Fundamentals of Energy Security and Resilience

Prateek Joshi and Carishma Gokhale-Welch

National Renewable Energy Laboratory

November 2022

Background

This slide deck was developed for and presented at an Energy Fundamentals Course hosted by the Bangladesh University of Engineering and Technology (BUET) in October 2022. The National Renewable Energy Laboratory (NREL) helped organize this course in partnership with the United States Agency for International Development (USAID). The students in this four-day course were postgraduates and working professionals in the energy sector or related industries in Bangladesh. While some of the content in the slide deck is tailored to Bangladesh specifically, this presentation is intended to be a general primer on energy security and resilience that can be utilized for similar purposes by other universities or organizations throughout the world. The content of this slide deck is not intended to be fully comprehensive of all energy security and resilience concepts.

Outline

1. Resilience Planning

a. Metrics
b. Methodology

2. Resilience Solutions

a. Non-technical solutions
b. Technical solutions

3. Energy Security

a. National security
b. Cybersecurity

Image: Werner Slocum (NREL)

Outline

1. Resilience Planning

a. Metrics
b. Methodology

2. Resilience Solutions

a. Non-technical solutions
b. Technical solutions

3. Energy Security

a. National security
b. Cybersecurity

Image: Werner Slocum (NREL)

Definitions

Resilience: "Ability to adapt to changing conditions and withstand and rapidly recover from disruption."

Robustness
Inherent strength in system to withstand external demands without loss of functionality

Resourcefulness
Ability to mobilize needed resources and services in emergencies

Redundancy
Property that allows for alternate options and choices under stress

Rapid recovery
Speed at which disruption can be overcome and system stability restored

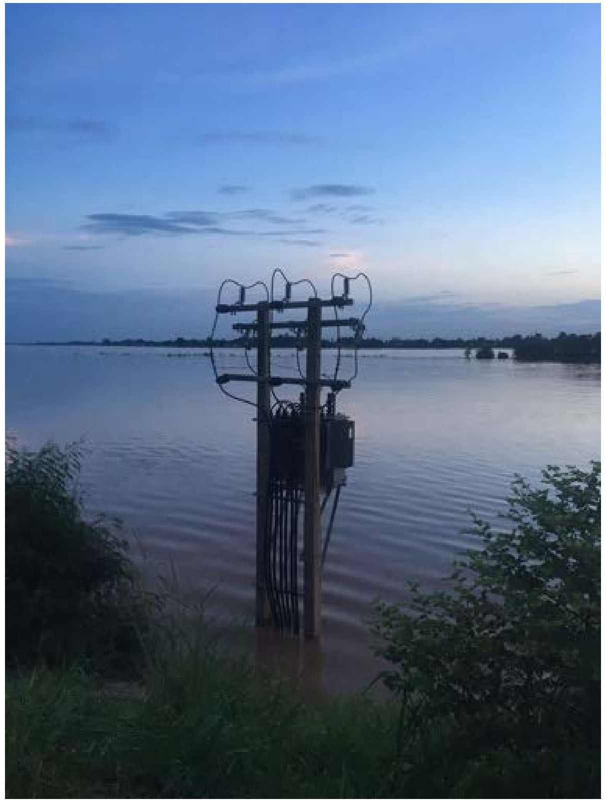


Image: Sherry Stout (NREL)

Image: Ian Metzger (NREL)

Source: U.S. Department of Homeland Security (2018)

USAID FROM THE AMERICAN PEOPLE NREL Transforming ENERGY

Grid Reliability Metrics

SAIFI

Number of times each customer, on average, experiences a sustained power interruption

$$\text{SAIFI} = \frac{\sum \text{Total Number of Interruptions}}{\sum \text{Total Number of Customers Served}}$$

SAIDI

Total amount of time each customer, on average, is without electric service for a given time period

$$\text{SAIDI} = \frac{\sum \text{Customer Interruption Durations}}{\sum \text{Total Number of Customers Served}}$$

CAIDI

Average outage duration if an outage is experienced (average restoration time)

$$\text{CAIDI} = \frac{\sum(\text{Duration of Interruption} \times \text{No. of Sustained Customer Interruptions})}{\sum \text{No. of Sustained Customer Interruptions}} = \frac{\text{SAIDI}}{\text{SAIFI}}$$

Source: Joshi and Evers (2020)

Resilience Planning

Identify Threats
Identify the potential threats to the power sector and assign a likelihood score for each.

Define Impacts
Describe the effects that threats have on the power sector.

Assess Vulnerabilities
Determine power sector vulnerabilities and assign a severity score for each.

Calculate Risks
Evaluate risk, which is the product of the threat likelihood and vulnerability severity score.

Develop Solutions
Develop and prioritize resilience action plans based on impact, ability to implement, and cost.

Figure. Steps of a resilience planning process for the power system

Resilient Energy Platform

https://resilient-energy.org/

Source: Stout et al. (2019)

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Identify Threats

THREATS

"Anything that can expose a vulnerability and, either intentionally or accidentally, can damage, destroy, or disrupt the power system."

