NREL NATIONAL RENEWABLE ENERGY LABORATORY

Sandia National Laboratories

INL Idaho National Laboratory

Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TA015

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Overview

Timeline

- **Project start date: 06/01/15**
- **Project end date: 09/30/19**

Budget

Total project budget: $5,740K

Total recipient share: $3,250K (INL), $2,290K(NREL), $200K (SNL)

Total federal share: $5,740K

Total DOE funds spent*: $4,394K

* As of 3/25/19

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, Idaho Falls Power, Santa Fe
  - Academic: Humboldt State University, Florida State University

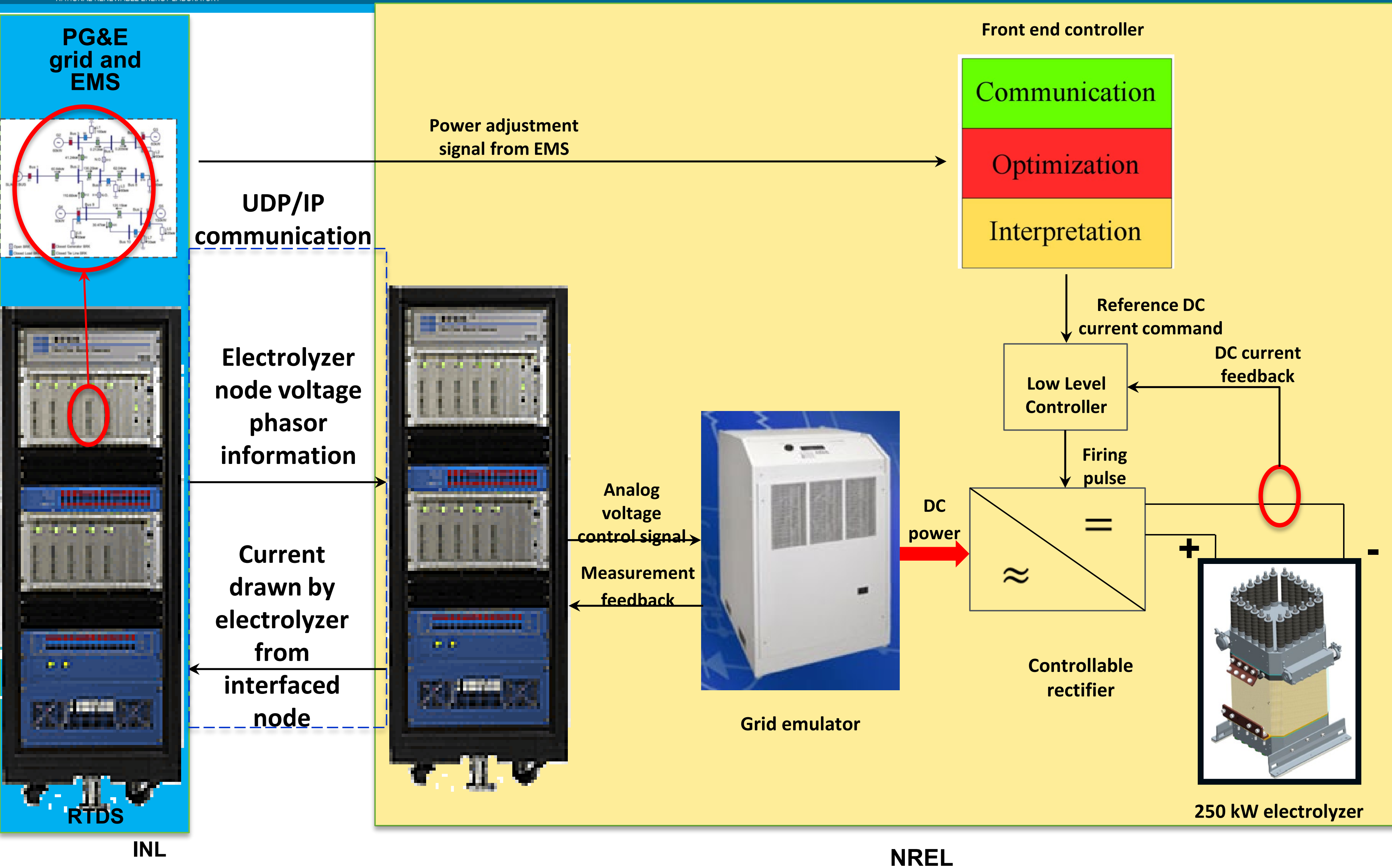
Relevance & Objective

- 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 with baseload nuclear and intermittent renewables on the grid.
  - Demonstrate the potential for mitigating voltage disturbances by at least 30% with electrolyzers versus no electrolyzers.
  - 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

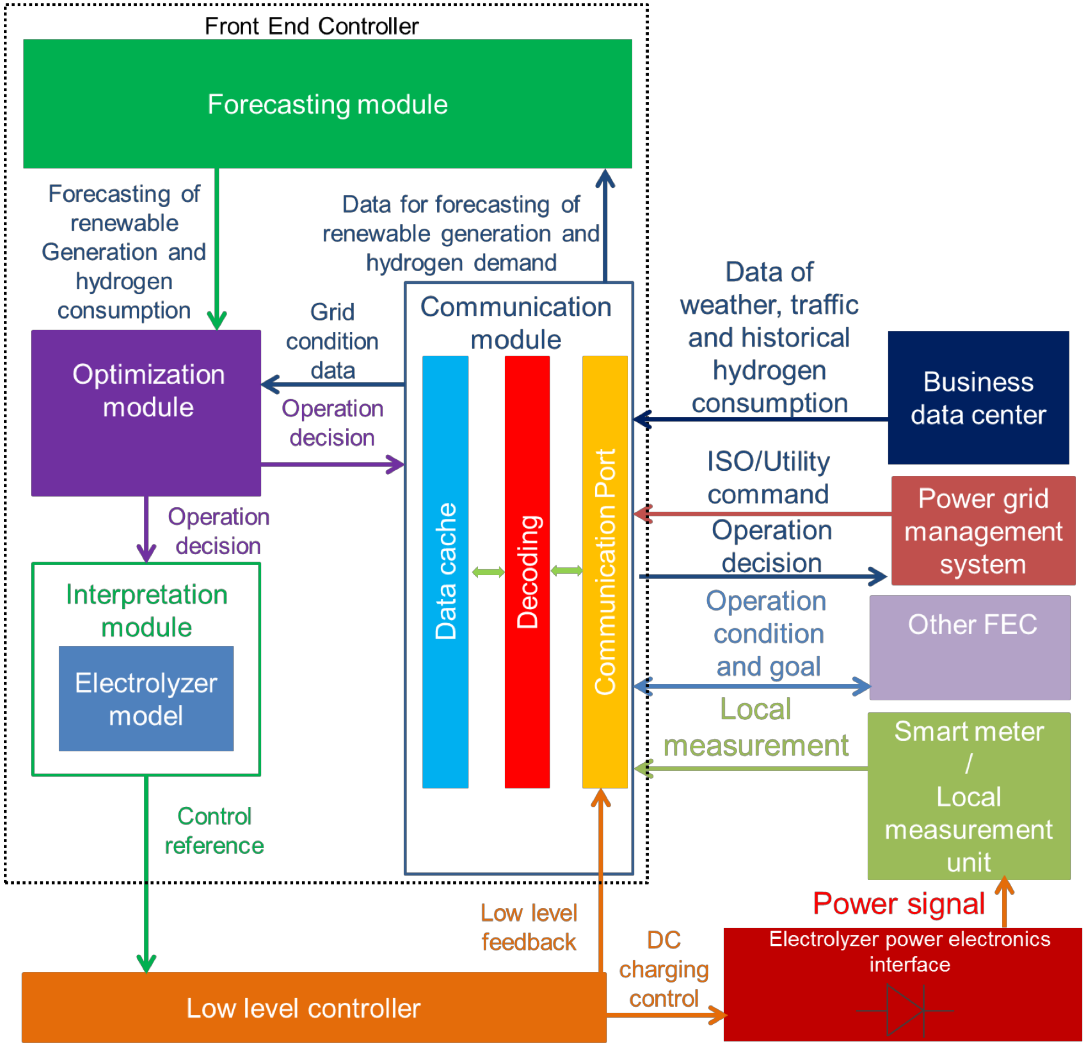
Hardware Testbed Configuration



Approach - Front End Controller (Smart Converters)

