Energy Storage Technology Advancement Partnership (ESTAP) Webinar:

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

March 13, 2017

Hosted by Todd Olinsky-Paul
ESTAP Project Director
Clean Energy States Alliance

Housekeeping

All participants are in "Listen-Only" mode. Select "Use Mic & Speakers" to avoid toll charges and use your computer's VOIP capabilities. Or select "Use Telephone" and enter your PIN onto your phone key pad.

Submit your questions at any time by typing in the Question Box and hitting Send.

This webinar is being recorded.

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State & Federal Energy Storage Technology Advancement Partnership (ESTAP)

Todd Olinsky-Paul

Project Director

Clean Energy States Alliance (CESA)

Thank You:

Dr. Imre Gyuk
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Sandia National Laboratories

Clean Energy States Alliance

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

ESTAP is a project of CESA

Clean Energy States Alliance (CESA) is a non-profit organization providing a forum for states to work together to implement effective clean energy policies & programs:

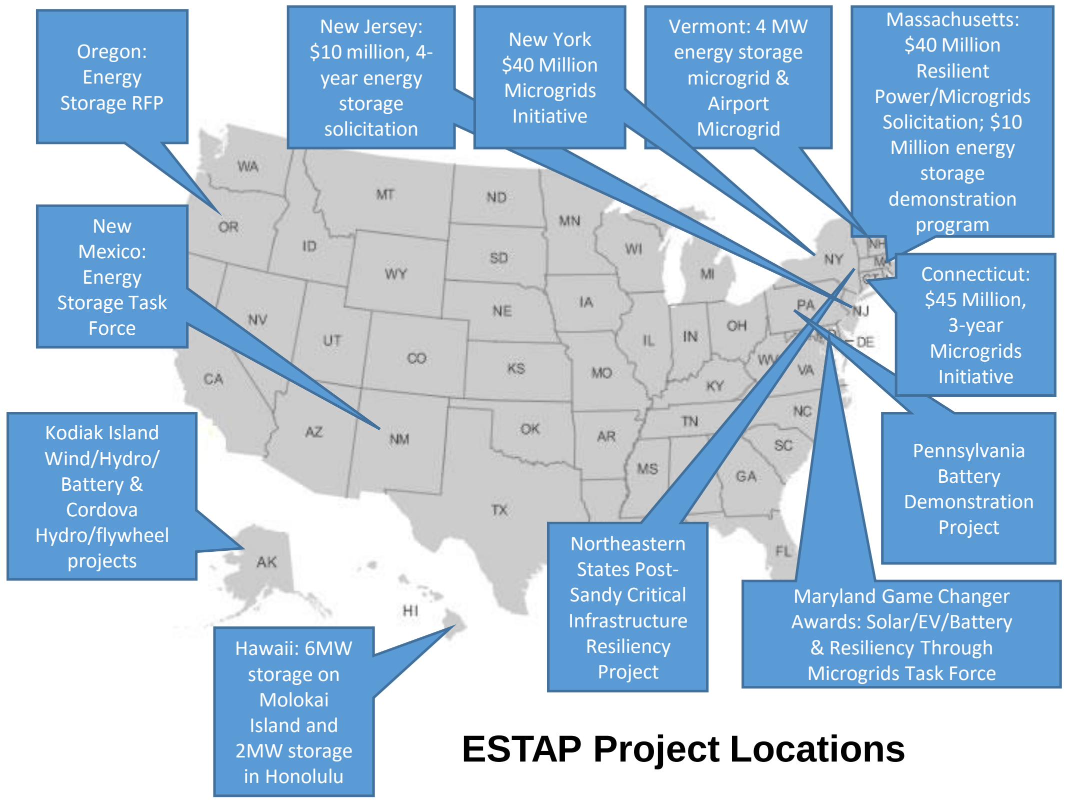
State & Federal Energy Storage Technology Advancement Partnership (ESTAP) is conducted under contract with Sandia National Laboratories, with funding from US DOE.

ESTAP Key Activities:

1. Disseminate information to stakeholders
   - ESTAP listserv >3,000 members
   - Webinars, conferences, information updates, surveys.

2. Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment

3. Support state energy storage efforts with technical, policy and program assistance



ESTAP Project Locations

Clean Energy States Alliance | Sandia National Laboratories | U.S. DEPARTMENT OF ENERGY

Energy Storage Technology Advancement Partnership

Overview
ESTAP Resource Library
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ESTAP

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The Energy Storage Technology Advancement Partnership (ESTAP) is a federal-state funding and information sharing project, managed by CESA, that aims to accelerate the deployment of electrical energy storage technologies in the U.S.

The project's objective is to accelerate the pace of deployment of energy storage technologies in the United States through the creation of technical assistance and co-funding partnerships between states and the U.S. Department of Energy.

ESTAP conducts two key activities:

1) Disseminate information to stakeholders through:

- The ESTAP listserv (>2,000 members)
- Webinars, conferences, information updates

NEW RESOURCES

October 14, 2015
Resilience for Free: How Solar+Storage Could Protect Multifamily Affordable Housing from Power Outages at Little or No Net Cost
By Clean Energy Group

September 30, 2015
Webinar Slides: Energy Storage Market Updates, 9.30.15

UPCOMING EVENTS

December 16, 2015
ESTAP Webinar: State of the U.S. Energy Storage Industry,

More Events

LATEST NEWS

November 30, 2015
Massachusetts Takes the Lead on Resilient

Panelists

David Rosewater, Sandia National Laboratories

Sudipta Chakraborty, National Renewable Energy Laboratory

Todd Olinsky-Paul, Clean Energy States Alliance (Moderator)

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

David Rosewater
Sandia National Laboratories

Sudipta Chakraborty
National Renewable Energy Laboratory

March 13th, 2016

SAND2017-2704 PE

Outline

- ► Introduction (David)
- ► Photovoltaic System Device Model (Sudipta)
- ► Battery System Device Model (David)
- ► Summary

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

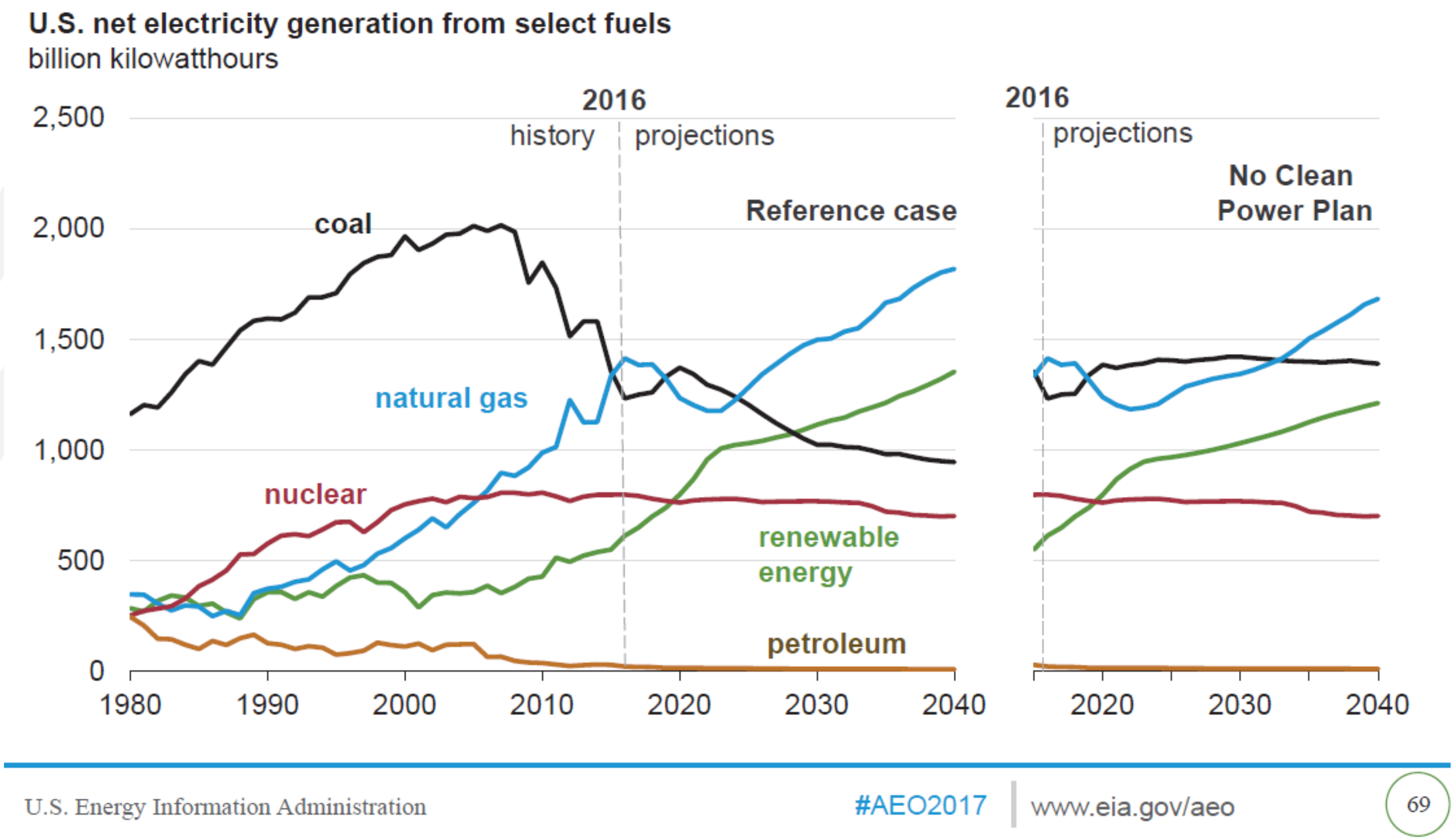


Figure Source: Energy Information Administration Annual Energy Outlook 2017: https://www.eia.gov/outlooks/aeo/pdf/0383%282017%29.pdf

