Adapting optimization models to better inform energy planning decisions

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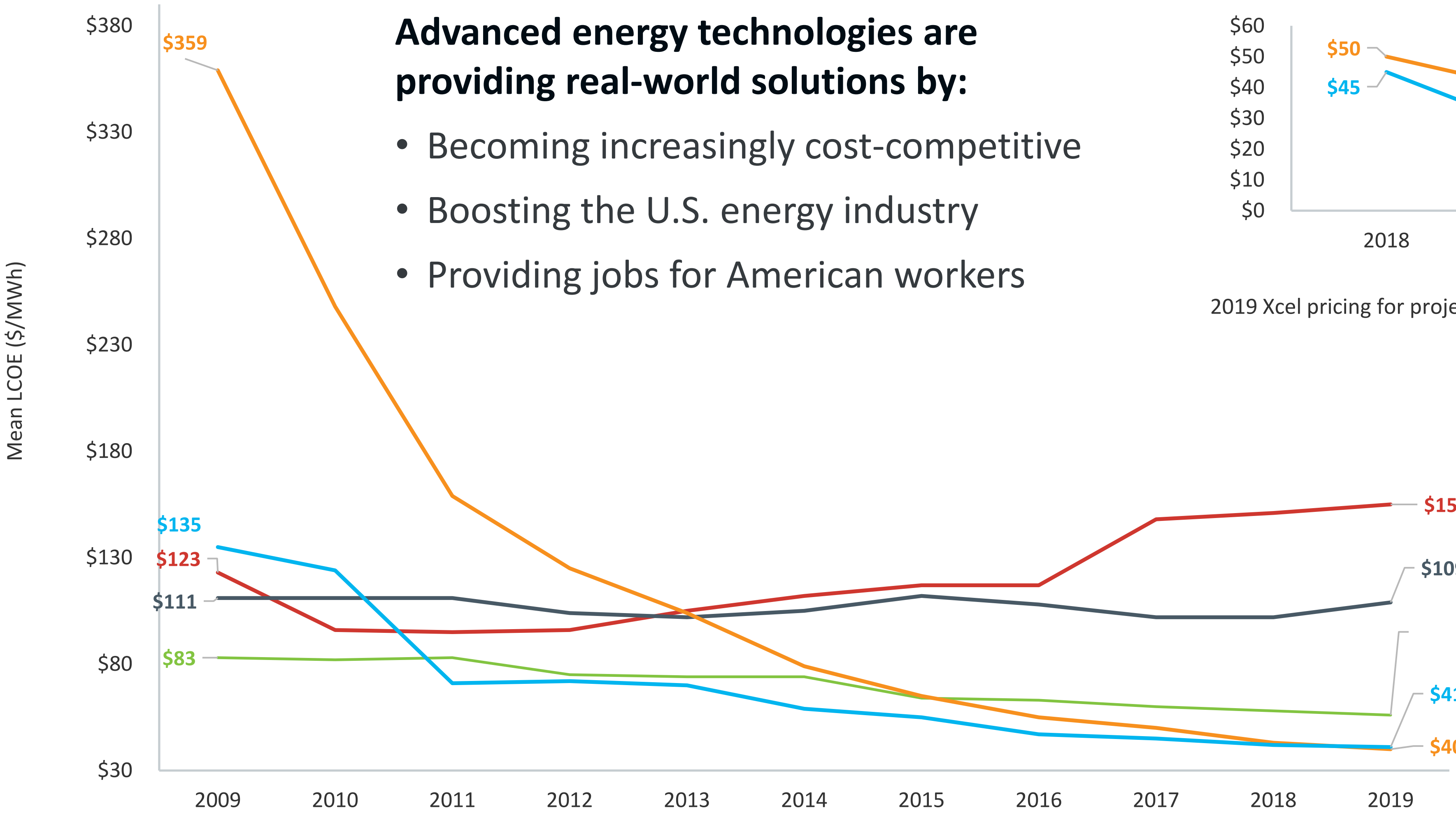
February 4, 2021

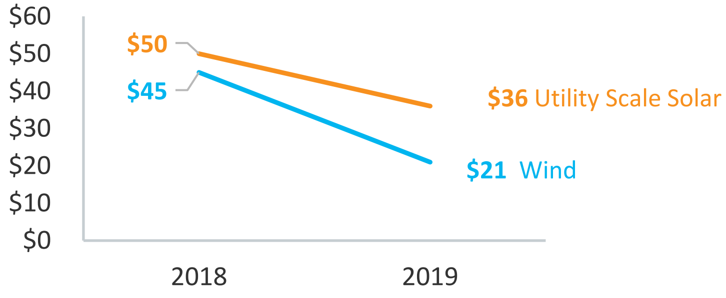

An Energy Revolution
Is Sweeping the Nation

Cost for Renewables are Falling



Advanced energy technologies are providing real-world solutions by:

- Becoming increasingly cost-competitive
- Boosting the U.S. energy industry
- Providing jobs for American workers