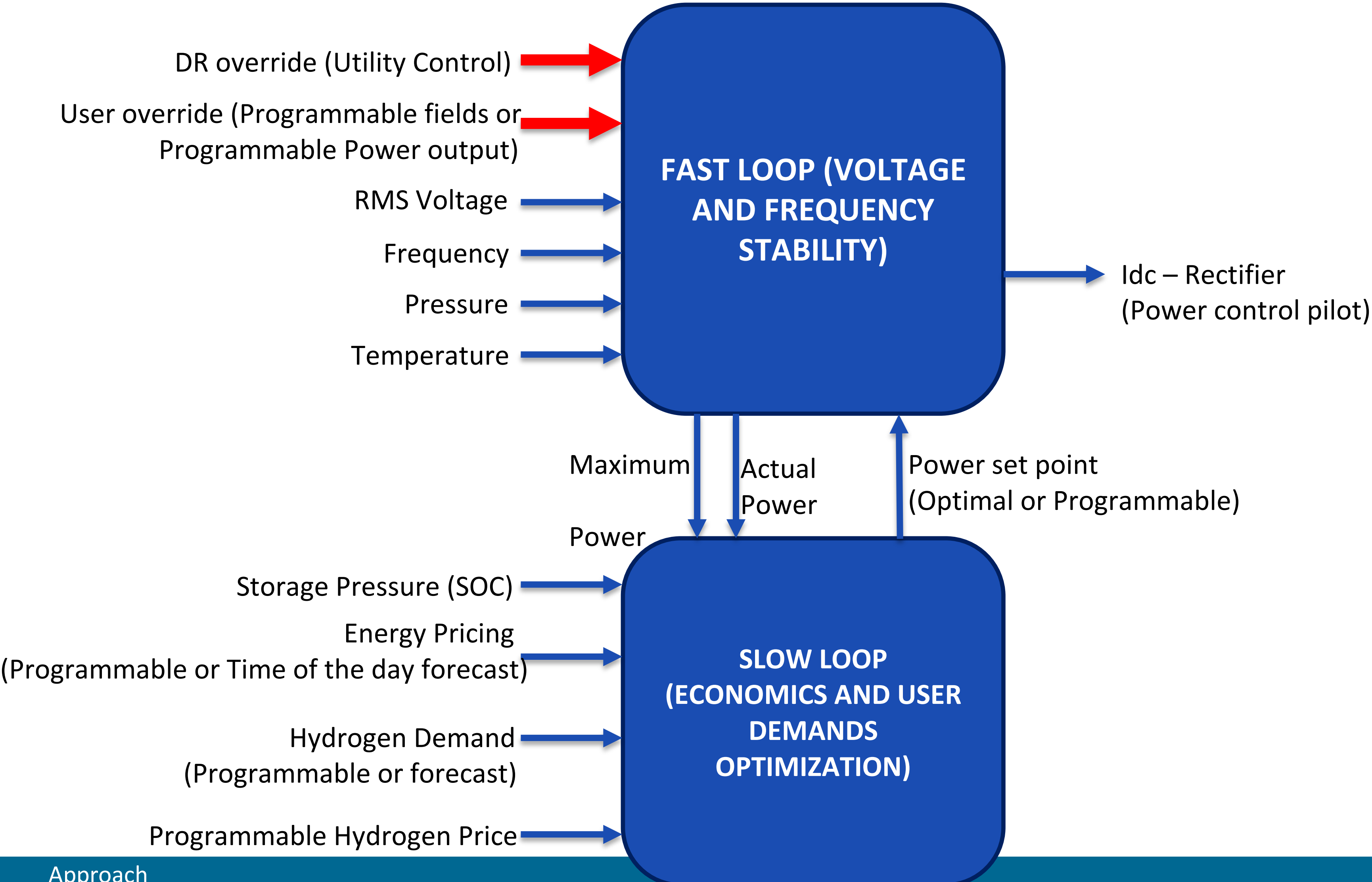
Front End Controller to support the grid signals and renewable energy penetration

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

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 consisting of slow and fast loop completed and deployed at NREL
- 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
- Ability to incorporate any optimization functionality in slow loop module
- Updating to IEEE standard 1547 for connecting with any energy storage device

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

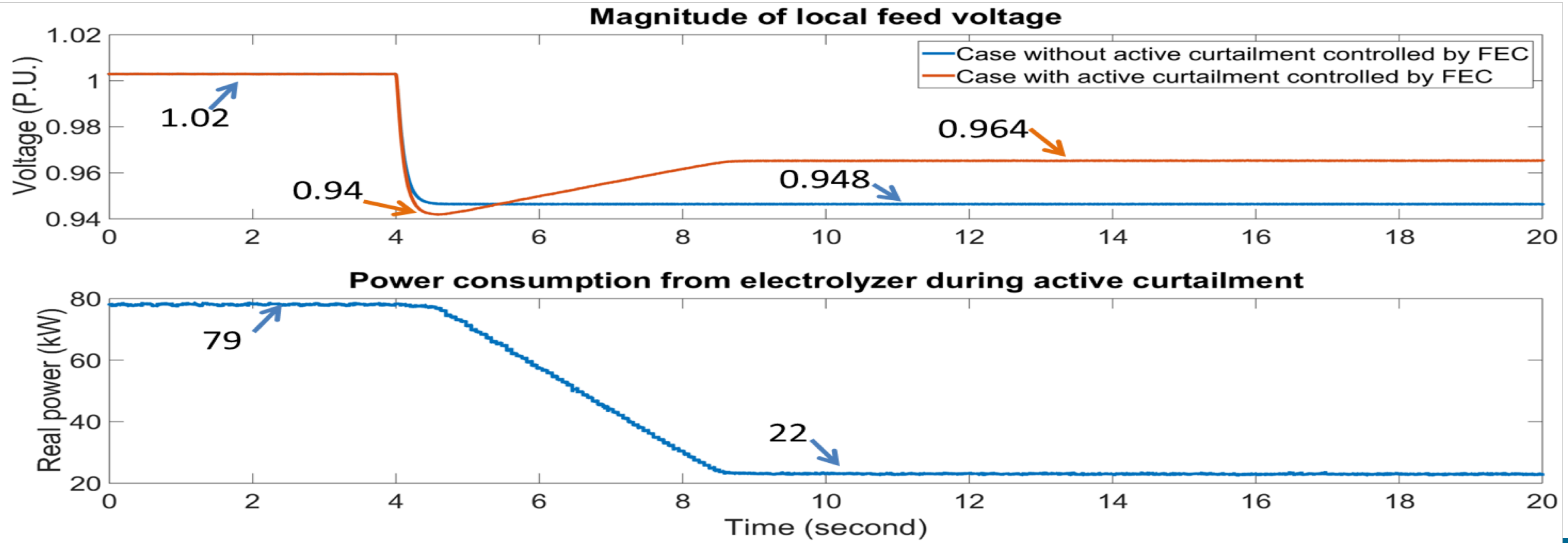
M1	Develop hydrogen station demand, size and economics based on the modified PG&E grid which includes different renewable energy penetration	March 2019
M2	Integrate, verify and validate optimization routines into FEC deployed at NREL incorporating new IEEE 1547 standards for high renewable penetration.	May 2019
M3	Physics based modeling of thermal power plants in DRTS of the grid selected and integrate with nuclear power plant model and other renewable energy sources.	July 2019
M4	Demonstrate distributed RT HIL of 225 kW stack to substantiate frequency stabilization and sub-transmission voltage mitigation through dispersed network of electrolyzers.	July 2019
M5	Analysis of electrolyzer operation, compare system performance with and without electrolyzers, and final report.	September 2019
G1	Identify time dependent customer load demand	April 2019

