NREL
NATIONAL RENEWABLE ENERGY LABORATORY

REopt: Energy Decision Analysis

NREL REopt Team

reopt.nrel.gov

REopt Integration and Optimization

The Nation’s Energy Supply Is in the Midst of a Transformation

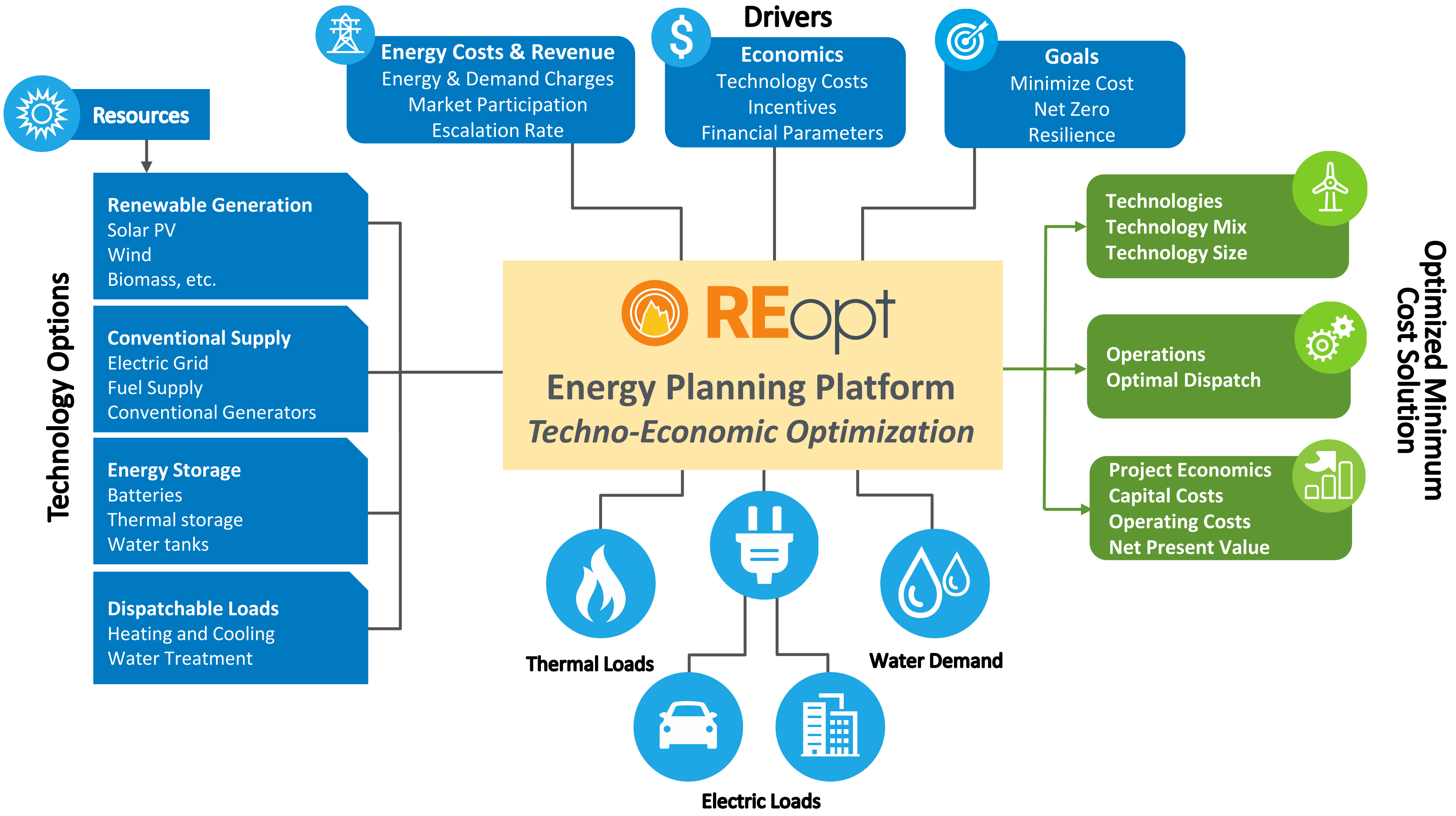
- As costs decrease, renewable energy deployment is growing worldwide
- Generation is increasingly distributed, with 31% of new capacity behind-the-meter
- With increasingly integrated and complex systems, back-of-the envelope calculations are no longer sufficient to determine distributed energy project potential

REopt Optimizes Integrated Energy Systems

- NREL's REopt™ platform optimizes planning of generation, storage, and controllable loads to maximize the value of integrated systems
- It transforms complex decisions into actionable results for building owners, utilities, developers, and industry
- REopt analysis guides investment in economic, resilient, sustainable energy technologies

REopt Energy Planning Platform

Formulated as a mixed integer linear program, REopt provides an integrated, cost-optimal energy solution.



REopt Provides Solutions for a Range of Users

Including researchers, developers, building owners, utilities, and industry

What is the optimal size of distributed energy resources (DERs) to minimize my cost of energy?

How do I optimize system control across multiple value streams to maximize project value?

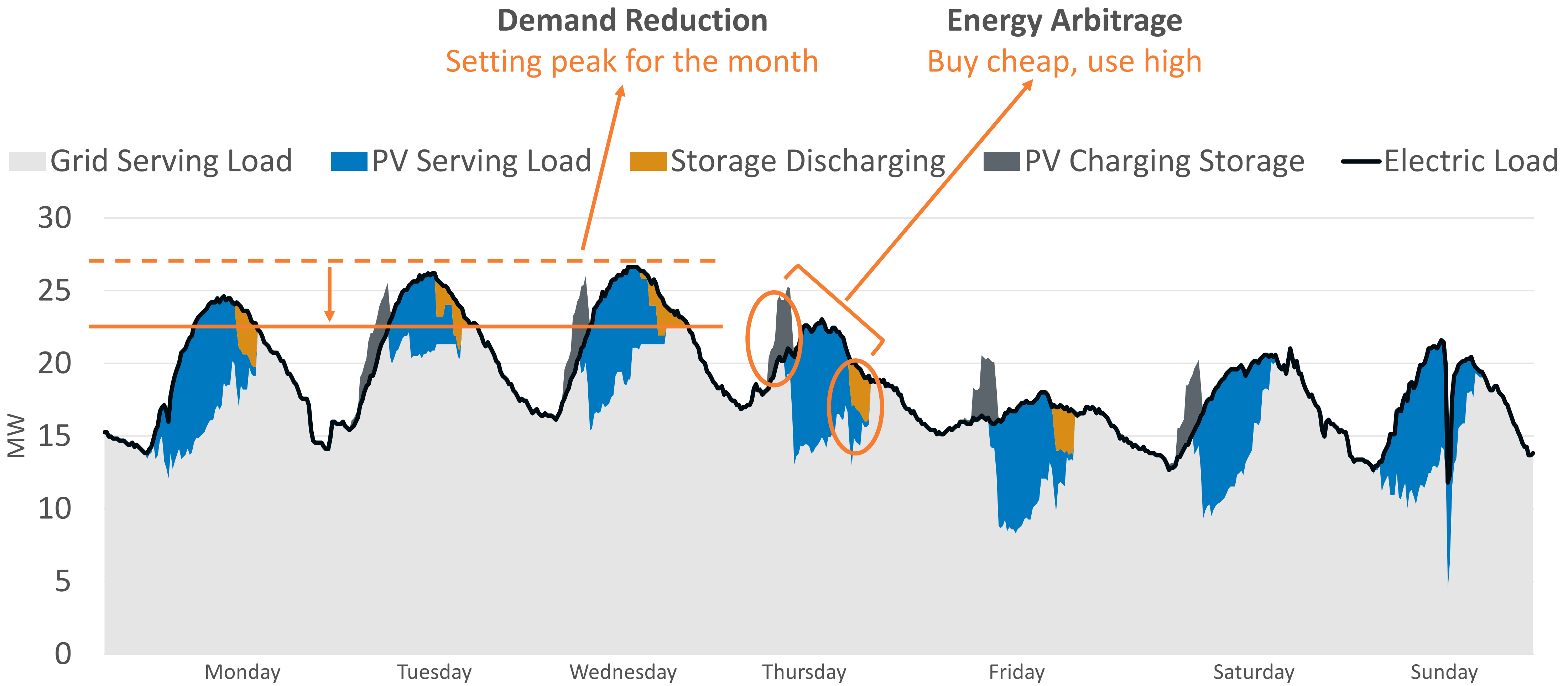
Where do market opportunities for DERs exist? Now and in the future?

What will it cost to meet my sustainability or resilience goal?

What is the most cost-effective way for me to survive a grid outage?

How Does REopt Work?

REopt considers the trade-off between ownership costs and savings across multiple value streams to recommend optimal size and dispatch.



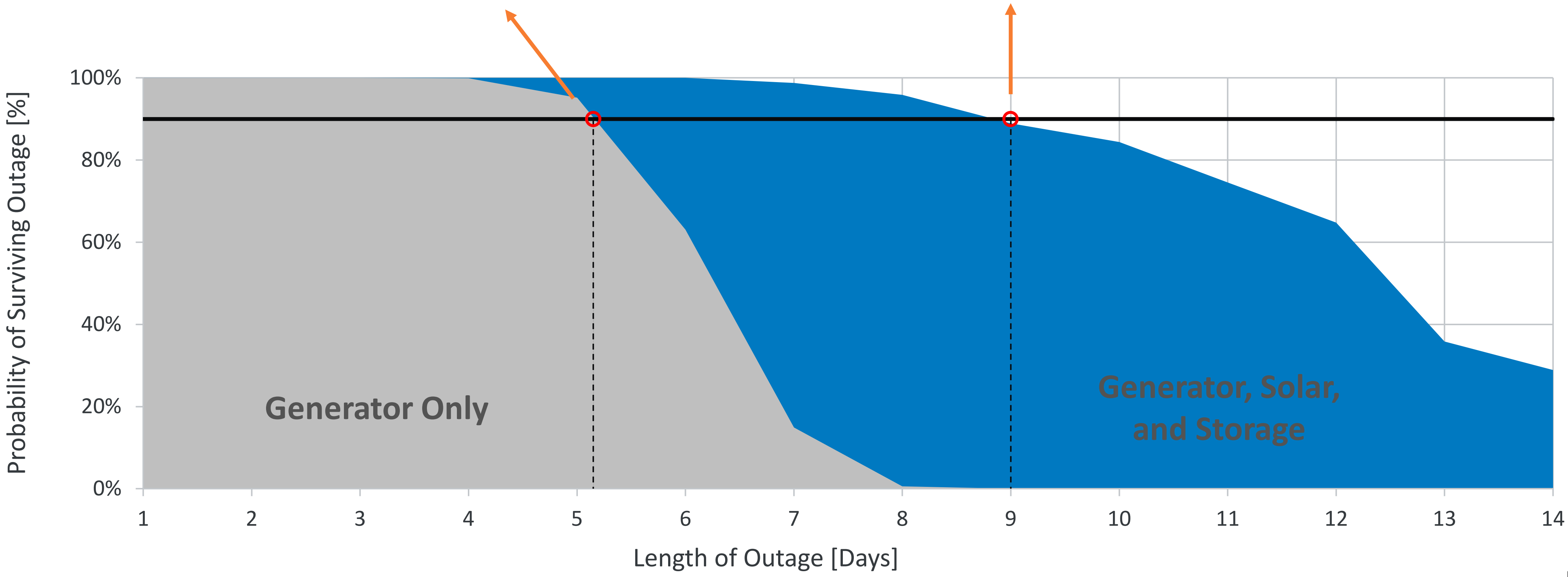
Example of optimal dispatch of PV and BESS

How Does REopt Evaluate Resilience?

