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GRID MODERNIZATION LABORATORY CONSORTIUM
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Comparing the Abilities of Energy Storage, PV, and Other Distributed Energy Resources to Provide Grid Services

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Changing Landscape of Electrical Power

Changing Generation Mix on the Grid

The grid was designed and built using controlled generation and predictable load

Tomorrow's grid will have less control over generation form renewable sources

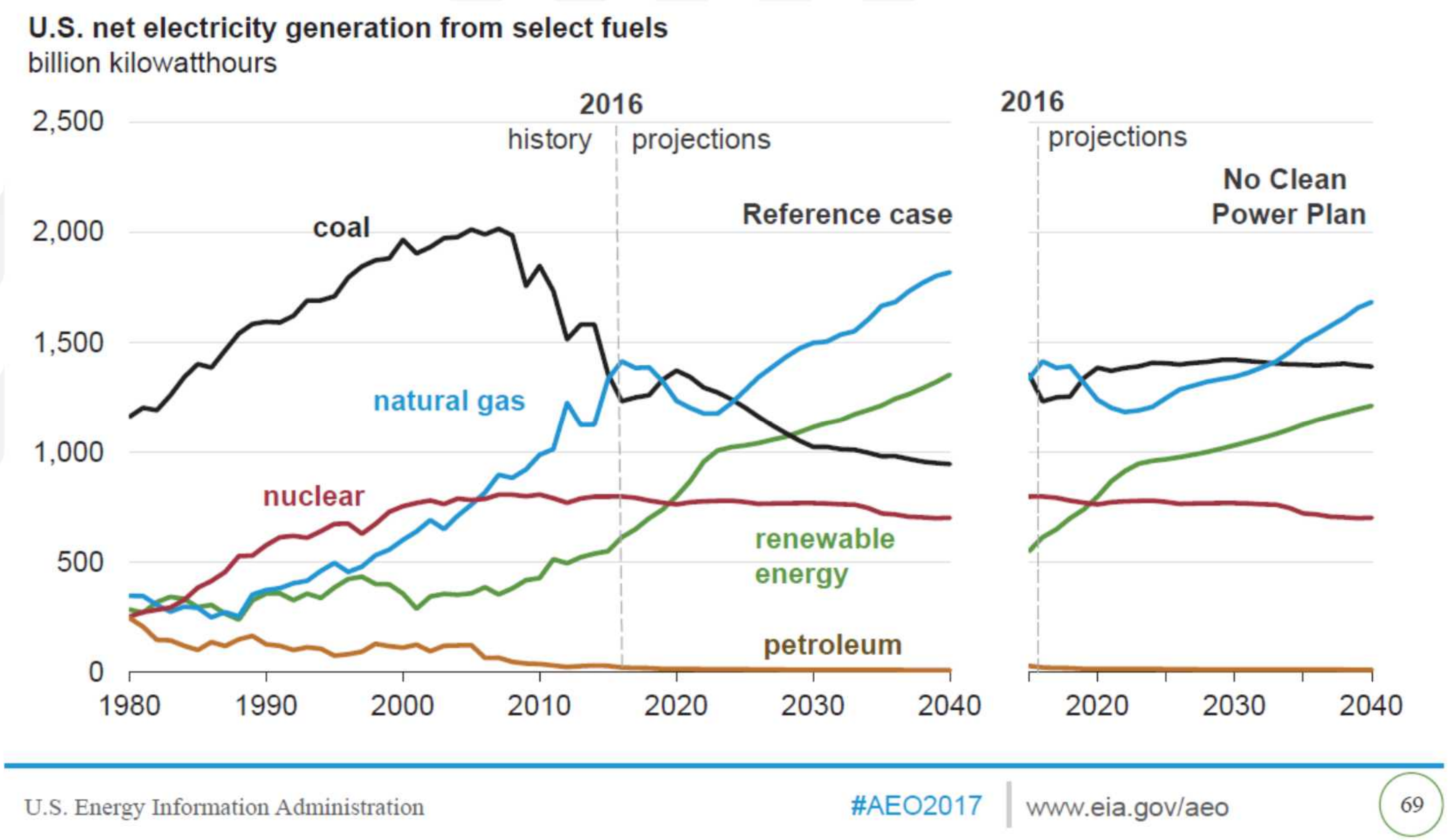


Figure Source: Energy Information Administration Annual Energy Outlook 2017: https://www.eia.gov/outlooks/aeo/pdf/0383%282017%29.pdf

Expanding Role of Distributed Energy Resources (DER) in the Grid

- ***Conventional Generators*** supply many services to the grid
  - Wholesale energy (kWh)
  - Peak Supply
  - Inertia
  - Voltage management
  - Capacity
  - Frequency Regulation
  - Spinning reserve
  - Ramping
- ***Renewable Generators (presently)*** supply one
  - Wholesale energy (kWh) based on how much is available from the environment

Expanding Role of Distributed Energy Resources (DER) in the Grid

- ***Services are Being Decoupled***
  - Wholesale energy (kWh)
  - Peak Supply
  - Inertia
  - Voltage management
  - Capacity
  - Frequency Regulation
  - Spinning reserve
  - Ramping

New Markets or Established Value to Rate Payers

- ***DER can Supply These Services***
  - But how well?
  - Are they as effective as generators?
  - How do they compare to one another?