Approach – Deliverables Summary

D1	Develop the size, location, and generation profiles for the renewable system and electrolyzer system.	April 2019
D2	Complete validation of enhanced FEC which includes economic optimization in slow loop.	May 2019
D3	Modify the PG&E distribution network model (expanded) in RTDS® in order accommodate the nuclear power plant model and other renewable energy sources.	July 2019
D4	Demonstrate and validate using HIL experiments electrolyzer performance for mitigating voltage disturbance on the grid.	July 2019
D5	Analysis and final report	September 2019

Summary of Accomplishments

- 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
- Validated availability of hydrogen along with multiple revenue streams in peak hour by slow loop testing of FEC.
- Demonstrated electrolyzer can provide voltage regulation by fast loop testing of FEC.



AMR 2018 Feedback & Questions

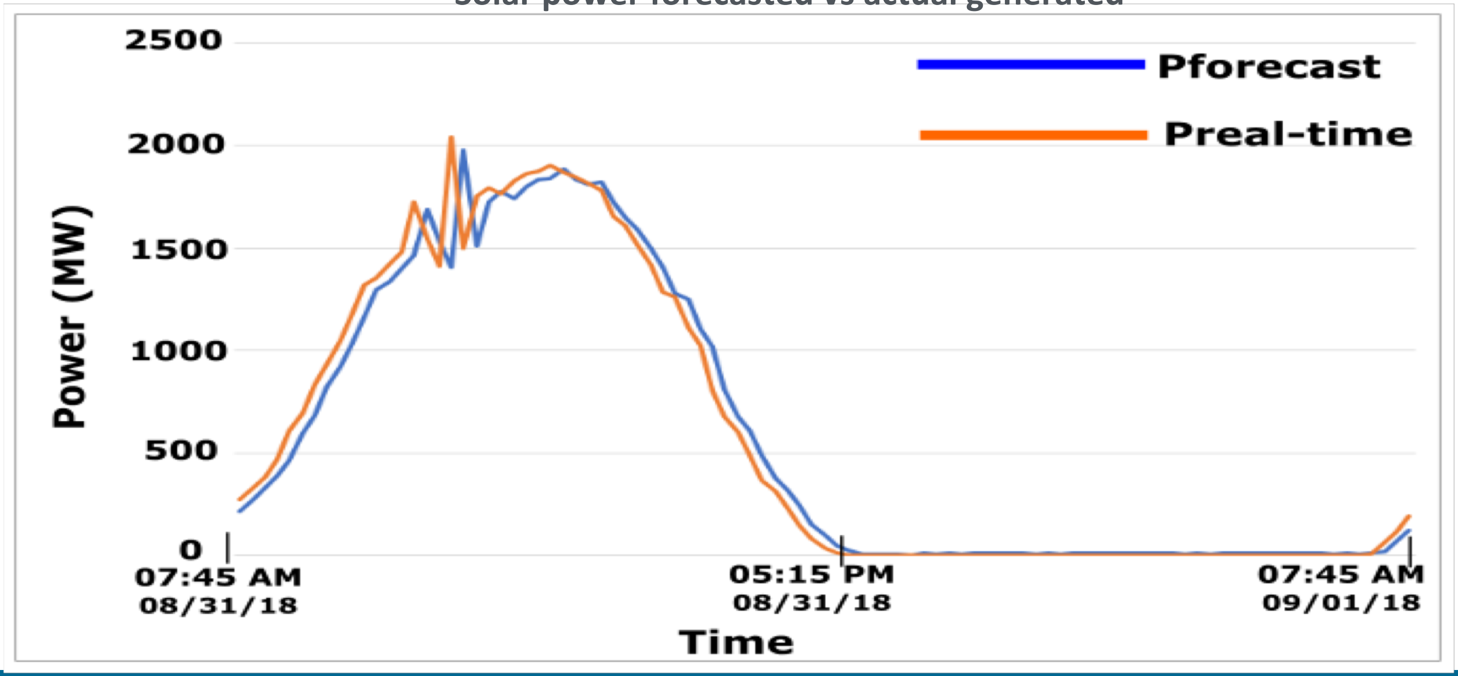
Project weaknesses:

- One of the project's weaknesses was the validation of testing protocols; the project would be strengthened by having an independent evaluation of the test protocols by a broader cross-section of utility operators.
  - Tests were conducted using actual electrolyzer hardware-in-the-loop in real-time environment, and controls are being developed as per IEEE Std. 1547.
- Establishing a method to determine the value of voltage/frequency regulation to the utility is an important need.
  - Agreed. Presently, IEEE 1547-2018 standard does not explicitly consider Electrolyzers as grid service devices. We are working with Standards community and GMLC 1.4.1, and 1.4.2 to address these gaps.
- Detailed analyses should have been completed for more locations.
  - Agreed. FY19 activities include three locations: PG&E, Idaho Falls Power (notional), and Santa Fe – with mix of renewables such as wind and solar.

Accomplishment - Power system modeling

- Identified and modeling 3 sub-transmission utility systems:
  - PG&E / Santa Fe / Idaho Falls Power
- Developed solar forecast module and integrated with the FEC
- The high penetration level of renewable energy sources mandates us to use "*IEEE standard 1547 for Interconnecting Distributed Resources With Electric Power Systems*"
- Integrate IEEE standard 1547 with the FEC

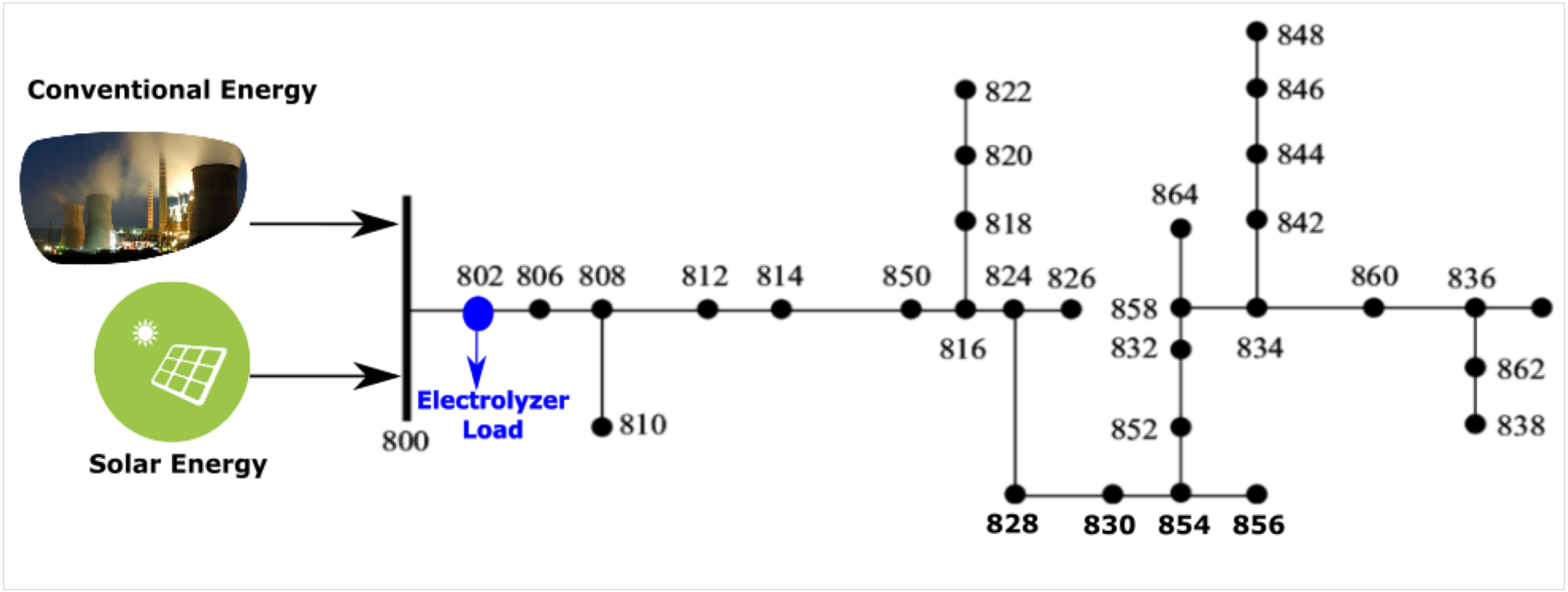
Solar power forecasted vs actual generated