2019 Xcel pricing for projects due to go online in 2023

Source: *Lazard's 2019 Levelized Cost of Energy Analysis*

NREL at-a-Glance

2,926

Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

World-class

facilities, renowned technology experts

More than **900**

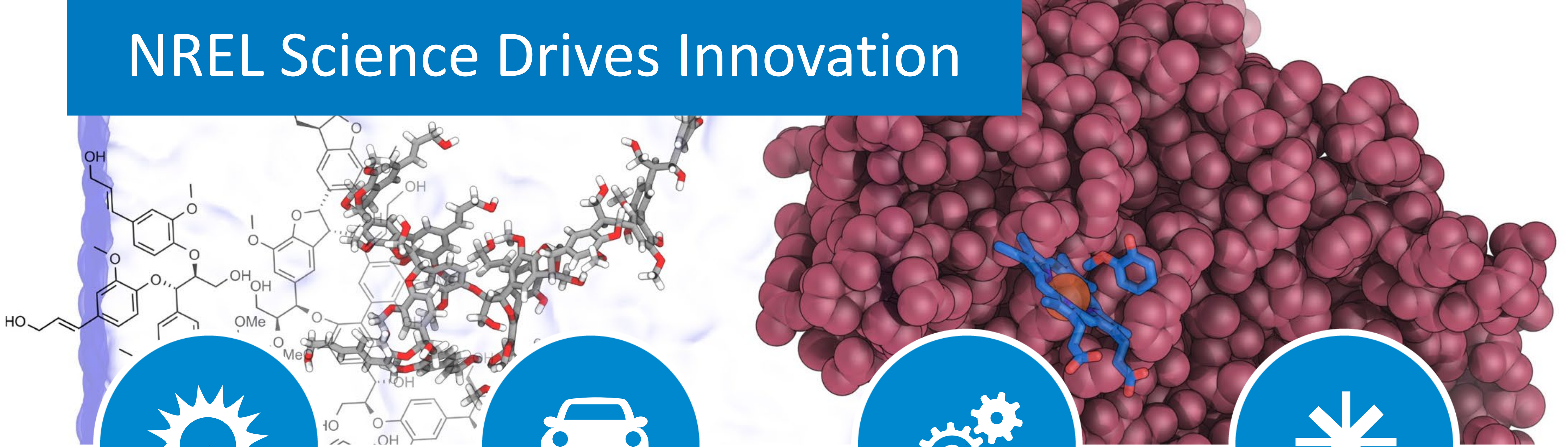
Partnerships

with industry, academia, and government

Campus

operates as a living laboratory

NREL Science Drives Innovation



Renewable Power

Solar

Wind

Water

Geothermal

Sustainable Transportation

Bioenergy

Vehicle Technologies

Hydrogen

Energy Efficiency

Buildings

Advanced Manufacturing

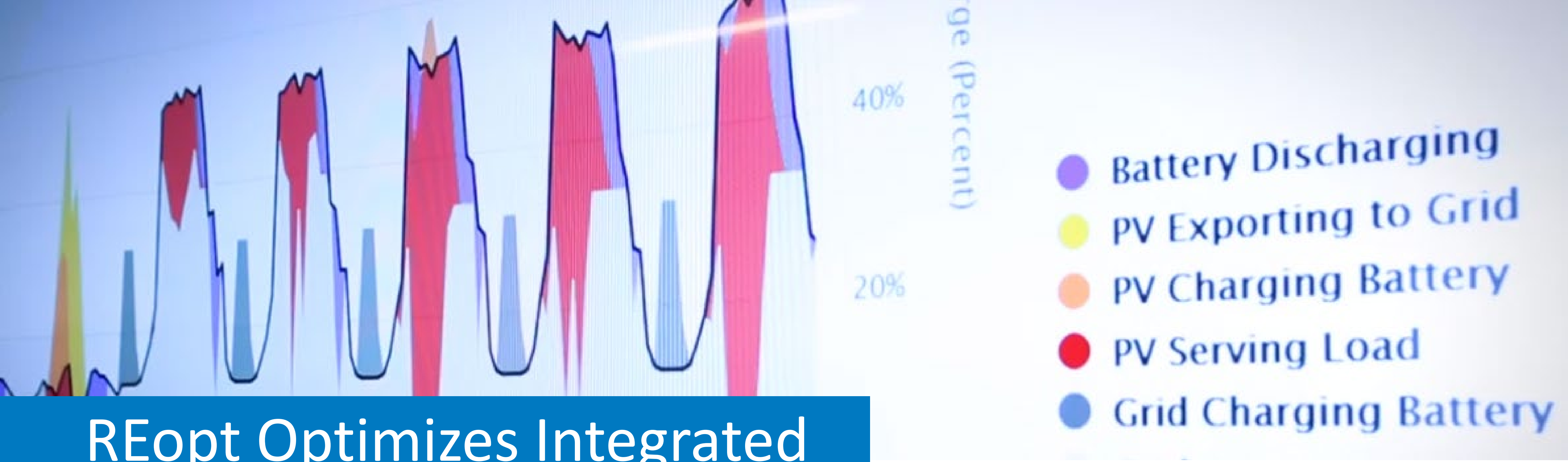
Government Energy Management

Energy Systems Integration

Grid Integration

Hybrid Systems

Security and Resilience



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

Will RE + Storage Work for Your Site?

RE Resource

Utility Cost & Consumption

Technology Costs & Incentives

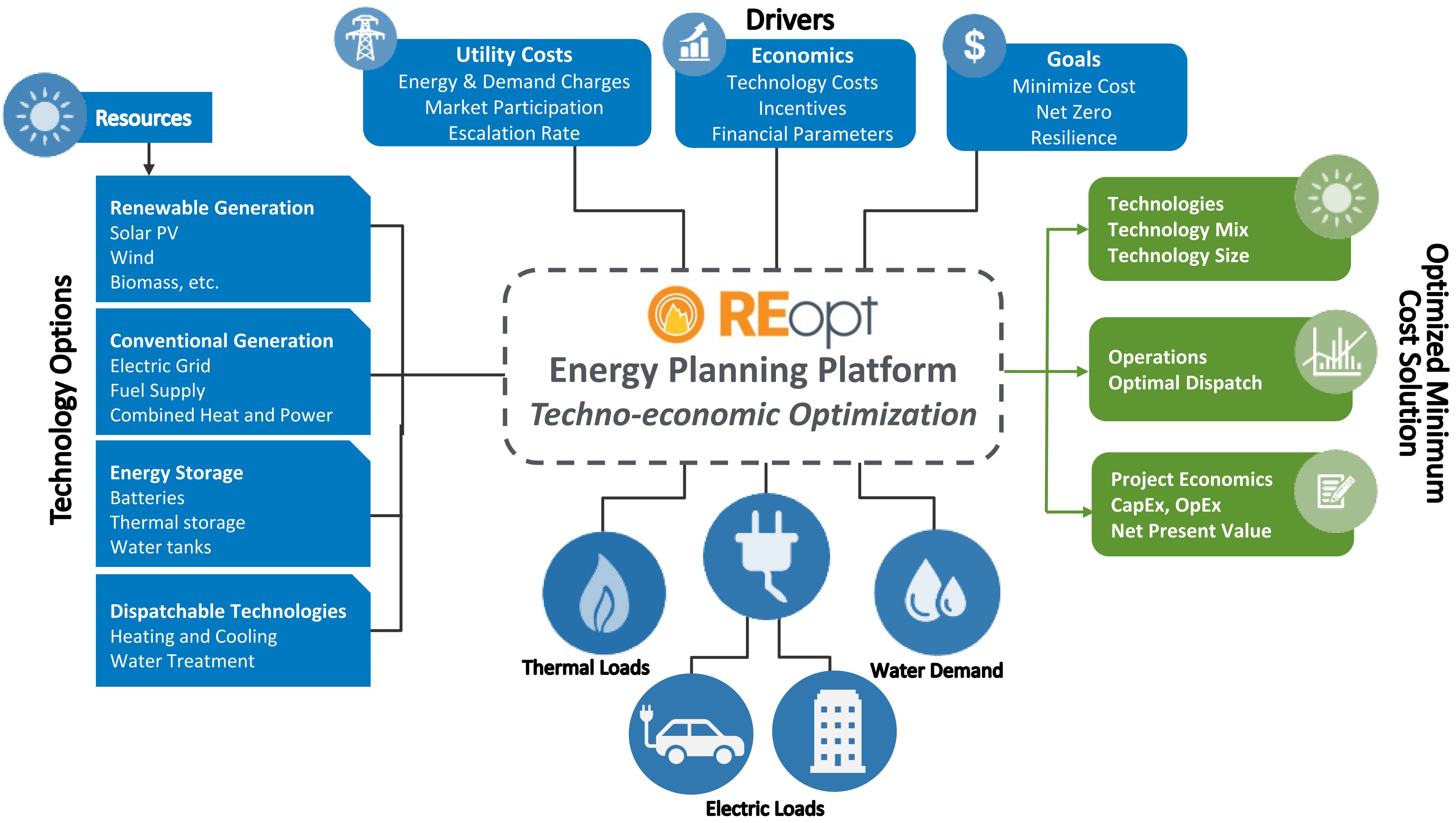
Financial Parameters

Resilience Goals

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

REopt

Formulated as a mixed integer linear program, REopt considers the integration of multiple technologies and evaluates the trade-off between capital costs and savings to find the most cost-effective mix of technologies to meet the load(s)



REopt Objective Function

The objective function minimizes the lifecycle cost of energy, including capital costs, operation and maintenance costs, energy costs, and maximizes incentives.

