THE HONG KONG POLYTECHNIC UNIVERSITY
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The Frontier Research on Microgrid Technologies and Implementations

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Acknowledgement: Thanks for the materials from my ex-colleagues at EPRI and NREL.

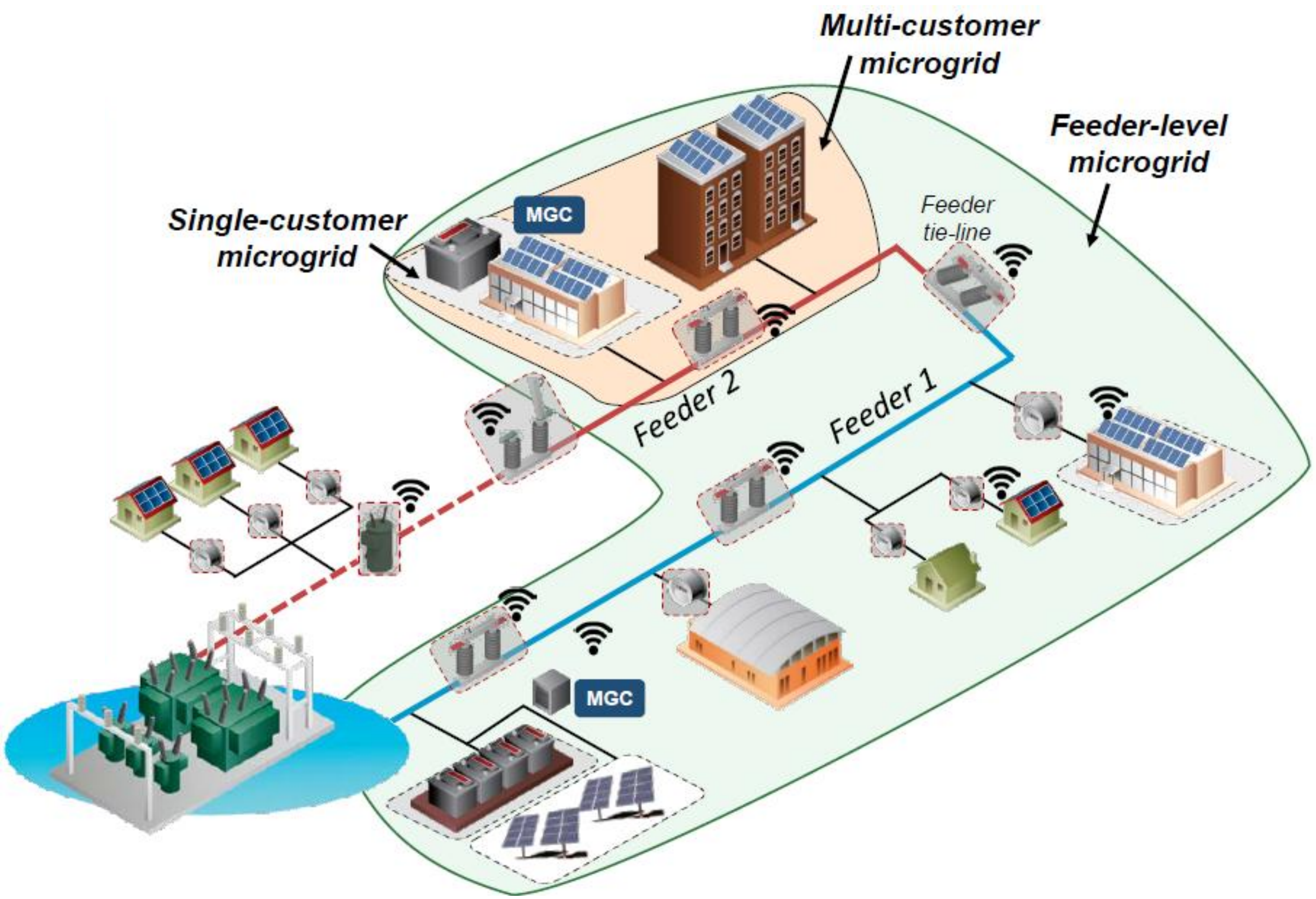
Outline

- Microgrid Introduction
  - Definition, features, goals, technologies and challenges of microgrids
- Microgrid Design Considerations
- Microgrid Techno-Economic Assessment
  - DER-VET: A Tool Developed by EPRI
- Microgrid Controls
- Testing of Microgrid Control Systems

Microgrid Introduction

Definition of Microgrid: EPRI's Definition of "Microgrid"

- A group of inter-connected loads and DER equipment and devices, within defined electrical boundaries.
- Acting as a single controllable entity with respect to the grid.
- Able to connect and disconnect from the grid, operating in both grid-connected or island-modes.



Types of Microgrids and the Range of Objectives

- Commercial/Industrial Microgrids
  - Generally built with the goal of reducing demand and costs during normal operation, although the operation of critical functions during outages is also important, especially for data centers
- Community/Utility Microgrids
  - Designed to improve reliability and to promote community participation
- Campus/Institutional Microgrids
  - Many campuses already have DG resources, with microgrid technology linking them together. They are usually large and may be involved with selling excess power to the grid
- Military Microgrids
  - Critical loads, cyber and physical security, both for fixed bases and forward operating bases.

Most microgrids will be grid-connected >99% of the time

Why Build a Microgrid? Understanding Microgrid Objectives

Objective	Solutions...
Integrating more renewables (hosting capacity)	Infrastructure upgrade, smart inverters, energy storage
Reducing local emissions	Grid-tied renewables, CHP, building and transportation electrification
Defer / Avoid Utility Upgrade (non-wires alternative)	Smart inverters, energy storage, flexible load – coordinated by DERMS/ADMS/etc.
Enable building and transportation electrification	Aggregation of local controllers, flexible load management
Improve Local Resilience / Reliability	Infrastructure upgrade, backup generators, energy storage, **microgrid**

Features of Microgrids

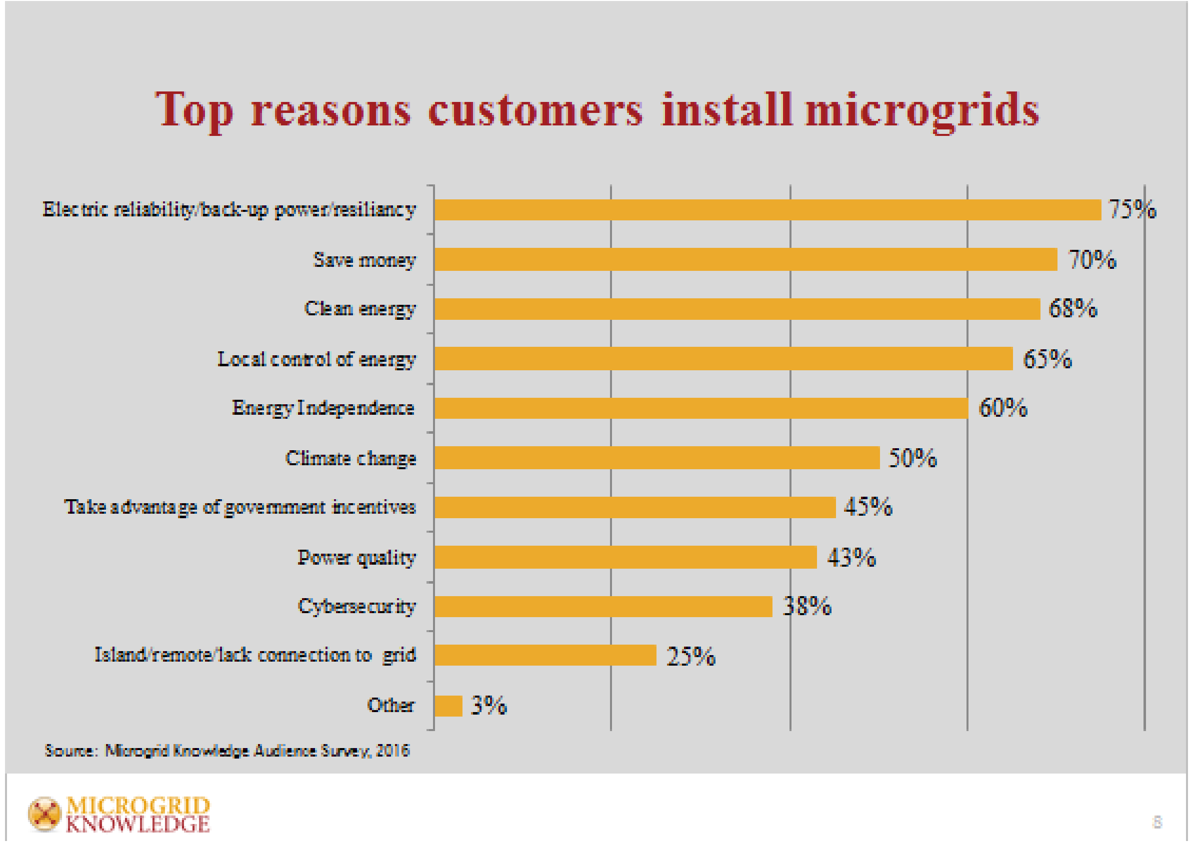
Three Key Features Characterize a Microgrid

1. **A microgrid is local –** It creates energy for itself or nearby customers.

2. **A microgrid is independent –** It can disconnect from the central grid & operate by itself.

3. **A microgrid is intelligent –** The "Central Brain" or microgrid controller is where the intelligence originates.

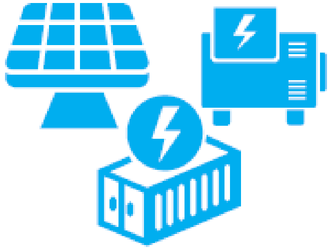
Industry Survey Results



Microgrid Technology, Components and Costs

Components

- DER (Generation and Storage)
  - Diesel, natural gas, combined heat and power (CHP), biofuel, solar photovoltaic (PV), wind, and fuel cell and energy storage
- Microgrid Controller
  - Primary, Secondary, Tertiary
- Additional Infrastructure
  - Distribution system infrastructure (switchgear, protection equipment), information technology communications upgrades, metering
- Soft costs
  - Engineering, construction, commissioning, regulatory



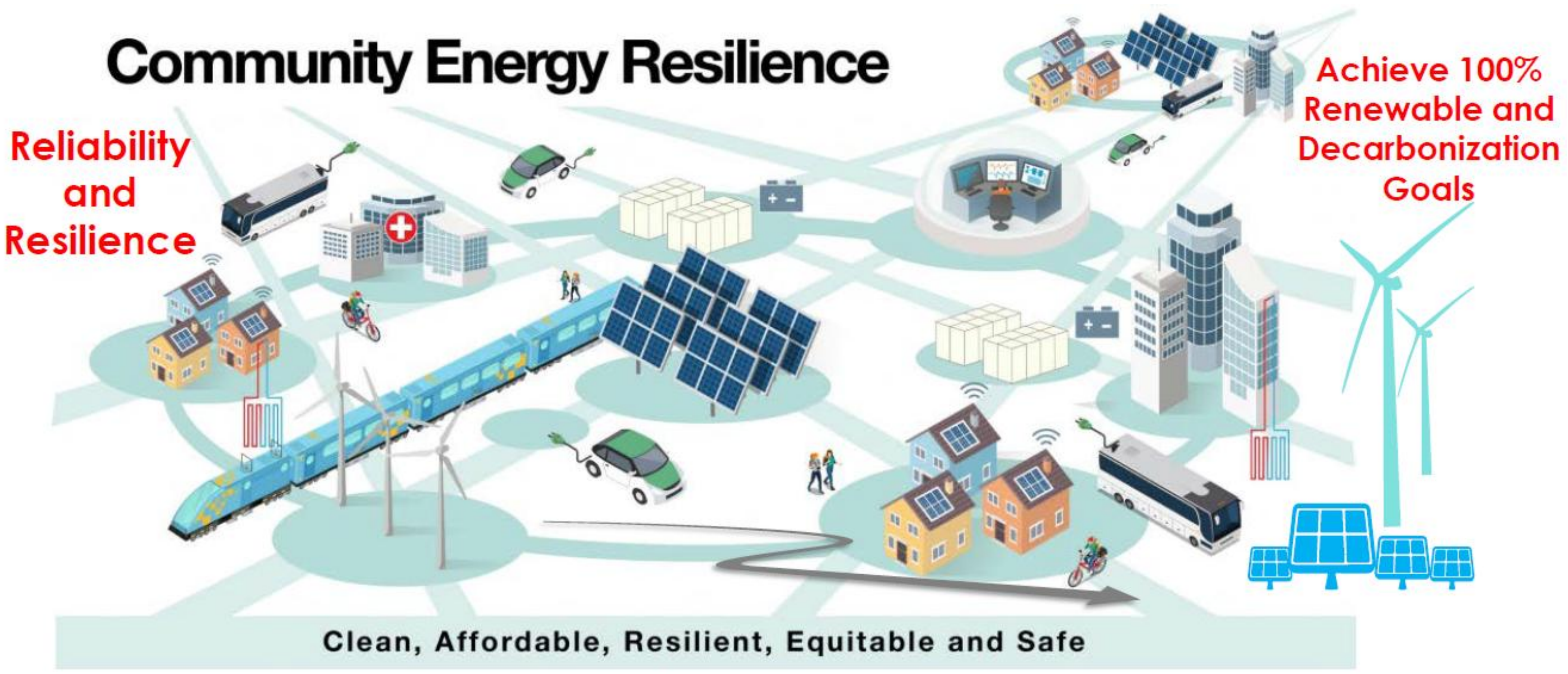
Costs

- Leverage existing DER
- Lowest average cost in Community and Utility microgrid markets

Type	Typical Cost Range ($M/MW)
Campus/Institutional	$2.5 – $4.9
Commercial/Industrial	$3.4 – $5.4
Community	$1.4 – $3.3
Utility	$2.3 – $3.2

Source: NREL *"Phase I Microgrid Cost Study"* 2018

Achieving Resilience and Carbon Reduction Goals through Microgrids



The Utility Challenges of Microgrid Integration

Regulatory Challenges:

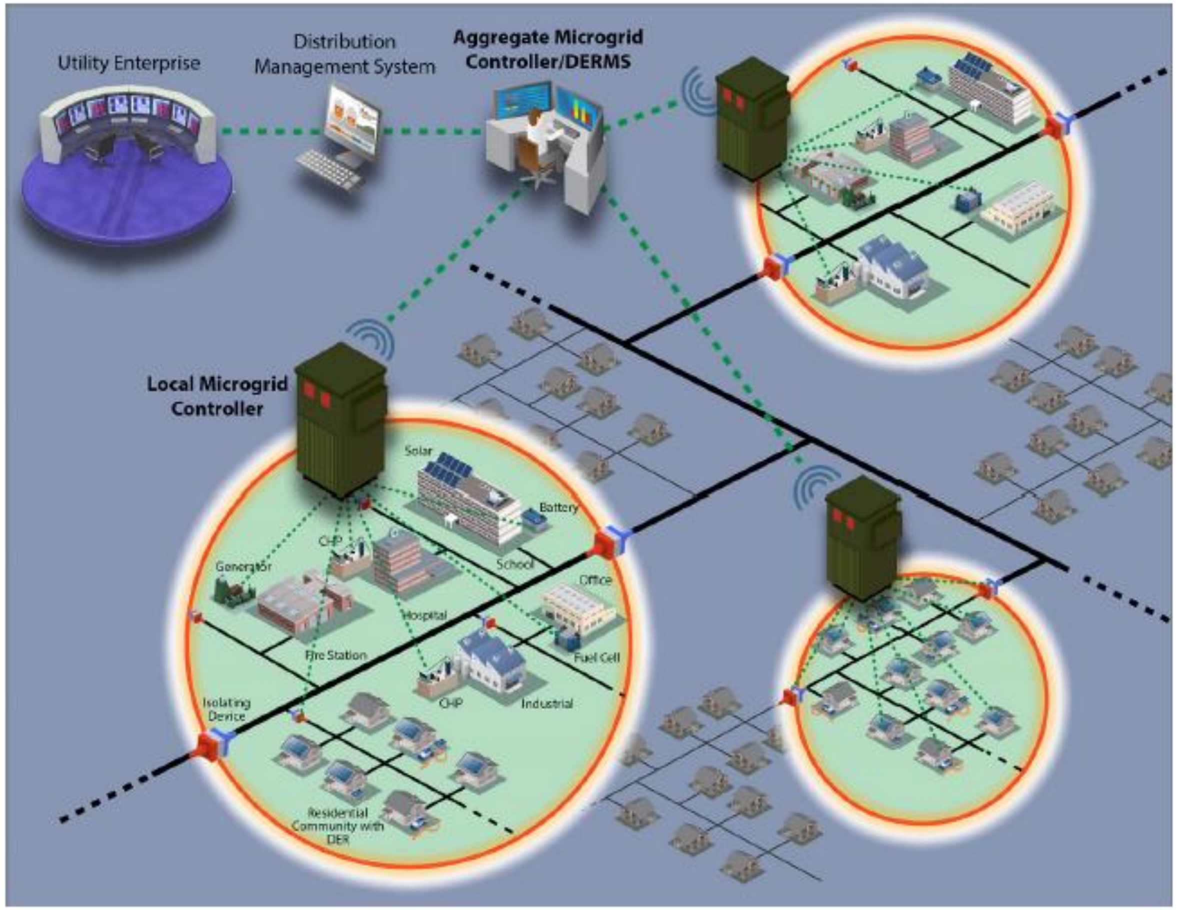
- Ownership of generation
- Administrative burden of regulation

Technical Challenges:

- Bi-directional power flows
- Fault current contribution
- Unit Level Volt/VAR support
- Islanded Operation