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 enabled to supply the same services to the grid

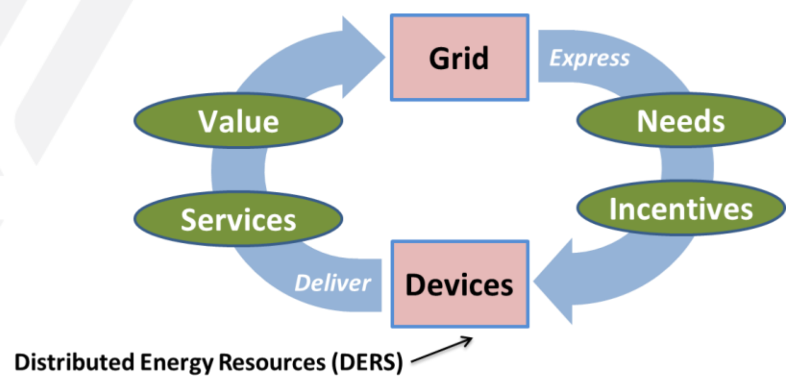
High-Level Project Summary

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.

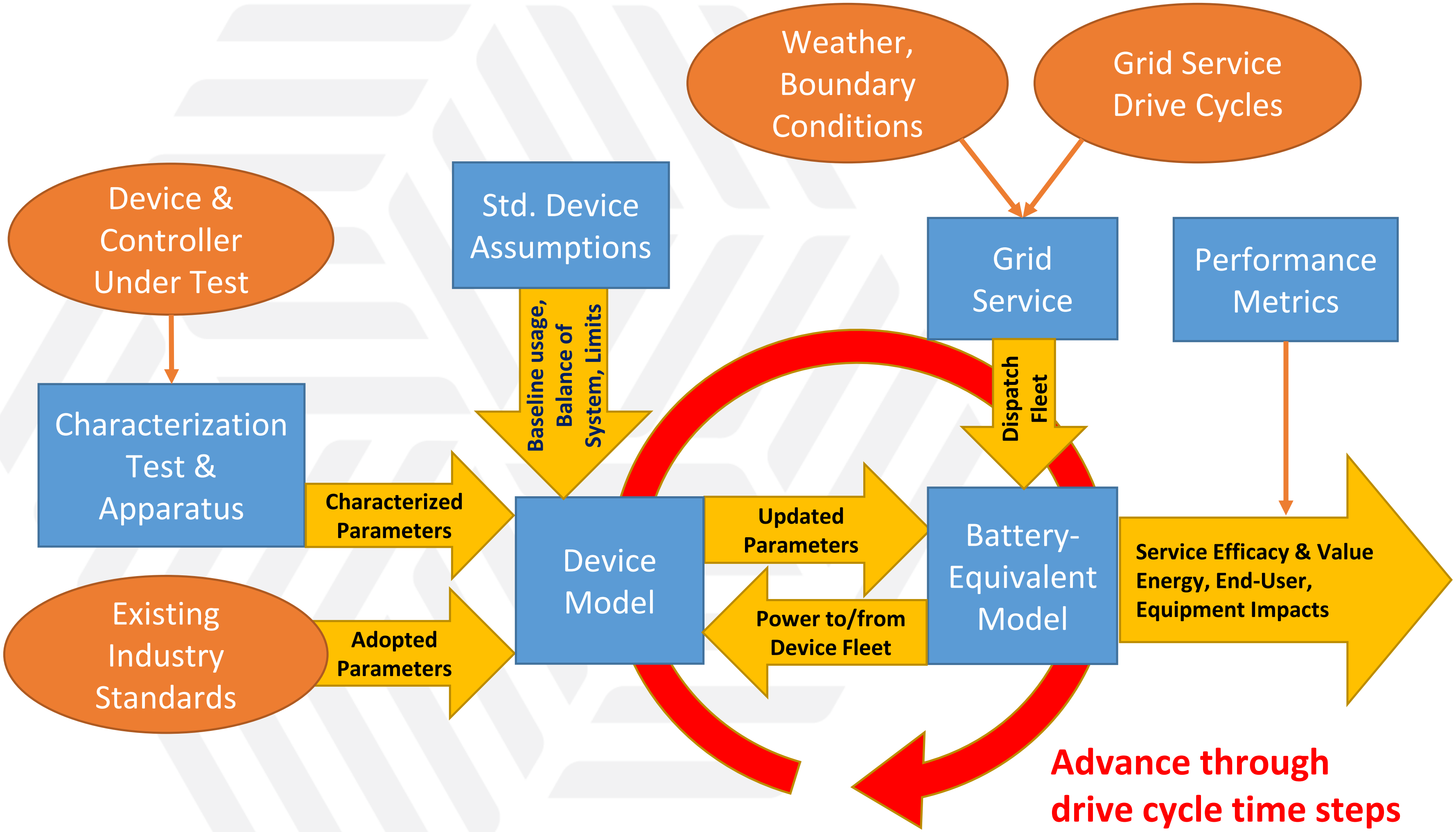
Lab	Device Class	Grid Services
PNNL	1. Thermal storage	A. Peak load management B. Artificial inertia/fast frequency response
NREL	3. Water heaters 4. Refrigerators 5. PV/inverters	C. Distribution voltage management / PV impact mitigation
SNL	6. Batteries/inverters	
ANL	7. Electric vehicles (DR, V2G)	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

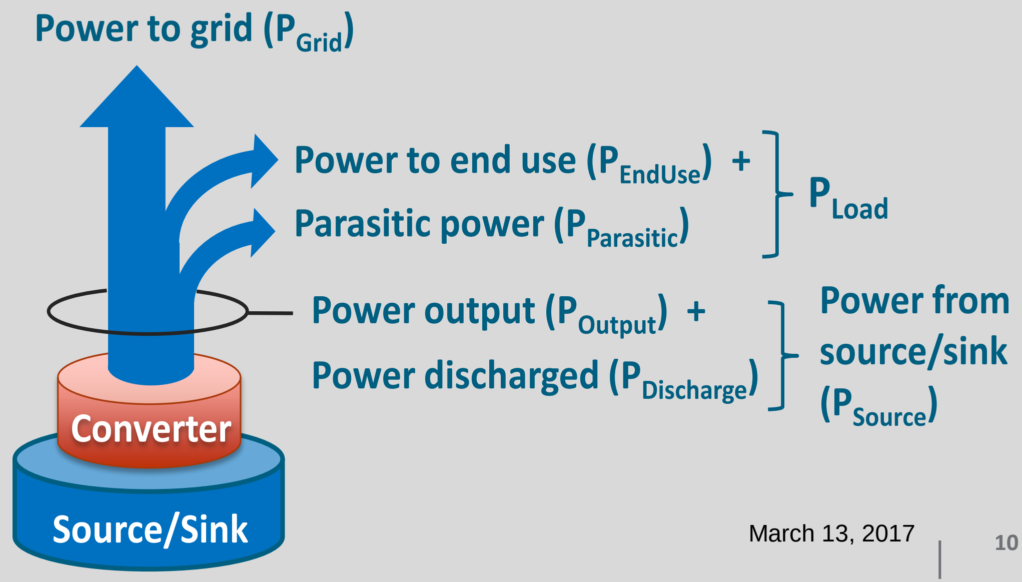
Nameplate Parameters

- Energy Storage Capacity
- Max real/reactive power
- Min real/reactive power
- Ramp rate real/reactive up/down
- Charging Efficiency
- Discharging Efficiency