$$
\begin{aligned}
\text{Minimize} \quad & \underbrace{\sum_{t\in\mathcal{T},k\in\mathcal{K}^{c},s\in\mathcal{S}_{tk}} \left(c^{\text{cm}}_{ts}\cdot X^{\sigma s}_{tks} + c^{\text{cb}}_{ts}\cdot Z^{\sigma s}_{tks}\right)}_{\text{Total Technology Capital Costs}} + \underbrace{\sum_{b\in\mathcal{B}} \left(c^{\text{kW}}_{b}\cdot X^{\text{bkW}}_{b} + (c^{\text{kWh}}_{b} + c^{\text{omb}}_{b})\cdot X^{\text{bkWh}}_{b}\right)}_{\text{Total Storage Costs}} + (1-f^{\text{tow}})\cdot f^{\text{om}}\cdot\left(\underbrace{\sum_{t\in\mathcal{T}} c^{\text{om}\sigma}_{t}\cdot X^{\sigma}_{t}}_{\text{Fixed O\&M Costs}} + \underbrace{\sum_{t\in\mathcal{T}^{\text{f}},h\in\mathcal{H}} c^{\text{omp}}_{t}\cdot X^{\text{rp}}_{th}}_{\text{Variable O\&M Costs}}\right) + \\
& (1-f^{\text{tot}})\cdot\left(\underbrace{\Delta\cdot\sum_{f\in\mathcal{F}} c^{\text{u}}_{f}\cdot\sum_{t\in\mathcal{T}_{f},h\in\mathcal{H}} f^{\text{pf}}_{t}\cdot X^{\text{f}}_{th}}_{\text{Total Production Costs}}\right) + (1-f^{\text{tot}})\cdot f^{\text{e}}\cdot\left(\underbrace{\Delta\cdot\sum_{u\in\mathcal{U}^{\text{P}},h\in\mathcal{H}^{\text{g}}} c^{\text{g}}_{uh}\cdot X^{\text{g}}_{uh}}_{\text{Total Demand Charges}} + \underbrace{\sum_{r\in\mathcal{R},e\in\mathcal{E}} c^{\text{r}}_{re}\cdot X^{\text{de}}_{re}}_{\text{Peak Ratchet Charges}} + \underbrace{\sum_{m\in\mathcal{M},n\in\mathcal{N}} c^{\text{rm}}_{mn}\cdot X^{\text{dn}}_{mn}}_{\text{Peak Monthly Demand Charges}} - \right. \\
& \left. \underbrace{\Delta\cdot\left(\sum_{h\in\mathcal{H}^{\text{g}}}\left(\sum_{u\in\mathcal{U}^{\text{sb}}} c^{\text{e}}_{uh}\cdot X^{\text{stg}}_{uh} + \sum_{t\in\mathcal{T},u\in\mathcal{U}^{\text{s}}_{t}} c^{\text{e}}_{uh}\cdot X^{\text{ptg}}_{tuh}\right)\right)}_{\text{Total Energy Exports}} + \underbrace{c^{\text{afc}} + X^{\text{mc}}}_{\text{Total Fixed Charges}}\right) - (1-f^{\text{tow}})\cdot\underbrace{\sum_{t\in\mathcal{T}} X^{\text{pi}}_{t}}_{\text{Production Incentives}}
\end{aligned}
$$

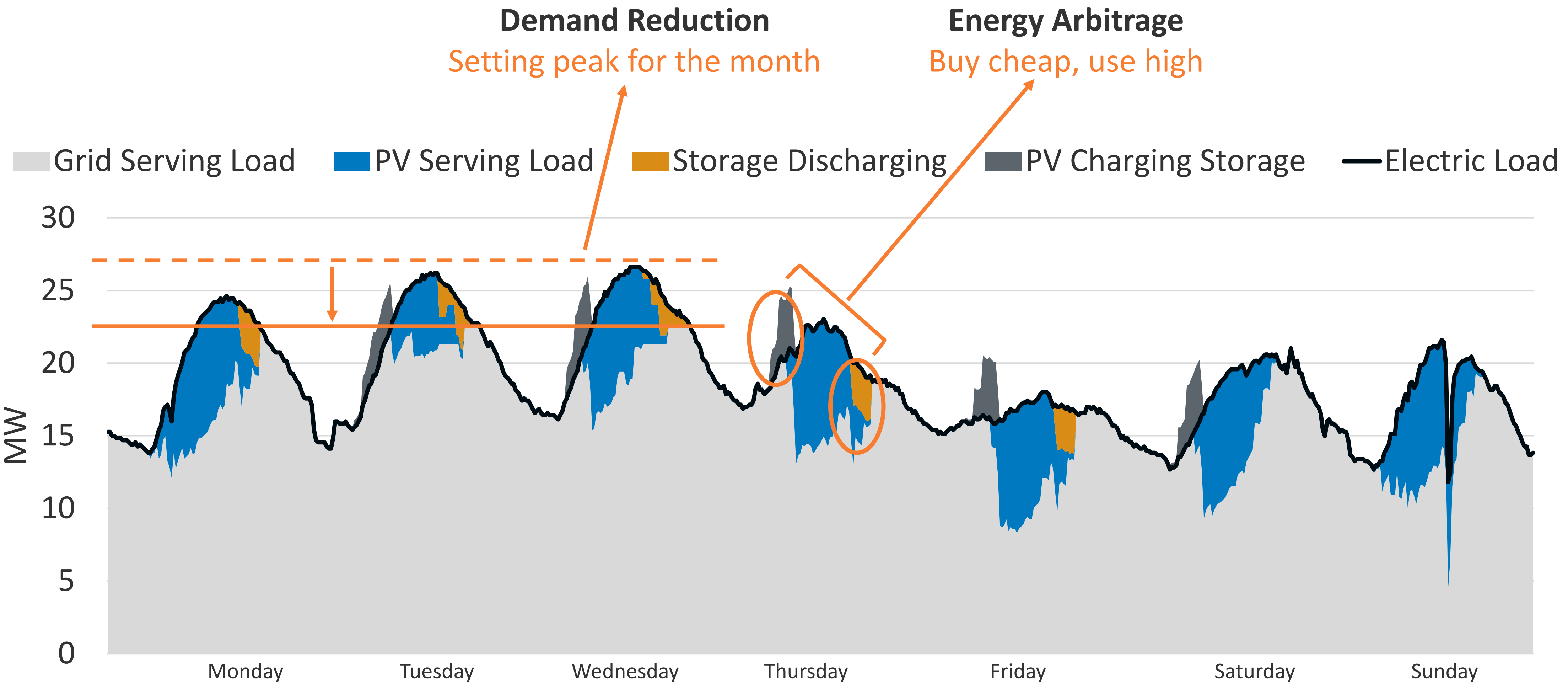
Ogunmodede, O., Anderson, K., Cutler, D., & Newman, A. (2021). Optimizing Design and Dispatch of a Renewable Energy System. Accepted for publication in *Applied Energy*.

REopt Lite Constraints

- Fuel constraints
- Switch constraints
- Storage size, state of charge, and operational constraints
- Production incentive cap
- Power rating
- Load balancing and grid sales
- Rate tariff constraints
- Minimum utility charge
- Non-negativity and integrality

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

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?

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 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?

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.

Design Tradeoffs between Economics and Resilience

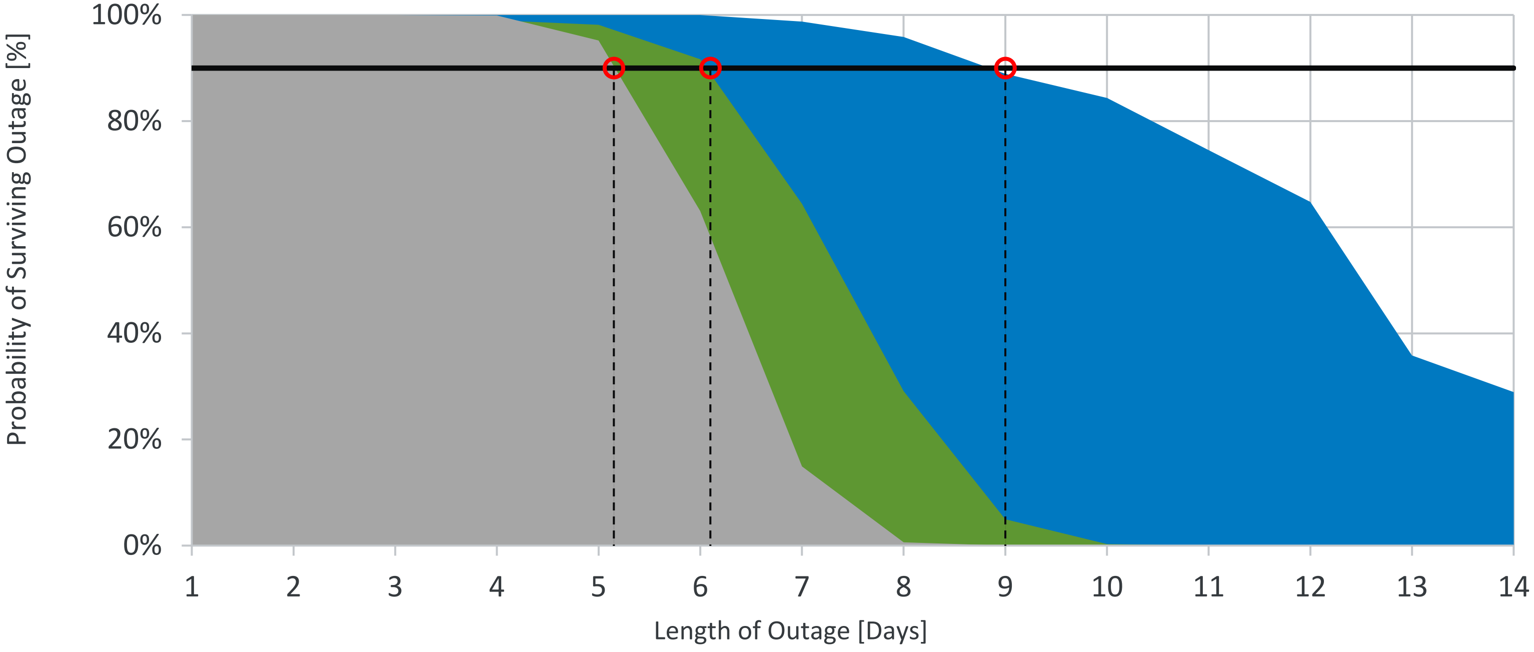
Description: NREL used REopt to evaluate how long existing and proposed backup energy systems could sustain the critical load during an outage at an Army National Guard base. REopt evaluated thousands of random grid outage occurrences and durations and compared hours survived with diesel gensets vs.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