DER Device Classes

- Thermal storage
- Water heaters
- Refrigerators
- PV/inverters
- Batteries/inverters
- Electric vehicles (DR, V2G)
- Res. & com. HVAC
- Commercial refrigeration
- Commercial lighting
- Fuel cells
- Electrolyzers

These very different devices can be enable to supply the same services to the grid

High-Level Project Summary

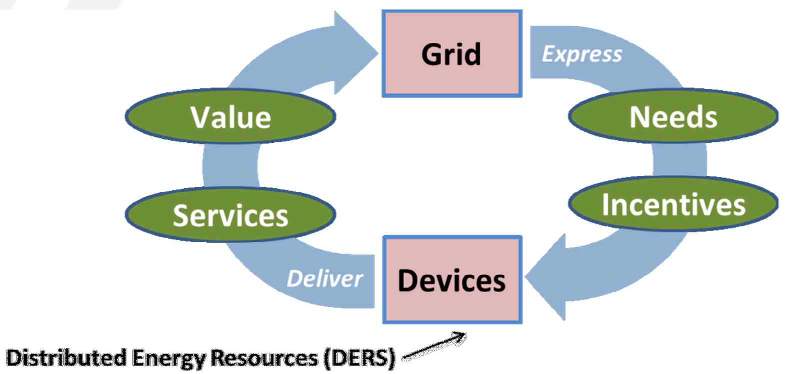
Project Description

Develop a characterization test protocol and model-based performance metrics for *devices'* ability to provide a broad range of *grid services,* i.e., provide the flexibility required to operate a clean, reliable power grid at reasonable cost.

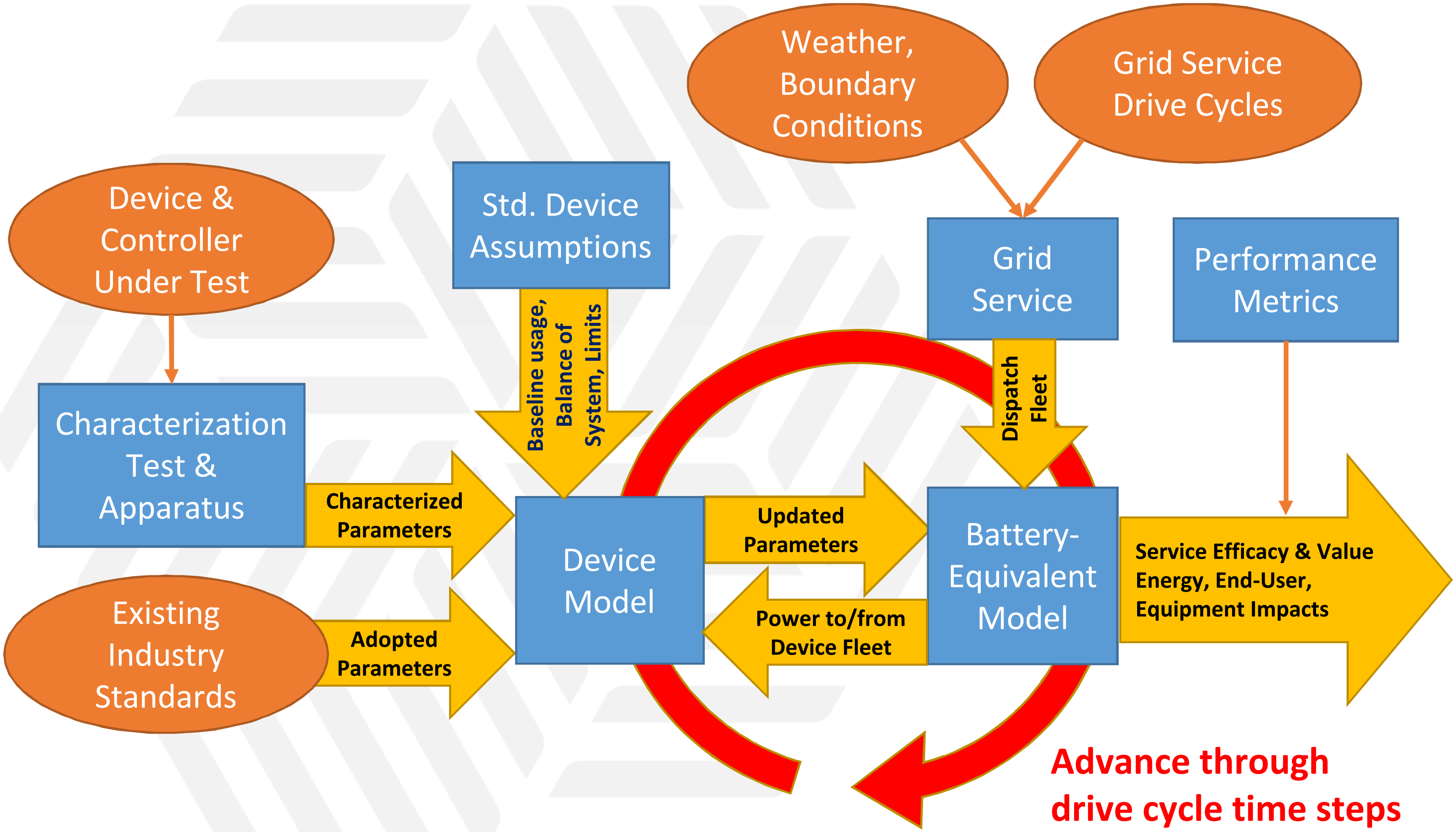
Lab	Device Class	Grid Services
PNNL	1. Thermal storage	A. Peak load management B. Artificial inertia/fast frequency response
NREL	3. Water heaters 4. Refrigerators 5. PV/inverters	C. Distribution voltage management / PV impact mitigation
SNL	6. Batteries/inverters	
ANL	7. Electric vehicles (DR, V2G)	D. ISO capacity market (e.g., PJM's)
ORNL	8. Res. & com. HVAC 9. Commercial refrigeration	
LBNL	10. Commercial lighting	E. Regulation F. Spinning reserve G. Ramping
INL	11. Fuel cells 12. Electrolyzers	
LLNL		H. Wholesale energy market/production cost

Expected Outcomes

- ✓ ***Reward innovation*** by device/system/control manufacturers, helping them understand opportunities & enlarging the market for devices
- ✓ ***Validated performance & value for grid operator decisions*** on purchases, subsidies or rebates, programs, markets, planning/operating strategies
- ✓ ***Independently validated information for consumers & 3rd parties*** for device purchase decisions



General Framework and Approach



Foundational Concepts – State-of Charge for a Device

State-of-charge:

$$\text{SoC} = \frac{\text{Current energy stored for grid services}}{\text{Maximum potential energy stored}}$$

Examples:

Air conditioners:

$$\text{SoC} = \frac{\text{Temperature rise of bldg. thermal mass}}{\text{Allowable temperature rise of bldg.}}$$

