REopt: Energy Decision Analysis

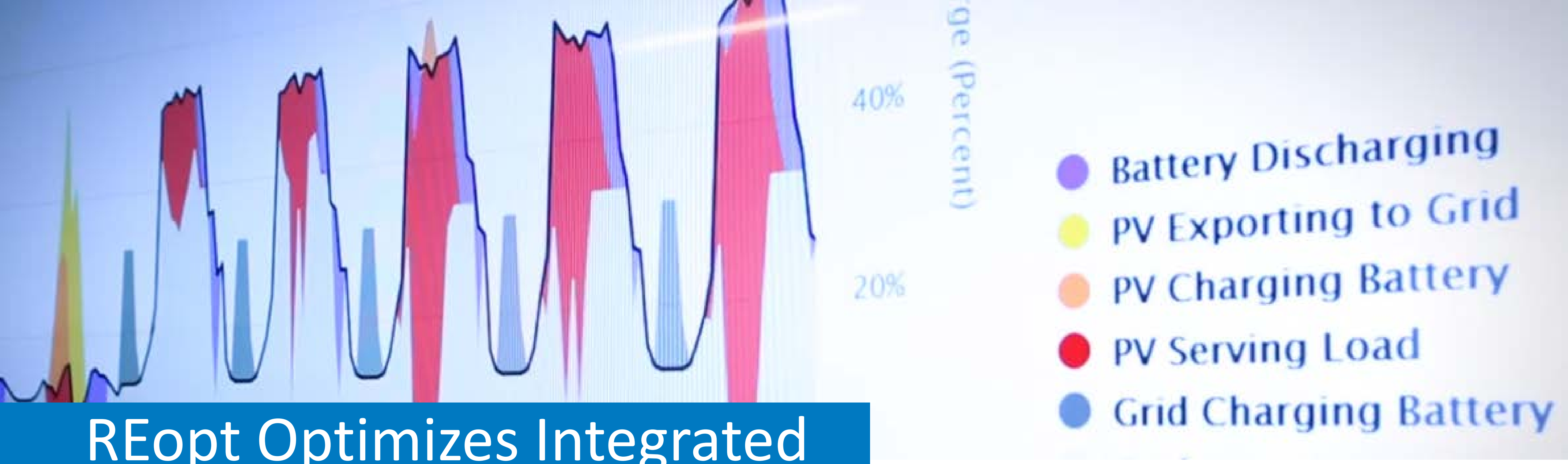
NREL REopt Team

reopt.nrel.gov

Contents

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.
- Distributed energy technologies can provide cost savings, resilience, and emissions reduction.
- 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.
- REopt considers electrical, heating, and cooling loads and technologies simultaneously to identify the optimal technology or mix of technologies.
- It transforms complex decisions into actionable results for building owners, utilities, developers, and industry.
- REopt analysis guides investment in economic, resilient, sustainable energy technologies.

Will Distributed Energy Resources (DERs) Work for Your Site?

Renewable Energy Resource

Technology Costs and Incentives

Site Goals

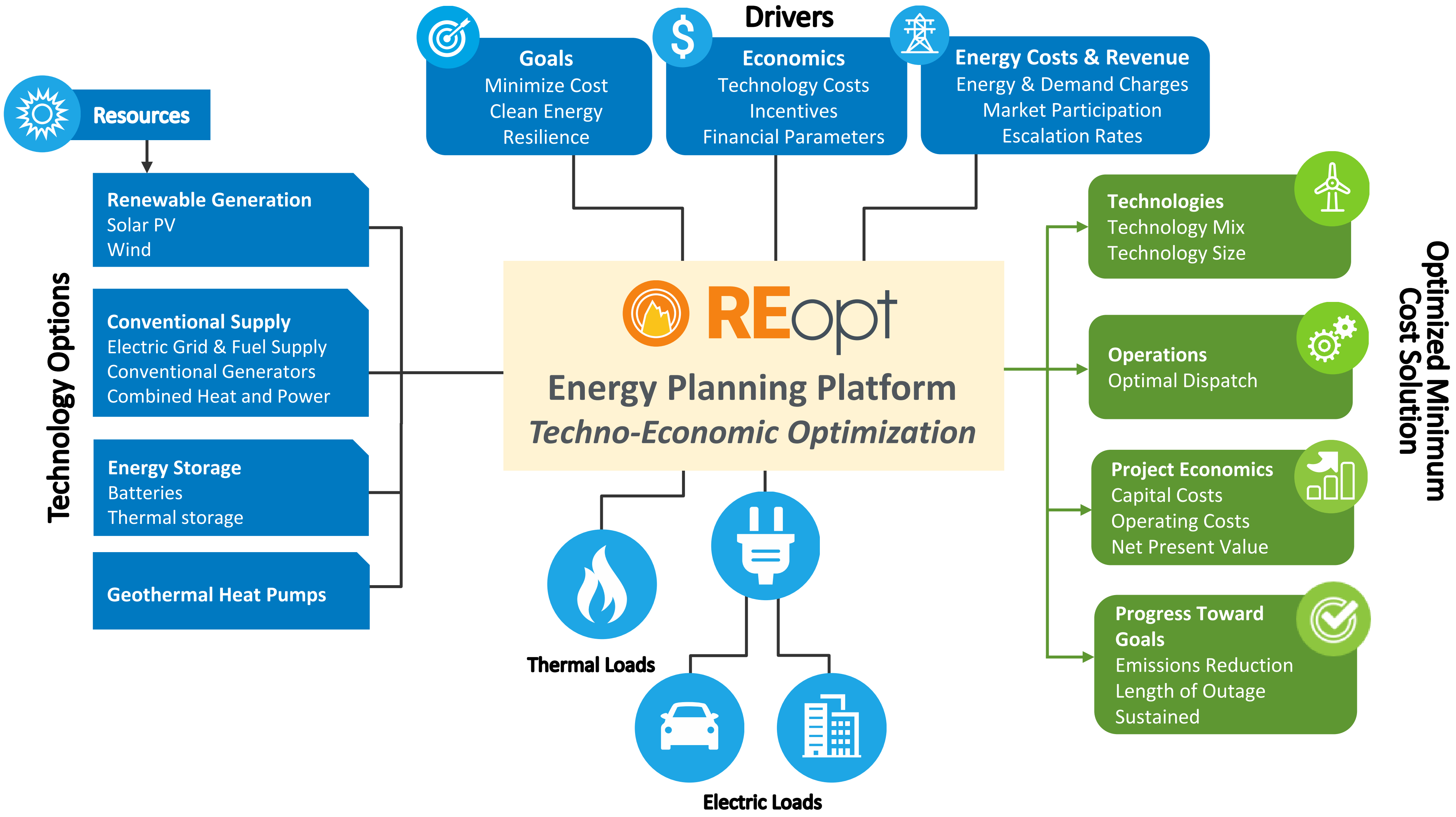
Utility Cost and Consumption

Financial Parameters

Many factors affect whether distributed energy technologies can provide cost savings and resilience to your site, and they must be evaluated concurrently.

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 DERs to minimize my cost of energy?

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

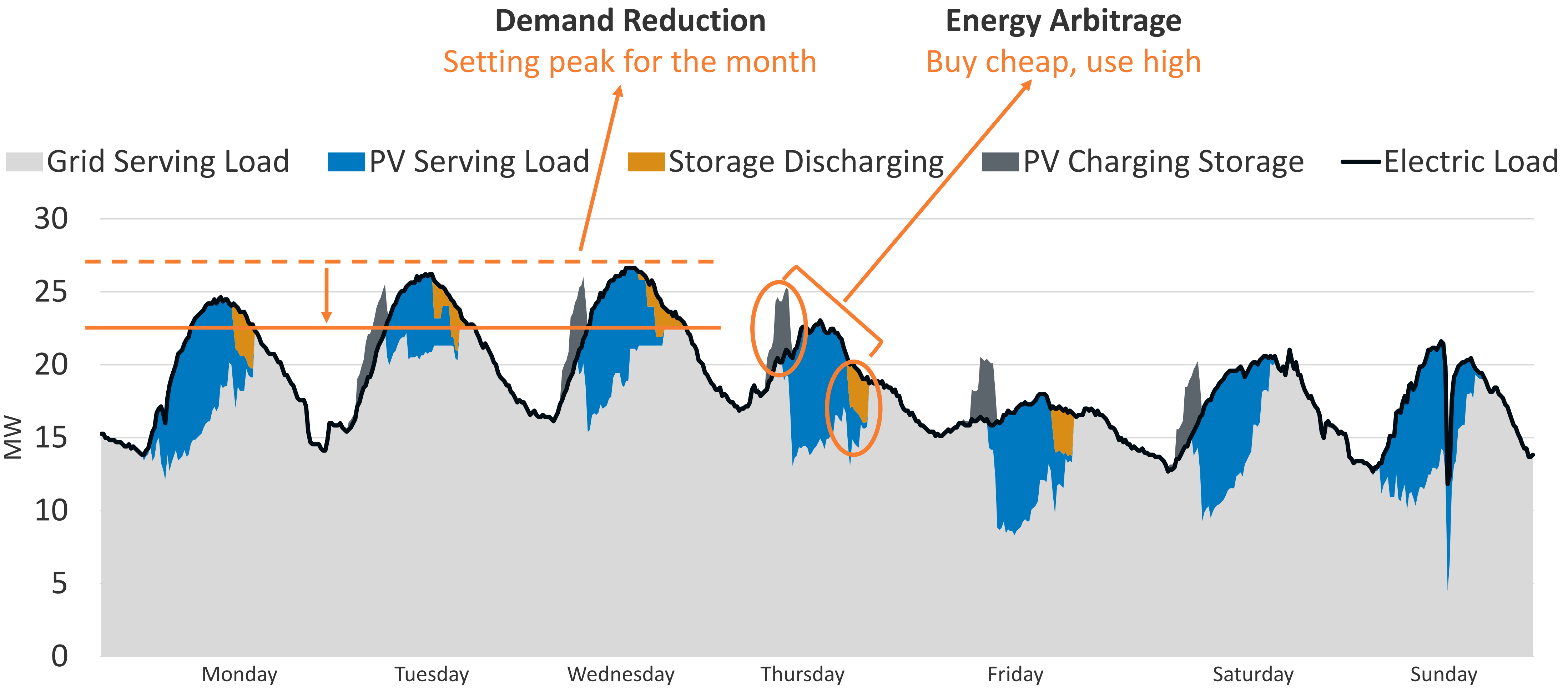
Where do market opportunities for DERs exist? Now and in the future?

What will it cost to meet my sustainability or renewable energy goal?

What is the most cost-effective way to sustain a grid outage spanning 1 day? What about 9 days?

How Does REopt Work?

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



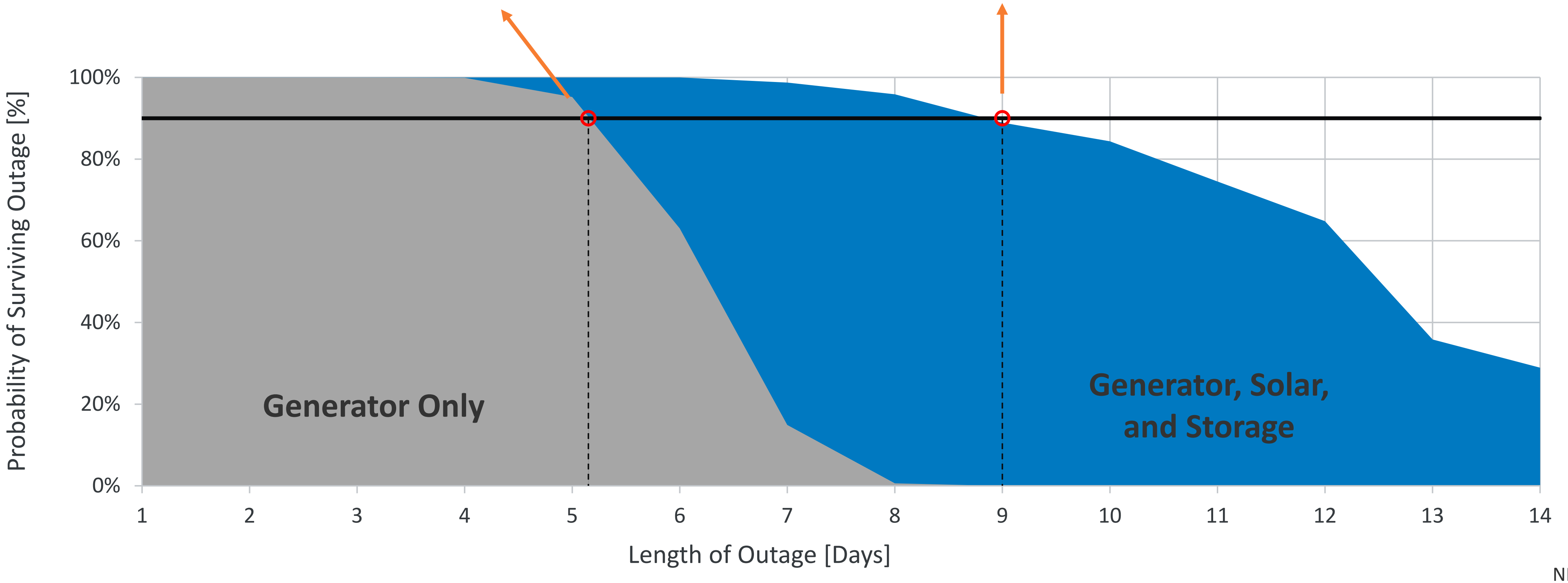
Example of optimal dispatch of PV and BESS

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.

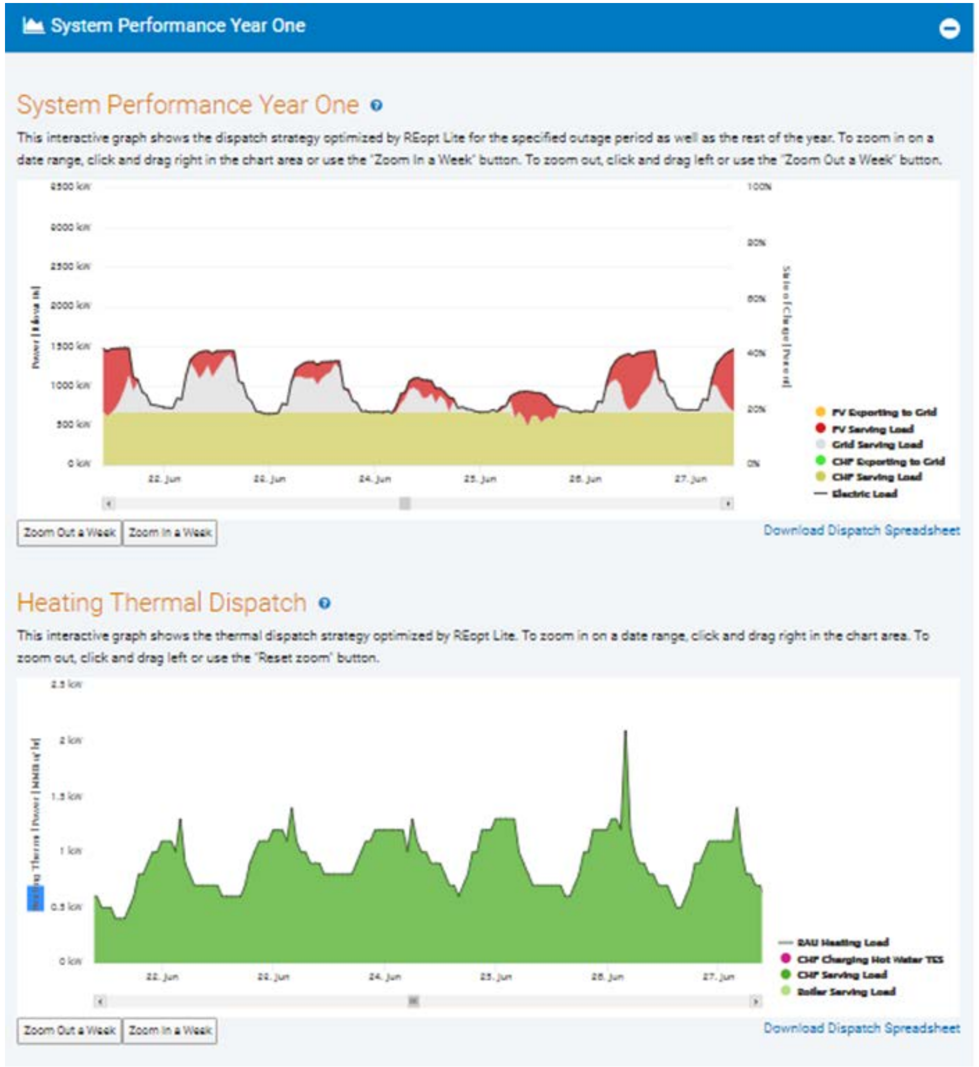
Existing generator with fixed fuel supply sustains the critical load for 5 days with 90% probability.

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.



Thermal Technologies in REopt

- In addition to solar PV, wind power, and battery energy storage systems (BESS), REopt includes combined heat and power (CHP), geothermal heat pumps (GHP), absorption chillers, and thermal energy storage (TES).
- These technologies enable analyses of electric and thermal loads together:
  - Simultaneously serving heating and electricity loads with CHP
  - Switching from heating with fuels to electricity with GHP
  - Switching from generating cooling with electricity to heat with an absorption chiller
  - Value of decoupling thermal loads from thermal energy production with TES.

