SAND2019-6585PE

ESS Performance Metrics

Model Based ESS Testing Approach

PRESENTED BY

David Rosewater - 9 – 18 – 2018

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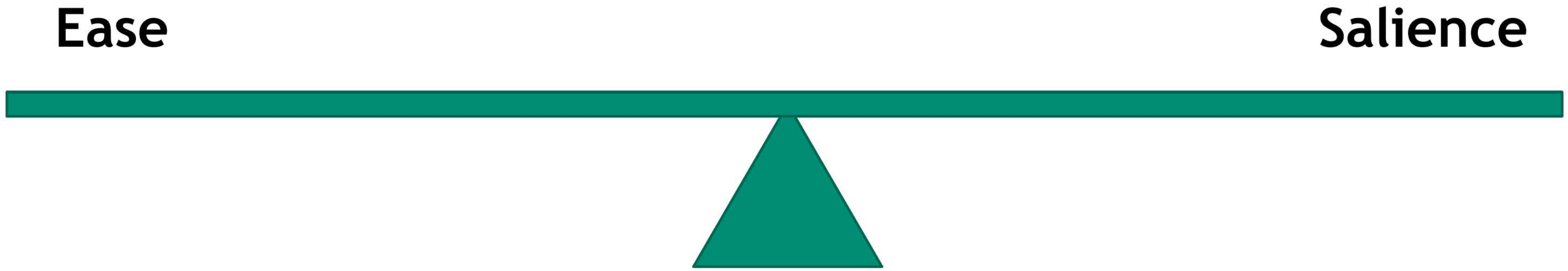
Outline

- Introduction
  - The problem with applying traditional testing methods to ESS
- Model Based Testing Alternative
  - Characterization of Physical Parameters
  - Model Development
    - Example Performance Metrics
  - Application Simulation
    - Modeling Uncertainty
- Conclusions

Why haven't duty-cycle tests been as widely adopted by customer/manufactures as we expected in 2013?

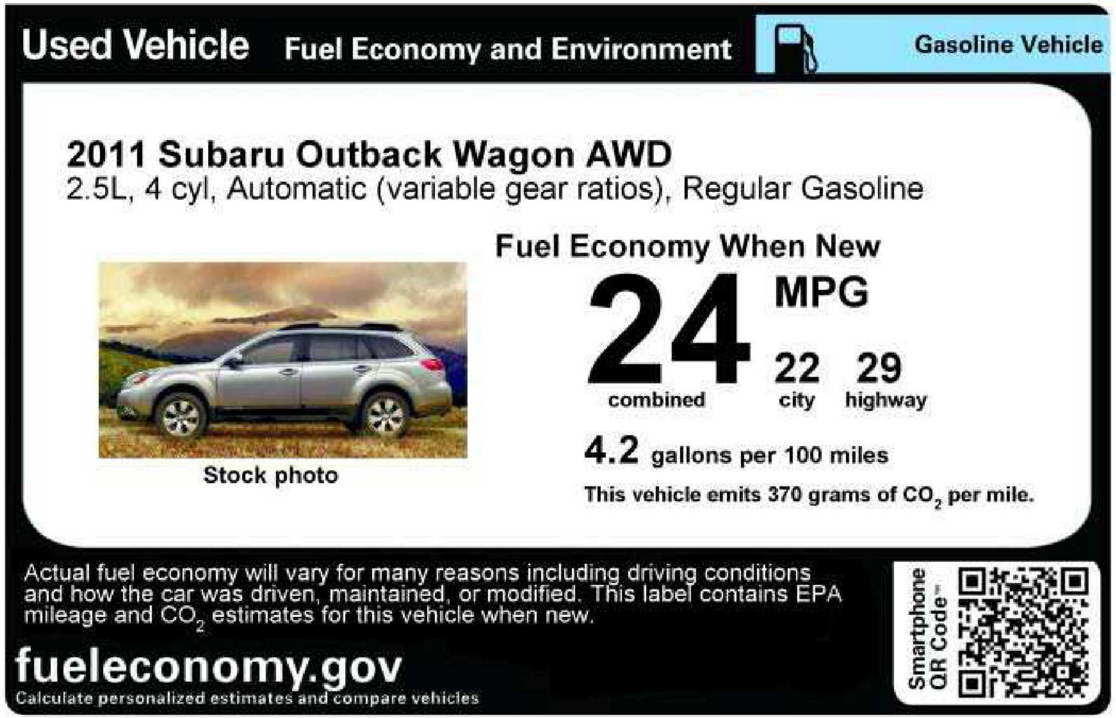
The duty-cycle approach, as with any testing program, must balance **ease** (cost of testing to manufactures) and **salience** (usefulness of the derived metrics to decision makers).



Introduction

The state-of-the-art approach to measure energy storage performance is a rough allegory to the solution for miles per gallon (mpg) in cars.

CAR ANALOGY



Source: USEPA https://www.flickr.com/photos/usepagov/

Why does mpg work for cars?

- Standardized usage with limited applications (city/highway)
- Road conditions are demonstrably similar across the country
- Roughly linear relationship between usage and life
- Absolute accuracy not needed for the metric to be useful

This approach, which we will term the duty-cycle approach, is motivated by the balance of ease (cost of testing to manufactures), and salience (usefulness of the derived metrics to decision makers).

Introduction

The duty-cycle approach breaks down in when exclusively applied to BESS

Energy Storage Performance | Lithium-ion Battery

Company X Containerized Energy Storage Solution

1 MW, 4 MWh grid scale storage system

From Wikimedia Commons, the free media repository

Stock Photo

Round-Trip Efficiency When New

90% CEC score

92% Frequency Regulation

83% Peak Shaving

52 kW **average losses when cycling daily**

This ESS generates 420 grams of CO2 per cycle

Actual round trip efficiency will vary for many reasons including application, temperature, and how the system was maintained or modified.