Electric vehicles:
(for a recharge cycle)

$$\text{SoC} = 1 - \frac{\text{Charging energy deferred}}{\text{Charging energy required}}$$

Battery Equivalent Model

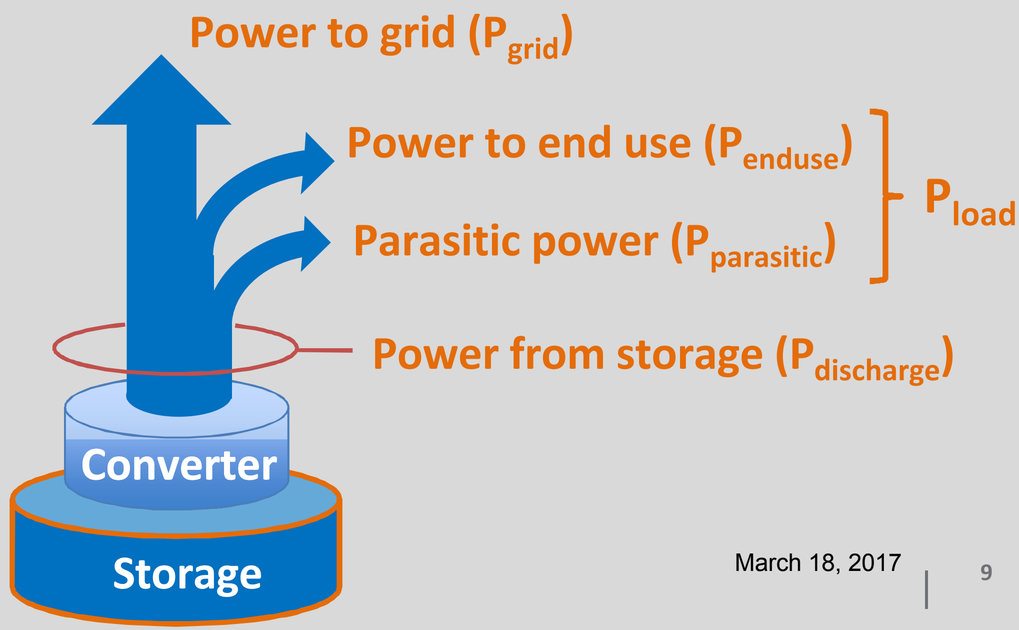
Modes of Operation

- **Hold – maintain current SoC**
  (may require power from grid to serve end-use or parasitic loads)
- **Discharge – allow SoC to decrease** to deliver power from storage
- **Charge – increase SoC** by consuming power from grid

Modeling a fleet of identical devices, not individual devices

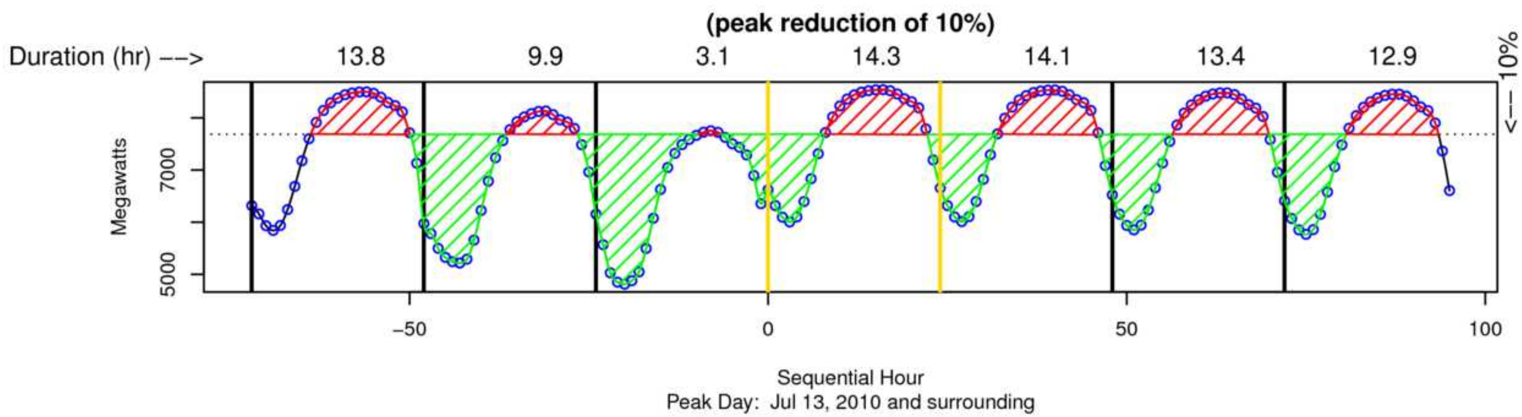
- **Continuously variable response possible**
- **State variables reflect the mean of the distribution of states in fleet**

Power balance & sign convention



Service Example
Peak Supply / Peak Demand Management

- Analyze daily peak loads for entire year
  - Start with peak demand reduction target (f) = 10%
  - Skip days where Max Load < (1 – f) Peak Demand$_{yr}$



- Design a timestep-by-timestep dispatch plan for each day
  - Design daily plan to dispatch battery equivalent fleet while
    - Ensuring all device fleet energy & power constraints are satisfied
    - Ensuring all fleet constraints on time when State-of-Charge must be restored
    - Satisfying reduction target (f)
  - If <u>any</u> daily plan is infeasible, reduce f, repeat previous 3 steps

