NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INL
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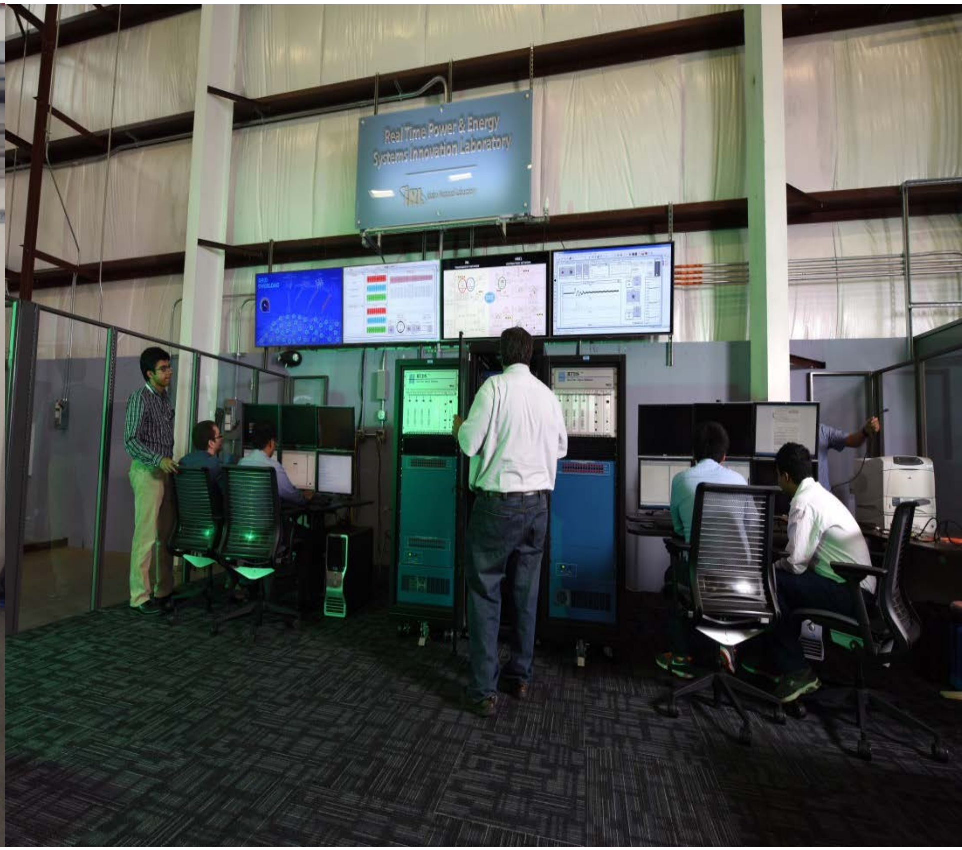

Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TV031

June 8, 2017

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Overview

Timeline

- **Project start date: 06/01/15**
- **Project end date: 09/30/17**

Budget

Total project budget: $3660K
Total recipient share: $2100K(INL), $1560K(NREL)
Total federal share: $3660k
Total DOE funds spent*: $2250K
* As of 3/31/17

Barriers

- **Barriers addressed**
  - Lack of Data on Stationary Fuel Cells in Real-World Operation
  - Hydrogen from Renewable Resources
  - Hydrogen and Electricity Co-Production

Partners

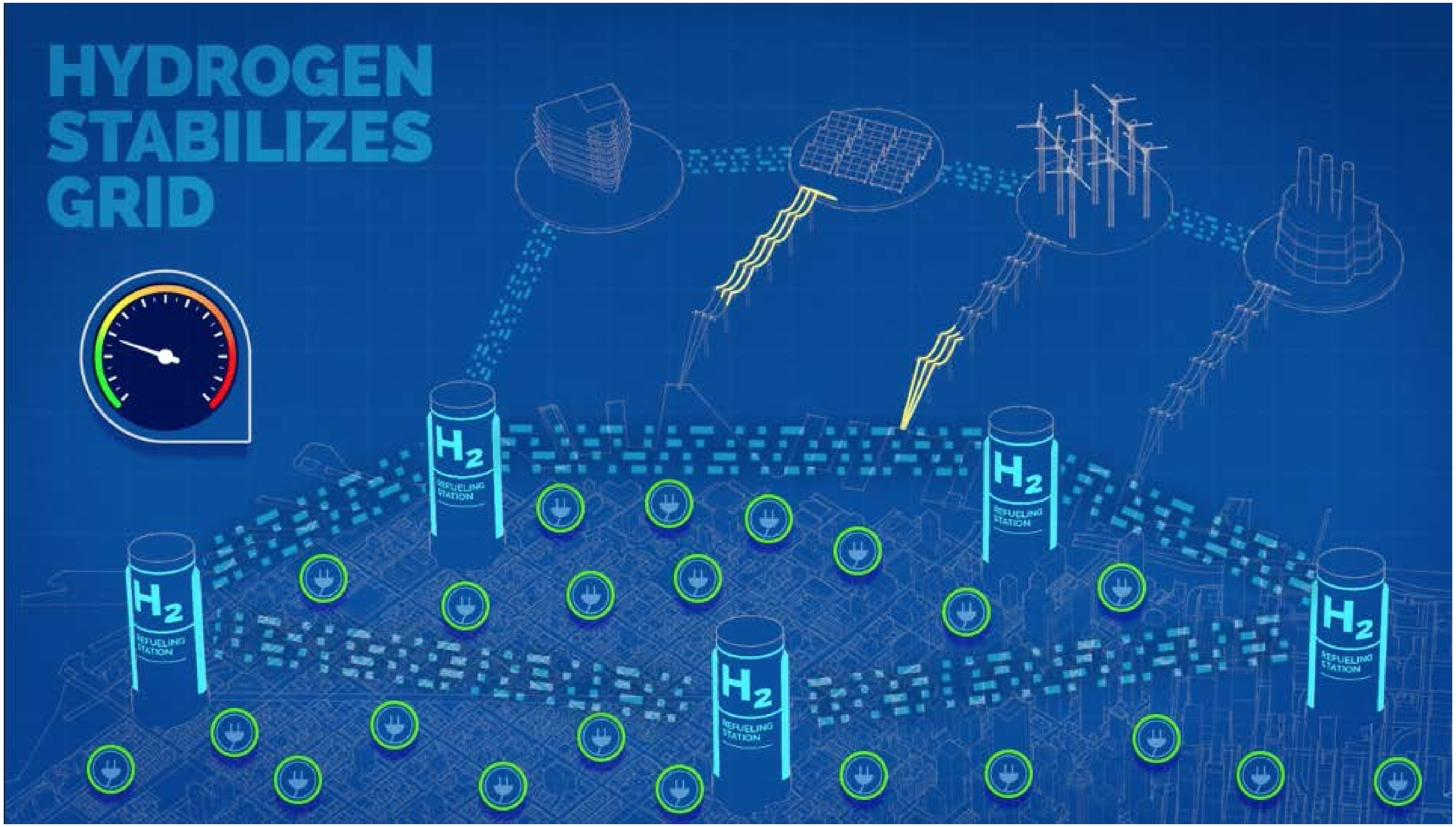
- **Funded partners**
  - Idaho National Laboratory and National Renewable Energy Laboratory
- **Collaborators**
  - Utilities: PG&E, CAISO, Xcel Energy, EnerNOC; California Air Resources Board
  - Academic: Humboldt State University, Florida State University

Relevance & Objective

- Relevance: Electrolyzers can be a controllable load with utilities, verification and validation of electrolyzer performance (within hydrogen refueling infrastructure demands) under dynamic grid conditions is needed for grid stakeholders, hydrogen station operators, and decision-makers
- Objective: Validate the benefits of hydrogen electrolyzers through grid services and hydrogen sale to fuel cell vehicles (California Bay Area focus)
  - Demonstration of the reliable, fast-reacting performance of hydrogen-producing electrolyzers for at-scale energy storage devices.
  - Verification of the communications and controls needed for successful participation in DR programs and ancillary services, leading to additional revenue and reduced hydrogen production cost.
  - Evaluation at scale, electrolyzer operation by performing co-simulation of the communication layer with the front end controller operation under various dynamic grid conditions

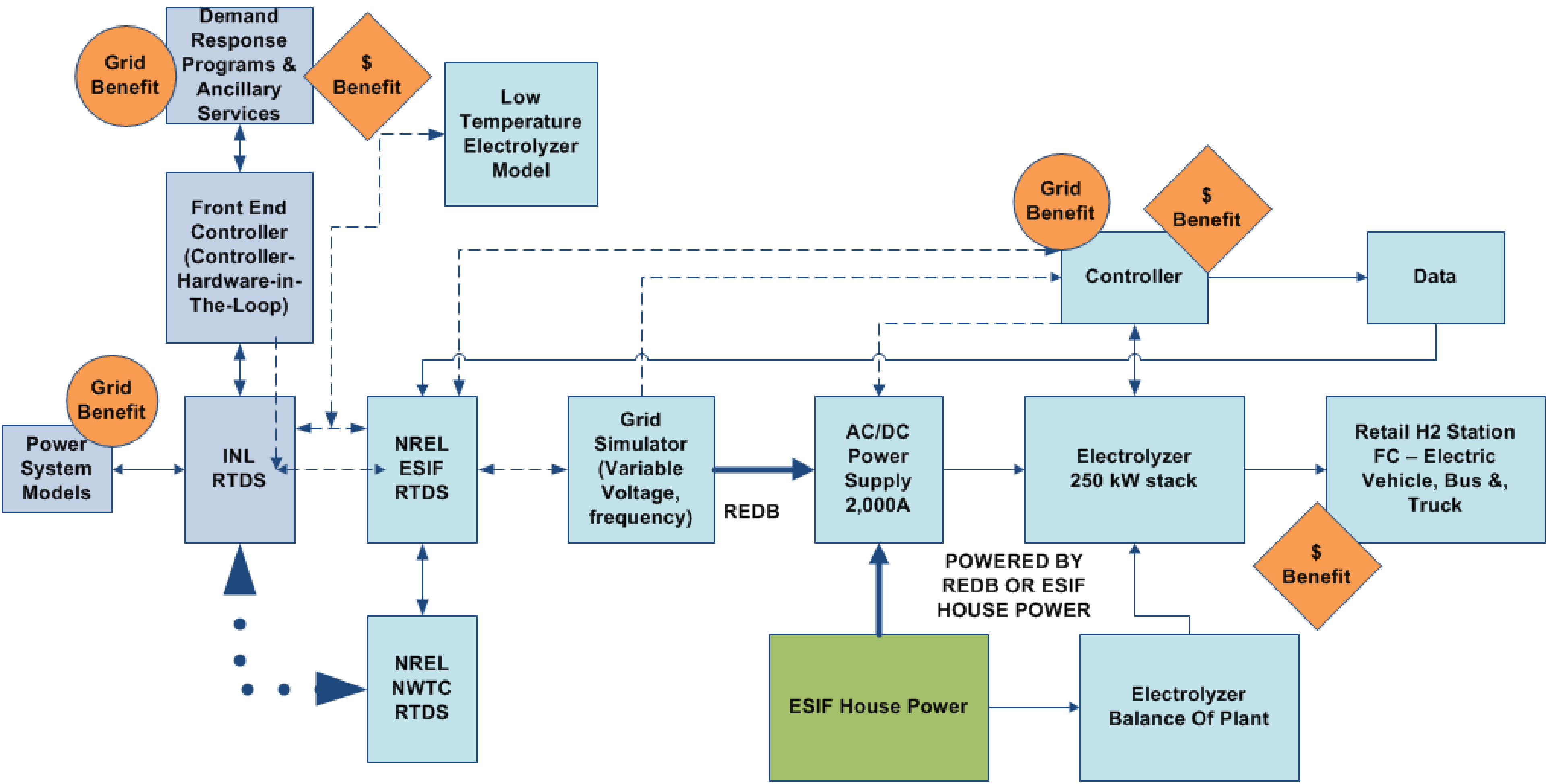
Project Overview - Summary

- Validation of electrolyzer capability to reduce operating cost by supporting utility needs as a controllable load using realistic conditions
- Demonstration of compensation of variability of renewable energy sources leading to better grid management