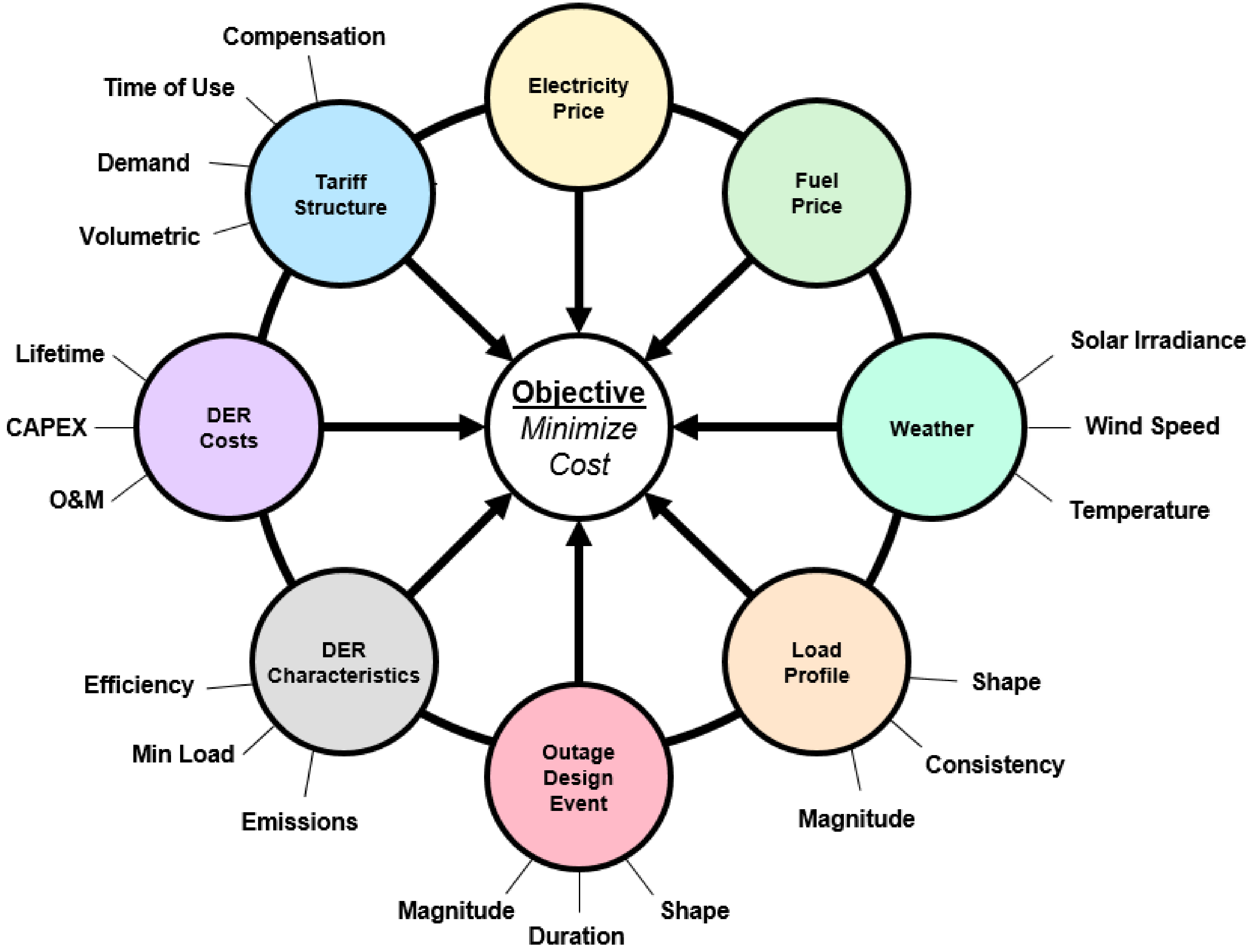
Economic Challenges:

- DER technologies still costly and with uncertain lifetimes
- Business model still undeveloped
- Utility rate structures in early implementation



Microgrid Design Considerations

Key Parameters Impacting Microgrid Operations and Cost

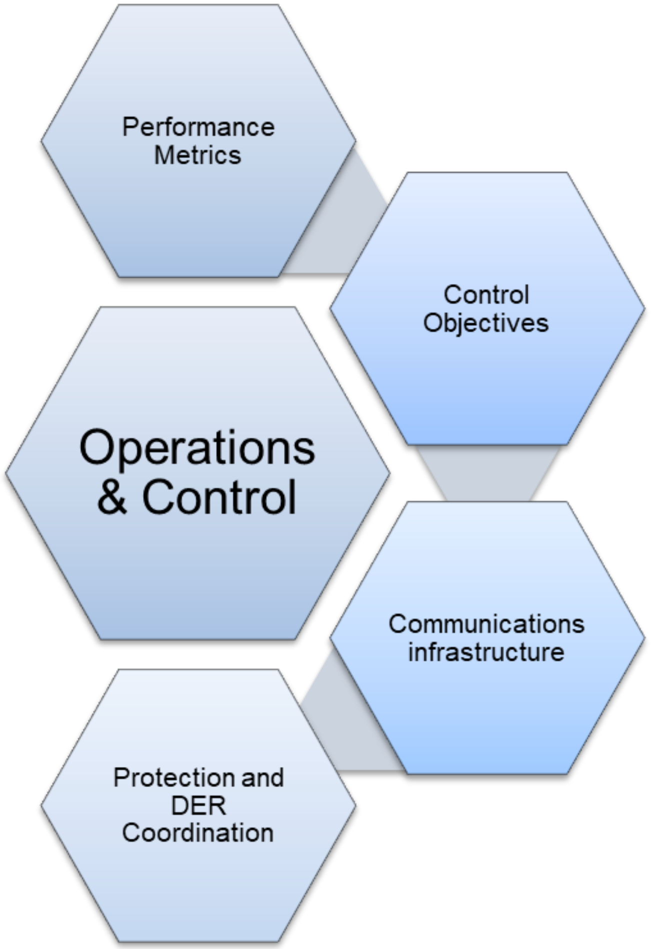


A variety of factors, many interconnected, impact the overall design and cost of a microgrid. Certain factors are considered fixed inputs (i.e. assumptions) while other factors are varied to in order to evaluate the sensitivity of their impact on overall cost.

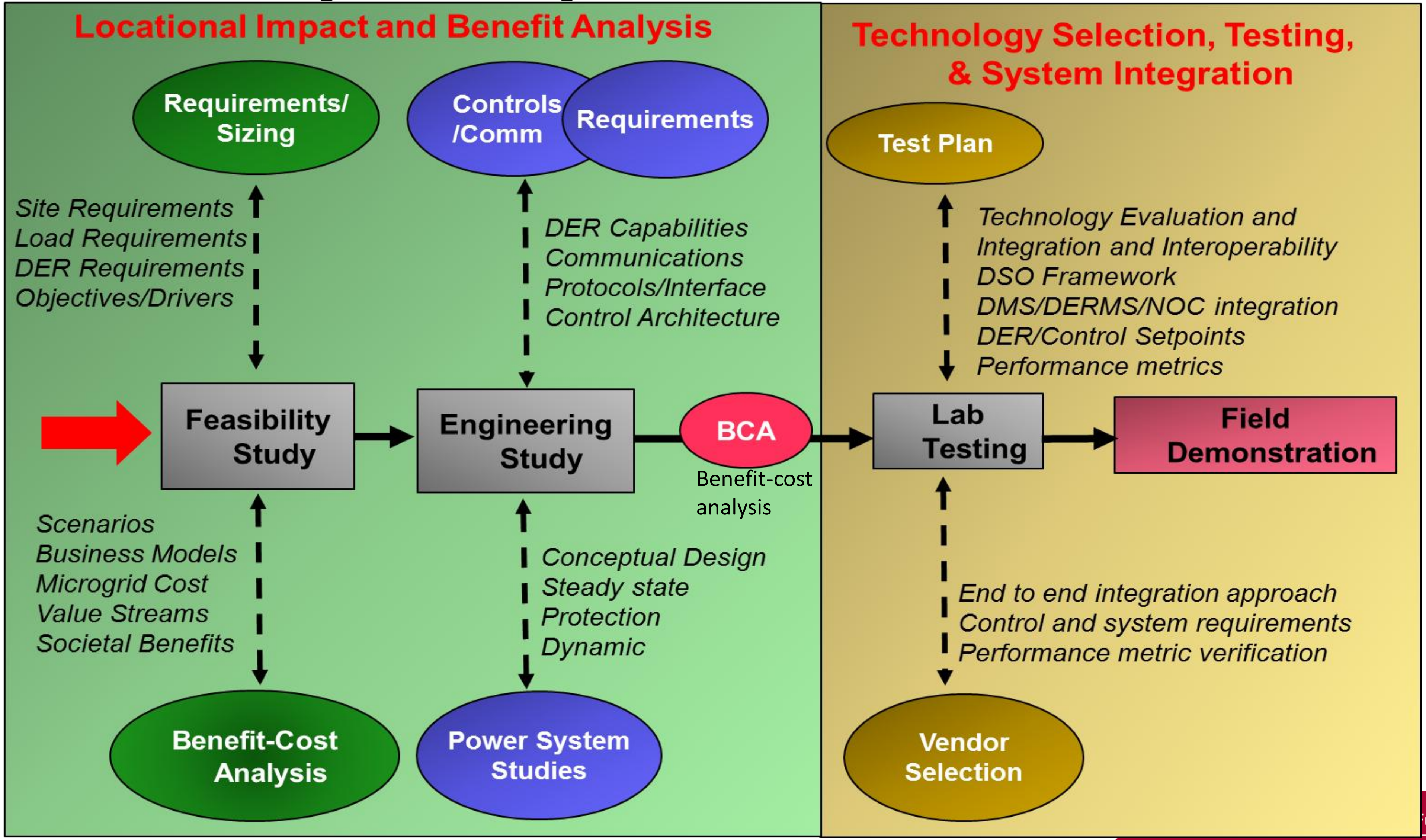
Microgrid Design Goals

Maximize project lifecycle value for economic and technically feasible opportunities in our evolving grid environment

- Creating a microgrid is complicated ….
  - Involves multiple power, operations management and control system components from diverse vendors that must be integrated and optimized for interoperability and security
  - Integrated controls, communication & coordination, and new protection approaches are needed
  - Assets within the microgrid must comply with the distribution system operator's interconnection requirements

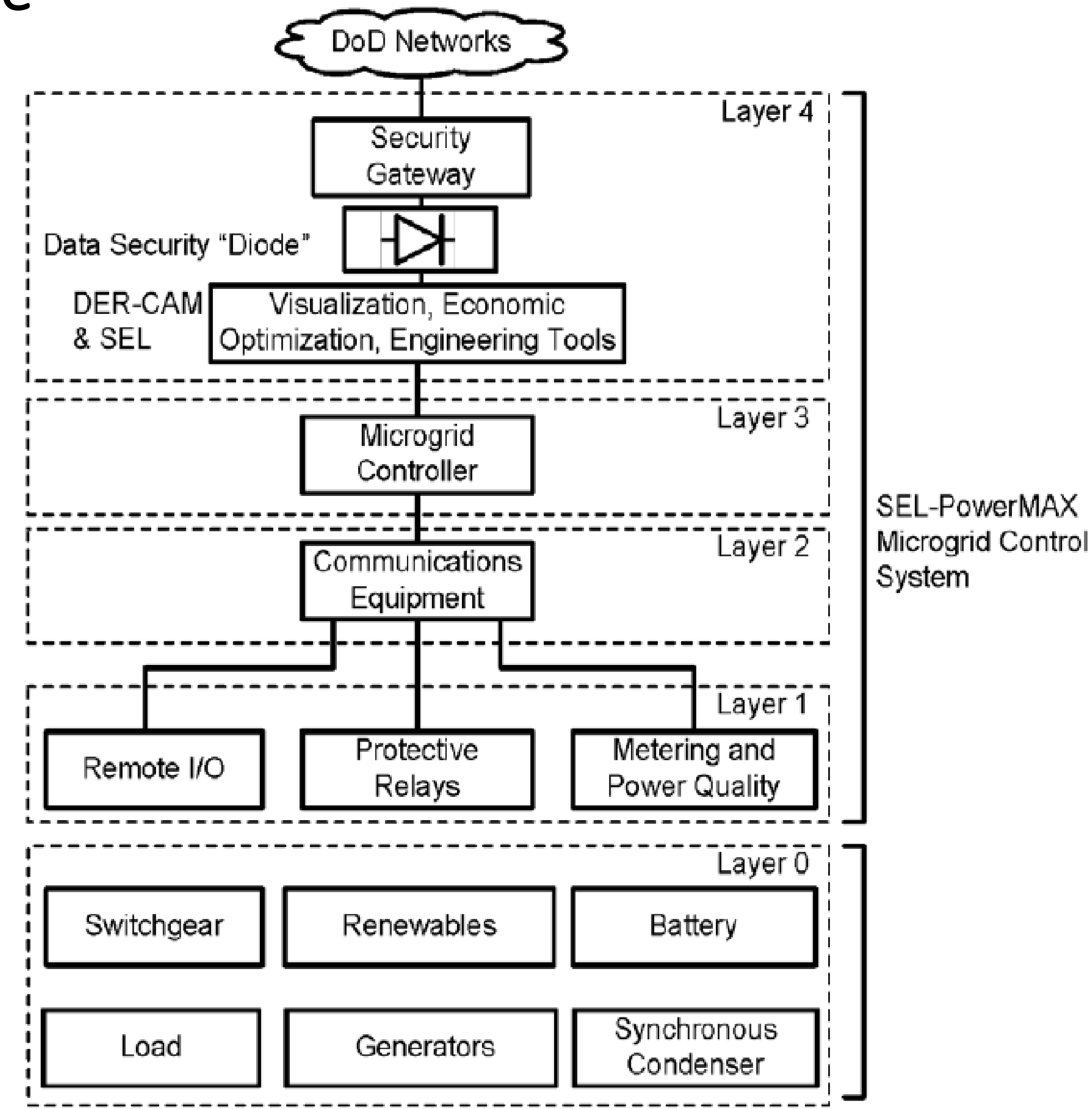


Develop Consistent Approaches to Evaluate Microgrid Adoption:
Evaluation, Design, Testing & Demo



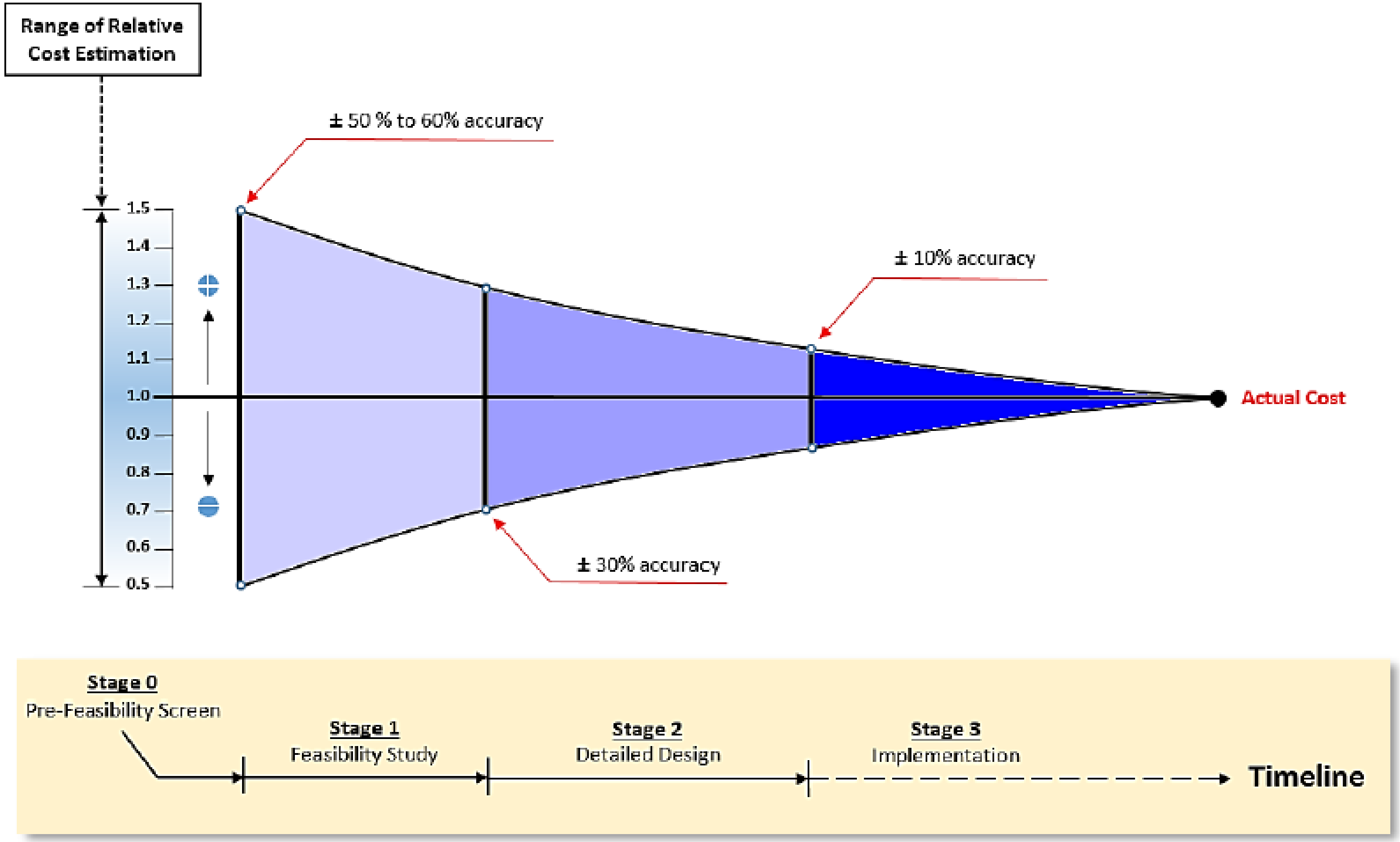
Microgrid Project Components & Architecture
(example of a navy microgrid project)

- Modular & Transportable
- Monitors and Controls
  - Diesels
  - PV
  - Battery
  - EV Chargers
  - PH1388 Building Transformer
  - Circuit Breakers
  - Synchronous Condenser
  - Adaptive Protection Relays
- Factory Acceptance Testing
- For Cybersecurity, No Wi-Fi, No Internet, and Firmware Updates Done By Navy Staff Trained by Vendors
- DoD Cybersecurity Risk Management Framework (RMF) Implemented



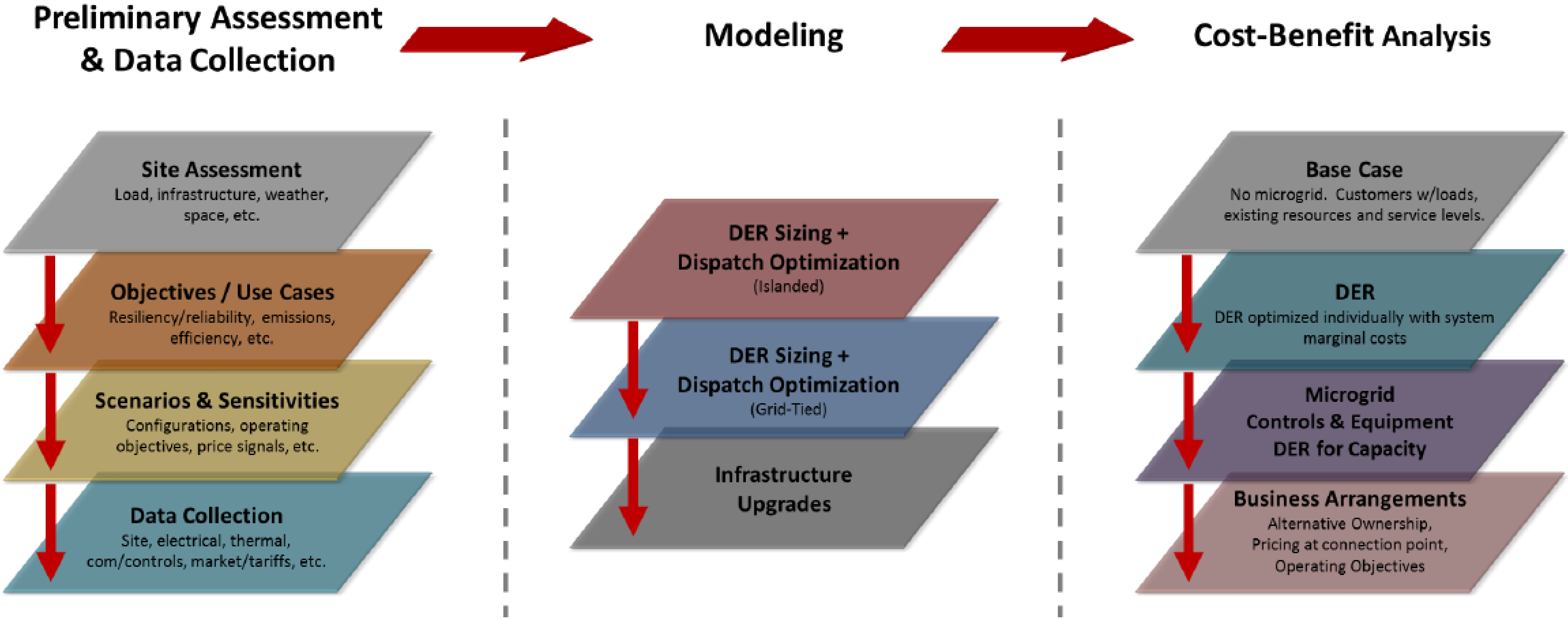
Microgrid Techno-Economic Assessment

What is Feasibility (Techno-Economic) Assessment?