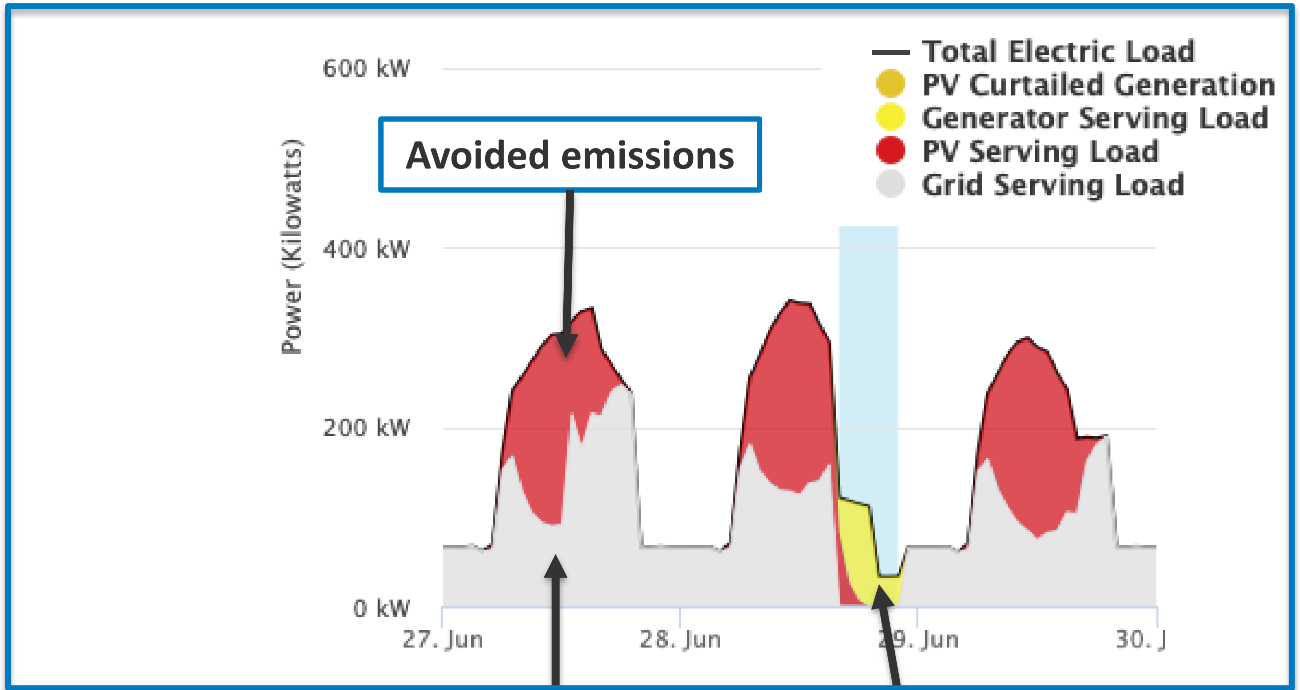


Emissions in REopt

REopt determines the emissions and emissions cost impacts of a DER investment, accounting for the hourly emissions intensity of grid electricity as well as on-site fuel consumption.

Using REopt, users can:

- Quantify **emissions changes** and the **monetary impact** of emissions reductions on **climate** (CO_2) and **health** (NOx, SO_2, PM2.5) outcomes
- Set a **climate emissions reduction target** and allow REopt to determine the cost-optimal DER investment to meet the target
- **Include climate and/or health costs within the optimization objective**, allowing these costs to impact system sizing and dispatch
- Use locational **default** emissions rates and costs or **input custom values**
- Evaluate health and climate emissions over the project life, considering future "greening of the grid."



Grid emissions [tons] =
Electric grid purchases [kWh]
x
Marginal emissions intensity [ton/kWh]
of the grid (location-specific) in each hour

Fuel emissions [tons] =
Fuel burned on-site [gal]
x
Fuel emissions intensity
[ton/ gal]

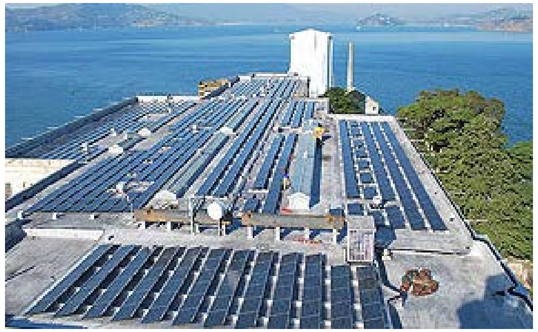
Currently, REopt uses the following defaults:

Grid emissions rates: marginal rates calculated from EPA's AVERT
Grid emission rate change projections: calculated from NREL's Cambium
Climate costs: U.S. Interagency Working Group 2021 social cost of carbon
Health emissions costs: location-specific, obtained from EASIUR model

Informing Deployment

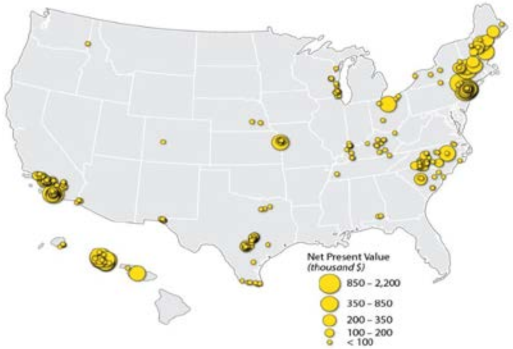
REopt helps partners make well-informed energy investment decisions backed by credible, objective data analysis by answering questions such as:

- How should DERs be sized to minimize site energy costs, achieve a renewable energy or emissions reduction target, and/or provide resilience value?
- How should I dispatch these technologies to maximize their value?
- What is the value (or net present value) of a project?



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.

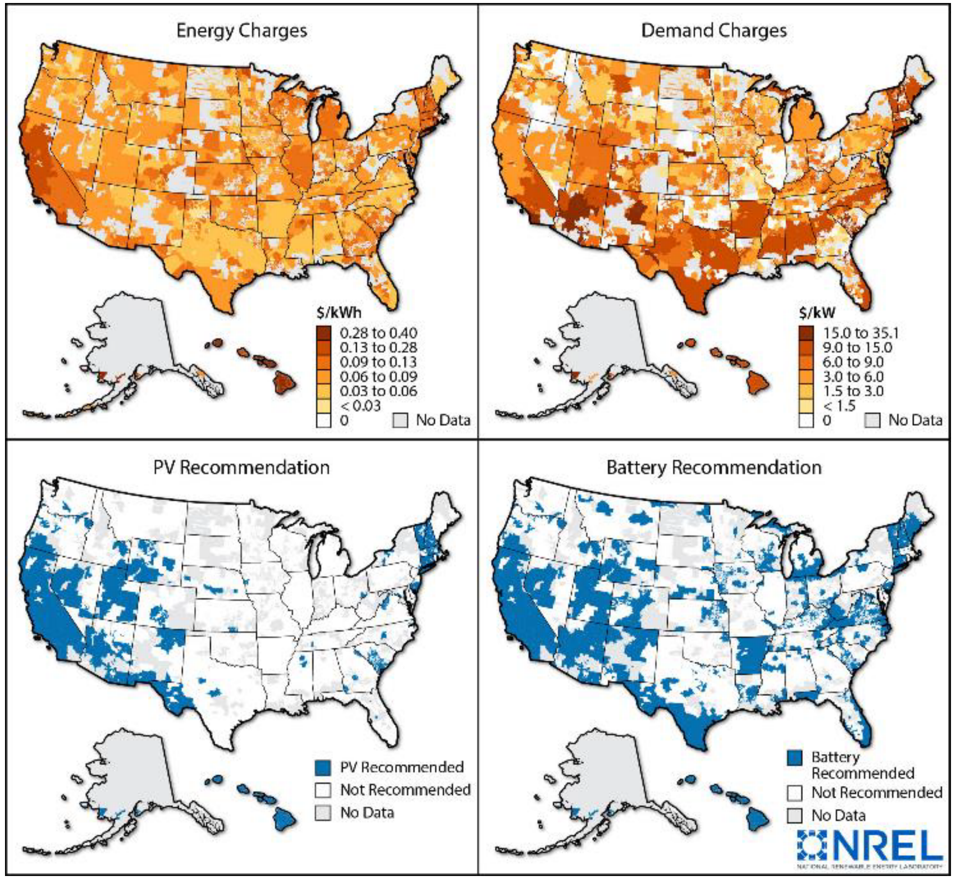


Identified cost-effective renewable energy and microgrid projects to meet Time Warner Cable energy goals for reduced energy use, reduced energy cost, and increased resilience.

San Diego Gas & Electric and Sumitomo partnered with REopt team to develop daily dispatches for front-of-the-meter flow battery in SDG&E territory.

Project Economics at National Scale

- REopt enables national-scale analysis of renewable energy and storage economics and impacts on deployment
- Analysis questions include:
  - Where in the country is solar PV, storage, and CHP currently cost-effective?
  - At what capital cost is storage adopted across the United States?
  - Under what conditions (utility rate, load profile, location) can renewable energy 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 works with stakeholders to** provide a suite of trusted techno-economic **decision support services** to optimize energy systems for buildings, campuses, communities, microgrids, and more.

The team also develops publicly available **REopt software**; capabilities developed by the team are transferred to REopt based on broad use and validation, customer needs, and available funding.

REopt Decision Support Services

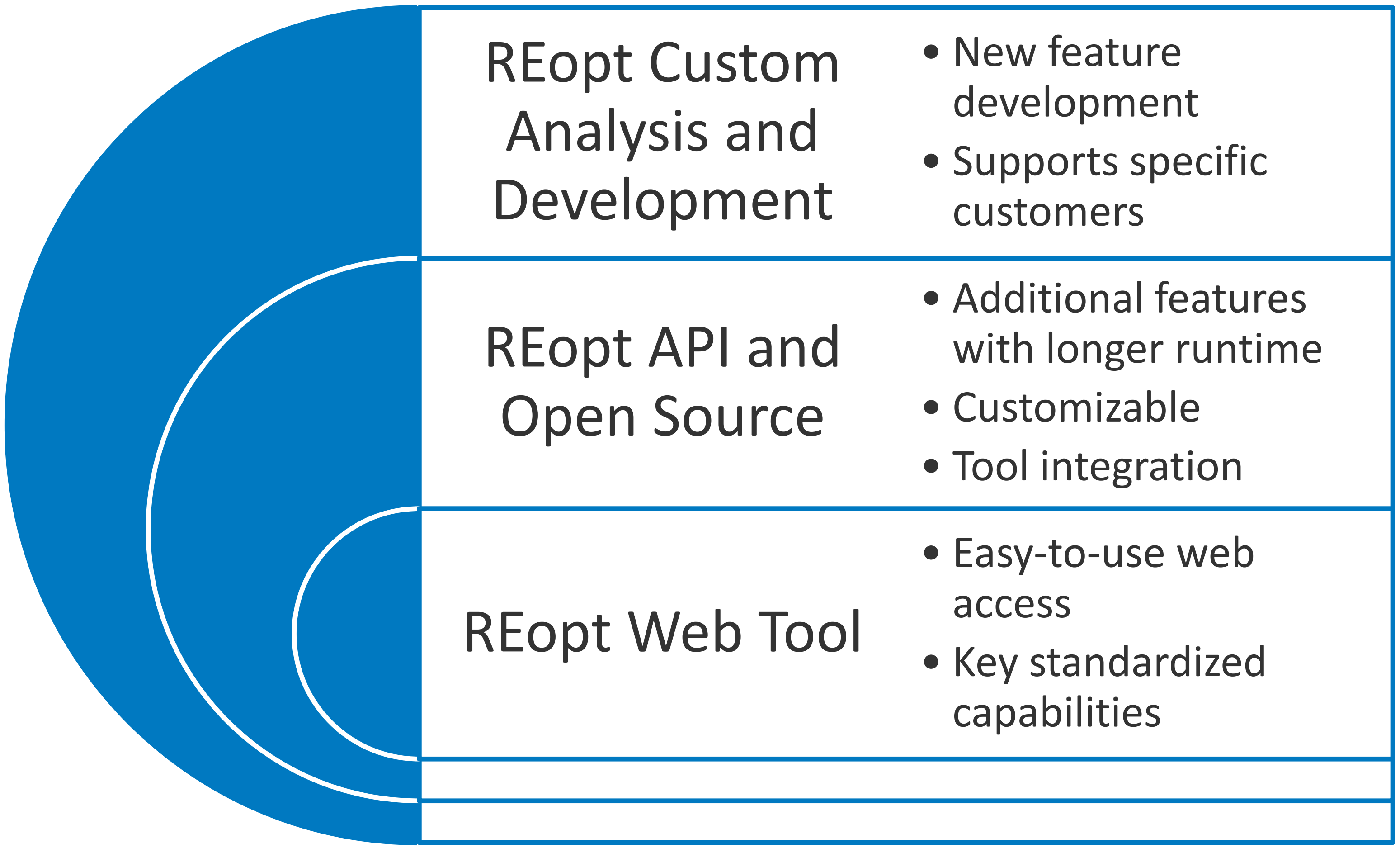
Allows organizations to work closely with NREL's team of experts on customized analysis, answering complex energy questions using an expanded set of internal modeling capabilities.

REopt Software

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

NREL. "REopt Web Tool." Accessed March 2022. https://reopt.nrel.gov/tool.
NREL. "REopt API V1." Accessed March 2022. https://developer.nrel.gov/docs/energy-optimization/reopt/v1/.
GitHub. "NREL/REopt_API." Accessed March 2022. https://github.com/NREL/REopt_API.

REopt Capability Development



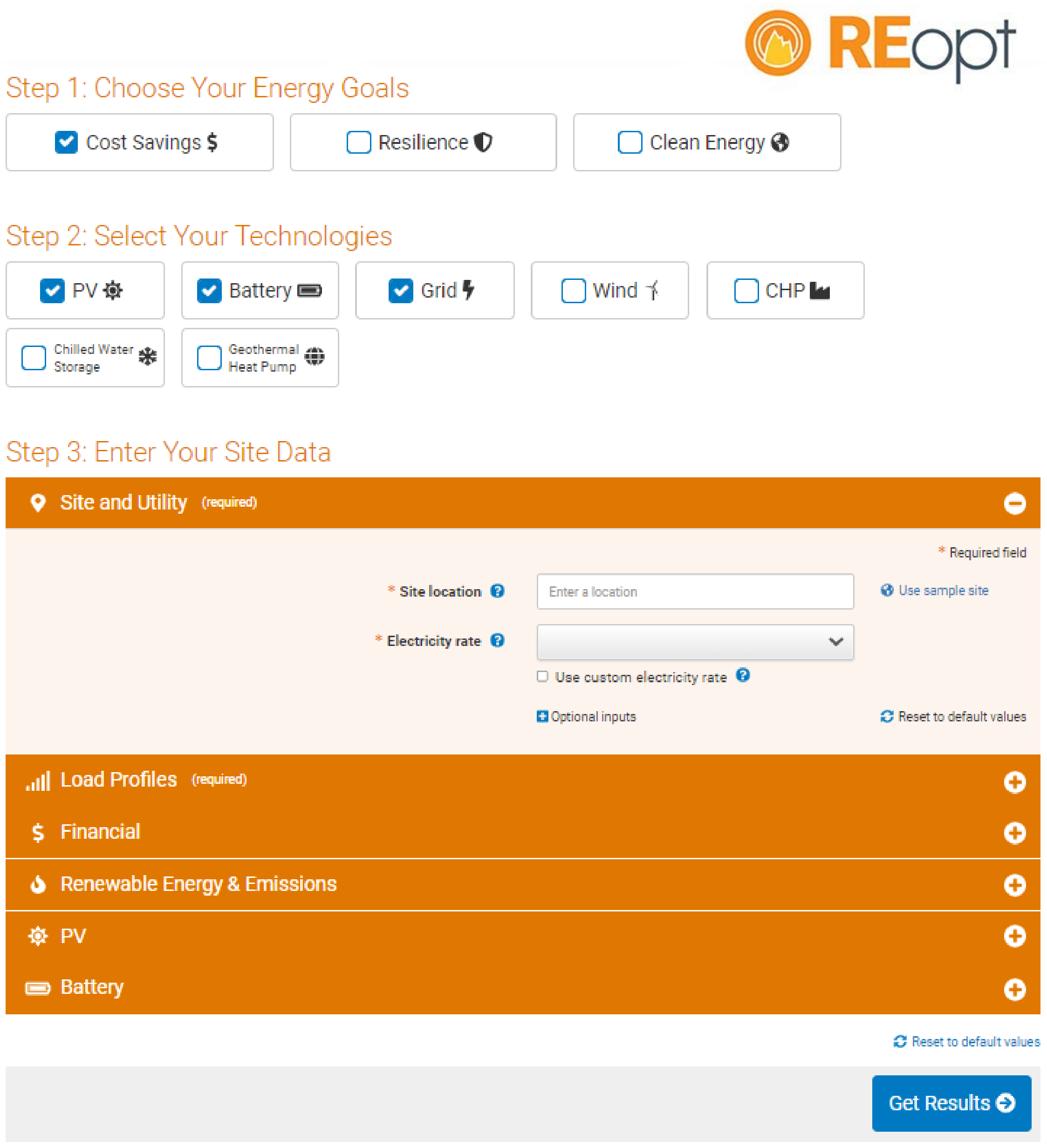
Capabilities developed by the team are transferred to REopt based on broad use and validation, customer needs, and available funding.