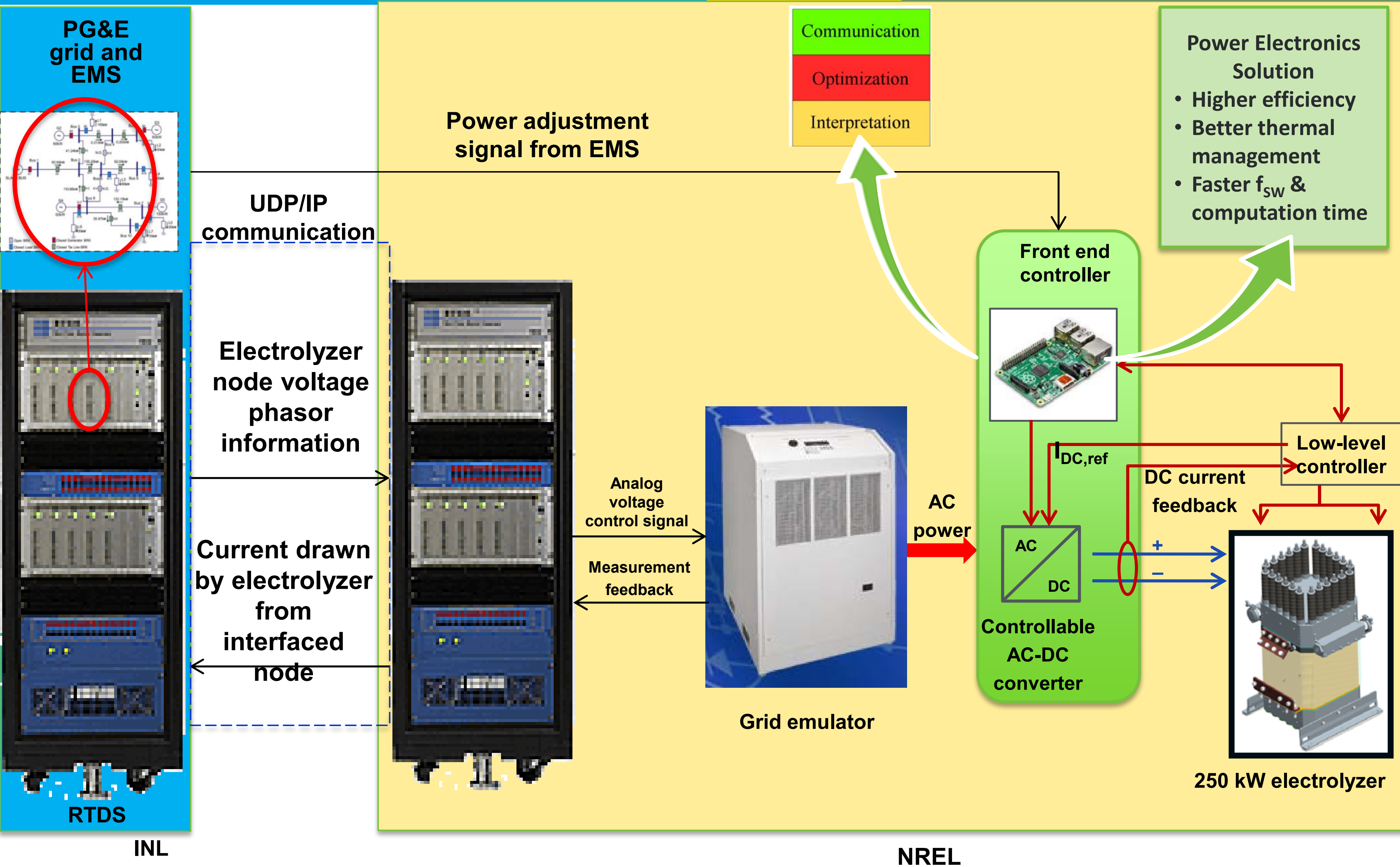


Approach – Experimental Setup

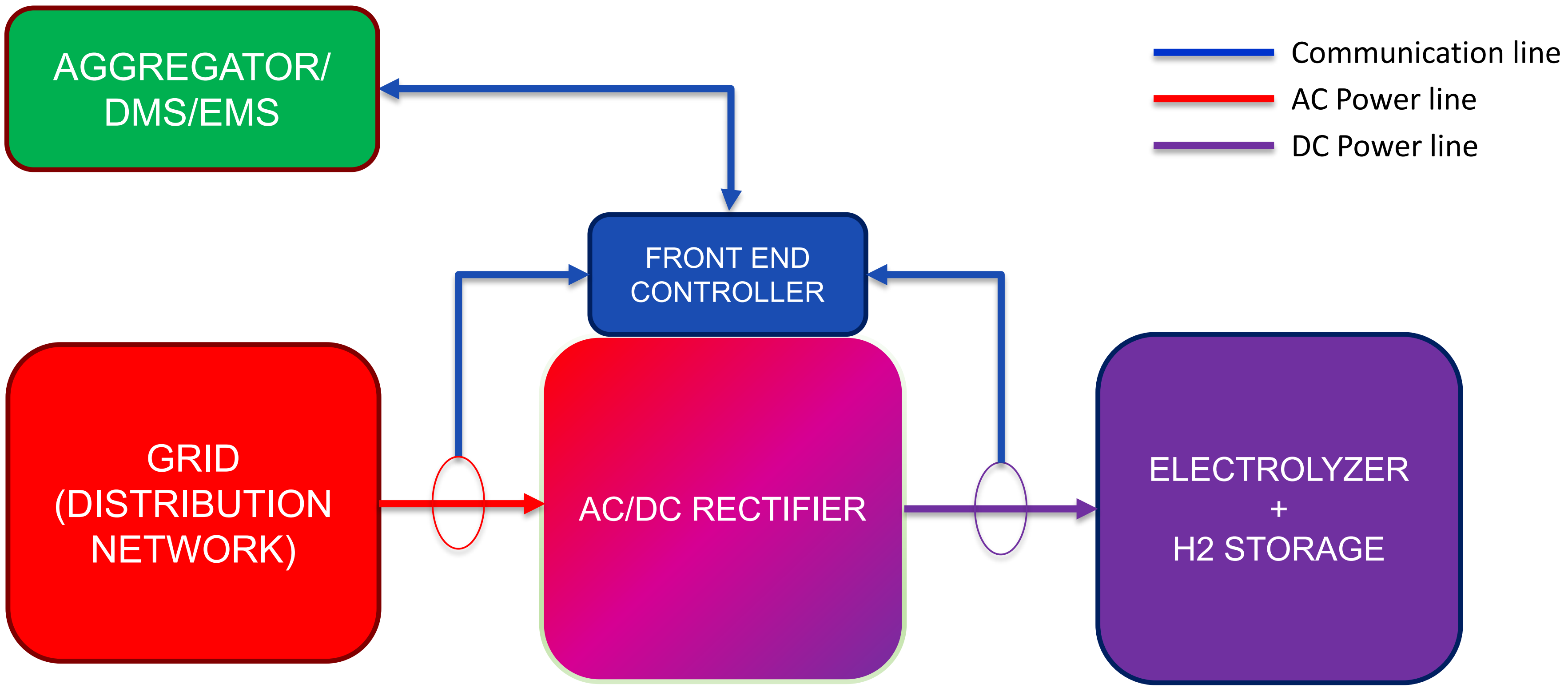
Real Time Digital Simulator (RTDS) enables communication, control, and experimental operation between grid modeling, Front End Controller (FEC), electrolyzer system, and economic benefit evaluator.



Hardware Testbed Configuration



The project combines modeling, simulation, and hardware for the validation of system performance and to quantify economic benefit based on different operation scenarios relevant to utilities