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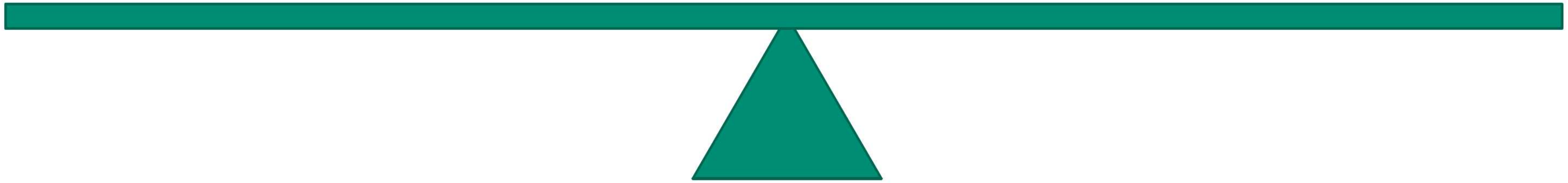
Why this doesn't work like we want it to

- Many diverse ES applications
  - A metric that is critical for some, can be irrelevant to others
- Each application is different in different parts of the country and currently in flux
  - Frequency reg. in CA ver. PJM
- For some technologies, higher performance can be achieved by shorting life (duty cycle gaming)

Imagine a world where driving some cars faster makes them break down early, where roads and traffic laws vary widely across the country and are contently changing, and where people use cars for heating their homes or doing laundry as often as they do for driving and you will get a sense for how challenging it is to find a duty-cycle based test protocol for BESS that balances ease and salience.

How many hours of duty-cycle testing would it take to capture an ESSs performance for

- All 14 applications in the ESSHB (+ additional applications and stacked applications)?
- All ISOs RTOs and different state and local utilities?
- In such a way as to fairly compare batteries and flywheels?



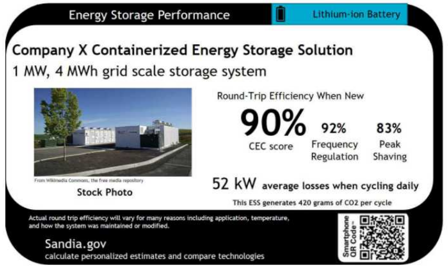
Model-Based Testing Alternative

Ease → **Salience**

Characterize Physical Properties (with uncertainties) → Develop a predictive computer model of the ESS → Use the model to Simulate Application Specific Performance