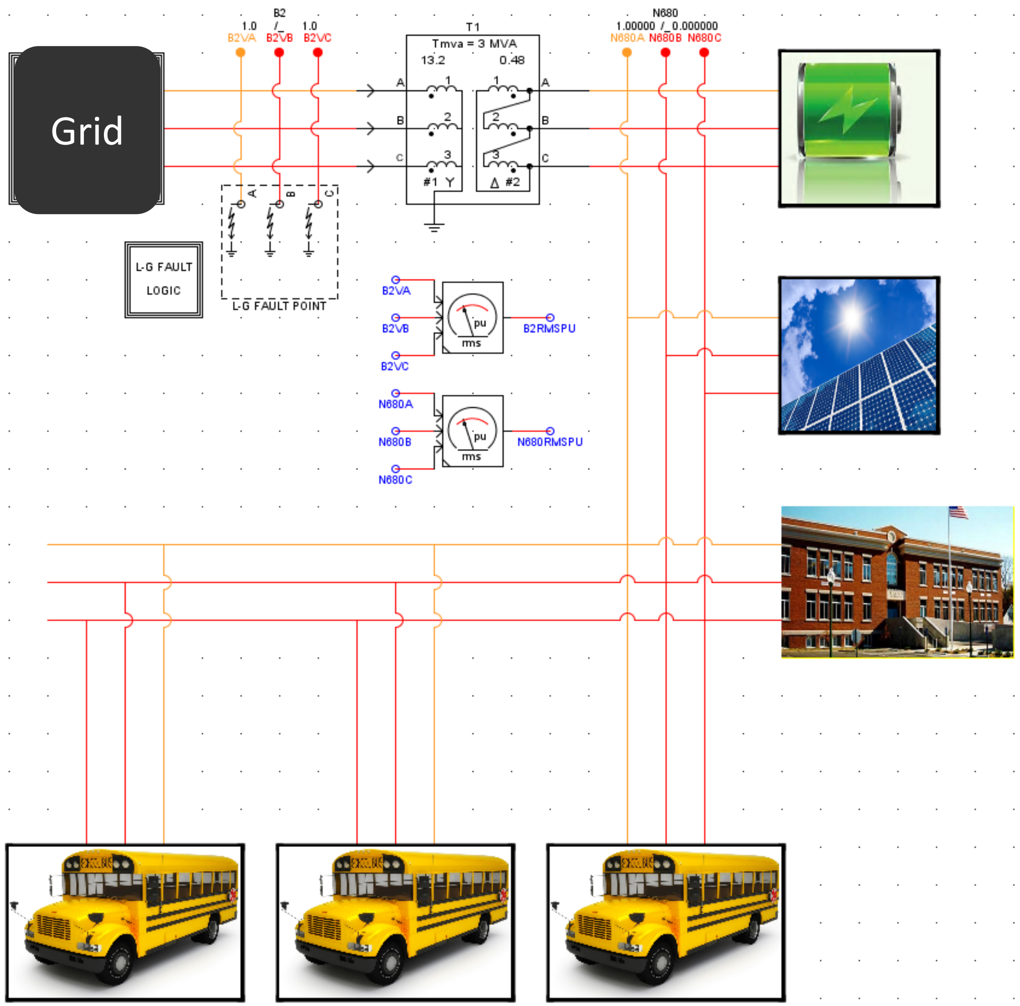
Integrating EV Fleets With DER and Grid

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.

The Gap Between Modeling and Deployment

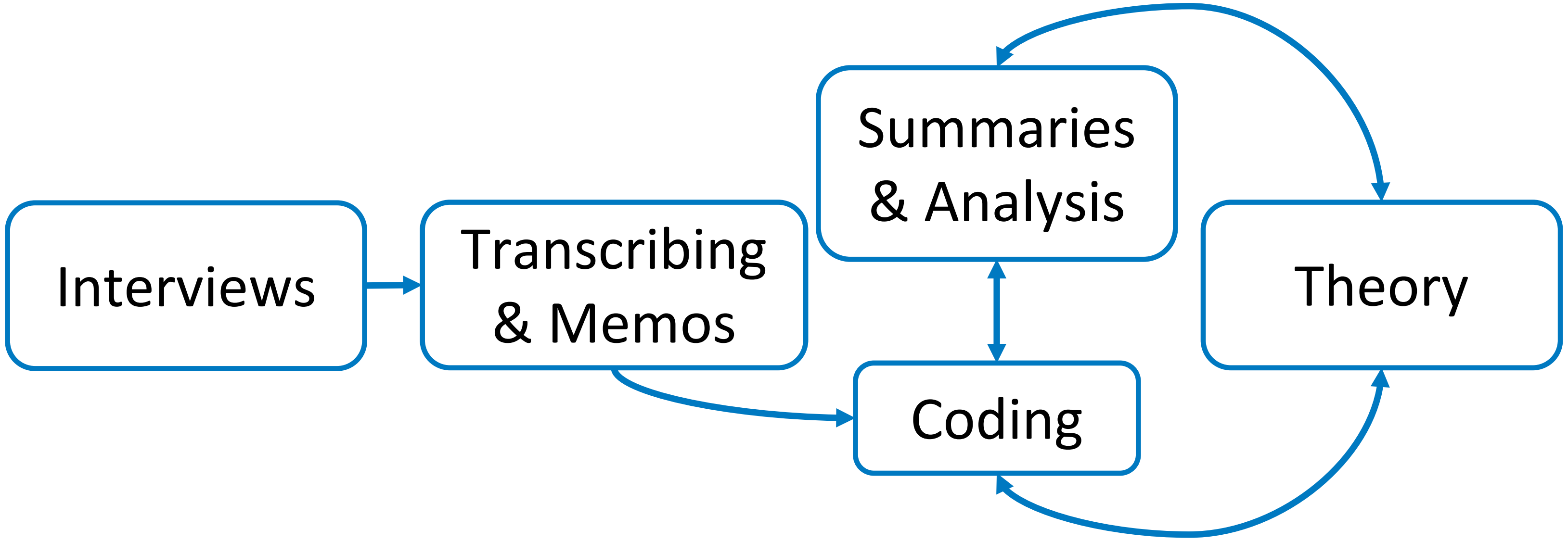
- A gap exists between actual and modeled optimal clean energy deployment.
- Qualitative values and practical deployment barriers are not always captured in models.
- This can lead decision makers down paths that will ultimately fail.
- This research explores how models can be adapted to inform more realistic energy solutions.