Battery / Inverter Device Model

Battery/Inverter Systems

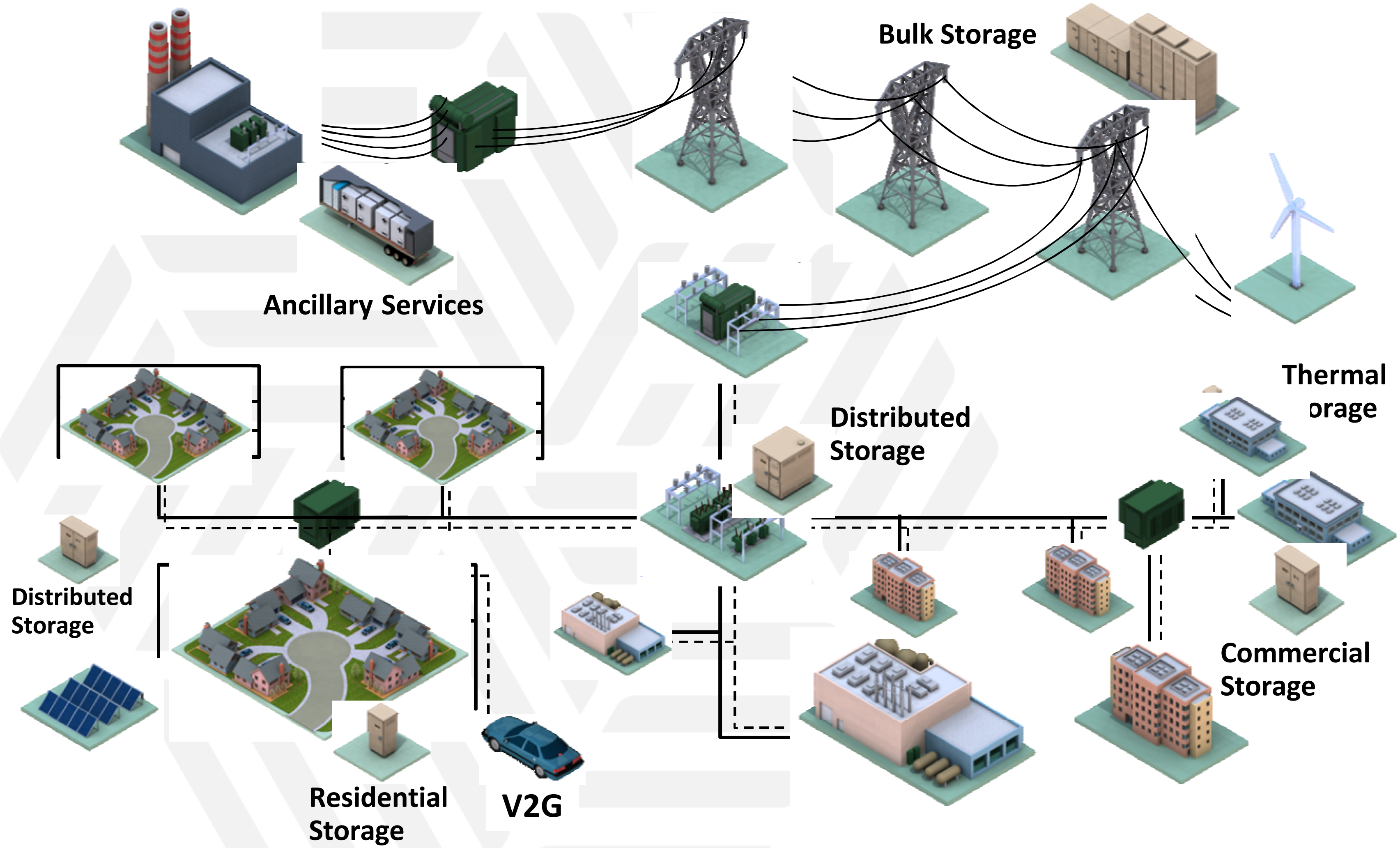


Figure Source EPRI

Battery/Inverter Systems

► Battery Types (short list)

- Sodium Sulfur (NaS)
- Flow Batteries
- Lead Acid
- Advanced Lead Carbon
- Lithium Ion

Sodium Sulfur Battery
2 MW / 8 hour

500-kW/1-MWh Adv LA: Time-shifting
900-kWh Adv Carbon Valve-regulated: PV Smoothing

Tehachapi Wind Energy Storage Project - Southern California Edison
Lithium-Ion Battery
8-MW / 4 hour duration

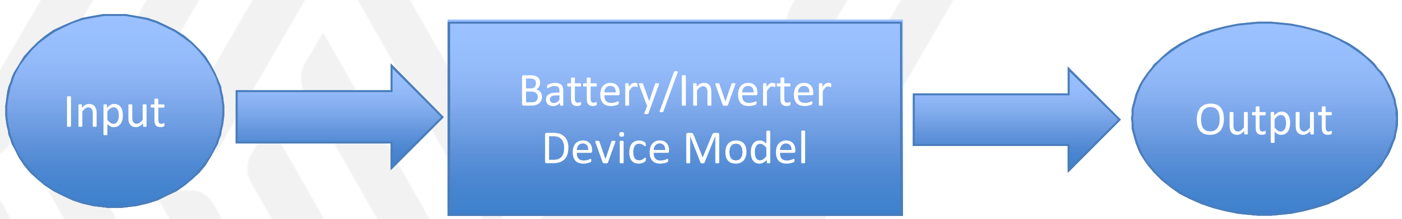
Source DOE: Global Energy Storage Database www.energystorageexchange.org

Standard Device Assumptions

- Each battery/inverter device is composed of
  - A battery made up of one or more strings of many cells connected in series
  - An grid connected bidirectional inverter that can charge or discharge the battery from or to the grid
  - A device controller that maintains internal limits
- Manual Control - Power control with Battery limits
  - This control mode sets limits for battery parameters (current, voltage, temperature), and then attempts to achieve an AC power set point. If battery/inverter limits are reached the power actualized by the inverter is also limited through feedback control such that equilibrium is achieved at the battery limit. Otherwise, the AC power set point is maintained until another command is give or a limit is reached.
- Automatic Control
  - Schedule of Manual Control Actions
  - Sequence of Manual Control Actions
  - Many Other Functions Based on Service

Model Based Approach

- Input
  - Requested Power
  - Environmental Temperature
- States
  - State-Of-Charge
  - Battery Voltage
  - Battery Current
  - Battery Temperature
- Output
  - Power Delivered
  - Efficiency
  - Life Acceleration Factors
  - Operational Cost



Model parameters describe the relationships between state variable and input/output variables