Limited Testing Program

Some model parameters can be used as relevant performance metrics

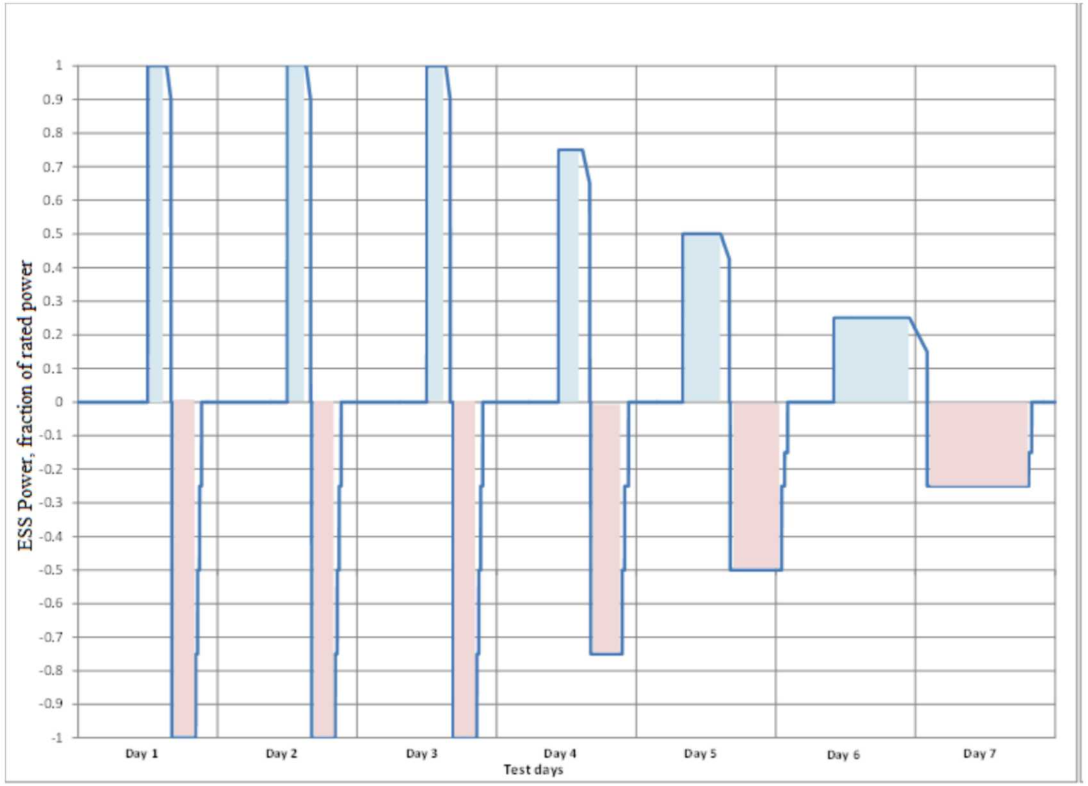


Probabilistic performance, specific to the specific application

Accurate and Actionable Information

Characterize Physical Parameters

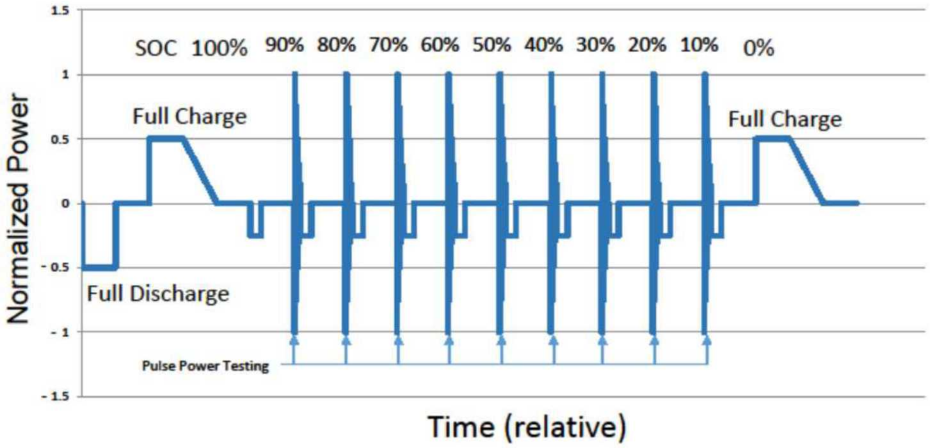
Capacity Testing

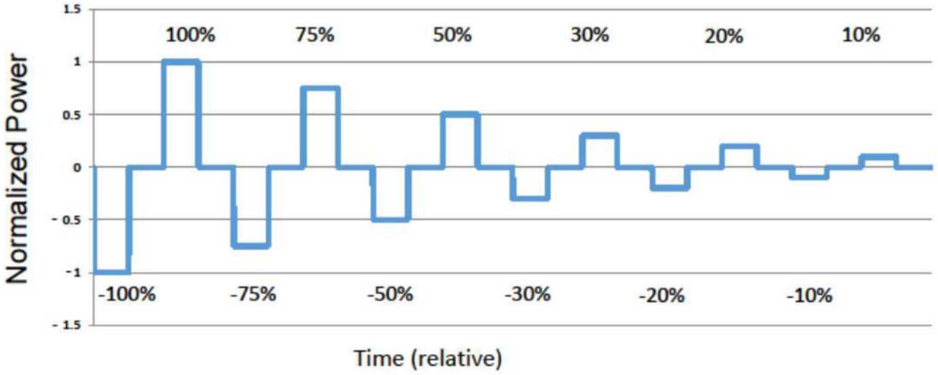


E. Minear "Energy Storage Integration Council (ESIC) Energy Storage Test Manual" EPRI Energy Storage Integration Council, December 2017

Capacity and Energy Efficiency

Energy Storage Pulsed Power Characterization (ESPPC) Test



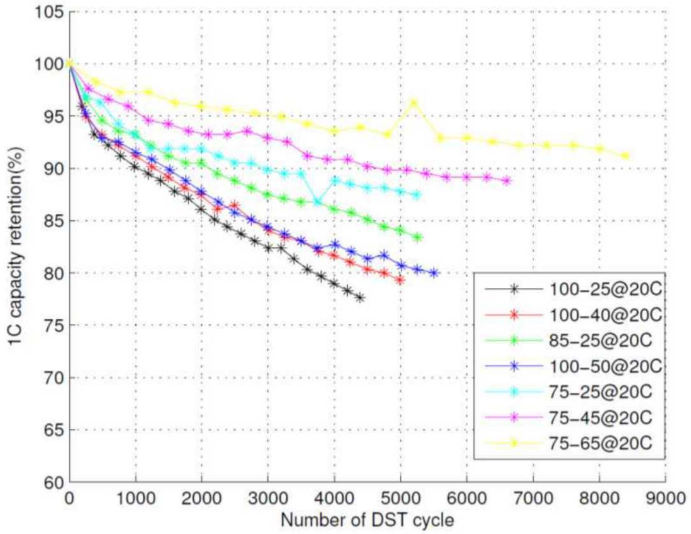


Open Circuit Voltage Curve, Impedance, Max Power/SoC Function

Characterize Physical Parameters

Degradation Testing

Battery degradation is not linear. Instead it is an exponential decay function (like half-life) that is driven by stress factors based on time, SoC, temperature, and depth of discharge.



Not B. Xu, A. Oudalov, A. Ulbig, G. Andersson, and D. Kirschen, "Modeling of lithium-ion battery degradation for cell life assessment," IEEE Transactions on Smart Grid, vol. PP, no. 99, pp. 1–1, 2016..

$$\varrho = e^{-f_d}$$

$$f_d = \underbrace{S_t(t) S_\varsigma(\varsigma) S_T(T)}_{\text{Calendar Life}} + \sum_{i=1}^{N} w_i \underbrace{S_\delta(\delta) S_\varsigma(\varsigma) S_T(T)}_{\text{Cycle Life}}$$

- Time Stress Function (linear)
- Average SoC Stress Function (exponential)
- Temperature Stress function (exponential)
- Depth of Discharge Stress Function. (polynomial or reciprocal)

Develop a predictive computer model of the ESS

Name	Symbol	Mean
Charge Capacity	C_{cap}	800 Ah
Coulombic Efficiency	η_c	94.6 %
Self Discharge Current	i_{sd}	0.50 A
Inverter Efficiency Coefficient	ϕ_0	-2.0503e-04
Inverter Efficiency Coefficient	ϕ_1	0.99531
Inverter Efficiency Coefficient	ϕ_2	-6.1631
Battery Internal Resistance	R_0	71.6 mΩ
Maximum Power Discharge	p_{max}	500 kW
Maximum Power Charge	p_{min}	500 kW
Maximum SoC	ς_{max}	95 %
Minimum SoC	ς_{min}	20 %
Maximum Battery Voltage	v_{max}	820 V
Minimum Battery Voltage	v_{min}	680 V
Maximum Current Discharge	p_{max}	1000 A
Maximum Current Charge	p_{min}	1000 A
Regularization weight	Π	1e-5

Cubic Polynomial Fit	α	β	γ	δ
$0.2 \leq \varsigma \leq 0.95$	320.377	-368.742	201.004	669.282

Note: these model parameters are meant to represent a hypothetical battery system and do not necessarily reflect any specific equipment.

