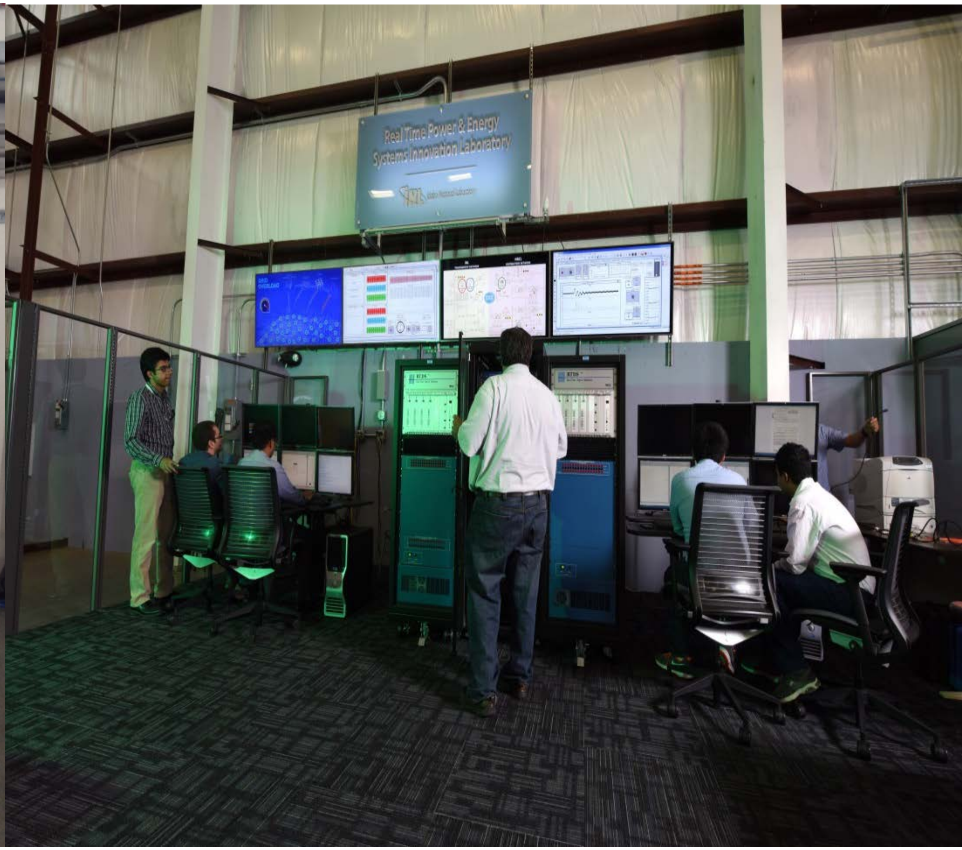
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Idaho National Laboratory



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

June 13, 2018

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Overview

Timeline

- **Project start date: 06/01/15**
- **Project end date: 09/30/18**

Budget

Total project budget: $3,890K

Total recipient share: $2,100K+ (INL), $1690K(NREL), $100K (SNL)

Total federal share: $3,890K

Total DOE funds spent*: $3,407K

* As of 4/30/18

Barriers

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

Partners

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

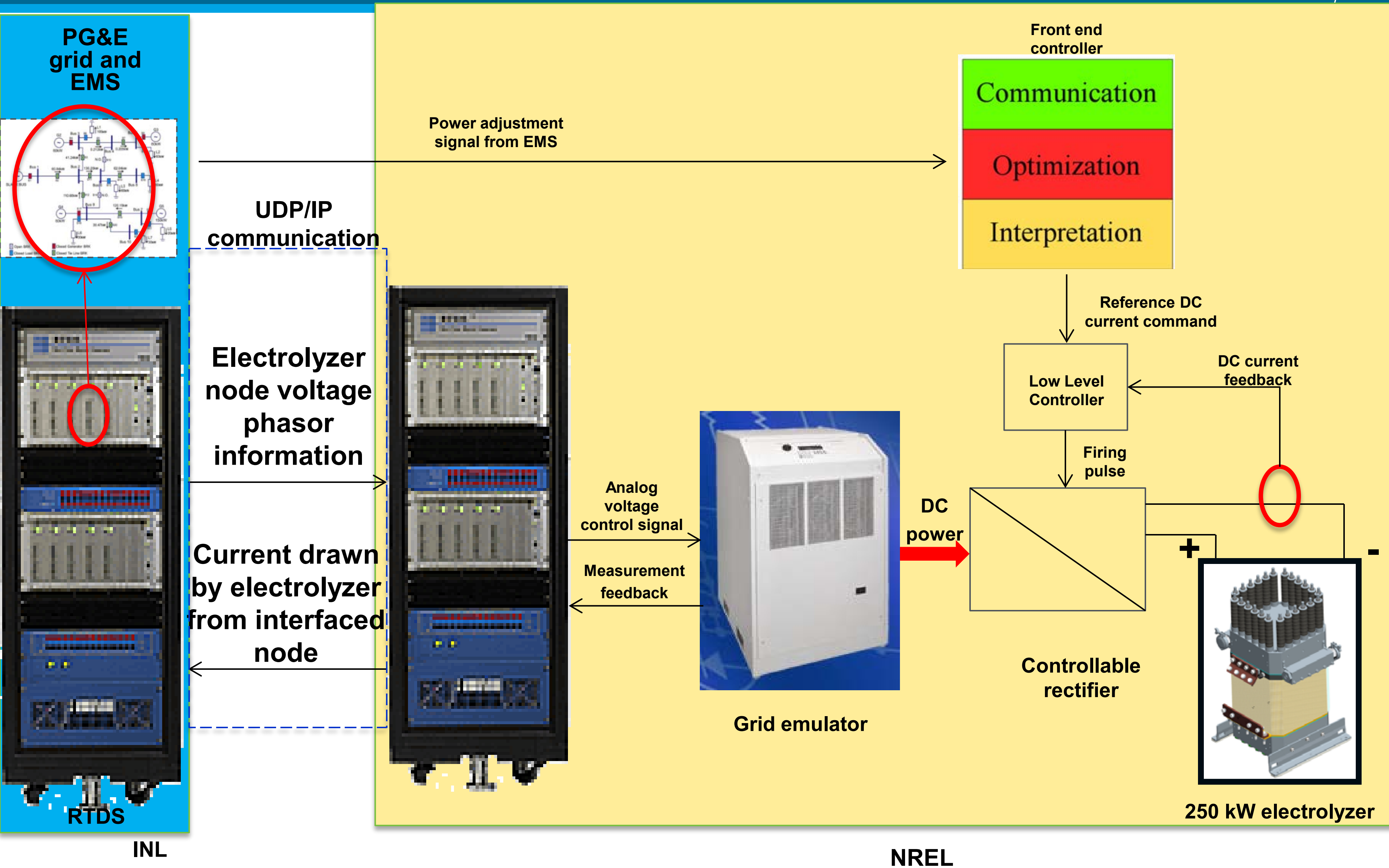
Relevance & Objective

- 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 coordinated with renewable energy through grid services and hydrogen sale to fuel cell vehicles
  - 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
  - Role of hydrogen refueling station in grid stability and inertia addition in cases of increased renewable energy penetration and de-commissioning of thermal power plants
  - Optimization of renewable energy generation and controllable loads i.e., hydrogen refueling stations based on spatial and temporal scales

