d	Distance from pickup to delivery point (mi),
q	Shipment weight (tons), and
q_{max}	Maximum payload (tons),

where $\lceil x \rceil = \min\{n \in \mathbb{Z} \mid n \geq x\}$ is the ceiling function and $\mathbb{Z}$ denotes the set of integers.

An additional level of evaluation in the model is the road conditions during the emergency disruption event since the disruption events used for the model were all severe weather events, which have a likelihood of impacting transportation conditions. This factor was applied directly to the transportation model as delays in P2P delivery using three levels: normal, intermediate, and poor road conditions. Intermediate conditions represent minor damage to road networks. Poor conditions represent significant damage to the road network. However, road conditions do not impact the transport charge since they are confirmed before deployment in this logistics model (see assumptions in Section 3.1).

3.6 Power Distribution

The simulation model, modeled after Mita (2020) and illustrated in Figure 3, exploits MATLAB's Simscape Specialized Power Systems distribution model to identify the required MNR capacity meet hourly scenario energy demand and assess whether the microgrid would succeed with MNR resources deployed to the disruption site. The interested reader can find the mathematical details for the simulation's electrical transition, three-phase transformers, and sample outputs in Ivey (2021, (pp. 18–22, 49–52)).

3.7 Design Of Experiments

We examine the fully integrated recovery model with a full factorial design using the scenario, strategy, demand scaling coefficient, and road conditions as factors. This results in 288 unique experiments, each of which records the recovery time (hours) and recovery cost (\$).

4 Tradeoffs Between Recovery Time And Cost

Figure 3 shows that scenarios based on H. Irma have a higher average and maximum recovery time than the other case studies. This is likely due to this case study's P2P distance of 1157 miles, which is 438 miles greater than the average P2P distance. Another insight from this plot shows a higher concentration of scenarios from H. Isaias near the maximum recovery cost of \$160,000. This case study requires 20 MW

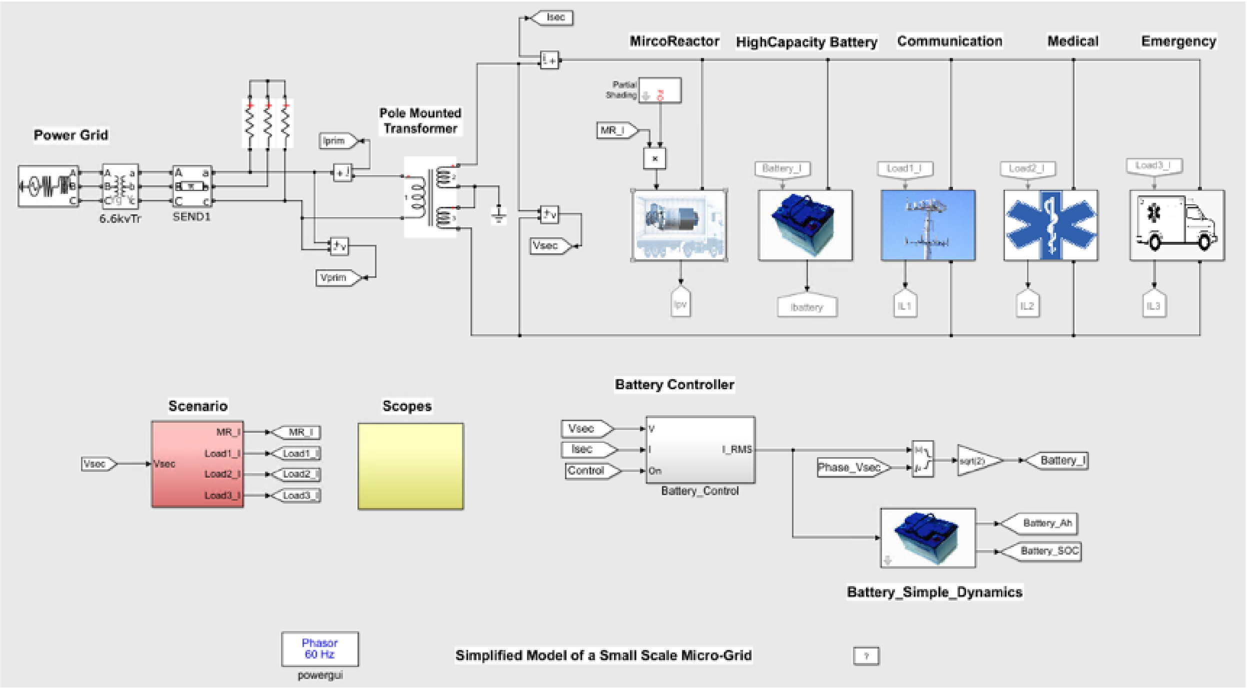

Figure 2: (color online) Simscape Specialized Power Systems distribution model adapted from Mita (2020).

of MNRs for most scenarios despite the demand factor, because the net generation of power at this grid is far lower than the demand after disruption.