REopt finds the system size and dispatch that minimizes life cycle energy costs for grid-connected operations and survives a specified grid outage. It evaluates thousands of random grid outage occurrences and durations to identify the probability of survival.

Existing generator with fixed fuel supply sustains the critical load for 5 days with 90% probability

Adding solar and storage to the existing generator increases survivability from 5 to 9 days by extending fixed diesel fuel supplies and provides utility cost savings while grid-connected.



Optimal Sizing and Dispatch at Single Site

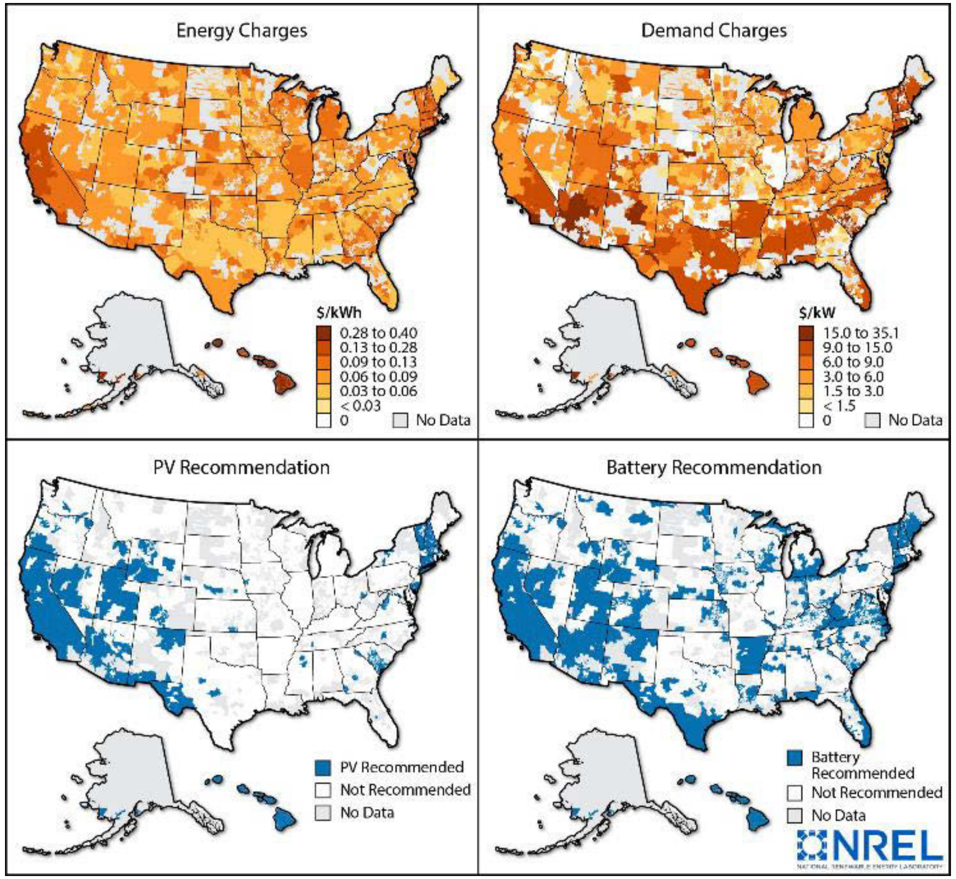
- REopt helps partners make well-informed energy investment decisions backed by credible, objective data analysis.
- Typical questions from clients include:
  - How should RE and storage be sized and dispatched to minimize site energy costs?
  - What is the value (or net present value) of a project?
  - How should I dispatch my battery to maximize the value across multiple value streams? During an outage?
  - What technologies will sustain my critical load during an outage at lowest cost?
  - What is the optimal mix and size of technologies to meet a renewable energy goal? How much will it cost?
  - How can dispatchable loads, such as smart domestic water heaters, air conditioners, water purification and treatment, electric vehicles, and storage, be used to maximize the value of RE and provide grid services?

Alcatraz PV-battery-diesel hybrid system completed in 2012. NREL provided technical assistance to optimize the dispatch.

Ft. Carson 4.25 MW/8.5 MWh peak-shaving Li-ion BESS completed in 2019. NREL provided technical assistance to validate the $0.5 million/year savings.

Project Economics at National Scale

- REopt enables national-scale analysis of renewable energy (RE) and storage economics and impacts on deployment
- Analysis questions include:
  - Where in the country is storage and photovoltaics (PV) currently cost-effective?
  - At what capital cost is storage adopted across the United States?
  - Under what conditions (utility rate, load profile, location) can RE and storage provide cost savings and resilience benefits for commercial buildings?
  - How do varying utility rates, projected costs, and incentive structures impact storage profitability?
  - How do I prioritize projects across a portfolio of sites with varying energy costs and use, renewable energy resources, and land availability?



NREL explored solutions for increasing affordability of DC fast charging (DCFC) nationwide through pairing with solar, storage, and building loads.

Accessing REopt

The **REopt team** provides a suite of trusted techno-economic **decision support services** and **software** to optimize energy systems for buildings, campuses, communities, microgrids, and more.

The team also develops the publicly available REopt Lite tool, which contains a subset of REopt's features. Capabilities developed in REopt are transferred to REopt Lite based on broad use and validation, customer needs, and funding available.

REopt Decision Support Services

Allows organizations to work closely with NREL's team of experts on customized analysis, answering complex energy questions using an expanded set of internal modeling capabilities.

REopt Lite™ Software

Developed by the REopt team, the tool guides users to the most cost-effective or resilient PV, wind, and battery storage options at no cost to users. Available via web tool, application programming interface (API), and open source.

NREL. "REopt Lite Web Tool." Accessed April 22, 2020. https://reopt.nrel.gov/tool.
NREL. "REopt Lite API (Version 1)." Accessed April 22, 2020. https://developer.nrel.gov/docs/energy-optimization/reopt-v1/.
GitHub. "REopt Lite API." Accessed April 22, 2020. https://github.com/NREL/REopt_Lite_API.
NREL. "REopt Lite Web Tool: Capabilities and Features." Accessed April 22, 2020. https://www.nrel.gov/docs/fy20osti/76420.pdf.

REopt Projects and Successes

Value of Behind-the-Meter Storage at Fort Carson

Description: NREL used REopt to independently verify the predicted utility savings estimated by the project developer from battery peak shaving.

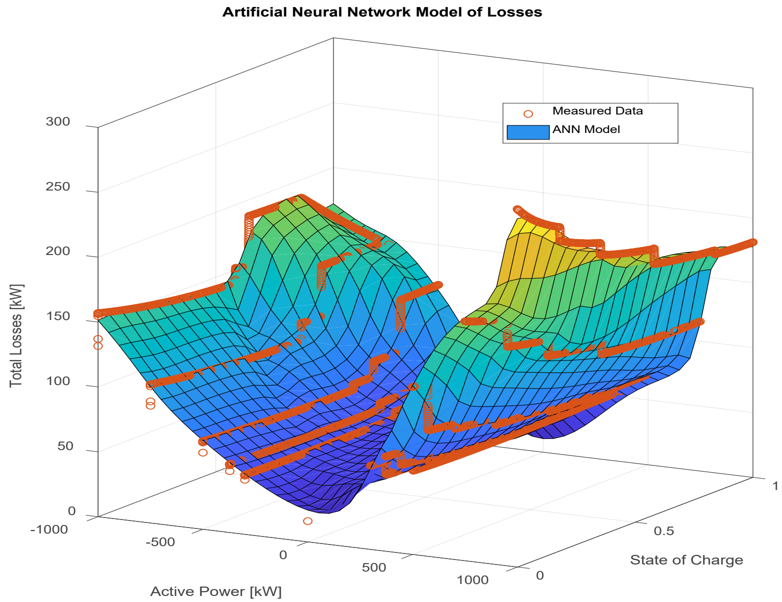
Technology: Li-ion battery storage

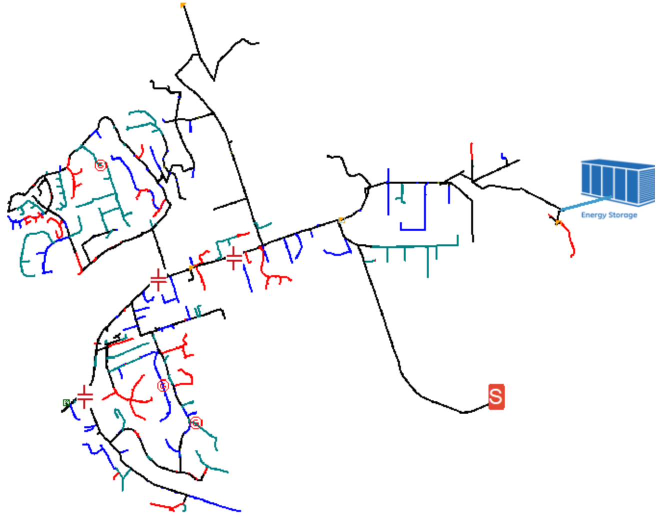
Impact: 4.2 M; 8.5-MWh battery installed at Ft. Carson under an ESPC. Largest battery in the Army at time of installation, saving Ft. Carson $500,000 per year in utility costs.

Partner: Army, AECOM

NREL. "Energy Systems Integration Newsletter: July 2019." Accessed April 22, 2020. https://www.nrel.gov/esif/esi-news-201907.html.
NREL. "NREL's REopt Helps Fort Carson Save Big." Accessed April 22, 2020. https://reopt.nrel.gov/projects/case-study-ft-carson.html.

Field Validation of Utility-Scale Storage Value Streams





Description: NREL validated the technical and economic feasibility of an emerging vanadium flow battery technology through loss modeling, characterization, and field test

Technology: High fidelity vanadium flow battery

Impact: Identified value streams through the application of utility-scale vanadium redox flow battery for local grid support use cases

Partners: Sumitomo and SDG&E

Adarsh Nagarajan et al. *Value Streams from Distribution Grid Support Using Utility-Scale Vanadium Redox Flow Battery: NREL-Sumitomo Electric Battery Demonstration Project.* Golden, CO: NREL. August 2018. https://www.nrel.gov/docs/fy18osti/71545.pdf.

