# GROWING ENERGY RESILIENCE THROUGH RESEARCH

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**GREEN AND RENEWABLE ENERGY SOURCES ARE JUST THE START OF RESILIENCY: SMART MANAGEMENT OF MICROGRIDS WILL HELP PROTECT NAVAL AND EXPEDITIONARY POWER SOURCES FROM ENEMIES BOTH NATURAL AND MAN-MADE.**

Our naval forces are increasingly enabled by, and dependent on, energy availability. Interruptions to the supply of energy equate to interruptions to the mission. To maximize warfighting effectiveness, naval forces require that we always understand energy supply and have strategies to repair and reinstate energy supply quickly after disruptions.

The Department of Defense's definition for energy resilience is "the ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability and reliability sufficient to provide for mission assurance and readiness, including mission essential operations related to readiness, and to execute or rapidly reestablish mission essential requirements" (10 US Code §101).

There are typical interruptions to energy supply that are more commonly understood, such as component failures, weather-related issues, etc. There are also other categories that we must understand, anticipate, and respond to—these can be categorized as high-impact, low-probability events. These include cyber intrusions, deliberate attacks, and climate effects. Understanding how to achieve energy resilience is an ongoing challenge that is common across both the military and civilian sectors. There are challenges in both military and civilian power grids, microgrids, and stand-alone systems. Figure 1 provides a means of visually understanding the concept of energy resilience. Reduction of the area above the curve represents improved energy resilience. Essentially, we want to limit any performance degradation (y-axis) and limit the duration of the disruption (x-axis).

Because there are common aspects of energy resilience across military and commercial sectors, the Office of Naval Research's energy resilience applied research efforts employ a team approach that includes both commercial

Photo by UT2 Maruyama Austin

and military electrical grid partners, naval platform developers, industry, and academia. The team includes the Naval Facilities Command, Naval Surface Warfare Center Philadelphia Division, the Naval Postgraduate School, and the State University of New York Stony Brook and the University of Massachusetts at Lowell. The following is a description of a few examples of the ongoing projects.

## Intelligent Microgrid Management

An intelligent microgrid monitoring system built at Stony Brook provides excellent situational awareness, the first step toward taking corrective action within the microgrid. Easily deployable self-configured sensors automatically generate a digital twin of the microgrid. This versatile monitoring system identifies the instantaneous topology of the grid when its structure spontaneously changes or if prior documentation of the grid is not available.

A novel single fiber bidirectional communication link using a single wavelength provides the radio silent communication infrastructure for the system. Since a regular single fiber link uses a different wavelength to carry data in each direction, the transmitter and receiver pairs must be matched. Therefore, two similar devices cannot be linked together without a switch/router. The system developed in this work allows for universal modular devices that can connect to each other and create a network of homogeneous devices. This facilitates installation of the system quickly and easily.

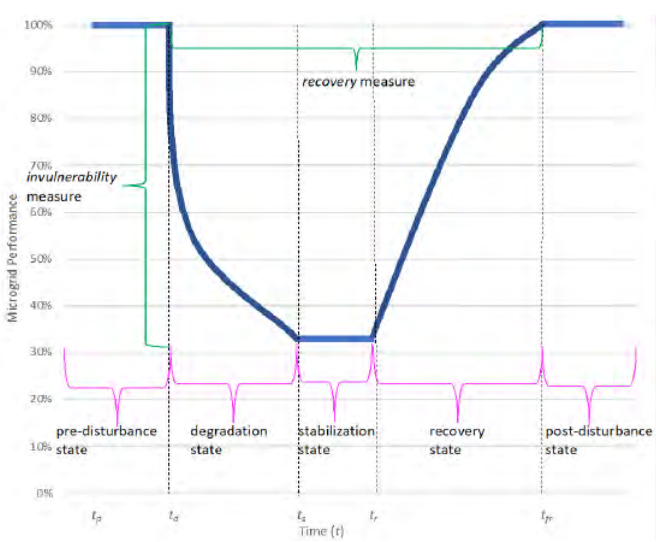
A self-healing network using smart switches provides extended stability for critical loads in the microgrid. The system automatically routes power from different distributed energy resources to the loads in the most efficient manner. Under extreme conditions, when power availability is less than demand, the critical loads are prioritized in the routing of the available power. The capacity of the power source, runtime, startup time, etc., is considered when choosing the sources to route power to critical loads. This ability to share power in the grid enables the critical loads to be powered for much longer periods of time than any local storage-based backup system. A laboratory-scale grid that demonstrates these novel technologies has been built to test the feasibility of real-world deployment.