Figure 4 provides more initial insight regarding the critical decision of deploying MNRs either in the Pre-Disruption or Post-Disruption Phase. The figure clearly distinguishes certain areas of the trade-off plot where specific strategies dominate. The majority of Strategy 1(-) scenarios are distributed higher on the recovery cost axis, while the opposite is true for Strategy 2. Both Strategy 1(-) and Strategy 2 appear to have similar recovery timelines but differ in potential cost. Strategy 1(+) has a constant recovery time grouping since a successful Pre-Disruption deployment of MNRs result in 48 hours of recovery, but there is greater variation in potential cost than Strategy 1(-). Differences in mean strategy performance for both recovery cost and recovery time are found in Tables 2 and 3, respectively.

Table 2: Recovery Cost ($) differences by strategy. Notes: Pre-Disrupt(U) is Strategy 1(-), Pre-Disrupt(O) is Strategy 1(+), and Post-Disrupt is Strategy 2.

Strategy Difference	Difference ($)	Std Error	*t* Stat	p-value
Pre-Disrupt(U) − Pre-Disrupt(O)	16315.90	5192.717	3.14	0.0053
Pre-Disrupt(U) − Post-Disrupt	36971.59	5192.717	7.12	< 0.0001
Pre-Disrupt(O) − Post-Disrupt	20655.69	5192.717	3.96	0.0003

Table 3: Recovery Time (hours) differences by strategy. Notes: Pre-Disrupt(U) is Strategy 1(-), Pre-Disrupt(O) is Strategy 1(+), and Post-Disrupt is Strategy 2.

Strategy Difference	Difference (hours)	Std Error	*t* Stat	p-value
Pre-Disrupt(U) − Pre-Disrupt(O)	30.9614	1.104445	28.03	< 0.0001
Pre-Disrupt(U) − Post-Disrupt	0.0000	1.104445	0	1
Pre-Disrupt(O) − Post-Disrupt	-30.9614	1.104445	-28.036	< 0.0001

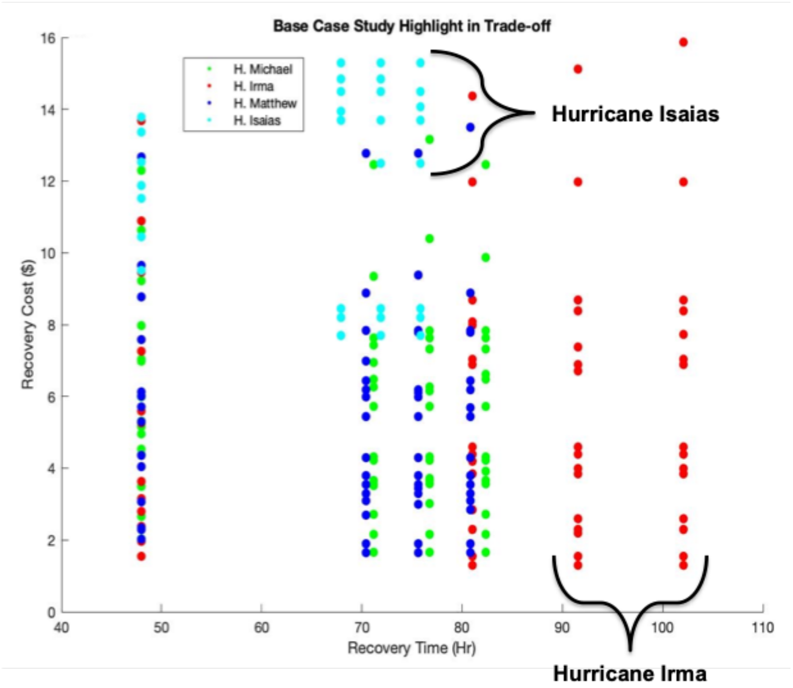

Figure 3: (color online) Case Study highlight of the generated output scenarios. Note: Recovery cost in tens of thousands of dollars ($).

