Role of Electrolyzers in Grid Services

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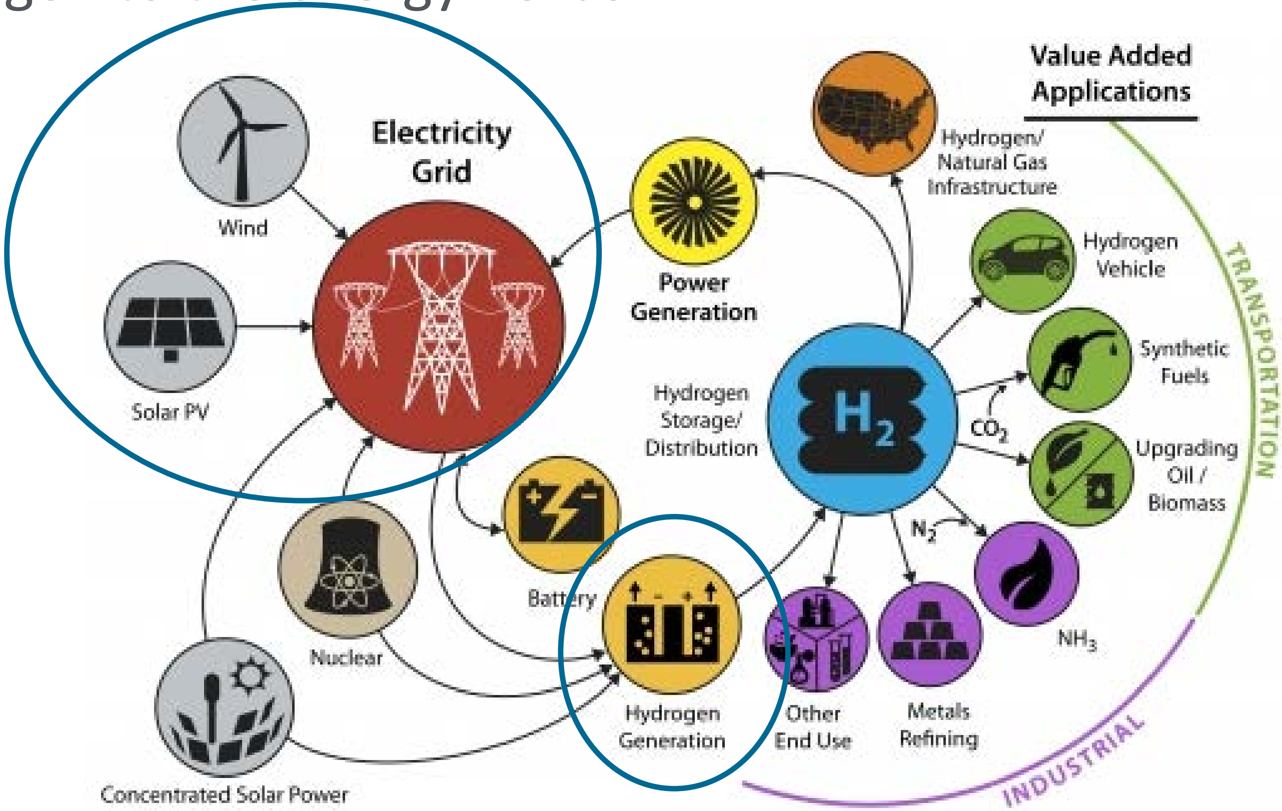
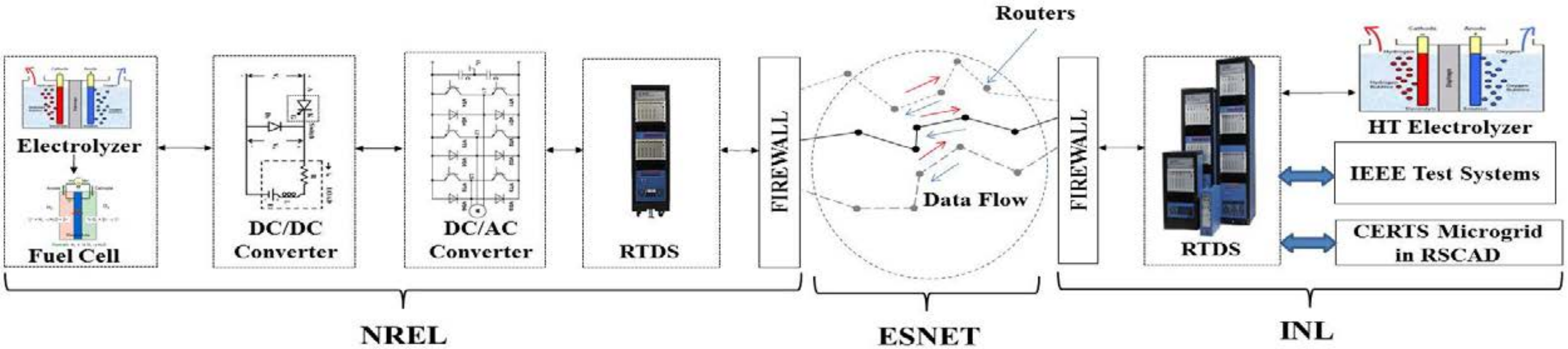
H2@Scale Relevance