## Microgrid Fault Resistance and Cyber/Physical Security

The Power Systems Lab at Stony Brook University is developing two critical solutions to ensure cyber and physical resilience in microgrids: a distributed and asynchronous active fault management (DA-AFM) technology and a deployable "three lines of defense" model.

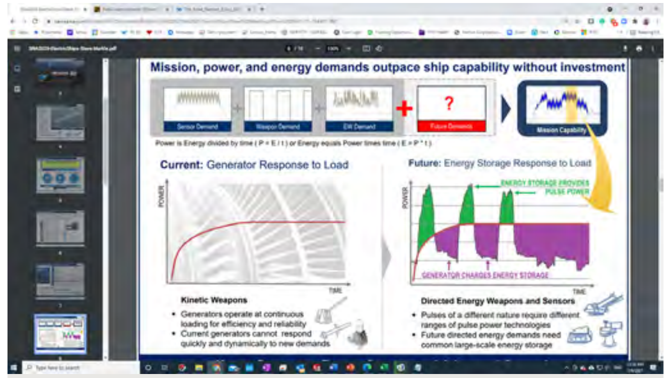
DA-AFM is a powerful real-time tool that manages fault currents by controlling the power electronic interfaces (e.g., microgrid inverters) and eliminates those barriers against microgrid resilience and ultra-reliable operations of distributed energy resources/microgrids in Navy sites and systems. When faults occur because of an accident, Mother Nature, or hostile attack, DA-AFM aims to: maintain the total fault current unchanged to avoid detrimental impacts on the naval power grid, eliminate the damaging power ripples for inverters in distributed energy resources/microgrids, and ensure that the quality of the power flow of each individual microgrid after the fault is identical to its quality before the fault to avoid loss of loads and maintain microgrid stability. DA-AFM has been virtualized in a distributed computing platform, executed through microgrid inverters, and fully tested on Stony Brook's cyber-physical microgrid testbed where its resilience benefits have been validated.

The Power Systems Lab is delivering a deployable three lines of defense model that integrates the lab's unique techniques—programmable active security scanning (PASS) and crypto-control and software-defined microgrid controls (SDC)—to enable unprecedentedly




The microgrid resilience curve.

self-protecting, cyber-resilient microgrids. The model will significantly boost microgrid resilience in that: PASS enables fast detection, localization, and mitigation of various cyberattacks and certain physical attacks; SDC provides ultra-fast recovery of controller functions upon attacks; and cryptocontrol prevents adversaries from intruding into microgrids. Together, these features will minimize the scope and timescale of adverse events and enable speedy recovery of microgrid operations.




The traditional (solid line) load curve of a grid and pulse load of a modern Navy microgrid.

Currently, the Power Systems Lab and partners plan to integrate DA-AFM and the three lines of defense model with advanced controls, high speed, and artificial intelligence into a programmable platform that can transform naval power infrastructures into autonomic microgrids capable of surviving cyberattacks, faults, and disasters. The demonstration will be performed in two stages. First, Stony Brook will integrate a functioning programmable microgrid platform through their newly established microgrid testbeds. Later, this programmable platform will be tested on Naval Facilities Command's microgrid testbed and, if possible, a real naval microgrid. Stony Brook will quantitatively examine how this platform improves cybersecurity, electricity resilience, stability, and reliability using both deterministic and randomized tests and validate how this platform can help achieve the Navy's resilience goals for zero-trust infrastructures. Our team will leverage the Navy's resilience metrics and follow the Department of Defense's Tactical Microgrid standard and Secure Tactical Advanced Mobile Power code while validating these technologies.

## Stored Energy Integration for Microgrid Resilience

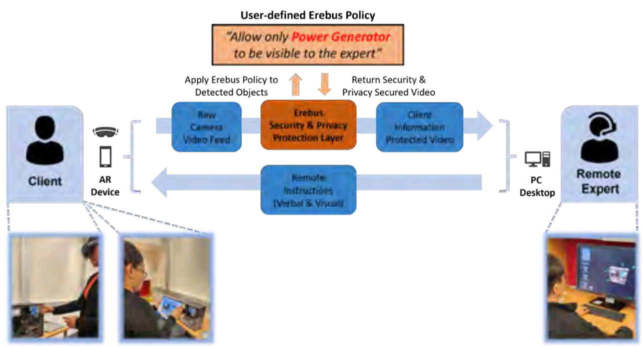
This project addresses the effective management of high-voltage supercapacitive energy storage to significantly improve resilience in high-voltage microgrids subjected to pulsed loads and disruptions, as part of the fully integrated power and energy systems we foresee in near-future Navy microgrids. Providing an instant high-power response to a voltage disturbance is critical for maintaining microgrid stability in either land-based or on-board microgrids.