Project Overview - Summary

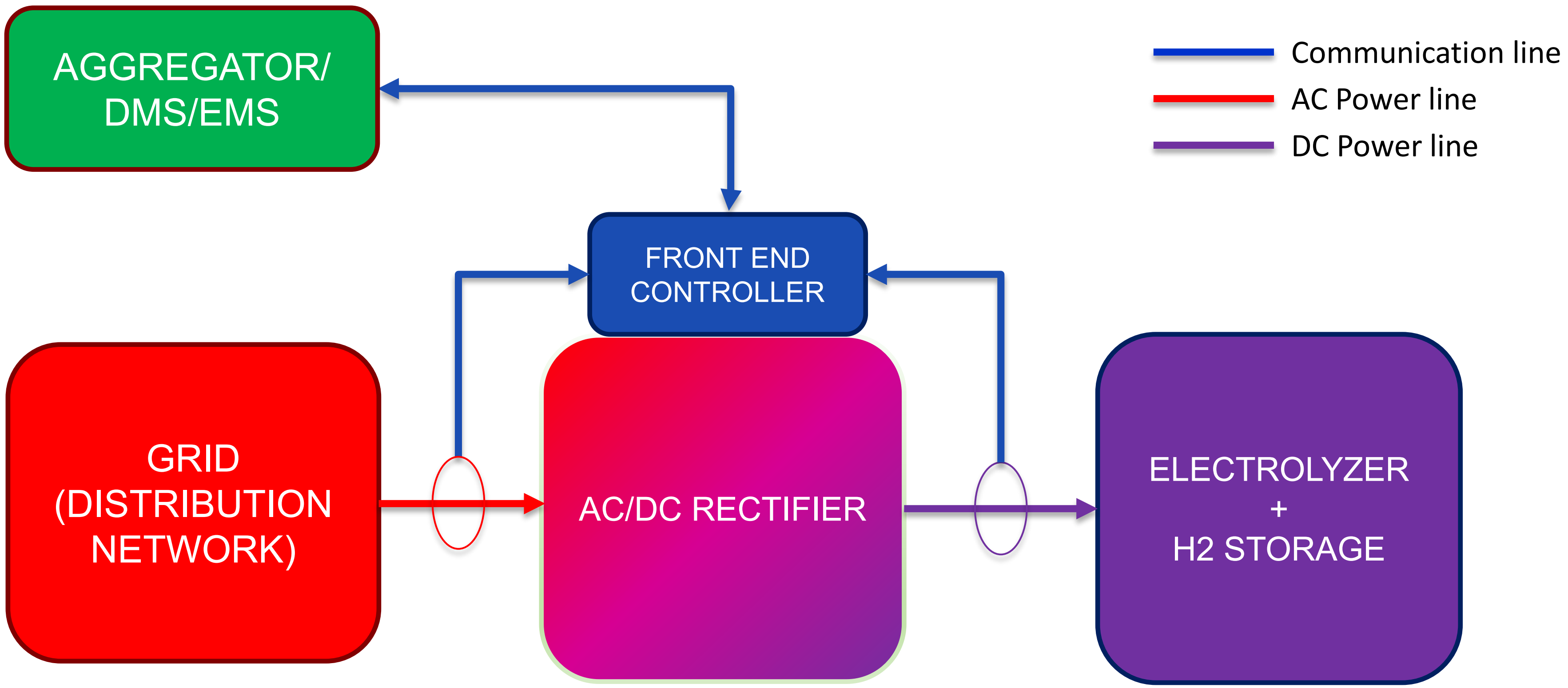
- Challenges from energy systems perspective
  - High penetration of renewable energy from highly variable generators connected over power converters does not necessarily match demand
  - Several energy storage technologies are being evaluated but suffer from limitations
  - Need of localized, economic, and reliable energy storage such as hydrogen
- Near-term RD&D challenges for the demonstration of electrolyzers in H2@Scale are
  - A lack of data to support deployment decisions by industry,
  - Advanced controls and communication network,
  - Impact of H2@Scale demand on long-term system durability,
  - Integrated system specifications and equipment capabilities, and
  - Impact of multi-MW-scale electrolysis for grid stability and renewable generation

Hardware Testbed Configuration



Approach - Conceptual Diagram

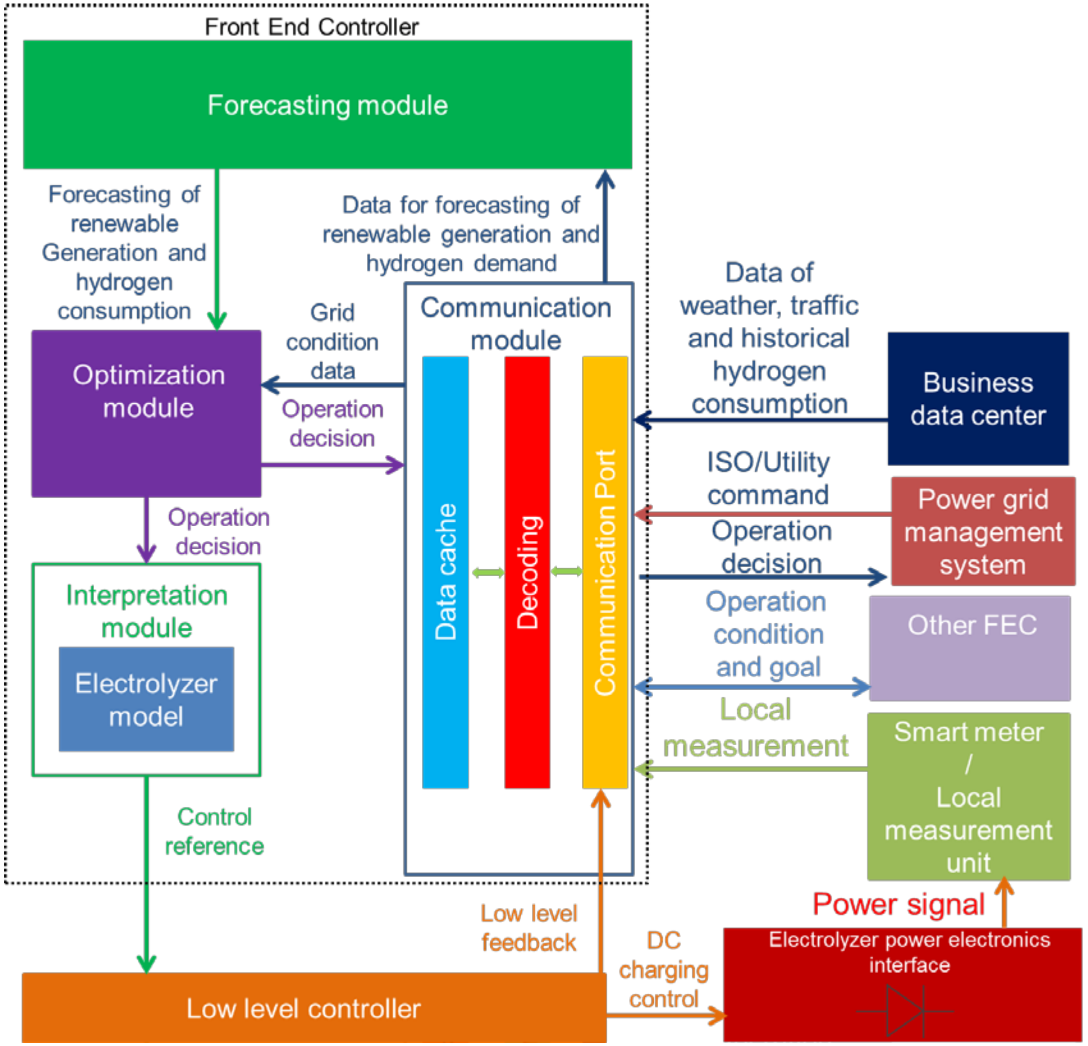
The project combines modeling, simulation, and hardware for the validation of system performance and to quantify economic benefit based on different operation scenarios relevant to utilities