- Current activities - role of hydrogen refueling stations in the electricity grid and renewable energy assimilation
- H2@Scale has a longer term vision with potential benefits of hydrogen to the energy nexus



Relevance & Objective

- Relevance: Electrolyzer model validation and simulation in a distributed real time environment that is used for electrolyzer based fueling station business case analysis (California focus)
- Objective: Validate the benefits of hydrogen electrolyzers through grid services and hydrogen sale to fuel cell vehicles for full-scale deployment.
  - Characterization of the potential and highest economic value based on the needs of multiple stakeholders for specific grid regions.
  - 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 electricity markets and DR programs and ancillary services, leading to additional revenue and reduced hydrogen production cost.



Electrolyzers, Renewables, and Power Grid

- Grid modeling: Utility distribution network identification and modeling in Real Time Simulator for present case
- Electrolyzer operation: Interface development between electrolyzer and Real Time Simulator to perform Power-Hardware-In-the-Loop (PHIL) model validation
- Utility/Aggregator involvement to provide real world test conditions
- Economic analysis: Operations optimization to calculate maximum revenue
  - Compare revenue to costs to determine competitiveness
  - Based on
    - 2015 Utility rate and/or CAISO nodal price (region, connection, operation strategy)
    - 2015 California renewable profiles (PV or wind)
    - Hydrogen production capacity factor (80, 90, or 95%)

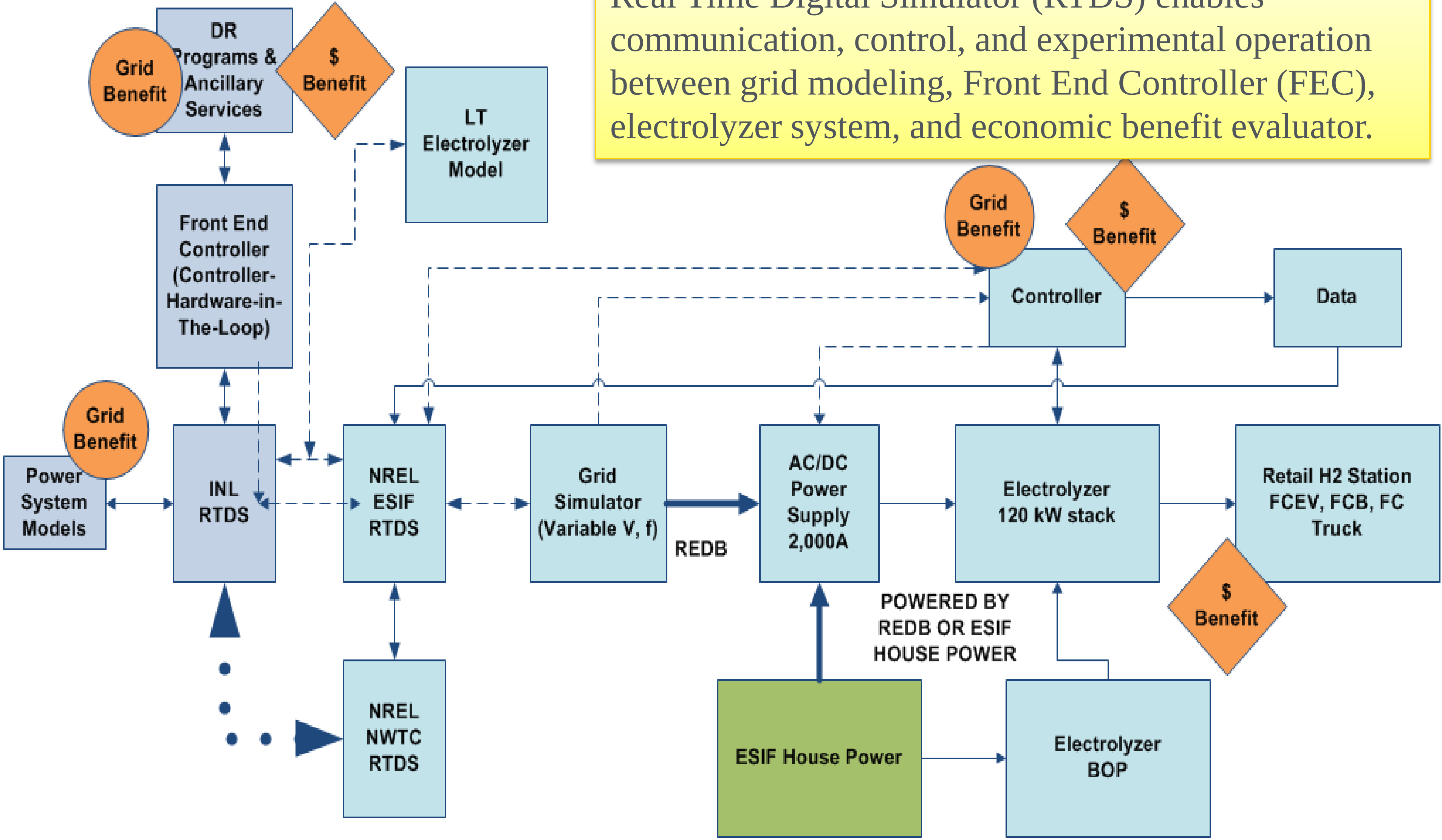
Electrolyzers and Response Metrics for Grid Services