Reliable high-power density supercapacitor storage can be tied directly into the microgrid through an inexpensive transformerless inverter, also working in tandem with longer-term battery storage. The Stony Brook team is working with two New York-based companies, IOXUS Inc. and Unique Electrical Systems, to develop and test the operation of kilovolt-class supercapacitor units in conjunction with lithium-ion battery storage in a testbed microgrid located at the New York State Advanced Energy Research and Technology Center of Excellence in Stony Brook's research and development park. The system features separate capacitor and battery units integrated through a high-speed broadband datalink.

The team has designed a 500-volt energy storage unit using six IOXUS 93V/83F modules, totaling 1.6 megajoules stored energy. The units are being integrated into an existing DC/AC test microgrid that is already supplied with Brenergy 480 lithium-ion battery storage units. The team is developing an energy dispatch algorithm that optimizes energy storage discharge based on the learned state of both lithium-ion and supercapacitor energy storage units.

## Smart Microgrid Security

Through recent smart grid initiatives, the electrical grid has been transformed into a connected, distributed system, where many semiautonomous microgrids, including Navy bases and ships, produce their own power and share resources, load, and information to achieve better efficiency, reliability, and availability. Achieving the smart grid vision, however, brings about unique security and privacy challenges. Maintaining the correct functionality of an interconnected infrastructure requires trustworthy real-time distribution of information across the various players




The Erebus design concept. The on-site client is communicating with a remote expert using an augmented reality device to receive instructions for microgrid maintenance (in this case, a mock power generator).

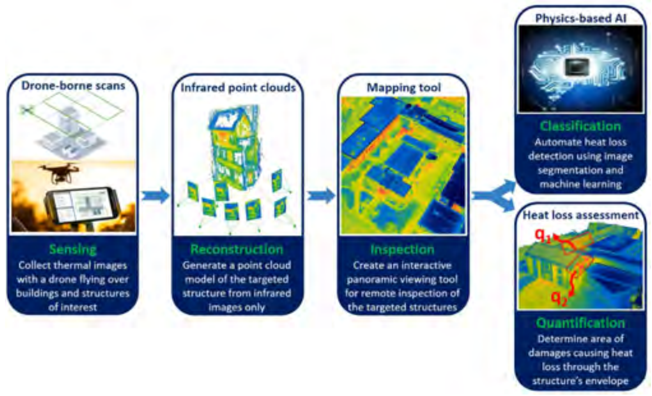
while preserving the security and privacy of information for entities at each level. In this research, Stony Brook has tackled the problems of access control and information leakage in microgrid environments, and they have focused on three challenges:

1. Identity management: The use of certificates and public key infrastructure for electrical cyber-physical systems
2. Allowing for remote shared maintenance: Selectively sharing information of the microgrid facility among on-site maintenance workers using augmented reality technology and remote experts through network communication
3. Side-channel information leakage: The use of side-channel aware power management in microgrids.

For identity management, Stony Brook has developed a public key infrastructure for the complex ecosystem of the microgrid that may include many heterogeneous sensors, generators, transformers, actuators, and the like. The new infrastructure is built on top of the existing infrastructure used for the web and provides a unique identity for each device. This identity is tied to the manufacturer of the device and can provide equivalent security guarantees for cyber-physical devices as for communications over the web. For remote shared maintenance, Stony Brook has implemented a framework called Erebus to prevent any security-sensitive visual information from being shared with unauthorized remote maintenance personnel. The client-defined Erebus policy is applied to the visual feeds acquired from the augmented reality device of the client. It can filter out all detected objects/information except the target objects/information that the client allows to be shared with the remote expert.