Accomplishment – Solar forecast integration

- Updated grid model now consists of conventional and renewable energy sources

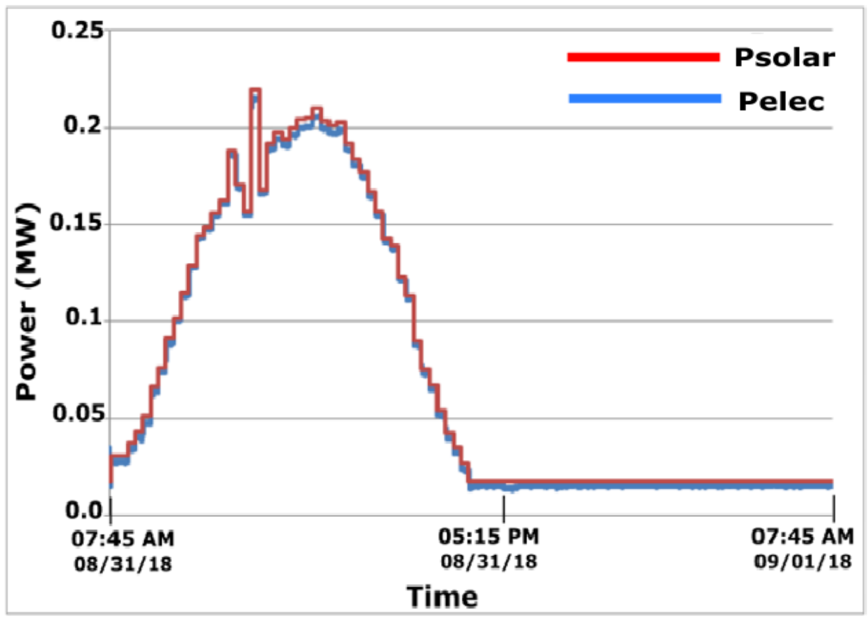
PG&E distribution model



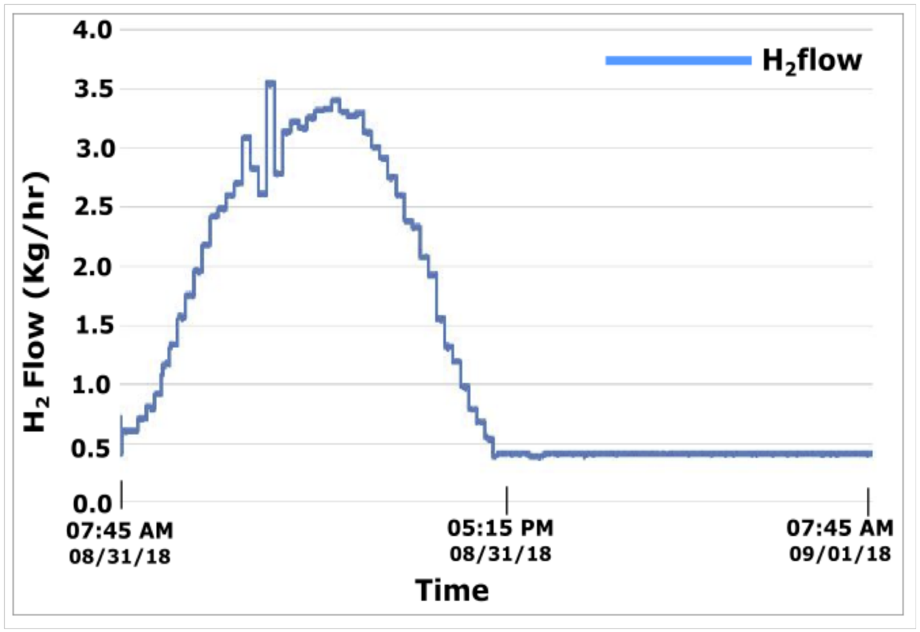
Accomplishment – Coordination of renewable generation and hydrogen production

- Completed 20,30 and 50% penetration of solar generation for hydrogen production under a) partly-cloudy, b) cloudy and c) sunny scenarios

P solar generated vs P electrolyzer consumed



H2 flow of electrolyzer



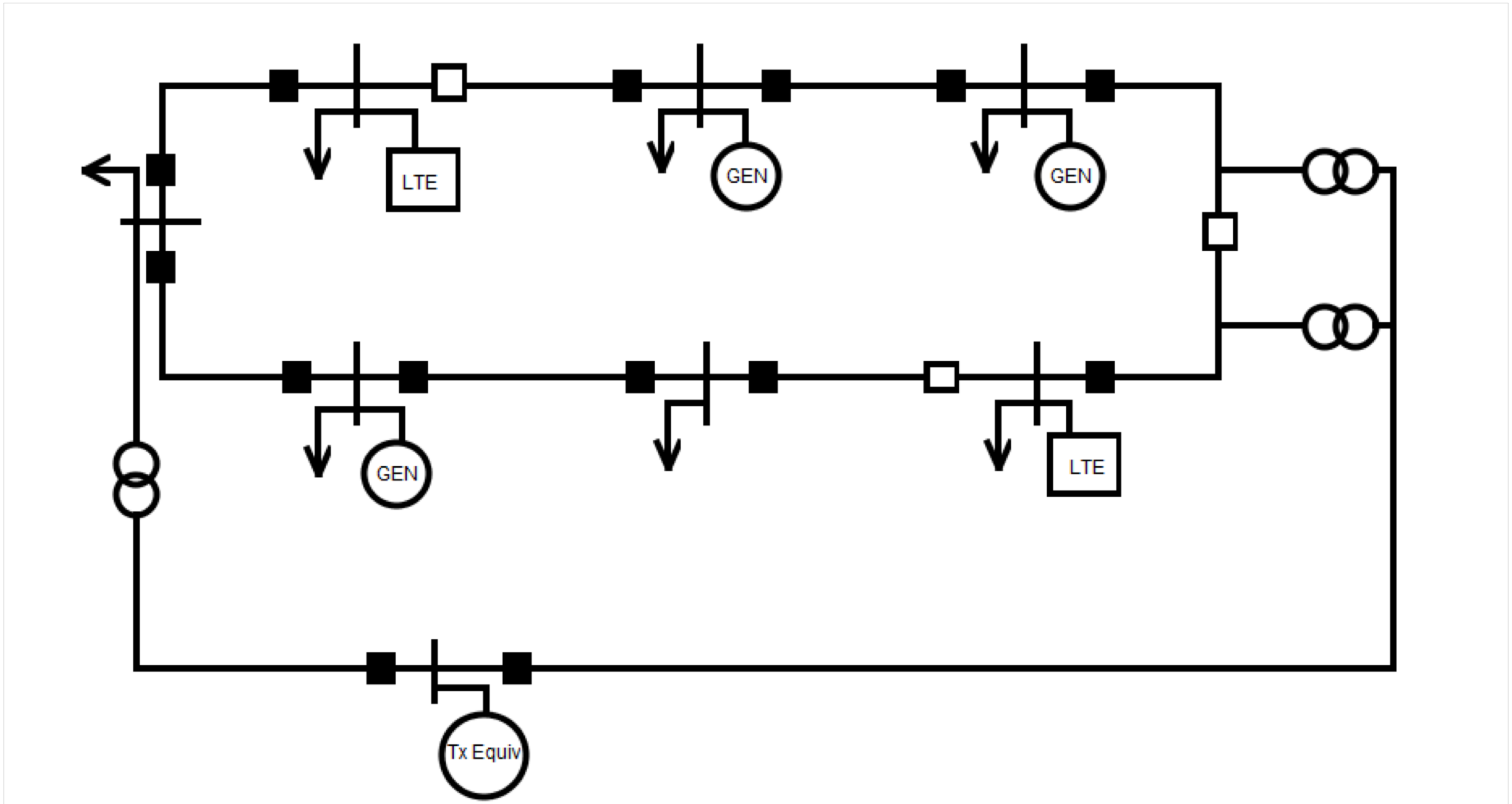
Accomplishments – Distribution Level Modeling for renewable assimilation