Adopted Parameters

- Existing Industry Protocols

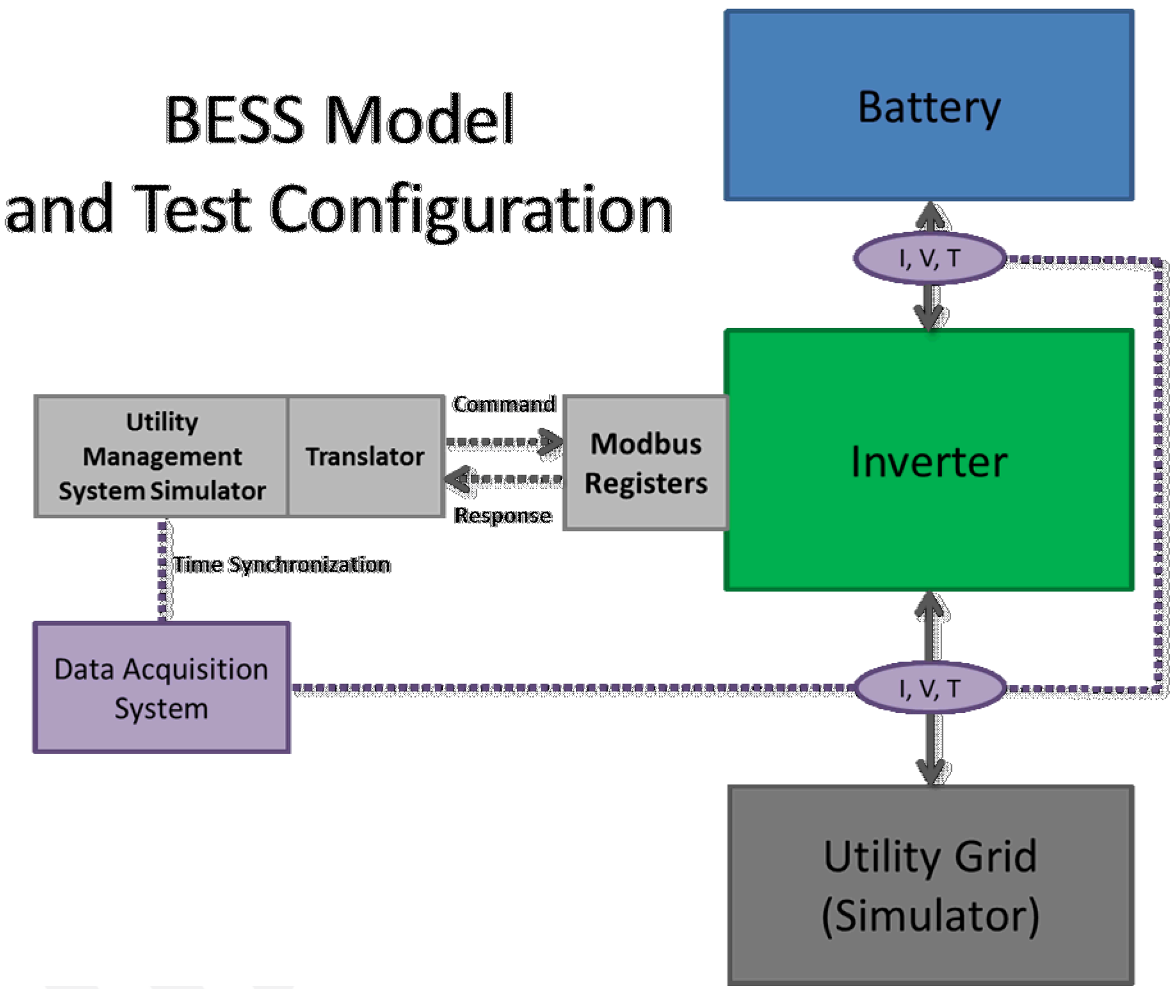
1. DR Conover et al, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems" Sandia National Laboratories, SAND2016-3078R, http://www.sandia.gov/ess/publications/SAND2016-3078R.pdf
2. Maurizio Verga, et al "SIRFN Draft Test Protocols for Advanced Battery Energy Storage System Interoperability Functions" Smart Grid International Research Facility Network, 2016 http://www.iea-isgan.org/force_down_2.php?num=19
3. Battery Test Manual For Plug-In Hybrid Electric Vehicles, U.S. Department of Energy Vehicle Technologies Program, rev 3, September 2014 https://inldigitallibrary.inl.gov/sti/6308373.pdf
4. Haskins H. et al "Battery Technology Life Verification Test Manual" Advanced Technology Development Program For Lithium-Ion Batteries, Idaho National Laboratory, February 2005, INEEL/EXT-04-01986
5. David L. King, Sigifredo Gonzalez, Gary M. Galbraith, and William E. Boyson "Performance Model for Grid-Connected Photovoltaic Inverters" Sandia National Laboratories, SAND2007-5036 http://energy.sandia.gov/wp-content/gallery/uploads/Performance-Model-for-Grid-Connected-Photovoltaic-Inverters.pdf

Characterization

- Model parameters can be derived using tests from existing standards and protocols. No additional testing is required.
  - Tests for capacity, efficiency, response rate can be found in [1,5]
  - Tests for DC battery performance and life can be found in [3,4]
  - Tests for advanced functionality (e.g. frequency/watt) can be found in [2]
- If the full set of tests have not been completed, or if additional confidence is wanted in the resulting model, an additional testing optimized for model parameterization can be performed
  - The Energy Storage Pulsed Power Characterization (ESPPC) test, based on a combination of tests from [1], [3] and [5], offers an efficient procedure for deriving most battery model parameters.
- The accuracy of the model can also be evaluated using service specific testing procedures

First we will consider the characterization apparatus

Characterization Test & Apparatus [2]