1. Assess Existing Conditions

- Integrated resource plans
- Emergency plans
- Maps and geographic data
- Historical data related to disasters, extreme conditions, and outages

2. Identify Threats

Natural	Technological	Human Caused
Cyclones	Infrastructure failure (because of aging, material defects, etc.)	Accidents
Floods		Terrorism
Earthquakes	Poor workmanship or design	Cyberattacks
Drought	Unpredictable loads	Political upheaval
Wildfire	Water-line disruption impacting power sector	
Wildlife interactions		
Solar flares		

Figure. Examples of threats

3. Score Threat Likelihoods

Threat Likelihood Scores		Threshold Descriptions
Categorical	Numerical	
High	9	Almost certain to occur. Historic and frequent occurrences.
Medium-High	7	More likely to occur than not.
Medium	5	May occur.
Low-Medium	3	Slightly elevated level of occurrence. Possible, but more likely not to occur.
Low	1	Very low probability of occurrence. An event has the potential to occur but is still very rare.

Figure. Description of threat likelihood scores

Source: Stout et al. (2019)

Define Impacts

IMPACTS *"The extent to which a threat affects power sector infrastructure, systems, or processes."*

1. **Identify impacts on the power sector**
   - Effect on delivery of power
   - Effect on capital and operating costs
2. **Identify impacts on the end user**
   - Effect on health and safety
   - Effect on economy

Figure. Examples of impacts on the power sector

	Generation	Transmission	Distribution	Customer	Operations	Workforce	Financial
Example *Earthquakes*	*Reduced generation capacity*	*Fallen transmission poles*	*Fallen distribution poles or cut lines*	*Loss of power*	*Need to compensate for load imbalance*	*Unable to access damaged infrastructure due to debris blocking access roads*	*Cost of rebuilding transmission infrastructure, loss of revenue, assets, production*

Figure. Examples of impacts on the end user

	Population	Communications	Transportation	Government Operations	Medical Service
Example *Strong Winds*	*Loss of power and economic activity*	*Disruption in communications for emergency services*	*Increased traffic and accidents due to traffic light outage*	*Lack of access to vital computer systems for governance*	*Lack of power in critical infrastructure*

Source: Stout et al. (2019)

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Assess Vulnerabilities

VULNERABILITIES *"Weaknesses within infrastructure, processes, and systems, or the degree of susceptibility to various threats."*

1. **Assess Existing Conditions**
   - Integrated resource plans
   - Emergency plans
   - Maps and geographic data
   - Historical data related to disasters, extreme conditions, and outages

2. **Identify Vulnerabilities**
   - Lack of backup systems and supplies
   - Single points of failure in infrastructure
   - Location prone to flooding, fire, etc.
   - Lack of cybersecurity defenses
   - Poorly resourced or undertrained workforce

3. **Score Vulnerabilities**

Threats	Impacts		Vulnerability Statements	Severity Scores
Example *Lightning strike*	*Damaged poles, power outage*	***Why?*** →	*Lack of lightning protection on transmission and distribution equipment increases the likelihood of a lightning strike damaging transmission poles, leading to a power outage.*	*Medium*

Figure. Example of vulnerability statement and score

Source: Stout et al. (2019)

Assess Risk

RISK *"The potential for loss, damage, or destruction of key resources or power system assets resulting from exposure to a threat."*

1. **Assess Risks**
   - Determine which threats and vulnerabilities are associated
2. **Score and Evaluate Risks**
   - Risk score = Threat likelihood score *x* Vulnerability severity score
3. **Identify levels of risk acceptance**

Figure. Example of a risk matrix

VULNERABILITIES	Vulnerability Severity Score	Extreme Precipitation	Extreme Temperatures	Flooding	Landslides	Wildfire Interactions	Wind	Human Actions: Bad Actors	Human Actions: Accidents	Technological Design	Technological Materials	Technological Workmanship	Drought	Lightning
Threat Likelihood Score		9	7	7	7	5	5	5	5	5	5	5	5	1
Power system rules, regulations, and technical standards do not meet current and changing environmental conditions	9	81		63	63			45		45	45			
Corruption leads to code violations	9	81			63	45	45	45			45	45		
Dam construction does not follow design specifications	9	81	63		63	45	45	45	45	45	45	45		
Installation does not follow design specifications	9			63	63	45		45	45	45		45		
Lack of compliance with codes in design	9	81	63	63	63	45	45			45	45	45		
System operations are not flexible enough to respond to changes in demand and supply	7	63	49	49			35			35			35	7
Demand forecasting is not responsive to changing load conditions	7	63	49							35			35	
Heavy power sector reliance on hydro generation	7		49	49						35			35	
Inadequate domestic generation capacity requires costly energy imports	7		49	49	49	35	35	35	35	35	35	35	35	

Source: Stout et al. (2019)

USAID FROM THE AMERICAN PEOPLE NREL Transforming ENERGY

Outline

1. Resilience Planning

a. Metrics
b. Methodology

2. Resilience Solutions

a. Non-technical solutions
b. Technical solutions

3. Energy Security

a. National security
b. Cybersecurity

Image: Werner Slocum (NREL)

Categories of Resilience Solutions

Long-Term Planning

- Comprehensive community plans, threat mitigation plans, watershed plans, etc.

Regulations and Policies

- Zoning, subdivision codes, floodplain regulations, building codes, etc.