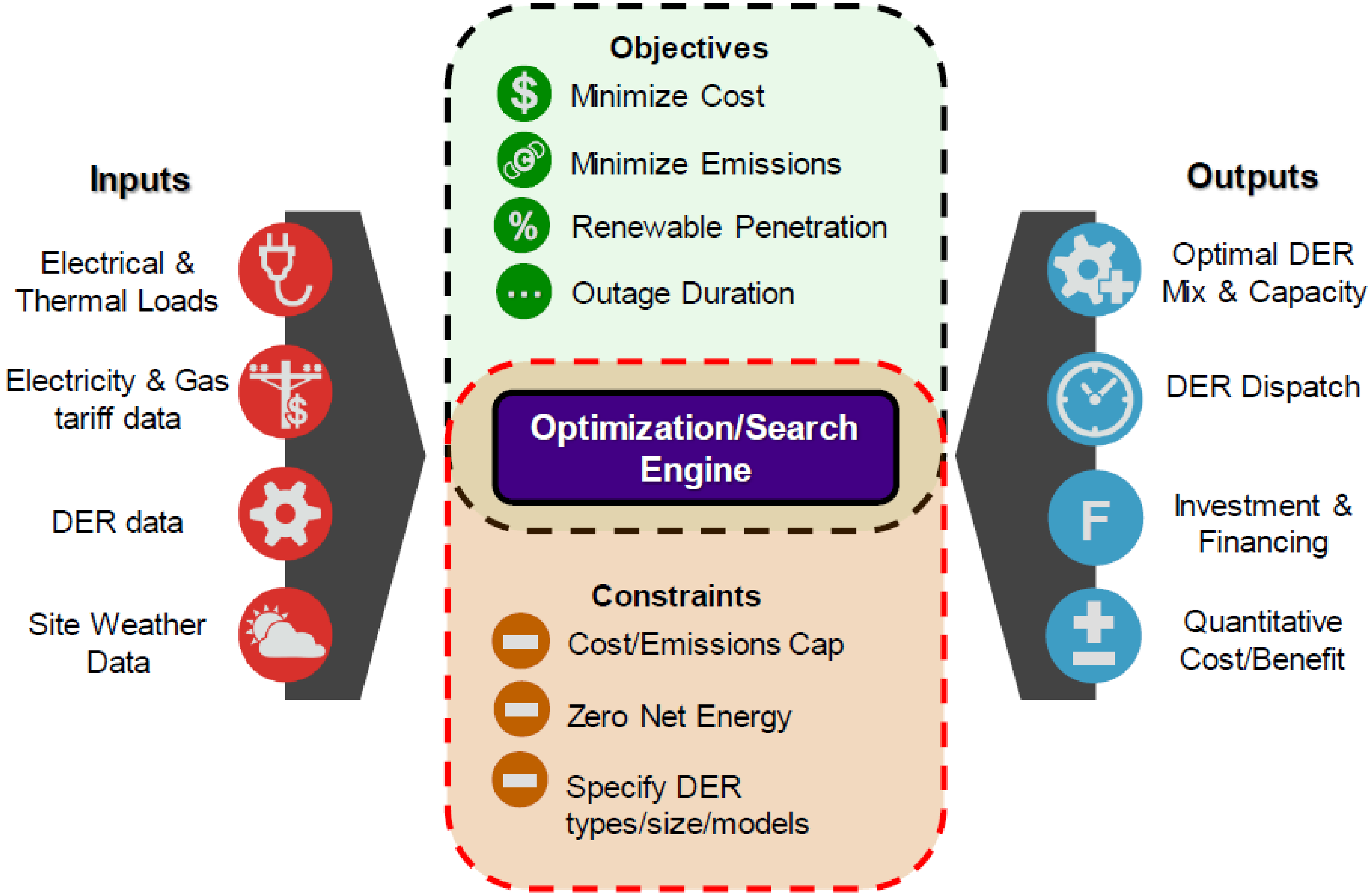


- Evaluate use cases for Microgrid & DERs
- Microgrid design
- DER sizing
- DER dispatch
- First-order analysis of Costs & Benefits

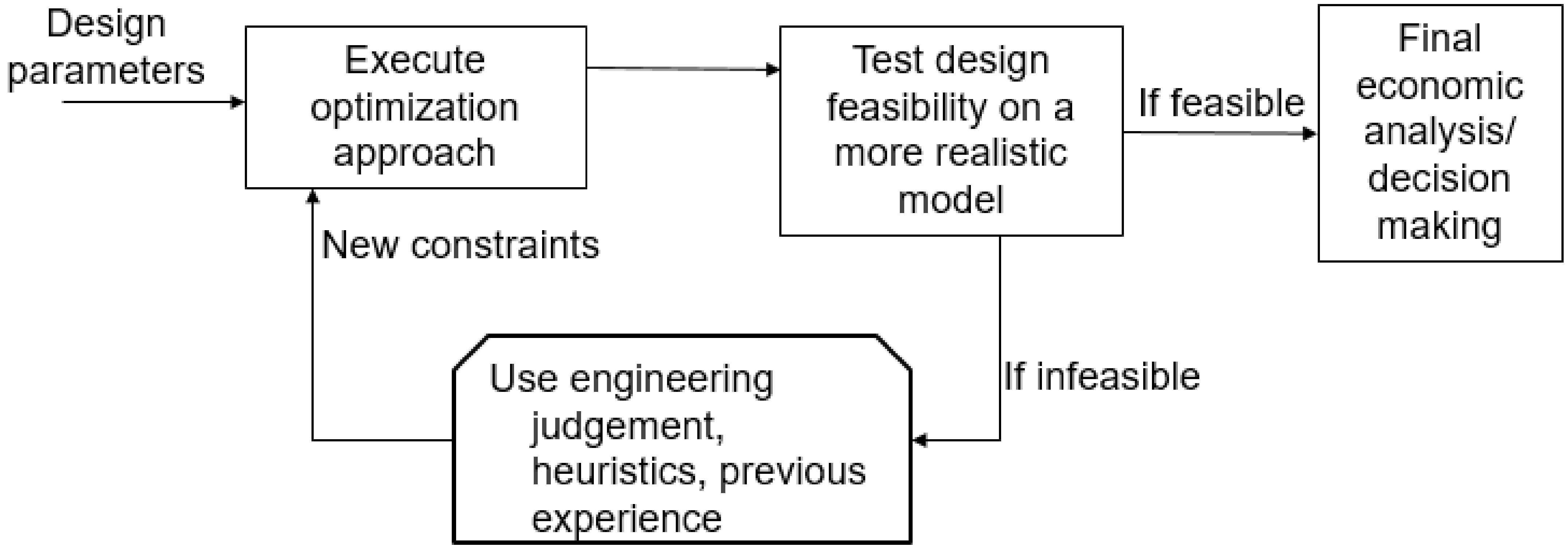
Study Process



Modeling Overview



Modeling Tools

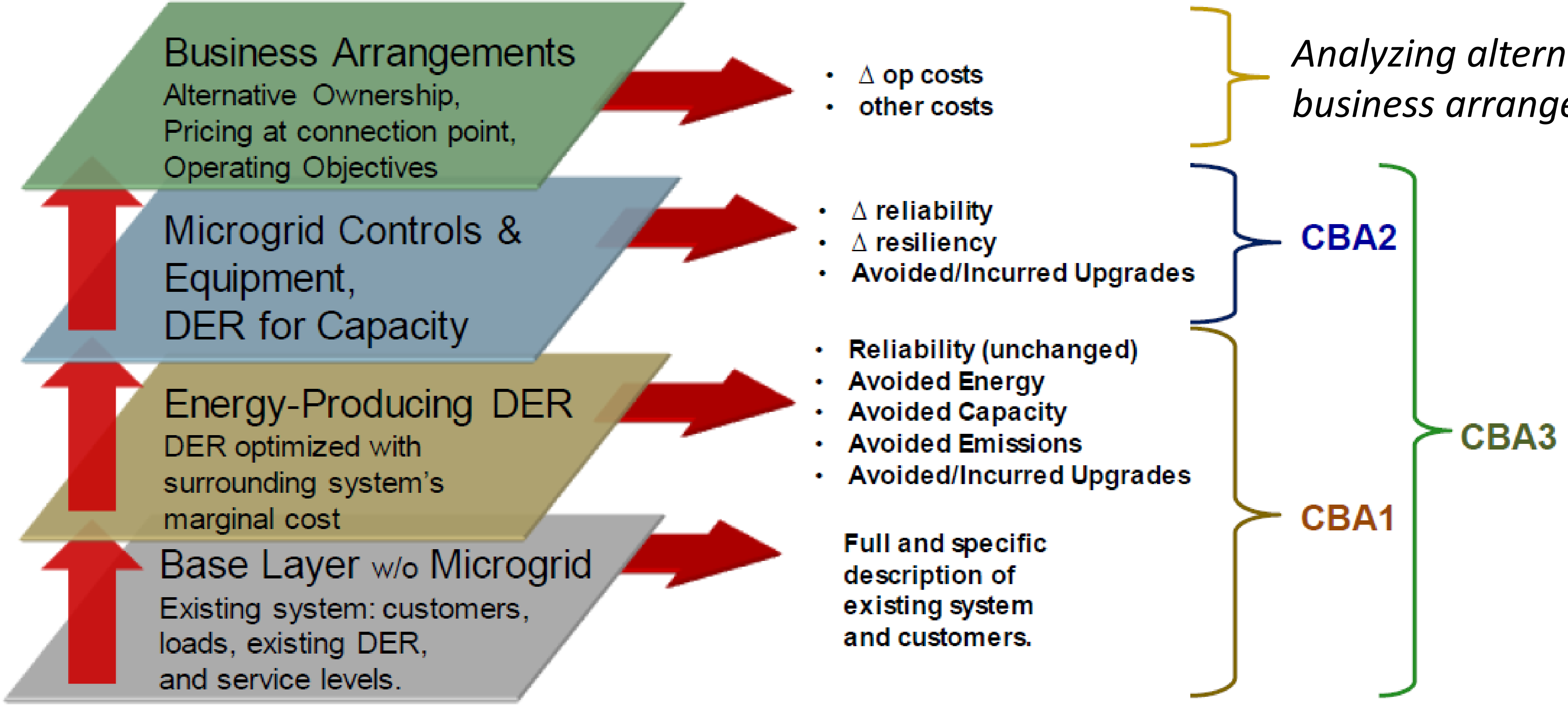


What drives Microgrid DER Size & Type?

- Outage Duration
- Climate & Load
  - Thermal load requirements
- Rates & Rate Structure
  - Energy/Capacity demand
  - Flat, TOU, real-time
  - Demand charge
- Existing DER assets & Infrastructure
  - Renewables based microgrid
  - Gas infrastructure resiliency

A complex project can be examined in stages, addressing a series of Cost/Benefit Analysis (CBA) questions

"Stacking Order" for DER and Microgrids

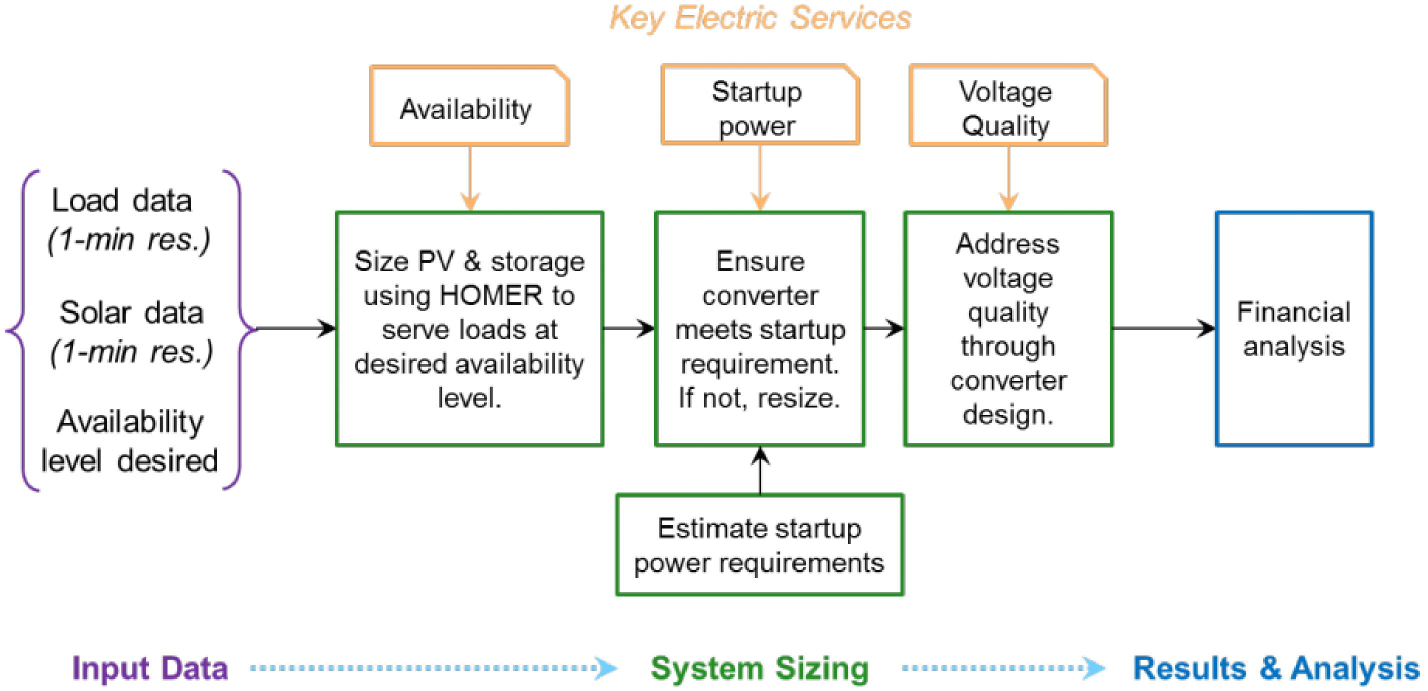


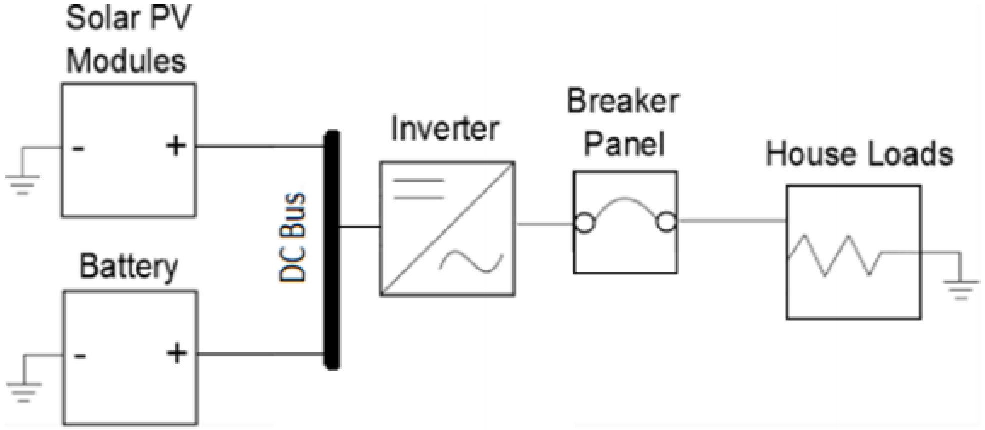
CBA 1: What is the net value of the energy-producing DER?

CBA 2: Does the value of incremental reliability/resiliency outweigh the incremental cost?