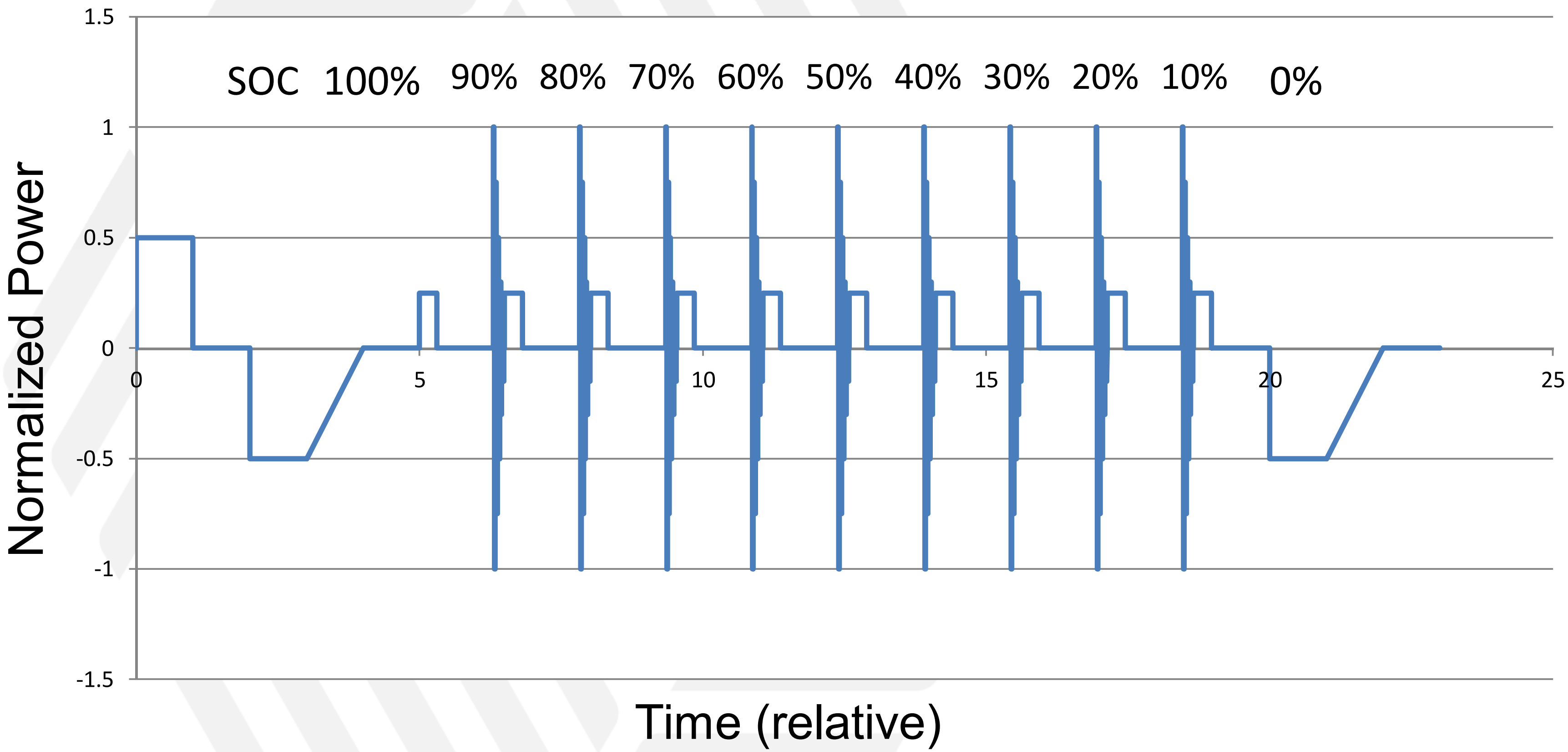


ESPPC Procedure (Proposed)

1. Discharge the system at P_{nom} until S_{min} has been reached
2. Float 1 hour
3. Charge the system at P_{nom} until S_{max} has been reached
4. Float 1 hour
5. Discharge the system at P_{nom} until 10% of C_{max} has been removed from the battery
6. Float 1 hour
7. Perform an impedance and conversion efficiency test
    - i. Discharge at $P_{inv,max}$ for 1 minute
    - ii. Float for 1 minute
    - iii. Charge at $P_{inv,min}$ for 1 minute
    - iv. Float for 1 minute
    - v. Repeat i through iv using 75%, 50%, 30%, 20%, and 10% of $P_{inv,max}/P_{inv,min}$
8. Repeat steps 5 through 7 until S_{min} has been reached (collecting impedance and conversion efficiency curves at nine total states of charge)
9. Charge the system at P_{nom} until S_{max} has been reached