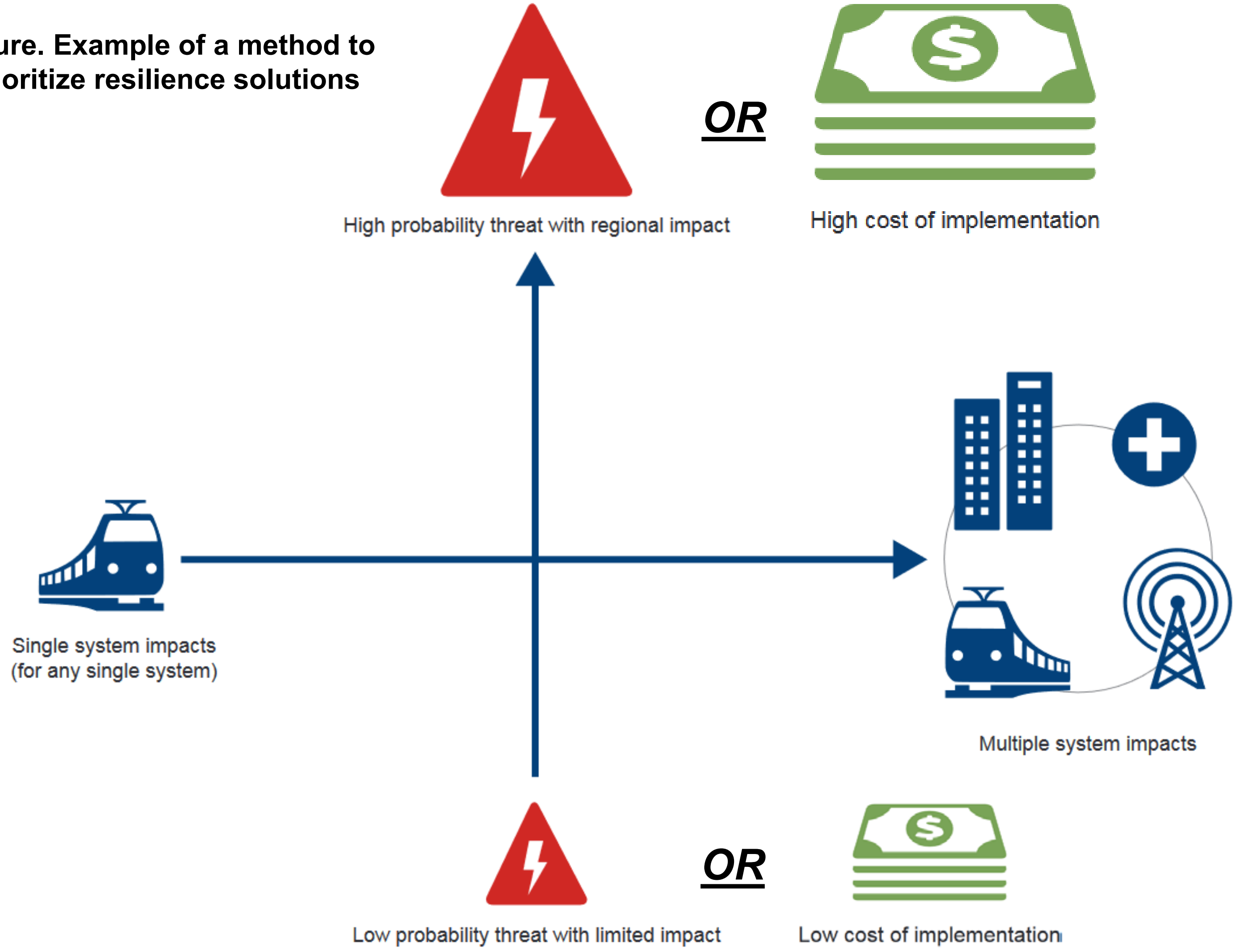
Programs

- Capacity building, land acquisition, low-income housing, etc.

Technical Projects

- Decentralized backup generation, passive stormwater management, microgrids, grid hardening, renewable energy, etc.

Figure. Example of a method to prioritize resilience solutions



Source: Stout et al. (2019)

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Renewable Energy Can Support Security and Resilience

Diversifying the generation mix

- Spatial diversity
- Resource and fuel diversity

Reducing water use

- Reduce vulnerabilities related to drought

Enabling modular and rapid deployment

- Decentralized power generation
- Locational flexibility

Islanding

- Reduce vulnerabilities related to broader grid outages

Coupling with storage

- Backup power
- Potential to enable black-start recovery

Source: Cox et al. (2019)

Solar PV Resilience

Measure	Base Case
1. System Audit	No system audit
2. Locking Fasteners	Hex bolts, flange nuts, stainless steel flat washers
3. Through Bolting	Top-down clamps
4. Marine-Grade Steel	18-8 stainless steel
5. Module Selection	Standard modules (2400 Pa uplift)
6. Three-Framed Rail System	Two-rail racking
7. Two-Pier Mounting	One driven steel pier
8. Racking Design	Cold rolled U channel aluminum
9. Wind-Calming Fence	Standard security fence
10. Watertight Enclosures	National Electrical Manufacturers Association (NEMA) 3 rated
11. Elevated Pads	Electronic components not on elevated pads
12. Drainage	Not well-designed drainage systems

Figure. Three-framed rail system to support rooftop solar PV in hurricane-prone Florida

Source and Images: Elsworth and Van Geet (2020)

Solar PV Pre-Storm Checklists:

https://www.nrel.gov/docs/fy22osti/81968.pdf.