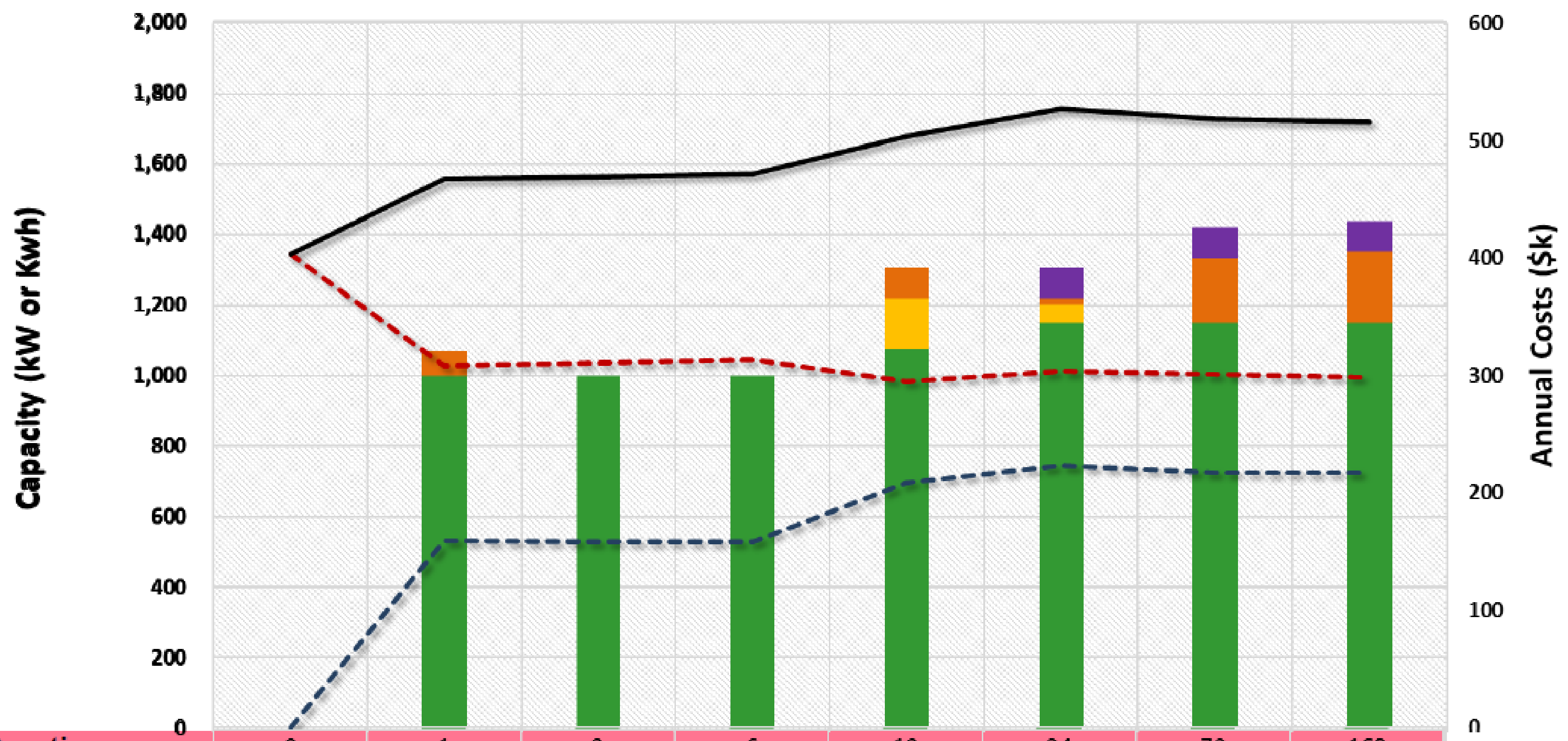
CBA 3: Does the total value of the microgrid outweigh its cost?

Case Study: Residential PV + ES Systems Microgrid Study Process





Microgrid Project Case Study: Outage Duration vs Capacity & Cost

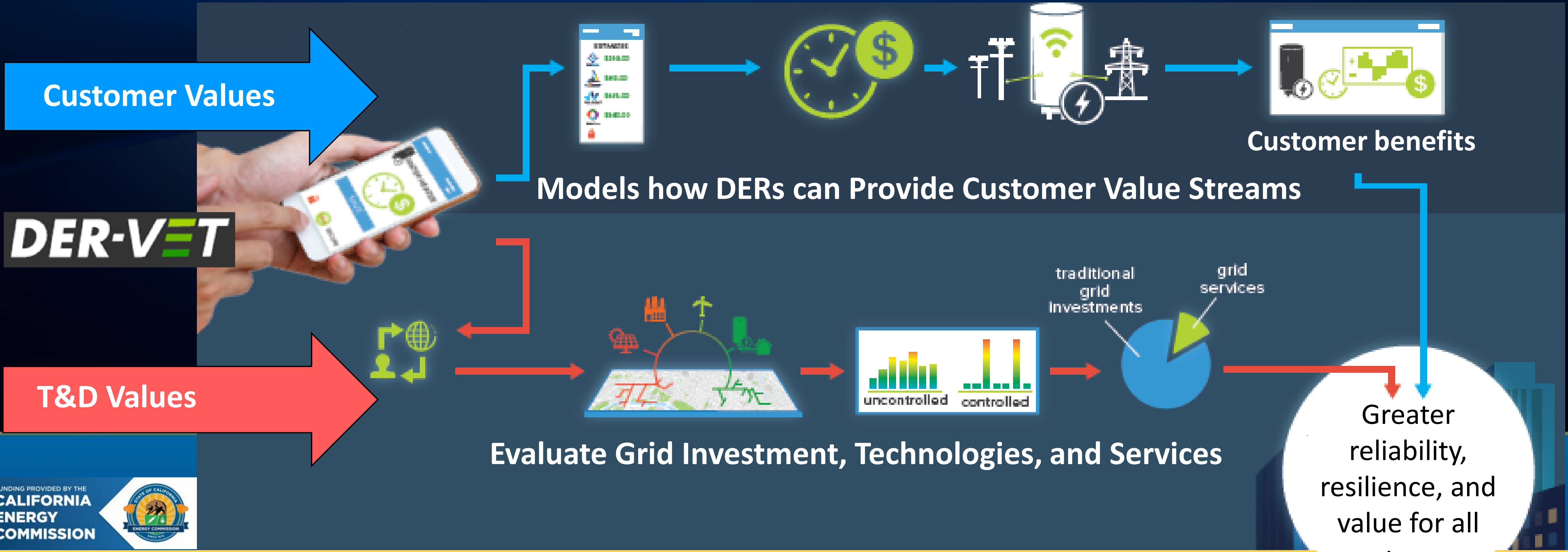


Outage Duration	0	1	3	6	12	24	72	168
Abs Chiller Capacity (kW)	0	0	0	0	0	0	0	0
ES Capacity (kWh)	0	0	0	0	0	85	88	88
Thermal Storage Capacity (kWh)	0	70	0	0	86	19	182	201
PV Capacity (kW)	0	0	0	0	144	51	0	0
Generator Capacity (kW)	0	1,000	1,000	1,000	1,075	1,150	1,150	1,150
Annual Operating Cost ($)	403,601	308,086	311,003	313,513	295,146	304,196	301,434	298,749
Total Annualized Capital Cost ($)	0	159,231	158,427	158,427	208,910	223,010	217,064	217,274
Total Annual Costs ($)	403,601	467,316	469,430	471,941	504,056	527,206	518,498	516,023

DER-VET: A Tool Developed by EPRI

DER-VET™ provides a free, publicly accessible, open-source platform for calculating, understanding, and optimizing the value of distributed energy resources (DER) based on their technical merits and constraints.

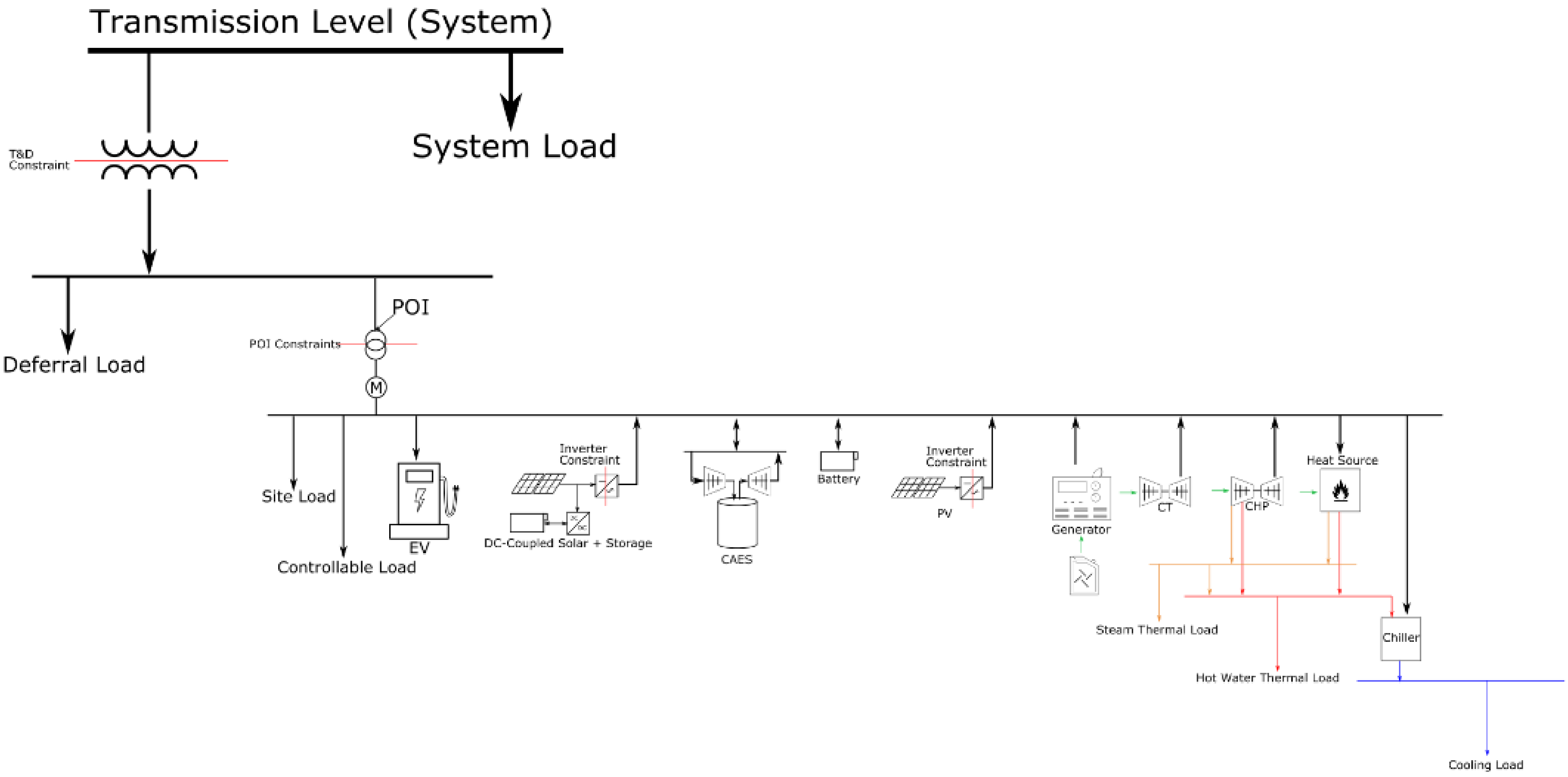
Validated, Transparent, and Accessible Microgrid Valuation and Optimization Tool: DER-VET™



FUNDING PROVIDED BY THE CALIFORNIA ENERGY COMMISSION

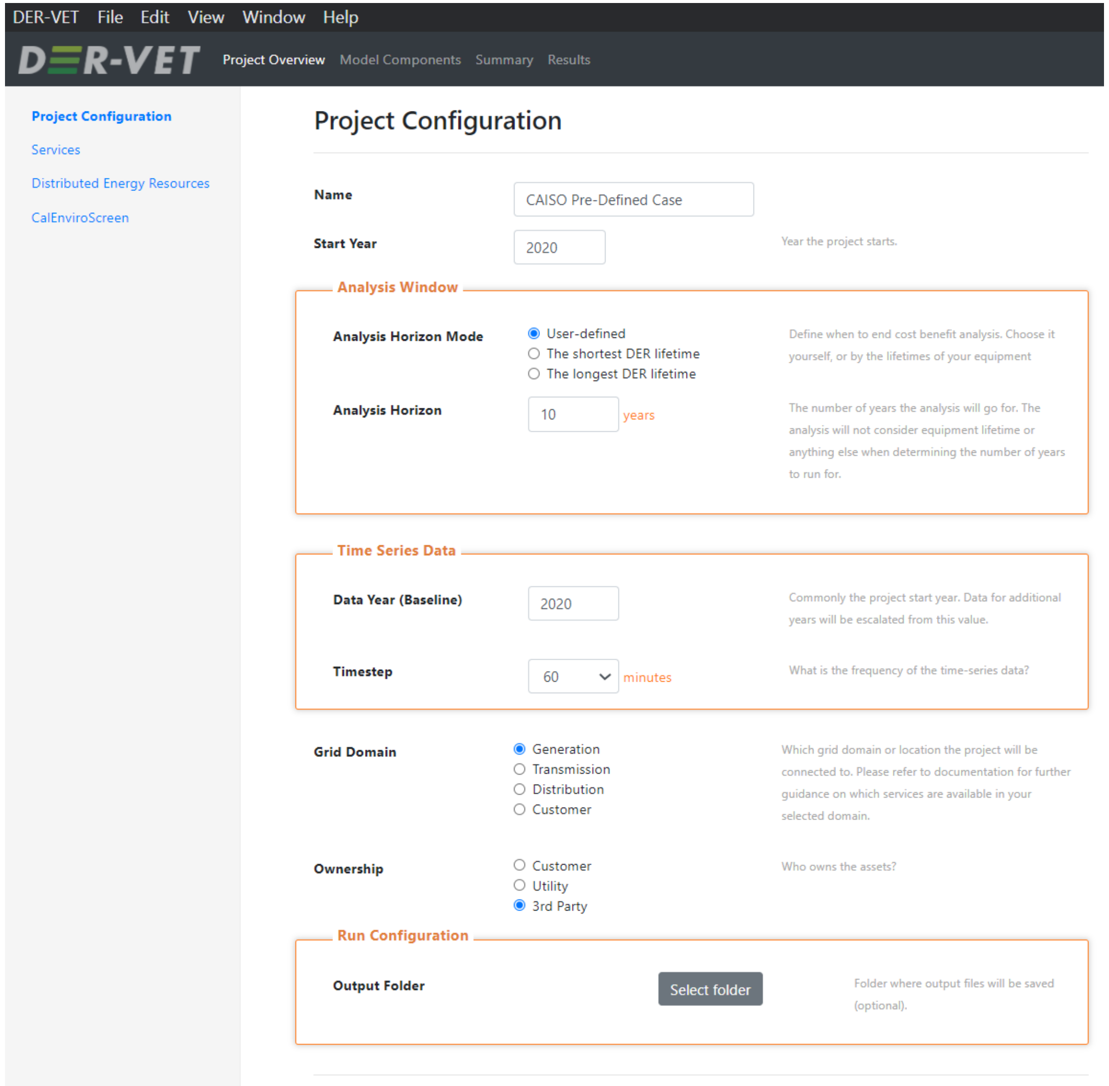
Develop a robust technical analysis and economic optimization tool used for the design of microgrids and DER deployments that is a publicly-available at www.der-vet.com