Santa Fe power grid representation for solar and hydrogen modeling

- Distribution level model developed in CYME using real utility data layout and load data from Santa Fe
- 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

Accomplishments – Distribution Level Modeling for renewable assimilation

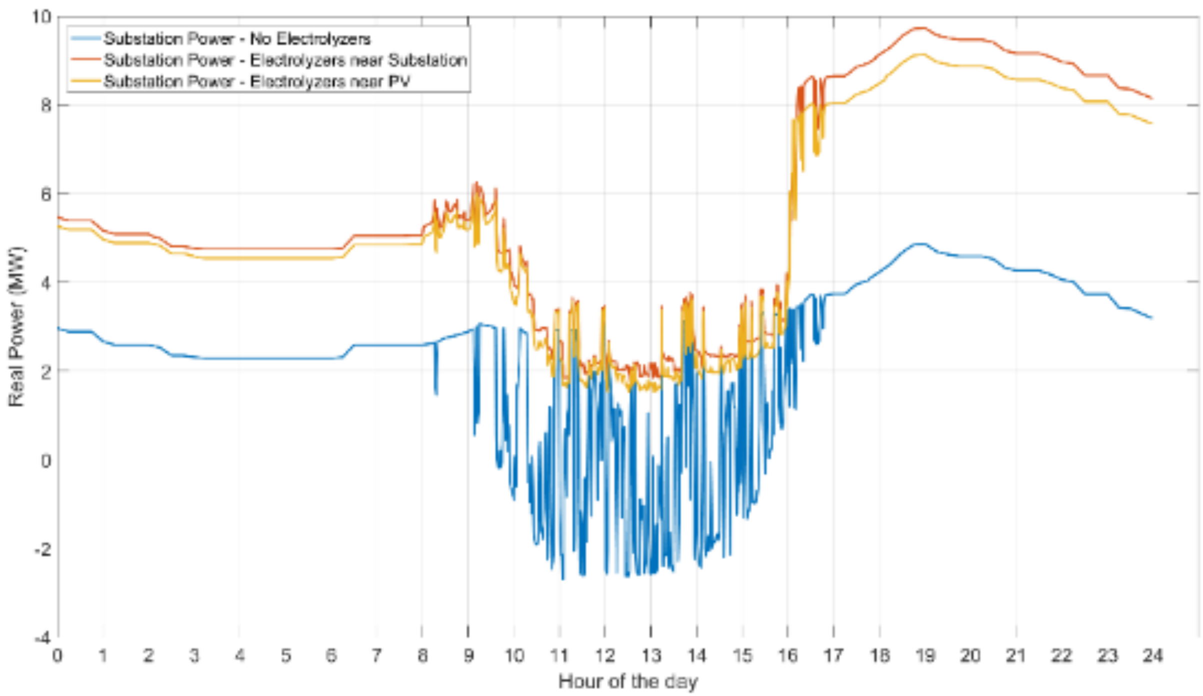
Idaho Falls Power notional grid representation for solar and hydrogen modeling



LTE – Low Temperature Electrolyzer
GEN – Hydropower Generation Plant
Tx Equiv – Transmission Equivalent

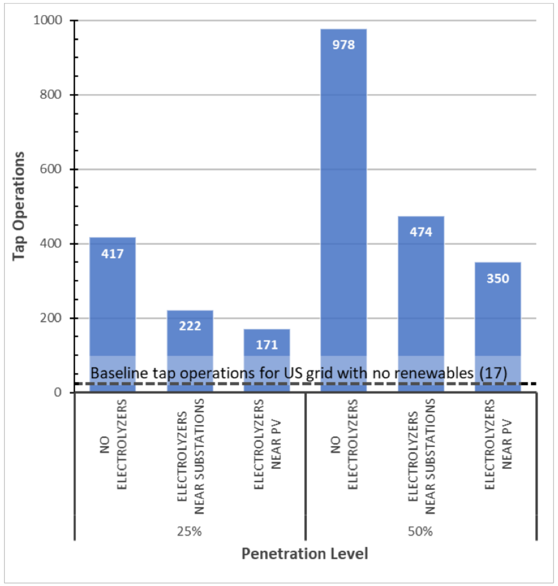
Electrolyzers avoid curtailed renewable generation with hydrogen production

Electrolyzers are operated at nearly steady state until PV generation, then the electrolyzer network operates during PV transients to dampen impacts of variable generation on a distribution feeder, utilize what would have been curtailed PV generation, and produce high-value hydrogen.

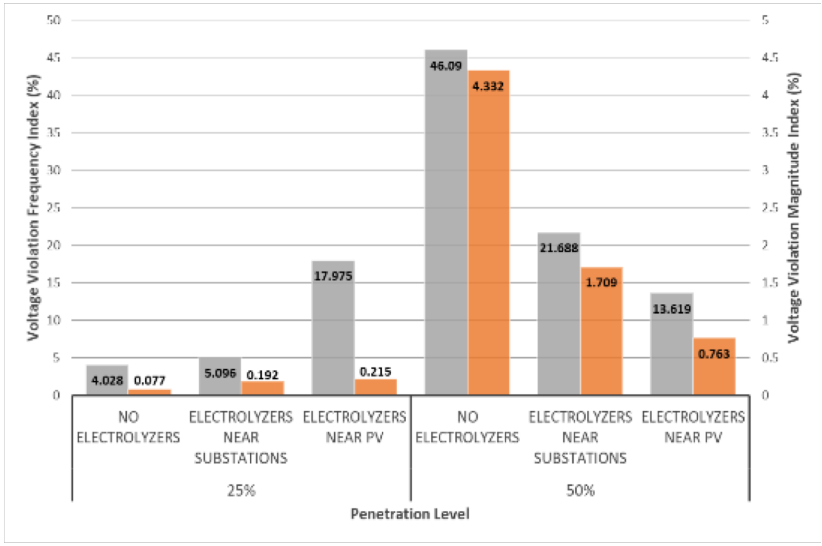


Leveraging Hydrogen Technologies for Integration of Hybrid Energy Solutions

The number of tap operations can be reduced significantly by including the electrolyzers which should result in extended life for grid hardware, improved reliability, and reduced maintenance and cost.