Modeling a fleet of identical devices, not individual devices

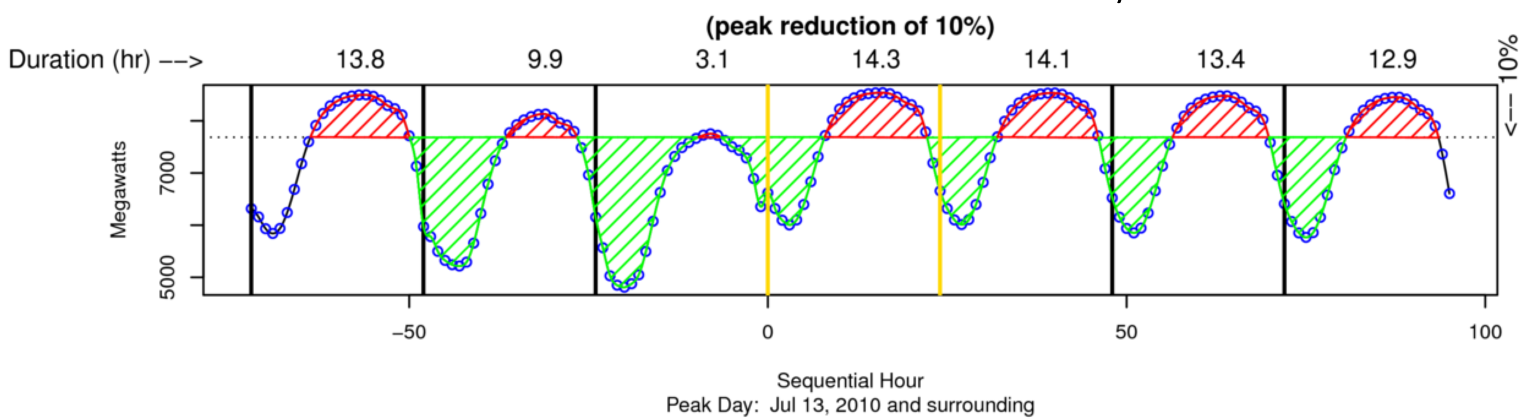
- Continuously variable response possible
- State variables reflect the mean of the distribution of states in fleet

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

Photovoltaic System Device Model

Grid Services from Photovoltaics (PV)

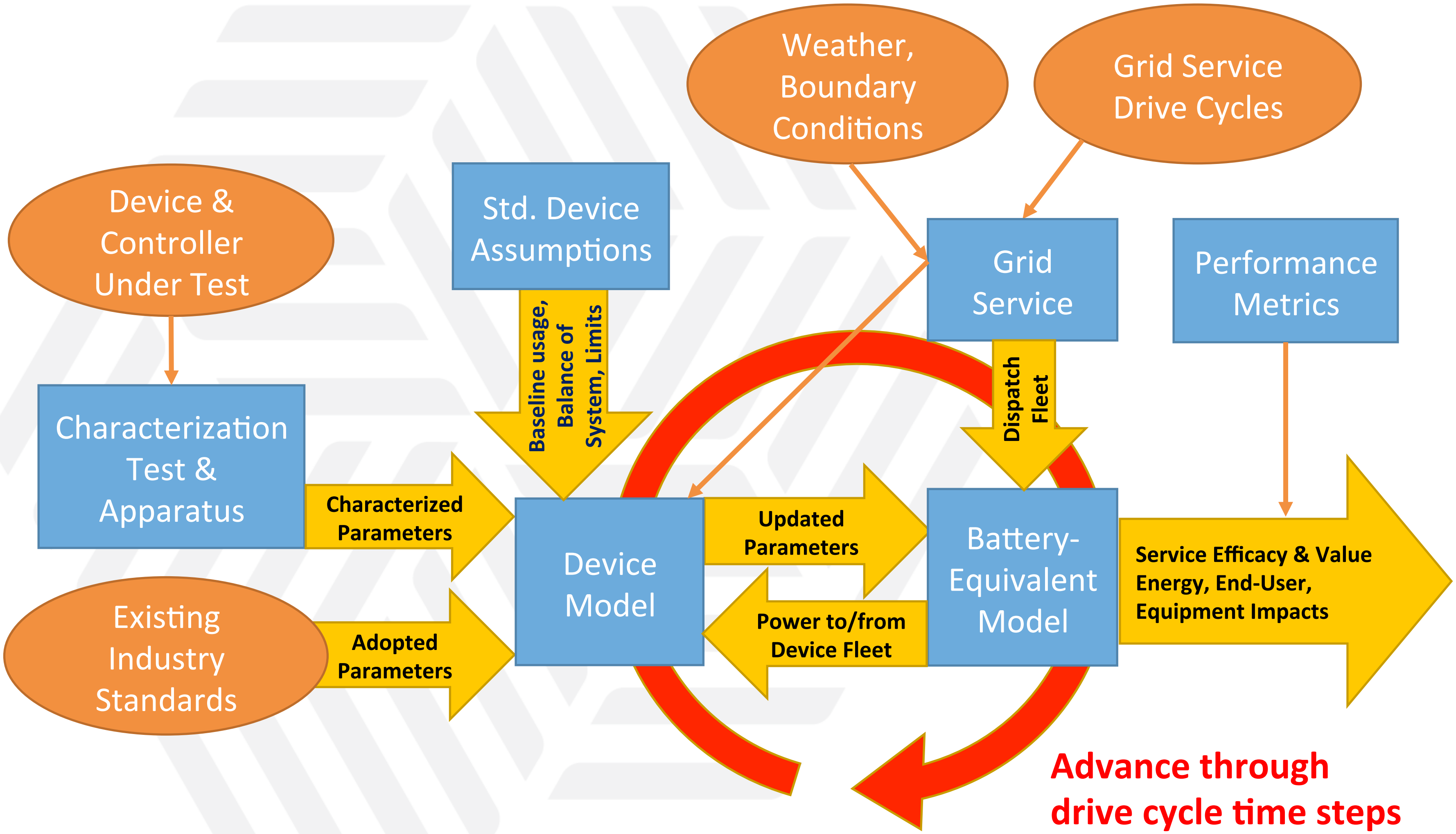
Sudipta Chakraborty

National Renewable Energy Laboratory

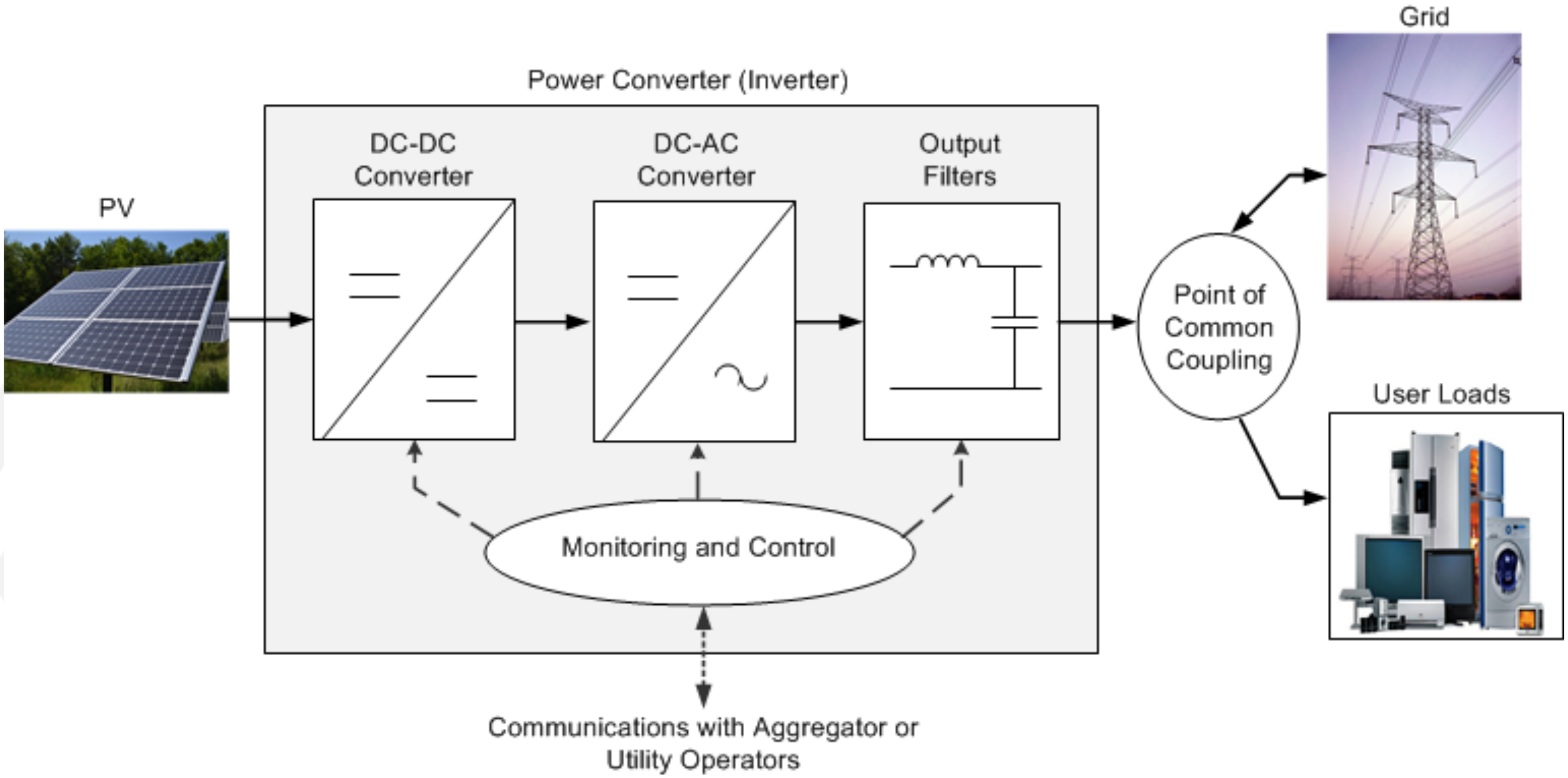
Recap of Primary Objectives

- Protocols for characterizing device fleet performance (of various classes) for a set of standard parameters
  - Based on a short-term (<24-hour) test
  - Suitable for adoption as a Recommended Practice
- Standard “drive cycles” representative of the required response for each service
- Metrics for a fleet of identical device’s ability to perform & value provided for each grid service
- Standard model for devices, with parameters determined by the characterization procedure
  - Proven to accurately estimate device’s actual ability to perform grid services
  - Suitable for adoption as a standard, general model describing the performance envelope of DER/device fleets