REopt Web Tool

User Interface and Key Results

REopt Web Tool User Interface

- **REopt Web Tool** offers a free, publicly available, user-friendly web tool that offers a subset of NREL's more comprehensive REopt model
- Optimizes **PV, wind, CHP, GHP, and energy storage** system sizes and dispatch strategies to **minimize life cycle cost of energy**
- **Resilience mode** optimizes PV, wind, and storage systems, along with backup generators, to sustain critical load during grid outages.
- **Clean energy goals** allow users to consider renewable energy targets, emissions reductions targets, and emissions costs in optimization
- Access REopt web tool at reopt.nrel.gov/tool.



REopt Web Tool Key Outputs

Your recommended solar installation size

3,885 kW
PV size

Measured in kilowatts (kW) of direct current, this recommended size minimizes the life cycle cost of energy at your site.

Your recommended battery power and capacity

276 kW
battery power

598 kWh
battery capacity

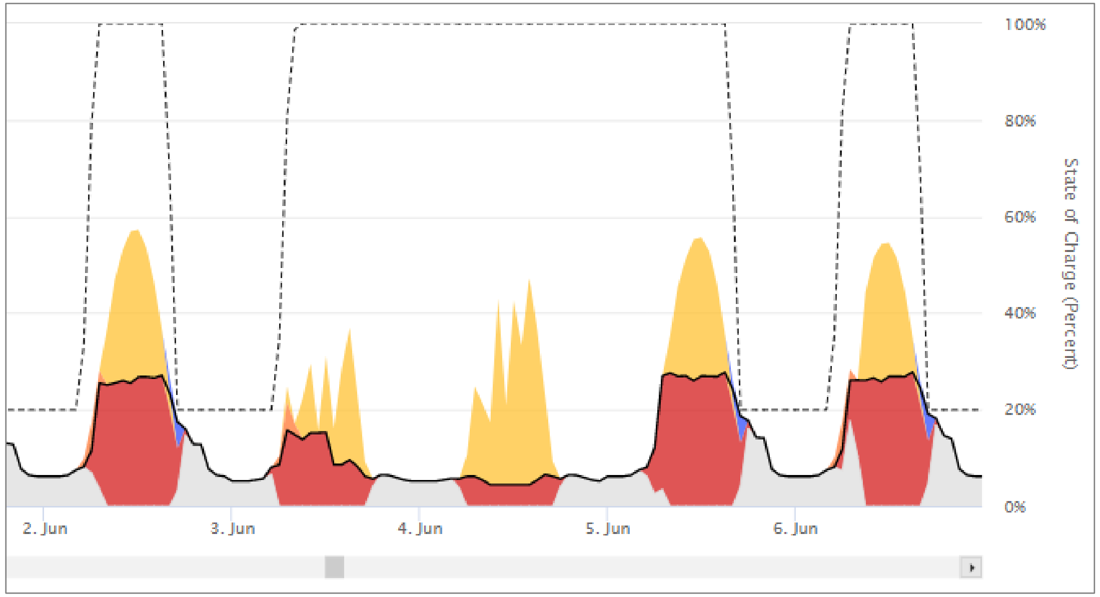
This system size minimizes the life cycle cost of energy at your site. The battery power and capacity are optimized for economic performance.

Your potential life cycle savings (20 years)

This is the net present value of the savings (or costs if negative) realized by the project based on the difference between the total life cycle costs of doing business as usual compared to the optimal case.

$1,972,493

System Size and NPV



Hourly Dispatch

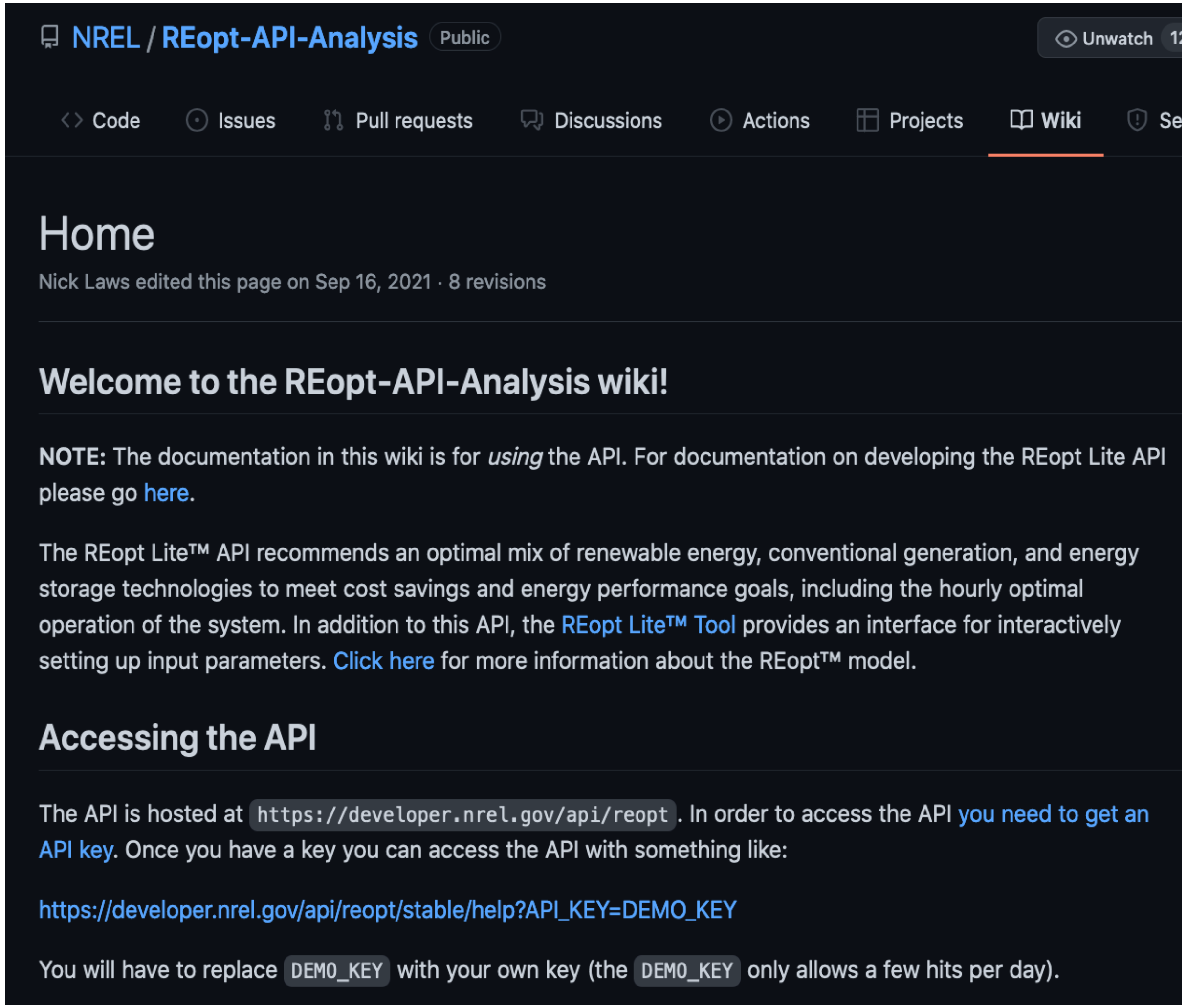
	Business As Usual	Financial	Difference
System Size, Energy Production, and System Cost			
PV Size	0 kW	113 kW	113 kW
Annualized PV Energy Production	0 kWh	132,000 kWh	132,000 kWh
Battery Power	0 kW	0 kW	0 kW
Battery Capacity	0 kWh	0 kWh	0 kWh
Net CAPEX + Replacement + O&M	$0	$133,318	$133,318
Energy Supplied From Grid in Year 1	132,000 kWh	65,384 kWh	66,616 kWh
Year 1 Utility Cost — Before Tax			
Utility Energy Cost	$18,112	-$404	$18,515
Utility Demand Cost	$0	$0	$0
Utility Fixed Cost	$0	$0	$0
Utility Minimum Cost Adder	$0	$0	$0

Detailed Financial Outputs

REopt API

REopt API Access

- What is an API?
  - Application Programming Interface
  - Programmatic way of accessing REopt web tool (sending and receiving data from a server)
  - File format used for sending and receiving the data: JSON.
- Advantages:
  - Multiple simulations for different sites can be run programmatically
  - Scenario analysis can be automated
  - Application can be integrated with other programs.



NREL / REopt-API-Analysis Public

Unwatch

Code Issues Pull requests Discussions Actions Projects Wiki

Home

Nick Laws edited this page on Sep 16, 2021 · 8 revisions

Welcome to the REopt-API-Analysis wiki!

NOTE: The documentation in this wiki is for *using* the API. For documentation on developing the REopt Lite API please go here.

The REopt Lite™ API recommends an optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings and energy performance goals, including the hourly optimal operation of the system. In addition to this API, the REopt Lite™ Tool provides an interface for interactively setting up input parameters. Click here for more information about the REopt™ model.

Accessing the API

The API is hosted at `https://developer.nrel.gov/api/reopt`. In order to access the API you need to get an API key. Once you have a key you can access the API with something like:

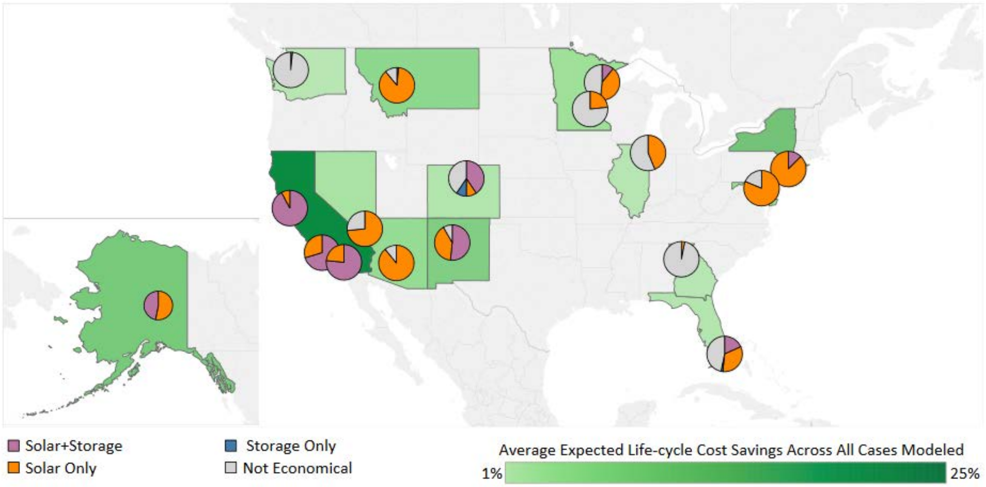
https://developer.nrel.gov/api/reopt/stable/help?API_KEY=DEMO_KEY

You will have to replace `DEMO_KEY` with your own key (the `DEMO_KEY` only allows a few hits per day).

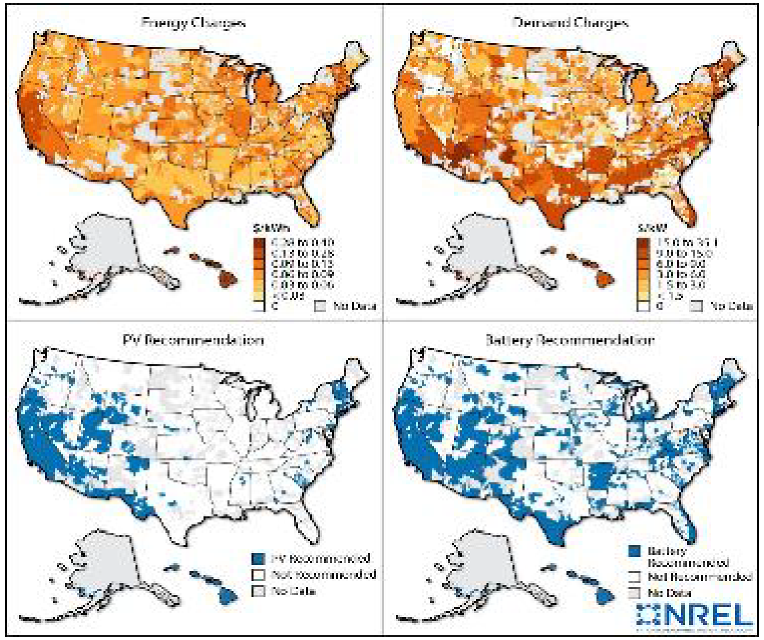
https://github.com/nrel/reopt-api-analysis/wiki

Analysis Enabled by API

- The REopt API enables national-scale analysis of storage economics and impacts on adoption/deployment.
- Analysis questions include:
  - Where in the country is storage (and PV) currently cost-effective?
  - At what capital costs is storage adopted across the United States?
  - How does varying utility rate, escalation rates, and incentive structures impact storage profitability?
  - How (and where) can stationary storage support DCFC electric vehicle economics and deployment?



Identifying critical factors in the cost-effectiveness of solar and battery storage in commercial buildings: https://www.nrel.gov/docs/fy18osti/70813.pdf



Technology solutions to mitigate electricity cost for electric vehicle DCFC: https://www.sciencedirect.com/science/article/pii/S0306261919304581

REopt Custom Analysis Projects

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.

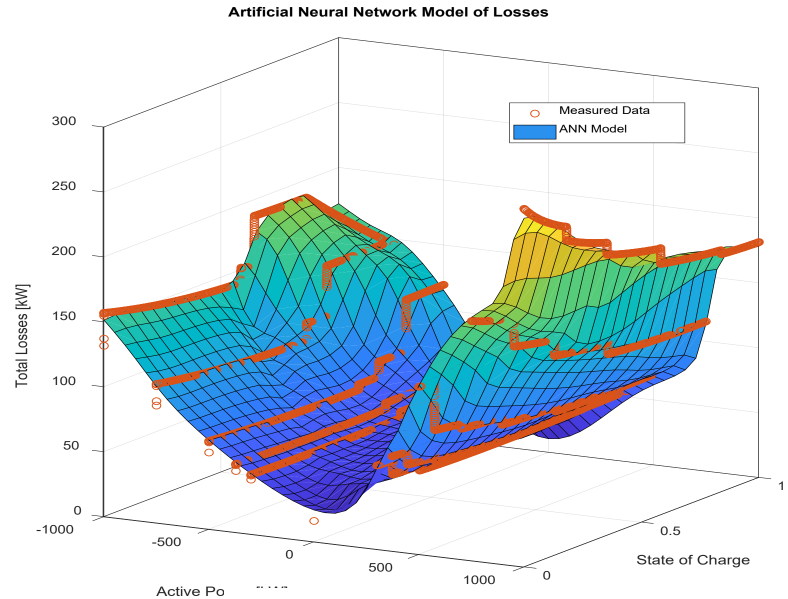
Technology: Li-ion battery storage

Impact: 4.2 M; 8.5-MWh battery installed at Ft. Carson under an energy savings performance contract. 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

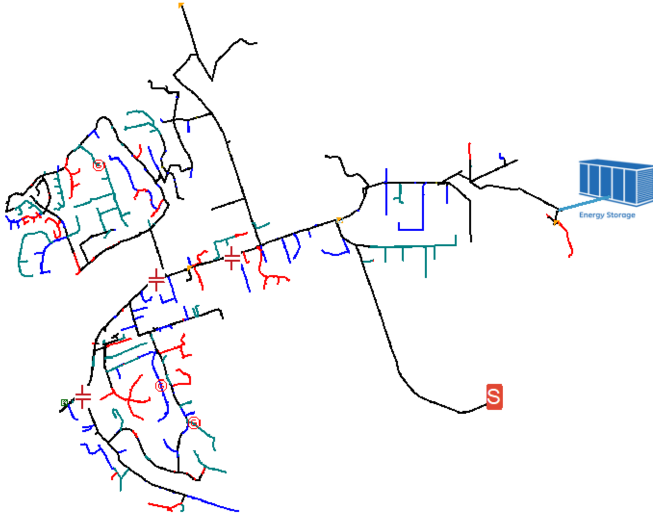


Description: NREL validated the technical and economic feasibility of an emerging vanadium flow battery technology through loss modeling, characterization, and field test.