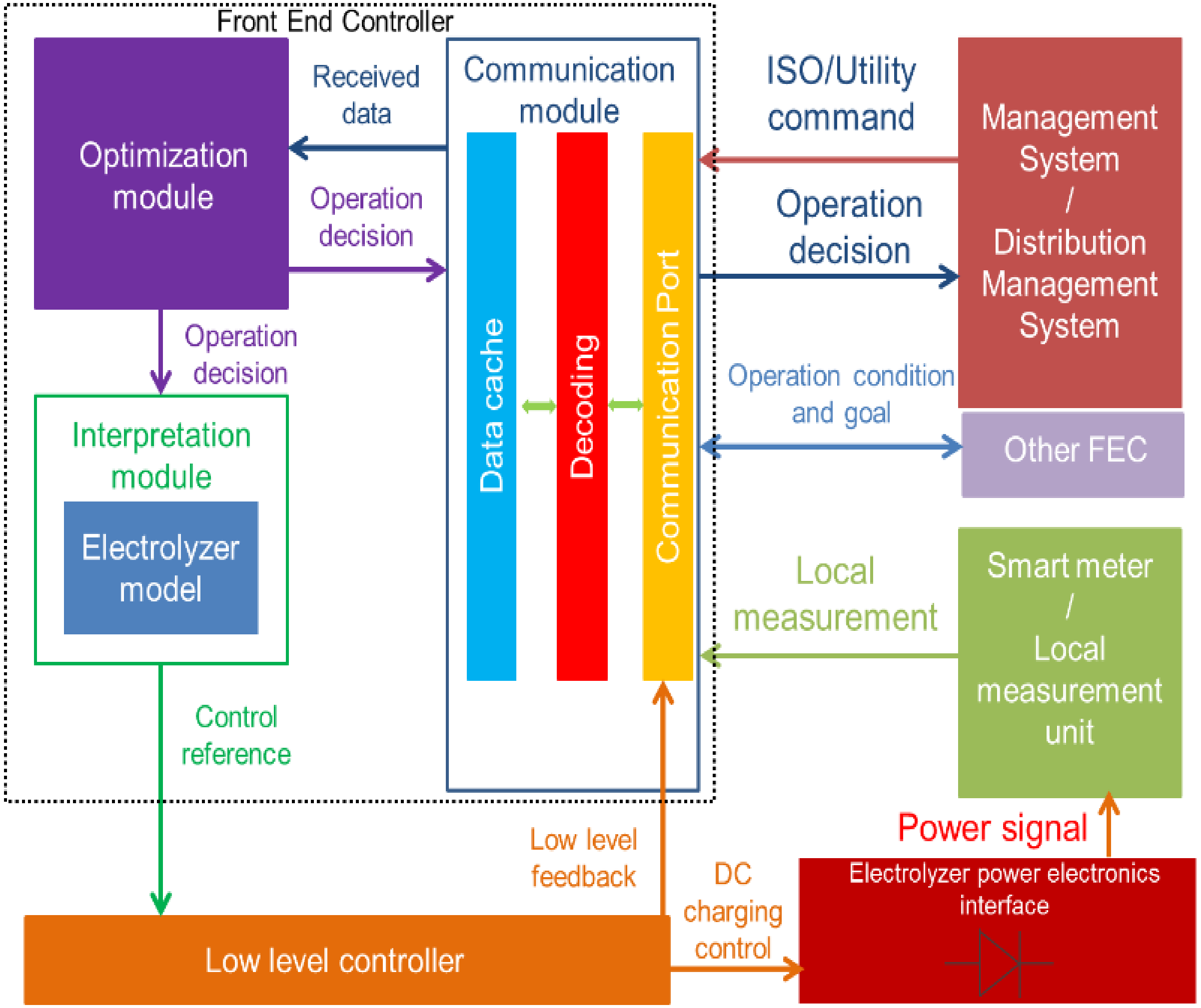


Approach - Front End Controller

Advanced controllability of electrolyzers by Front End Controller to support the grid signals

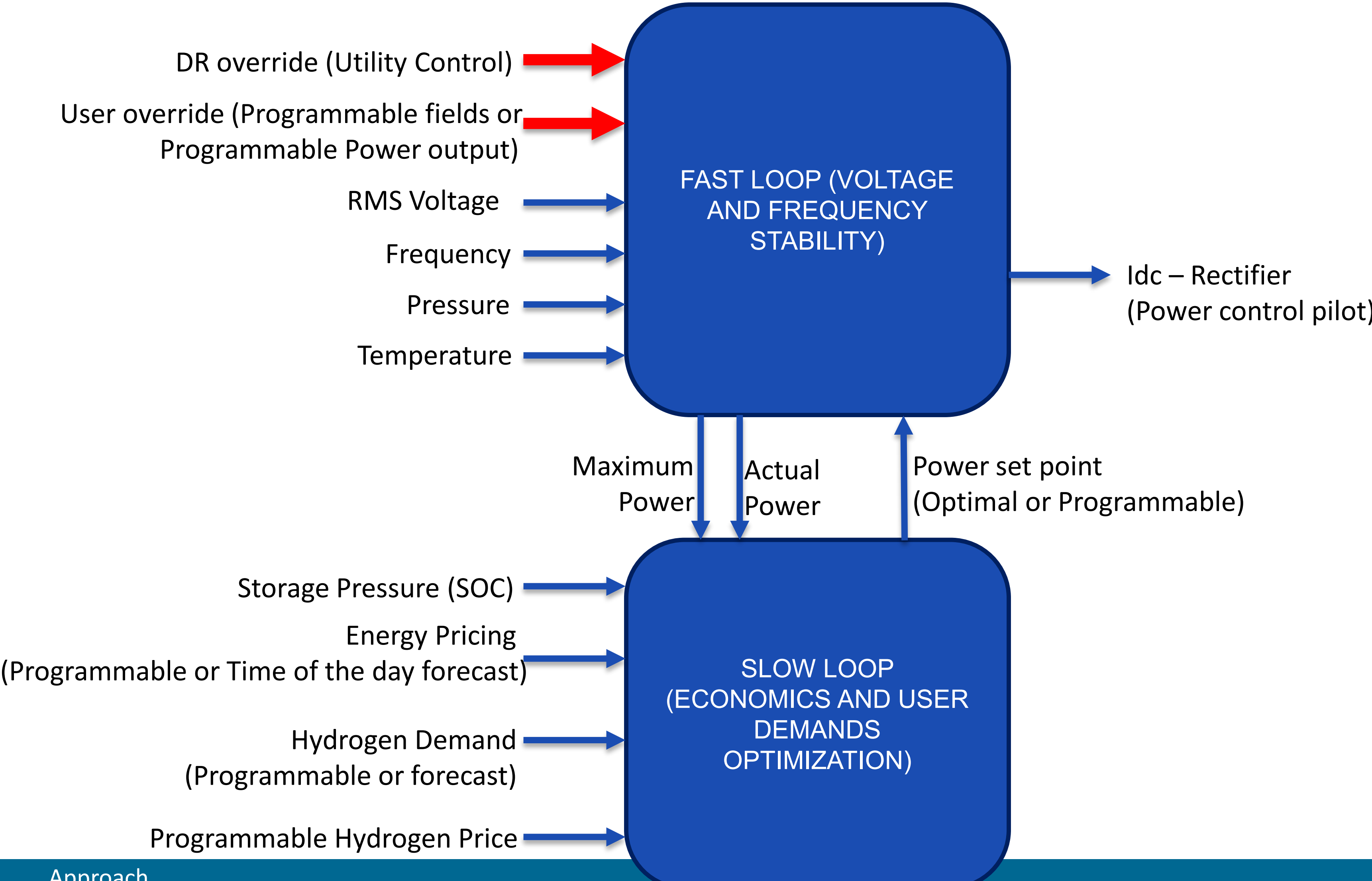
FEC consists of three modules:

1. **Communication module** realizes data exchange between FEC, utility, and electrolyzer's low level controller
2. **Optimization module** computes set point for electrolyzer operation that optimizes the revenue of the hydrogen refueling station
3. **Interpretation module** generates the reference control signal in order to ensure that the low level controller properly integrates with the FEC



Approach - FEC Inputs/Outputs

Front End Controller adds greater ‘awareness’ and hence ‘better response’