Drivers of energy deployment and their inclusion in models

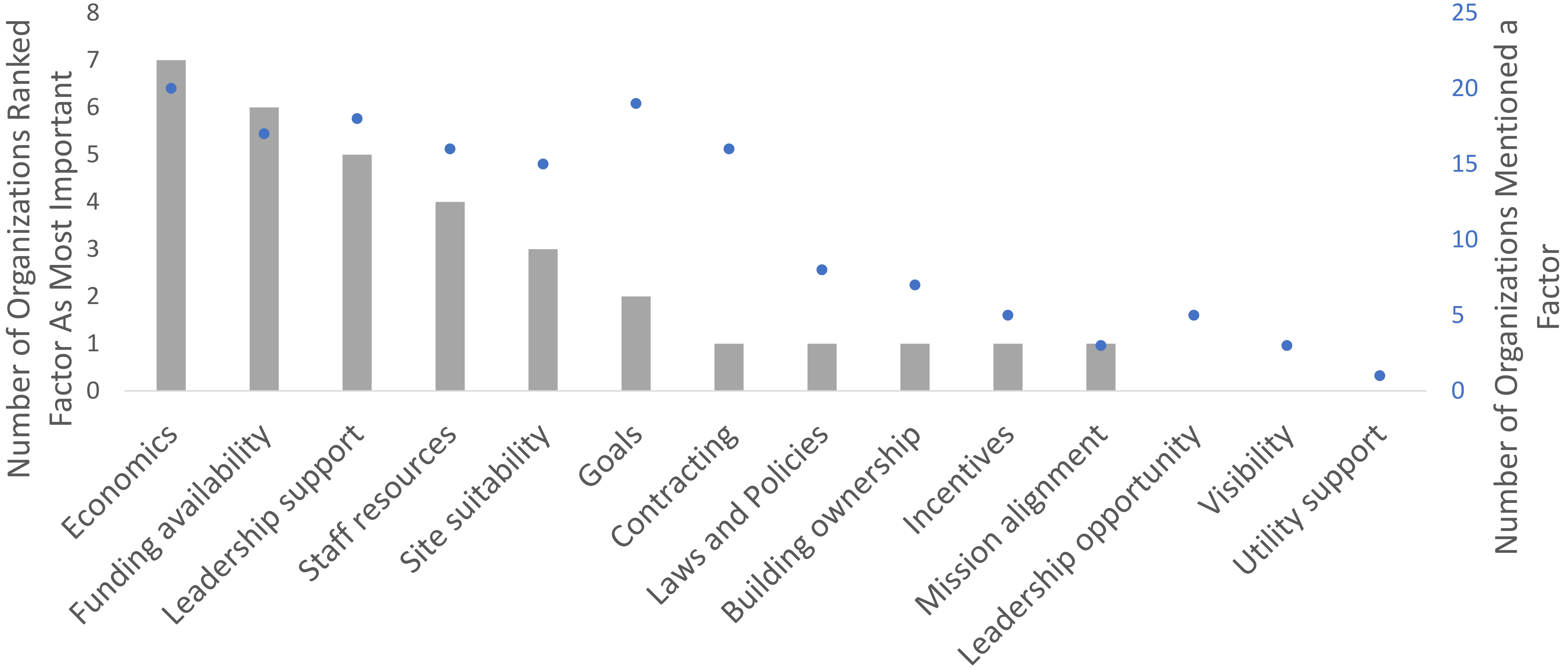
Type	Driver	Included in energy models
Technical	Energy generation or savings Site suitability	x
Economic	Energy price Discount rates Incentives	x
Regulatory	Unenforced, conflicting, unstable policy	
	Land ownership	
	Ease of permitting	
Organizational	Alignment with corporate strategy	
	Organizational divisions of labor & power	
	Capacity to act	
Social and Behavioral `	Aversion to risk and uncertainty	
	Non-monetary costs of information	
	Heterogeneity of preference	
	Peer effects	
	Social acceptance	
	Perceived status, recognition, and pride	
	Perceived fairness in decision-making	
	Trust between community and developer	
	Individual values	
	Aesthetics, branding, perceived reliability, comfort, quality, design	

Approach

- Research questions
  1. What are the drivers of and barriers to renewable energy deployment?
  2. How do decision tools impact deployment decisions?
  3. How could a tool or resource be adapted to increase deployment?
- Comparative case study methodology to develop grounded theory



Results: Factors in RE Deployment



Anderson, K., Nevrly, M., Elgqvist, E. & Bazilian, M. (2021). Closing the Gap Between Renewable Energy Decision Models and Deployment. Submitted for publication in *Energy Research and Social Science*.

Results: Factors Present in Stage Gates

Organizational Motivation
Mission alignment, goals, laws and policies, leadership opportunity

Site Characteristics
- Site suitability
- Building ownership

Economics
- Positive economic metrics
- Funding availability
- Incentives

People
- Leadership support
- Project champions and other staff resources

Other Contributors
- Visibility
- Contracting
- Utility support

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Results: The Role of Tools in Deployment Decisions

Factor	Provided by Tool	Not Provided by Tool
Site Suitability	-Estimate renewable energy resources -Estimate system size	-Estimate space available -Assess historical or cultural resource impacts
Building Ownership		-Assess ownership of building or land
Economics	-Calculate cost-effectiveness of RE, as measured by metrics such as net present value	-Gather site-specific load and utility data -Provide local cost estimates
Funding Availability	-Estimate system size, costs, and economic metrics for funding applications	-Identify funding sources -Apply for funding
Staff Resources	-Calculate metrics required to make a decision -Increase staff knowledge of RE opportunities	-Increase staff availability -Create project champion -Provide decision authority
Leadership Support	-Provide metrics to use in gaining support of leaders	-Gain leadership support -Provide legitimization through expert credibility
Goals	-Calculate contribution of RE toward goals	
Laws & Policies	-Estimate impact of interconnection and net metering limits	-Identify laws that govern RE deployment -Assess environmental compliance
Utility Support		-Identify if utility supports RE deployment
Mission Alignment		-Identify if project aligns with mission
Visibility		-Increase visibility
Leadership Opportunity		-Identify if project is new and innovative
Contracting	-Calculate economics of different options	-Develop contracting documents and execute contract
Incentives	-Calculate impact of incentives on economics	-Apply for incentives

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Results: Improvements to Tools and Resources to Increase RE Deployment

Additional Capabilities

- Site-specific data for more accurate size, production, and cost estimates
- Qualitative factors and local knowledge
- More accessible input data
- Additional technologies, goals, financing options
- Uncertainty and multiple scenarios

Results Communication

- Metrics for broader impact (health, jobs)
- Simplified graphical communication

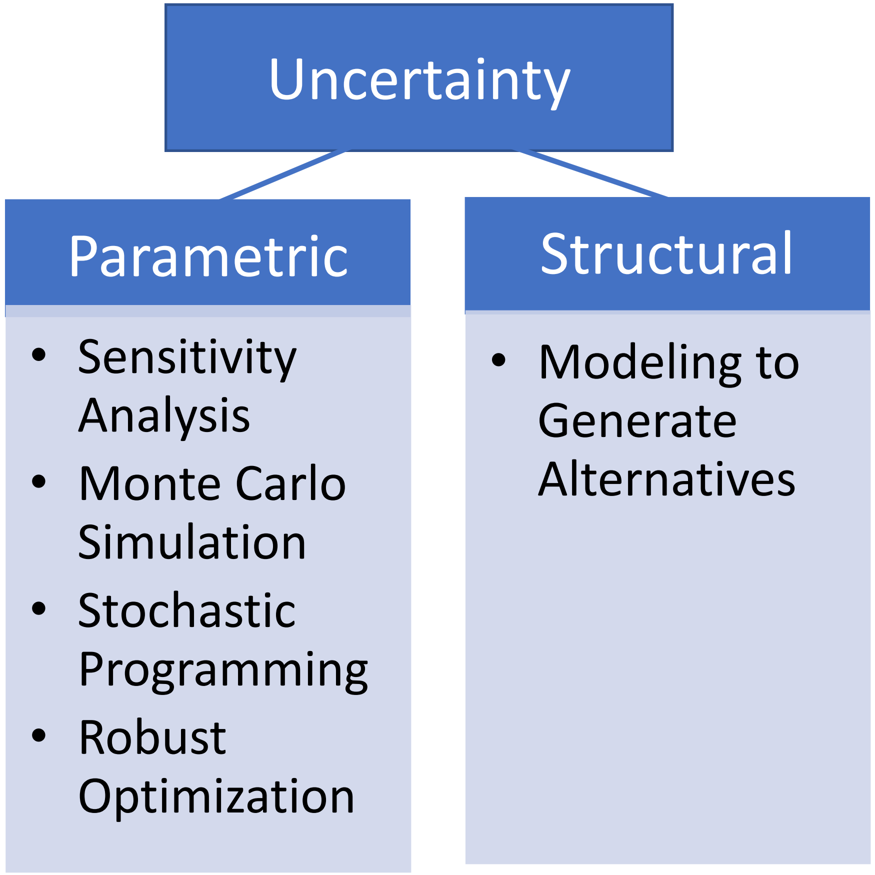
Additional Resources

- Peer network
- Example projects and contacts
- Vendor recommendations
- Funding opportunities list
- Example procurement specifications
- Training resources