Name	Symbol	Mean
Battery Thermal Transmittance	U	0.2 $W/°$C
Battery Heat Capacity	C_{heat}	1.495 $J/°$C
Maximum Temperature	T_{max}	45 oC
Minimum Temperature	T_{min}	-20 oC
Nominal Temperature	T_{nom}	20 oC
Enclosure Thermal Transmittance	U_{EN}	1 $W/°$C
Enclosure Heat Capacity	C_{EN}	30,000 $J/°$C
Max AC power	$p_{\text{HVAC-max}}$	100 kW
AC Efficiency	η_{HVAC}	700%

Note: these model parameters are meant to represent a hypothetical battery system and do not necessarily reflect any specific equipment.

Name	Symbol	Value
Thermal Degradation Constant	k_T	0.1311
Time Degradation Constant	k_t	1.49e-6
SoC Degradation Constant	k_ς	0.01
Reference SoC	ς_{ref}	60
Reference Temperature	T_{ref}	20
EoL Cost Assumed	C_{EoL}	-$800,000
Regularization weight	Π	1e-5

Polynomial Fit	a	b	c	d	e
Degradation Stress Factor	1.1581	-1.3658	6.6418 e-1	1.0739 e-1	1.2328 e-2

Parameters Estimated Through Testing

Example Performance Metrics

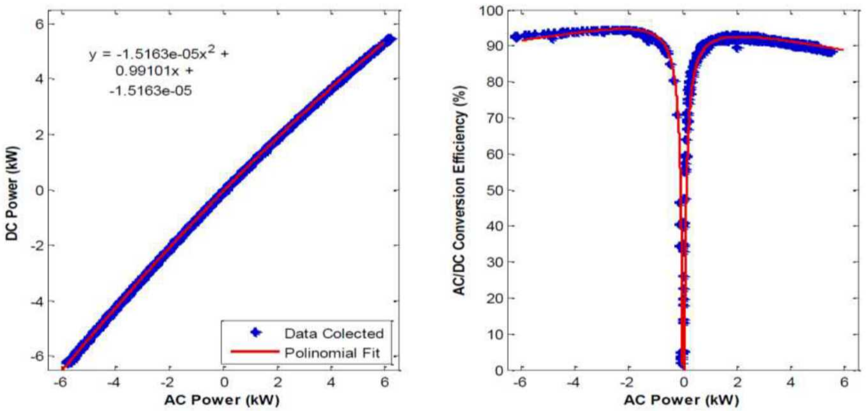
Table 4.4.2. Reference Performance

Subject	Description
Stored Energy (Section 5.2.1)	The amount of electric or thermal energy capable of being stored by an ESS, expressed as the product of rated power of the ESS and the discharge time at rated power
Round-Trip Energy Efficiency (5.2.2)	The useful energy output from an ESS divided by the energy input into the ESS over one duty cycle under normal operating conditions, expressed as a percentage
Response Time (Section 5.2.3)	The time in seconds it takes an ESS to reach 100 percent of rated power during charge or from an initial measurement taken when the ESS is at rest
Ramp Rate (Section 5.2.3)	The rate of change of power delivered to or absorbed by an ESS over time, expressed in megawatts per second or as a percentage change in rated power over time (percent per second)
Reactive Power Response Time (Section 5.2.3)	The time in seconds it takes an ESS to reach 100 percent of rated apparent power during reactive power absorption (inductive) and sourcing (capacitive) from an initial measurement taken when the ESS is at rest
Reactive Power Ramp Rate (Section 5.2.3)	The rate of change of reactive power delivered to (inductive) or absorbed by (capacitive) an ESS over time expressed as Mvar per second or as a percentage change in rated apparent power over time (percent per second)
Internal Resistance (Section 5.2.3)	The resistance to power flow of the ESS during charge and discharge
Standby Energy Loss Rate (Section 5.2.4)	Rate at which an ESS loses energy when it is in an activated state but not producing or absorbing energy, including self-discharge rates and energy loss rates attributable to all other system components (i.e., battery management systems, energy management systems, and other auxiliary loads required for readiness of operation)
Self-Discharge Rate (Section 5.2.5)	Rate at which an ESS loses energy when the storage medium is disconnected from all loads, except those required to prohibit it from entering into a state of permanent non-functionality