Technologies in DER-VET

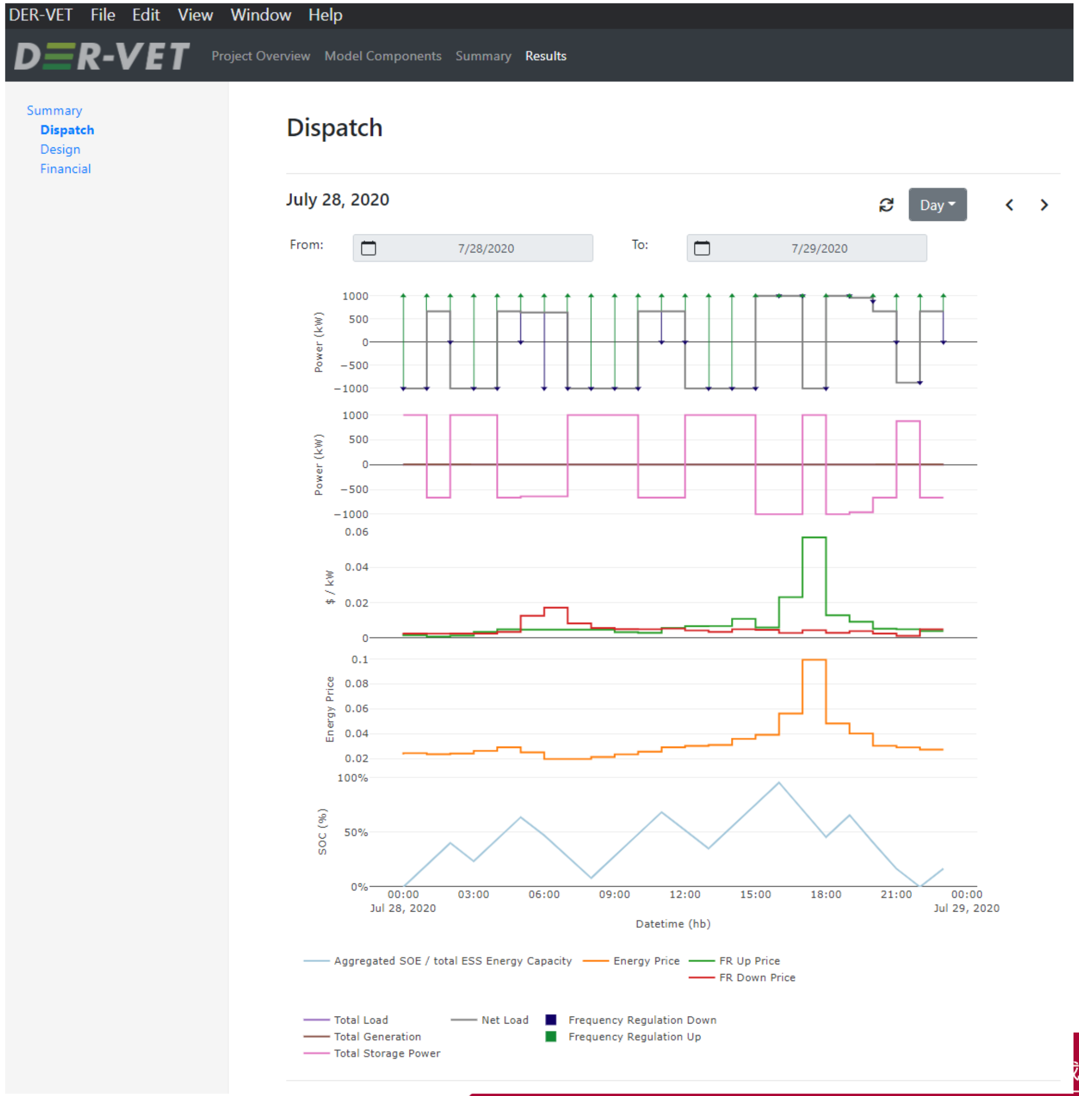


Input and Output Examples in DER-VET

DER-VET Project Configuration Example

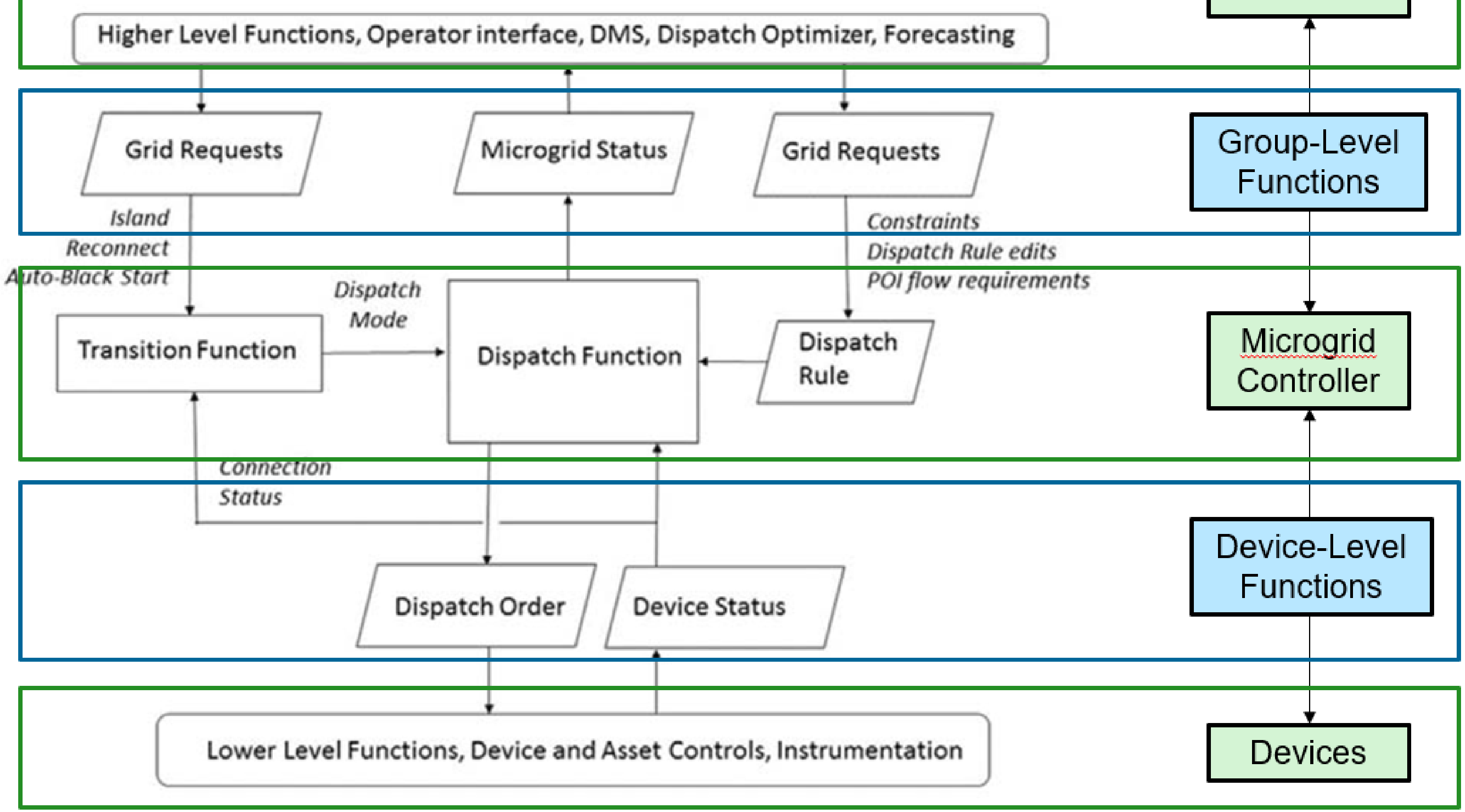


DER-VET Dispatch Results Example



Microgrid Controls

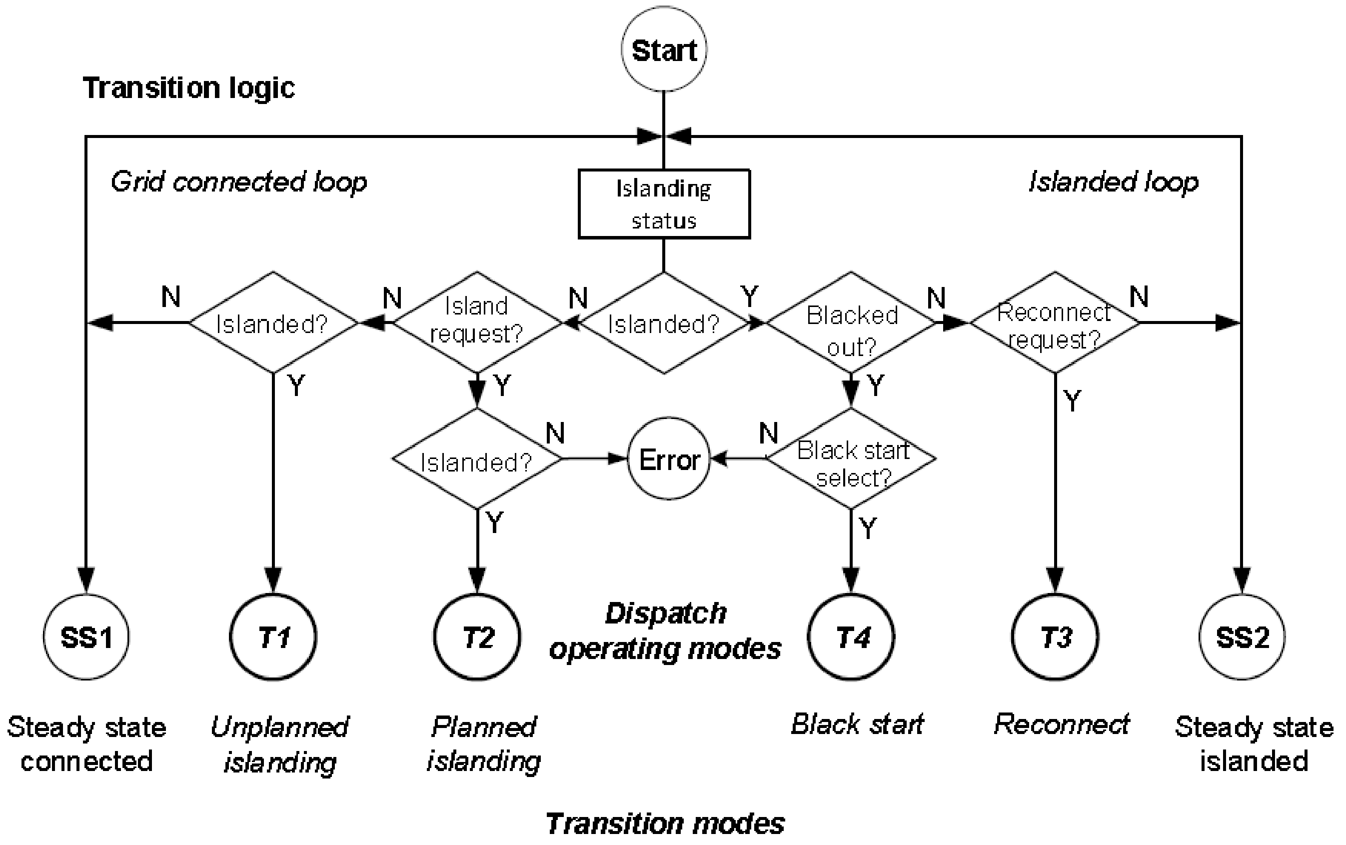
DMS-DERMS-Microgrid Controller-DER



Relationship between transition and dispatch functions

Microgrid Controller System Basic Functionality

- Local objective: manage generation, storage, and loads within microgrid boundaries to meet the needs of the local system.
- POI objective: manage power flow, power quality, and provided ancillary services at the point of interconnection (POI)
- Core Functions [1]:
  - Transition (island v.s. grid connected)
  - Dispatch

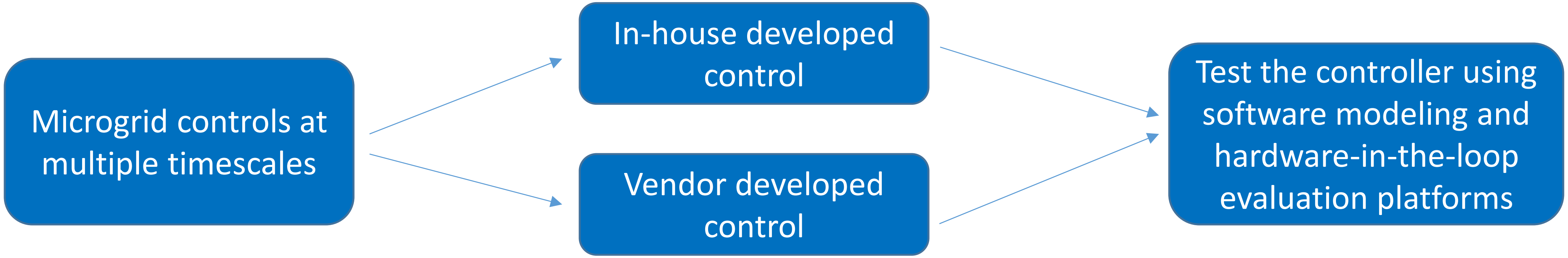


[1] IEEE Std 2030.7-2017, IEEE Standard for the Specification of Microgrid Controllers

Microgrid Control System Implementation Challenges

- The Microgrid Control System (MGCS) must successfully interact with many control devices:
  - Inverter, Generator, or Load controllers; Battery Management Systems
  - Protective relays
  - Distribution Management Systems
  - Supervisory Control and Data Acquisition systems
- Considerations:
  - Interoperability with many control devices
  - Reconfigurability to accommodate various microgrid designs
  - Robust to added, removed, or non-responsive assets
  - Local and POI objectives may be competing
  - Cyber security

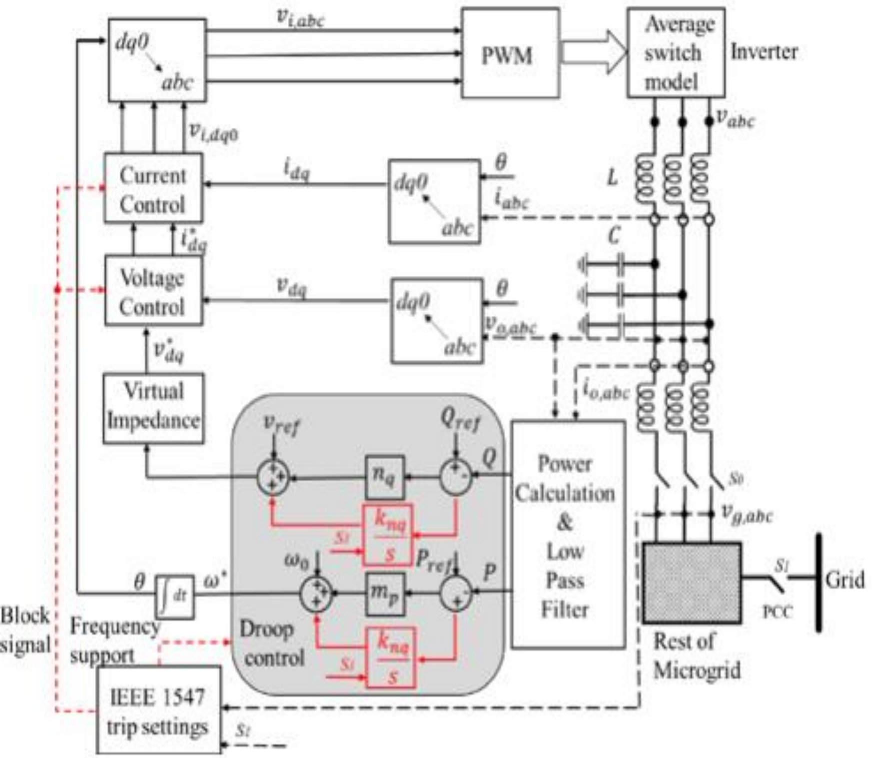
Role of Microgrid Controllers



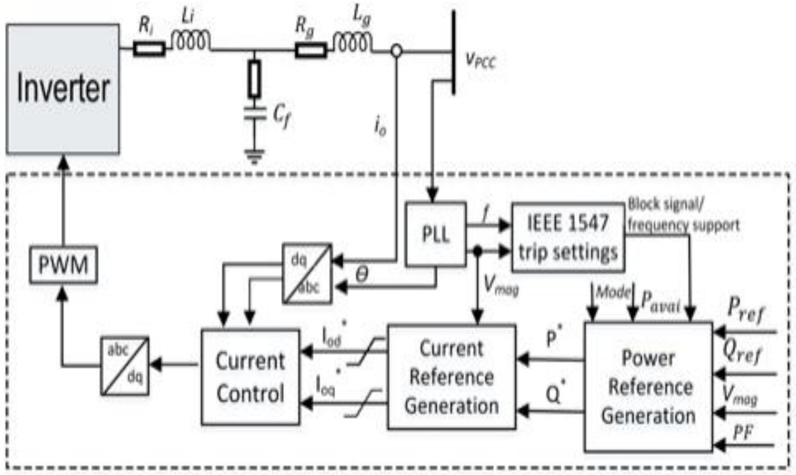
- Microgrids can include distributed energy resources such as generators, storage devices, and controllable loads.
- Microgrids generally must also include a control strategy to
  - Instantaneously maintain real and reactive power balance when the system is islanded
  - determine how to dispatch the resources over a longer time
- The control system must also identify when and how to connect/disconnect from the grid.

Examples of In-house Developed Microgrid Control

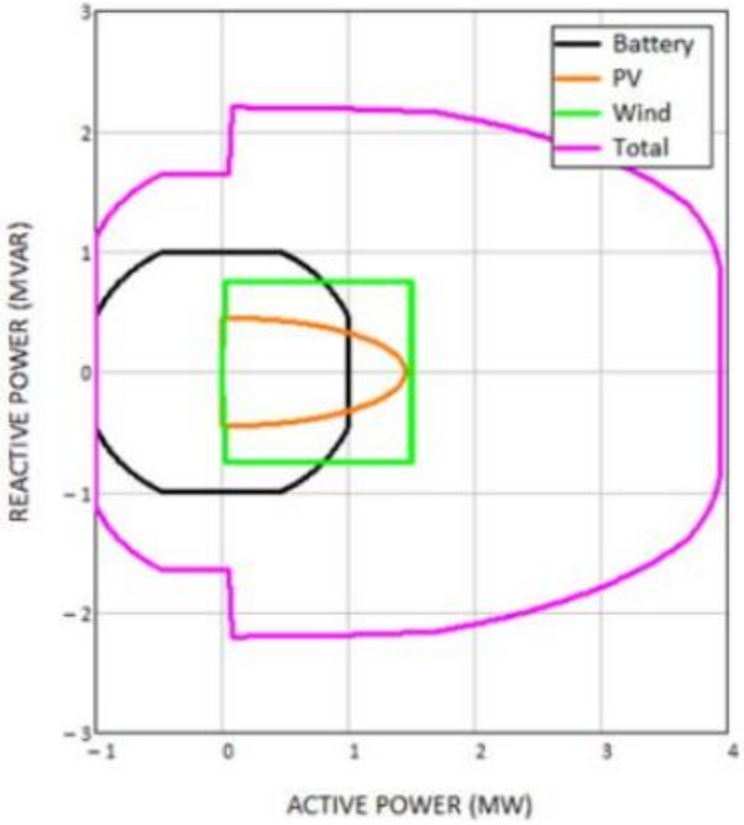
Control diagram of the grid-forming microgrid inverter



Control diagram of the grid-following microgrid inverter

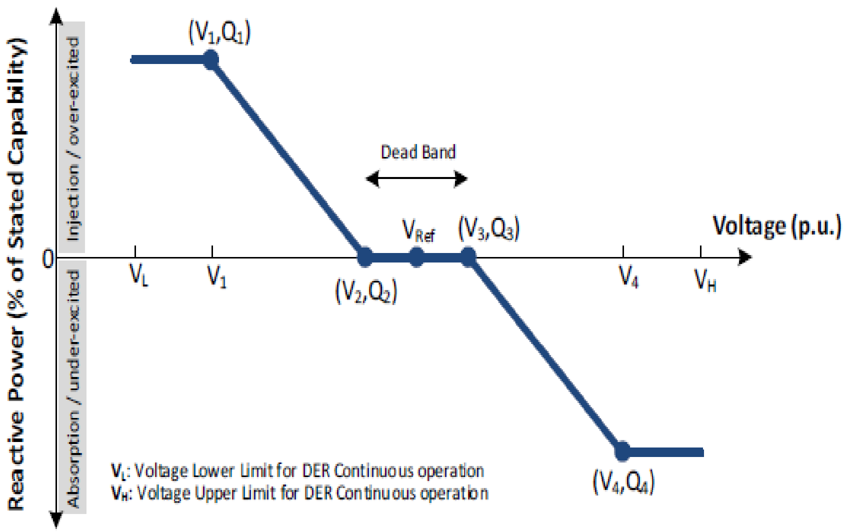


Reactive and real power characteristics of a hybrid power plant

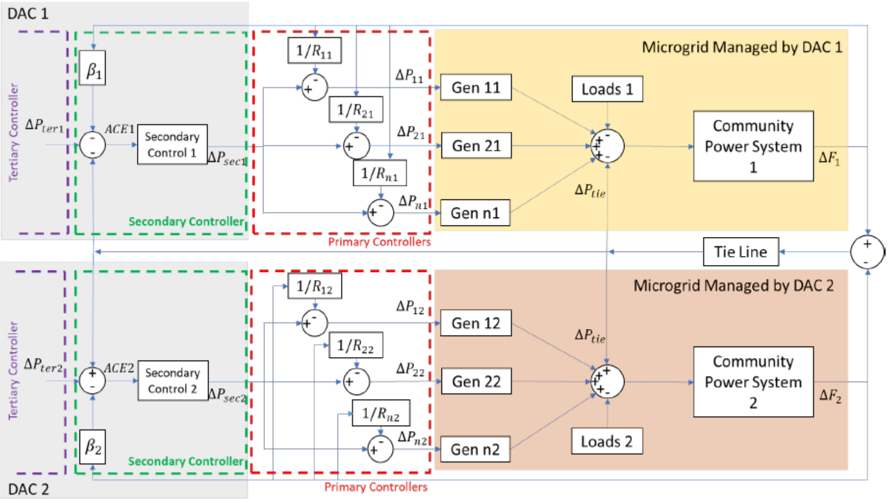


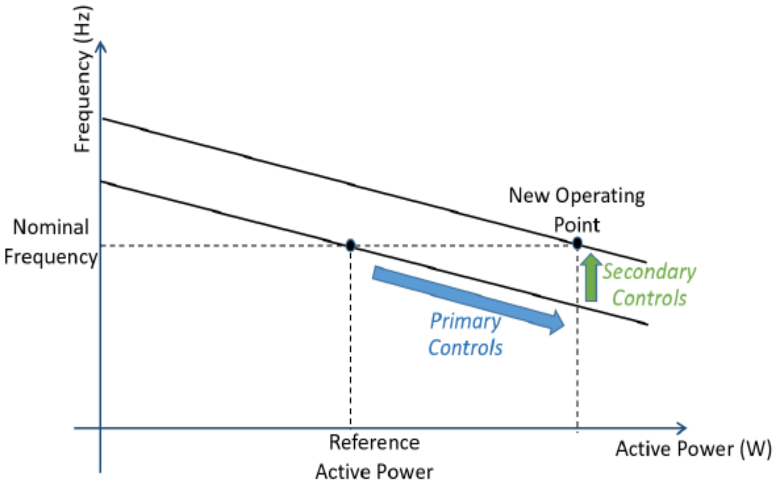
Examples of In-house Developed Microgrid Control