Design Tradeoffs between Economics and Resilience

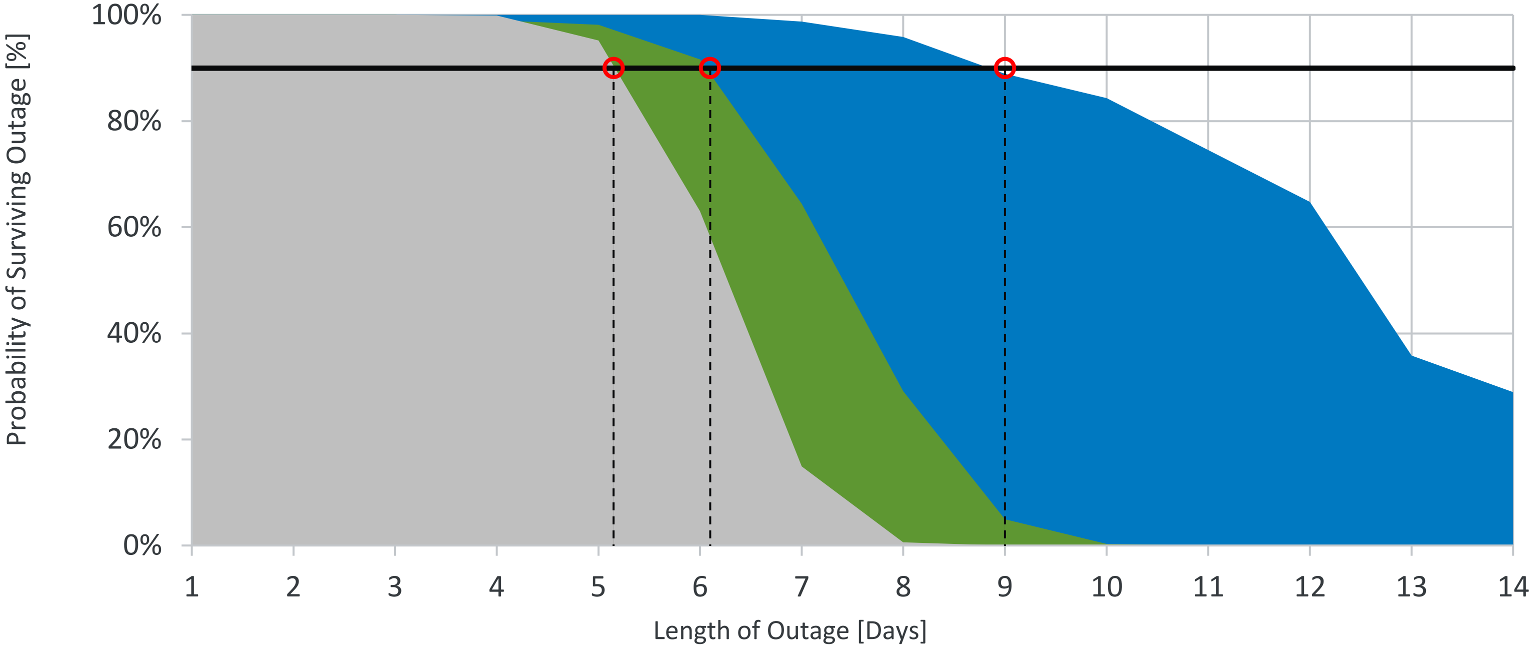
Description: NREL used REopt to evaluate how long existing and proposed backup energy systems could sustain the critical load during an outage at an Army National Guard base. REopt evaluated thousands of random grid outage occurrences and durations and compared hours survived with diesel gensets vs. gensets augmented with PV and battery.

Technology: Solar, storage, diesel generation

Impact: PV and battery can provide savings and resilience. Site can achieve 4 extra days of resilience with no added cost.

Partner: Army National Guard

	Generator	Solar PV	Storage	Lifecycle Cost	Outage
1. Base case	2.5 MW	-	-	$20 million	5 days
2. Lowest cost	2.5 MW	625 kW	175 kWh	$19.5 million	6 days
3. Proposed system	2.5 MW	2 MW	500 kWh	$20 million	9 days



Kate Anderson et al. *Increasing Resiliency Through Renewable Energy Microgrids*. Exton, PA: Journal of Energy Management. August 2017. https://www.nrel.gov/docs/fy17osti/69034.pdf.

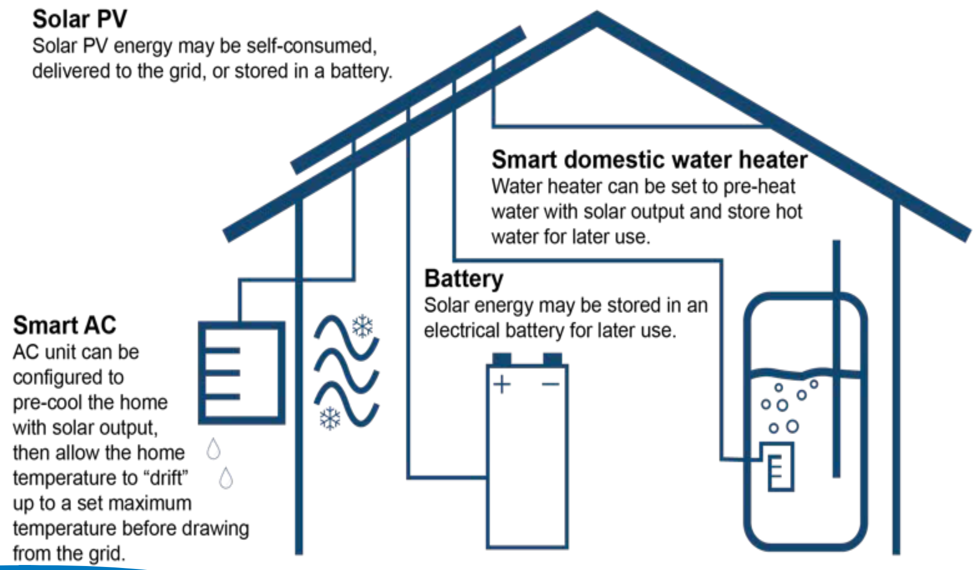
Aligning Generation and Load With Storage and Demand Flexibility

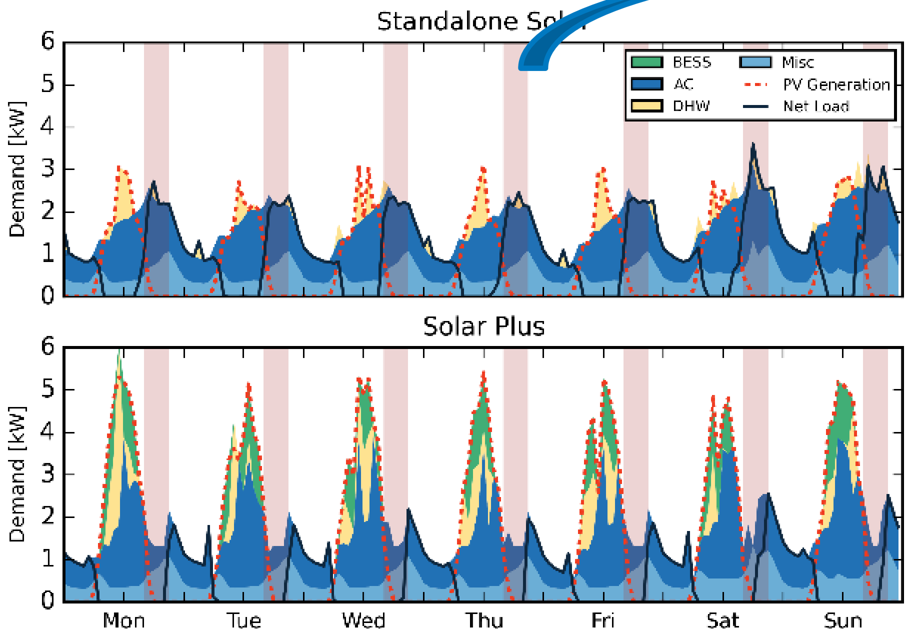
Description: NREL evaluated controllable load and storage options to improve customer economics of solar under post-net metering utility tariffs.

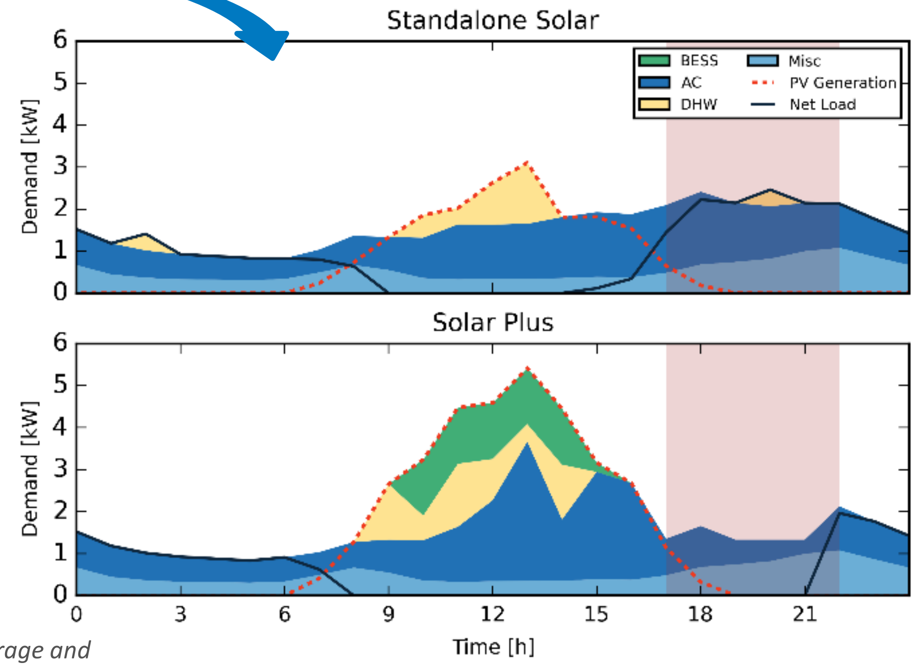
Technology: Solar, storage, buildings

Impact: Flexible loads increase the value of solar by aligning generation to load to maximize value.

Partner: DOE Solar







O'Shaughnessy, Eric, Dylan Cutler, Kristen Ardani, Robert Margolis. *Solar Plus: Optimization of Distributed Solar PV through Battery Storage and Dispatchable Load in Residential Buildings*. United Kingdom: Applied Energy, March 2018. https://doi.org/10.1016/j.apenergy.2017.12.118.