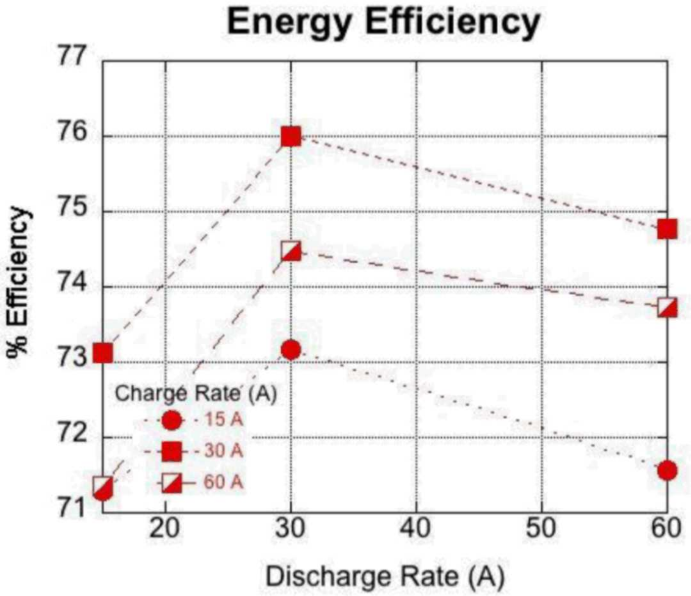
DR Conover et al “Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems” Sandia National Laboratories and Pacific Northwest National Laboratory, PNNL-22010 Rev 2 / SAND2016-3078 R, April 2016

Example Performance Metrics

- "CEC Bidirectional Inverter Efficiency Curve"

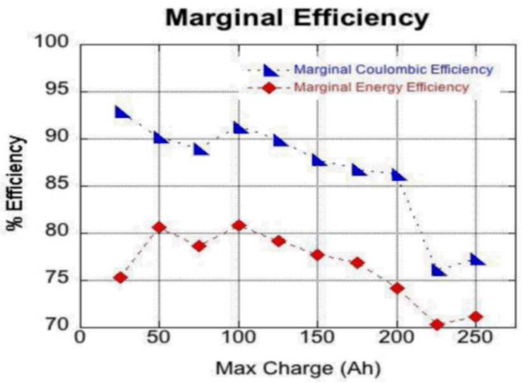


- "CEC Round-Trip Energy Efficiency"

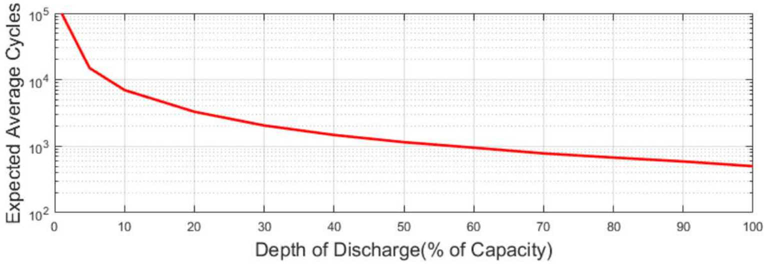


D. M. Rose and S. R. Ferreira "Initial Test Results from the RedFlow 5 kW, 10 kWh Zinc-Bromide Module, Phase 1" Sandia National Labs, SAND2012-1352

- "CEC Capacity"