Figure. Wind fence surrounding utility-scale ground-mount solar PV installation

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Wind Turbine Resilience

Interventions for Cyclone-Proof Wind Turbines:

- Downwind rotors, facing away from incoming wind, reduce risk of blades hitting the tower during high winds.
- General Electric is deploying cyclone-proof turbines with slightly shorter blades to reduce mechanical loads on towers and a thicker steel base.
- Twisted jacket foundations for offshore wind can increase resilience to strong storms.

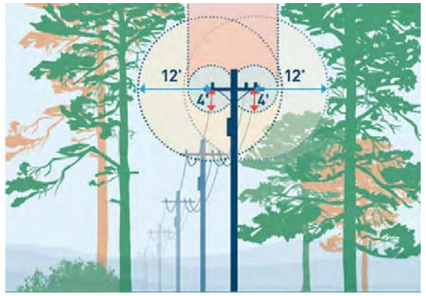
Source: General Electric (2018), U.S. Department of Energy (2018), University of Colorado Boulder (2022)

Figure. Schematic of select interventions for cyclone-proof wind turbines

Image: U.S. Department of Energy (2018)

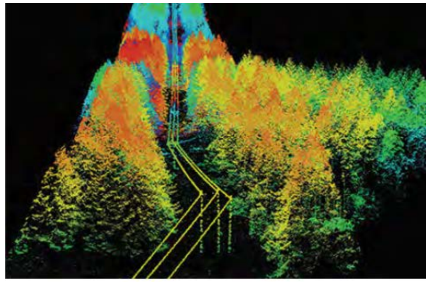
Grid Resilience

Vegetation Management



Tree Trimming

- Maintain a certain radial clearance around poles
- Remove vegetation overhangs



Inspections

- Patrols sent to survey distribution system
- Increase in use of LiDAR and drones
- Identify high-risk trees for removal

Grid Hardening

Undergrounding

- Move overhead cables underground
- Costs ~$1.16M per mile vs. ~$448K per mile for overhead lines

Pole Replacement

- Strengthen poles to withstand heavier covered conductors
- Replace wood poles with stronger composite poles

Sectionalization

- Circuit is divided into sections through the opening of remote-controlled switches and/or reclosers
- Isolates the fault, thereby limiting the extent of the outage

Devices

- Sectionalizer: self-contained circuit-opening device
- Used in tandem with protective devices such as circuit breakers and reclosers

Use

- Sectionalization is used to increase distribution system reliability because it protects against all forms of unplanned outages

Source and Images: Joshi and Evers (2020)

Microgrids

A group of **interconnected loads and distributed energy resources** within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid.

A microgrid can connect and disconnect from the grid to enable it to operate in **both grid-connected or island mode**.