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 Trade-Offs between Economics and Resilience

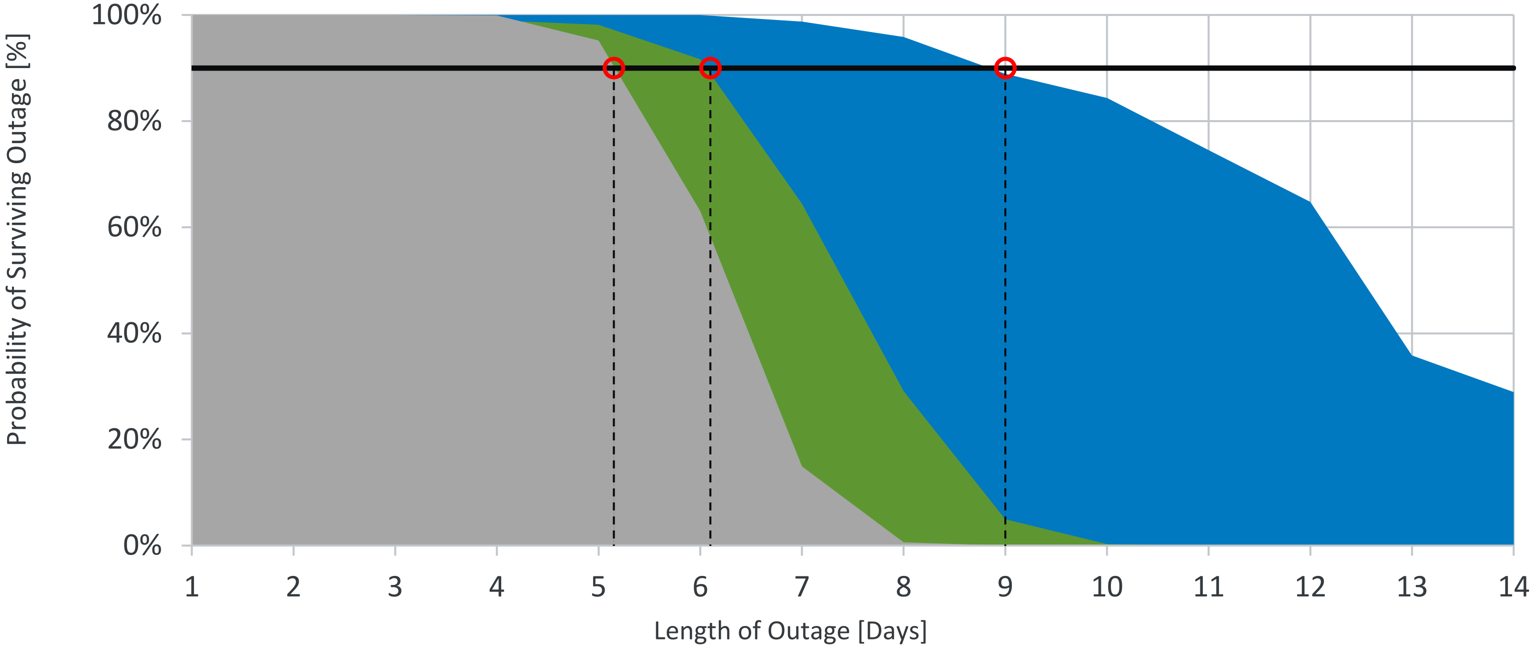
Description: NREL used REopt to evaluate how long existing and proposed backup energy systems could sustain the critical load during an outage at an Army National Guard base. REopt evaluated thousands of random grid outage occurrences and durations and compared hours survived with diesel gensets vs.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

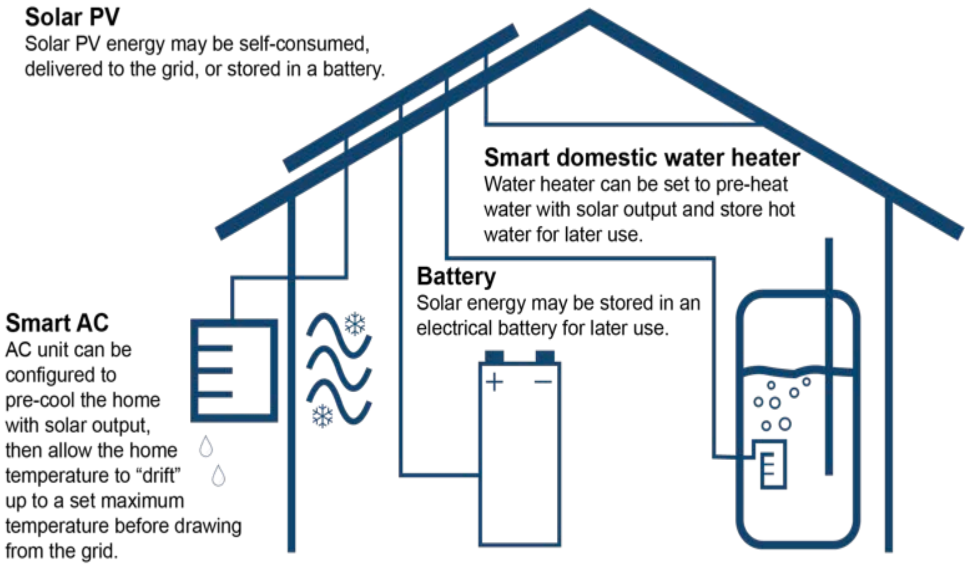
Partner: Army National Guard

	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

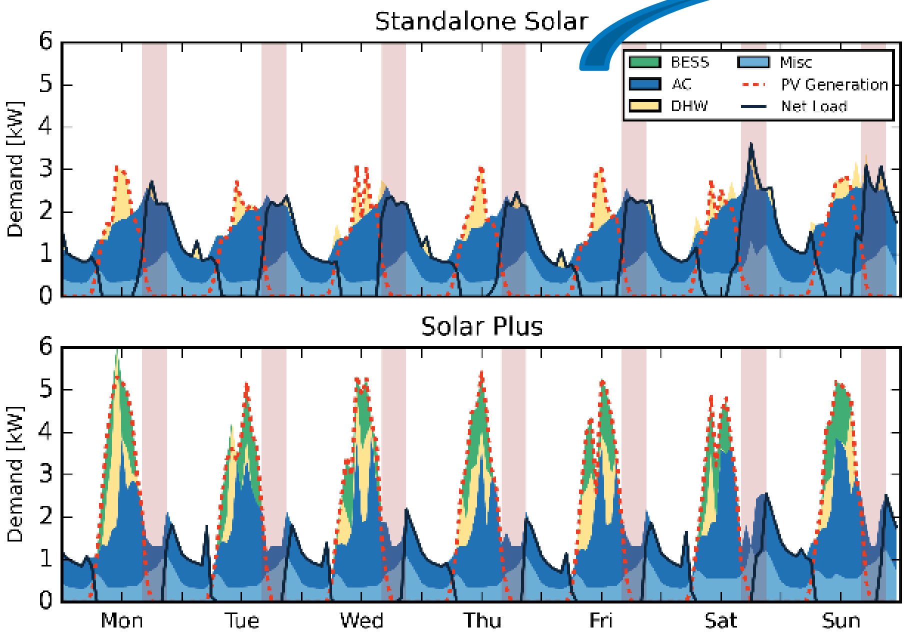


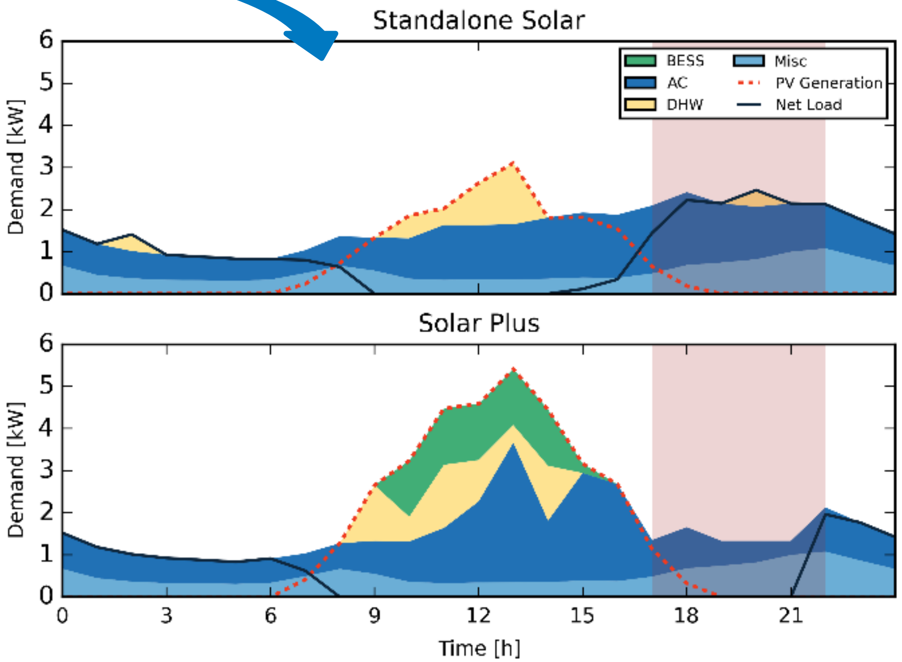
Description: NREL evaluated controllable load and storage options to improve customer economics of solar under post-net metering utility tariffs.

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.

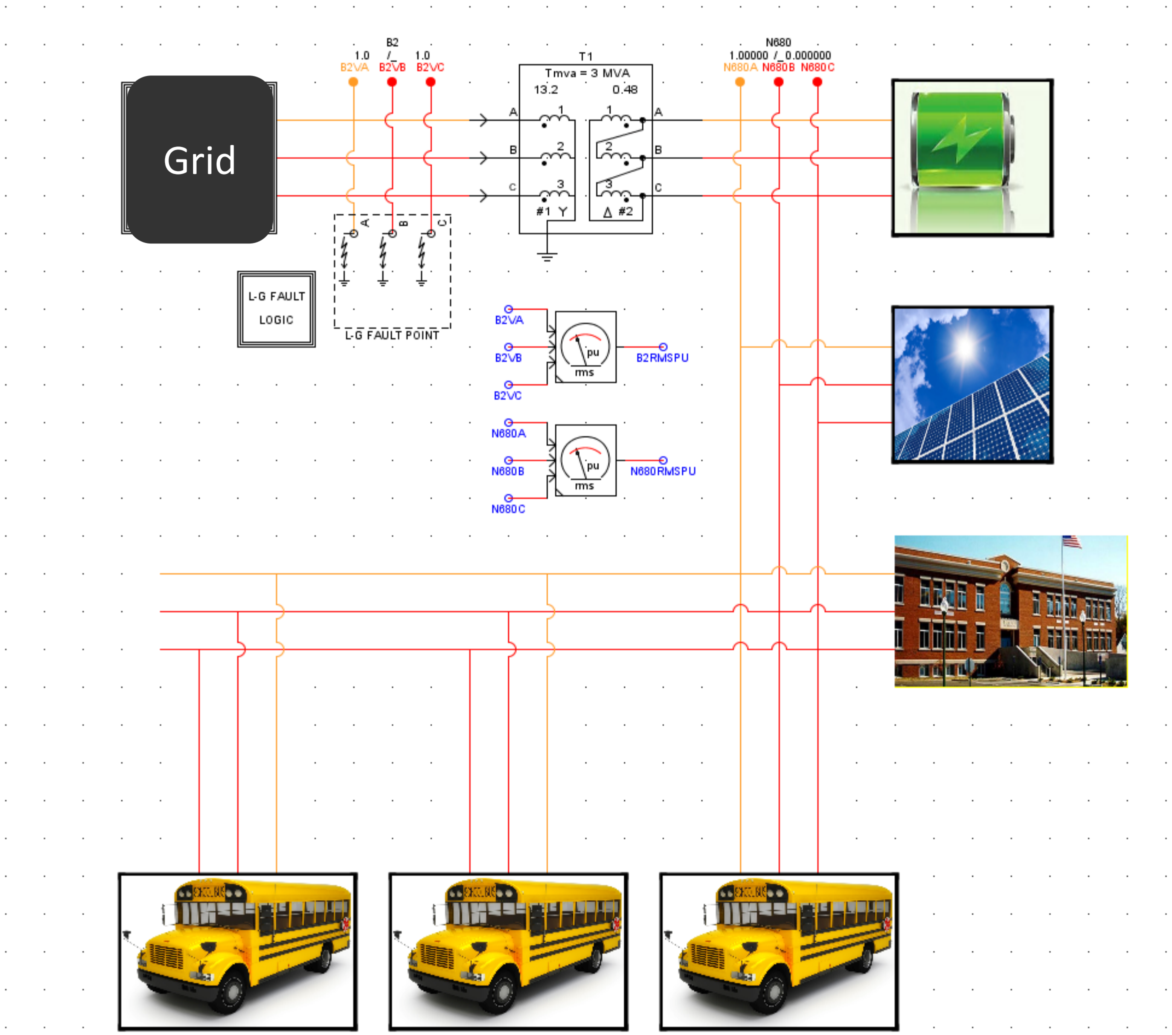
Integrating EV Fleets With DER and Grid

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

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

Impact: Demonstrated optimal control of integrated renewable energy, 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 REopt Information

REopt Technical Description

REopt Curriculum

REopt Journal Articles

REopt 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.

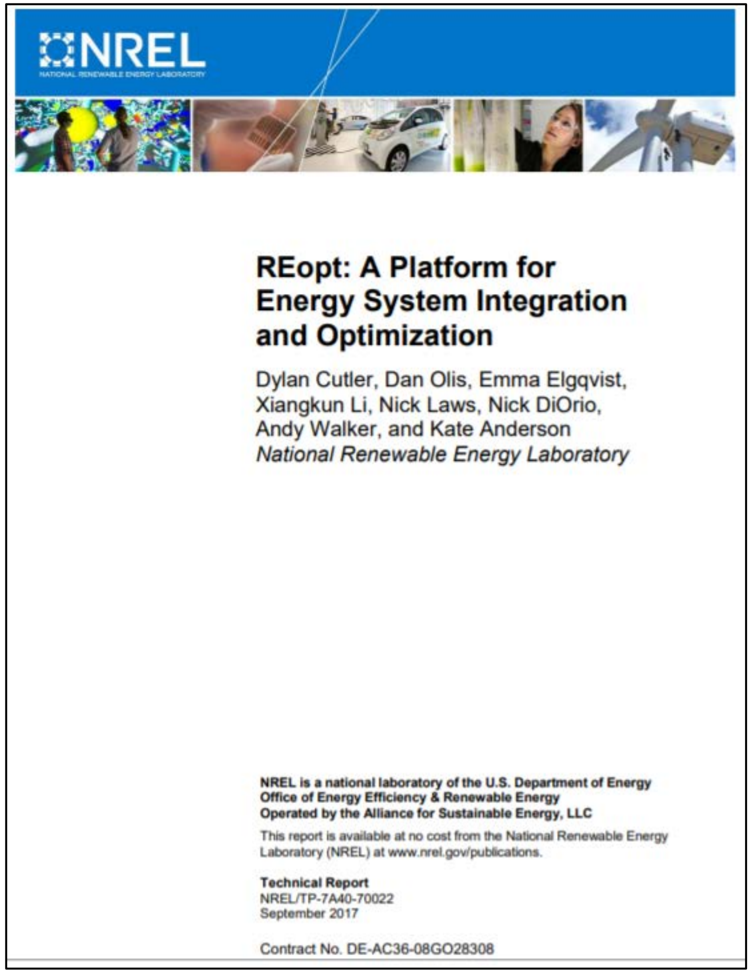
Solves energy balance at every time step for entire year (typically 15-minute or hourly interval)

- 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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NATIONAL RENEWABLE ENERGY LABORATORY

REopt: A Platform for Energy System Integration and Optimization

Dylan Cutler, Dan Olis, Emma Elgqvist, Xiangkun Li, Nick Laws, Nick DiOrio, Andy Walker, and Kate Anderson
National Renewable Energy Laboratory

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Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Technical Report
NREL/TP-7A40-70022
September 2017

Contract No. DE-AC36-08GO28308

REopt's Impact with Academia

REopt Web Tool Curriculum Materials

Introduction to the REopt Web Tool

REopt Web Tool Overview

Training deck features an overview of the REopt web tool's value proposition and capabilities.

User Guide, Tutorials, and Webinars

Quick-start tutorials and webinars guide users through REopt web tool inputs, results, and application programming interface (API).

Practice Exercises

Training deck provides an overview of the REopt web tool as well as a series of practice exercises.

- REopt is being used in higher education such as Colorado School of Mines' Advanced Energy Systems graduate program and DOE's Solar District Cup to train the next generation of energy professionals.
- Educators can access materials at reopt.nrel.gov/curriculum.html.

REopt Journal Articles

"Looking beyond bill savings to equity in renewable energy microgrid deployment." *Renewable Energy Focus*, June 2022.

"Off-design modeling of a microturbine combined heat & power system." *Applied Thermal Engineering*, February 2022.

"Optimizing Design and Dispatch of a Renewable Energy System with Combined Heat and Power." *Optimization and Engineering*, January 2022.

"Optimizing Solar-Plus-Storage Deployment on Public Buildings for Climate, Health, Resilience, and Energy Bill Benefits." *Environmental Science & Technology*, September 2021.

"Resilience and Economics of Microgrids with PV, Battery Storage, and Networked Diesel Generators." *Advances in Applied Energy*, August 2021.

"Optimality versus Reality: Closing the Gap Between Renewable Energy Decision Models and Government Deployment in the United States." *Energy Research & Social Science*, June 2021.

"Computational Framework for Behind-the-Meter DER Techno-Economic Modeling and Optimization: REopt Lite." *Energy Systems*, May 2021.

"Optimizing Design and Dispatch of a Renewable Energy System." *Applied Energy*, April 2021.

"Technoeconomic Design of a Geothermal-Enabled Cold Climate Zero Energy Community." *Journal of Energy Resources Technology*, January 2021.

"Assessing Uncertainty in the Timing of Energy Use During Cost-Optimal Distributed Energy Technology Selection and Sizing." *Renewable Energy Focus*, December 2020.

"Cost-Optimal Evaluation of Centralized and Distributed Microgrid Topologies Considering Voltage Constraints." *Energy for Sustainable Development*, June 2020.

"Integrating the Value of Electricity Resilience in Energy Planning and Operations Decisions." *IEEE Systems Journal*, January 2020.

"Technology Solutions to Mitigate Electricity Cost for Electric Vehicle DC Fast Charging." *Applied Energy*, May 2019.

"Coordinated Optimization of Multiservice Dispatch for Energy Storage Systems with Degradation Model for Utility Applications." *IEEE Transactions on Sustainable Energy*, April 2019.

"Solar-Plus-Storage Economics: What Works Where, and Why?" *The Electricity Journal*, January 2019.

"Impacts of Valuing Resilience on Cost-Optimal PV and Storage Systems for Commercial Buildings." *Renewable Energy*, November 2018.

"Solar Plus: A Review of the End-User Economics of Solar PV Integration with Storage and Load Control in Residential Buildings." *Applied Energy*, October 2018.

"Coordinated Optimization of Multiservice Dispatch for Energy Storage Systems with Degradation Model for Utility Applications." *IEEE Transactions on Sustainable Energy*, April 2019.