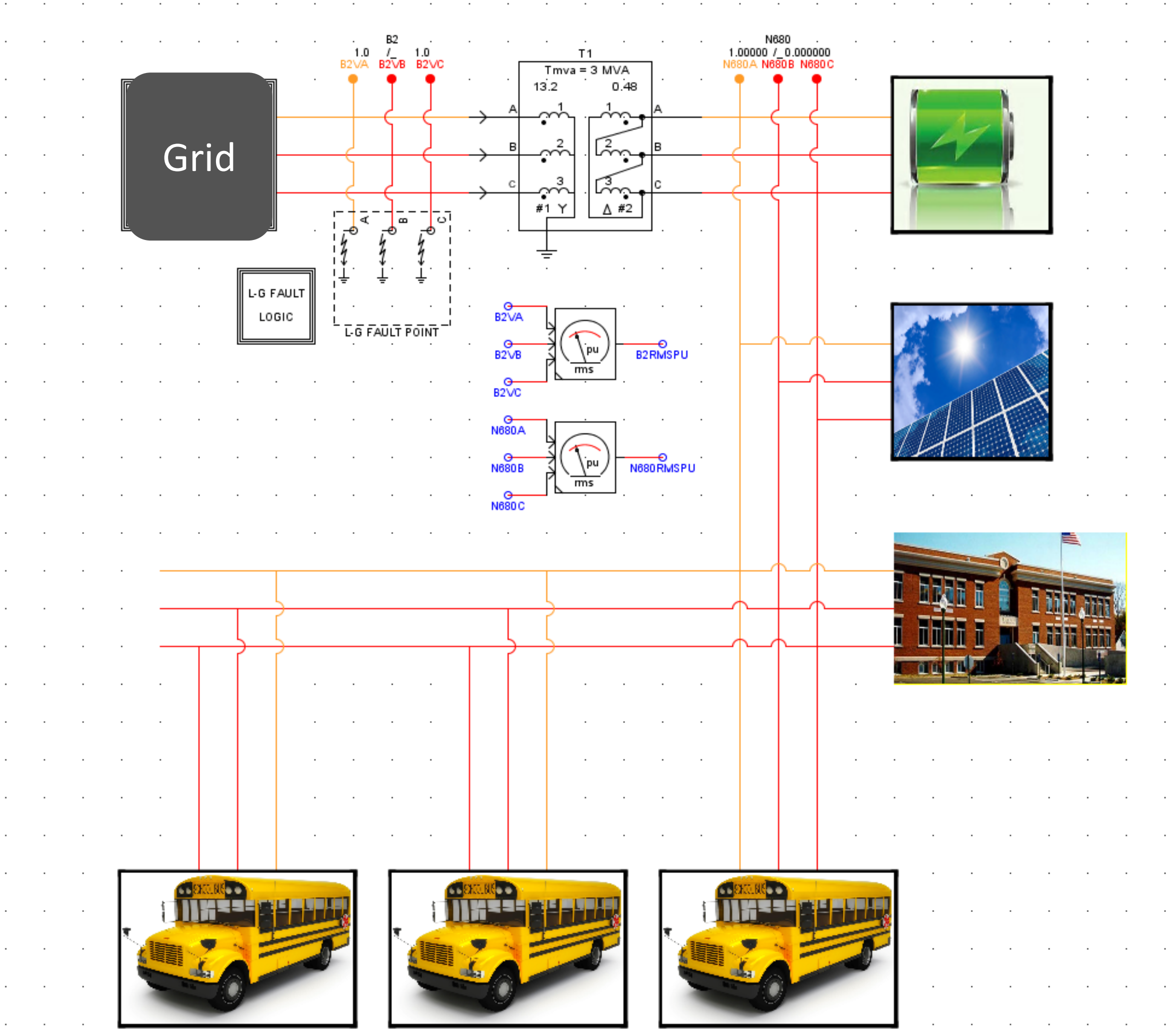
Integrating EV Fleets With DER and Grid

Description: NREL evaluated opportunities for synergistic integration and control of electrified transportation fleets with flexible buildings loads, RE, and stationary storage.

Technologies: Mobility, storage, buildings, solar, advanced system integration controls

Impact: Demonstrated optimal control of integrated RE, building loads, storage, and EV system in laboratory testing. Integrated system provided increased value to the site owner.

Partners: Eaton (funding partner), Holy Cross Energy, SDG&E, Duke Energy, UPS, EPRI



William Becker et al. *Cost Reduction of School Bus Fleet Electrification With Optimized Charging and Distributed Energy Resources*. Wichita, KS: North American Power Symposium. October 13–15, 2019. https://www.nrel.gov/docs/fy20osti/74187.pdf.

Additional Information

REopt Technical Description

REopt Development Team

REopt Model Technical Description

Mixed Integer Linear Program

- Mathematical model written in the MOSEL programming language solved using commercial FICO Xpress solver
- Analysis typically requires significant site-specific and client-requested customizations

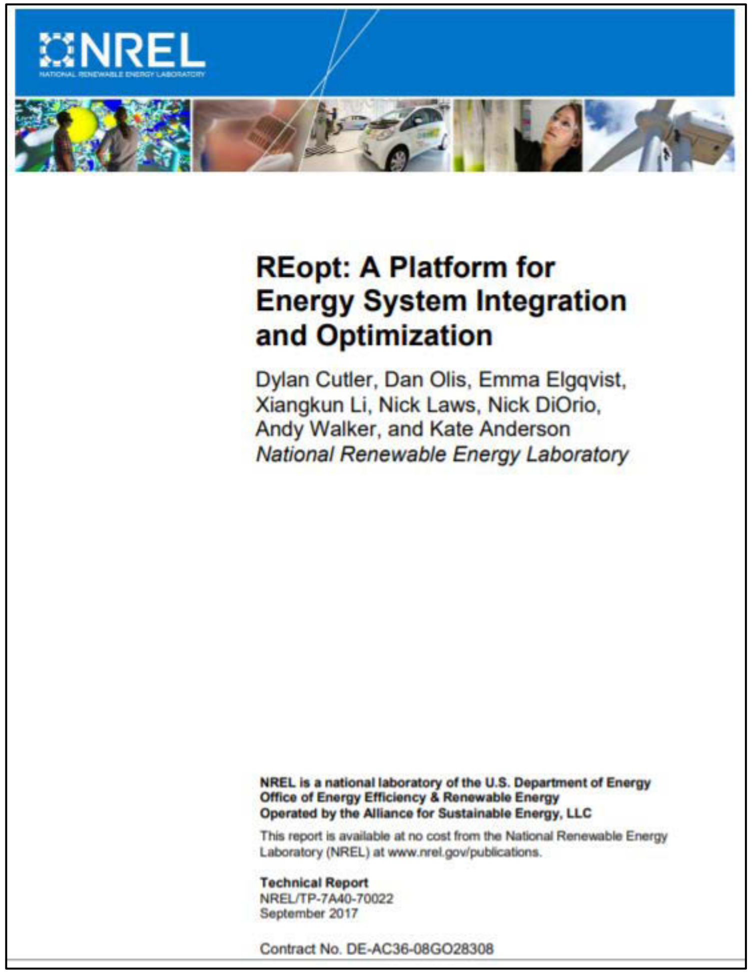
Solves energy balance at every time step for entire year (typically 15-minute or hourly interval)

- Load must be met from some combination of grid purchases, on-site generation, or discharge from storage
- Typically does not consider power flow or transient effects
- Has perfect prediction of upcoming weather and load
- Assumes all years in analysis horizon are the same (typically 25 years)

Technology modules based on empirical operating data

Finds optimal technology sizes (possibly 0) and optimal dispatch strategy subject to resource, operating, and goal constraints

- Objective function is to minimize life-cycle cost of energy
- Resulting life cycle cost is **guaranteed optimal** to within a known gap (typically 0.01%) subject to modeling assumptions



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REopt: A Platform for Energy System Integration and Optimization

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National Renewable Energy Laboratory

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More REopt Projects

Storage Sizing and Operation

Resilience and Microgrids

Integration of Flexible Loads

Electric Vehicles

Portfolio Optimization

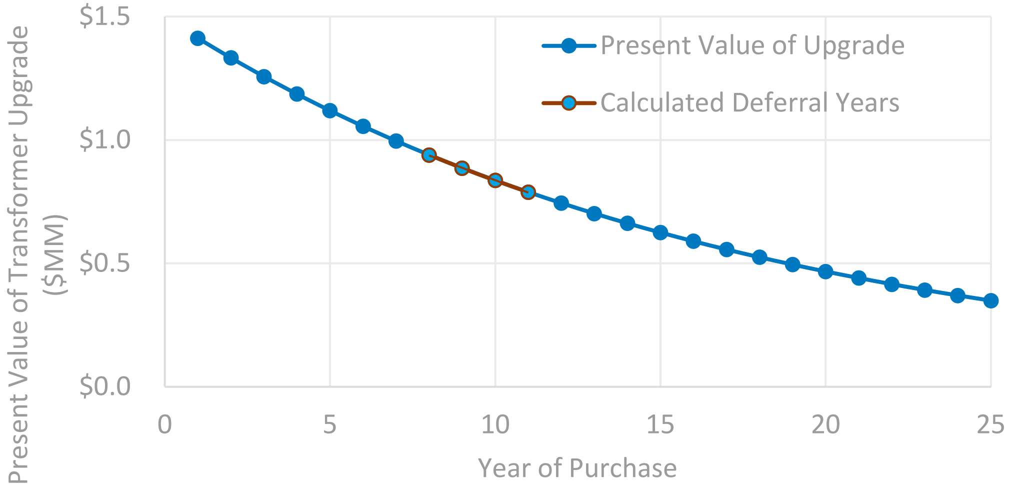
Market Participation Strategy for SDG&E Utility Storage

Description: NREL optimized the dispatch of a battery on a San Diego Gas & Electric (SDG&E) feeder with high-PV penetration across multiple value streams (locational marginal price [LMP] arbitrage, frequency regulation, grid support functions).

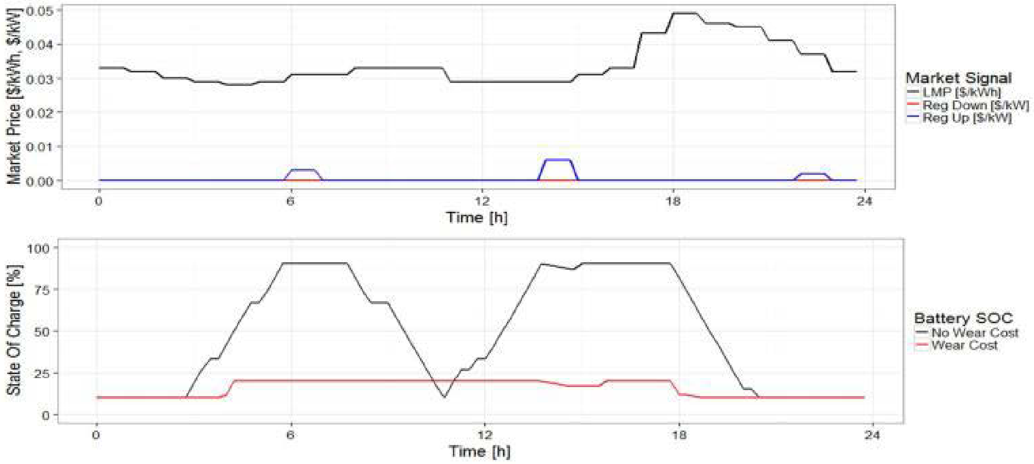
Technology: Li-ion battery

Impact: Informed battery market participation strategy to maximize value for SDG&E

Partners: SDG&E



NREL assessed the value the battery provided by enabling deferral of a transformer upgrade through peak shaving on the feeder



Battery market participation strategy: Incorporating degradation into the model changes optimal wholesale market dispatch

Murali Baggu et al. *Coordinated Optimization of Multiservice Dispatch for Energy Storage Systems with Degradation Model for Utility Applications*. Piscataway, NJ: IEEE Transactions on Sustainable Energy. April 2019. https://doi.org/10.1109/TSTE.2018.2853673.