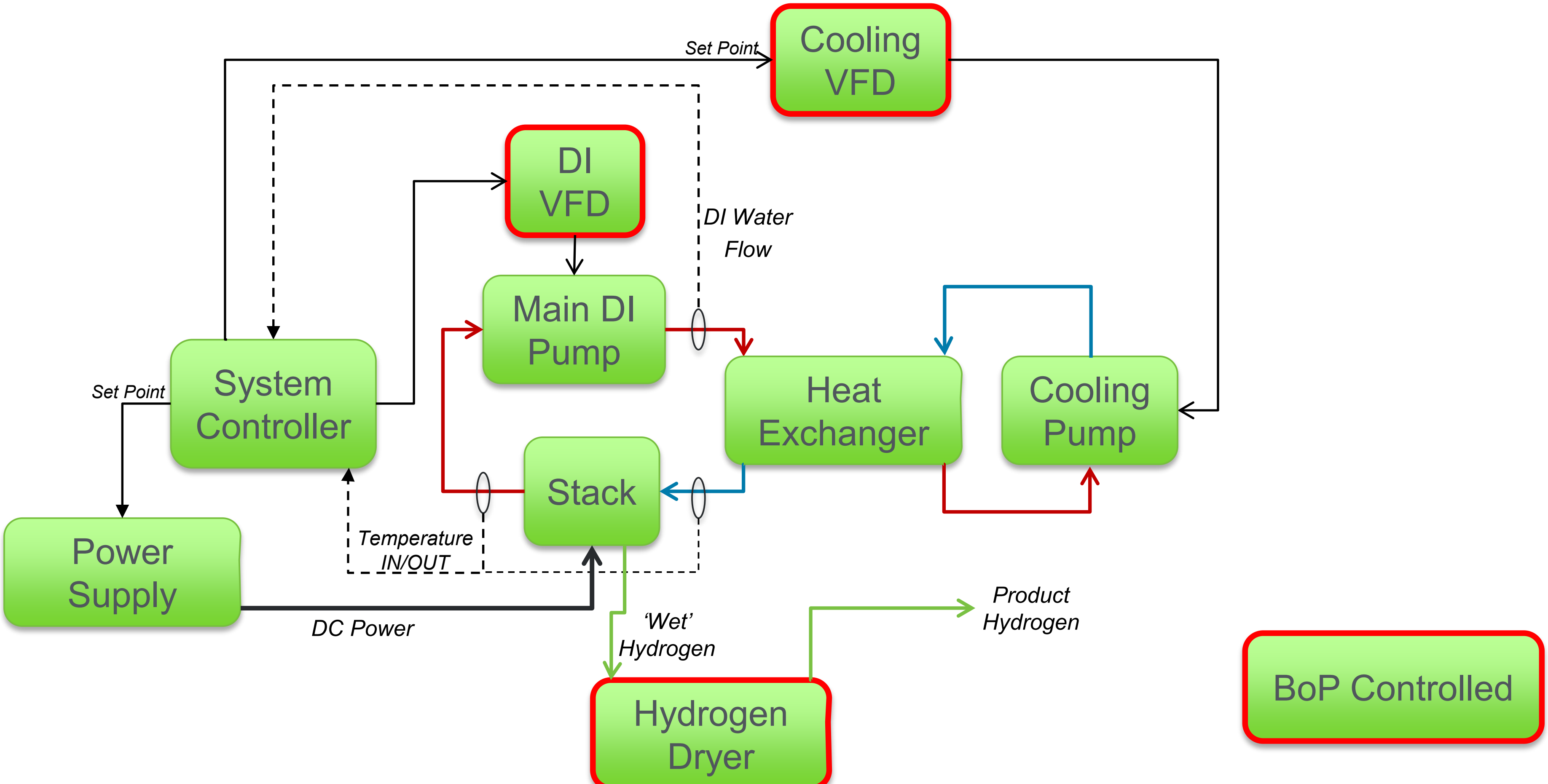


Approach - Operation Metrics

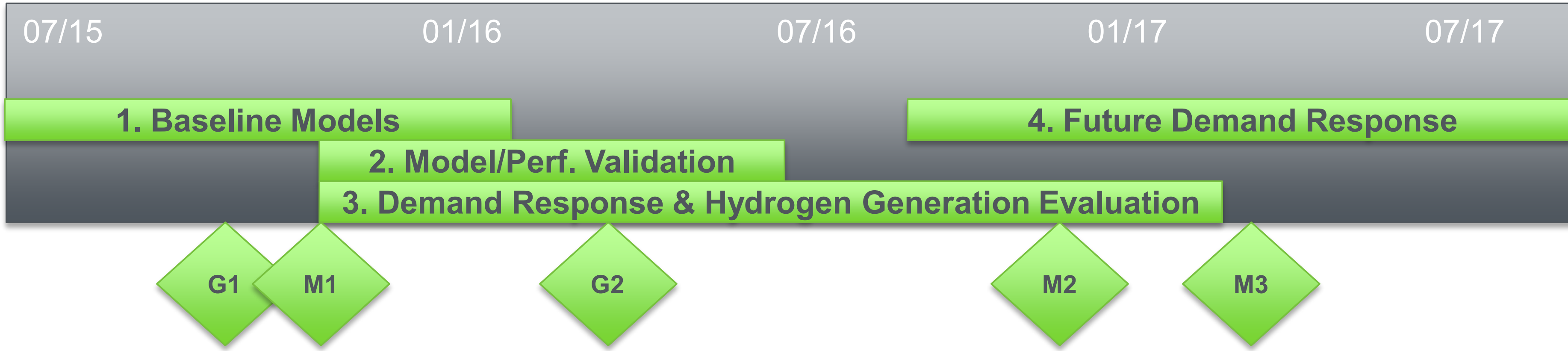
Category	Operation Metric	Target	Technical Goal
PHIL Validated Performance	Response time to a change in power set-point	One second response to full load change	Demand response and grid support
PHIL Validated Performance	Settling time after a set-point change	One second	Demand response and grid support
PHIL Validated Performance	Duration possible for a change in power consumption	Infinite	Demand response and normal operation as per schedule
PHIL Validated Performance	Turndown level	10% of full stack power	Safe operation
PHIL Validated Performance	Startup and shutdown time	30 seconds and < one second	Safe operation
Control Development	Control (multiple variations)	Power command from FEC to electrolyzer stack; grid management commands from EMS/aggregators to the FEC	Better controllability of the stack to respond to grid management signals
RT Simulation Validated Performance	Control signals and response	< One second for grid response; 3-5 seconds for demand response type signals	Validation of the electrolyzer and FEC response to grid events
PHIL Validated Performance	Reduce cost of hydrogen production versus normal operation	10% - Acceptable, 20% - Good, 30% - Excellent	Reduction in cost of producing hydrogen and increasing revenue by providing grid services

Approach – Balance of Plant Optimization

Increase system efficiency by reducing BoP energy consumption under variable stack power operation



Approach – Timeline (Milestones and Go/No-Go decisions)



M1	Demonstrate distributed Real Time Simulation (RTS) with data latency of less than 30 milliseconds during the data transfer between INL and NREL.	September 2015	Completed
M2	Demonstrate a 250-kW electrolyzer operating (for 500 hours) in 1) the energy market (hydrogen production) and 2) the ancillary service market both for a simulated electricity grid based on real-time pricing signals.	September 2016	Delayed – Expected Complete 6/17
M3	DR programs that optimize the revenue generated from participating in DR programs by a minimum of 10%. The optimization techniques will consider the tradeoff between the revenues generated from both the revenue stream (hydrogen delivery and DR participation) leading to optimal operational decisions.	March 2017	Competed
G1	1. Furnish a total of 3 utility/system operator support letters summarizing their potential roles in this project - Pacific Gas & Electric, California Independent System Operator, & DR aggregator (e.g., PG&E qualified aggregators for AMP program) 2. Created 3 current and future distribution systems based on PG&E data.	December 2015	Completed
G2	Demonstrated distributed RT PHIL of 120 kW stack with an efficiency of 60% for 200 hours to test dynamic conditions, demand response, and characterization.	March 2016	Completed

Approach – Deliverables Summary

All deliverables are completed on schedule and steady progress towards completing future ones

D1	Electrolyzer model compatible with RTDS® demonstrated and verified through exchanging instantaneous signals between the two.	June 2015 (100%)
D2	Complete the RTDS® models of IEEE 13 node feeder system with electrolyzer. This test system will provide the environment for performing dynamic simulations using the electrolyzer model.	June 2015 (100%)
D3	Assess the economic competitiveness of existing, current and planned electrolytic hydrogen stations, and determine the greenhouse gas emissions impacts for these stations compared with hydrogen station alternatives. Include participation in electricity markets and DR programs.	December 2015 (100%)
D4	Develop and test the 120 kW electrolyzer interface with RTDS® at NREL. Finalize details of the locations that will be simulated and tested within the Bay area served by PG&E.	December 2015 (100%)
D5	Perform distributed RT PHIL on the basis of dynamic conditions described in Appendix B with the electrolyzer connected to the CERTS based microgrid that is modeled as part of FY15 work. The objective of performing this RT PHIL is to characterize the response of the electrolyzer under typical grid conditions to obtain the transient response.	March 2016 (100%)
D6	Develop suitable PG&E distribution network model in RTDS® and dynamic test scenarios under existing DR programs. The dynamic scenarios (hydrogen demand, excess generation, deficit generation, etc.) will be planned such that it leads to DR signals being issued and hence leading to participation of electrolyzers accordingly.	June 2016 (100%)
D7	Modify the PG&E distribution network model (expanded) in RTDS® in order accommodate the future refueling stations as planned in the San Francisco Bay area served by PG&E.	December 2016 (100%)
D8	Perform distributed RTS for the expanded distribution networks with future refueling station under novel DR programs will be performed.	June 2017 (60%)
D9	Department of Energy Report summarizing – "Role of Hydrogen Refueling Stations in Demand Response and Grid Services".	September 2017

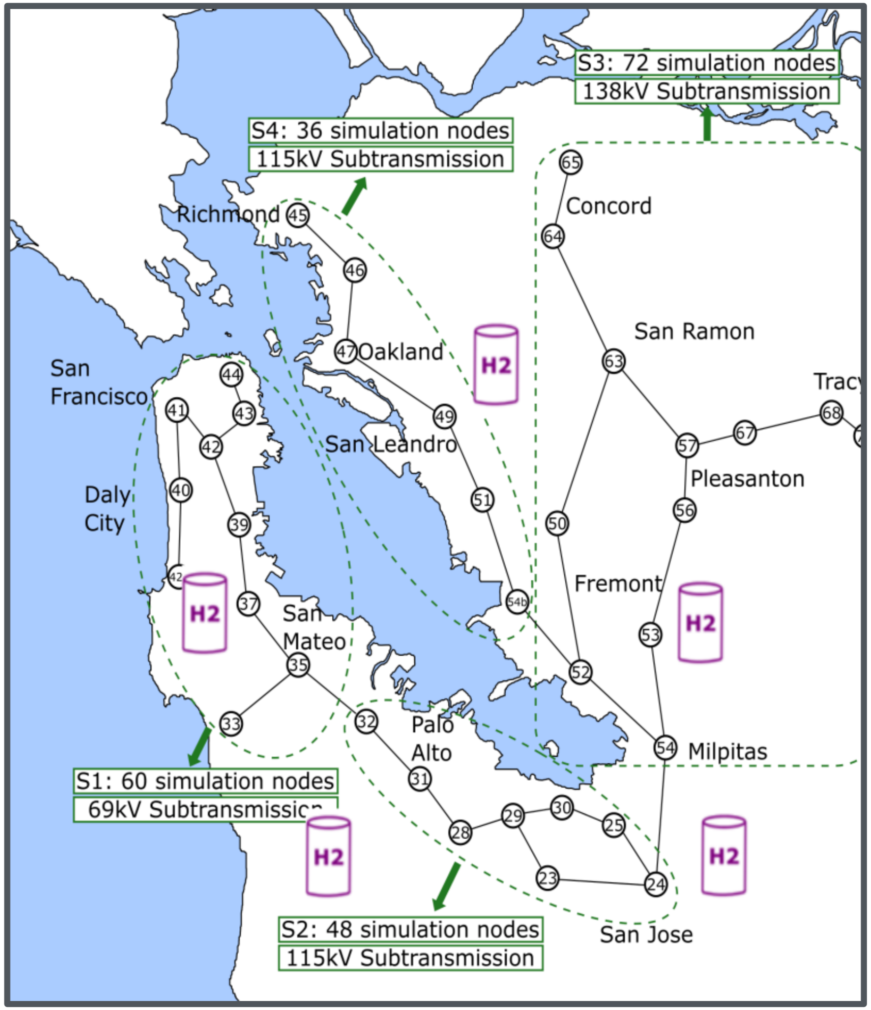
Summary of Accomplishments

- Grid Modeling
  - PG&E Real-Time Network Model
- PHIL Validation of Innovative System Integration Performance
  - Characterization (not covered in this presentation)
  - Frequency Support
  - Voltage Support
- PHIL Validation of Innovative System Integration Economic Benefit
  - Utility Tariff
- PHIL Operation Summary
  - Electrolyzer system connected to grid simulator at NREL driven by grid model and FEC run at INL

Accomplishment – Grid Modeling, Real-Time PG&E Network

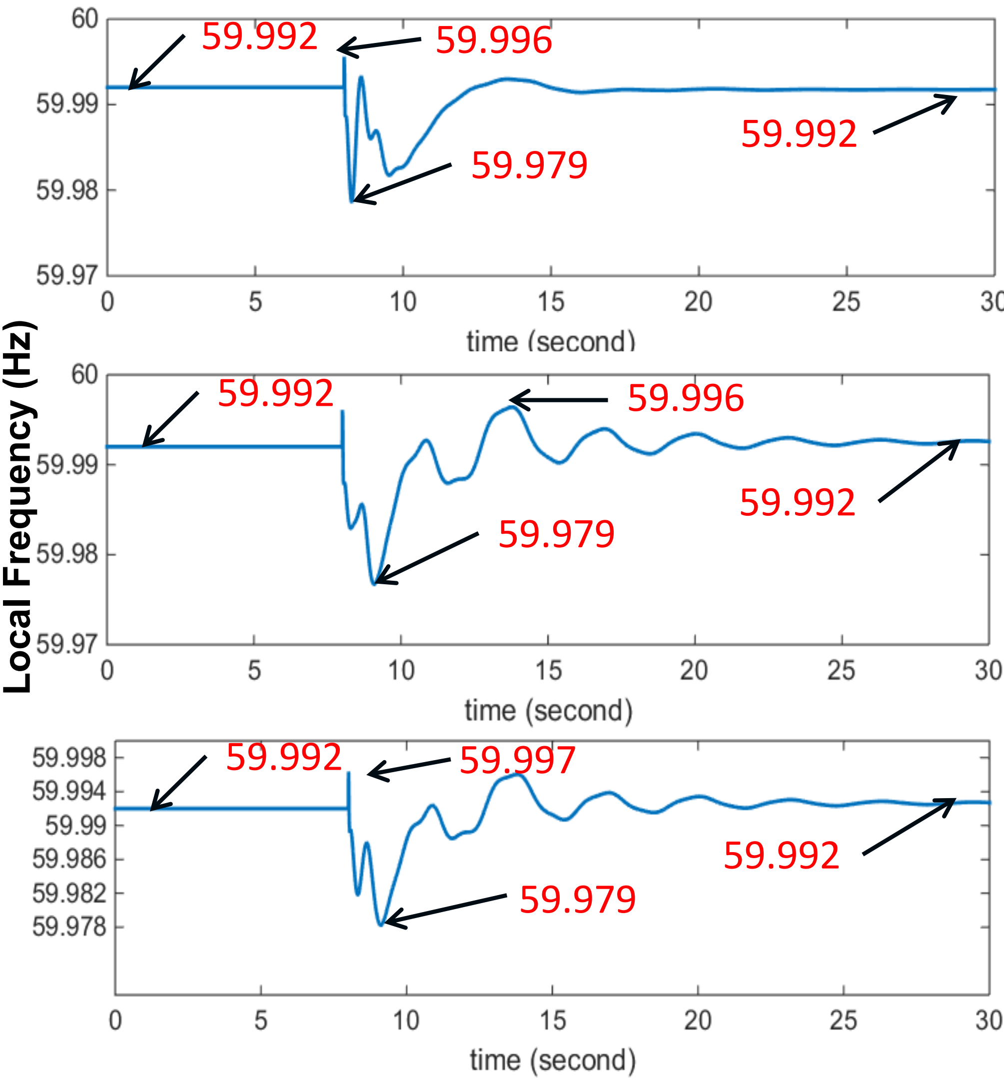
Real-time grid model of Pacific Gas & Electric that covers hydrogen refueling station interconnections