Approach - Front End Controller (DRAFT)

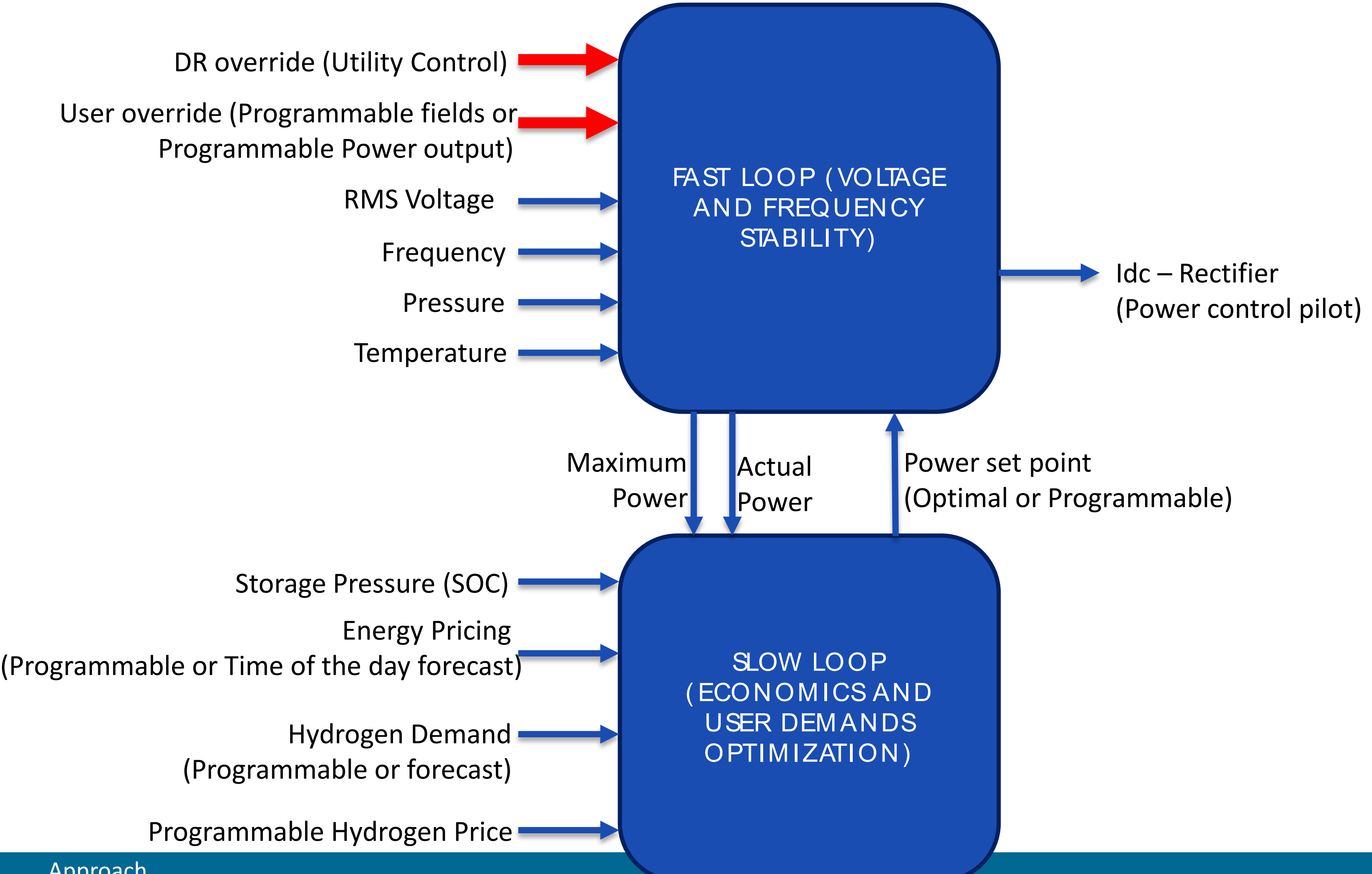
Front End Controller to support the grid signals and renewable energy penetration

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
4. **Forecasting module** forecasts the relevant renewable energy penetration and hydrogen demand that needs to be met by the hydrogen refueling station



Approach - FEC Inputs/Outputs (DRAFT)

Front End Controller adds greater 'awareness' and hence 'better response'