General Framework and Approach



Structure of Typical PV/Inverter System



- For the purpose of grid services, the PV and the PV inverter systems are considered together

Standard Controls and Operations for Smart/Advanced PV Inverters

- Deliver real power
  - MPPT
  - Constant power control
- Trip and Ride-through for grid faults
  - Voltage trip
  - Frequency trip
  - Voltage ride-through
  - Frequency ride-through
- Unintentional islanding detection
- Grid synchronization
- Grid support functions
  - Real power functions
    - Frequency-Watt
    - Volt-Watt
  - Reactive power functions
    - Fixed power factor
    - Fixed VAR
    - Volt-VAR
    - Watt-VAR
- Communications

Grid Services from PV/Inverter Fleet

- Types of services
  - Autonomous services:
    - PV/inverter systems can provide very fast autonomous real power (e.g. inertial response) or reactive power (e.g. voltage regulation) services
    - Time scale for such services can be as fast as 50-100ms
  - Dispatched services:
    - PV systems itself is non-dispatchable without a energy storage
    - To provide dispatched service from PV/inverter, forecasting of power output from PV is required. The forecasting errors needs to be accounted for to determine available power
    - Note that some of the variability of individual PV/inverter systems will be mitigated when a large fleet of PV systems are considered for grid services due to their geographic diversity

Constraints for Grid Services from PV

- End-user limits: The PV may operate at reduced power level than MPP to provide grid service reducing the energy revenue for the owner of the PV system. If there is not any compensation scheme, the owner may not opt to participate in providing grid service under such condition

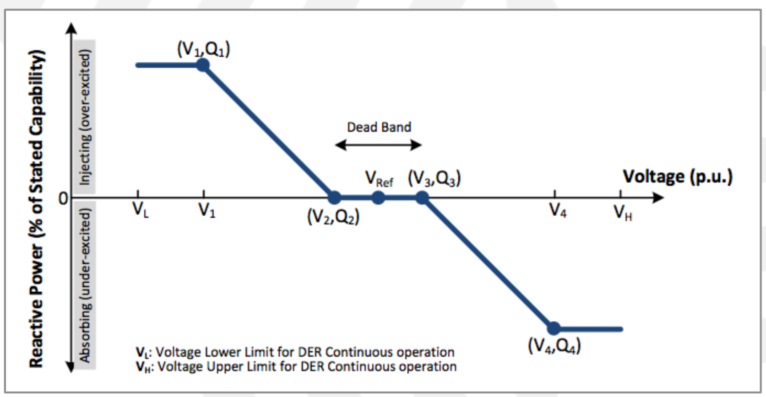
- Dispatchability limits: If no energy storage is used, the active power output from PV system is dependent on Solar irradiation. Forecasting of PV generation will have certain accuracy limits

- Equipment limits: The PV system may run longer time while providing grid service (e.g. reactive power generation) compared to the case when no grid service is being provided. This longer run may result in reduced reliability. PV system will also be subjected to design constraints (e.g. current limit, thermal limit) while providing grid services

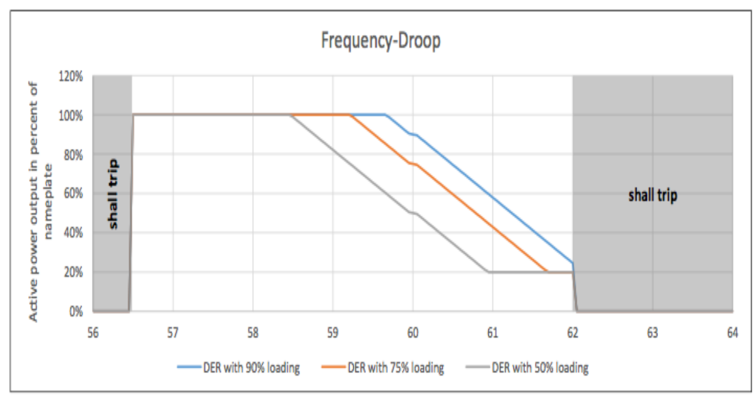
Minimum Controls Requirement for Providing Grid Services - Autonomous

- The PV system should have ability to change output real and/or reactive power autonomously based on local measurements
- Some control requirements include:
  - Capability to follow the preset set points (e.g. fixed power factor) or preset curves (e.g. frequency-Watt, volt-VAR)
  - Time response for autonomous voltage and frequency regulations
  - Command/communication to switch among different autonomous modes
  - Command/communication to set volt-VAR and frequency-Watt curves

Example Volt-VAR Curve (from Draft IEEE 1547 Revision)



Example Frequency-Watt Curve (from Draft IEEE 1547 Revision)

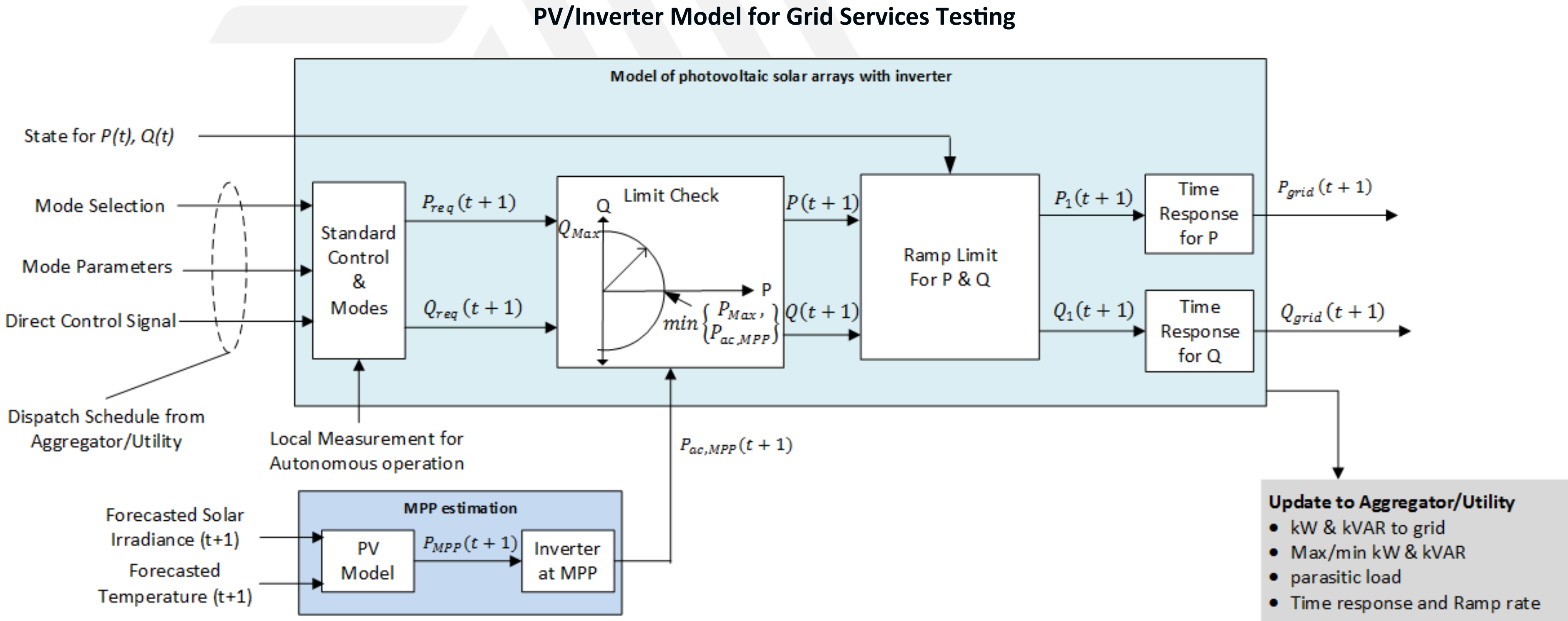


Minimum Controls Requirements for Providing Grid Services - Dispatched

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- The PV system should have ability to change output real and/or reactive power based on a externally communicated signals
- Some control requirements include:
  - Command to switch among different dispatch modes
  - Command to set real power
  - Command to set reactive power
  - Time response to change real/reactive power output based on communicated signals