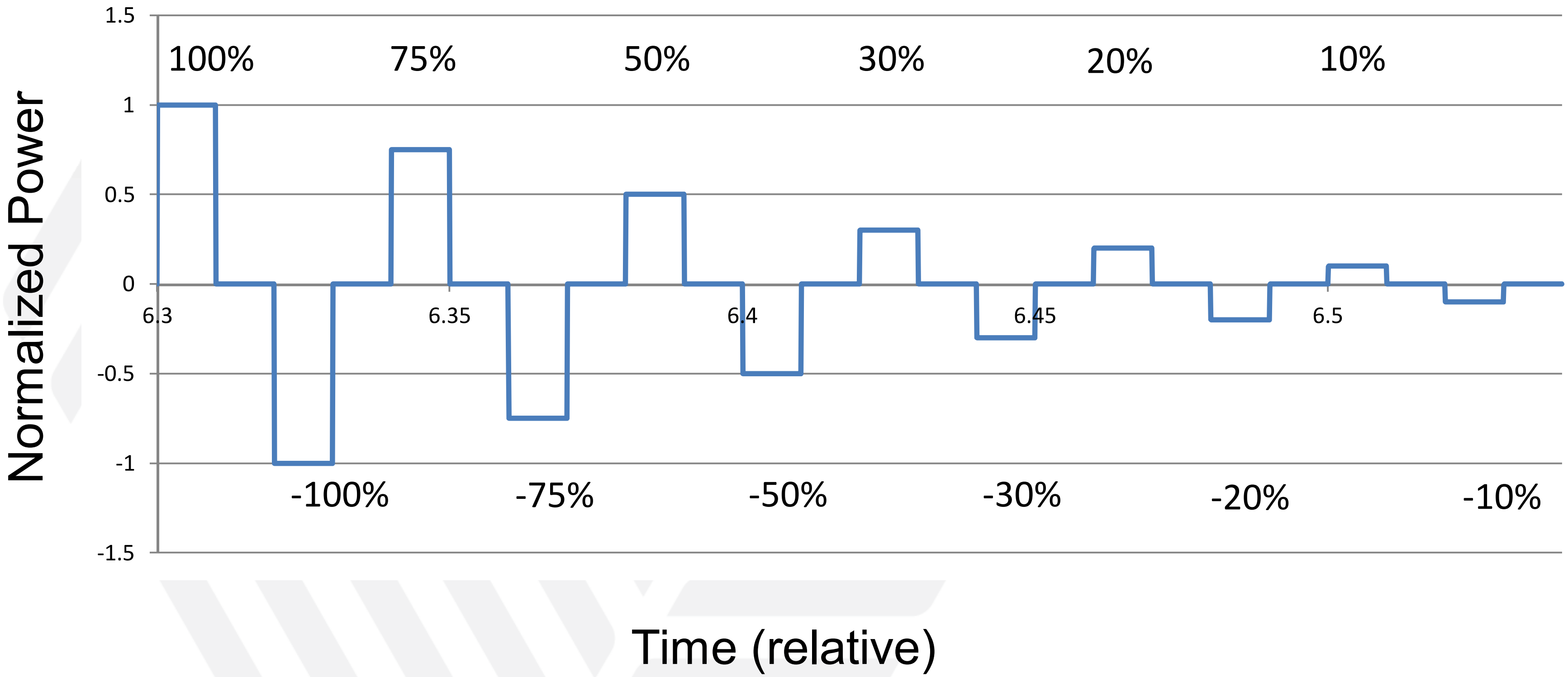
Characterization Procedure

Energy Storage Pulsed Power Characterization Test



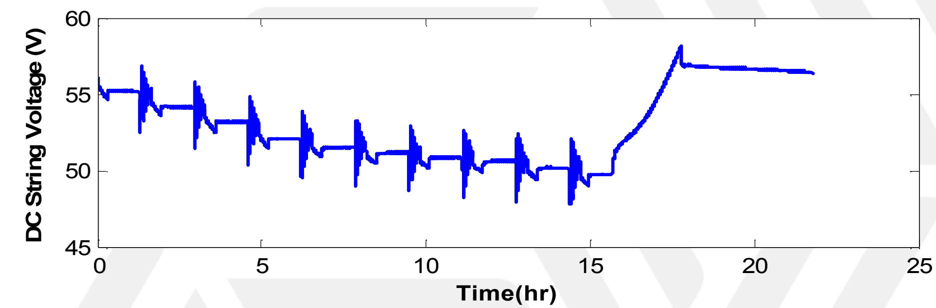
Characterization Procedure

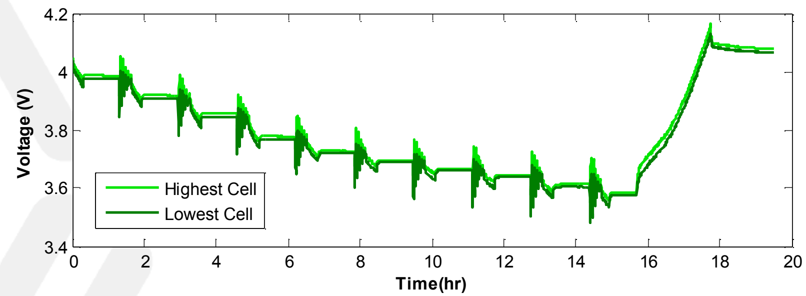
Pulsed Power Characterization at Each SOC Level

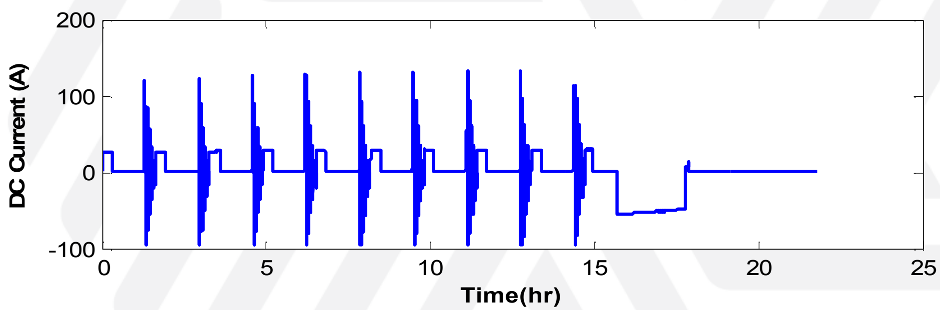


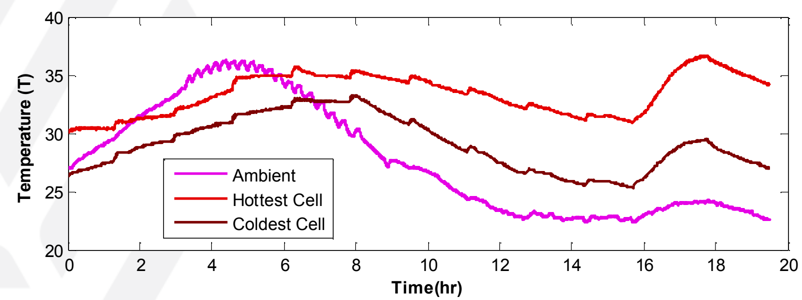
Characterization Procedure

ESPPC Test Applied to a Battery/Inverter System









Electrical Model Parameters

Thermal Model Parameters

Accuracy Assessment

- A duty cycle should be applied to the battery/inverter system under test. From these data, the following metrics should be computed based on the difference between the calculated state of charge / temperature and the values that the model would predict.