"Quantifying and Monetizing Renewable Energy Resiliency." *Sustainability*, April 2018.

"Thinking Creatively about Residential Solar PV System Optimization: The Solar Plus Approach." *Science Trends*, March 2018.

"Solar Plus: Optimization of Distributed Solar PV through Battery Storage and Dispatchable Load in Residential Buildings." *Applied Energy*, March 2018.

"Increasing Resiliency Through Renewable Energy Microgrids." *Journal of Energy Management*, August 2017.

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https://reopt.nrel.gov/about/team.html

REopt Renewable Energy Integration and Optimization

REopt website (analysis services and case studies): reopt.nrel.gov

Tool feedback and questions: reopt@nrel.gov

www.nrel.gov

NREL/PR-7A40-82426

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NATIONAL RENEWABLE ENERGY LABORATORY

More REopt Projects

Storage Sizing and Operation

Resilience and Microgrids

Integration of Flexible Loads

Electric Vehicles

Portfolio Optimization

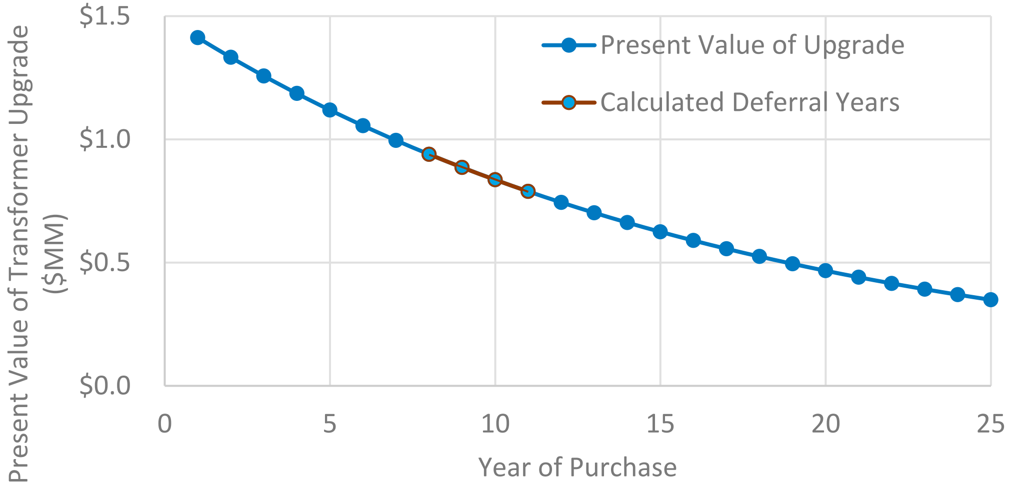
Market Participation Strategy for SDG&E Utility Storage

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).

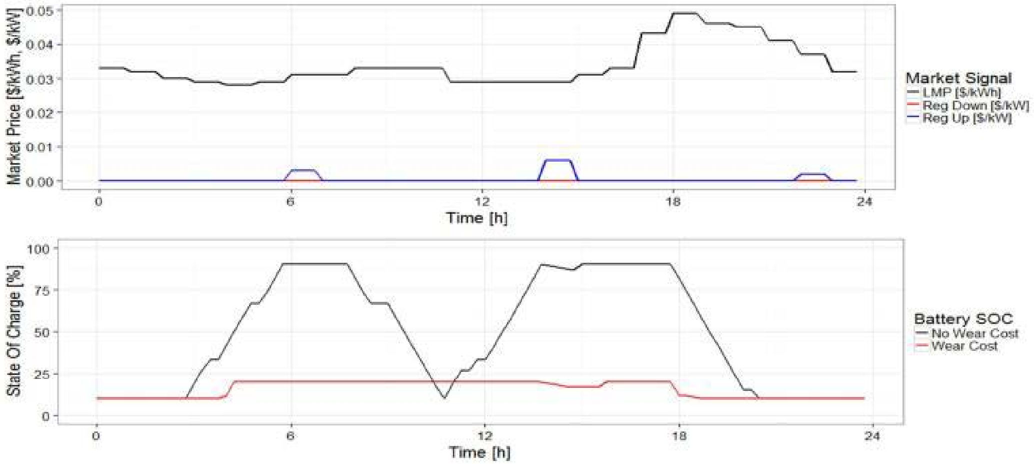
Technology: Li-ion battery

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

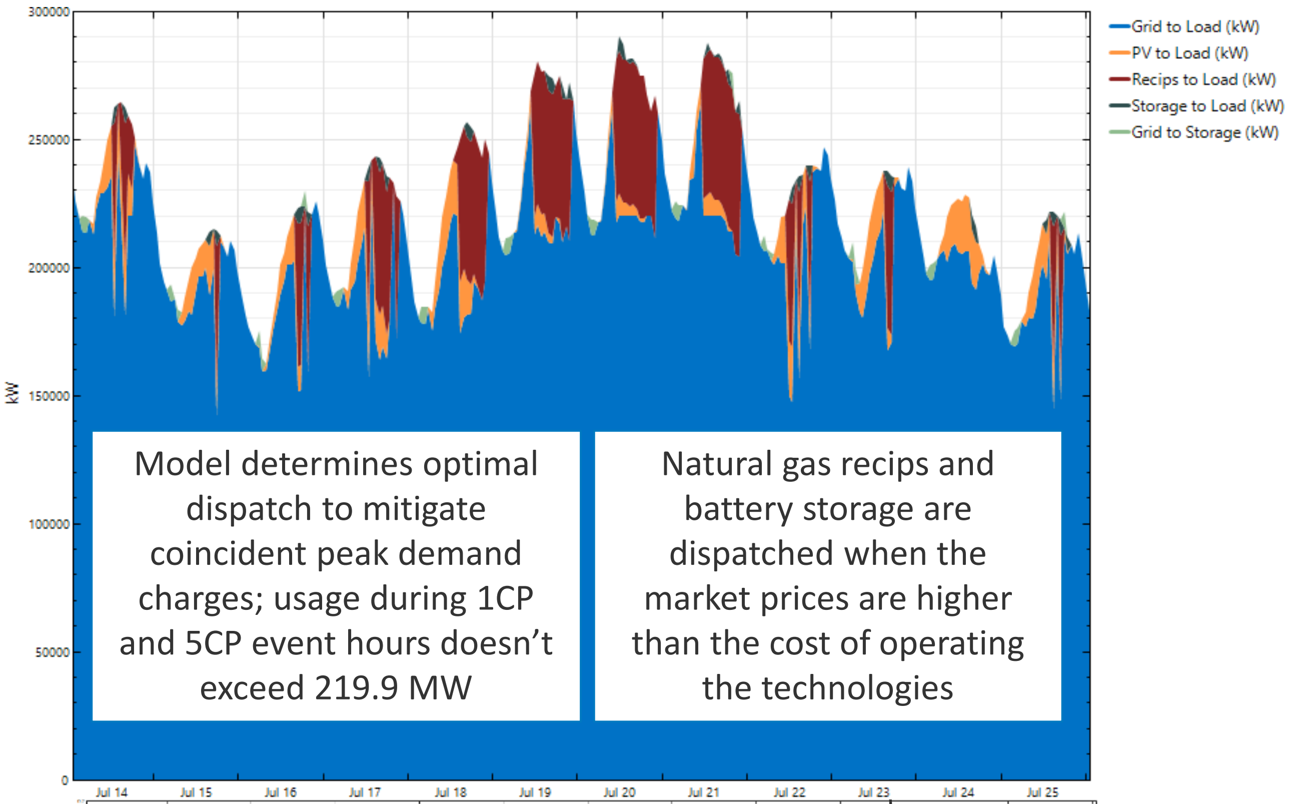
Description: NREL used REopt to determine the optimal dispatch to mitigate coincident peak demand charges.

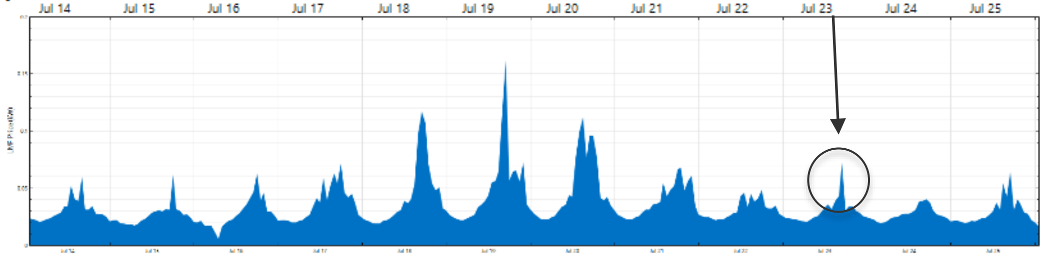
Technology: Natural gas reciprocating engines and battery storage

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





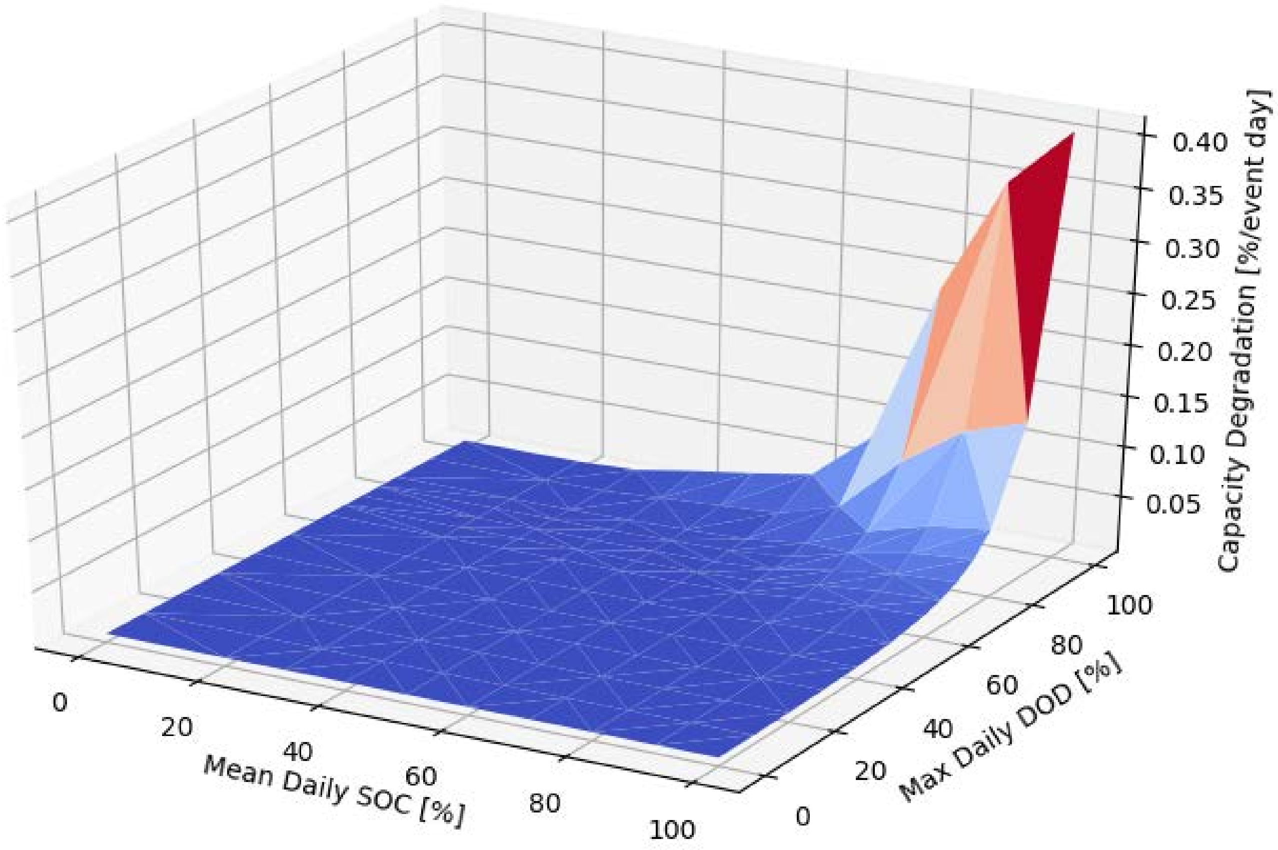
Health-Conscious Battery Economics

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. Decentralized Microgrid Options for Military Installations

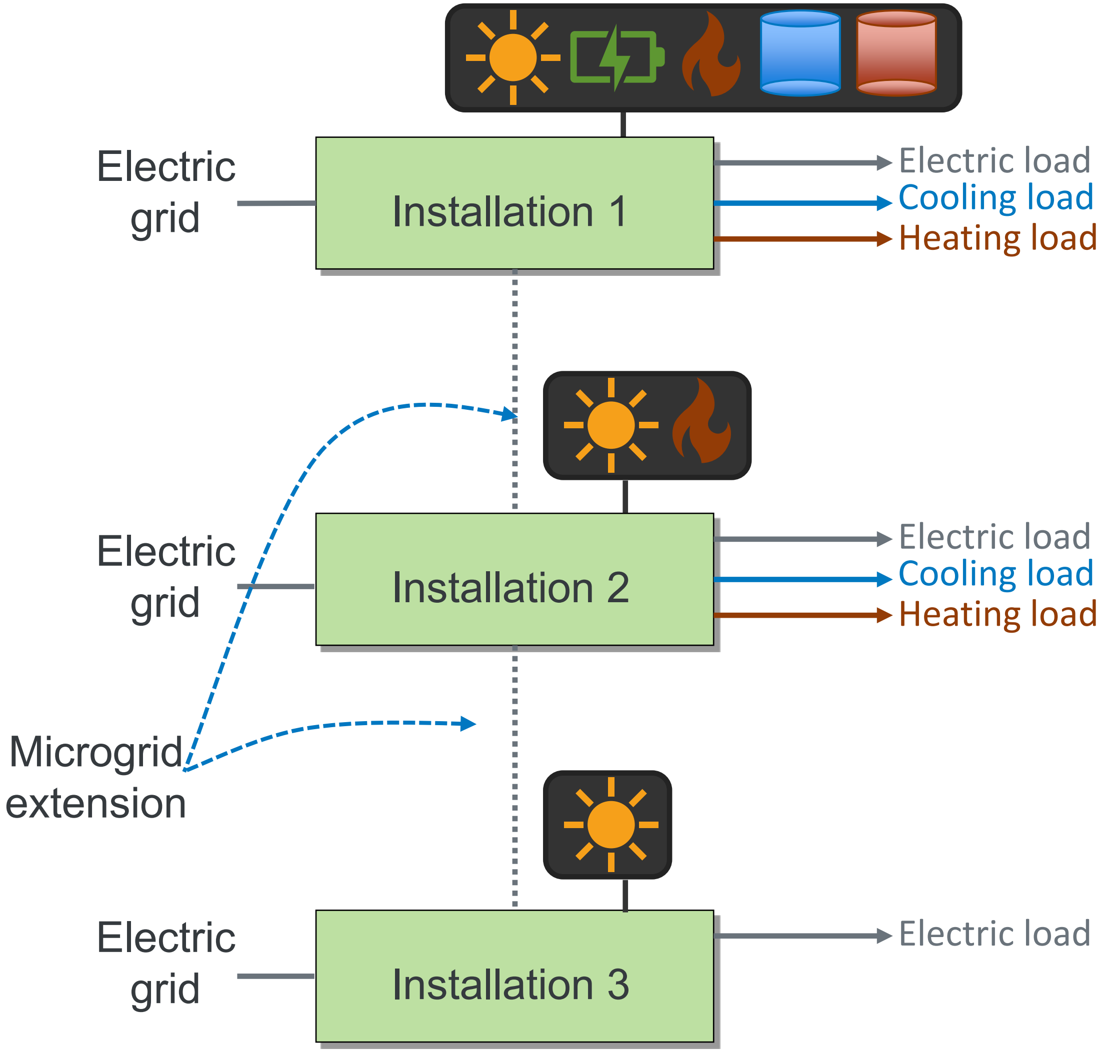
Description: NREL performed an integrated microgrid feasibility analysis for three U.S. military installations to support U.S. Army energy resilience requirements.

Technologies: Solar PV, battery storage, 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.