Anderson, K., Nevrly, M., Elgqvist, E. & Bazilian, M. (2021). Closing the Gap Between Renewable Energy Decision Models and Deployment. Submitted for publication in *Energy Research and Social Science*.

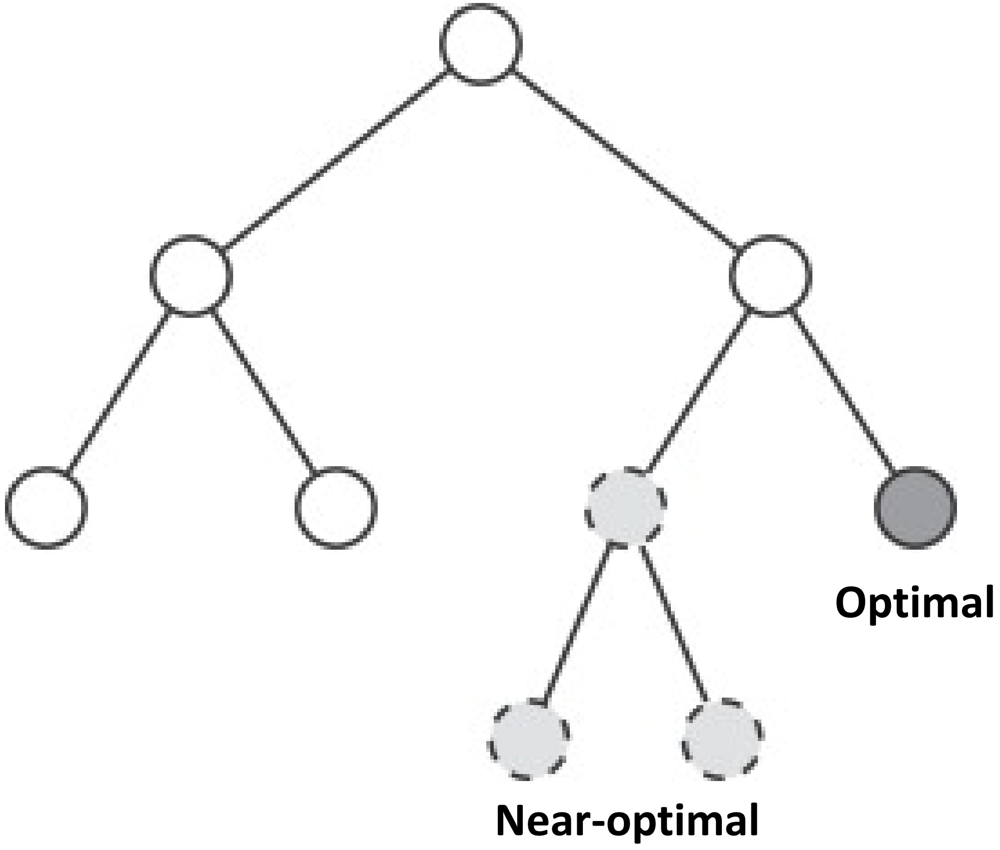
Uncertainty in Energy Models

- Accounting for uncertainty is a major challenge of optimization models.
- *Parametric* uncertainty arises from lack of knowledge about model inputs.
- *Structural* uncertainty results from inability to model certain factors.

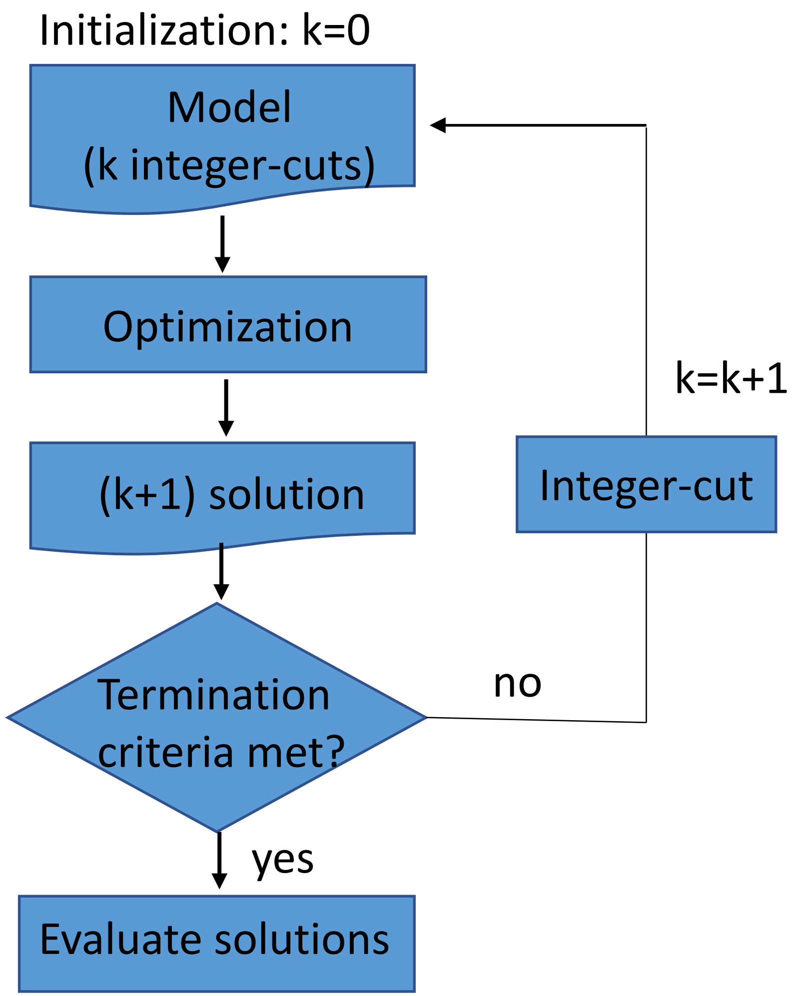


Method #1: Branch-and-Bound Tree

- Integer programs are solved through branch-and-bound trees, which eliminate sub-optimal branches for efficiency.
- We explore alternate solutions by retaining feasible, but near-optimal, solutions.
- The user defines the number of solutions, the maximum gap between alternate solutions and the optimal, and the diversity of solutions.