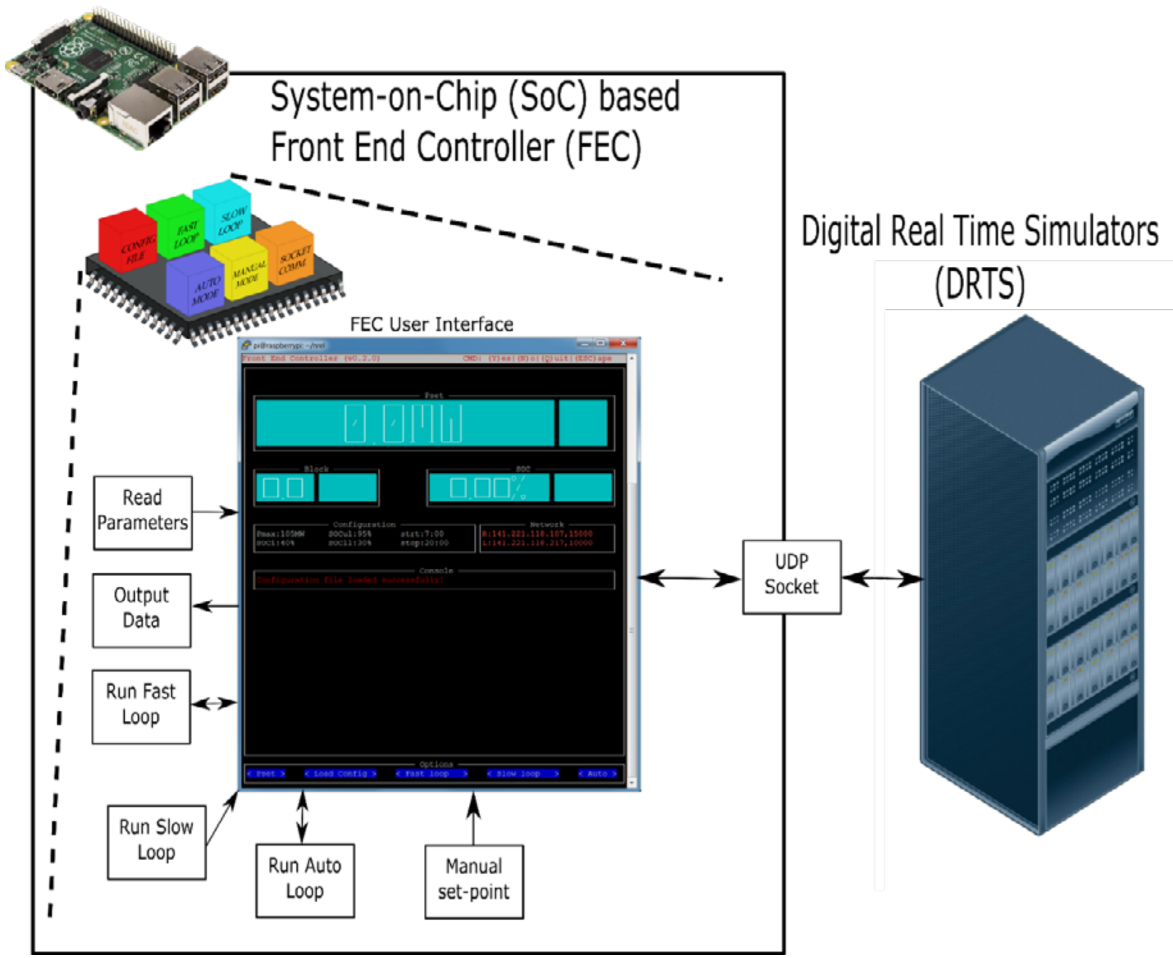


Approach – FEC Hardware Implementation

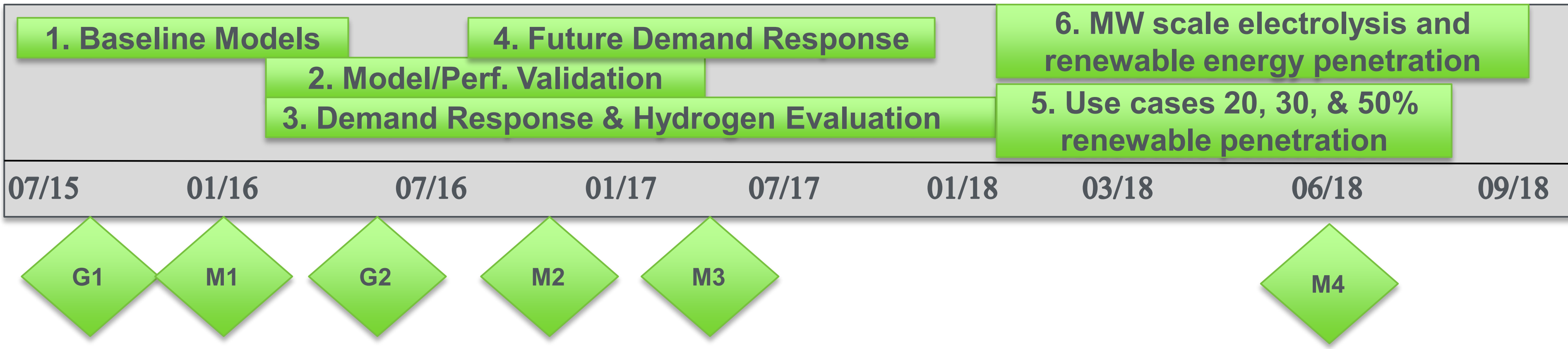
Front End Controller implemented as a hardware and deployed at NREL

Salient Features:

- Processor board implementation of FEC completed and deployed at NREL
- Friendly Graphical User Interface
- Read inputs to set network parameters
- Optimization parameters for slow loop can be edited
- Set manual power set-points on the fly to accommodate unusual high demands



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



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	Completed
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
M4	Integrate and demonstrate increased renewable energy penetration (20, 30, and 50%) with MW-scale electrolyzers based on utility data and real-world conditions.	June 2018	25%
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

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 (100%)
D9	Final project report summarizing – 'Role of Hydrogen Refueling Stations in Demand Response and Grid Services.'	September 2017 (90%)
D10	Integrate and demonstrate increased renewable energy penetration (20, 30, and 50%) with MW-scale electrolyzers based on utility data and real-world conditions.	July 2018 (40%)
M4	Testing DR programs that optimize the revenue generated from participating in DR programs by a minimum of 10%	March 2018