PV+Battery Dispatch for Municipal Utility in PJM

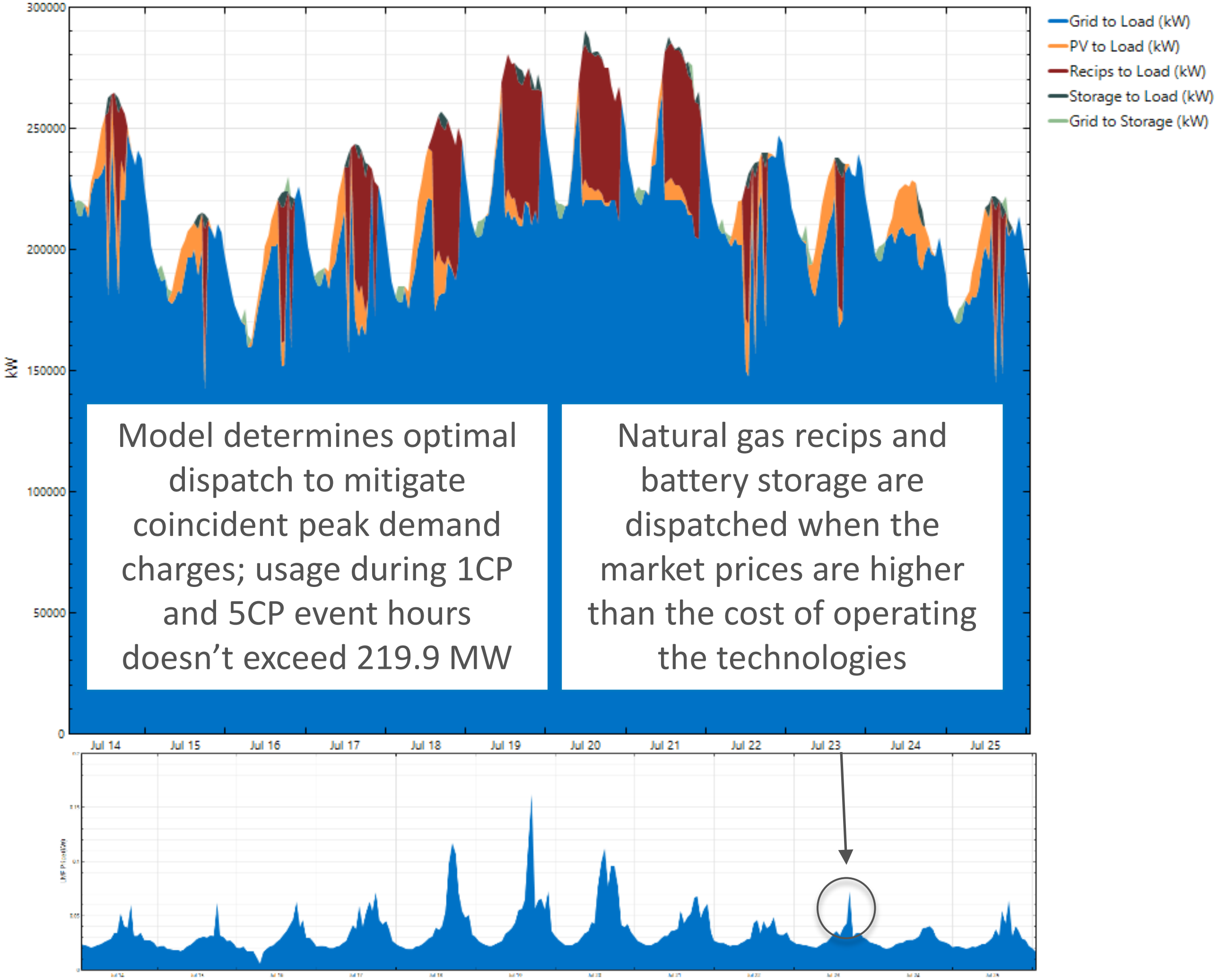
Description: NREL used REopt to determine the optimal dispatch to mitigate coincident peak demand charges.

Technology: Natural gas reciprocating engines and battery storage

Impact: Identified potential for $171 million in savings, including:

- **92.8-GWh** reduction in annual market purchases ($79.6 MM)
- **53.6-MW** reduction in 1 CP demand charges ($39.1 MM)
- **61.2-MW** reduction in 5 CP demand charges ($51.8 MM)

Partner: Utility in PJM



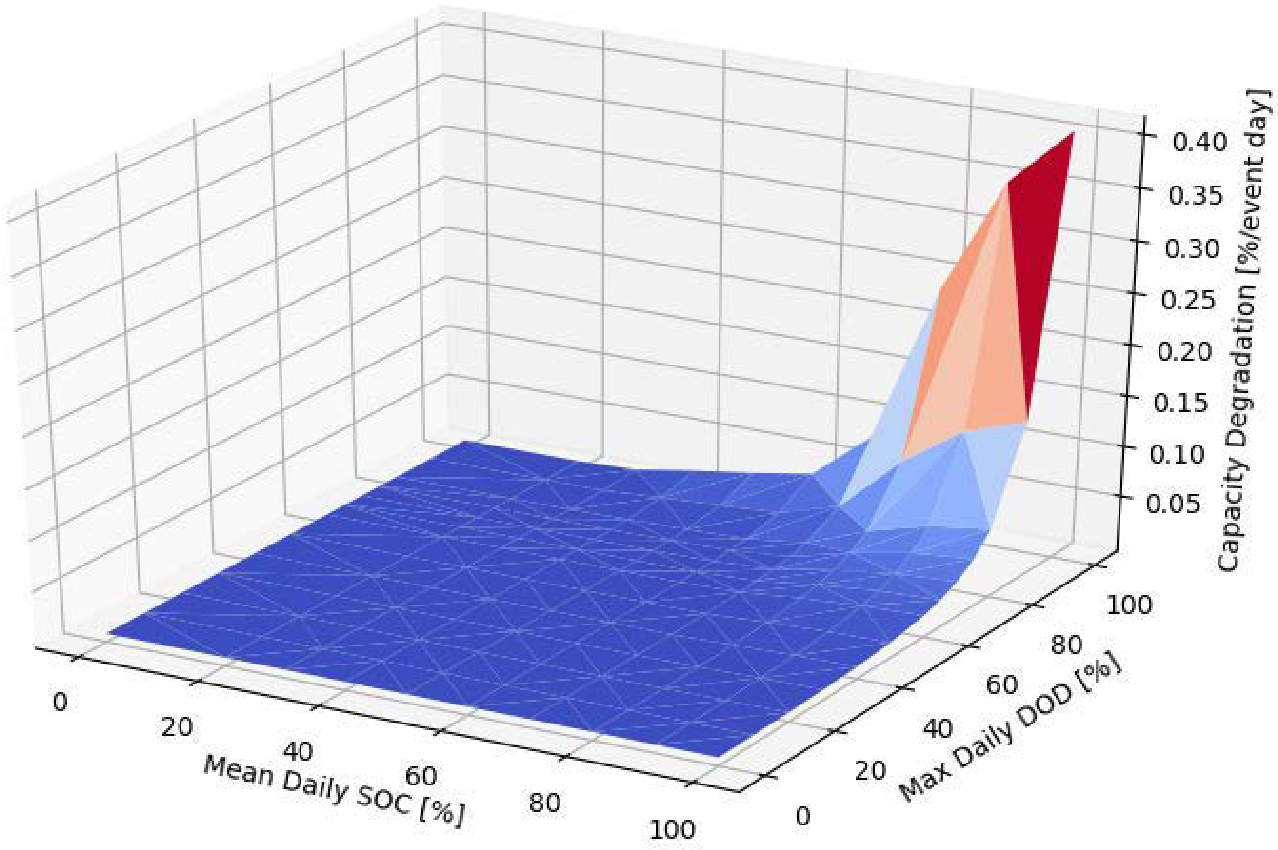
Health-Conscious Battery Economics

Description: NREL evaluated the economic impact of health-conscious battery controls that consider the trade-off between operational value and degradation cost.

Technology: Storage

Impact: Evaluated battery sizing and operational decisions considering degradation impacts. Findings are being validated through battery pack testing at NREL and will then be integrated into Eaton controls approaches.

Partner: Eaton



Degradation increases with maximum depth of discharge and high mean state of charge

Evaluating Centralized vs. De-centralized Microgrid Options for Military Installations

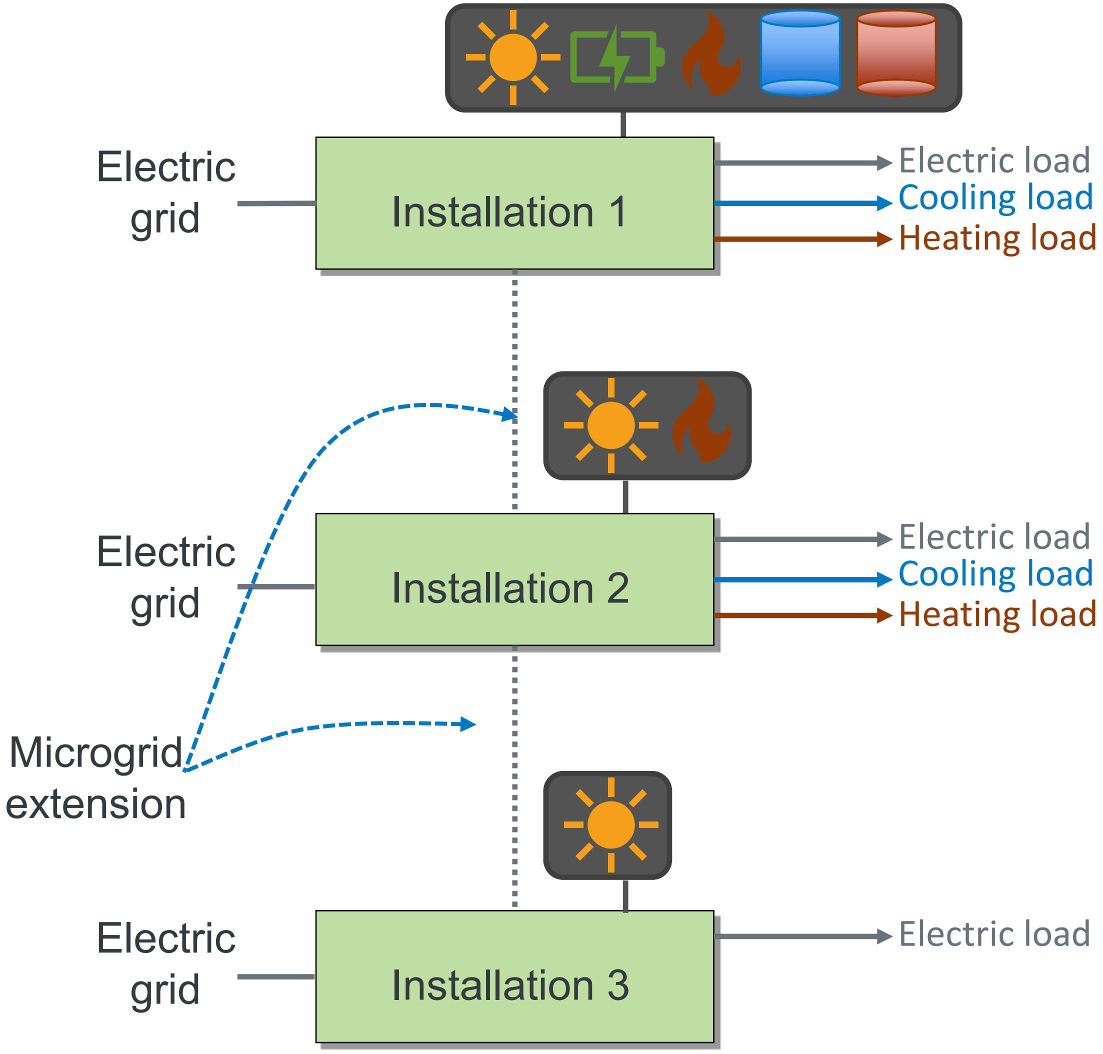
Description: NREL performed an integrated microgrid feasibility analysis for three U.S. military installations to support U.S. Army energy resilience requirements.

Technologies: Solar PV, battery storage, combined heat and power (CHP), chillers (adsorption and centrifugal), hot- and cold-water thermal storage, microgrid components

Impact: Developed conceptual design and cost estimate for integrated microgrids to provide energy cost savings and resilience across the three international U.S. military installations.