Source: U.S. Department of Energy

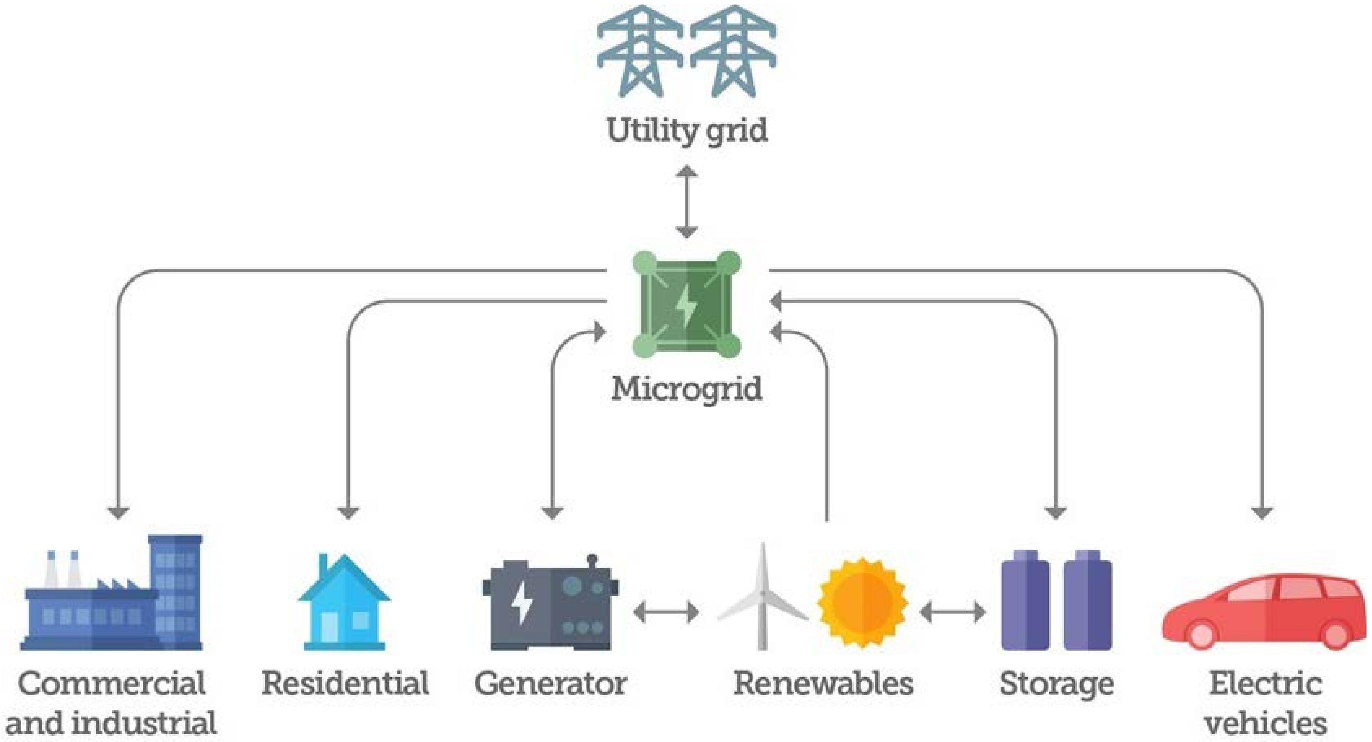


Figure. Schematic of microgrid with connected loads, generators, and storage

Image: Pew Charitable Trust

Energy Demand

Energy Efficiency and Demand Response

- Energy efficient loads reduce energy costs and fuel consumption, bolstering energy security.
- Grid-interactive loads and demand response can provide flexibility services to the grid to support resilience.
- Demand response: Changes in utility-supplied electric usage by end-use customers from their normal consumption patterns in response to utility signals or controls.
- Demand response can enable targeted load shedding when the grid is highly stressed to avoid larger and more damaging outages.

Source: Joshi and Logan (2022), Elsworth et al. (2022)

Electric Vehicles

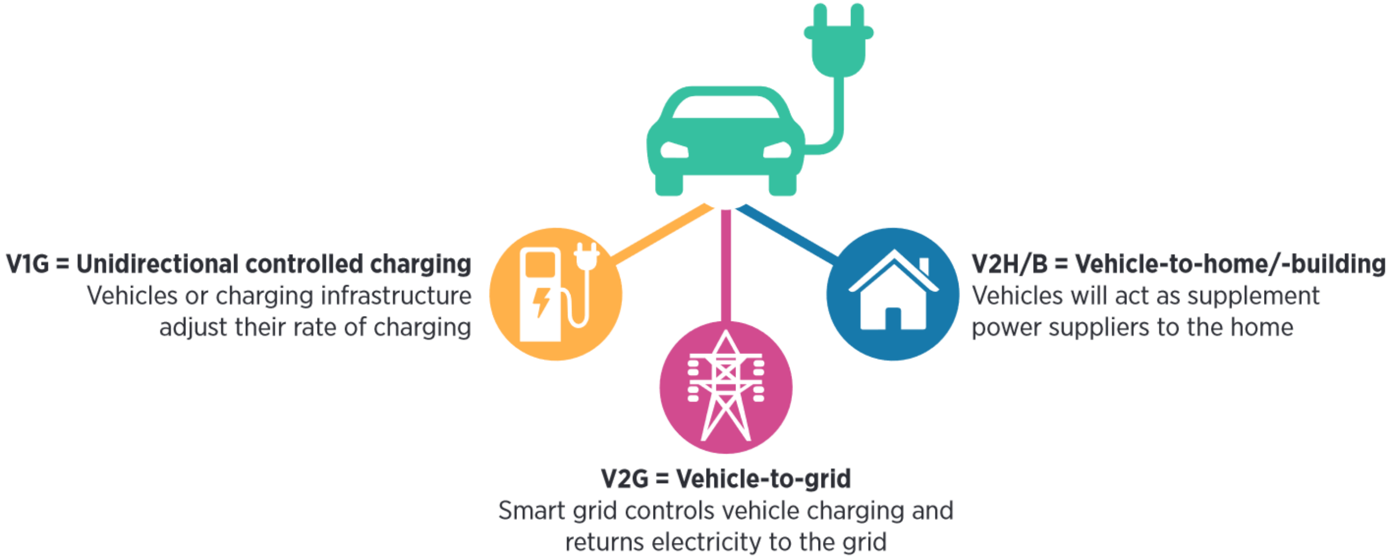


Figure. Schematic of electric vehicle (EV) charging modes

Image: International Renewable Energy Agency (2019)

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Outline

1. Resilience Planning

a. Metrics
b. Methodology

2. Resilience Solutions

a. Non-technical solutions
b. Technical solutions

3. Energy Security

a. National security
b. Cybersecurity

Image: Werner Slocum (NREL)

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

National Security

Natural disasters: “Severe weather events like droughts and storms are projected to become more intense and destructive; these events can decrease or disrupt supplies and impact energy infrastructure.”