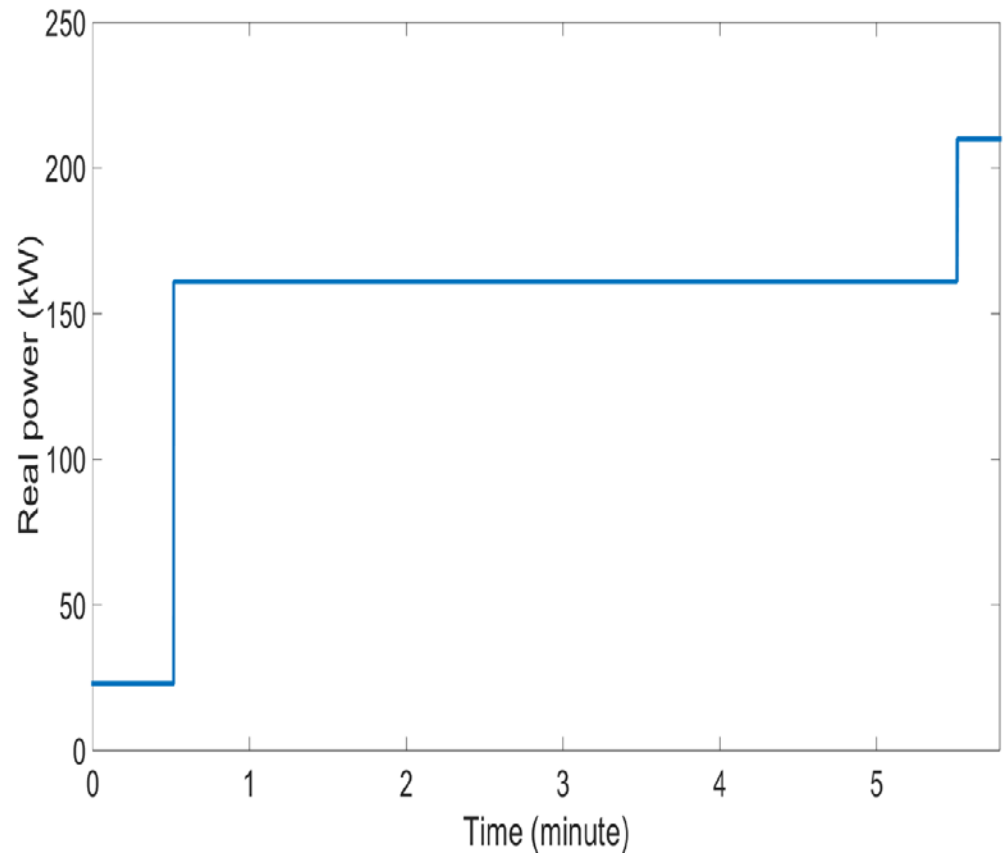
Summary of Accomplishments

- 200 Hour testing
  - 120 kW electrolyzer stack and balance of plant testing for understanding controllability
  - Sub-second level control of the electrolyzer stack with efficiency > 60%
- 500 Hour testing
  - Design, verification, and validation of the FEC as a software and hardware
  - Transient stability and voltage support by hydrogen refueling stations
- Controller Hardware in the Loop Testing of the FEC at NREL with the LT electrolyzer stack
  - Processor based (hardware) realization of the FEC deployed at NREL
  - Unit and functionality testing of the FEC completed
- Economic assessments of utility rates and hydrogen production
  - The hydrogen production cost is below $4/kg for 81 utility rates across 20 states

Accomplishments - Slow Loop Testing of the FEC Hardware

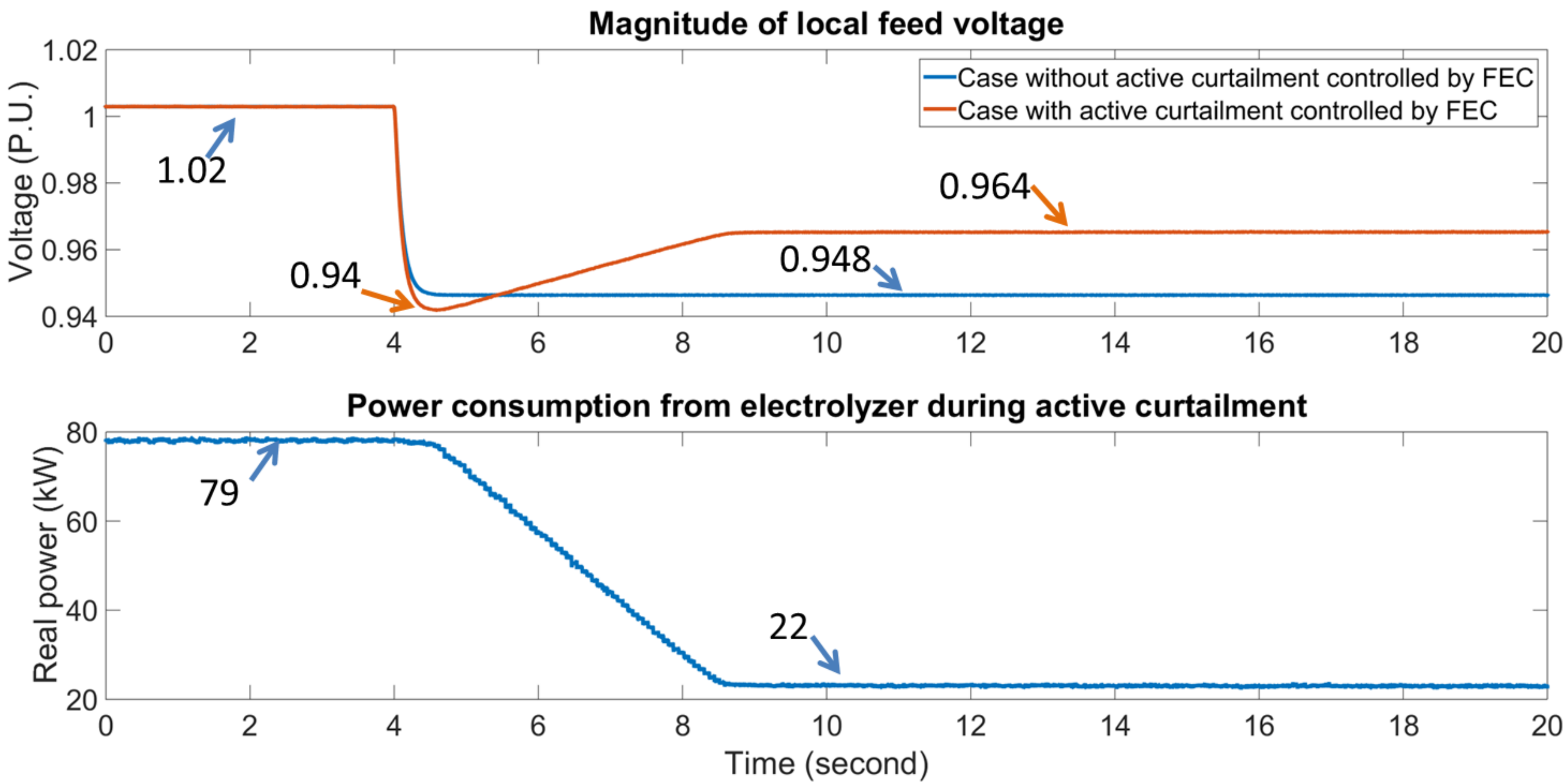
Slow loop ensures that availability of hydrogen along with multiple revenue streams

- PHIL Validation of Innovative System Integration Performance
- For the slow loop test, current storage and future demand forecasting of hydrogen are sent to FEC
- In peak hour, when hydrogen consumption is forecast to increase, FEC increases hydrogen production command with proper amount so that the demand is satisfied and the cost of hydrogen production is minimized.