Voltage–reactive power characteristic (IEEE 1547-2018)

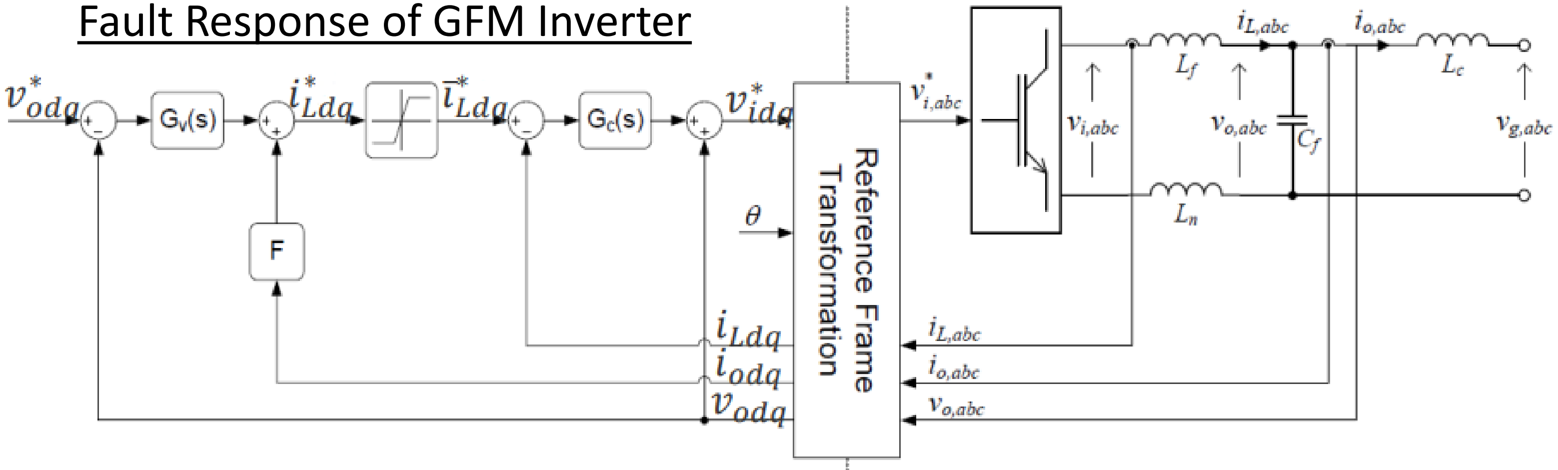


Frequency Control





Fault Response of GFM Inverter



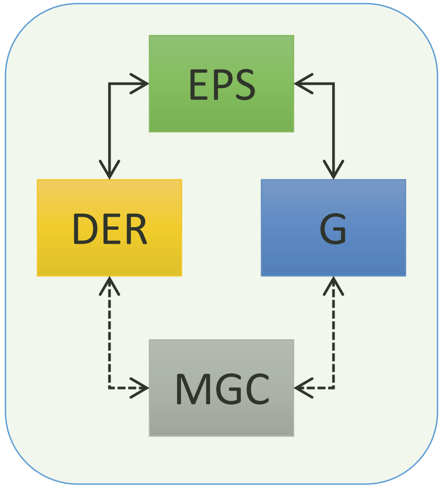
Examples of Vendor Developed Microgrid Control

List of Past Microgrid Controller Projects at EPRI

- **DOE Microgrid Projects**
  - FOA 997 Controller (End Date May 2017) Spirae Controller
  - DMS Structuring Project Phase 1/2 (October 2015 – November 2017) Schneider & GE Controller
  - ADMS Test bed (November 2016 – November 2019) Schneider & GE Controller
  - ARPA E with UTK TI Controller
- **DoD Microgrid Projects**
  - Transportable Microgrid (Dec 2016-Dec 2018). SEL Controller
  - Fort Hunter Liggett (Sep 2016 – Dec 2017). LBNL Controller
- **NYSERDA Microgrid Projects**
  - Phase 2 BNMC NYSERDA Spirae/OpusOne Controller
- **Utility Funded Demonstrations**
  - NCEMC, Xcel, HydroOne, Central Hudson

Testing of Microgrid Control Systems

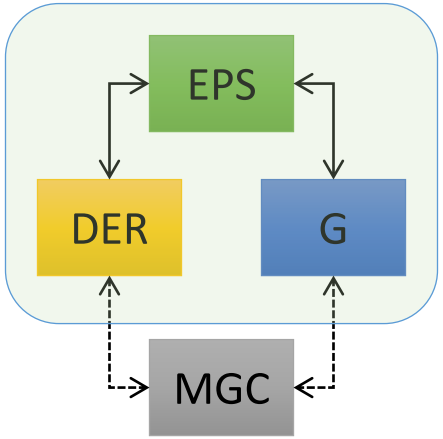
Microgrid Controller Test Options – Which is Better?



Pure simulation

Abstract or real-time

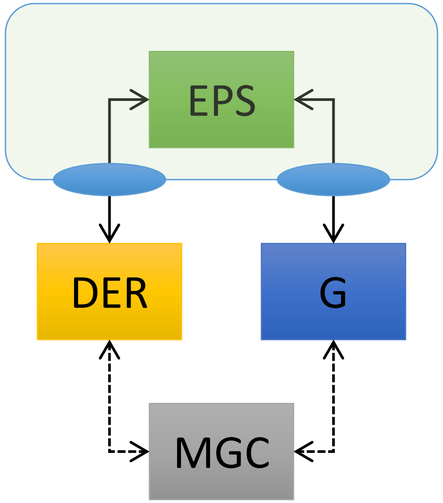
Need to integrate MGC



CHIL

Interface real controller

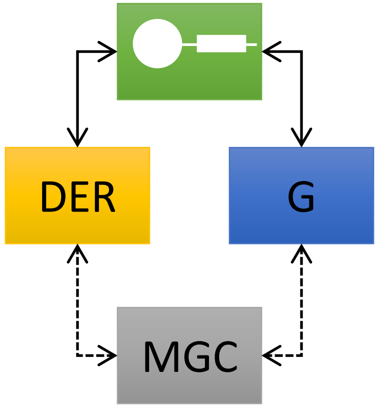
Real-time simulation



CHIL & PHIL

Interface real controller and assets

Power interface, more complex



Power

Real controller and assets

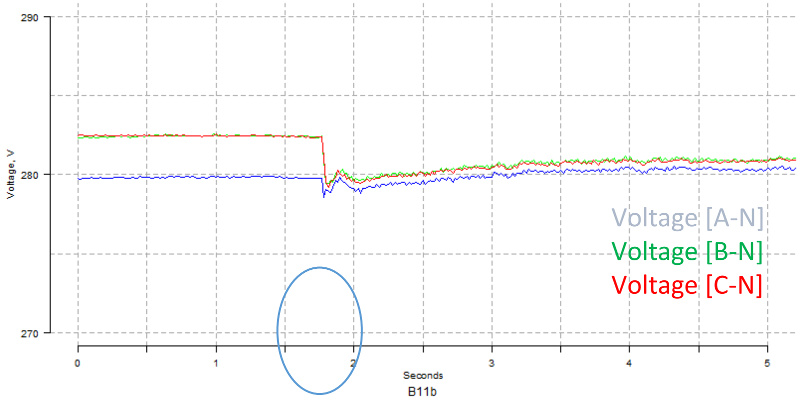
Simple EPS model

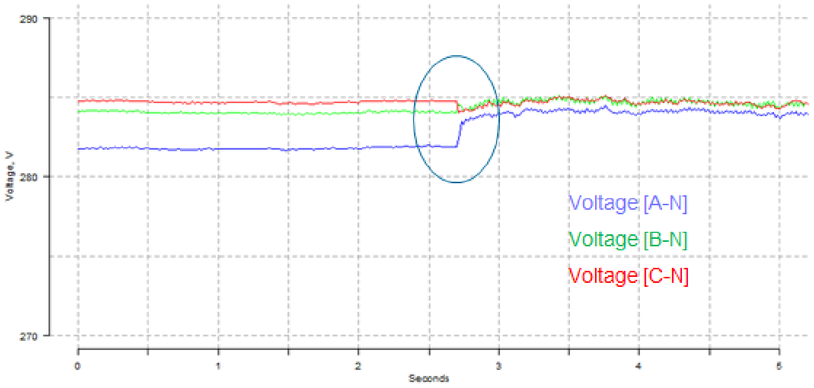
CHIL = Controller Hardware-in-the-Loop;
PHIL = Power Hardware-in-the-Loop
MGC = Microgrid controller;
DER = Distributed Energy Resource;
G = Generator;
EPS = Electric Power System

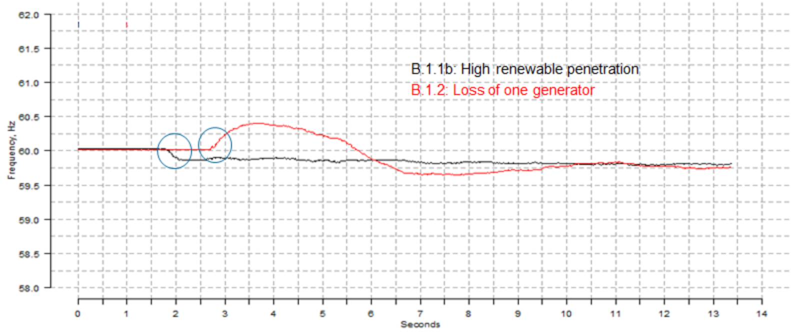
IEEE 2030.8 to Define Microgrid Controller Testing Procedures and Evaluations

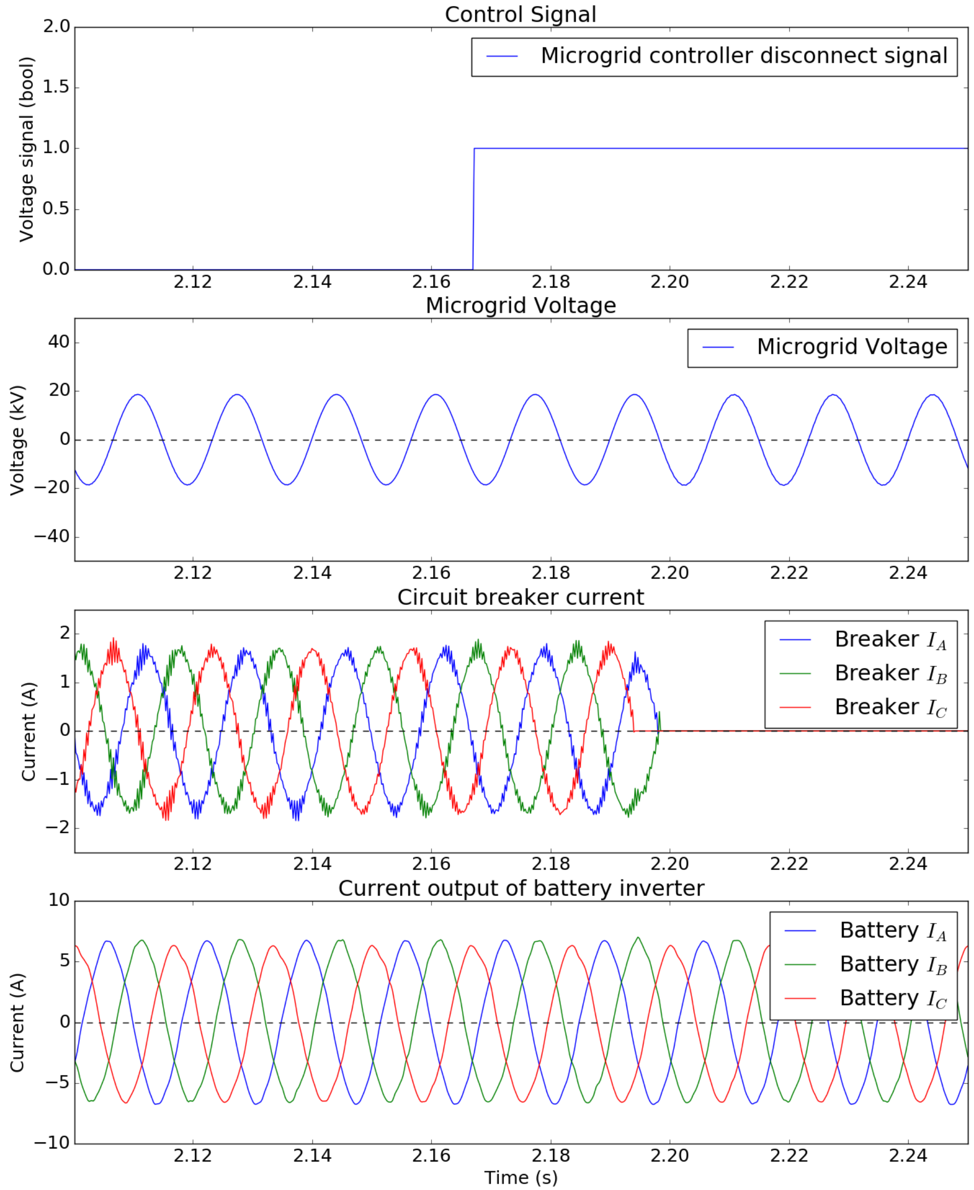
Test case:	Met Requirement?
A.1.1: DER available (renewables only); Wave offline.	✓
A.2.1: System importing power at PCC	✓
A.2.2: System importing power at PCC (loss of one generator)	✓
A.3.1: System exporting power at PCC	✓
A.3.2: System exporting power at PCC (loss of one generator)	✓
A.4.1: System net-zero power at PCC	✓
A.4.2: System net-zero power at PCC (loss of one generator)	✓
A.4.3: System net-zero power at PCC (loss of communications MG/Wave)	✓
B.1.1a: Planned disconnection using microgrid controller interface	✓
B.1.1b: Planned disconnection (high renewable penetration)	✓
B.1.2: Planned disconnection (loss of one generator)	✓
B.2.1: Unplanned disconnection via manual breaker trip	✓
B.2.2: Unplanned disconnection via manual breaker trip (loss one generator)	✓
B.2.3: Unplanned disconnection via protective relay trip	✓

Verify Controller Functions and Capabilities



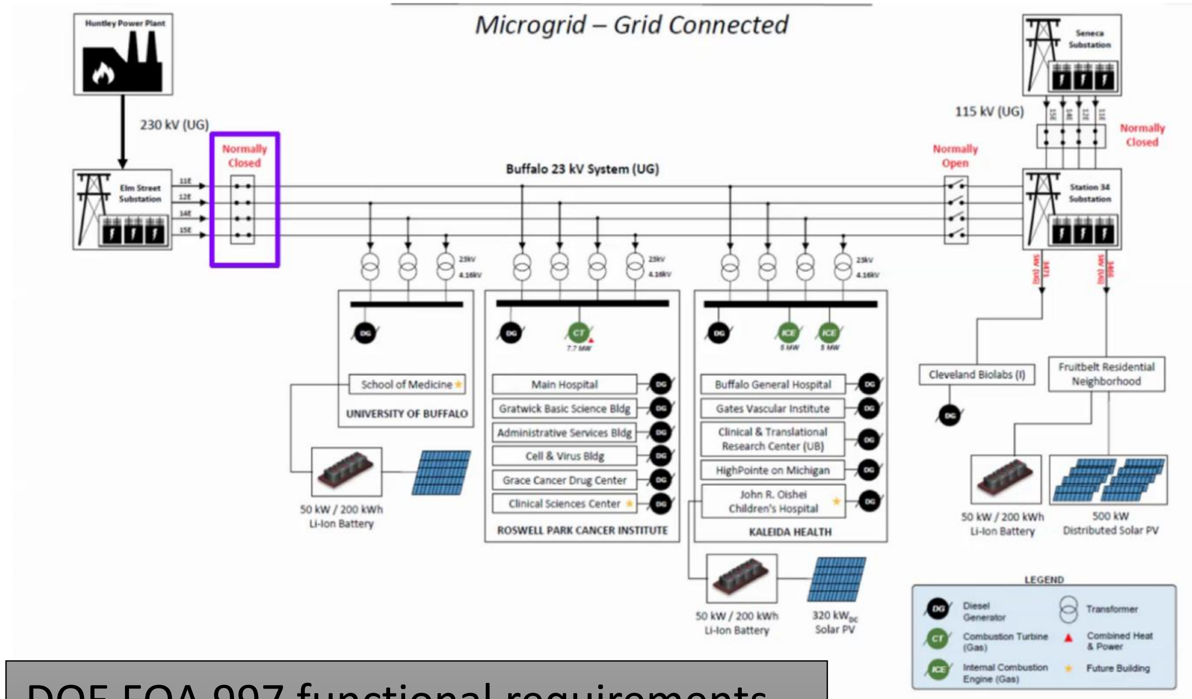


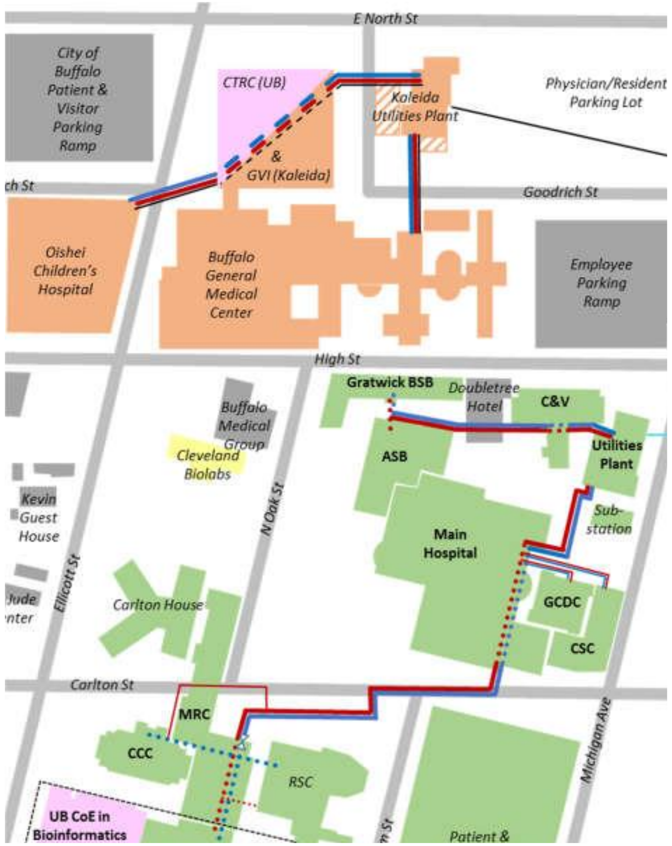




CHIL/PHIL Test @NREL

PHIL & CHIL evaluation of microgrid controller for Buffalo Niagra Medical Campus (BNMC) site



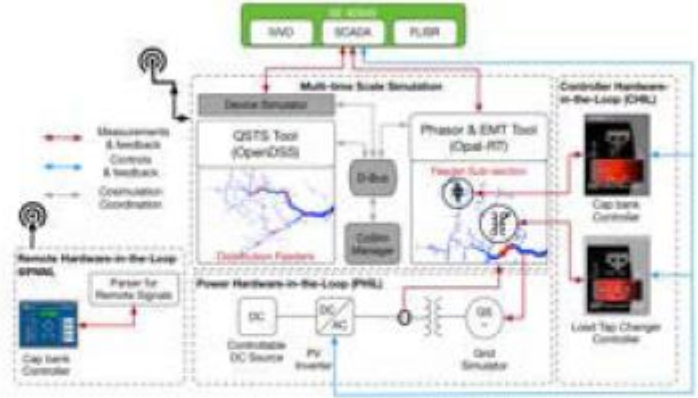


DOE FOA 997 functional requirements
CHIL: Spirae Wave controller
PHIL: ESS inverter (representative)

Controller and Power Hardware-in-the-Loop (CHIL/PHIL)

- NREL's megawatt-scale controller-and power-hardware-in-the-loop (CHIL/PHIL) capabilities allow researchers and manufacturers to test energy technologies at full power in real-time grid simulations to safely evaluate performance and reliability.