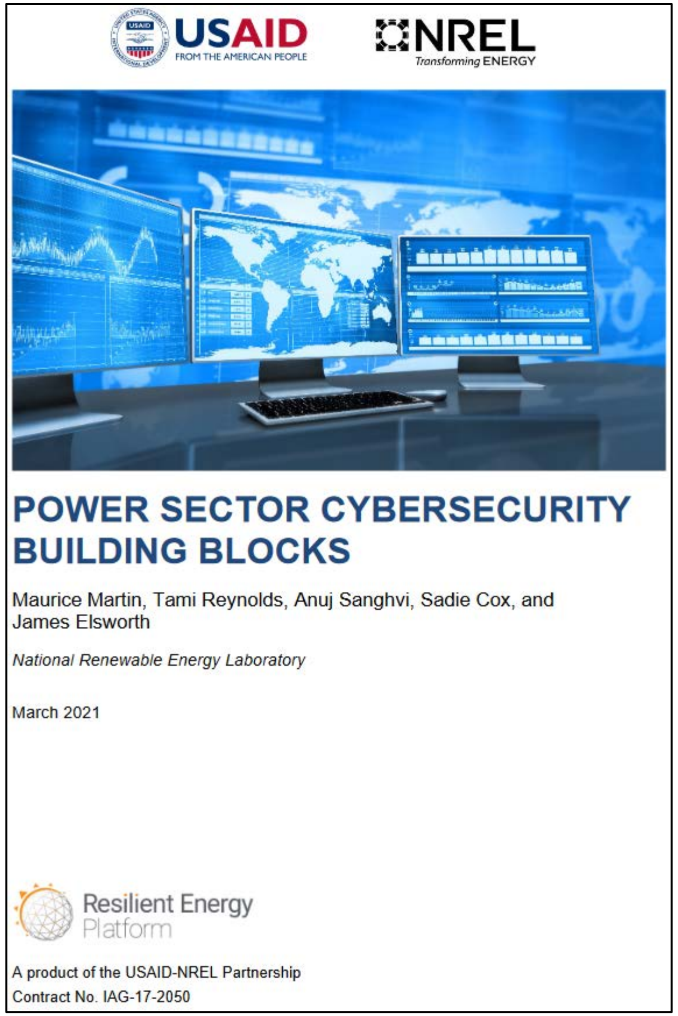
Cyberattacks: “Cyberattacks are becoming more common as the energy sector is becoming more automated, digitized, and interconnected.”

Geopolitics: “Interstate conflicts can threaten energy security, and political instability in fuel producing nations can impact energy prices.”

Fuel price fluctuations: “Changes in fuel prices can threaten energy security by impacting a nation’s ability to purchase fuels.”

Source: Cox et al. (2019)

Power Sector Cybersecurity


USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

POWER SECTOR CYBERSECURITY BUILDING BLOCKS

Maurice Martin, Tami Reynolds, Anuj Sanghvi, Sadie Cox, and James Elsworth

National Renewable Energy Laboratory

March 2021

Resilient Energy Platform

A product of the USAID-NREL Partnership
Contract No. IAG-17-2050

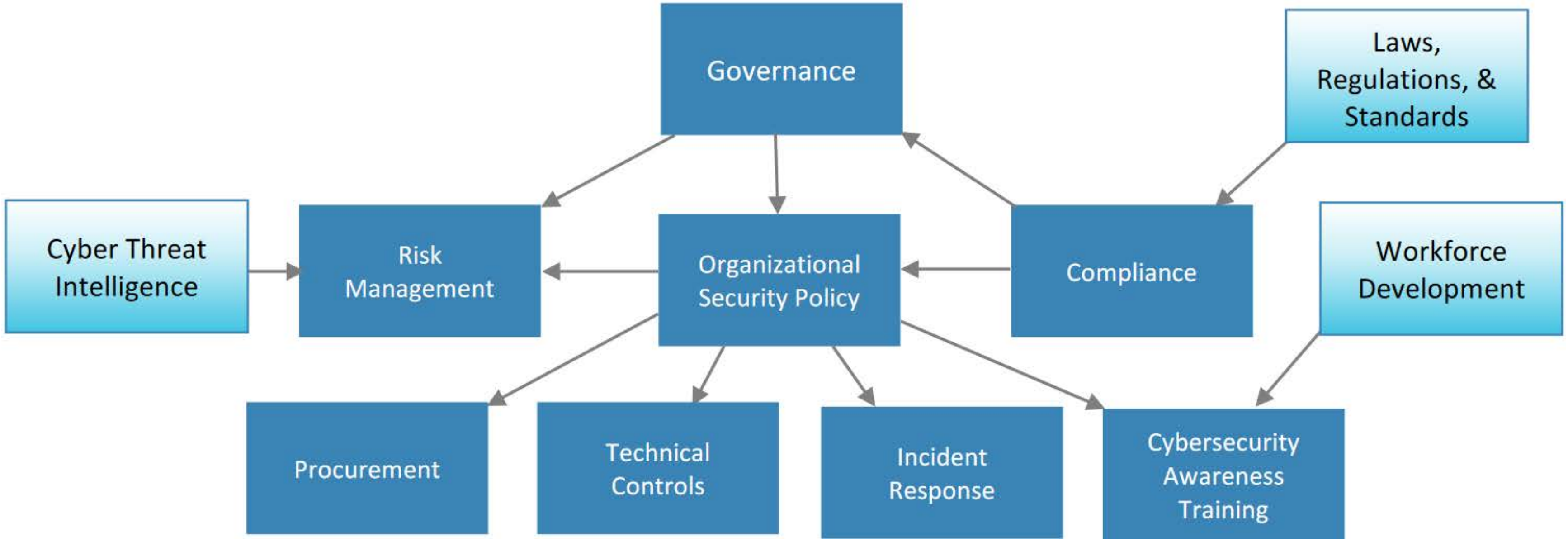


Figure. Schematic of power sector cybersecurity building blocks (solid color boxes are internal to the utility; shaded color boxes are external to the utility)

Source: Martin et al. (2021)