Accomplishments - Fast Loop Testing of the FEC Hardware

- PHIL Validation of Innovative System Integration Performance
- 100 KW load is added to an IEEE 34 system - local feeder voltage deviation can be reduced from 5% to 3.5%



Accomplishments – Distribution Level Modeling for renewable assimilation

Southern California power grid representation for solar and hydrogen modeling

- Distribution level model developed in OpenDSS using real utility data layout and load data from SDGE
- Electrolyzer and PV sited throughout the feeder
- Evaluating impacts of co-location and relative sizing
- PV will be sized to 20, 30, and 50% penetration levels

Accomplishment – Hydrogen cost for retail rates across the U.S. state

- Production cost of hydrogen for 7,182 retail rates in the U.S.

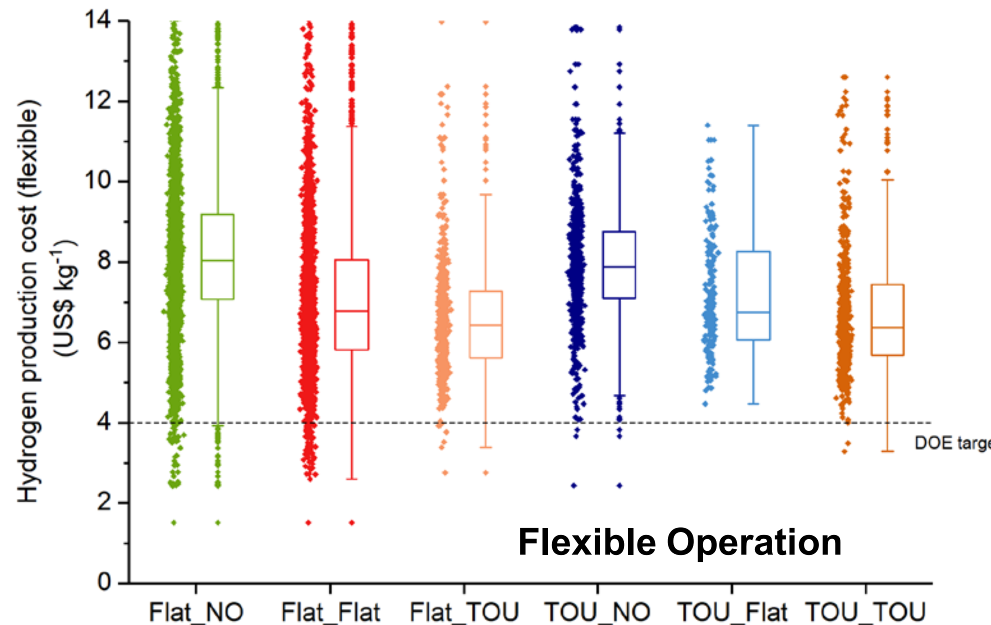
Electricity cost = energy charge + demand charge

Energy charge	Demand charge
Based on quantity of energy consumed during a single interval, i.e., kWh	Based on the maximum demand that occurs during a billing period

Three basic structures for energy and demand tariffs: NO, Flat, and TOU.

- NO: no charge for either energy or demand.
- Flat: single constant charge for electricity during each billing period
- TOU: any form of dynamic pricing for energy or demand (time-of-use).

Example: Flat_TOU = Flat charge for energy & TOU charge for demand.



Analysis Assumptions

Capital cost: $1,691/kW	H2 storage capital cost: $1000/kg	Efficiency: 54.3kWh/kg
Fixed O&M cost: $75.2/kW-yr	Lifetime: 20 yrs & Interest rate: 7%	Minimum part load: 10%
Replacement cost: $18.64/kW-yr	Capacity factor: 90%	Storage duration: 8 h

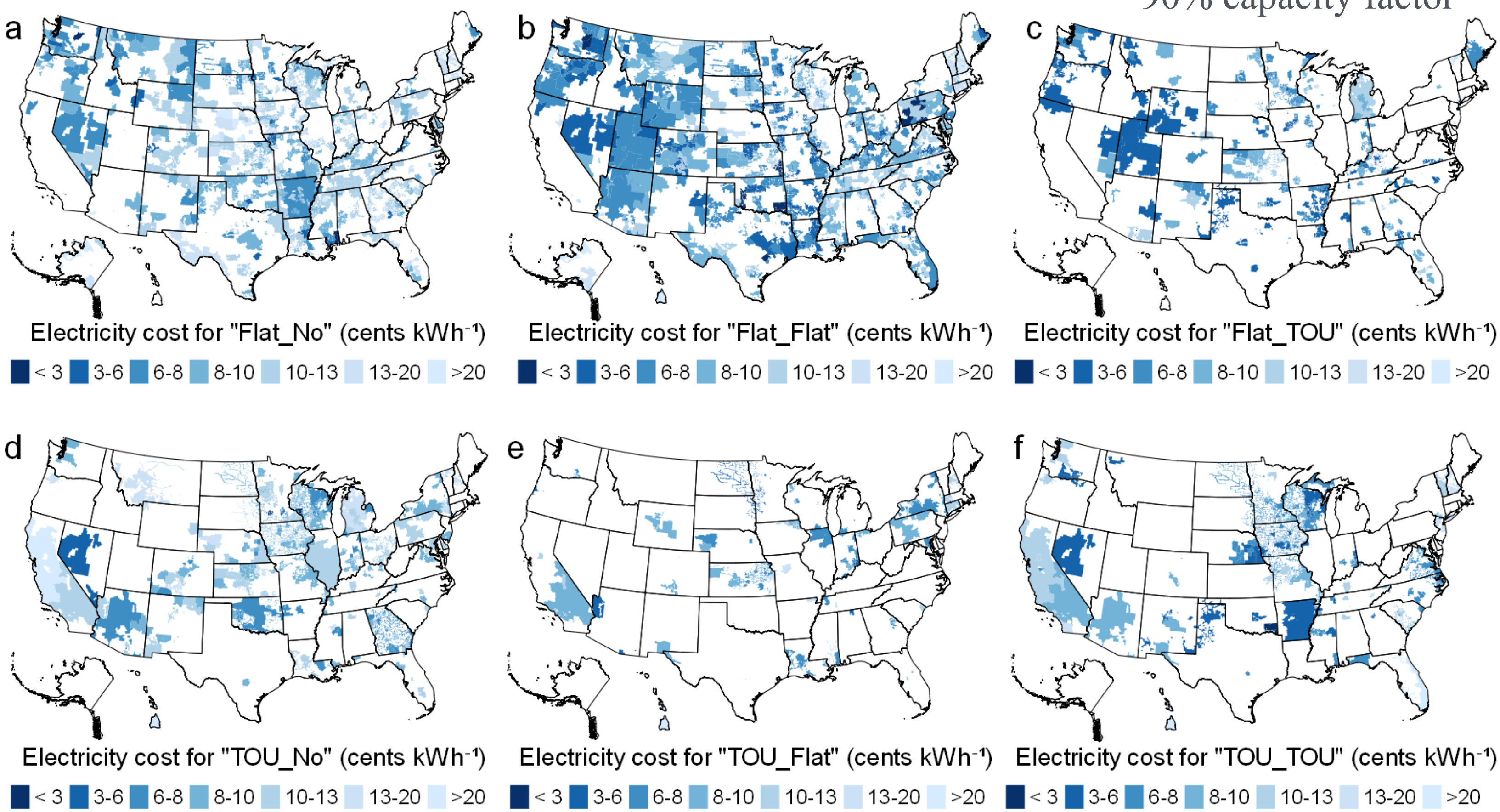
The hydrogen production cost is below $4/kg for 81 utility rates across 20 states