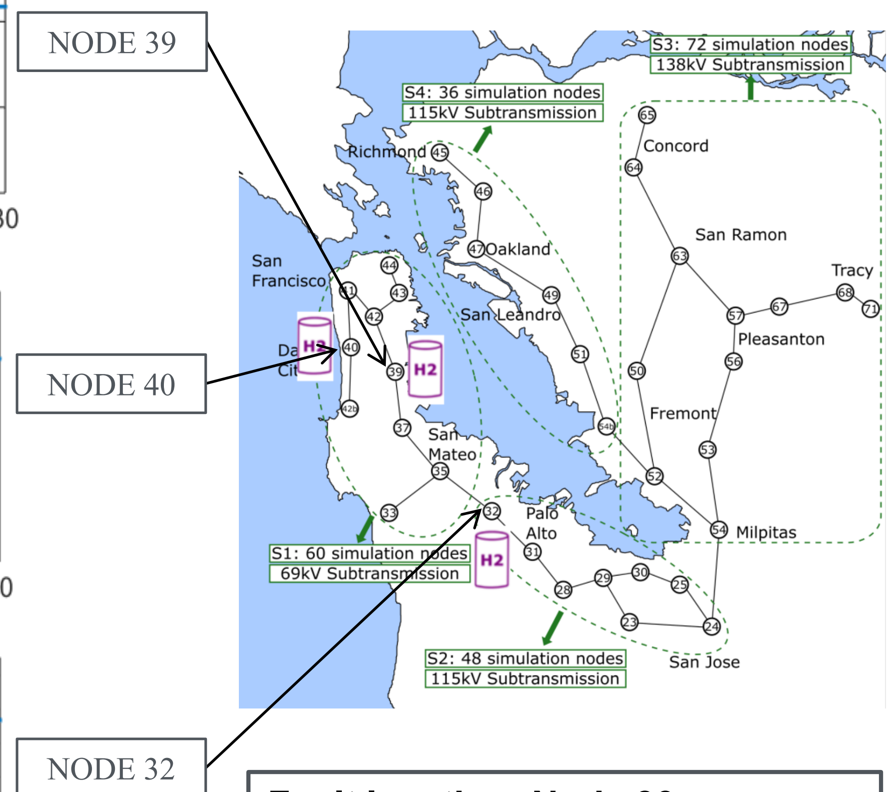
- Network synthesis and modeling in real-time simulator at INL, represents the PG&E infrastructure
- Electrolyzer connected as Hardware-In-the-Loop
- Served as a testbed for testing grid services and stability of connecting electrolyzers
  - Centralized and distributed electrolysis is assessed under varying conditions
  - Fault conditions within the grid
    - Balanced and unbalanced faults
    - Step load changes in the grid
    - Voltage and frequency variations
  - Demand response signals and response of the electrolyzer



Accomplishments Frequency Support by Multiple Electrolyzers with FEC

Multiple electrolyzers controlled by FEC can enhance overall grid stability by limiting frequency excursions

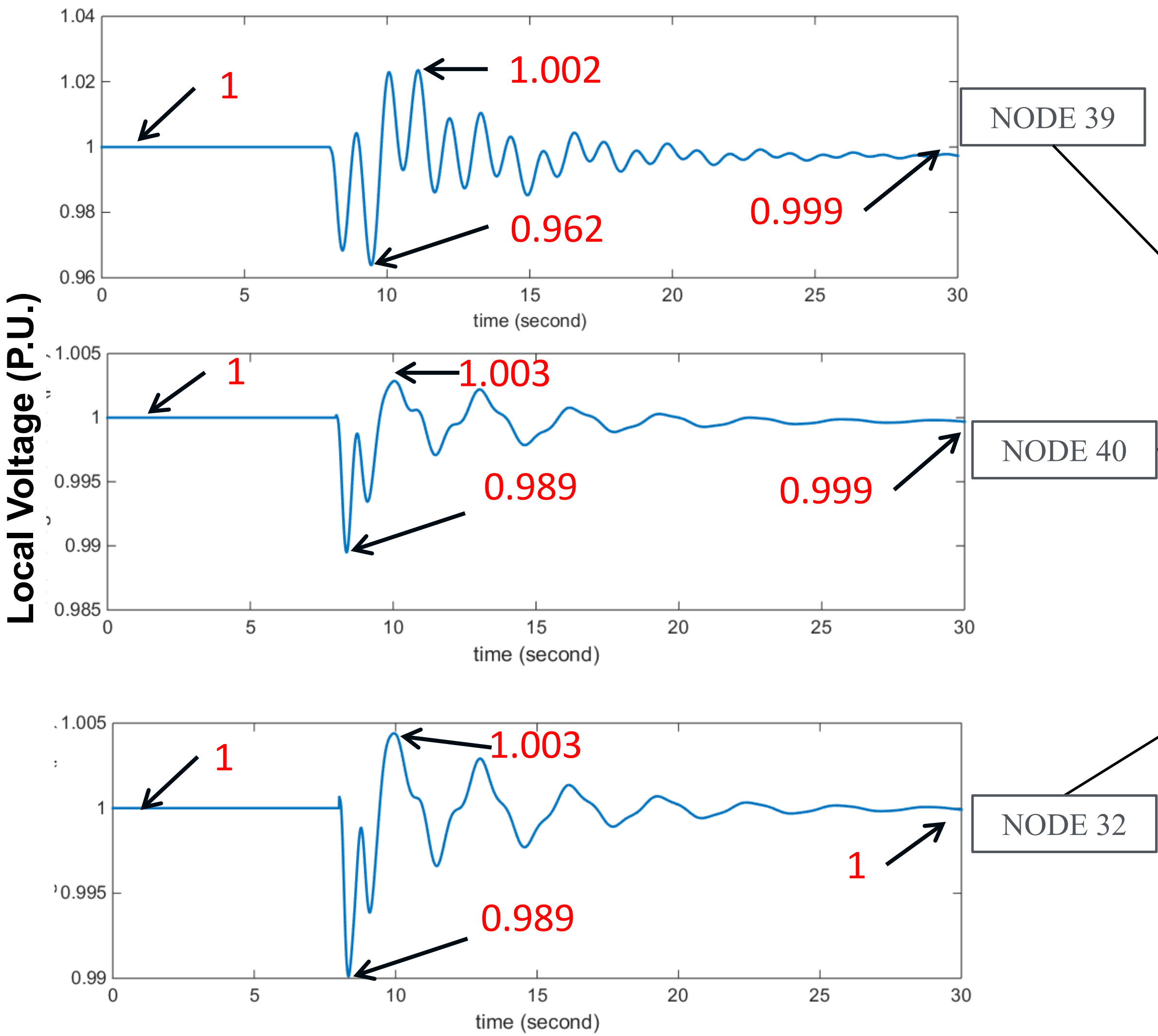


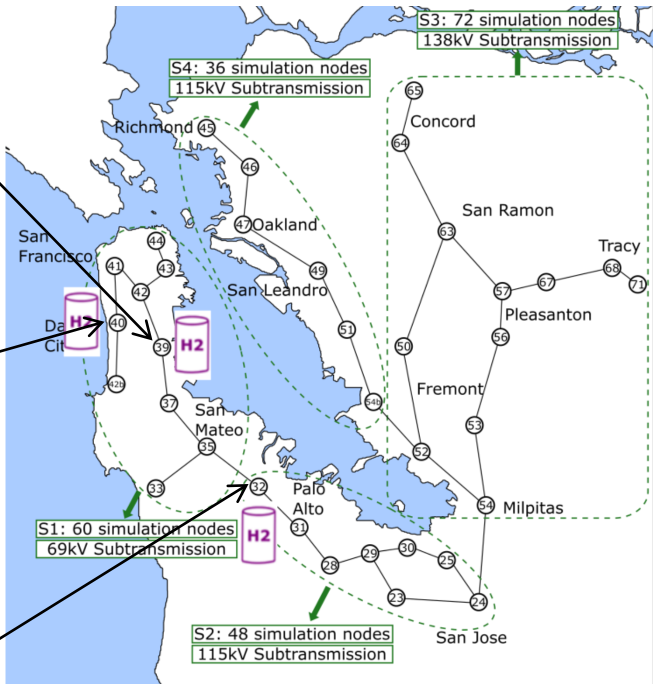


Fault location: Node 39
Fault type: Three phase balance
Fault duration: 0.1 seconds

Accomplishments Voltage Support by Multiple Electrolyzers with FEC

Multiple electrolyzers controlled by FEC can enhance overall grid stability by limiting voltage excursions