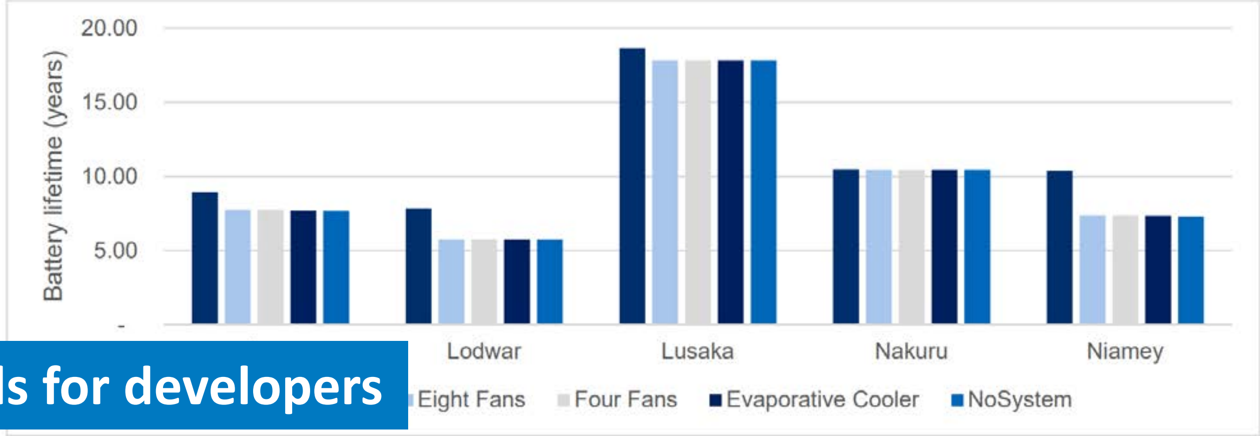
Microgrids for Rural Energy Access In Africa

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

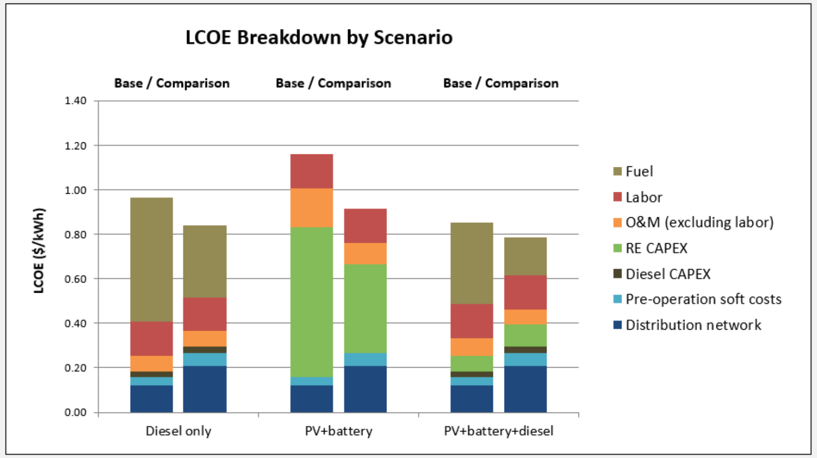
Partners: USAID, AMDA, individual microgrid developers, national governments in sub-Saharan Africa



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.

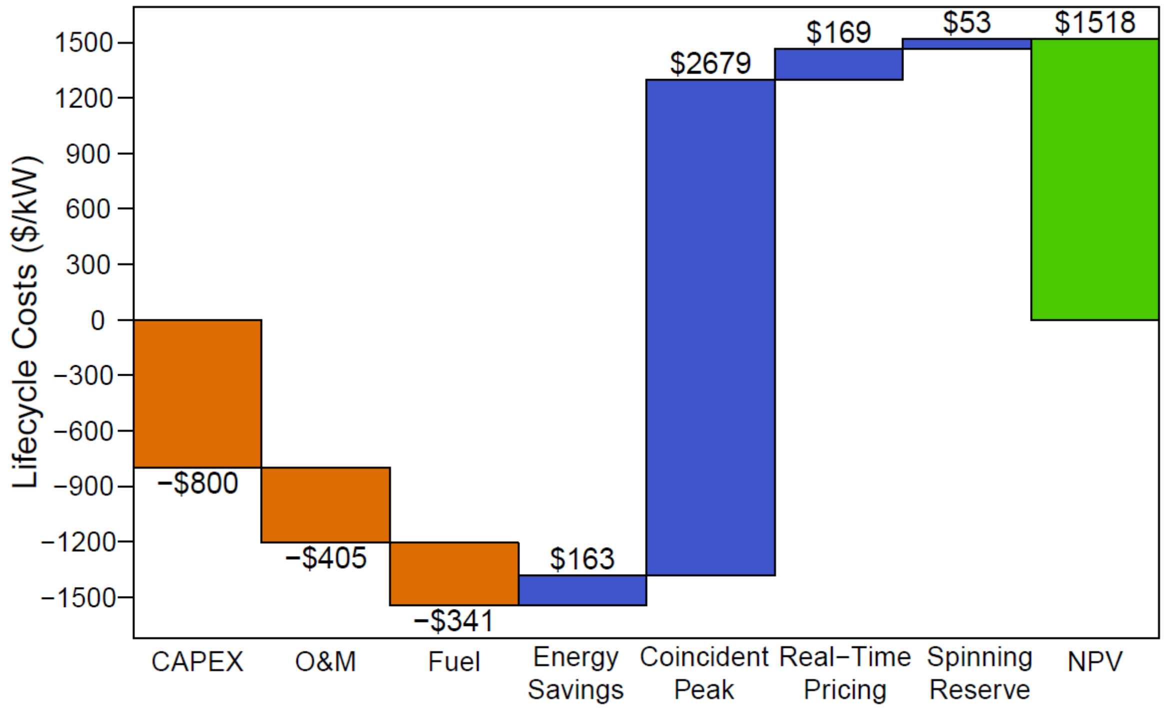
Market Revenues for Backup Generators

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 backup 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

Evaluating Grid-Scale Battery Storage at an Offshore Windfarm in the United Kingdom

Description: NREL assessed stacked value streams for grid-scale battery storage co-located at a windfarm in the United Kingdom:

- Energy arbitrage in day-ahead markets
- Mitigating forecast error penalties in imbalance markets
- Capacity markets
- Avoiding curtailment losses.

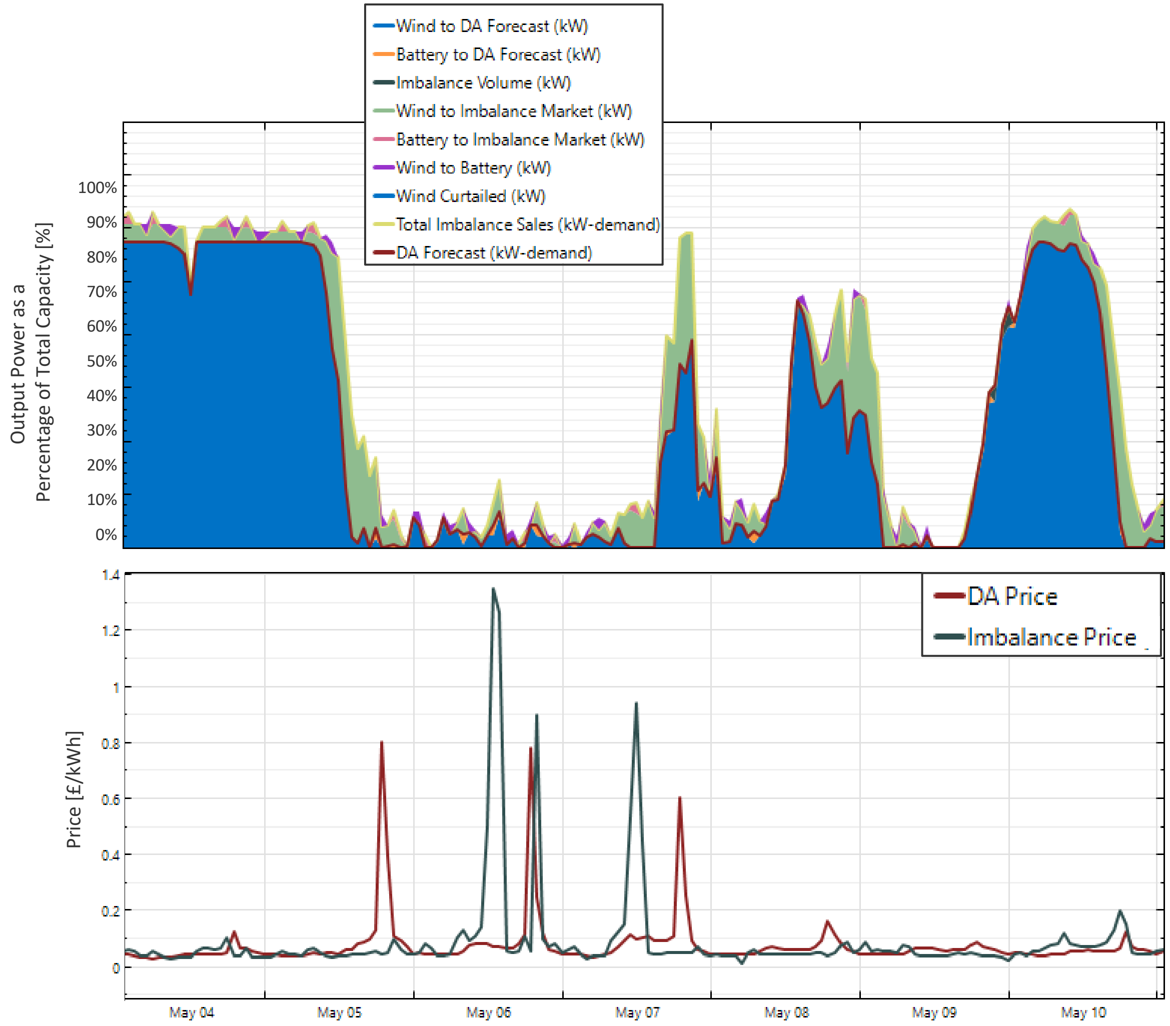
Several sensitivity studies were performed:

- Forecast accuracy
- Battery size
- Battery capital costs
- Grid electricity price escalation rate.

Technologies: Grid-scale battery storage; offshore wind

Impact: Identified market conditions that would make a battery cost effective at an offshore windfarm in the United Kingdom to inform Equinor's investment decisions.

Partners: Equinor (formerly Statoil)



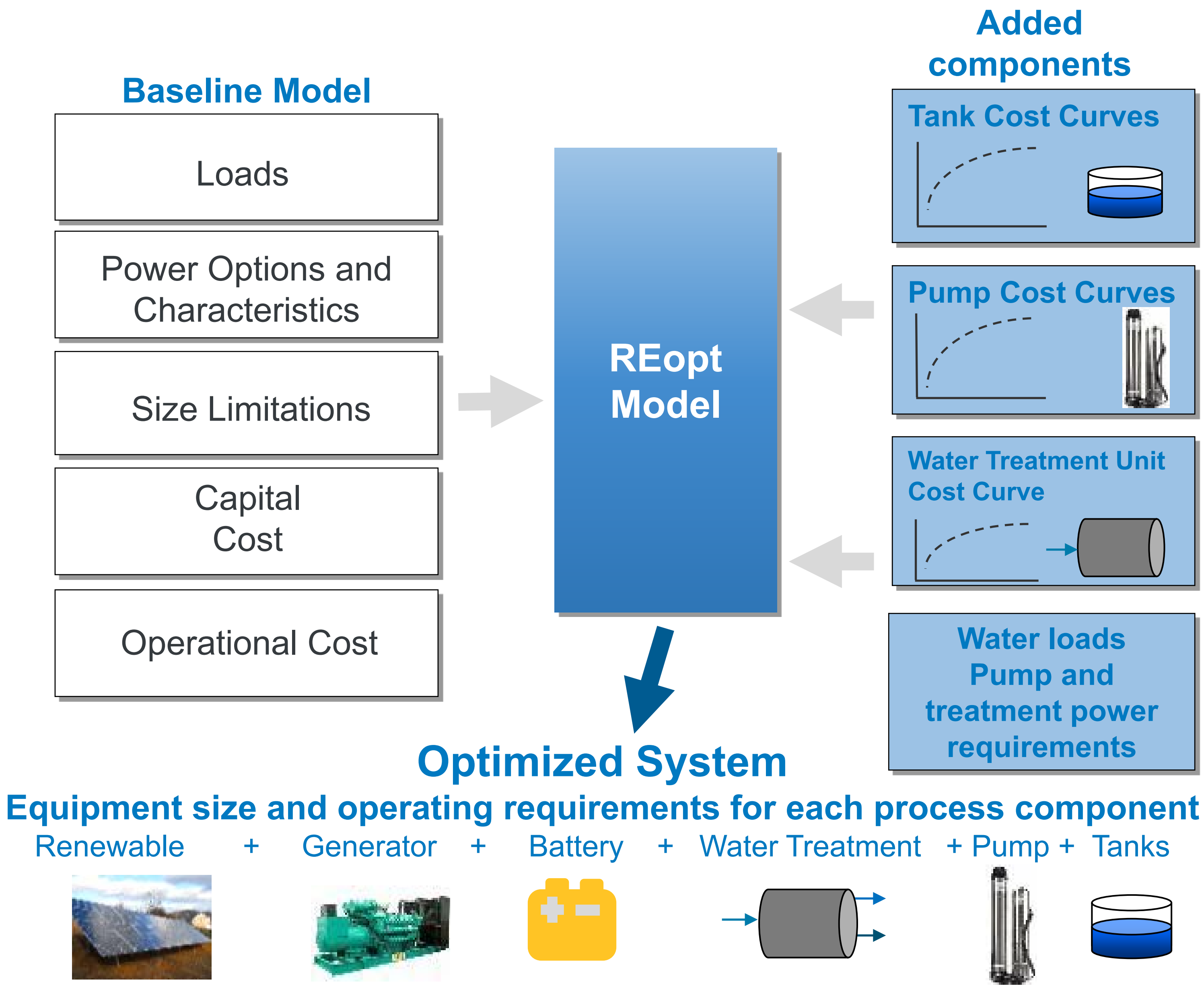
Optimizing Off-Grid Water Treatment and Storage

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.

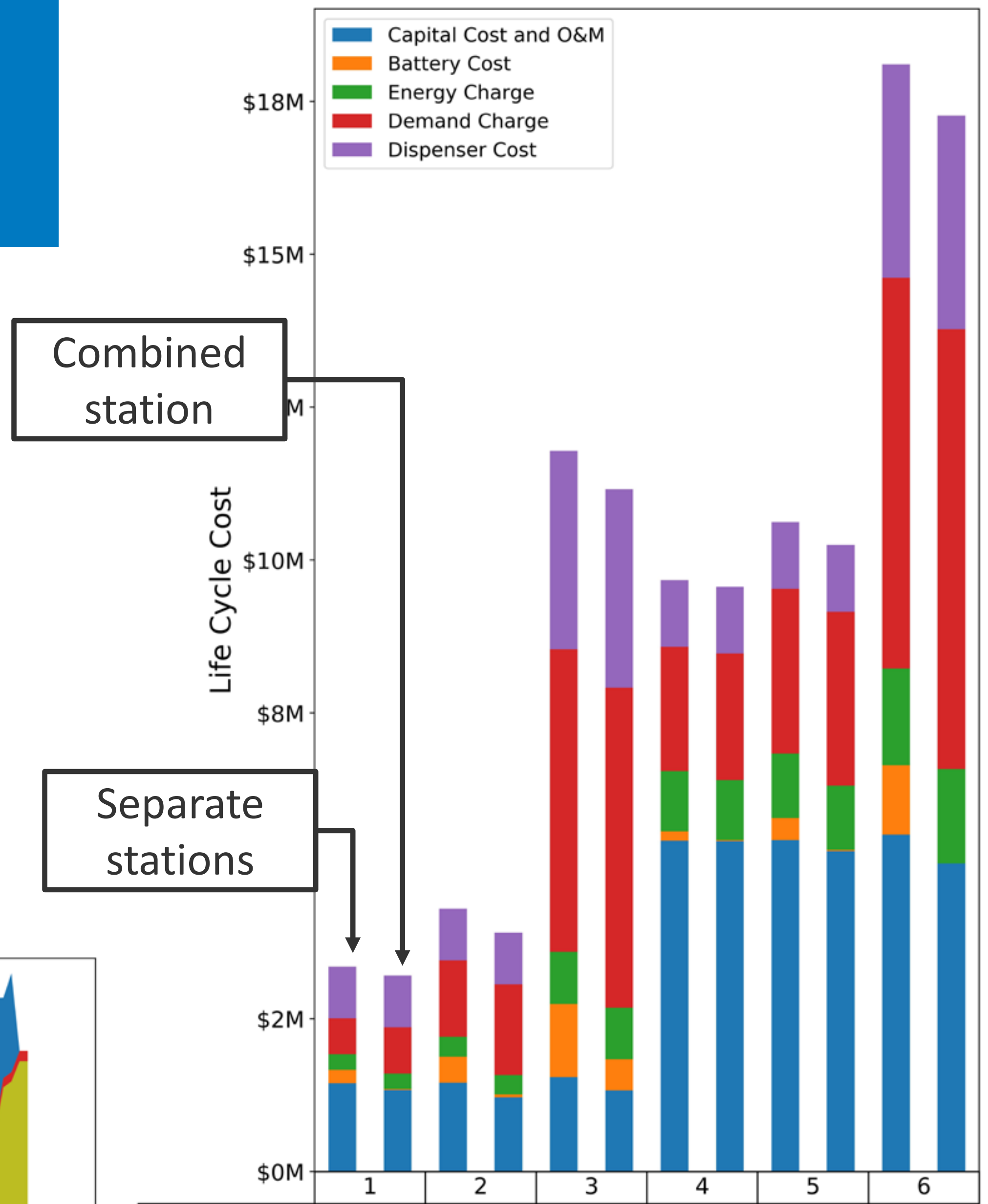
Combined Hydrogen/Electric Fueling Station Financial Screening

Description: NREL analyzed potential for life cycle cost reduction by co-locating DCFC and H_2 fueling stations. Evaluated coordinated system dispatch and renewable integration across a variety of load and utility tariff scenarios.