Device Model for PV/Inverter for Grid Services



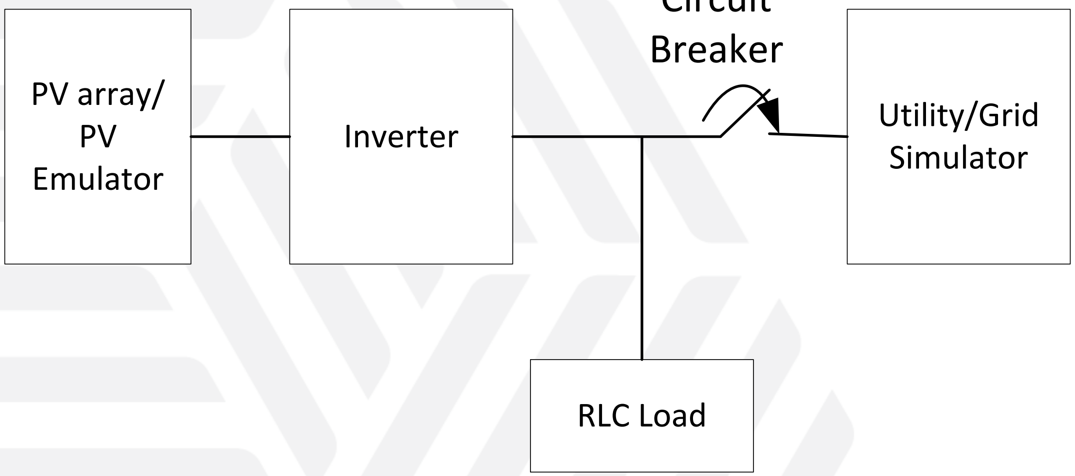
Adopted Parameters

- Parameters of the PV system that may be adopted from existing test results (standardized industry tests, manufacturer provided specifications)
- Some example of adopted parameters include:
  - Inverter kW rating (nominal condition, maximum)
  - Inverter kVA rating (nominal condition, maximum)
  - Inverter operating ranges (DC voltage, AC voltage and frequency)
  - Inverter conversion efficiency for inverter (peak, CEC)
  - Inverter maximum continuous output current
  - PV efficiency (standard test condition)
  - PV panel size in KW

Parameters to be Characterized

- Parameters of the PV system that need to be characterized. It is important to note that some of these parameters will be available in future as a part of standard/ certification testing (such as revised IEEE 1547.1, UL 1741SA)
- Some example of parameters to be characterized:
  - Conversion efficiencies for grid service duty cycle
  - VAR capability and modes (e.g. fixed power factor, fixed VAR, volt-VAR, Watt-VAR)
  - Response time, ramp rates for VAR modes
  - Watt modes (e.g. curtailment, frequency-Watt, volt-Watt)
  - Response time, ramp rates for Watt modes
  - Responses for Watt-priority v/s VAR priority
  - Startup ramp rates
  - Responses to communicated signals

Example of Test Setup



1.5 MVA PV Simulator

1 MVA RLC Load Bank

1.08 MVA Grid Simulator

Example Test Protocols (Adopted Parameters)

- Efficiency testing is part of inverter rating and currently PV inverters specify CEC and peak efficiency. CEC efficiency is a weighted efficiency number that's designed to estimate the average efficiency of PV inverter
- Even though CEC efficiency is available from the manufacturer, for grid services purpose, we will need to know various efficiency numbers at various input and output conditions. Furthermore, the impact of advanced functions on the efficiency will also need to be determined

Example of Efficiency Testing

Minimum Leading Power Factor: 0.9

Rated Output Apparent Power: 1.0 kVA **Rated Output Real Power:** 0.9 kW

Vmin: 300 Vdc Vnom: 360 Vdc Vmax: 480 Vdc

			Inverter AC Output Real Power Level at Stated Power Factor					
Test	Vdc	Vac	10%	20%	30%	50%	75%	100%
C	Vmin	Vnom						
B	Vnom	Vnom						
A	Vmax	Vnom						

Resultant Efficiency = ______

Minimum Lagging Power Factor: 0.9

Rated Output Apparent Power: 1.0 kVA **Rated Output Real Power:** 0.9 kW

Vmin: 300 Vdc Vnom: 360 Vdc Vmax: 480 Vdc

			Inverter AC Output Real Power Level at Stated Power Factor					
Test	Vdc	Vac	10%	20%	30%	50%	75%	100%
C	Vmin	Vnom						
B	Vnom	Vnom						
A	Vmax	Vnom						

Resultant Efficiency = ______

Power Factor: Unity

Rated Output Apparent Power: 1.0 kVA **Rated Output Real Power:** 1.0 kW

Vmin: 300 Vdc Vnom: 360 Vdc Vmax: 480 Vdc

			Inverter AC Output Real Power Level at Unity Power Factor					
Test	Vdc	Vac	10%	20%	30%	50%	75%	100%
C	Vmin	Vnom						
B	Vnom	Vnom						
A	Vmax	Vnom						

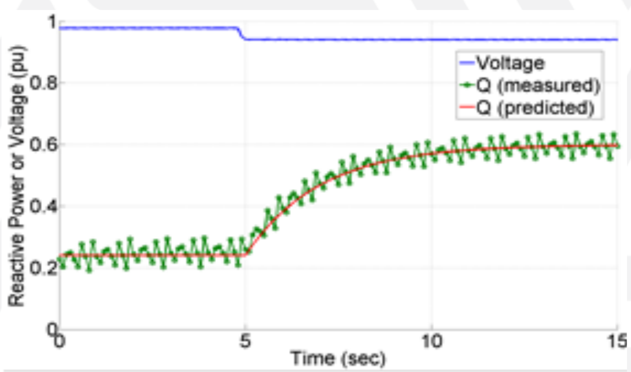
Resultant Efficiency = ______

Source: J. Newmiller, D. Blodgett, and S. Gonzalez, "Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems," SAND2015-4418R, 2015.

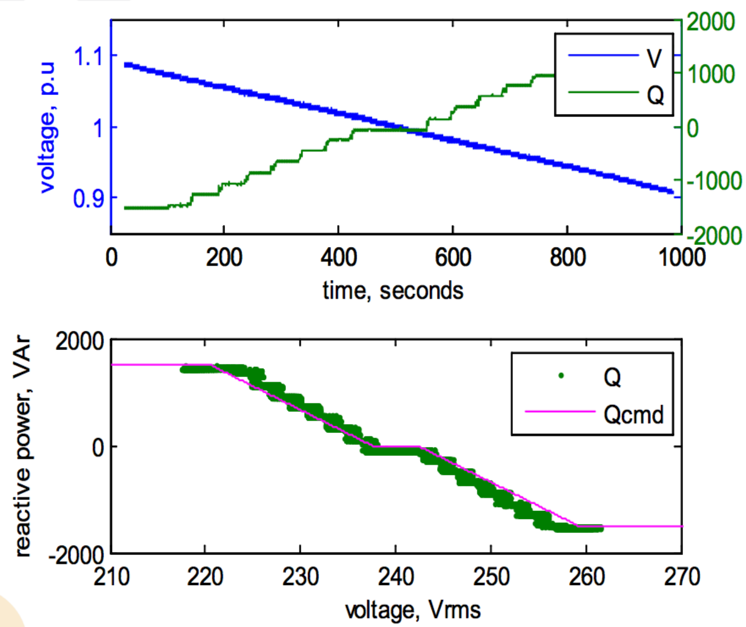
Example Test Protocols (Parameters to be Characterized)

- Voltage regulation by volt-VAR control
  - UL1741SA or other draft test standards
  - Revised IEEE 1547.1 – will be out in 2018

Volt-VAR Time Response



Volt-VAR Output



Source: A. Hoke, S. Chakraborty, T. Basso, M. Coddington, "Beta Test Plan for Advanced Inverters Interconnecting Distributed Resources with Electric Power Systems ," NREL/TP-5D00-60931, 2014.

