A Definition of Resilience

The ability to **anticipate**, **prepare for**, and **adapt** to changing conditions and **withstand**, **respond** to, and **recover** rapidly from disruptions through adaptable and holistic planning and technical solutions.

**Sequence of the NIAC Resilience Construct**

**Prior to an Event**
- Robustness: The ability to absorb shocks and keep operating.

**During an Event**
- Resourcefulness: The ability to manage a disruption as it unfolds.

**After an Event**
- Rapid Recovery: The ability to get back to normal as quickly as possible.

**Adaptability/Lessons Learned**
- The ability to absorb new lessons after a disaster.

“**A Framework for Establishing Critical Infrastructure Resilience Goals,”**
National Infrastructure Advisory Council, October 19, 2010
Grid Modernization Laboratory Consortium

GMLC Co-Leads

- Institutional Support
- Devices and Integrated System
- Sensing and Measurement
- System Operations and Control
- Planning and Design Tools
- Security and Resilience

87 projects, $220M over 3 years
GMLC Framework for Security and Resilience
Based on NIST Cybersecurity Framework

Identify:
- Develop understanding of threats, vulnerabilities, and consequences to all hazards
  Outcome: Improved risk management and streamlined information sharing

Protect:
- Inherent system-of-systems grid resilience
  Outcome: Increase the grid’s ability to withstand malicious or natural events

Detect:
- Real-time system characterization of events and system failures
  Outcome: Accelerated state awareness and enhanced event detection

Respond:
- Maintain critical functionality during events and hazards
  Outcome: Advanced system adaptability and graceful degradation

Recover:
- Real-time device management and transformer mobilization
  Outcome: Timely post-event recovery of grid and community operations
Example GMLC Resilience Projects

- Grid Resilience & Intelligence Platform (GRIP) – SLAC, LBNL
- Resilient Alaskan Distribution system Improvements using Automation, Network analysis, Control, and Energy storage (RADIANCE) – INL, PNNL, SNL
- Increasing Distribution System Resiliency using Flexible DER and Microgrid Assets Enabled by OpenFMB – PNNL, ORNL, NREL
- Integration of Responsive Residential Loads into Distribution Management Systems – ORNL, PNNL
- CleanStart DERMS- LLNL, PNNL, LANL
- Designing Resilient Communities: A consequence-based approach for grid investment - SNL
Changes to the electricity mix:

Natural gas and renewable energy generated nearly 50% of U.S. electricity in 2016, up from 30% in 2007

Natural gas increased from 22% to 34%

Renewable energy climbed from 8% to 16%
Why Renewable Energy for Resilient Systems

- Diesel sensitivity to fuel supply chains
  - especially in extreme weather events, which along with outages are increasing.
- Diesel back-up often neglected
  - high probability of failure; single point of failure
- RE systems have additional grid-connected benefits
  - diesel usually precluded due to air quality impacts.

Figure source: Kate Anderson et al. Quantifying and Monetizing Renewable Energy Resiliency. Sustainability, 10(4), 933, 2018, https://doi.org/10.3390/su10040933
Key Challenge 1: Control Systems

With advanced, autonomous control systems we can:

- **provide grid support services,**
- **meet critical loads during outages,**
- and reduce operating costs for system owners.

![Graph showing Frequency Regulation Signal](pjm.com)

![Graph showing kW dispatch during outage from REopt.nrel.gov/tool](REopt.nrel.gov/tool)

![Bar chart showing NPV](BarChart)

- **Benefits** include Energy Savings and Demand Charge Savings.
- **Costs** include CapEx and O&M.
Key Challenge 2: the Value of Resilience

**Perspective**
What matters to you?

**Metric**
How you quantify resilience

**Value**
How do you assign value?

Perspective from Gary Larson.

Example of quantifying resilience from materials science (image credit: engineeringarchives.com)
Step 1: Perspective

What matters to you?

Global and interdependent energy systems

What is critical to...

• Keeping my business open
• Health care facilities
• Emergency response
• National security
• Global energy markets
Step 2: Metrics for Resilience

Many metrics have been proposed, but no agreement on the best measures.

A few examples:

**Utility** perspective
- Customer-hours of outages
- Customer energy not served
- Avg (or %) customers experiencing an outage during a specific time period
- Cost of damages

**Community** perspective
- Critical services without power after backup fails
- Key military facilities w/o power

**Business** perspective
- Lost revenues, assets, and/or perishables

Credit to: Caitlin Murphy at NREL for summary of existing metrics (only a cross-sample shown here).
See [https://gridmod.labworks.org/sites/default/files/resources/GMLC1%20Reference_Manual_2%20final_2017_06_01_v4_wPNLNo_1.pdf](https://gridmod.labworks.org/sites/default/files/resources/GMLC1%20Reference_Manual_2%20final_2017_06_01_v4_wPNLNo_1.pdf) for more.
Step 3: Value of Resilience

How do you value what matters to you?

Macroscopic example

\[
\text{Outage Cost} \left( \frac{\$}{kWh} \right) = \frac{\text{GNP (or GDP) in $}}{\text{Total Annual Energy Consumption in kWh}}
\]

Microscopic example

Note the time varying value – currently integrating into REopt

Key Challenge 2: the Value of Resilience

We made this problem tractable by considering:

1. **Perspective** = commercial building
2. **Metric** = unmet critical load [kWh]
3. **Value** = **Value of Lost Load** (VoLL) [$/kWh] ~willingness-to-pay

(And addressed the control challenge using REopt)
Balance cost of system with grid-connected benefits ...

Balance cost of system with grid-connected benefits ...

... and resiliency benefits.

The maximum islandable premium is the difference of the Net Present Values (NPV).

\[ I_{\text{max}} = \text{NPV}_{\text{resilient}} - \text{NPV} \]
In some cases, valuing resilience can make PV and storage cost effective where it was not before.

Ongoing work

How can we **monetize** the Value of Resilience?

Banking, Insurance
- lower rates for lower risk assets

Government incentives
- ITC could include islandable premium
Thank you

NREL/PR-7A40-72884
Methods for Determining VoLL

**Direct (survey)**
- Blackout studies
  - record real damage costs after event
- Willingness to pay for avoidance
- Direct costs
  - from hypothetical scenarios

**Indirect**
- Production function
  - estimate costs from lost production (commercial/industrial) or lost time (residential, using household income)
- Revealed preferences
  - equivocate outage costs with money spent on mitigation measures, such as backup power supply and interruptible supply contracts