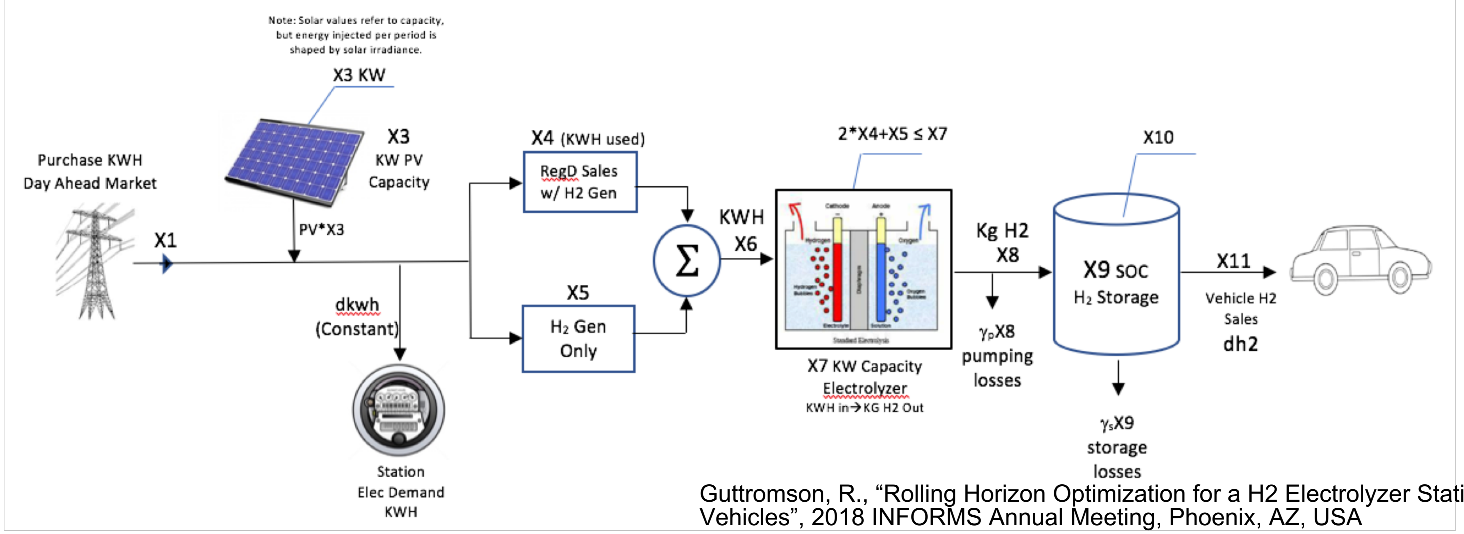


The location of electrolyzers (e.g., near the PV source or near the substation) does have an impact in all the metrics studied.



FEC Optimization module

- Objective: Find power setpoints to produce H2 at least cost considering:
  - forecasts of bulk power and ancillary services prices, H2 demand and PV/Wind (Renewable) power
  - H2 capacity limits and state of charge



Guttromson, R., "Rolling Horizon Optimization for a H2 Electrolyzer Station Used to Service H2 Vehicles", 2018 INFORMS Annual Meeting, Phoenix, AZ, USA

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, Santa Fe Utility, Idaho Falls Power
  - 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:** 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

- **Challenge:** Integration of the advanced control algorithms and optimization routines into an existing power electronics platform.
- **Mitigation:** Working with number of power converter manufacturers to ingrate into their existing power electronics platform.

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 - 50 % will be studied at the sites selected
- The project will identify one utility grid to perform real-time modeling and assessment of hydrogen refueling station providing frequency stabilization and voltage support to a grid with nuclear base load and intermittent renewables
- 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
- Looking for a vendor to integrate FEC functionality with a power converter which is implemented using IEEE 1547 standard.

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 grid services
- Integration of a prototype controller with the electrolyzer stack is completed and successfully deployed to facilitate grid services in real-time
  - Integration of fast and slow loop optimization in preparation for implementation on power converter
  - 500 hours of control functionality testing and demonstration was completed
  - Hardware control prototype is deployed at NREL to operate the LT electrolyzer stack and balance of plant
- Validate electrolyzer performance with baseload nuclear and intermittent renewables to provide
  - Frequency stabilization
  - Mitigate voltage disturbance
- Implementation of fast control response as per IEEE 1547 Standard of grid services

Thank You

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.

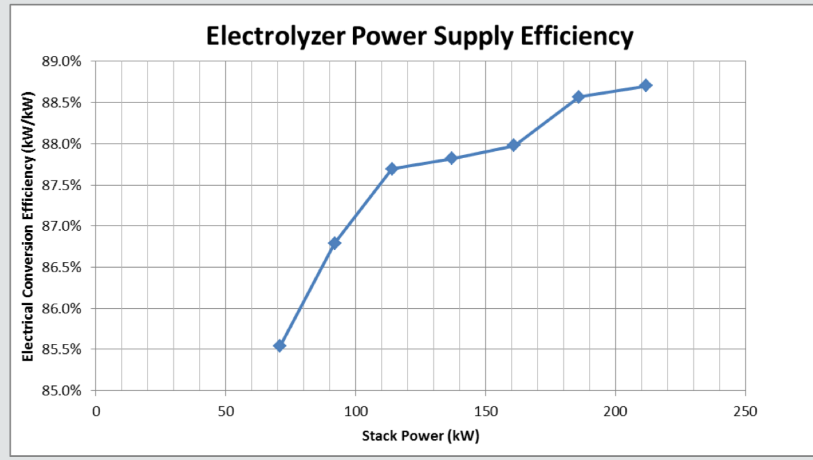
Serial no.	Test Title	Completed Hours
1	Stack Characterization	10
2	Variable electrolyzer balance of plant (BOP) operation	15
3	Power Converter Characterization	5
4	Grid Model Testing	50
5	FEC Model Testing	140
6	FEC Hardware Testing	80
7	FEC ARM Board Testing	0
	Total Hours Completed	300

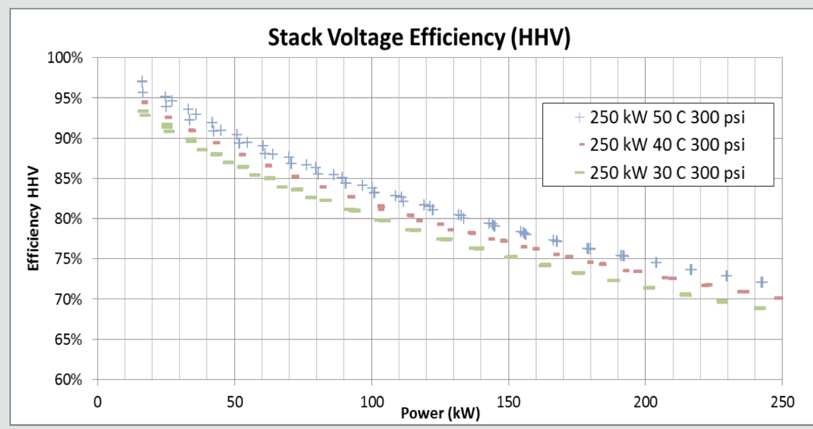
Accomplishments – Efficiency Measurements