Battery / Inverter Device Model

Battery/Inverter Systems

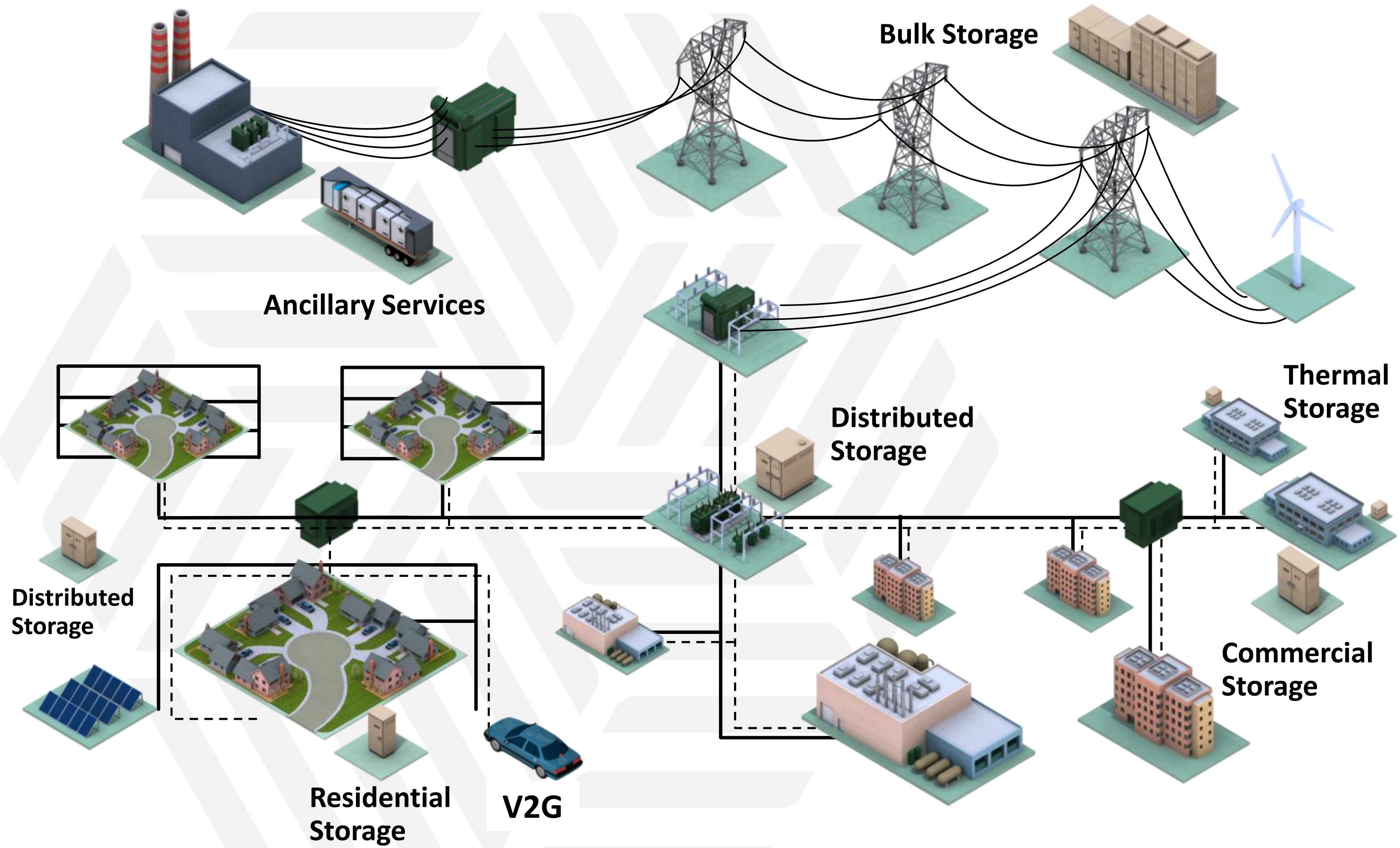


Figure Source EPRI

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

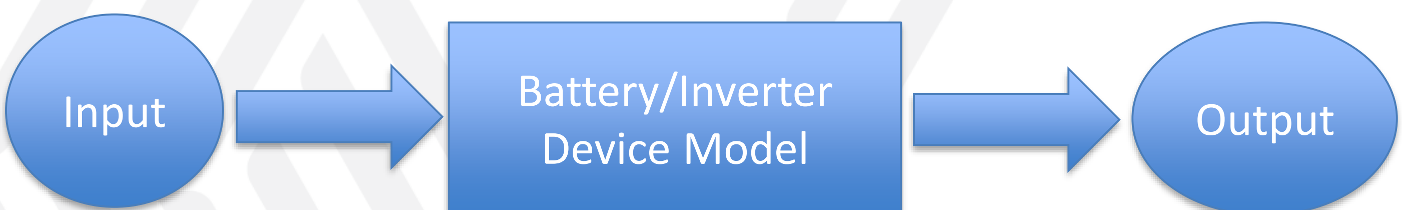
Source DOE: Global Energy Storage Database www.energystorageexchange.org

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

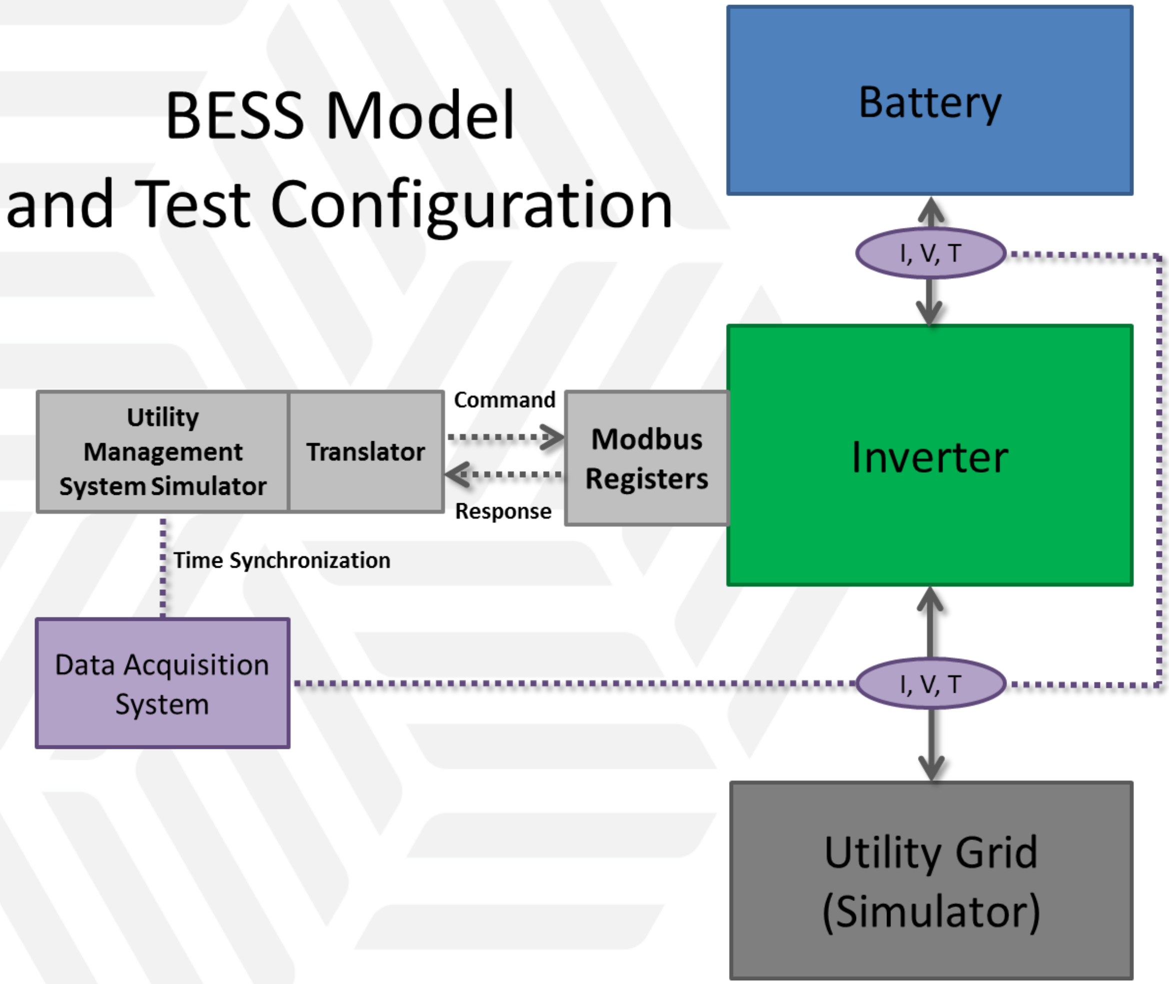
1. DR Conover et al, "Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems" Sandia National Laboratories, SAND2016-3078R, http://www.sandia.gov/ess/publications/SAND2016-3078R.pdf
2. Maurizio Verga, et al "SIRFN Draft Test Protocols for Advanced Battery Energy Storage 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]