Flexible electrolyzer operation reduces cost on retail rates by up to 14%

Accomplishment – Economic Benefit for each U.S. state

- Combined electricity cost (energy+demand) to produce hydrogen

90% capacity factor



The electricity cost to produce hydrogen varies significantly across the U.S. and depends heavily on the rate structure

AMR 2017 Feedback & Questions

- **Weakness:** The only weakness is that the project approach allows only for evaluation of the possibilities provided by present-day electrolyzer technology. Electrolyzer hardware is rapidly evolving, and there are expectations for significantly greater operational capabilities in the not-too-distant future
- **Response:** we agree, however for hardware based evaluations such as the ones presented here, existing electrolyers can be evaluated. However, future technologies can also be evaluated using model-based approaches
- **Weakness:** The project has not fully demonstrated that the BOP response time will be acceptable
- **Response:** we disagree, the whole project results and presentation is not limited to stack response but the entire plant

Collaborations

- Idaho National Laboratory, National Renewable Energy Laboratory, and Sandia National 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 with renewable energy assimilation 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
- **Challenge:** Real-world data representing electrical data and renewable energy with hydrogen refueling stations providing energy storage and services
- **Mitigation:** Real-world information and data from a diverse set of sources is being integrated to mitigate along with utility contacts are being harnessed

Proposed Future Work

- A total of three sites with diverse conditions of renewable energy and hydrogen refueling stations will be considered
- Varying renewable energy penetration 20, 30, & 50 % will be studied at the sites selected
- Real-time modeling and assessment of hydrogen providing energy storage to assimilate renewable energy
- Enhancement of FEC (existing technology) to enable the assimilation along with hardware implementation
- Controller-Hardware-In-the-Loop (CHIL) testing using the real-time models with the LT electrolyzer stack as Power–Hardware-In-the-Loop for verification and validation

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

Project Summary

- First of a kind, distributed real-time simulation with PHIL (electrolyzer) between INL and NREL
  - Demonstrated electrolyzer including balance of plant (balance of plant) response to be within sub-second to support grid services
  - Voltage and frequency response obtained using PHIL
  - 250 hours of hardware operation was used to demonstrate the grid services
- A FEC (software and hardware) and its integration with the electrolyzer stack is completed and successfully deployed to facilitate grid services interaction
  - 500 hours of FEC functionality testing and demonstration was completed
  - Hardware FEC is deployed at NREL to operate the LT electrolyzer stack and balance of plant
- Leveraged to demonstrate the assimilation of higher renewable energy penetration under real world conditions
  - Demonstrate the value of electrolyzer to provide short (subseconds) and long term storage (hours/days)
- **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

(Include this "separator" slide if you are including back-up technical slides **[maximum of five]**. These back-up technical slides will be available for your presentation and will be included in the electronic media and Web PDF files released to the public.)

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.

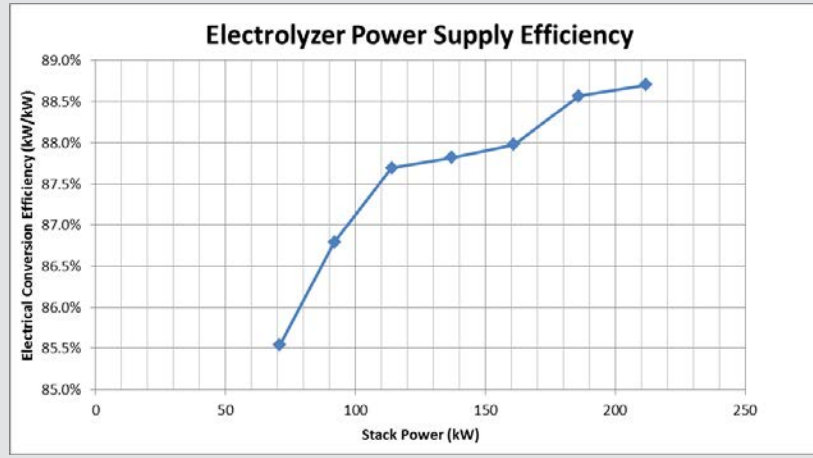
Serial no.	Test Title	Completed Hours
1	Stack Characterization	10
2	Variable electrolyzer balance of plant (BOP) operation	15
3	Power Converter Characterization	5
4	Grid Model Testing	50
5	FEC Model Testing	140
6	FEC Hardware Testing	80
7	FEC ARM Board Testing	0
	Total Hours Completed	300

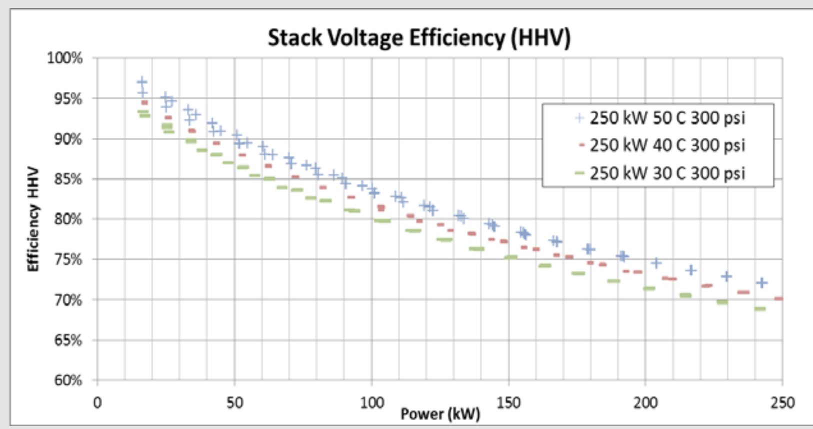
Accomplishments – Efficiency Measurements