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

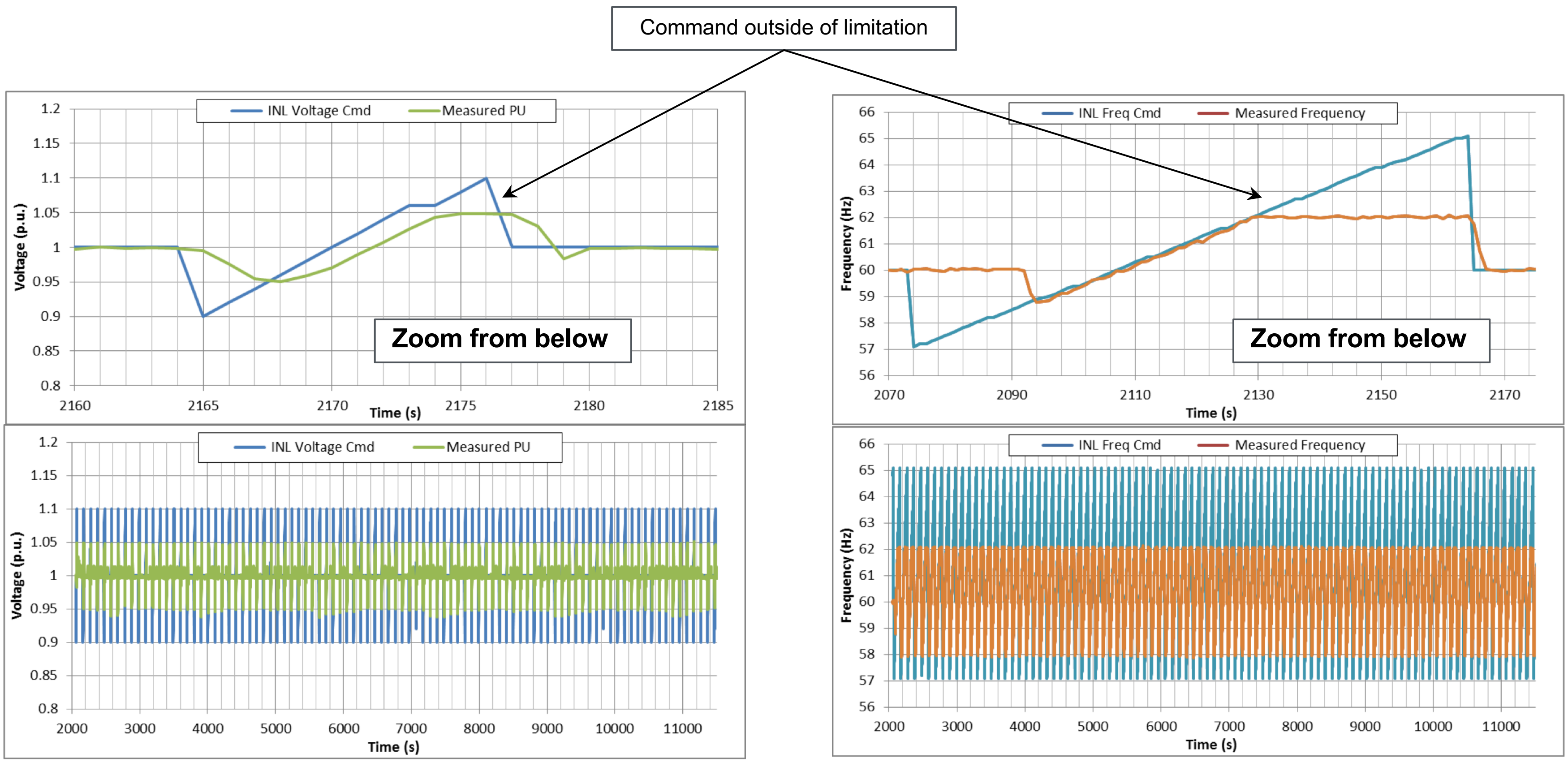




Accomplishments – Grid Simulator

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

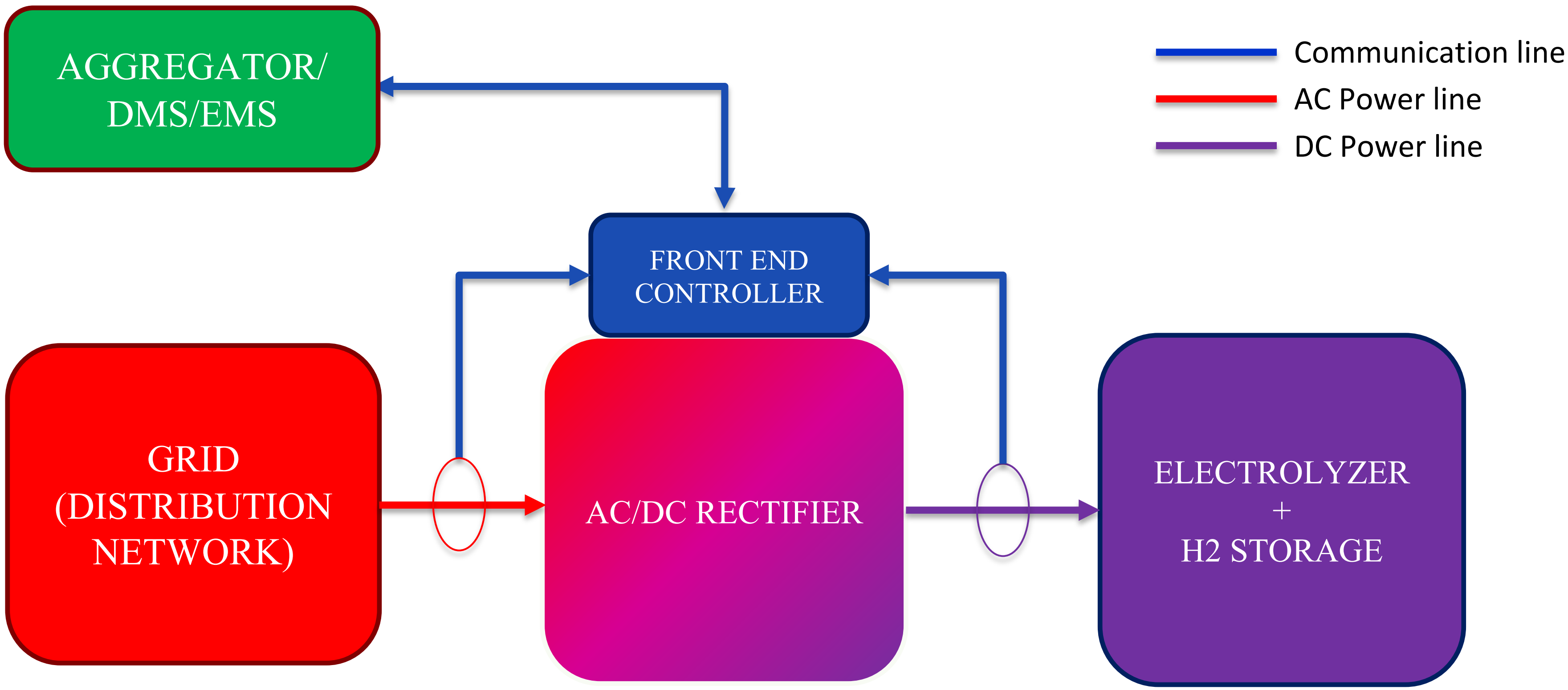
- Demonstration of a major power hardware-in-the-loop capability for NREL
- Control via remote command from INL RTDS and safety limits verified