Microgrids



Cosimulation

Power system studies

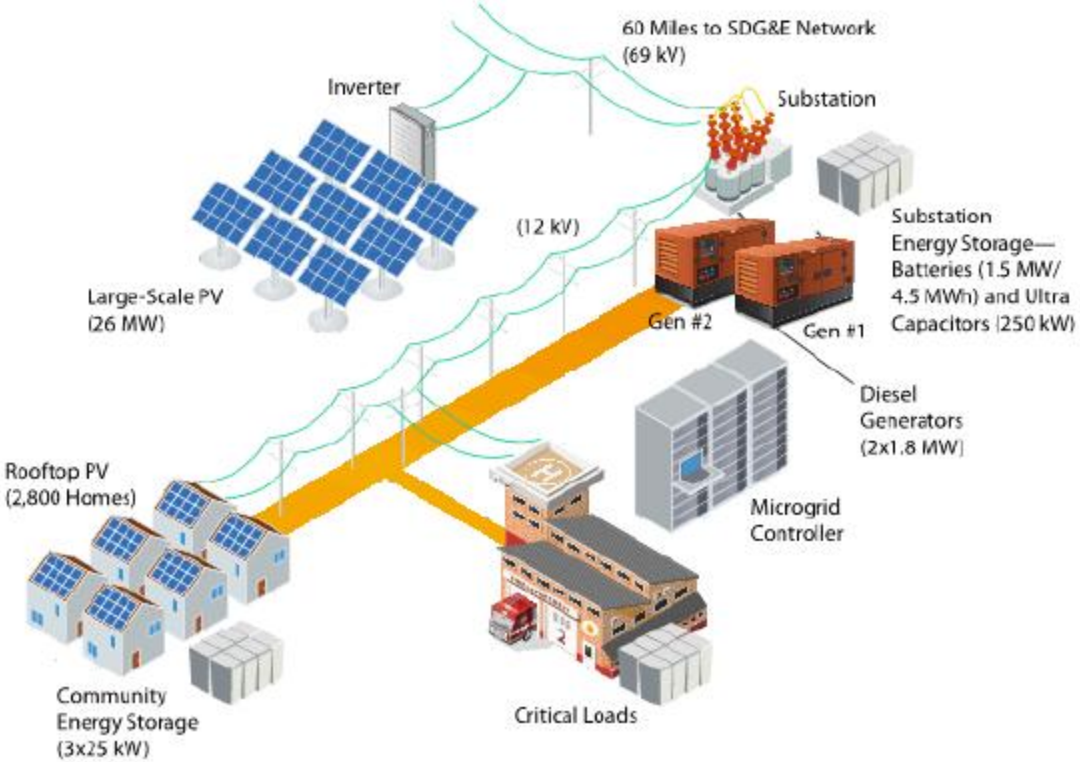
Project Example: High-Penetration Microgrid: SDG&E Borrego Springs

- **Goal:** Demonstrate the viability of a microgrid to manage large amounts (up to 100%) of renewable, intermittent energy resources to meet community load that can be replicated by others while leveraging (post-project) off-the-shelf software
- **Impact:** Successful implementation of the largest microgrid in North America will prove that a community-scale, highly renewable microgrid can be implemented with economic benefits.

Funded by:
California Energy Commission

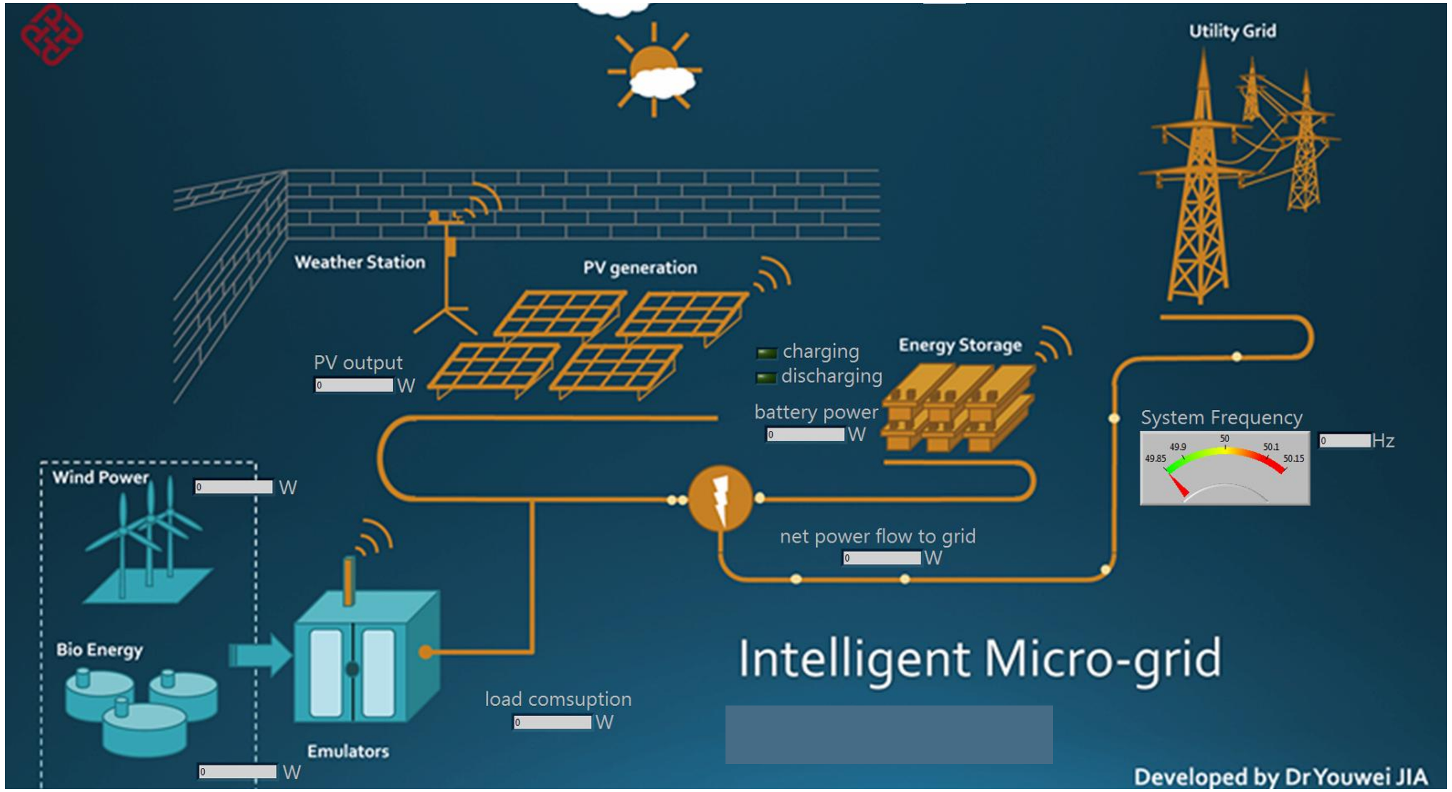
Led by:
San Diego Gas & Electric Company (SDG&E)

Partners:
NREL, Spirae, UCSD, OSIsoft, SMA, NRG



Project Example: Microgrid at the Hong Kong Polytechnic University

The PolyU laboratory microgrid platform comprises photovoltaics, energy storage and optimization dispatch components. It is the first-of-its-kind in Hong Kong, with total capacity of 4 kw.



Source: Prof. Xu Zhao

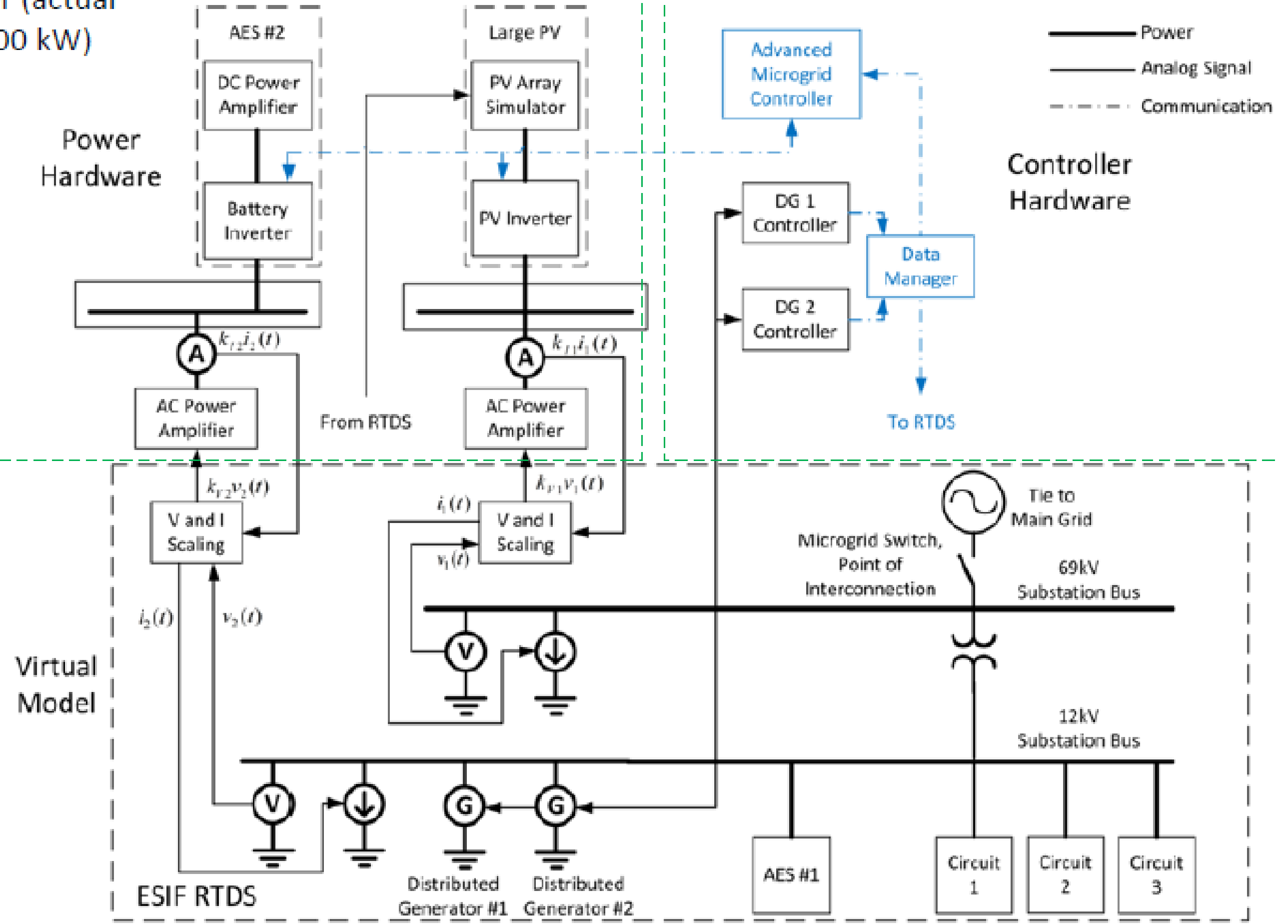
Controller-/Power-Hardware-in-the-Loop Test Bed

PHIL:

- Energy storage system inverter (representative Schneider 540 kW)
- Photovoltaic (PV) inverter (actual SMA 500 kW)

CHIL:

- Microgrid controller
- Diesel generator controllers



Metrics for Evaluating Microgrid Controller Performance

Steady-state Performance Metrics

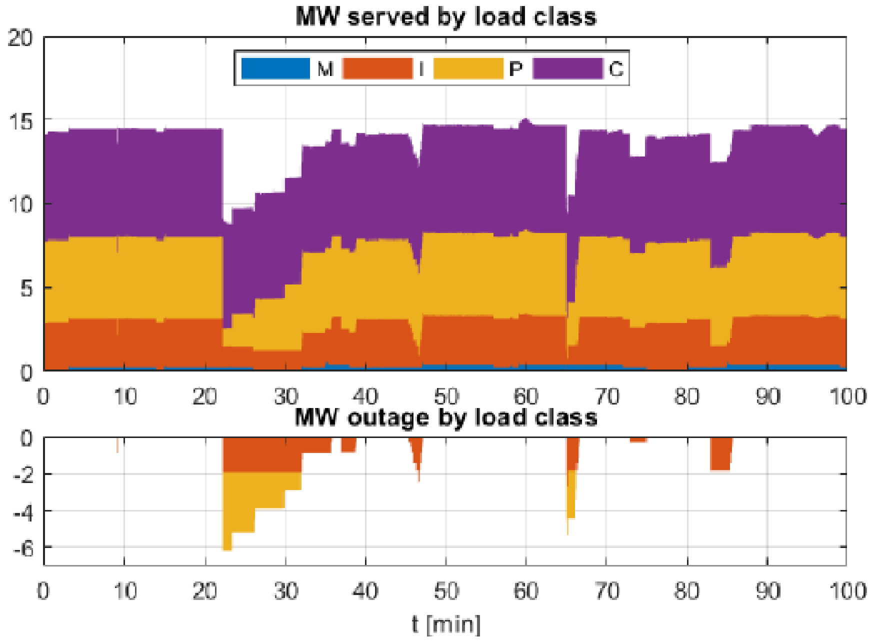
KPP1 – Resiliency and Reliability

Measured by calculating the energy delivered to predetermined categories of load. A penalty will be added for any outage on critical loads.

$$\mathrm{KPP1} = E_C P_{11} + E_P P_{12} + E_I P_{13} - E_{CO} P_{15} - E_{PO} P_{16} + E_{ESS} P_{17}$$

where:

Energy [kWh]		Unit cost [$/kWh]
Energy delivered to Critical loads	E_C	$P_{11} = 1.00$
Energy delivered to Priority loads	E_P	$P_{12} = 0.90$
Energy delivered to Interruptible loads	E_I	$P_{13} = 0.85$
Energy Critical loads Outage	E_{CO}	$P_{15} = 4.50$
Energy Priority loads Outage	E_{PO}	$P_{16} = 2.25$
Energy left in ESS at the end of the sequence compared to beginning	E_{ESS}	$P_{17} = 1.00$



Loads served (top) and outages (bottom) during a test sequence measuring KPP1

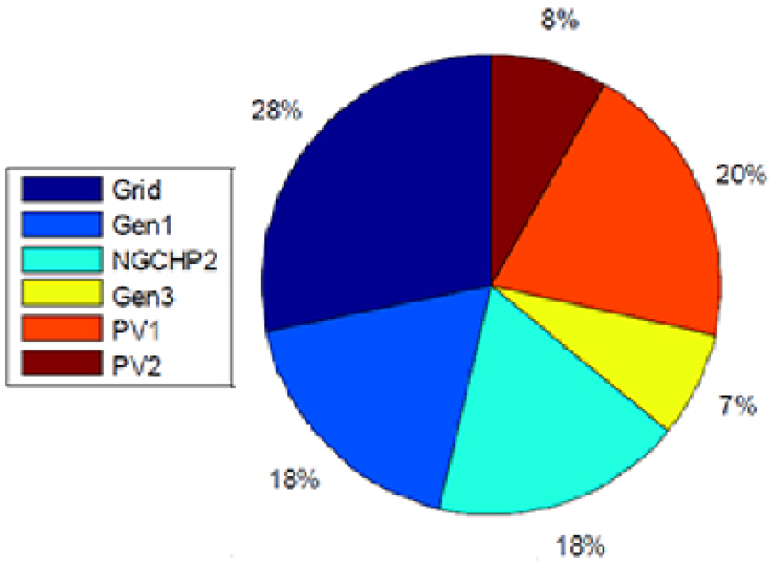
Load types:
M = motor, I = interruptible,
P = priority, C = critical

Metrics for Evaluating Microgrid Controller Performance

Steady-state Performance Metrics

KPP2 – Fuel Costs
The cost of fuels to run generators with a credit for heat delivered

Used Fuel - Diesel	F_D [gal]	P_{21} = 74.55 [$/gal]
Used Fuel- Natural Gas	F_{NG} [m³]	P_{22} = 4.18 [$/m³]
Energy delivered as Heat	E_H [MBtu]	P_{28} = 147.00 [$/MBtu]



The breakdown of energy resources used by a microgrid controller under evaluation. Solar PV and grid energy were prioritized in this evaluation, as their respective costs were lower than energy generation from on-site generators.