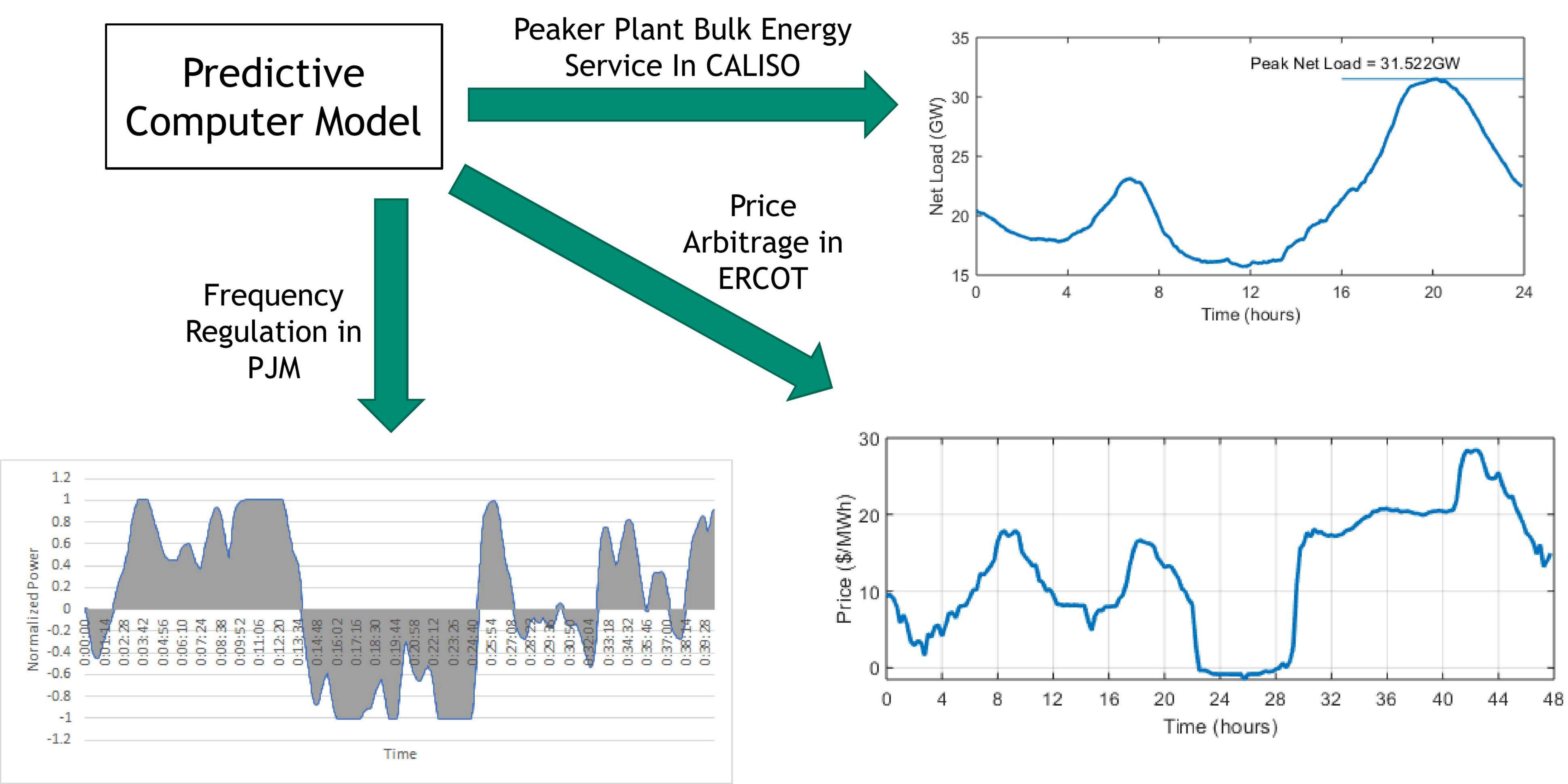


- "CEC Cycle-Life Curve"

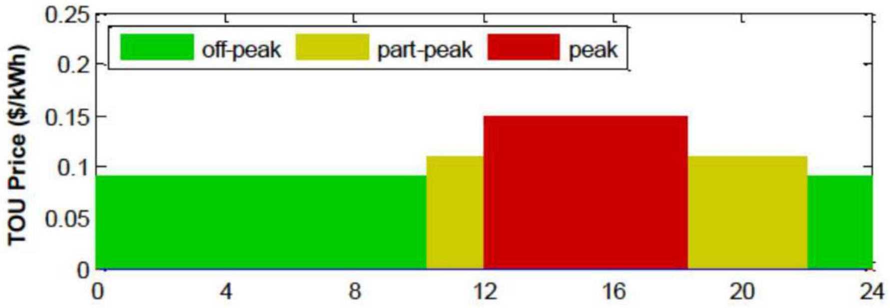


An Overview of Different Approaches for Battery Lifetime Prediction - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Cycle-life-versus-DOD-curve-for-a-lead-acid-battery_fig2_317107750 [accessed 10 Jun, 2019]

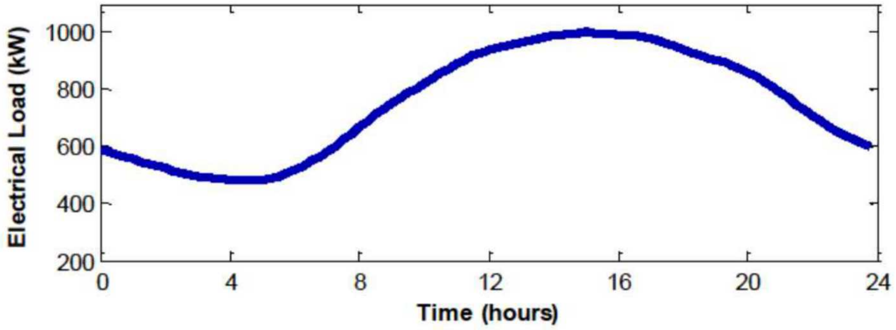
Use the model to Simulate Application Specific Performance



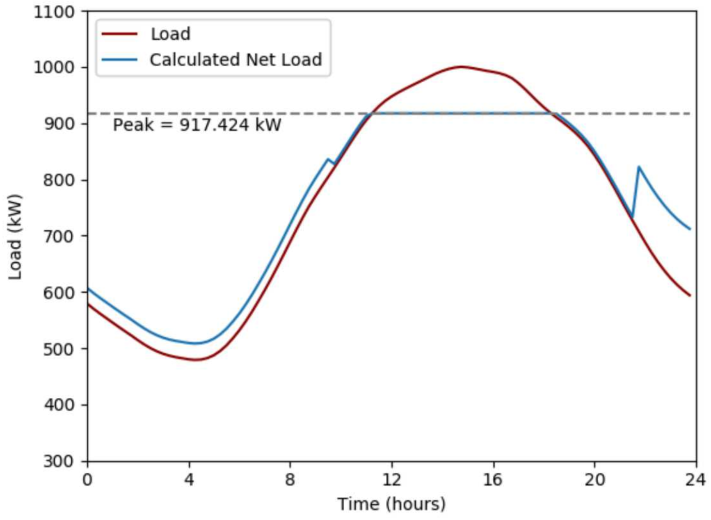
Use the model to Simulate Application Specific Performance