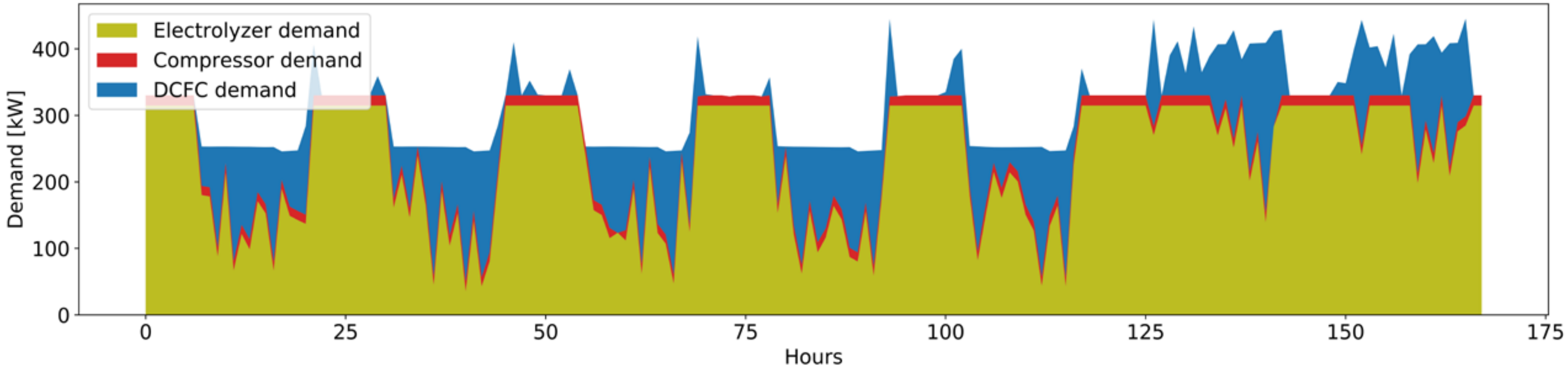
Technologies: H_2 fueling stations (w/ electrolyzer, compressor, low- and high-pressure storage), DCFC stations, solar PV, battery storage

Impact: Demonstrated savings of over 11% of total life cycle cost for combined H_2 and DCFC system design w/ solar PV

Partners: Car manufacturer, DOE



	1	2	3	4	5	6
% Savings	6.4	11.7	7.5	1.5	4.1	5.9
Location	NY	NY	NY	NY	NY	NY
Hydrogen	Low	Low	Low	High	High	High
DCFC (Plugs)	4_lu	4	20	4_lu	4	20
Storage	Yes	Yes	Yes	Yes	Yes	Yes
PV	Yes	Yes	Yes	Yes	Yes	Yes



DCFC
Station Design

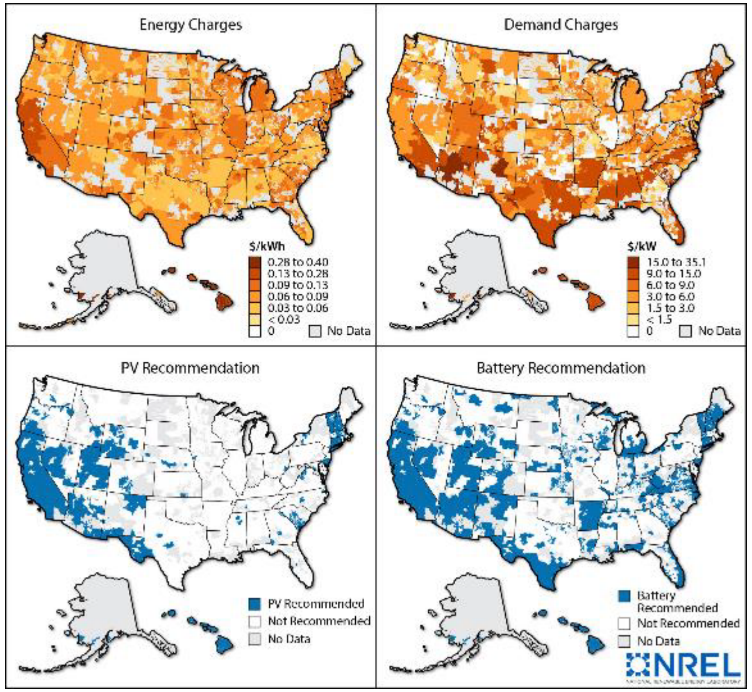
Description: NREL explored solutions that can help make DCFC more affordable for electric vehicle (EV) drivers in the United States:

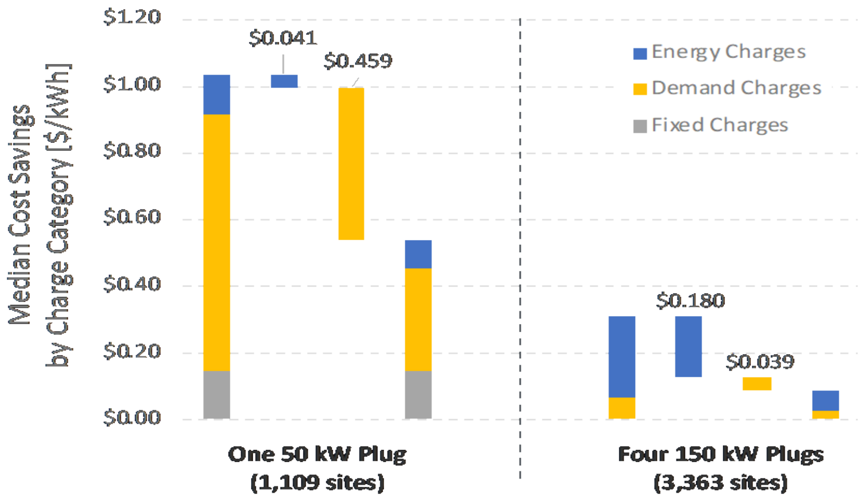
- Solar PV and/or energy storage (batteries)
- Co-locating DCFC with a commercial building.

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.

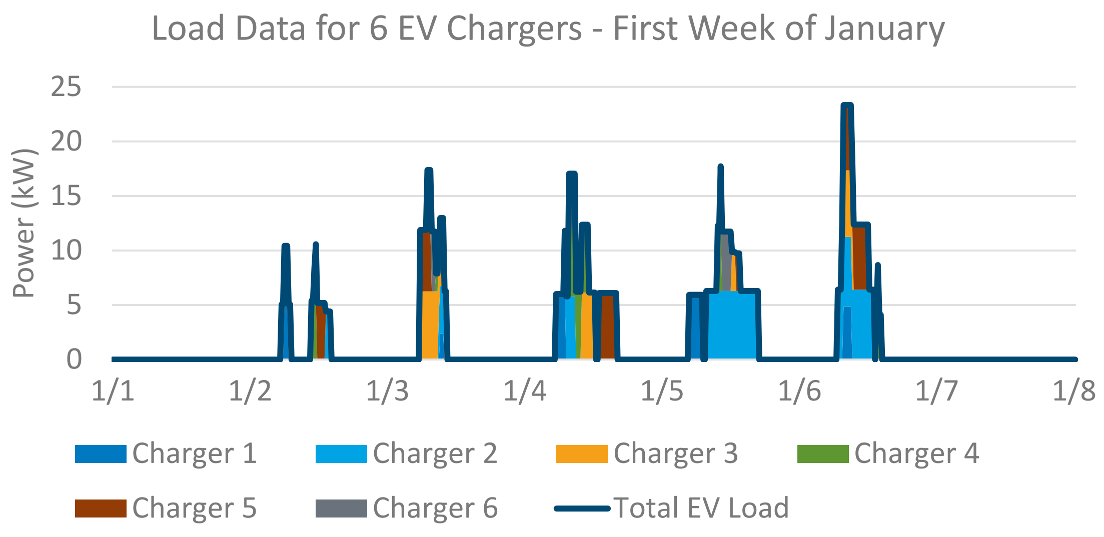
Impact of EV Workplace Charging in Minnesota

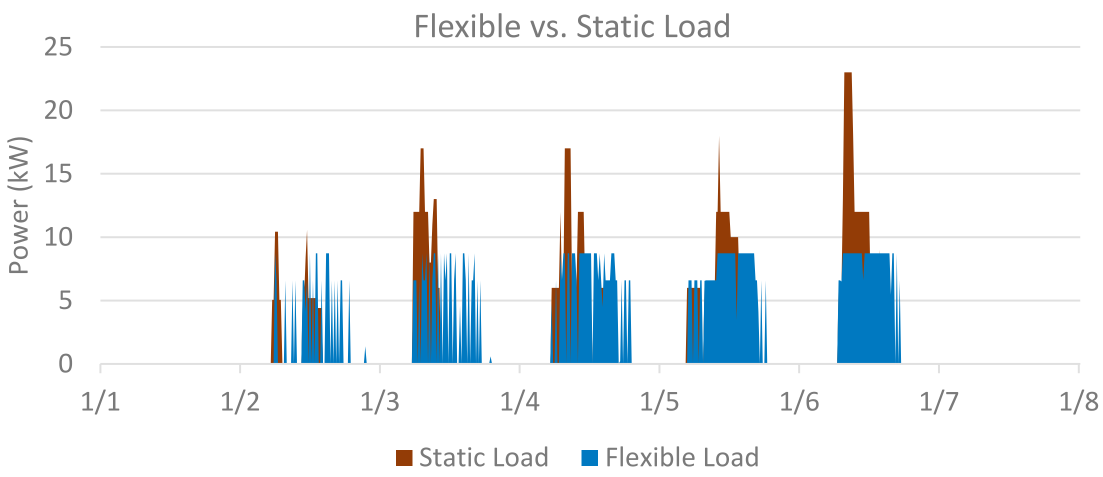
Description: NREL used REopt to evaluate the economics of workplace EV charging. NREL's EVI-Pro database used to generate static and flexible EV load profiles.

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.

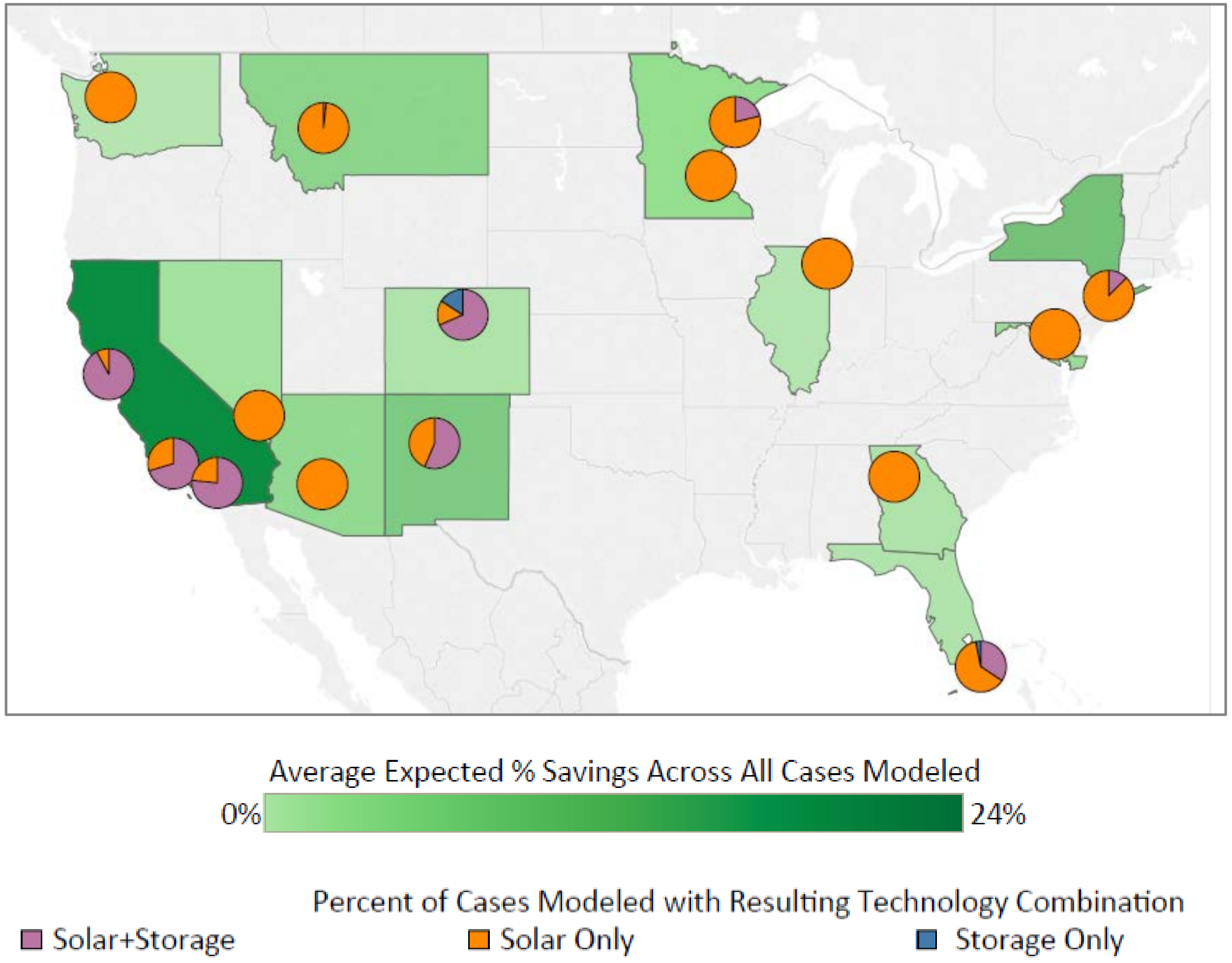
National Economic Analysis of Behind-the-Meter Storage

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.

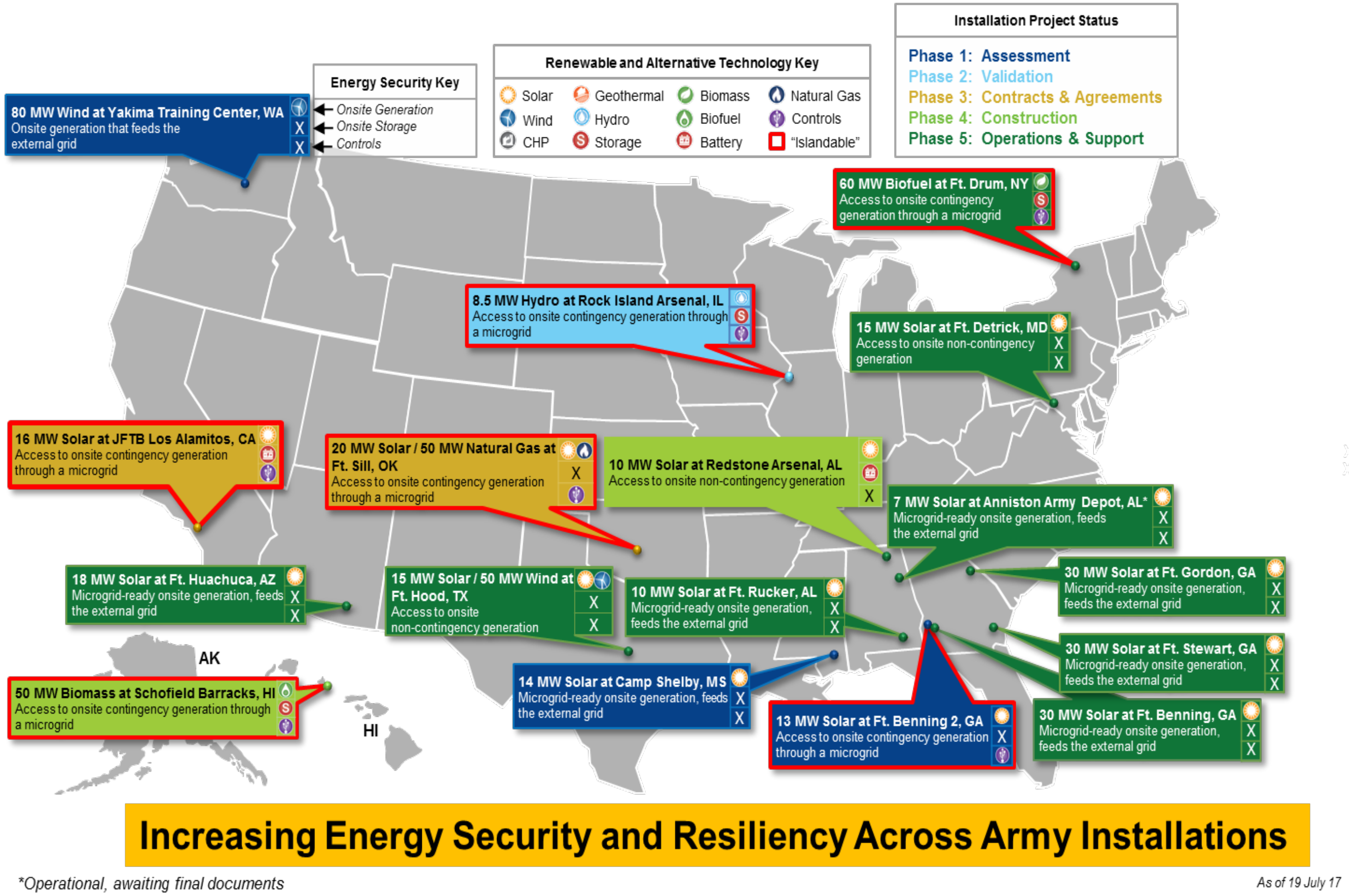
Deploying Cost-Effective Efficiency, Renewable Energy, and Storage

Description: NREL is working with the Army Office of Energy Initiatives to evaluate renewable energy 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 renewable energy, 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.