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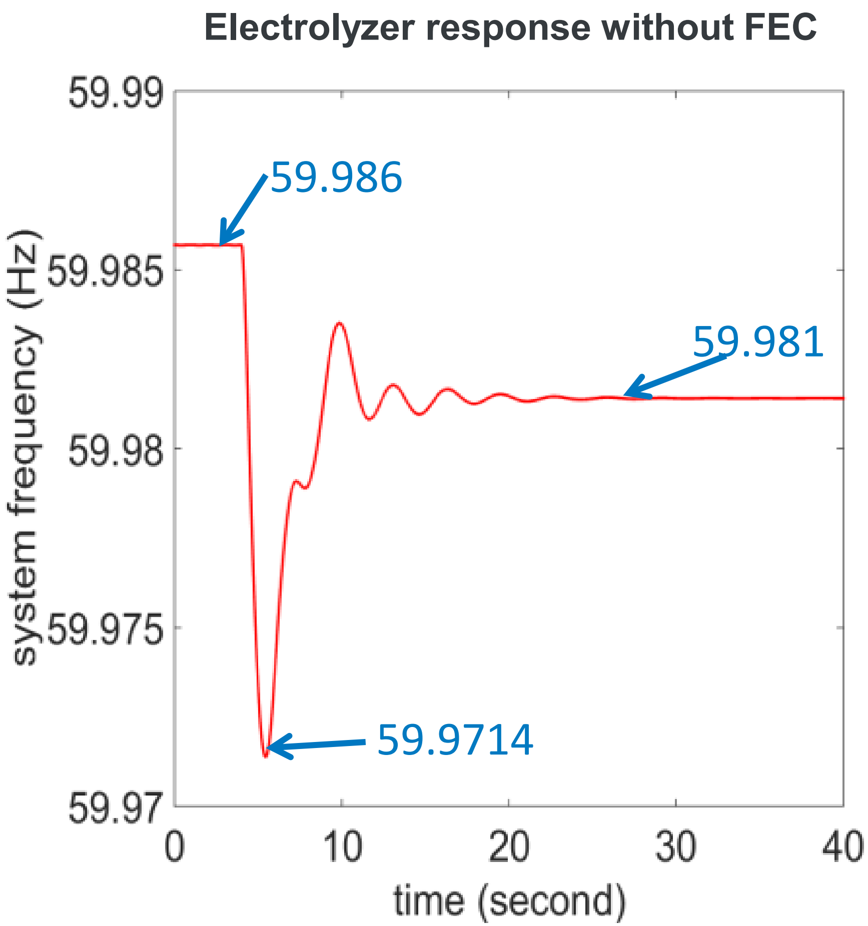
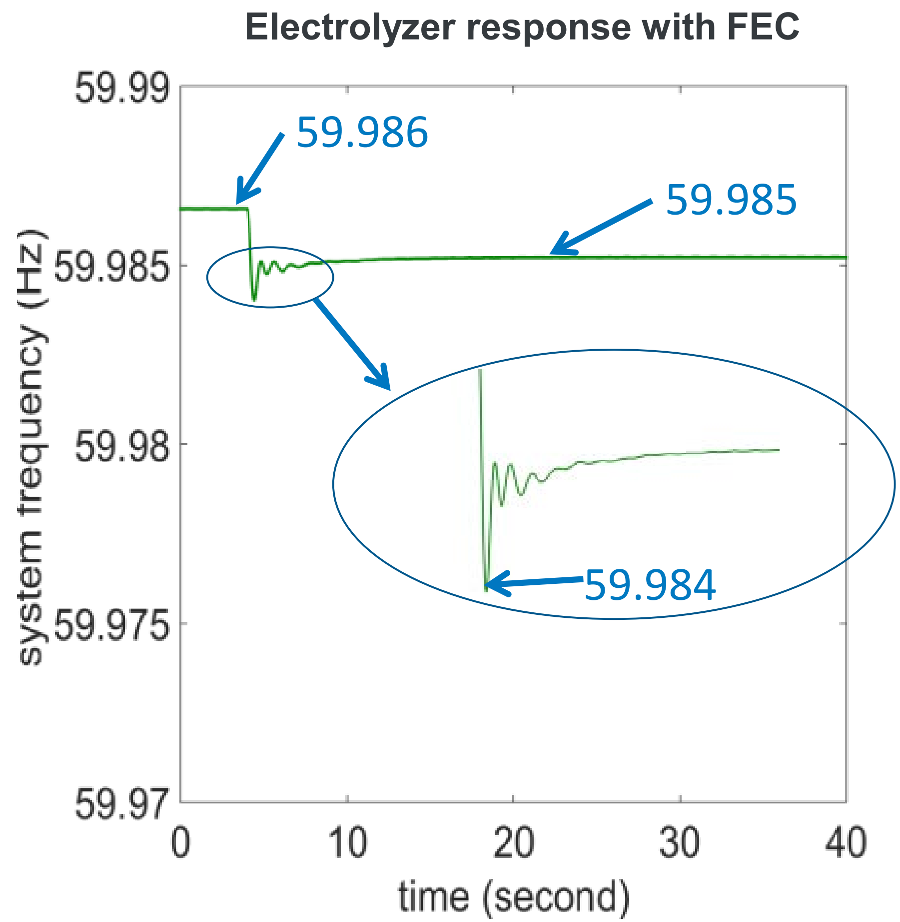
Accomplishments Frequency Support by Centralized Electrolysis

Electrolyzers controlled by FEC can enhance grid stability by limiting frequency excursions

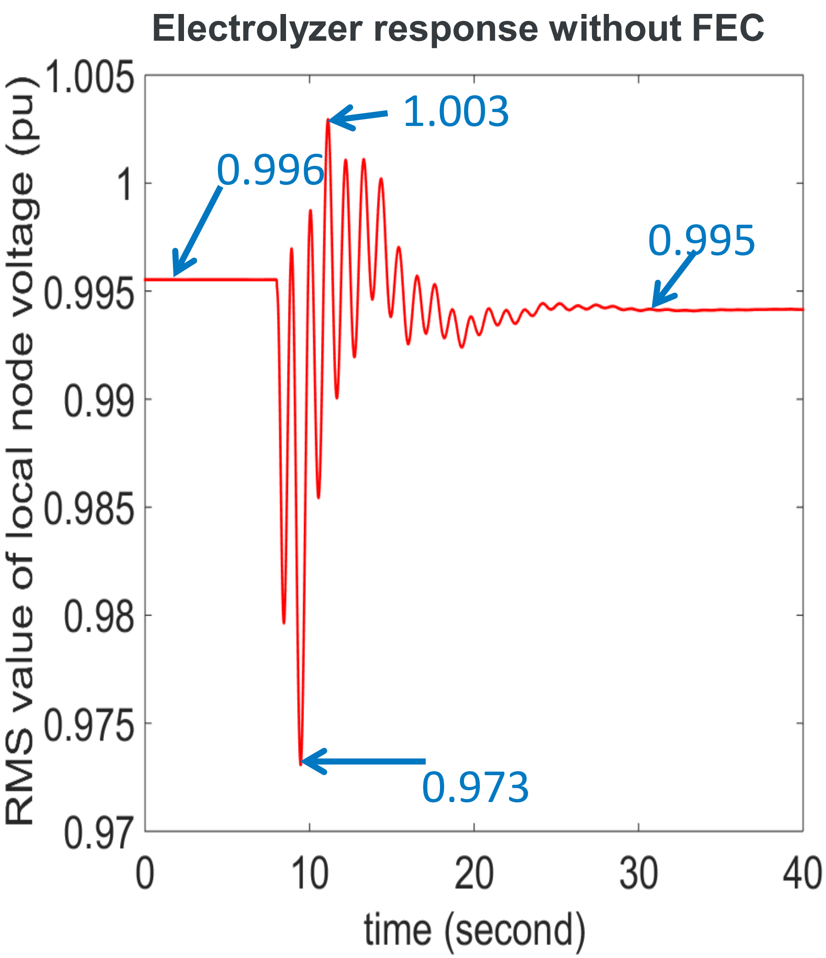


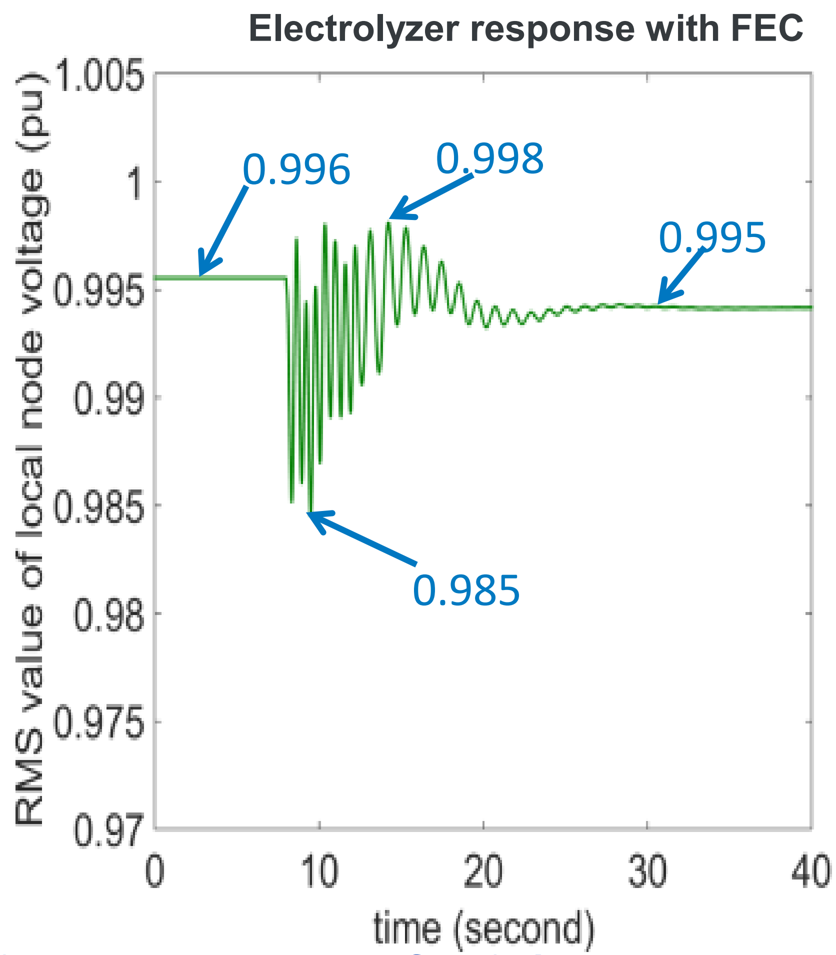


Fault location: Node 39; Fault: 3 phase balanced for 0.1 seconds; Electrolyzer location: Node 39

Accomplishments Voltage Support by Centralized Electrolysis

Electrolyzers controlled by FEC can enhance enhance grid stability by limiting voltage excursions





Fault location: Node 39; Fault: 3 phase balanced for 0.1 seconds; Electrolyzer location: Node 39

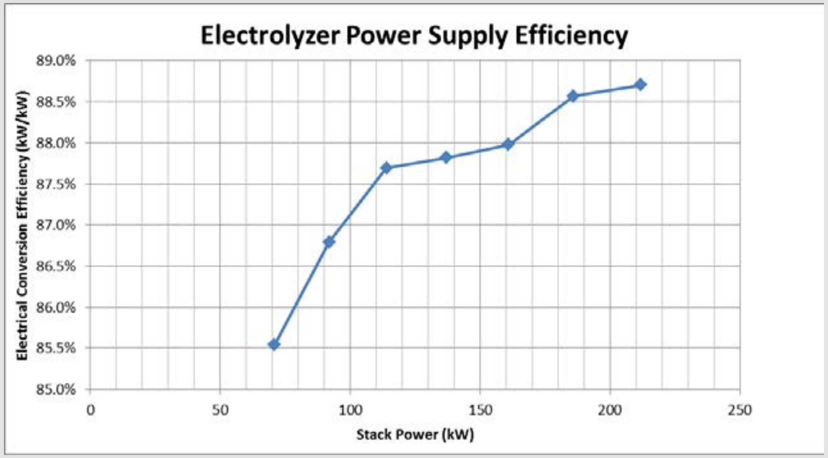
Accomplishments – Efficiency Measurements