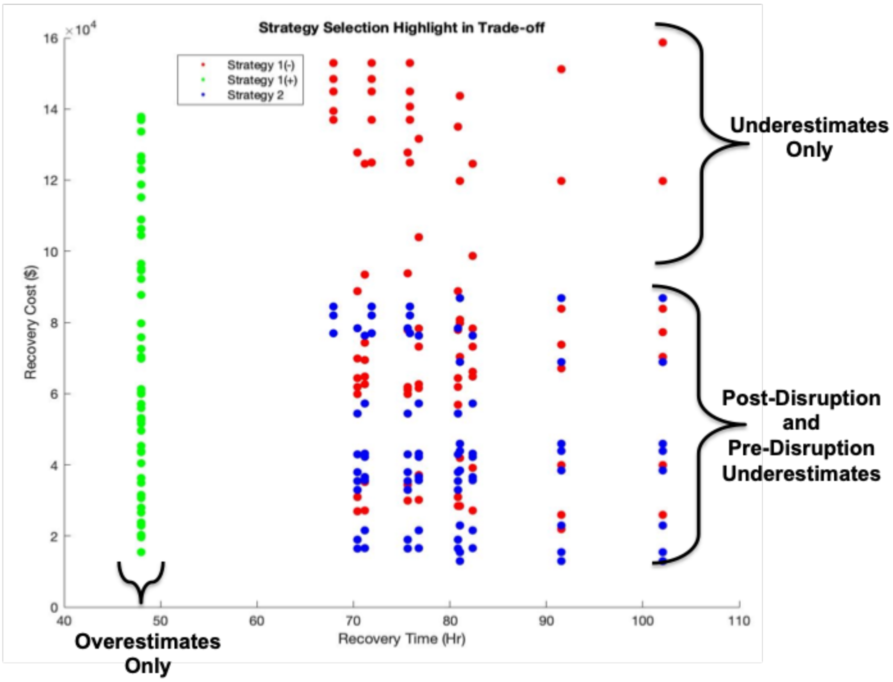

Figure 4: (color online) Strategy selection highlight of the generated output scenarios. Note: Recovery Cost in tens thousands of dollars ($)

5 Conclusions

5.1 Discussion

The goal of this research is to design an emergency response model that utilizes MNRs for recovery operations and identifies scenarios of best performance. Scenarios base their grid demand on real-world input from regional balancing authorities, while other controllable factors provide variety in the scenario outputs of recovery cost and recovery time. Overall, this emergency logistics model integrates critical decision strategies, transportation logistics, and power distribution to generate multiple scenarios.

Results show the average difference in grid demand and net generation, which is the unfulfilled demand, contributes to the MNR capacity required and primarily drives recovery cost. The P2P distance to the disrupted grid site contributes to longer recovery times if any Post-Disruption MNR deployment occurs. Among the case studies used, Case Study 4 (H. Isaias) contains an outlier for average unfulfilled demand (2502 MWh), and Case Study 2 (H. Irma) contains an outlier value for distance (1157 miles). These conditions are not ideal for MNR deployment since they drastically increase recovery cost and time.

Pre-Disruption deployment (Strategy 1) is best for scenarios with smaller demand requirements despite the P2P distance. The chance of underestimating demand is smaller when that unfulfilled demand is lower than 280 MWh, leading to grid recovery within 48 hours based on our models. Post-Disruption deployment is best for higher demand expectations since it is costly to underestimate MNR capacity past the 280 MWh median point. This strategy deploys MNRs in the Post-Disruption phase, so a P2P distance less than 573 miles would create a more desirable scenario where MNR capacity can reach the affected area quickly. If both the unfulfilled demand and P2P distance are too great, the grid conditions make MNRs for emergency response less favorable.

5.2 Limitations

The several limitations within this study are discussed below.

1. **Limited Literature.** MNRs have little scholarly literature that models their operational use in potential markets. Most MNR literature discusses their characteristics and future markets without any applied methods. MNRs also possess different properties from normal DGs that limit model comparisons. Therefore this research addresses the operational use of MNRs with specific modeling methods with limited literature as its basis.

2. **Case Studies.** The four base case studies provide real-world elements to the modeling methods and scenario generation. However, a greater variety of case studies would have improved the model and potential outcomes. The EIA-930 database has a limited number of balancing authorities that retrieve data. The selected case studies fit the narrow criteria discussed in Section 3.2, and were the only case studies screened in the interest of time.

3. **Power Distribution Modeling.** MATLAB's Simscape Specialized Power Systems Library provides the necessary power distribution modeling to confirm MNR support for disrupted grids. This modeling, however, limits the range of time output metrics in other parts of the model. Specifically, the phasor simulation in Simscape evaluates MNR grid operations over a fixed 24 hour period instead of a continuous-time horizon. This simulation method constrains the power distribution model to specific time blocks and limits the recovery time variation. The knowledge gap in electrical modeling prevented other approaches to power distribution modeling.

5.3 Future Work

Recent disruption events, such as the 2020 Wildfires in California or the 2021 Polar Vortex in Texas, stress the importance of having a reliable and resilient grid infrastructure. Regional and federal authorities recognize disruption events are incoming during the Pre-Disruption phase but lack the necessary resources to ensure customers' reliable utilities. Ivey (2021) describes the many applications for MNRs, where their portability and small MW capacities are a better solution to emergency backup power than industrial diesel generators.

As MNR development progresses, more literature should focus on modeling their DG capabilities for future markets and compare other alternatives with MNR capabilities.

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Army, the Department of Defense, or the United States Government.

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