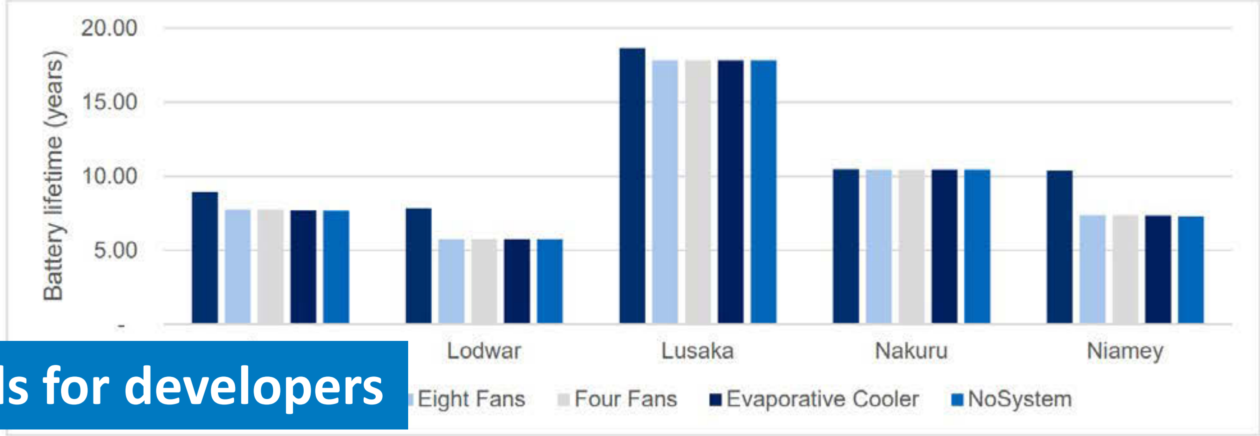
- Addressed electric vs. heat and resiliency vs. cost prioritization for CHP operation
- Resulted in successful RFP for optimized microgrid design.

Partners: United States Army Garrison Italy



NREL. "REopt Identifies and Evaluates Microgrid Options for the U.S. Army Garrison Italy." Accessed April 22, 2020. https://reopt.nrel.gov/projects/case-study-usag-italy.html.

Microgrids for Rural Energy Access In Africa



Description: NREL used REopt to optimize microgrid designs for systems across sub-Saharan Africa, analyzing the impact of cost trends, technology choices, business models, and regulatory structures to identify least-cost pathways to rural electrification

Technology: PV, li-ion and lead-acid batteries, diesel generation

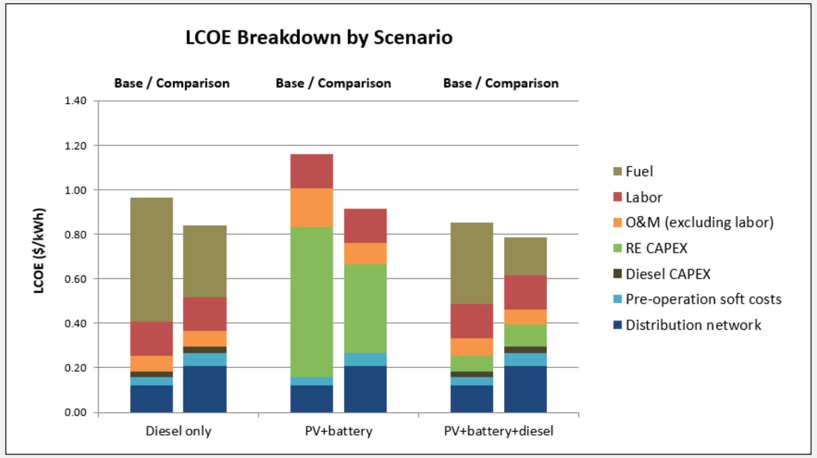
Impact: Informed rural microgrid design decisions and government policies around energy access goals

Partners: USAID, AMDA, individual microgrid developers, national governments in sub-Saharan Africa

Tools for developers

Inputs	Base Case	Comparison
Geographical region	Lodwar, Kenya	Lusaka, Zambia
Load profile	NREL average	Business heavy
Percent of load served	100%	85%
Discount rate	10%	20%
PV/Battery Costs	High	Low
Diesel Generator Costs	Medium	Medium
Diesel Fuel Price	$4.40	$3.20
Total distribution system costs	Default	Default
Pre-operating soft costs ($/kW)	Default	Default
Annual labor costs	Default	Default
Annual land lease costs	Default	Default

Assumptions		
Length of analysis	20 years	20 years
Average solar resource (GHI)	6.1 kWh/m2/day	5.3 kWh/m2/day
Installed PV cost [$/kW]	$2,200	$1,400
PV O&M [$/kW]	$44	$28
Useful life	20 years	20 years
Battery storage cost [$/kWh]	$500	$300
Battery useful life	7 years	7 years
Inverter and BOS costs [$/kW]	$1,200	$600
Inverter replacement cost [$/kW]	$600	$300
Battery O&M [$/kWh-installed]	$30	$20
Inverter useful life	10 years	10 years
Diesel genset cost [$/kW]	$400	$400
Useful life	10 years	10 years
Fuel consumption rate [kWh/gal]	10	10
Fuel cost [$/gallon]	$4.40	$3.20
Fuel escalation rate	3%	3%
Total distribution system costs	$20,000	$20,000
Pre-operating soft costs [$/kW]	$1,200	$1,200
Annual labor costs [$/year]	$3,000	$3,000
Annual land lease costs [$/year]	$800	$800



RESULTS SUMMARY	Base case			Comparison		
	Diesel only	**PV+battery**	**PV+battery+diesel**	**Diesel only**	**PV+battery**	**PV+battery+diesel**
PV size	0 kW	27.9 kW	5.5 kW	0 kW	16.8 kW	6.7 kW
Battery size	0 kWh	49 kWh	0 kWh	0 kWh	30.1 kWh	0 kWh
Inverter size	0 kW	5.7 kW	0 kW	0 kW	4 kW	0 kW
Diesel generator size	7 kW	0 kW	7 kW	6 kW	0 kW	6 kW
Total life-cycle cost	$161,800	$194,595	$143,244	$80,557	$87,700	$75,329
Total CAPEX	$30,732	$139,283	$42,898	$28,500	$63,976	$37,881
Total OPEX	$131,068	$55,313	$100,346	$52,057	$23,724	$37,447
LCOE	**$0.96**	**$1.16**	**$0.85**	**$0.84**	**$0.91**	**$0.78**

Eric Lockhart et al. *Comparative Study of Techno-Economics of Lithium-Ion and Lead-Acid Batteries in Micro-Grids in Sub-Saharan Africa*. Golden, CO: NREL. June 2019. https://www.nrel.gov/docs/fy19osti/73238.pdf.

Tim Reber et al. *Tariff Considerations for Micro-Grids in Sub-Saharan Africa*. Golden, CO: NREL. February 2018. https://www.nrel.gov/docs/fy18osti/69044.pdf.

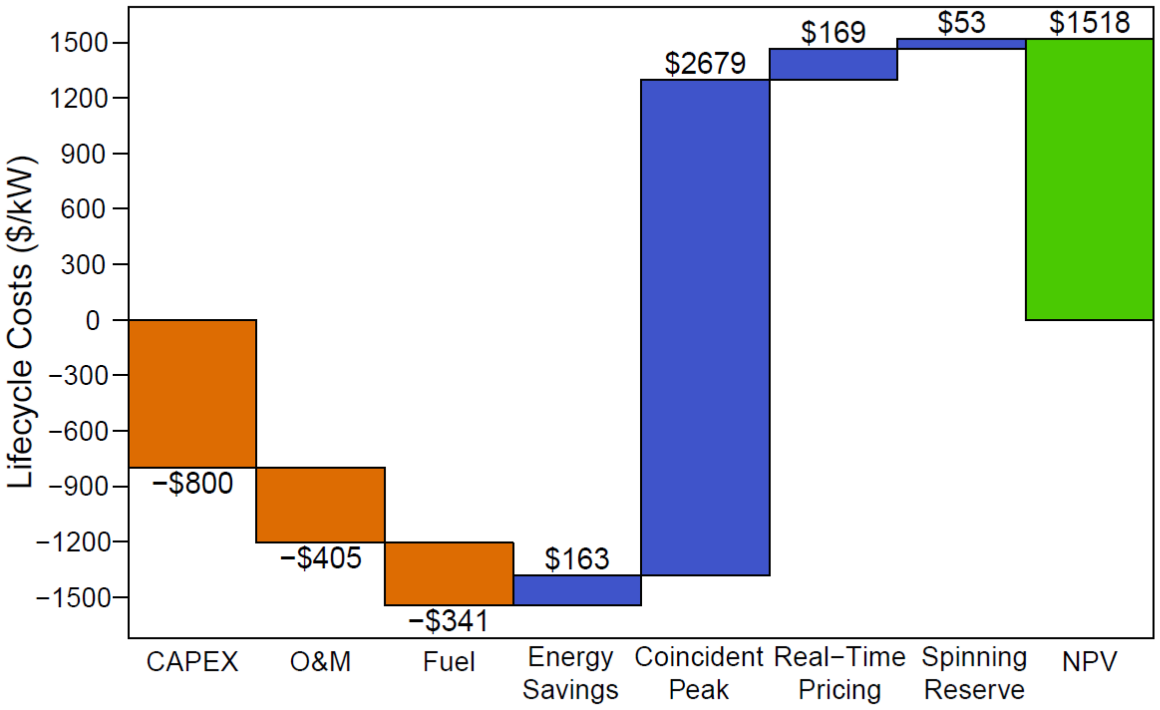
Market Revenues for Backup Generators

Description: NREL evaluated the value backup generators can provide when used for grid-connected economic dispatch. NREL considered potential revenues from tariff switching, peak shaving, energy self-generation, coincident peak reduction, wholesale real-time pricing, spinning reserve markets, and emergency standby programs.

Technology: Natural gas and diesel generators

Impact: The overall cost of back-up generation can be lowered, but opportunities vary across the United States, depending on markets.

Partner: Enchanted Rock



Life cycle costs and revenues ($/kW) for diesel generator providing grid services in Camden, NJ

Generator Type	Diesel			Natural Gas		
Region	TX	FL	NJ	TX	FL	NJ
CAPEX + O&M ($/kW)	-$1,205			-$1,405		
Revenues/savings ($kW)	$968	$1,380	$3,064	$1,091	$1,380	$3,153
Fuel cost for ($/kW)	-$187	$0	-$341	-$199	$0	-$272
NPV ($/kW)	-$425	$175	$1,518	-$513	-$25	$1,476

Net present values by region and by fuel type

Ericson, Sean and Dan Olis. *A Comparison of Fuel Choice for Backup Generators*. Golden, CO: NREL. March 2019. https://www.nrel.gov/docs/fy19osti/72509.pdf