Electric Vehicle Cybersecurity

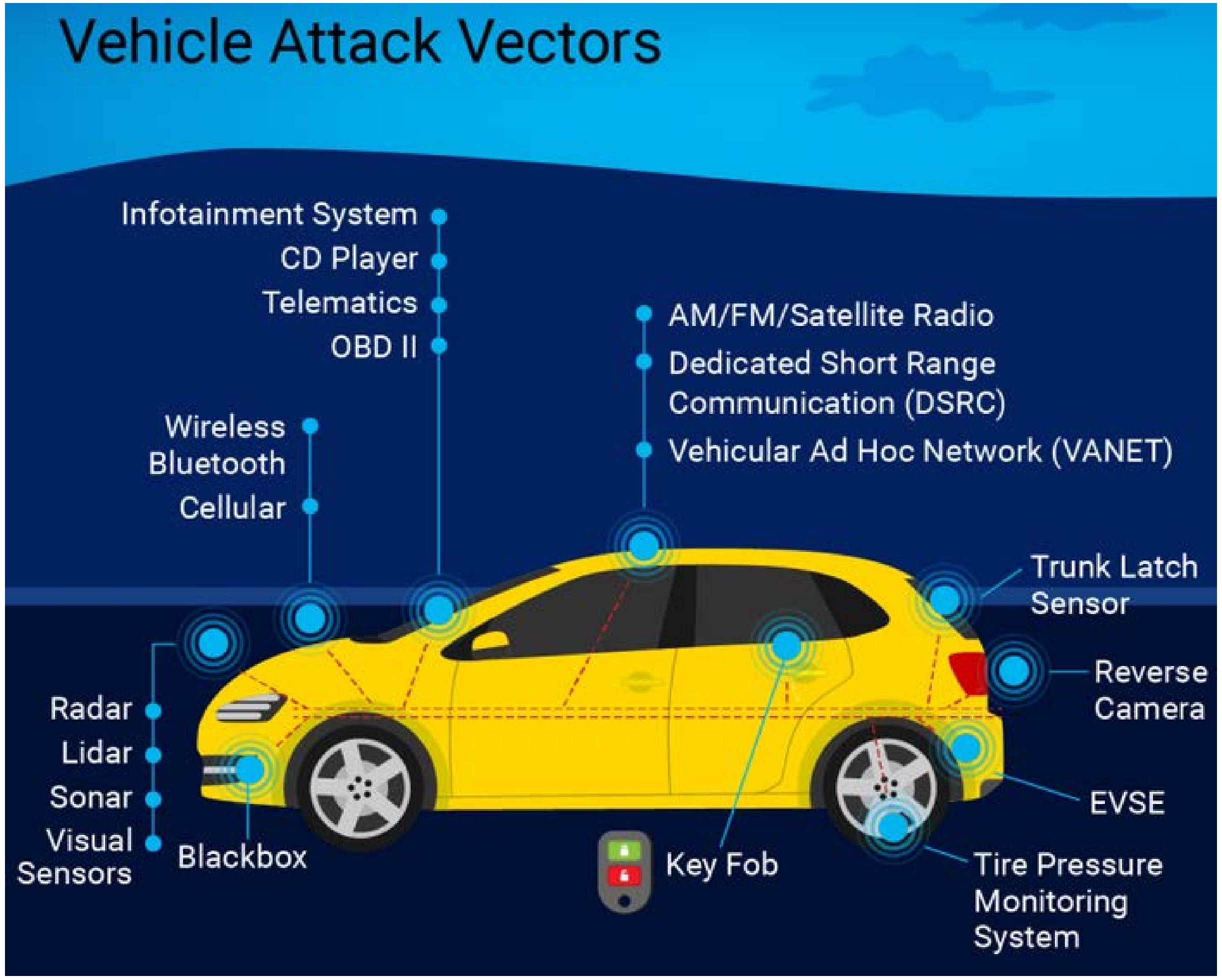


Figure. Potential attack vectors in many modern vehicles

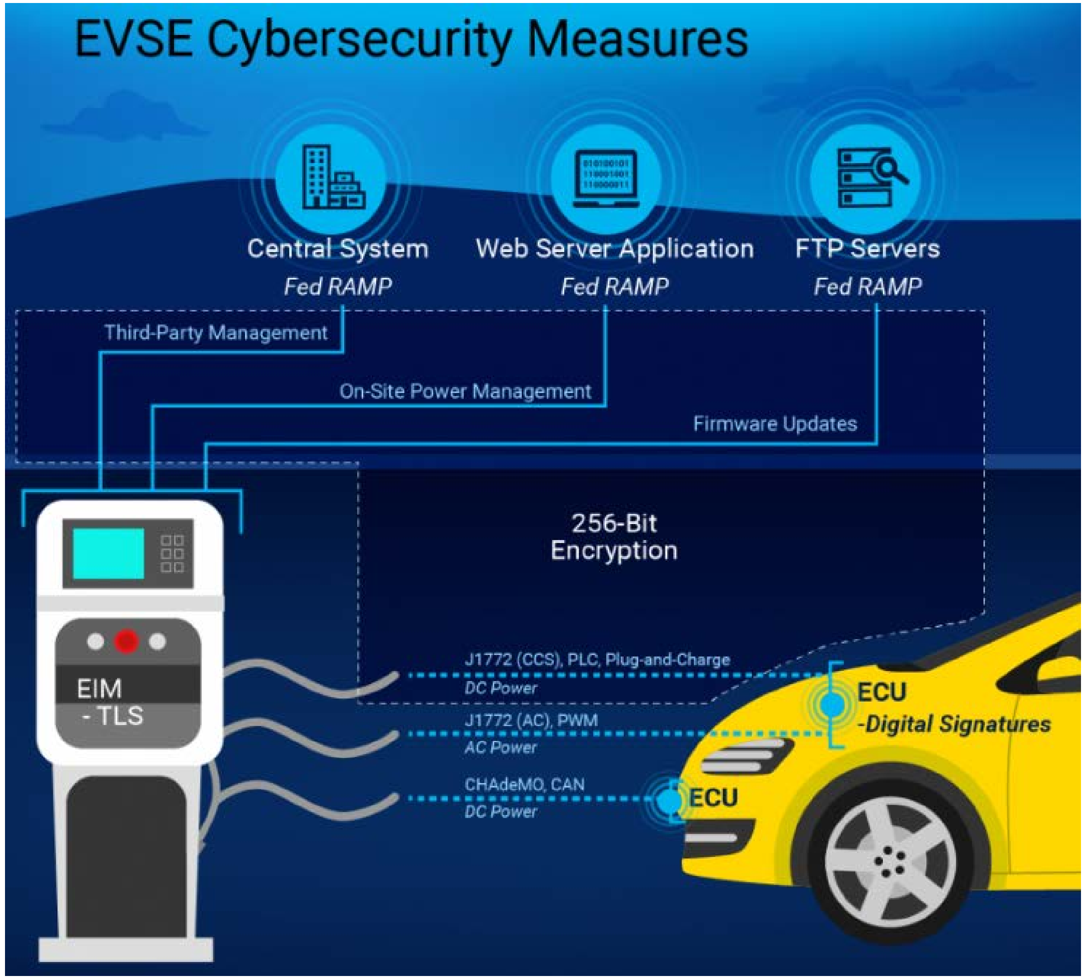


Figure. Electric vehicle support equipment communications and cybersecurity implications

Source and Images: Hodge et al. (2019)

Thank you!

Prateek.Joshi@nrel.gov

https://www.nrel.gov/usaid-partnership/reinforcing-advanced-energy-systems-bangladesh.html

This work was authored, in part, by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the United States Agency for International Development (USAID) under Contract No. IAG-17-2050. The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof, including USAID.

NREL/PR-5R00-84499

References

Cox, Sadie, Laura Beshilas, and Eliza Hotchkiss. “Renewable Energy to Support Energy Security.” Resilient Energy Platform. Golden, CO: National Renewable Energy Laboratory (NREL), United States Agency for International Development (USAID), October 2019. https://www.nrel.gov/docs/fy20osti/74617.pdf.

“DHS Resilience Framework: Providing a Roadmap for the Department in Operational Resilience and Readiness.” Washington, DC: U.S. Department of Homeland Security, July 2018. https://www.dhs.gov/sites/default/files/publications/dhs_resilience_framework_july_2018_508.pdf.

Elsworth, James, Prateek Joshi, and Monisha Shah. “Puerto Rico Demand Response Impact and Forecast Tool (PR-DRIFT): Beta Version.” Presented at the National Renewable Energy Laboratory (NREL), Golden, CO, n.d. https://www.nrel.gov/docs/fy22osti/81363.pdf.

Elsworth, James, and Otto Van Geet. “Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience.” Technical Report. Golden, CO: National Renewable Energy Laboratory (NREL), June 2020. https://www.nrel.gov/docs/fy20osti/75804.pdf.