Method #2: Integer-Cut Constraints



We iteratively solve the optimization model, each time adding a constraint to exclude the previous solution.

$$Z^{\text{to}}_{th} \le y^{\text{to}}_{t} \quad \forall t \in \mathcal{T}, h \in \mathcal{H}$$

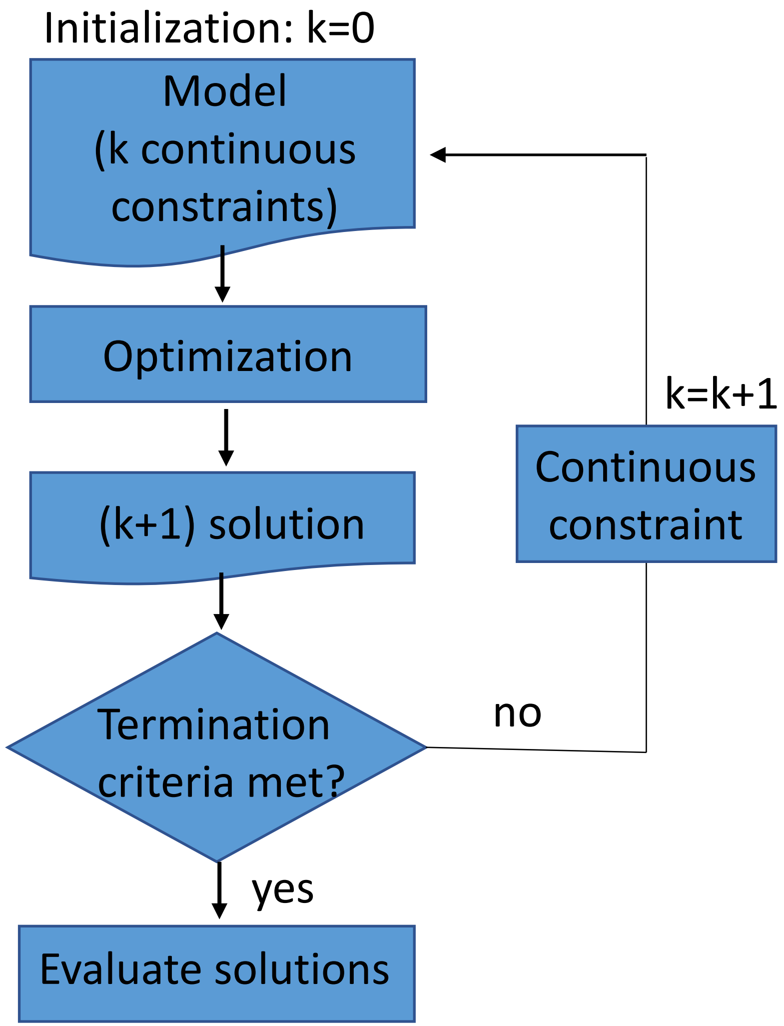
- Ensures binary is 1 if the technology operates in any hour

$$\sum_{t \in \mathcal{T}'} y^{\text{to}}_{t} \le |\mathcal{T}'| - n$$

- Sums over all technologies that operate in the optimal solution and requires the alternate solution to be different from the optimal by at least *n* technologies

Where *T*= set of all technologies, *T'*= set of all technologies operating in the base case, y_t^{to}= 1 if technology *t* ever operates and 0 otherwise, Z_{th}^{to}= 1 if technology *t* operates in timestep *h* and 0 otherwise, and *n* = the number of technologies that must be different.

Method #3: Continuous Constraints



We iteratively solve the optimization model, each time adding a constraint to restrict the size of technologies to be at least some percent different from the sizes given in previous solutions.

$$X \geq (1+n)X^* - M\alpha$$

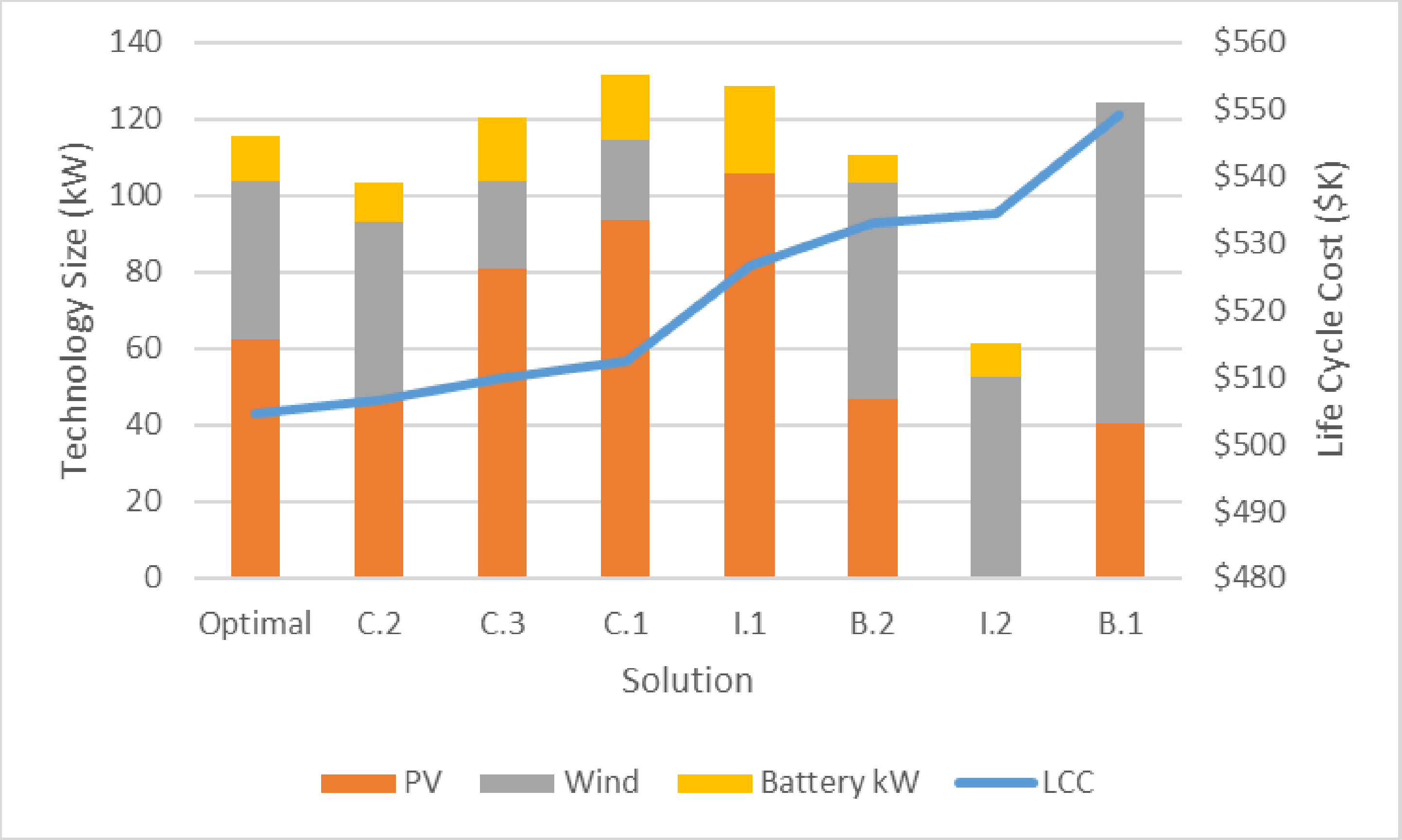
$$X \leq (1-n)X^* + M(1-\alpha)$$

- Restrict the size of technologies to be some percentage greater than or less than their size in the previous solution

Where *X*= size of technology, *X**= size of technology in the previous case, *n*= decimal percent difference, *M*= a big number, and α= variable that enforces binary logic (1 if some fraction of technology *X** is greater than or equal to *X* and 0 otherwise).

Results Summary

- Seven alternate solutions are within 10% of the optimal objective function value.
- These provide the decision maker with a useful set of near-optimal choices to consider, along with qualitative factors not represented in the model when making an investment decision.