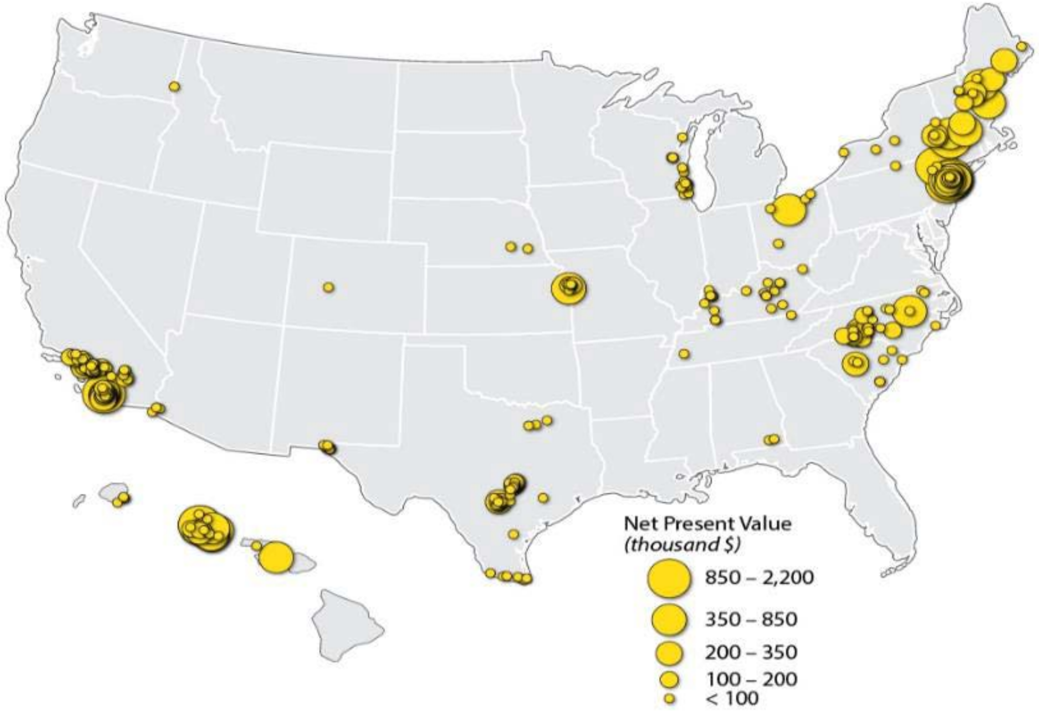
Identifying and Prioritizing Projects Across a Portfolio

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

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

Impact: Identified cost-effective renewable energy 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.

Where Does Solar and Storage Make Sense?

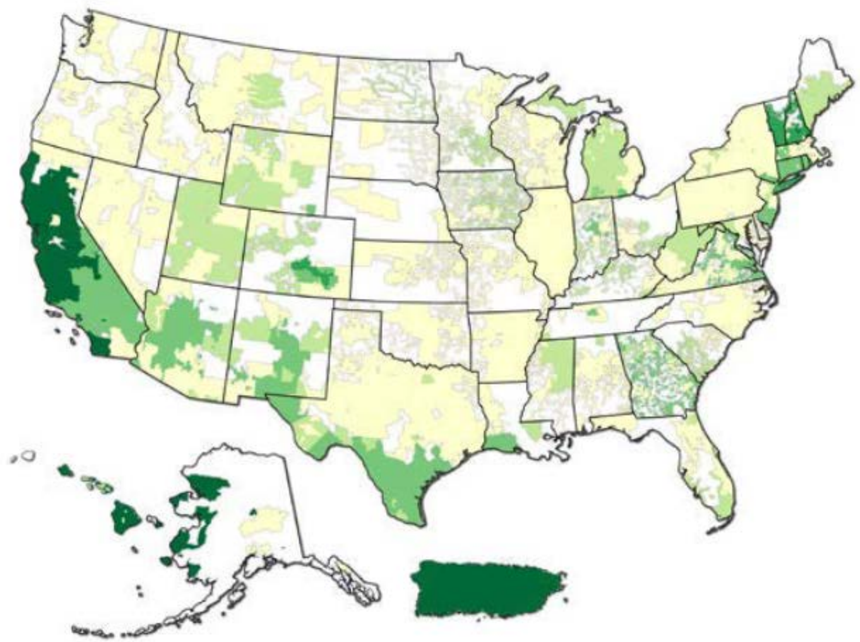
Description: NREL evaluated thousands of combinations of utility territories, solar resources, climate zones, and capital costs to identify scenarios where battery storage is cost-effective across the United States.

Technology: Solar PV and Li-ion battery storage

Impact: Solar-plus-storage systems generate greater savings across more tariff rates and more geographic locations than storage alone.

Partners: Federal Energy Management Program

Percent life cycle cost savings from deploying behind-the-meter BESS, potentially coupled with solar PV



This map shows where in the United States there is potential for cost savings from implementing a behind-the-meter storage system with solar PV, compared to purchasing all electricity from the utility. Areas in green indicate percentage life cycle cost savings (including utility costs as well as capital and operations and maintenance costs) of the deployed systems. Areas in yellow indicate that the area was evaluated, but a system would not provide life cycle cost savings. *Image from NREL*

NREL. *Where and When Does Solar Plus Storage Make Sense for Commercial Buildings?* Golden, CO: NREL. October 2020. https://www.nrel.gov/docs/fy21osti/77112.pdf.

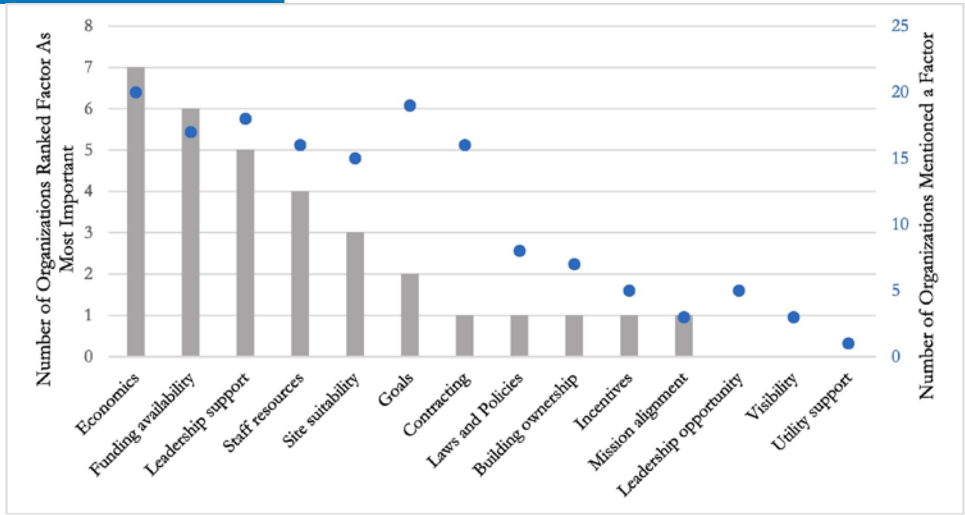
REopt Gap Analysis

Description: Exploring gaps between optimal model solutions and technology deployment using results from interviews with 20 federal, state, and city government agencies that have used REopt to inform energy decisions.

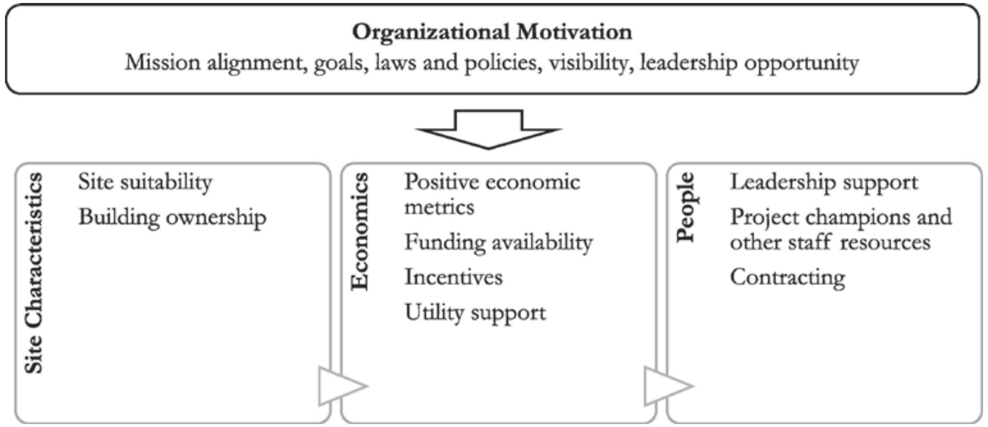
Technology: Renewable energy and battery storage

Impact: Key factors include economics, funding availability, and leadership support; factors present in stage gates where factors in earlier stages must be satisfied first. Suggested improvements include tool improvements, results communication, and additional resources.

Partners: Federal Energy Management Program, state, local, federal government agencies

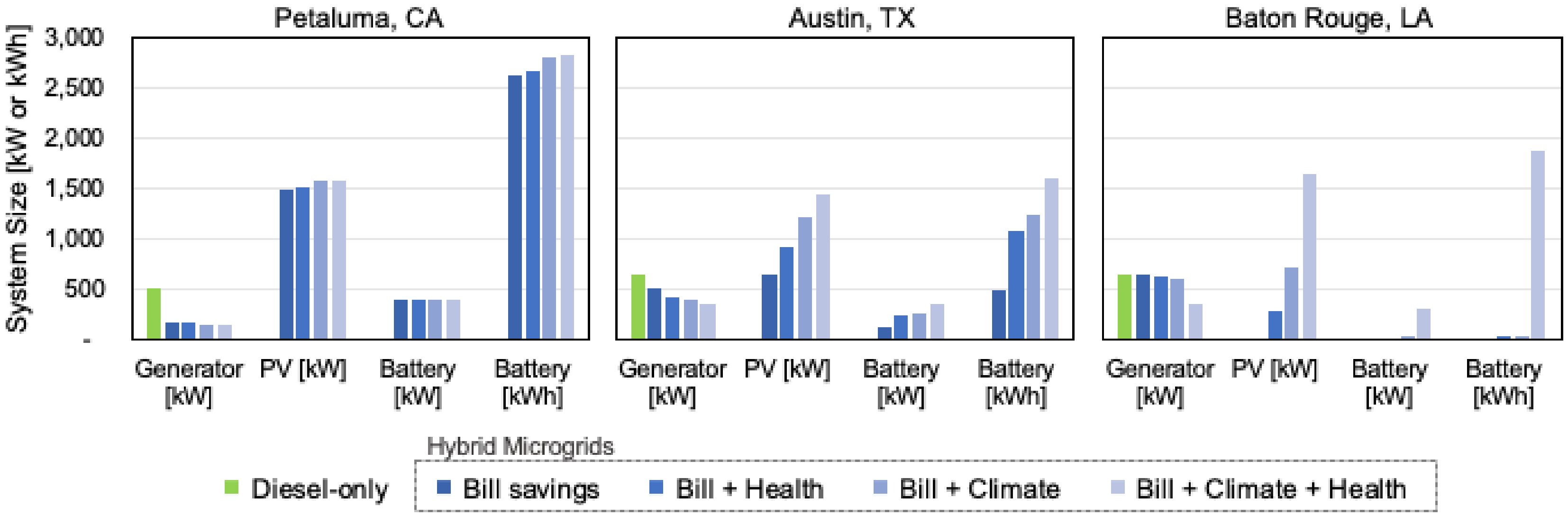


Count of number of organizations that mentioned a factor and the number of organizations that ranked a factor as most important



Factors typically present in stage gates, where factors in earlier stages must be satisfied first.

Looking Beyond Bill Savings to Equity in Microgrid Deployment



Cost-optimal system sizes across locations and optimization scenarios. Smaller diesel generators and larger PV and storage systems become cost-optimal as health and climate costs are incrementally included within the life cycle cost calculation.

Description: The value of microgrids is often measured by economic savings and resilience; here we quantify broader costs and benefits, including utility bill savings, value of resilience, social cost of carbon, public health costs, and jobs associated with the construction and operation of microgrids.

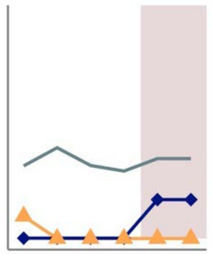
Technology: Solar PV, battery storage, diesel generators

Impact: When climate, health, resilience, and job creation are considered, cost-optimal microgrids include more renewable generation, leading to a 52%–82% reduction in emissions and diesel fuel use. The net present values grow by $10–16 million, indicating potential for greater microgrid deployment if energy justice values are incorporated in decision-making. These findings may be useful to communities as they seek to strengthen resilience to natural disasters while also improving public health, meeting climate goals, and providing economic opportunity for residents.

Partners: Federal Energy Management Program

Anderson, Kate, Amanda Farthing, Emma Elgqvist, Adam Warren. 2022. “Looking Beyond Bill Savings to Equity in Renewable Energy Microgrid Deployment”, *Renewable Energy Focus* Volume 41: pages 15-32. https://doi.org/10.1016/j.ref.2022.02.001.

Lessons From Observed and Modeled Solar-Plus-Storage Systems

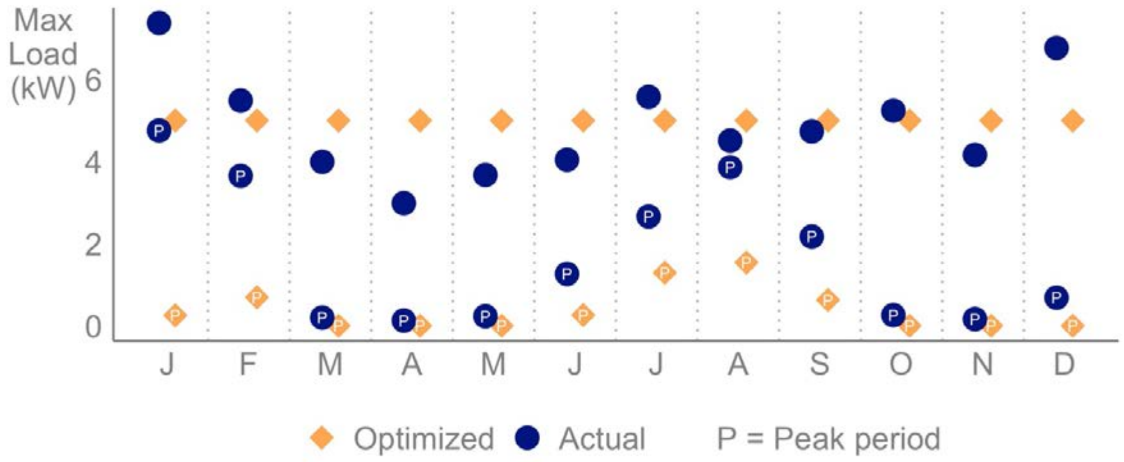


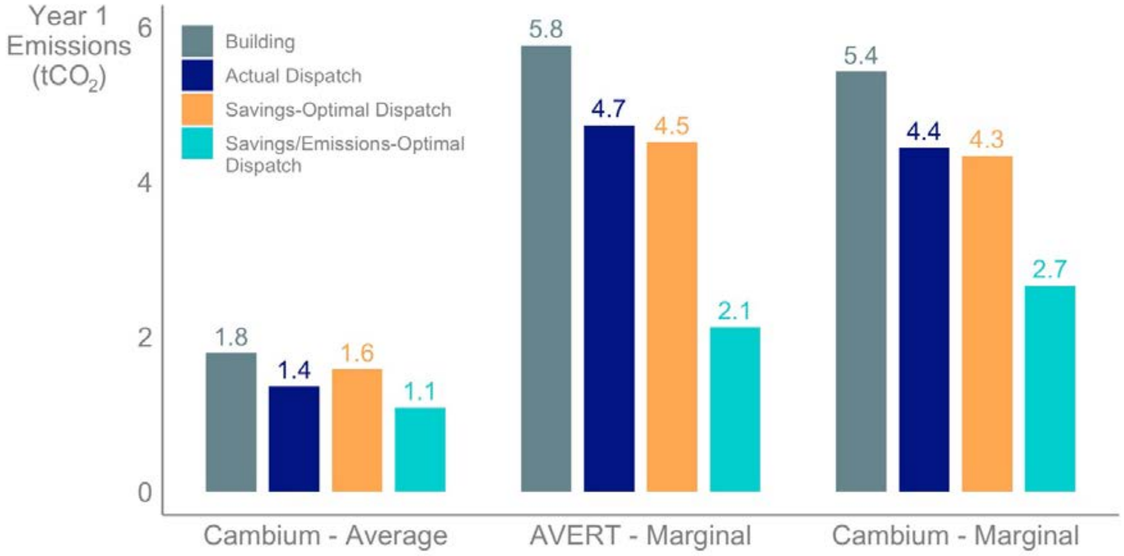
Description: Utilizing actual data from new-construction homes with solar PV and battery storage systems, NREL evaluated differences in optimal system operations and sizes to inform improvements to dispatch strategy improvements and future technology deployment.

Technology: Solar PV and Li-Ion battery storage

Impact: Demand charges can be reduced significantly by moderating the battery dispatch across the whole peak period. The dispatch could be modified to reduce emissions without sacrificing cost savings.

Partners: Solar Energy Technology Office, sonnen Inc.





Balancing Cost and Resilience With CHP at Wastewater Treatment Facility

Northside Wastewater Treatment Plant. Source: CFPUA

Description: NREL evaluated opportunities for CHP and other DERs to provide cost savings and resilience benefits to the Northside Wastewater Treatment Plant, a critical infrastructure susceptible to power outages.

Technology: CHP fueled by free on-site biogas and natural gas, diesel generator, solar PV, battery storage

Impact: Building a hybrid CHP-PV-storage system reduces life cycle cost of energy for the site by 3% ($301,000 over 25 years).

- If load can be reduced during the outage by storing and deferring wastewater treatment, required system sizes and costs decrease.
- 60% of the load can be met in the No-Diesel scenario, and 80%–85% in the CHP-Only or All-Technologies scenario, at no additional life cycle cost, compared to the business-as-usual (BAU) no-outage case.

Partners: DOE Advanced Manufacturing Office