Erebus eradicates the potential security and privacy threats that may reside in the video feed of the client during the process of collaborative telecommunication while providing intact visuals of the target object to the remote expert. Furthermore, Erebus connects the remotely located maintenance expert to collaborate with the client on a maintenance task through video and audio network channels. This removes the need for an expert to be physically present at the site, enabling prompt, responsive, and secured maintenance. In addition, Stony Brook has developed a permission control framework for augmented reality applications. This provides the client fine-grained control over the permissions of augmented reality applications and heightens the safeguarding of clients' security and privacy sensitive information. For side-channel information leakage, a side-channel-aware power management system has been developed for microgrids. This system allows the microgrid infrastructure to reduce information leakage by selectively using stored energy (to flatten an energy spike) and storing generated energy (to create a spike) as needed.

This research provides a more reliable, resilient, efficient, and secured use of microgrids. Achieving trustworthy identity management across cyber-physical energy systems in a microgrid ensures the integrity and trustworthiness of the data and operations across these devices, increasing their reliability and resiliency against adversaries. Allowing remote shared maintenance enables microgrids to operate with increased efficiency and reliability while ensuring




Approach workflow to generate photorealistic models from droneborne infrared images to create 3D maps of targeted areas and detect defects causing heat loss. Graphic provided University of Massachusetts at Lowell

resilience against adversaries who wish to exfiltrate data. Preventing side-channel information leakage in microgrids also ensures the resiliency of the microgrid against attackers who wish to discern information about the operation of the unit based on its activities.

## Tunable Plasma Catalytic Reactor

The on-demand production of ammonia as a carbon-free energy storage medium from nitrogen (from air) and hydrogen (water electrolysis) has potential for increasing the autonomy and resiliency of future naval operations in some scenarios. Plasma provides alternative energy channels to thermo-chemical activation that can lead to compact and rapid-response systems suitable for modular and scalable deployment. A tunable plasma catalytic-membrane reactor is being investigated by the University of Massachusetts at Lowell team for the synthesis of ammonia at atmospheric pressure and low-temperature conditions.

## Assessment of Energy Infrastructure Systems

This University of Massachusetts at Lowell project uses drone-borne infrared scans combined with a point cloud technique to reconstruct photorealistic three-dimensional thermal models of buildings to identify heat loss, subsurface damages, and water infiltrations. The automated classification of defects causing heat loss also is implemented using customized convolutional neural network algorithms. This research develops a cost-effective monitoring tool for assessing energy loss on naval bases and platforms to reduce energy consumption and to facilitate periodic inspection of critical energy infrastructure to reduce their risk of failure.

At Naval Facilities Engineering Command, researchers are assessing a microgrid's climate resilience and corresponding costs by adapting resilience and cost models employed by the command's Engineering and Expeditionary Warfare Center. These models are being adapted by first creating an optimized renewable energy microgrid architecture and changing the objective function from minimizing lifecycle costs (or lifetime costs of energy for the demand) to minimizing carbon dioxide emissions.

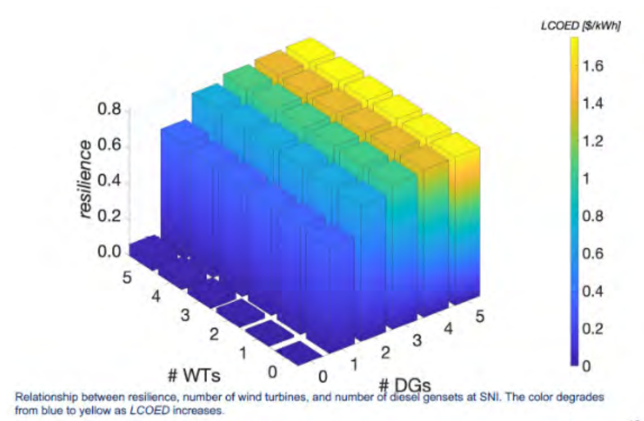
Variations on this optimized microgrid are then created by altering type, capacity, and number of distributed energy resources. Each of these architectures is subjected to a climate-driven extreme disturbance, such as wildfires, tsunamis, or hurricanes. The resilience score is then calculated by running the model through time steps until full recovery is attained.

Each of the data points (climate resilience, and costs) are plotted with as many as two distributed energy resources to create the climate resilience and costs trade space. This trade space is then used to enable more meaningful decisions on how much climate resilience is desired, for a corresponding cost. Once this decision is made, the corresponding microgrid architecture can be designed, installed, and operated.