Metrics for Evaluating Microgrid Controller Performance

Steady-state Performance Metrics

KPP3 – Interconnection Contract

- Accounts for cost of power exchange with the grid, including the variable price of energy during the sequence
- Penalty for exceeding active and reactive power export and import limits

Exported Energy	E_E [kWh]	P_E [$/kWh]
Exported Energy Over limit	E_{EO} [kWh]	P_{EO} [$/kWh]
Energy imported from grid	E_B [kWh]	P_B [$/kWh]
Energy imported over limit	E_{BO} [kWh]	P_{BO} [$/kWh]
Reactive power over limit penalty	E_{RP} [kVArh]	$P_{33} = 0.50$ [$/kVArh]

KPP4 – Grid Services

Incentivizes controllers to support the grid by following DMS commands and autonomously responding to detected grid contingency events (e.g., underfrequency)

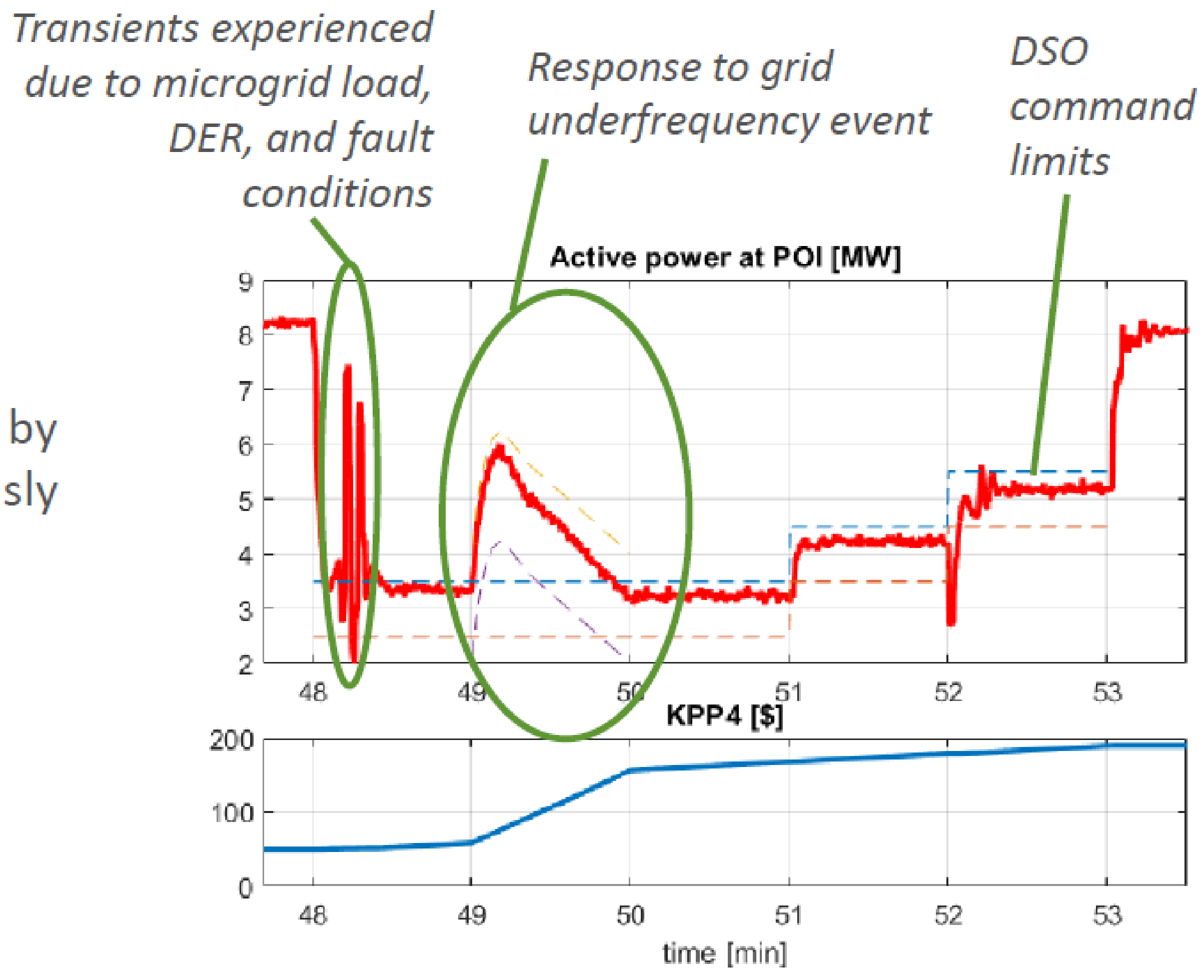
Meeting dispatch command premium (DP). Power imported from Grid to µG	T_{DP} [min]	$P_{41} = 23.60$ [$/min]
Meeting demand command premium (DM). Power exported from µG to Grid	T_{DM} [min]	$P_{41} = 23.60$ [$/min]
Following Volt/Var support premium (VV)	T_{VV} [min]	$P_{43} = 290.00$ [$/min]
Following Demand response curve (Freq/kW, FkW)	T_{FkW} [min]	$P_{44} = 149.50$ [$/min]
Meeting power factor request (PF)	T_{PF} [min]	$P_{46} = 11.21$ [$/min]
Violating planned disconnect request (DR)	T_{DR} [min]	$P_{45} = 19.50$ [$/min]
Unplanned disconnect – failure to disconnect (UD)	T_{UD} [min]	$P_{47} = 26.40$ [$/min]

Metrics for Evaluating Microgrid Controller Performance

Steady-state Performance Metrics

KPP4 – Grid Services

Incentivizes controllers to support the grid by following DMS commands and autonomously responding to detected grid contingency events (e.g., underfrequency)



Metrics for Evaluating Microgrid Controller Performance

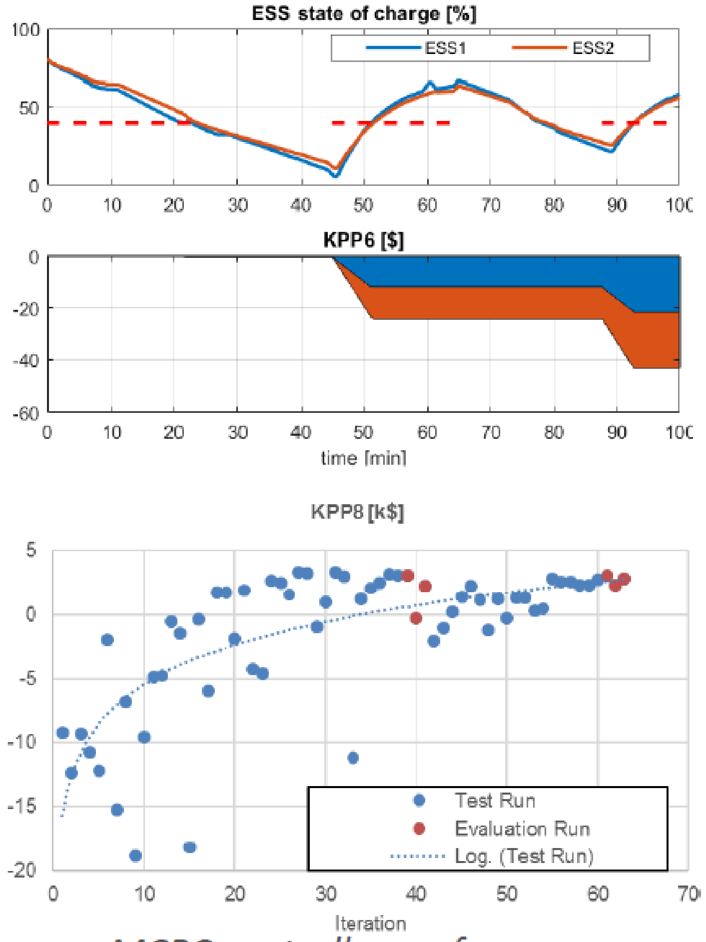
Steady-state Performance Metrics

KPP5 – Power Quality
Voltage and frequency monitored at all nodes and deviations violating IEEE 1547a-2014 clearing times (Tables 1 and 2 of the standard) are penalized

KPP6 – Microgrid Survivability
Allowing battery State of Charge (SoC) below the predetermined level during grid connected conditions results in a penalty

KPP7 – Operation and Maintenance
Accounts for microgrid component use that will result in component degradation, including generator starting, battery cycling, CB switching, and overcurrent conditions

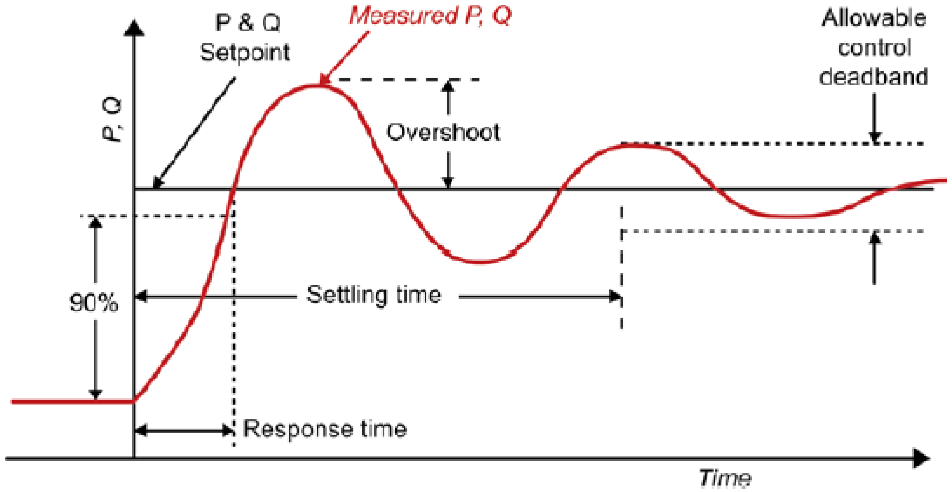
KPP8 – Economic Operation
Dollar sum of KPP1 to KPP7 allowing for overall comparison of various controllers under test

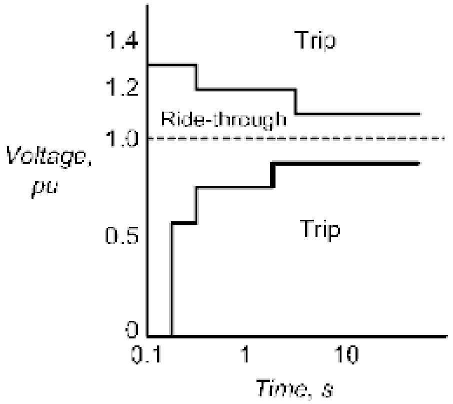


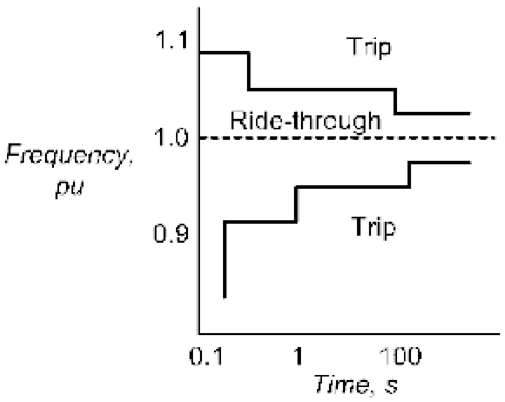
MCPC controller performance improvement through design iteration

Metrics for Evaluating Microgrid Controller Performance
Dynamic Performance Metrics

- Approach in IEEE Std 2030.8 [2]:
  - Evaluated at transition to unplanned island, planned island, and reconnection
  - V, f, P, Q settling time, overshoot, and steady-state values within contractual limitations



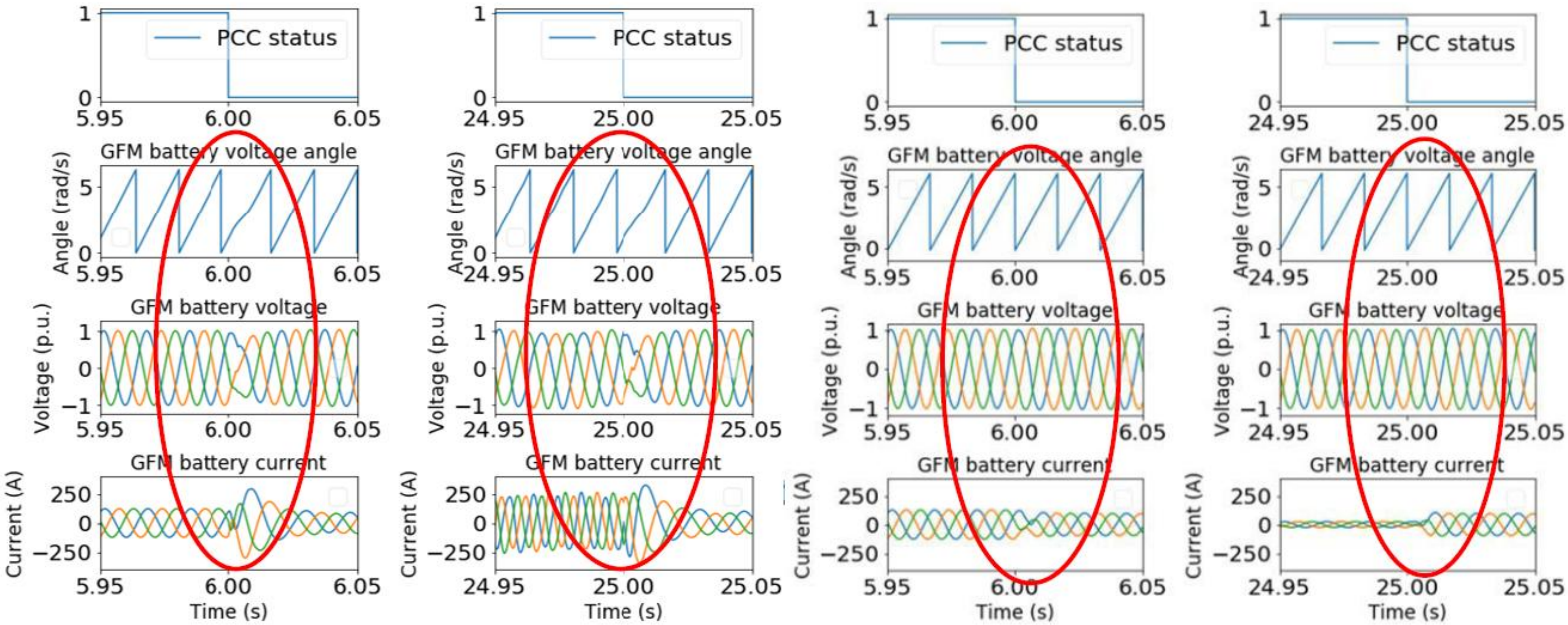




Figures from: [2] IEEE Std 2030.8-2018, IEEE Standard for the Testing of Microgrid Controllers

Metrics for Evaluating Microgrid Controller Performance

Dynamic Performance Metrics: Example of Unintentional Islanding Event

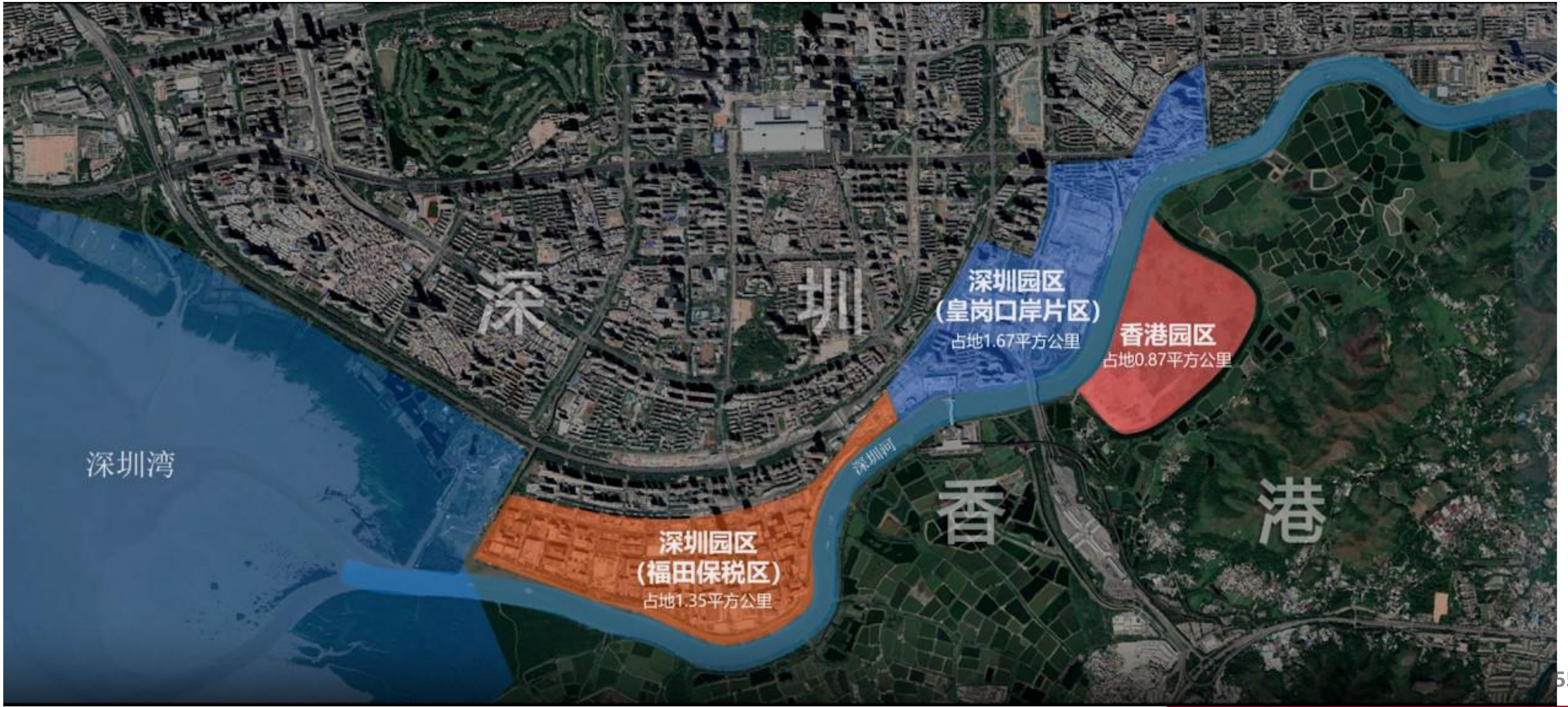


Traditional method

Improved method [4]

[4] J. Wang, B. Lundstrom, A. Bernstein, "Design of a Non-PLL Grid-forming Inverter for Smooth Microgrid Transition Operation," in *IEEE PES General Meeting,* 2020.

Outlook of Microgrids in GBA



Summary

To understand the *what*, *why*, *who when where*, and *how* of Microgrids

What

- Inter-connected loads, DERs and devices within defined electrical boundaries
- Grid-connected or island-modes

Why

- Improve local resilience and reliability
- Clean energy
- Save money

Who When Where

- Microgrid Techno-Economic Assessment
- Distributed Energy Resource Value Estimation Tool (DER-VET™)

How

- Microgrid Controls
  - In-house developed control
  - Vendor developed control

- Testing of Microgrid Control Systems
  - Controller-/Power-Hardware-in-the-Loop
  - Steady-state/Dynamic Performance Metrics

Questions?