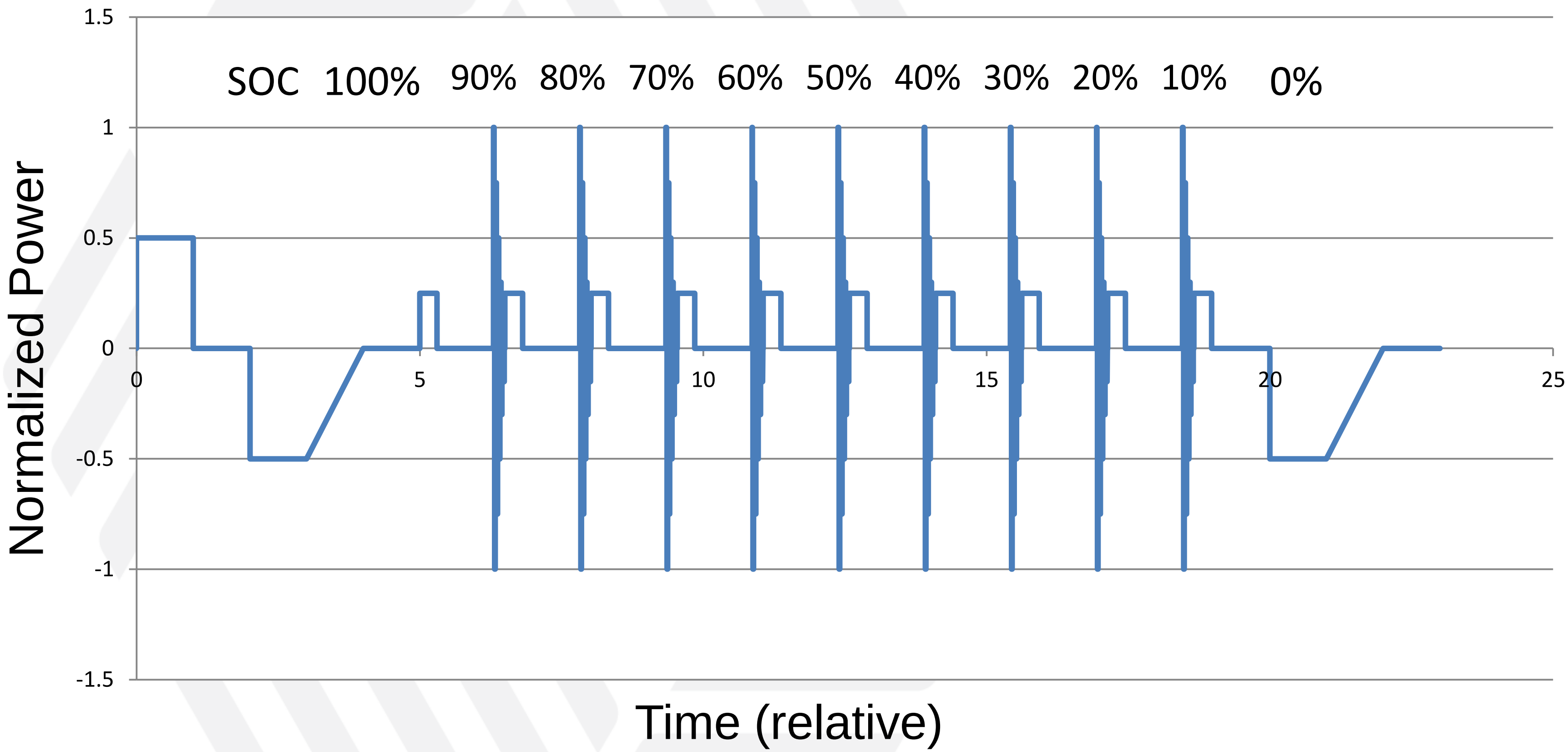


ESPPC Procedure (Proposed)

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

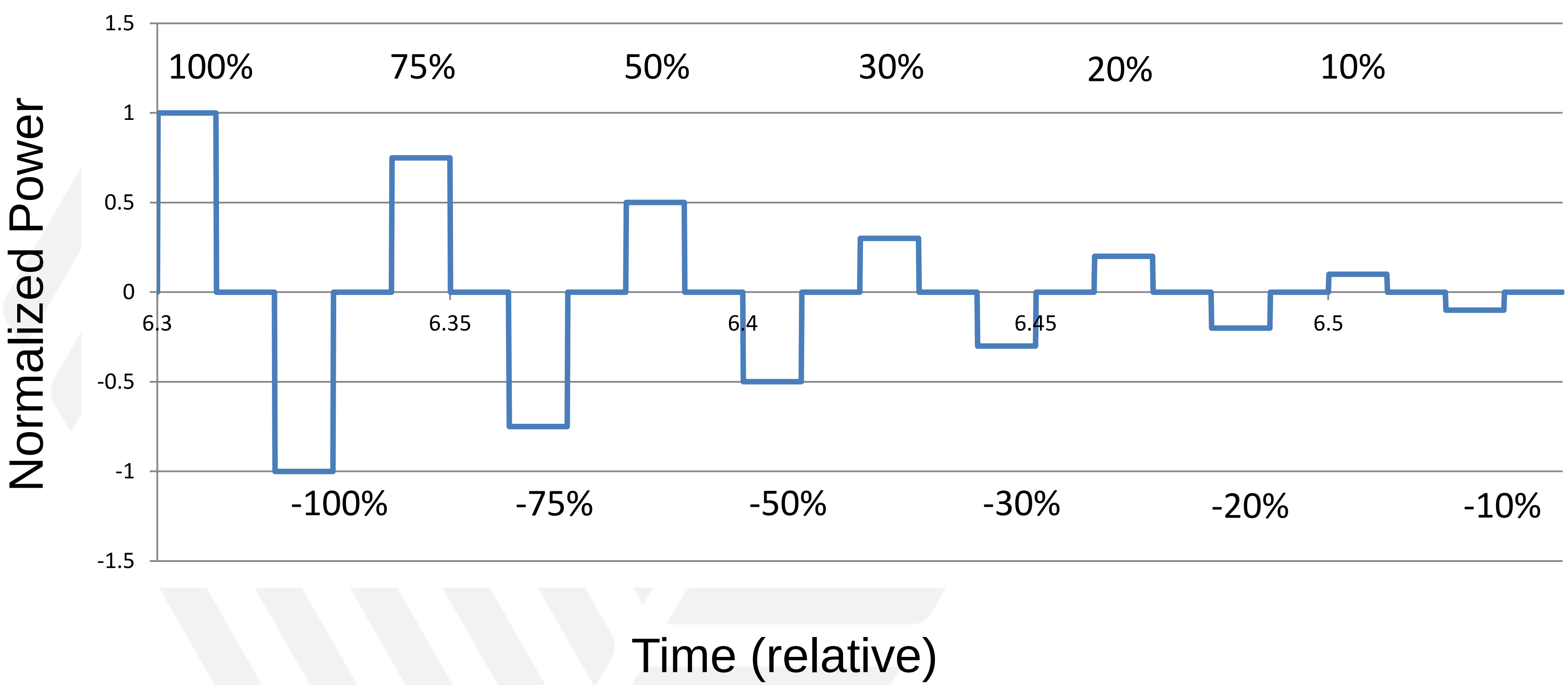
Characterization Procedure

Energy Storage Pulsed Power Characterization Test



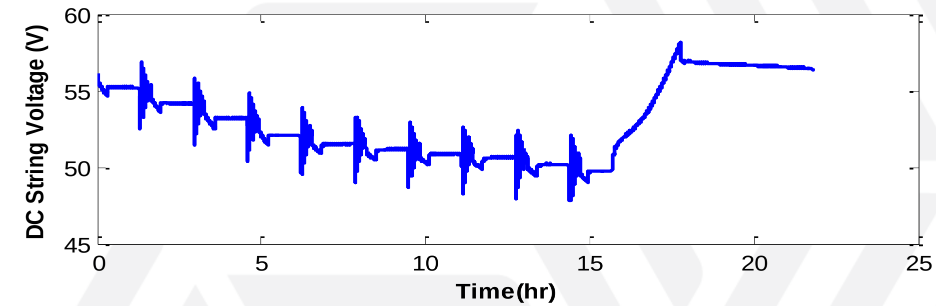
Characterization Procedure

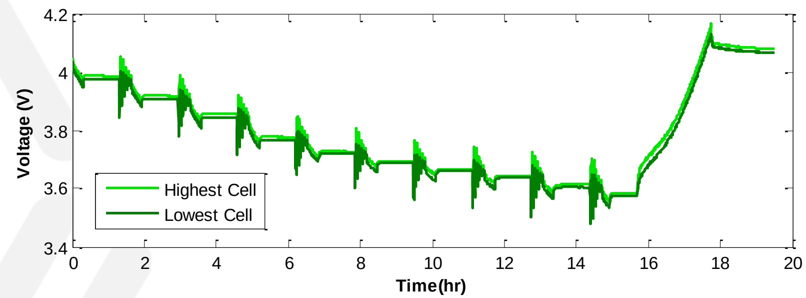
Pulsed Power Characterization at Each SOC Level

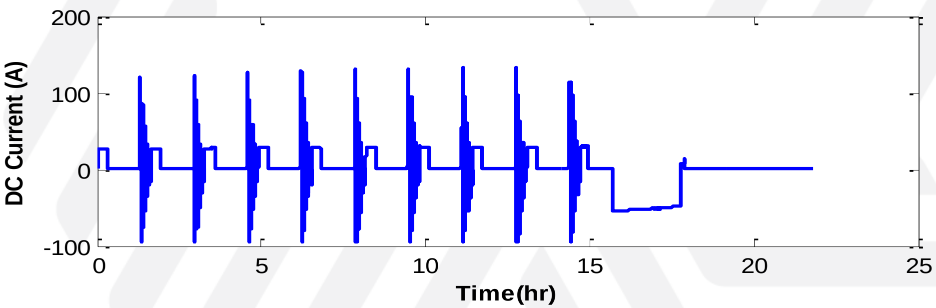


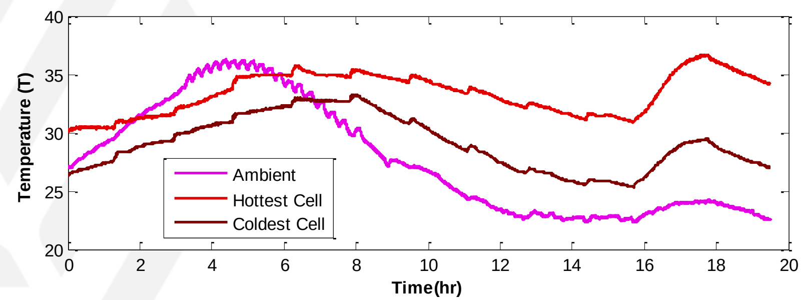
Characterization Procedure

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]