Root Mean Squared (RMS) SoC Error

$$\mu_{SoC} = \sqrt{\frac{\sum_{n=1}^{N}\left(S_{BMS}(n) - S_{Model}(n)\right)^2}{N}}$$

Root Mean Squared (RMS) Temperature Error

$$\mu_{T} = \sqrt{\frac{\sum_{n=1}^{N}\left(T_{BMS}(n) - T_{Model}(n)\right)^2}{N}}$$

Example Duty Cycle from [1]

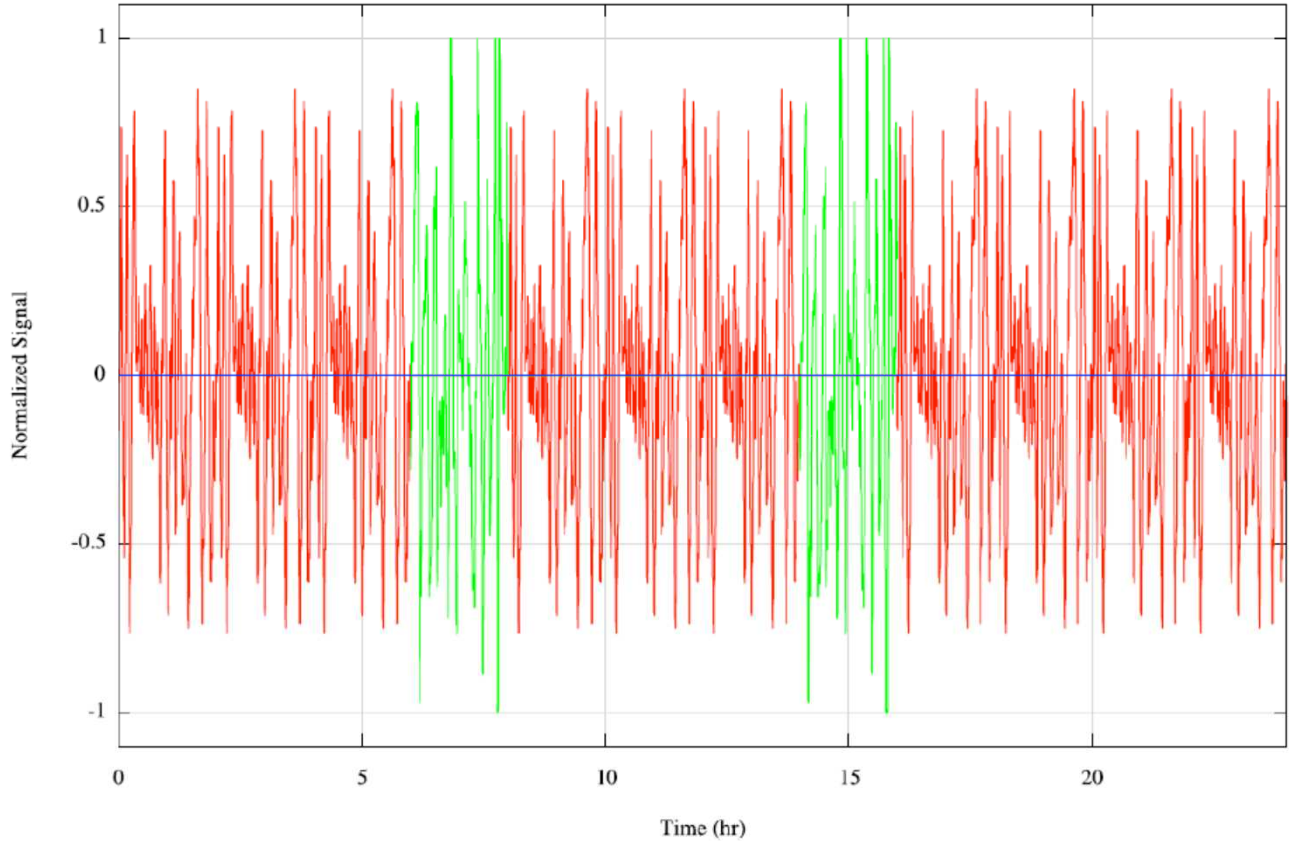


Figure 5.3.2. Frequency-Regulation Duty Cycle

Equipment Impact Metrics

- As batteries age, one aging mechanism is a growth in internal resistance. This reduces the instantaneous available power, reduces energy capacity, and increases heat generation.

Not having a calibrated model for resistance growth, the following can be used.

Calendar Life Acceleration Factor [4] (parameters derived from test data)

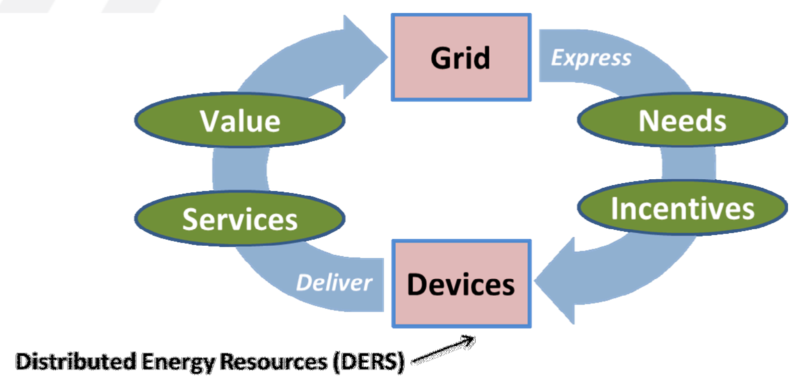
$$F_{CAL} = e^{T_{ACT}\left[\frac{1}{T_{REF}} - \frac{1}{T}\right]}$$

Cycle Life Acceleration Factor [4] (parameters derived from test data)

$$F_{CYC} = 1 + (K_P)\left(\frac{P}{P_{Rated}}\right)^{\omega}\left[1 + (K_T)(T - T_{REF})\right]$$

Summary

- As the resource mix of the grid changes, the emerging mix of distributed energy resources can be utilized to maintain reliability and energy cost.
- The value these DER can provide depends on their service specific performance
- This performance can be assessed fairly and equitably using a combination of characterization, modeling, and simulation
  - Characterization tests to develop device specific models
  - Service simulation to using device specific models to understand performance
- This approach can also quantify accuracy and assess equipment impact (if applicable)



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