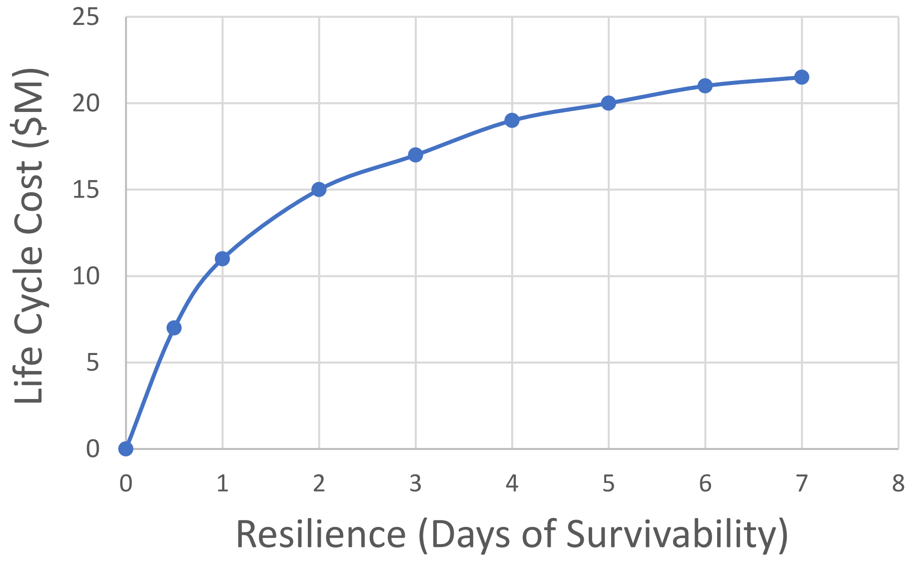
Comparison of optimal solution to the set of near-optimal choices (B=Branch and Bound; I=Iterative Constraint; C=Continuous Constraint)

Co-Optimization

We use two techniques to co-optimize cost and resilience goals and develop solutions that balance multiple competing objectives:

a) **Efficient frontier**: Minimize cost while parametrically varying the grid outage length to develop an efficient frontier of pareto optima solutions for different levels of resilience

b) **Goal programming**: Set target cost and resilience goals, and then minimize the amount the solution falls short of these.



Efficient frontier of solutions for varying resilience levels

Value of Resilience

- Resilience benefits are difficult to quantify and value, and therefore are often not included in energy decision modeling.
- This work develops a method for valuing resilience and integrates it in two energy decision models at microgrid and macrogrid scales.
- We test whether including a value of resilience changes investment and/or operational decisions.

Campus Planning and Operation Case Study

- **Research Question:** If a site owner understands the duration-dependent magnitude of losses they will incur during an outage, will they make different investment and operational decisions to minimize their lifecycle cost of energy?
- **Method:** We incorporate a duration-dependent value of lost load in REopt to optimize system size and dispatch to minimize lifecycle energy costs for a site, including outage costs.
- **Results:** Knowledge of duration-dependent value of lost load allows a site owner to reduce outage costs and overall lifecycle energy costs using larger PV and storage systems to provide longer duration backup power.

Anderson, K., Murphy, C., Hotchkiss, E., Barrows, C., Dalhi, S., Li, X., Ericson, S., Lisell, L. Integrating the Value of Electricity Resilience in Energy Planning and Operations Decisions. IEEE Systems Journal January 2020.

Outage Cost Functions

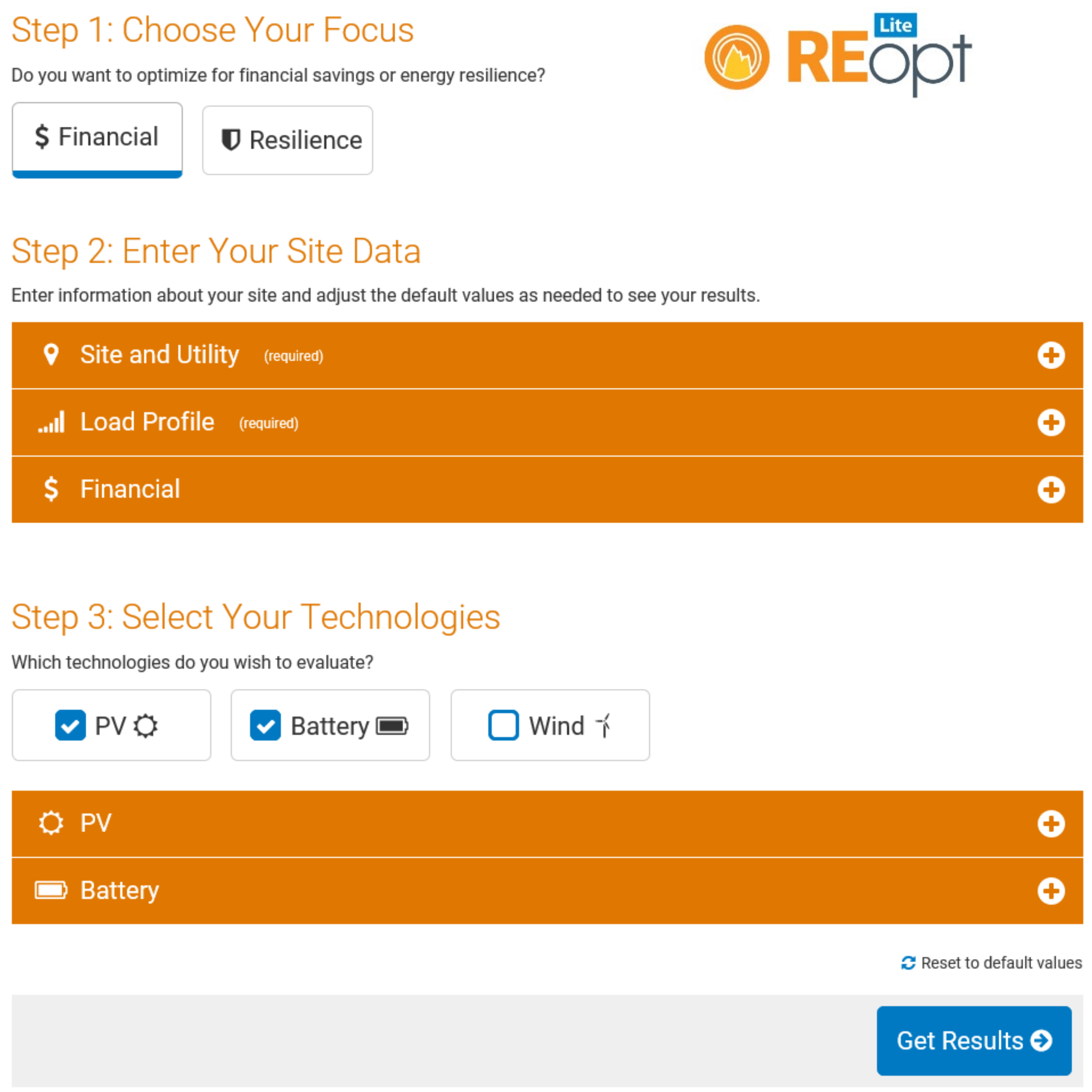
	Resilience Value	
	Constant	**Duration-dependent**
Fixed cost	$0/kW	$16/kW
Flow cost	$13/kW	$8/kW
Stock cost	$0/kW	$0/kW

Optimal System Sizing and Cost Results

	Resilience Value		
	None	**Constant**	**Duration-Dependent**
PV size (kW)	265	283	321
Battery size (kWh)	300	599	692
Outage survival (hours)	0.24	0.66	0.87
Total outage cost ($)	$315,319	$238,788	$214,853
Outage cost reduction (%)	-	24%	32%
Value of resilience ($)	-	$76,531	$100,466

Accessing REopt Lite

- Web tool: reopt.nrel.gov/tool
- API: https://developer.nrel.gov/docs/energy-optimization/reopt-v1/
- Open Source code: https://github.com/NREL/REopt_Lite_API



Acknowledgments

- National Renewable Energy Laboratory
  - Dr. Adam Warren, REopt team, Dr. Alex Zolan, Josiah Pohl, Maggie Nevrly, Emma Elgqvist
- Colorado School of Mines
  - Dr. Alexandra Newman, Dr. Tulay Flamand, Dr. Rob Braun, Dr. Morgan Bazilian, Seun Ogunmodede, Jamie Grymes, Dr. Jesse Wales, Jusse Hirwa, Chris Hampel, Valerie Holt, Suzanne Beach
- Department of Energy Advanced Manufacturing Office and Federal Energy Management Program
  - Rachel Shepherd, Bob Gemmer, Patti Garland, Bruce Hedman

Thank you!

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