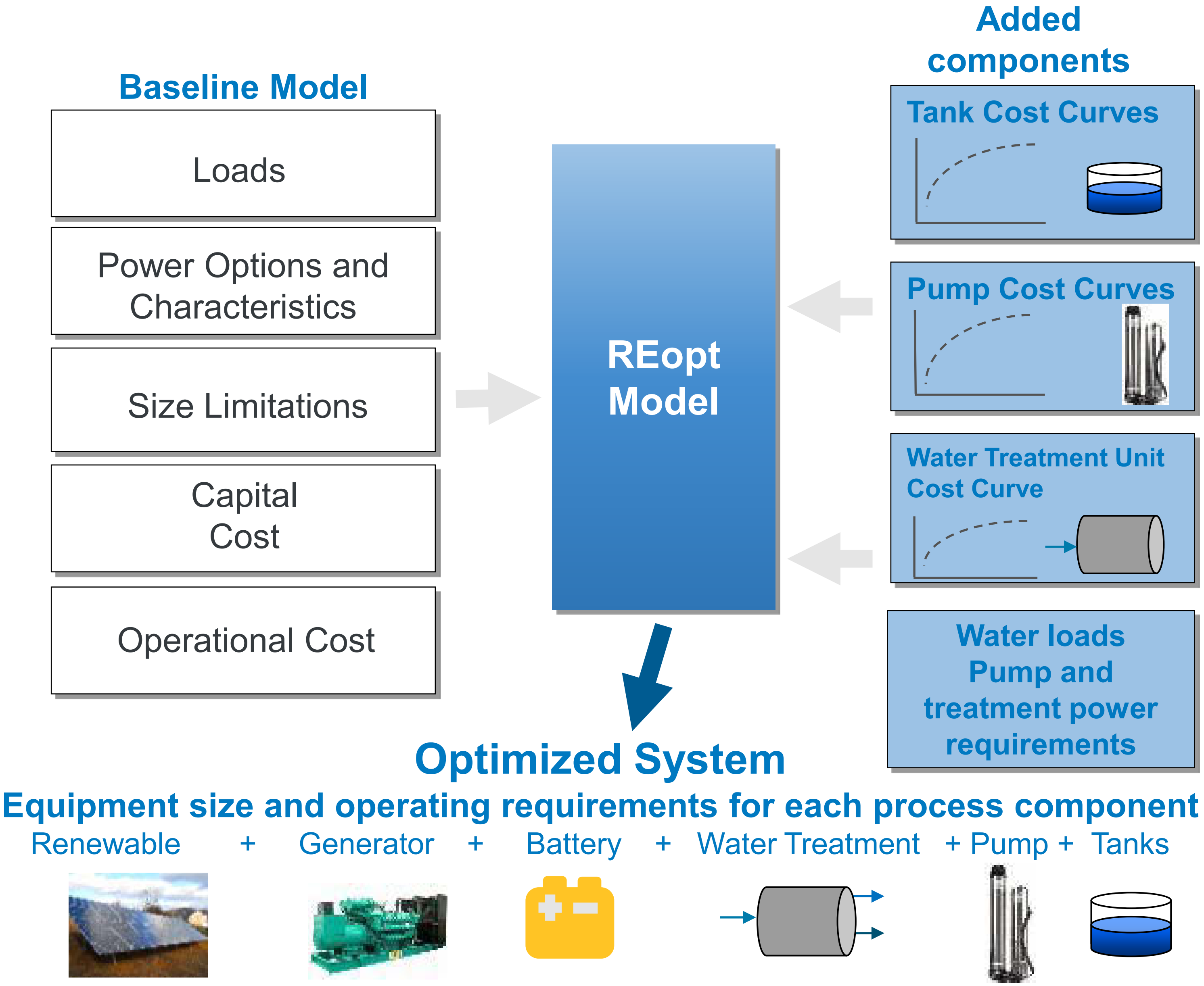
Optimizing Off-Grid Water Treatment and Storage

Description: NREL optimized an off-grid water treatment and storage system on Navajo lands.

Technologies: PV, diesel generator, storage, water treatment and storage

Impact: Identified opportunities to reduce battery size and fuel use by flexing pumping loads and using storage inherent in water tank.

Partner: U.S. Bureau of Reclamation



NREL. "REopt Modeling Informs Design of Off-Grid Water System Under Study for Navajo Nation." Accessed April 22, 2020. https://reopt.nrel.gov/projects/case-study-usbr.html.

DC Fast Charging Station Design

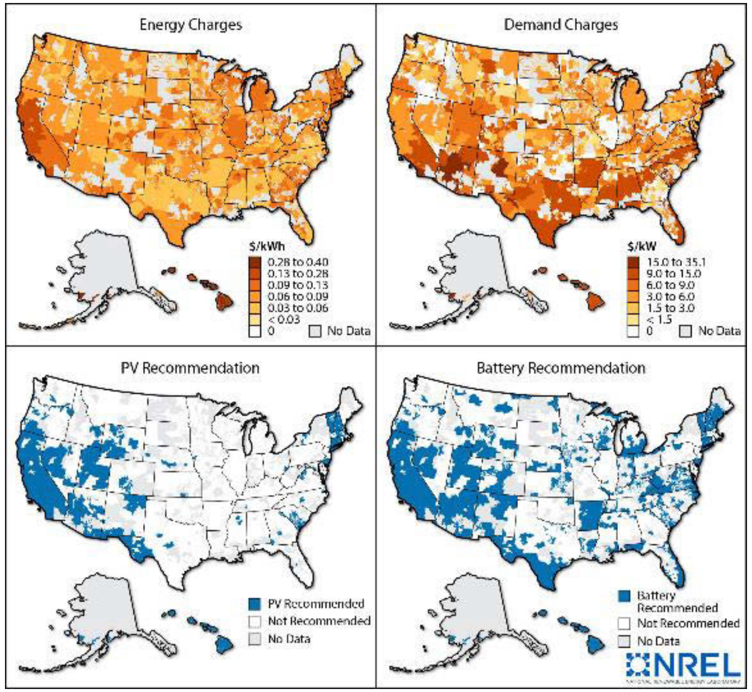
Description: NREL explored solutions that can help make DC fast charging (DCFC) more affordable for EV drivers in the United States:

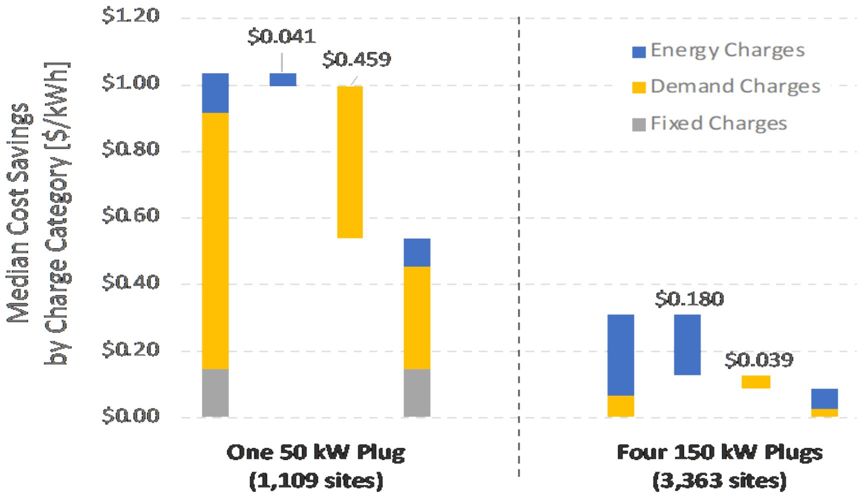
- Solar PV and/or energy storage (batteries)
- Co-locating DCFC with a commercial building

Technologies: DCFC, solar, battery storage

Impact: Found 11%–40% of sites can reduce lifetime electricity cost by installing technologies. Co-location often economically preferable but relative savings diminish as load increases.

Partners: DOE Vehicle Technologies Office





Matteo Muratori et al. *Technology solutions to mitigate electricity cost for electric vehicle DC fast charging.* United Kingdom: Applied Energy, May 2019. https://doi.org/10.1016/j.apenergy.2019.03.061.

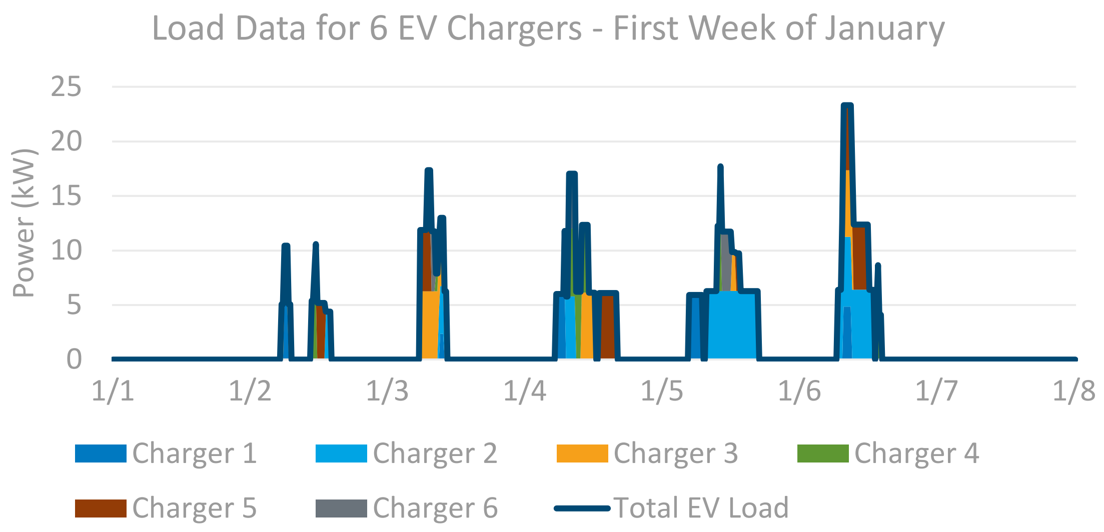
Impact of EV Workplace Charging in Minnesota

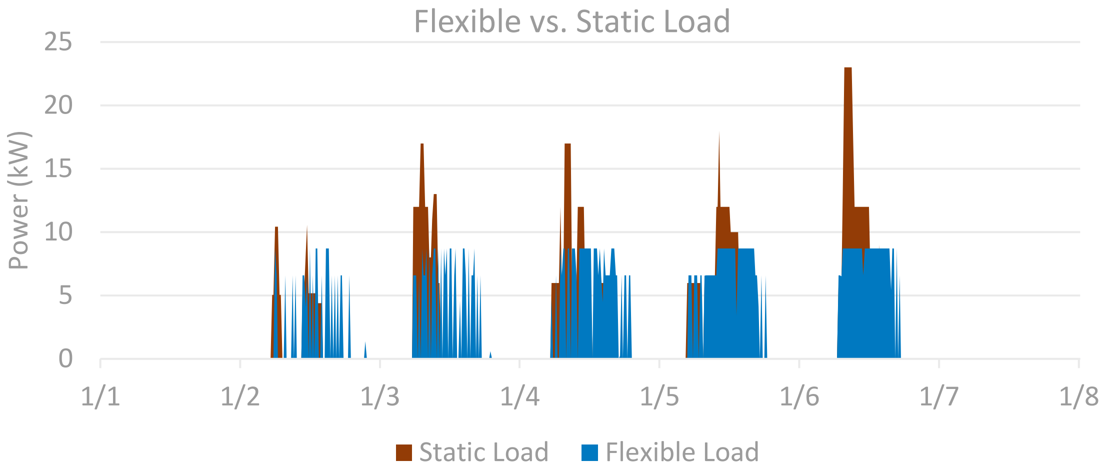
Description: NREL used REopt to evaluate the economics of workplace EV charging. NREL's EVI-Pro database used to generate static and flexible EV load profiles.

Technology: EVs, PV, storage

Impact: Found savings from adding PV and storage to EV charging infrastructure and/or flexibility in EV charging times.

Partner: City of Minneapolis





Elgqvist, Emma and Josiah Pohl. *Evaluating Utility Costs Savings for EV Charging Infrastructure*. Golden, CO: NREL. November 2019. https://www.nrel.gov/docs/fy20osti/75269.pdf.