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

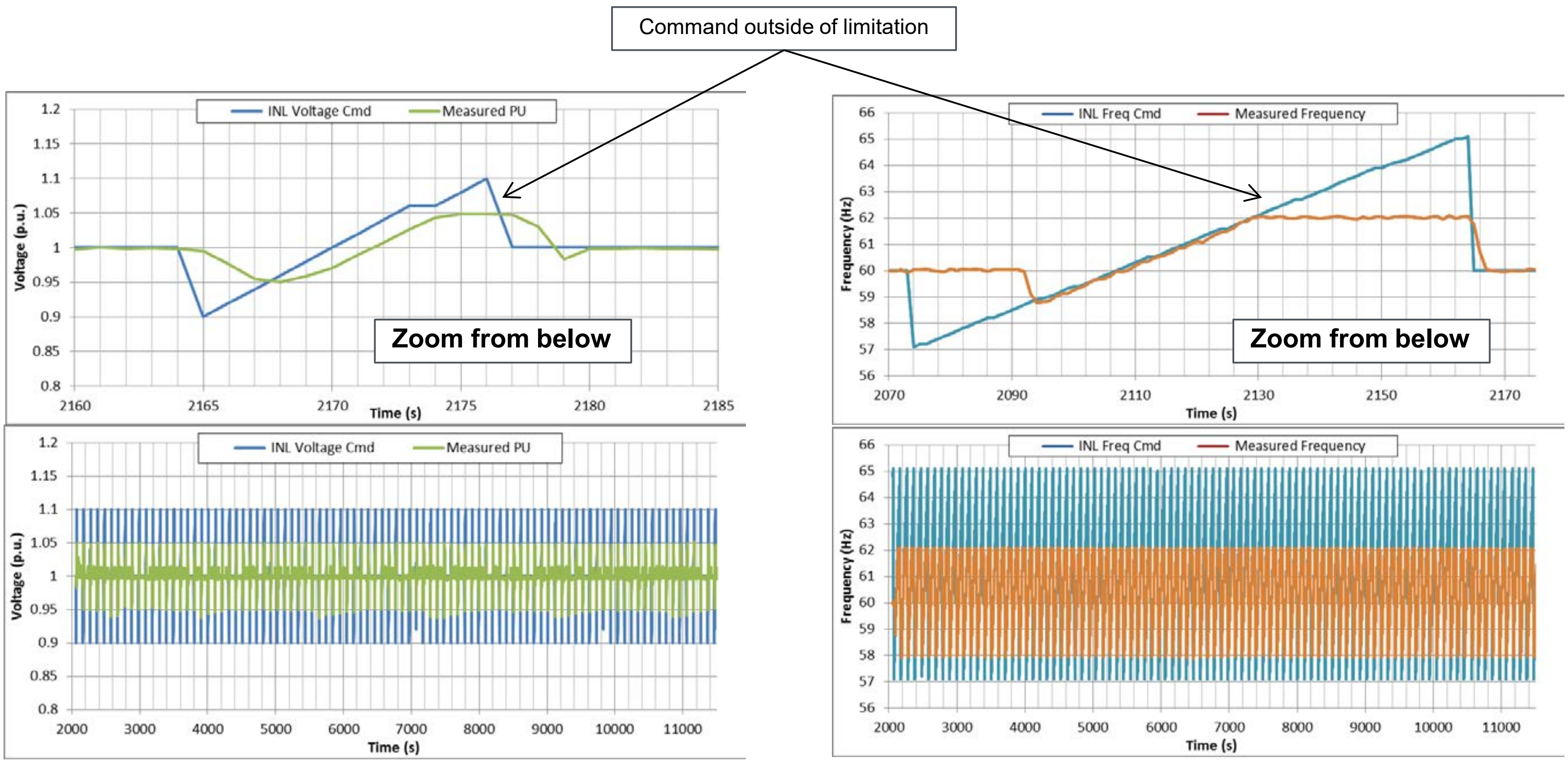




Accomplishments – Grid Simulator

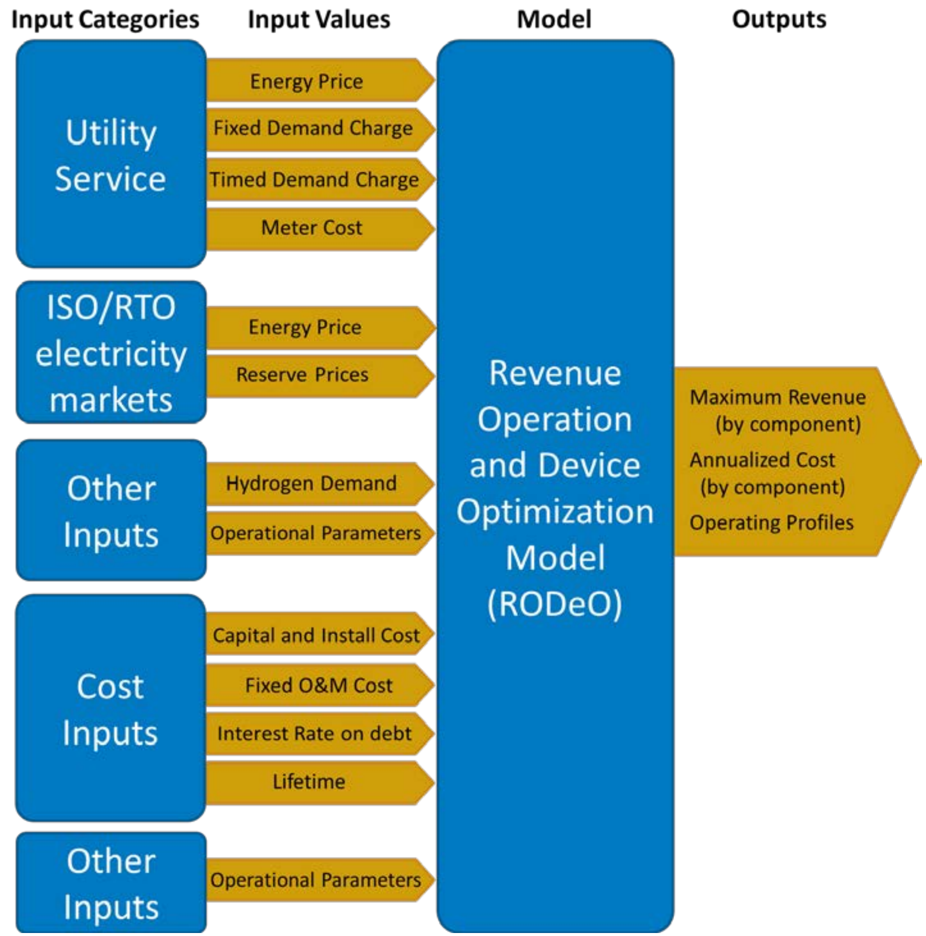
First use of grid simulator capability at ESIF to control the electrolyzer power supplies

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



Accomplishment – 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