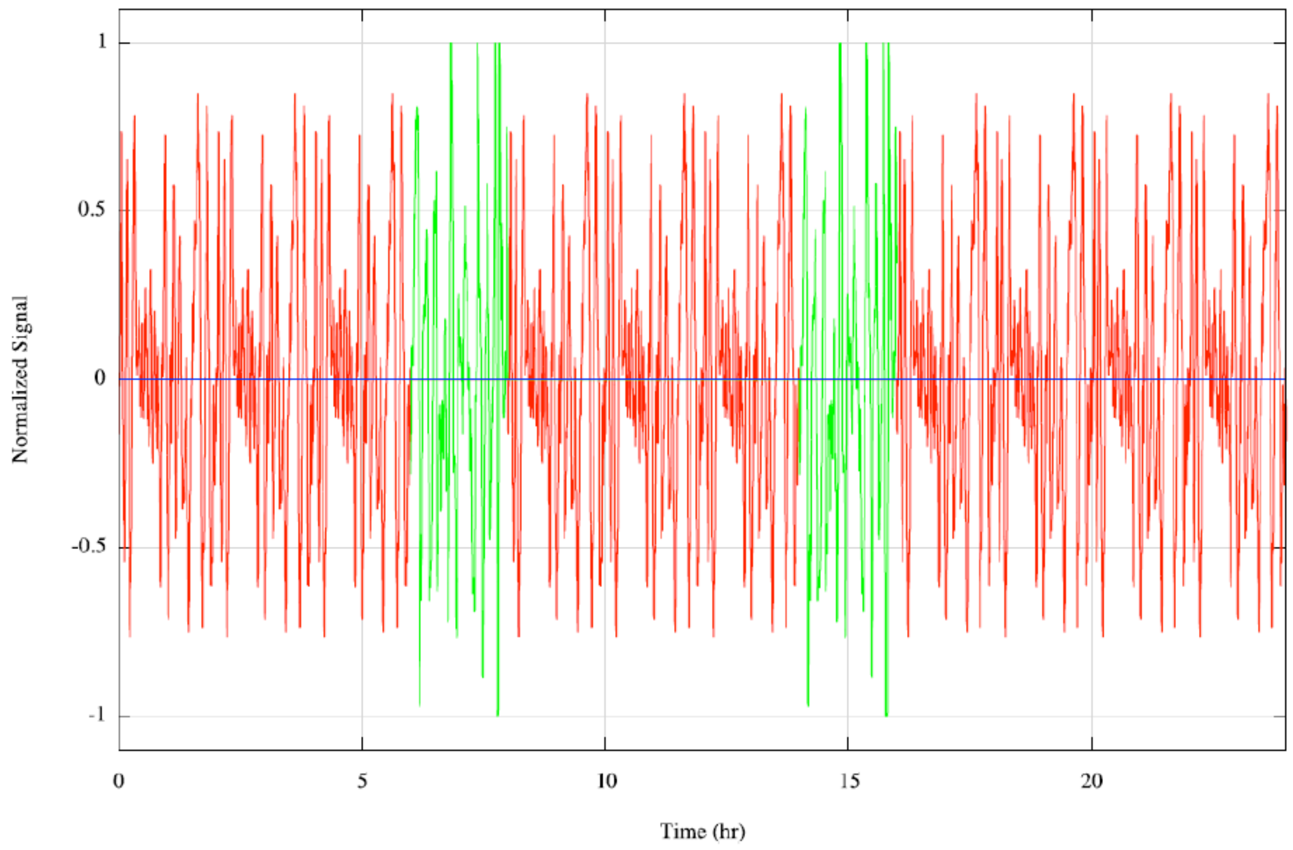


Figure 5.3.2. Frequency-Regulation Duty Cycle

Equipment Impact Metrics [4]

- 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)

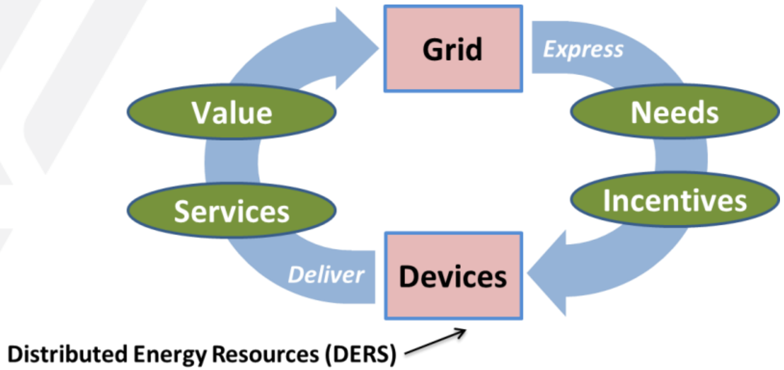
$$F_{CAL} = e^{T_{ACT}\left[\frac{1}{T_{REF}} - \frac{1}{T}\right]}$$

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

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

Summary

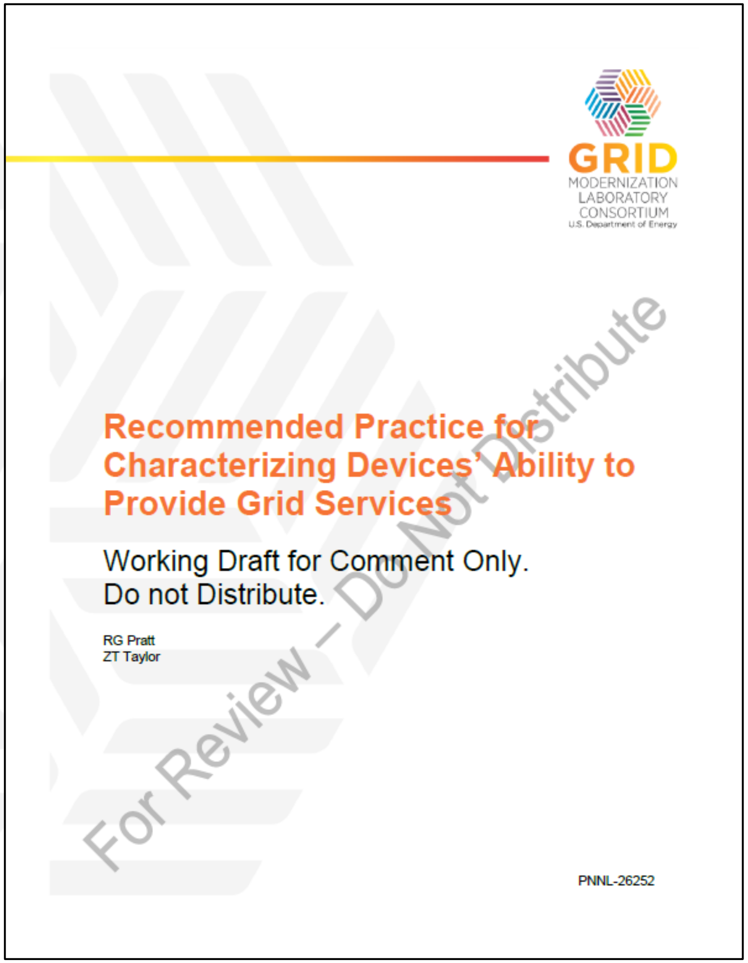
- As the resource mix of the grid changes, the emerging mix of distributed energy resources can be utilized to maintain reliability and energy cost.
- The value these DER can provide depends on their service specific performance
- This performance can be assessed fairly and equitably using a combination 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)



Draft Recommended Practice

- ► Available for Review
- ► Chapter 1 Purpose and Scope
- ► Chapter 2 General Definitions

► https://gridmod.labworks.org/resources/recommended-practice-characterizing-devices%E2%80%99-ability-provide-grid-services


GRID MODERNIZATION LABORATORY CONSORTIUM U.S. Department of Energy

Recommended Practice for Characterizing Devices' Ability to Provide Grid Services

Working Draft for Comment Only. Do not Distribute.

RG Pratt
ZT Taylor

For Review – Do Not Distribute

PNNL-26252

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- **Learn from your peers** on how they envision a modernized grid

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Thursday, March 23, 1-2pm ET

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Thursday, March 30, 1-2pm ET

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Thursday, April 6, 1-2pm ET

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