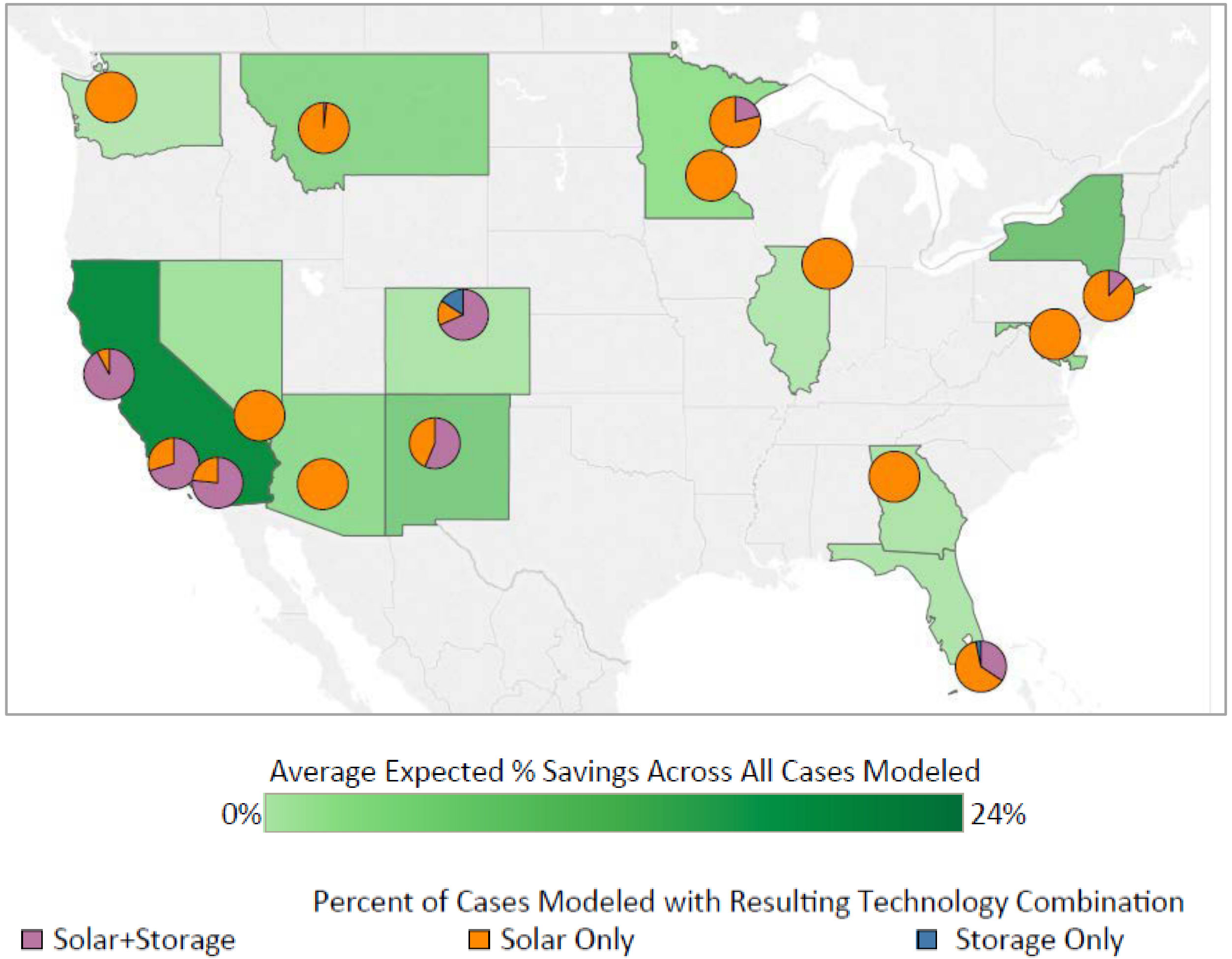
National Economic Analysis of Behind-the-Meter Storage

Description: Analyzed behind-the-meter solar and storage economics across 16 climate zones, 16 building types, 80 utility rate tariffs, and varying technology price points

Technology: PV, storage

Impact: Identified critical factors in the cost-effectiveness of solar+storage in commercial buildings

Partner: DOE Solar Energy Technologies Office



Joyce McLaren et al. *Solar-plus-storage economics: What works where, and why?* Netherlands: Electricity Journal. January–February 2019.
https://doi.org/10.1016/j.tej.2019.01.006.

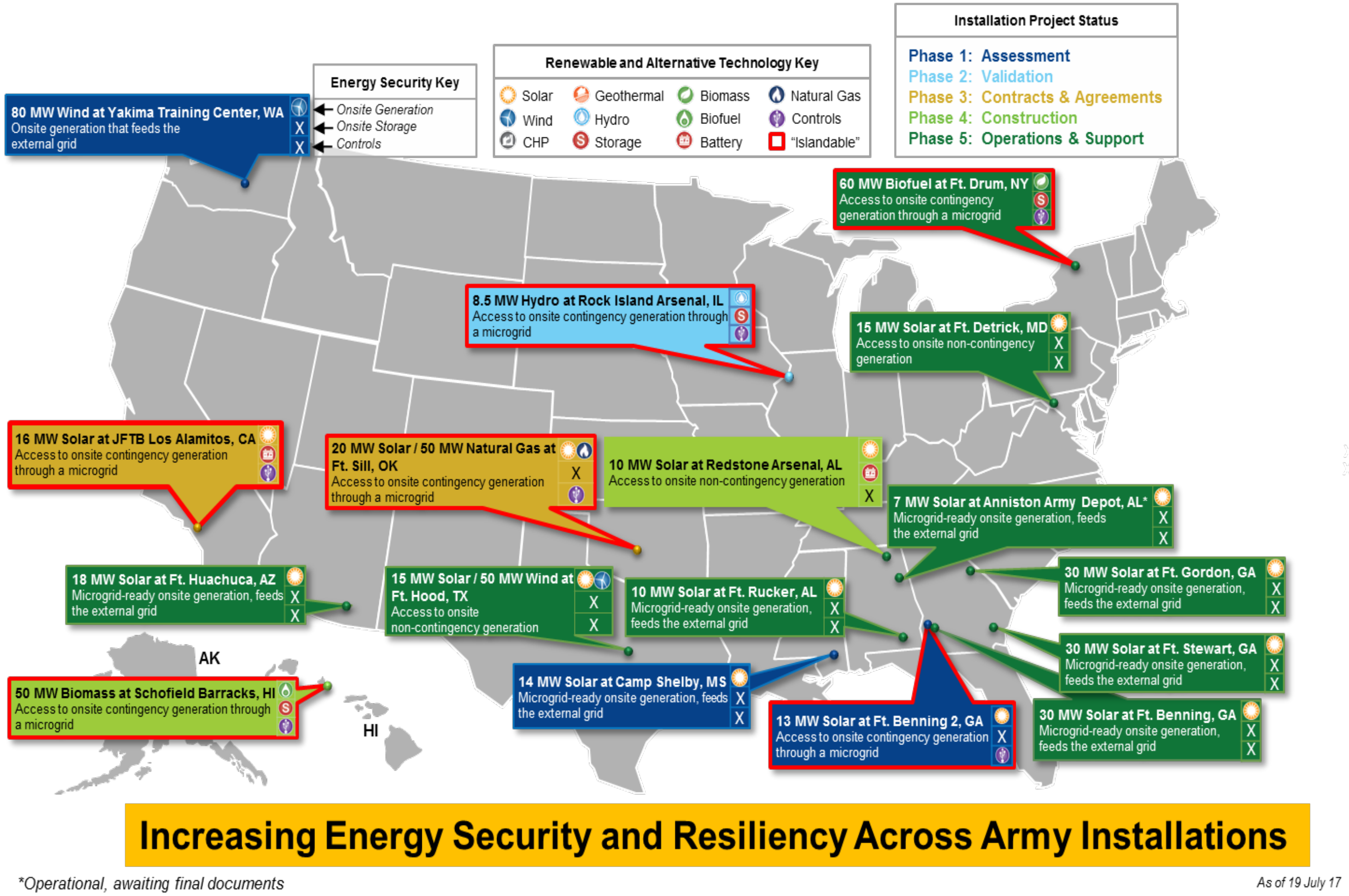
Deploying Cost-Effective Efficiency, Renewable Energy, and Storage

Description: NREL is working with the Army Office of Energy Initiatives to evaluate RE and storage projects across 100 Army bases. NREL is prioritizing technically and economically feasible projects and assisting in project development.

Technology: PV, wind, CHP, biomass, natural gas, storage, microgrids

Impact: Identifying cost-effective RE, storage, and microgrid projects to reduce Army energy cost and increase installation resilience

Partners: U.S. Army Office of Energy Initiatives



NREL. *REopt Screenings Catalyze Development of Hundreds of Megawatts of Renewable Energy for Federal Agencies.* Golden, CO: NREL. April 2017. http://www.nrel.gov/docs/fy17osti/68219.pdf.

Identifying and Prioritizing Projects Across a Portfolio

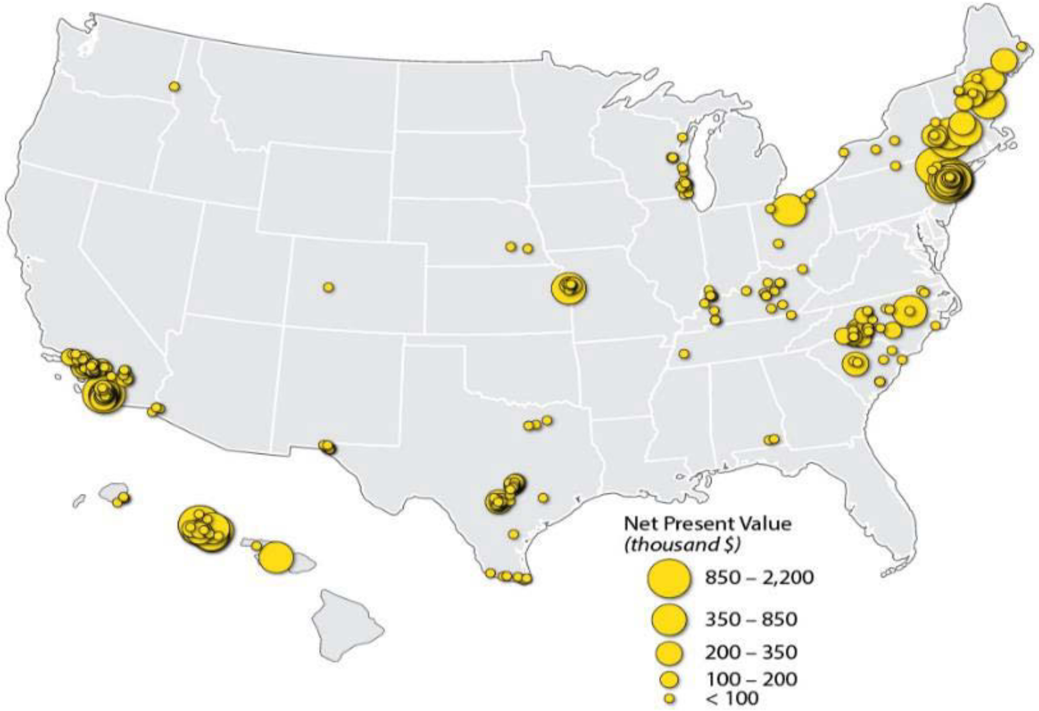
Description: NREL evaluated 700 sites for Time Warner Cable to identify and prioritize technically and economically feasible RE and storage projects and estimate the cost of meeting renewable energy goals.

Technology: PV, wind, ground-source heat pump, storage

Impact: Identified cost-effective RE and microgrid projects to meet Time Warner Cable energy goals for reduced energy use, reduced energy cost, and increased resilience.

Partners: Time Warner Cable, Inc.

Economically viable PV projects across TWC portfolio



Sites Evaluated	696
Sites with Cost-Effective PV	306
Size	38.79 MW
NPV	$37 million

Allison Richards et al. 2016. *Portfolio Analysis of Renewable Energy Opportunities*. Philadelphia PA: SCTE/ISBE Cable-Tec Expo. September 26–29, 2016. https://www.nrel.gov/docs/fy17osti/67281.pdf.