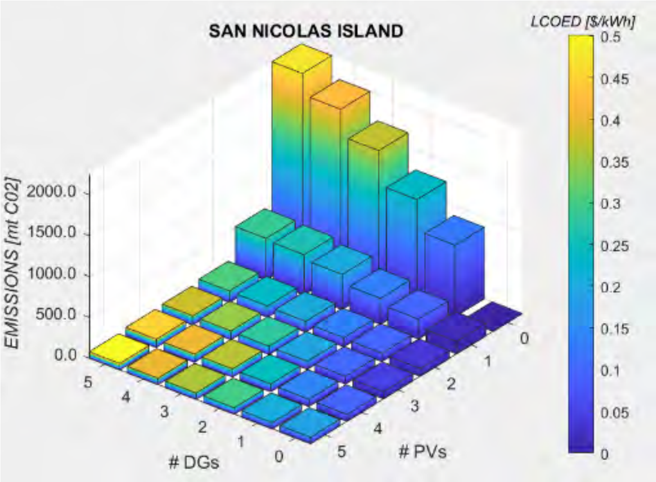
Finally, the two trade spaces ((below and opposite) can be compared to determine the optimal architecture that best meets both objectives. Ultimately, it is expected that a multiobjective optimization will generate this solution. The initial research into this was conducted by Jennifer Chavez and the University of Texas at El Paso.

## Training and Education

It is important to educate naval officers, enlisted personnel, and civilians on energy resilience to ensure the fleet understands the relevancy of resilient energy and can rapidly implement resilience improvements. Energy resilience touches all parts of the Navy, from shore facilities and bases to operational activities and tactical activities. The




The relationship between resilience, number of wind turbines, and number of distributed energy resources (diesel generators). The color degrades from blue to yellow as lifetime costs of energy for the demand increases. Image provided Naval Facilities Engineering and Expeditionary Warfare Center




The relationship between climate (emissions), number of distributed energy resources (diesel generators), and amount of photovoltaics available. Again, the color degrades from blue to yellow as lifetime costs of energy for the demand increases. Image provided Naval Facilities Engineering and Expeditionary Warfare Center

complex relationship of energy systems with every aspect of naval operations demonstrates the need for multidomain education to address the challenge. The Navy has tasked the Naval Postgraduate School to lead efforts to develop educational curricula that address naval energy resilience across multiple domains.

The Naval Postgraduate School's Energy Academic Group has a purpose to educate warfighters on the critical importance of operational energy to the Navy-Marine Corps mission. This group's Curricula Development Team is making progress under the Naval Enterprise Energy Education and Training program, an effort sponsored by Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation and Director, Innovation, Technology Requirements, and Test and Evaluation (N94). Three graduate-level certificates have been created: directed energy logistics, refuel (contested) logistics, and unmanned systems persistence. All three certificates focus on energy resilience in contested environments. The unmanned systems persistence certificate will be Energy Academic Group's first offering and will commence in spring 2023 through asynchronous distance learning. All three certificates focus on energy resilience in contested environments.

The curricula development team is developing introductory courses in operational energy. The preliminary course, Operational Energy I, will be in-residence and is designed for forward-deployed Sailors and Marines. This course will address the four primary operational energy competencies of fuel, power development and distribution, energy storage, and energy management.

The Navy Shore Energy Technology Transition and Integration and Energy System Technology Evaluation program funded by the Office of Naval Research has supported a multidisciplinary team of faculty, students, engineers, and installation energy managers led by the Naval Postgraduate School in partnership with the University of Wisconsin Milwaukee, Naval Facilities Engineering and Expeditionary Warfare Center, Naval Station Rota, and Naval Air Station Sigonella to develop analysis tools that assess existing and proposed installation and operational microgrids for resilience. The tools span the systems engineering, electrical engineering, and power engineering domains to provide a more holistic interpretation of microgrid resilience, and they provide potential paths forward to improve resilience.

The energy resilience research and training activities described above are just a few of the ongoing initiatives. There are many other efforts in progress that aim to improve our collective understanding of how best to affect the energy resilience of systems, whether they be commercial power grids, naval installation grids, or ship microgrids. The multidisciplinary team assembled here is making contributions applicable to naval installation as well as operational energy resilience. As we move forward with this energy resilience work, the emphasis will lean more toward lab and field demonstrations of the emerging technology, training, and advancement of concepts in formal transition projects such as Office of Naval Research Technology Candidate projects, Future Naval Capabilities, and Innovative Naval Prototypes.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