Hodge, Cabell, Konrad Hauck, Shivam Gupta, and Jesse Bennett. “Vehicle Cybersecurity Threats and Mitigation Approaches.” Technical Report. Golden, CO: National Renewable Energy Laboratory (NREL), August 2019. https://www.nrel.gov/docs/fy19osti/74247.pdf.

Joshi, Prateek, and Alex Evers. “Western Interconnection Data System to Inform Utility Wildfire Mitigation Efforts.” Presented at the Western Interstate Energy Board, Stanford University, August 21, 2020. https://www.westernenergyboard.org/wp-content/uploads/2020/08/08-2020-summer-joint-wieb-stanford-intern-project-on-data-system-to-inform-utility-wildfire-mitigation-efforts.pdf.

Joshi, Prateek, and Jeff Logan. “Lessons Learned for Rapid Decarbonization of Power Sectors: Collaborative Report from the Clean Energy Ministerial.” Global Clean Energy Action Forum (GCEAF/CEM13/MI7). Golden, CO: National Renewable Energy Laboratory (NREL), September 2022. https://www.nrel.gov/docs/fy22osti/83951.pdf.

Martin, Maurice, Tami Reynolds, Anuj Sanghvi, Sadie Cox, and James Elsworth. “Power Sector Cybersecurity Building Blocks.” Resilient Energy Platform. Golden, CO: National Renewable Energy Laboratory (NREL), March 2021. https://resilient-energy.org/cybersecurity-resilience/resources/file/@@download/file/79396.pdf.

Stout, Sherry, Nathan Lee, Sadie Cox, James Elsworth, and Jennifer Leisch. “Power Sector Resilience Planning Guidebook: A Self-Guided Reference for Practitioners.” Resilient Energy Platform. Golden, CO: National Renewable Energy Laboratory (NREL), United States Agency for International Development (USAID), June 2019. https://resilient-energy.org/training-and-resources/publications/73489-guidebook-final.pdf/@@download/file/73489-GUIDEBOOK-FINAL.pdf.