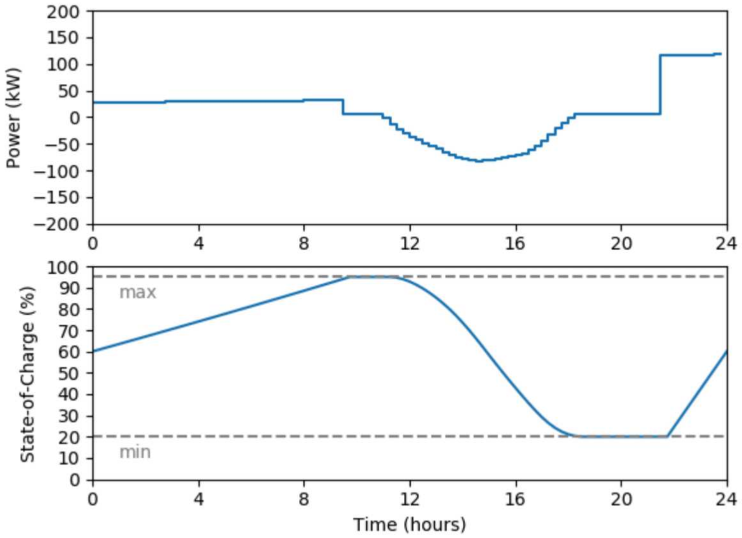


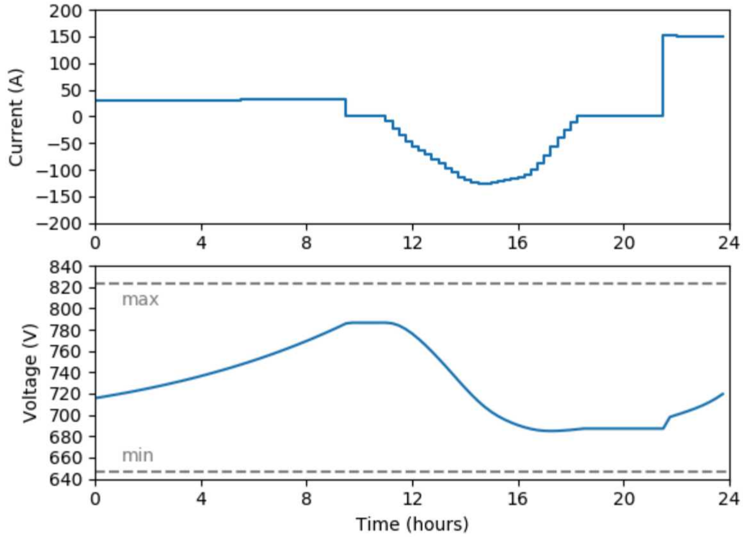
Example: Consider a hypothetical commercial electrical customer billed for power under both time-of-use (TOU) and a $50/kW demand charge.



Simulated Performance:

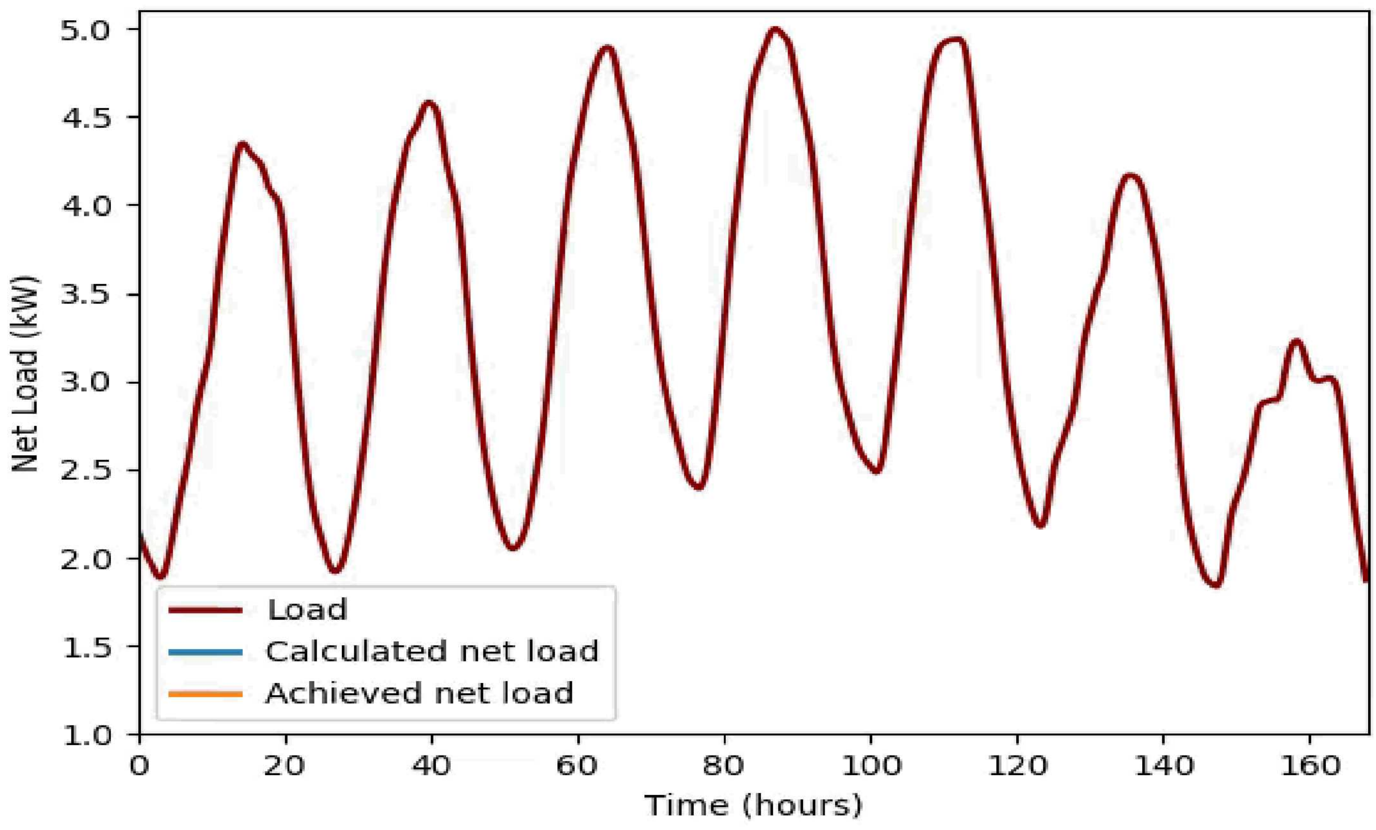






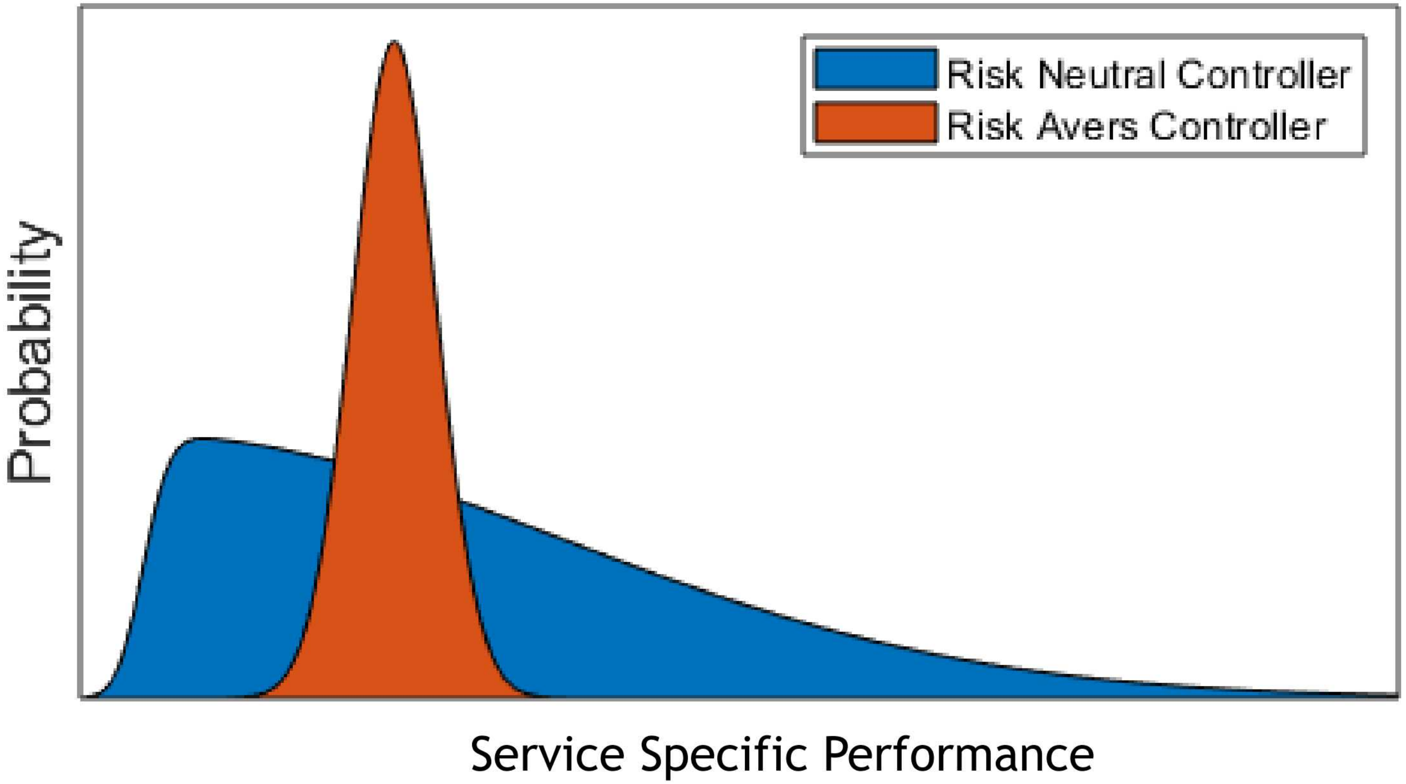
Closed-loop control: Available Energy Overestimation

Example of model overestimation with closed loop control



Probabilistic Performance

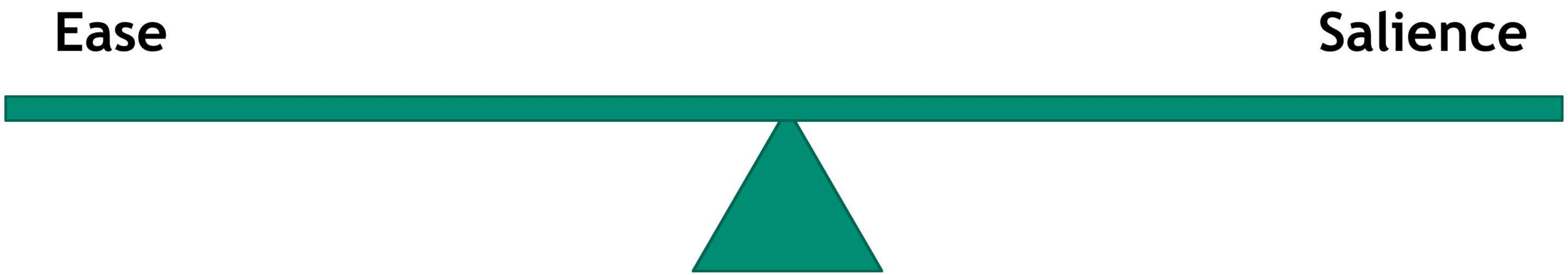
Uncertainty in model parameters can be incorporated into a probabilistic understanding of optimal system performance



Accurate and Actionable Information

Conclusions

- The duty-cycle approach breaks down in when exclusively applied to BESS
- All testing protocols must balance ease and salience
- Model-based testing optimizes ease and salience by decoupling testing and applications specific performance
- The steps to model-based testing are:
  - Characterize Physical Properties (with uncertainties)
  - Develop a predictive computer model of the ESS
  - Use the model to Simulate Application Specific Performance



Thank You to the DOE OE for supporting research to understand and improve the performance of energy storage systems

Questions?

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