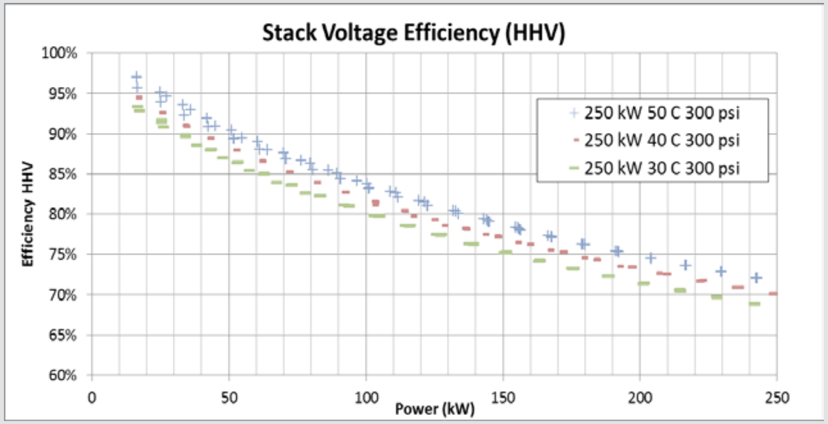
Power supply electric conversion and 250 kW stack voltage efficiencies quantified

- **Power meters used to measure power supply (aka rectifier) efficiency and stack production efficiency**
  - Power supply conversion efficiency greatly improves as power output increases
  - Stack production efficiency suffers as stack power consumption increases

- **Stack polarization curves measured and used to create efficiency plot**
  - Stack efficiency decreases as power increases and as temperature drops
  - Results can be used as an input to controller to maximize efficiency of stack operation

Baseline System Efficiencies

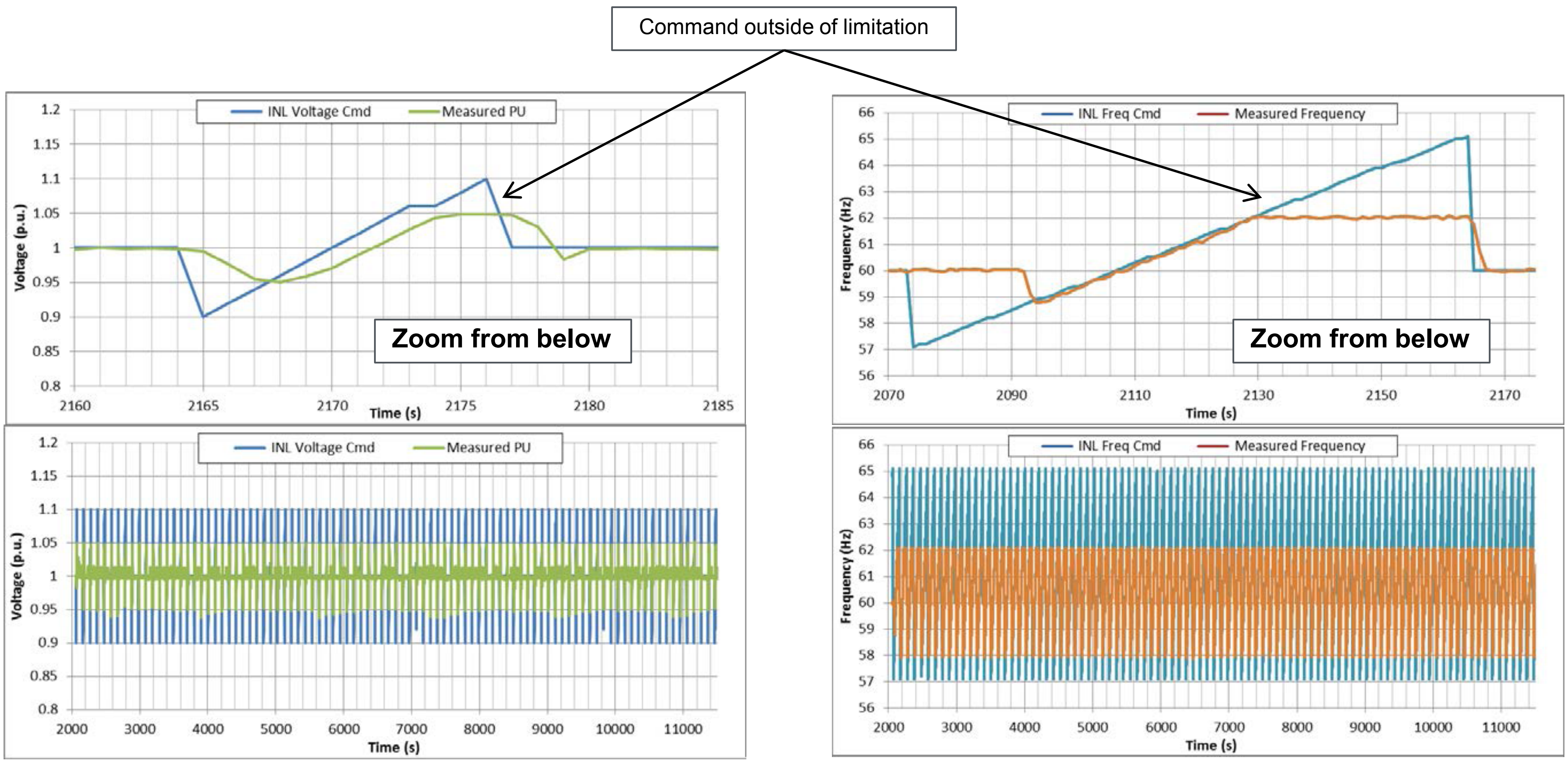




Accomplishments – Grid Simulator

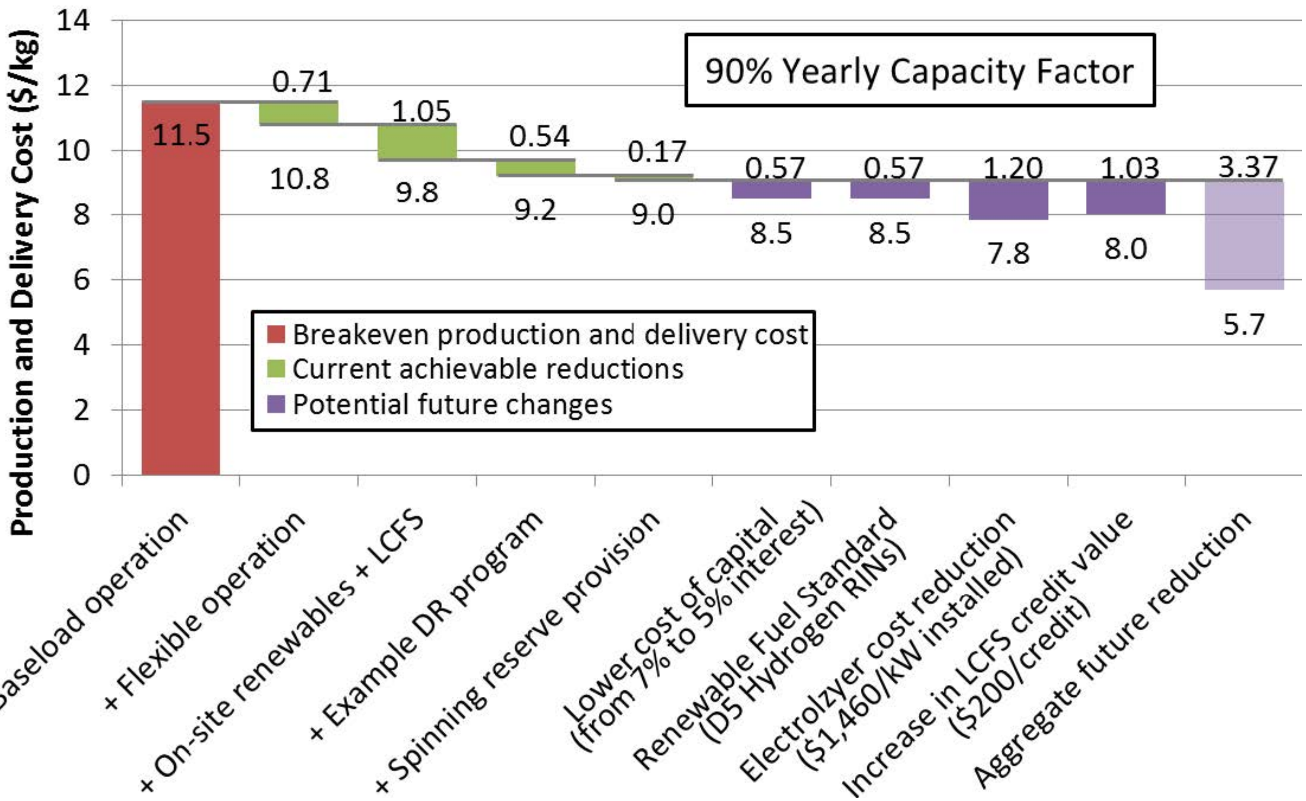
First use of grid simulator capability at ESIF to control the electrolyzer power supplies

- Demonstration of a major power hardware-in-the-loop capability for NREL
- Control via remote command from INL RTDS and safety limits verified



Accomplishment - California Business Case Analysis Summary

- Near-term business case opportunities for power-to-gas and power-to-hydrogen technologies in California were explored
  - Project Partners: California Air Resources Board and Department of Energy
- RODeO (Revenue Operation and Device Optimization Model) is used to maximize revenue and optimize equipment operation