Other backup slides

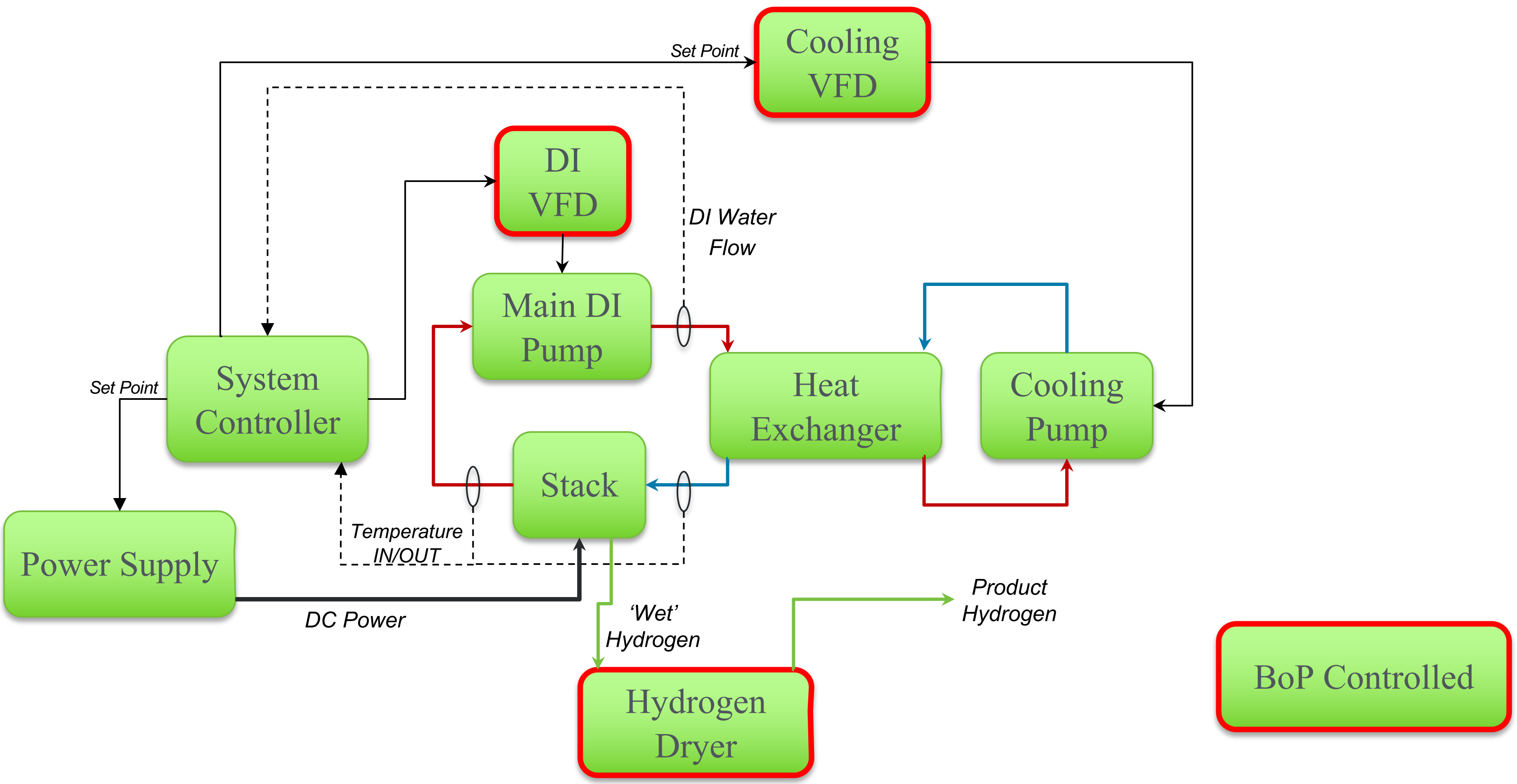
Approach - Conceptual Diagram

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

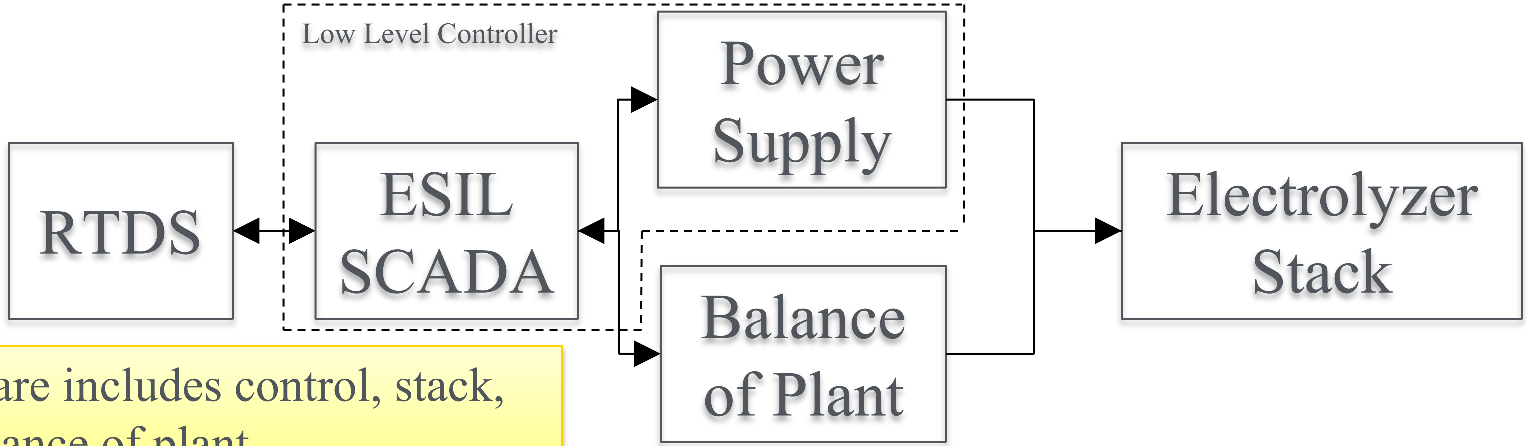


Approach – Balance of Plant Optimization

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

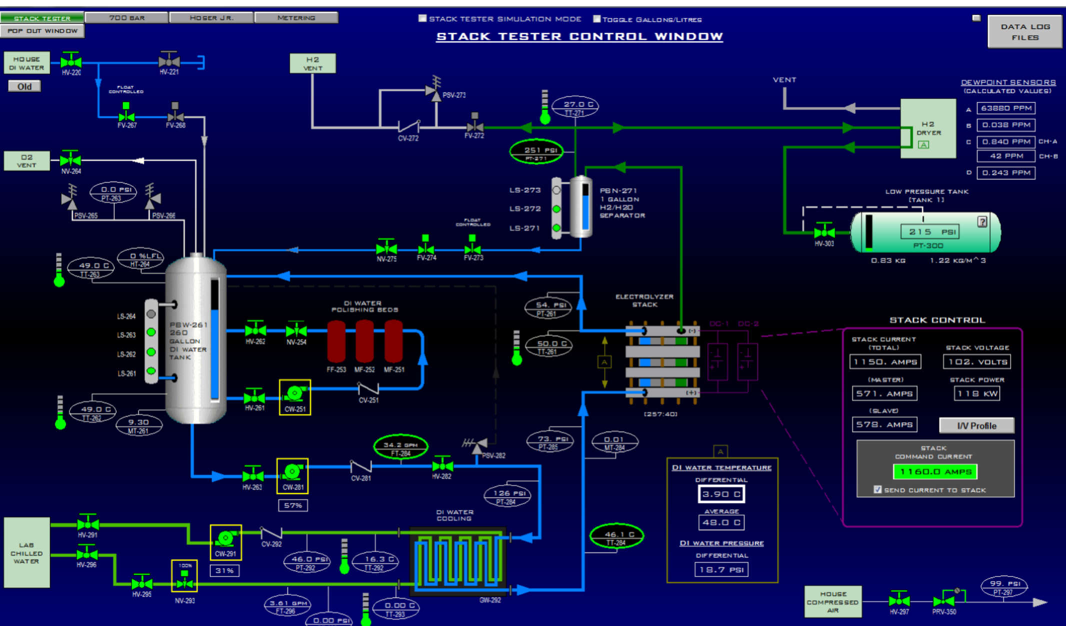


Approach - Electrolyzer System Setup



Hardware includes control, stack, and balance of plant

ESIL SCADA



Electrolyzer System (Stack & BOP)

Technology Transfer

- Publications:
  - Manish Mohanpurkar, Yusheng Luo, Danny Terlip, Fernando Dias, Kevin Harrison, Joshua Eichman, Rob Hovsapian, Jennifer Kurtz, “Electrolyzers Enhancing Flexibility in Electric Grids,” Energies, 2017, 10(11), pp. 1-17.
  - Y. Luo, M. Xian, M. Mohanpurkar, B. Bhattarai, A. Medam, R. Kadavil and R. Hovsapian, "Optimal Scheduling of Electrolyzer in Power Market with Dynamic Prices." Probabilistic Methods Applied to Power Systems, June 2018, pp.1-6.