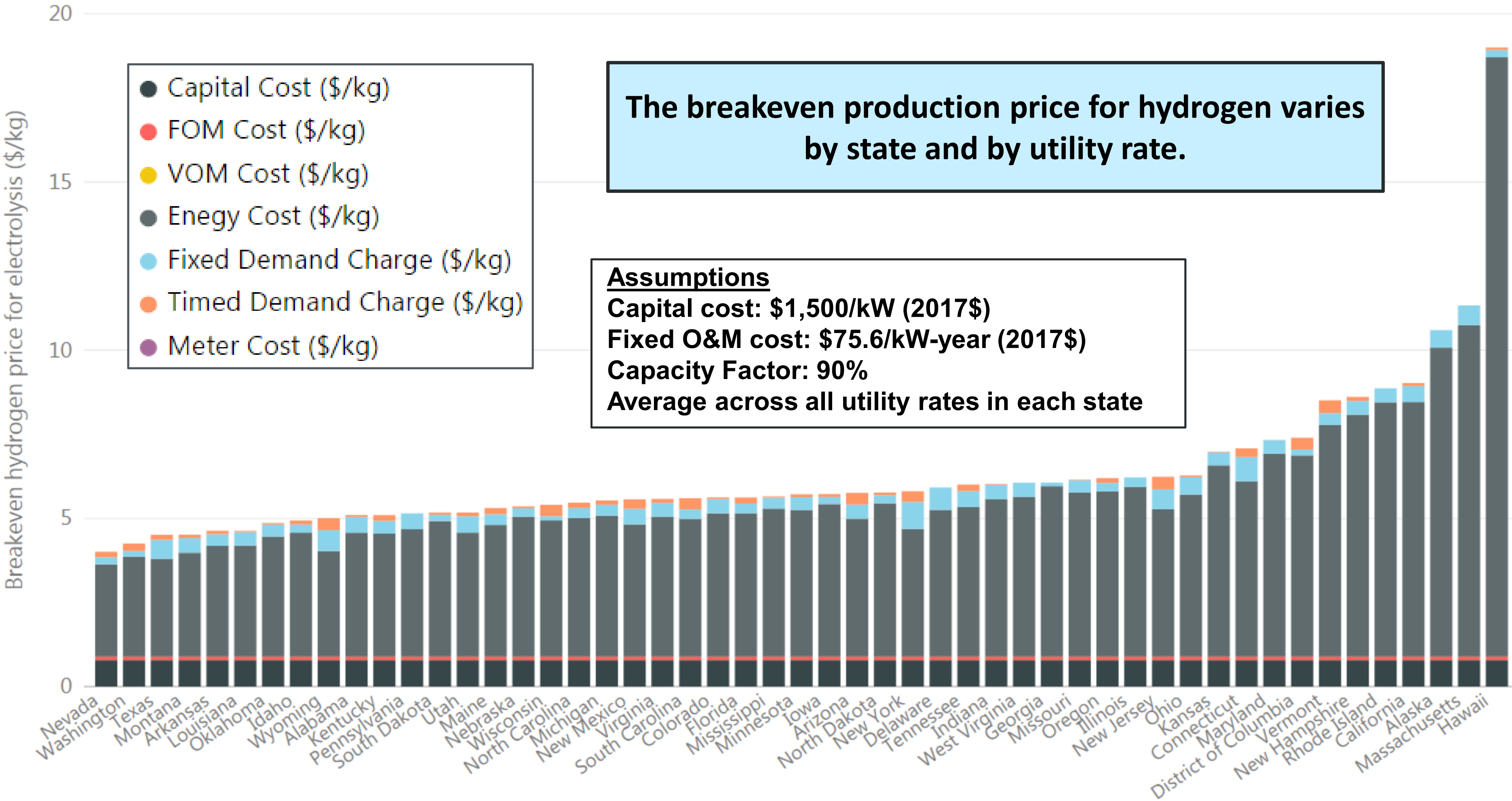


Better integration with the grid can reduce electrolyzer operation costs by up to 20% using current markets and rate structures within California.

Source: Eichman, J., Flores-Espino, F., (2016). www.nrel.gov/docs/fy17osti/67384.pdf

Accomplishment – Economic Benefit for each U.S. state

- Example result for retail utility rates across the U.S. using RODeO with the Utility Rate Database



AMR 2016 Feedback & Questions

- Review question: Are the response times of electrolyzer set points recorded on the cell level?
  - Response: No, the responses recorded and the whole project deals with the control of the electrolyzer stack plus the balance of plant
- Review question: The grid modeling approach is not associated with any specific grid system
  - Response: Disagree, the grid modeling emphasis and data is corresponding to the Bay Area, California i.e., Pacific Gas & Electric that has current and future plans of installing hydrogen refueling stations
- Review comment: The project should consider evaluating the impact that the subsystems supporting will have on response times. The project should determine whether the pumps, blowers, and valves spin up fast enough to match stack response time
  - Response: Subsystem characterization for both 120 kW and 250 kW stack were performed and presented at AMR 2016 and 2017, respectively

Collaborations

- Idaho National Laboratory and National Renewable Energy Laboratory
  - Prime and jointly funded project partner
  - Laboratory resources will be leveraged for research and development
- Utilities: PG&E, CAISO, Xcel Energy, EnerNOC
  - Real world and market information for direction in research
  - Actual data and system models for case studies, technology evaluation, and demonstrations
- Universities: Humboldt State University, Florida State University
  - Research partners for modeling, simulation, and information dissemination
- California Air Resources Board
  - CA power-to-gas business case evaluation

Remaining Challenges and Barriers

- **Challenge:** Hardware implementation of the FEC and its integration with the existing lower level controller of the electrolyzer
- **Mitigation:** As a de-risking process, the team is performing software model and hardware testing of the FEC in real-time at INL with the electrolyzer at NREL as a first step. After this functionality tests and integration tests at NREL with the FEC hardware and electrolyzer will are planned

Proposed Future Work

- Hardware implementation and integration of FEC with the electrolyzer stack at NREL
- Successful verification and validation of the FEC functionalities of providing grid services as requested
- Renewable energy integration and smoothing based on the controllability aspects of electrolyzer and the FEC
- Quantification of the value of hydrogen refueling stations in renewable integration
- Role of hydrogen refueling stations in grid stability, flexibility, and participating in various demand response scenarios

Any proposed future work is subject to change based on funding levels.

Technology Transfer Activities

- Technology Transfer Activities include
  - H2@Scale demo was performed to the hydrogen industry, academia, and DOE program office at NREL in November 2016
  - Industry webinar on the grid service capabilities of electrolyzer is scheduled in April 2017
  - Journal publications and report will be produced

Project Summary

- Verifying and validating the participation of electrolyzers (hydrogen refueling station) in providing grid services
- First of a kind, distributed real-time simulation with PHIL (electrolyzer) between INL and NREL
  - FEC and electrolyzer responding to grid signals and providing required services
  - Extensive 200 hours (FY 2016) and 300 hours (FY 2017) of testing completed
- Electrolyzer stack efficiency and hydrogen quality is ensured to be acceptable during the whole project
- Improved transient stability observed under grid fault conditions verified with PHIL
- Hardware realization of FEC and its integration with the electrolyzer stack is under progress
- **Contributes directly to the DOE Milestone 3.9 related to Systems Analysis & Technology Validation**
  - [From MYRDD 3.9] *Validate large-scale system for grid energy storage that integrates renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40%. (4Q, 2020)*

Discussion

Technical Back-Up Slides

Acronyms

- RTDS = Real-Time Digital Simulator
- LT = Low Temperature
- DR = Demand Response
- ESIF = Energy Systems Integration Facility
- NWTC = National Wind Test Center
- BOP = Balance of Plant
- AC = Alternating current
- DC = Direct current
- FCEV = Fuel Cell Electric Vehicle
- V, f = voltage, frequency
- FEC = Front End Controller
- REDB = Research Electrical Distribution Bus

Approach - Grid Simulator Connection

- **Power supplies do NOT protect themselves on over/under frequency & voltage**
  - NREL self-prescribed power supply limits
    - 59 to 61 Hz, 480V ± 5%
- **Using front panel controls of power supplies**
  - Validate frequency and voltage limits keep power to the stack
- **NREL RTDS generates (3) ± 10V AC waveforms to drive grid simulators (Ametek RS270)**
  - Frequency and voltage controlled and limited at the RTDS
  - Grid simulators also have hardware limits

Equipment	Location	Power Rating	Voltage Rating	Frequency Rating	Current Rating
Ametek RS270 Grid Simulator (Quads #3)	AC REDB ROOM	270 kW	400/690 V_{rms}	16-400 Hz	600 A_{AC} @ 480V_{AC}

Accomplishment – Hardware based Testing

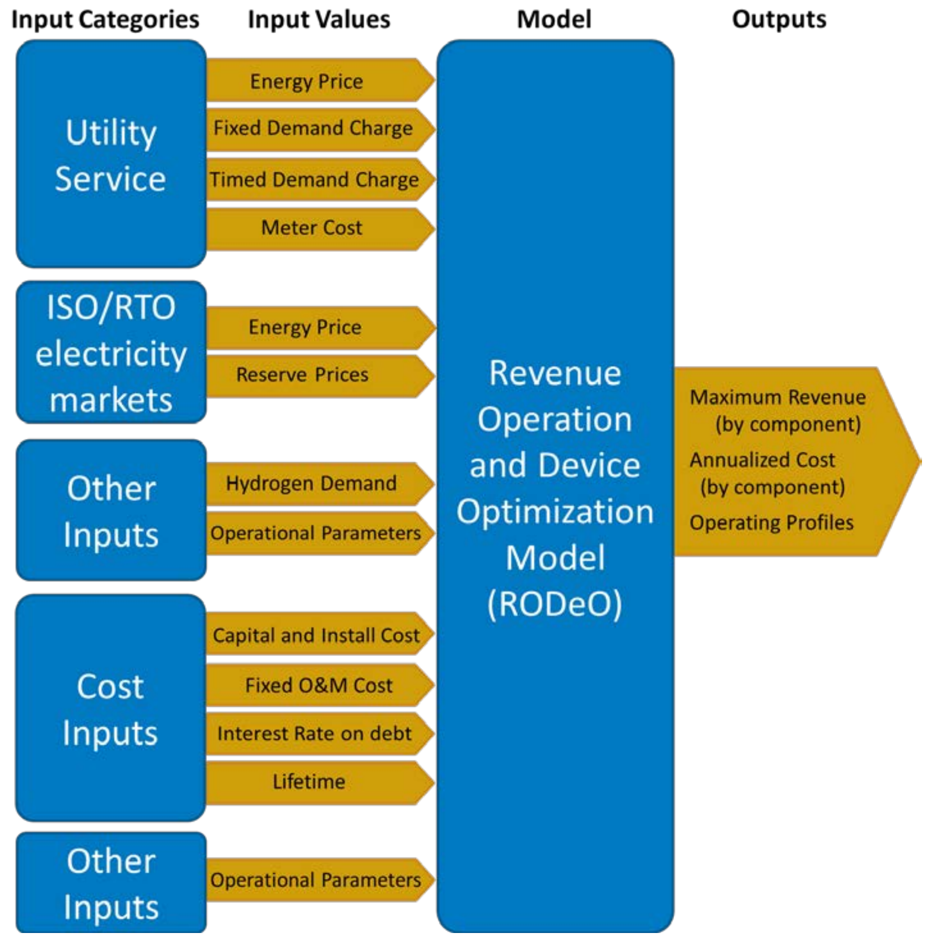
- Status (M2): 250-kW PHIL system operation time 300 hours (March 2017)

PHIL validated system (includes BOP) performance of response time, turn-down capability, and controllability for integrated grid and electrolyzer operation.

Serial no.	Test Title	Completed Hours
1	Stack Characterization	10
2	Variable electrolyzer balance of plant (BOP) operation	15
3	Power Converter Characterization	5
4	Grid Model Testing	50
5	FEC Model Testing	140
6	FEC Hardware Testing	80
7	FEC ARM Board Testing	0
	Total Hours Completed	300

Accomplishment – Economic Benefit

- Status (M3): (March 2017)
  - Flexibly operating electrolyzers provides grid flexibility while also reducing costs for electrolysis systems.
    - The RODeO (Revenue Operation and Device Optimization Model) is used to maximize revenue and optimize equipment operation
  - Greater integration with the electricity system and electricity markets enables greater revenues
    - Demand response devices need to be able to participate more completely in electricity markets (i.e., wholesale energy and ancillary service markets)



Optimization modeling is used to determine the economic competitiveness for grid integrated electrolysis equipment

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Thank you