Time response and level of variation in power consumption of 120 kW stack electrolyzer at NREL

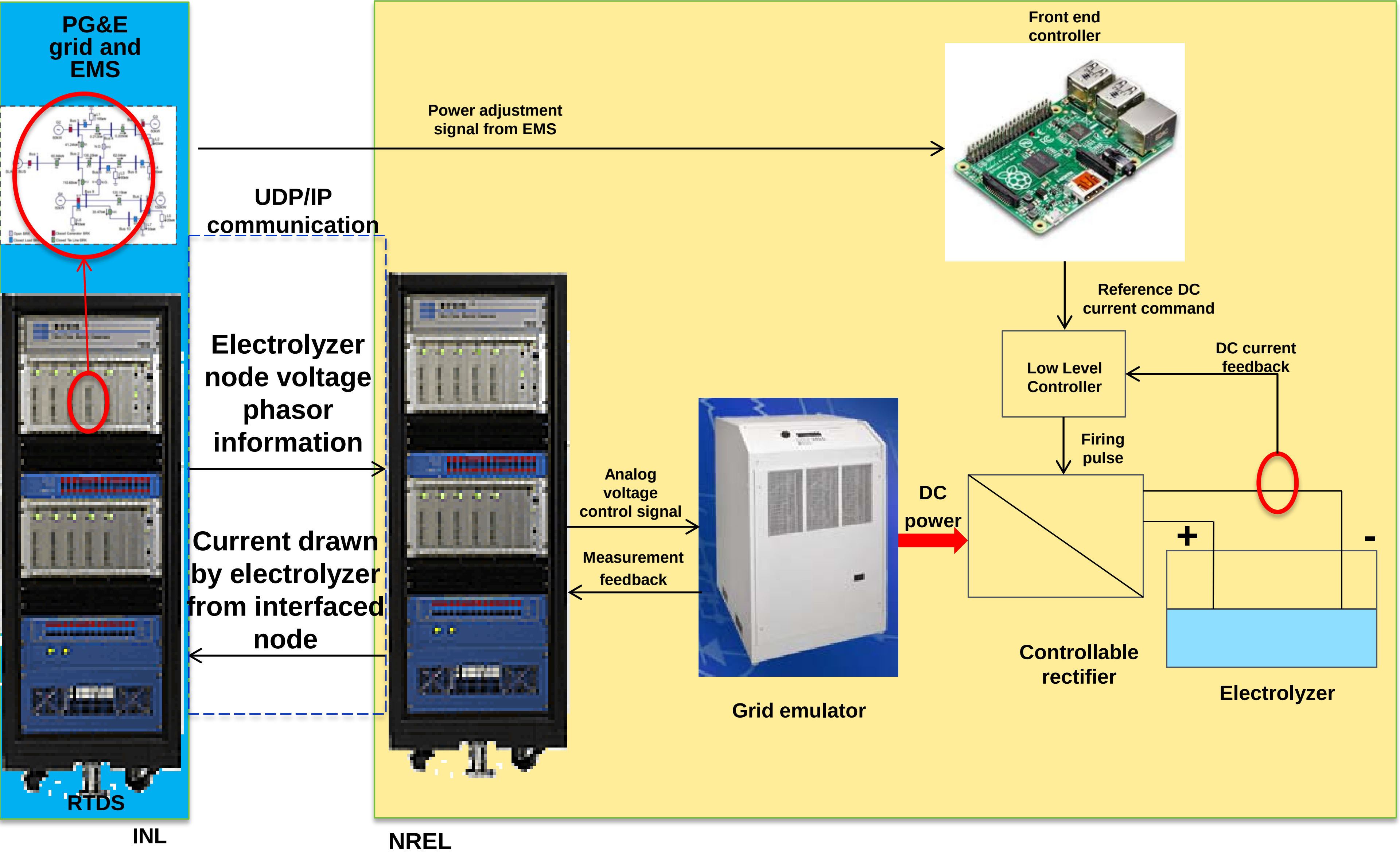
- Response time to a change in power set-point (electrolyzer demonstrated to be milliseconds)
- Settling time after a set-point change (electrolyzer demonstrated to be milliseconds)
- Duration possible for a change in power consumption (electrolyzer demonstrated to be unlimited)
- Turndown level (electrolyzer demonstrated to have a 10:1 turndown capability)
- Startup and shutdown time (electrolyzer demonstrated to start and stop in less than 30 seconds)

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



PG&E grid and EMS

UDP/IP communication

Power adjustment signal from EMS

Front end controller

Reference DC current command

Low Level Controller

DC current feedback

Firing pulse

Electrolyzer node voltage phasor information

Current drawn by electrolyzer from interfaced node

Analog voltage control signal

Measurement feedback

DC power

+

-

Grid emulator

Controllable rectifier

Electrolyzer

RTDS

INL

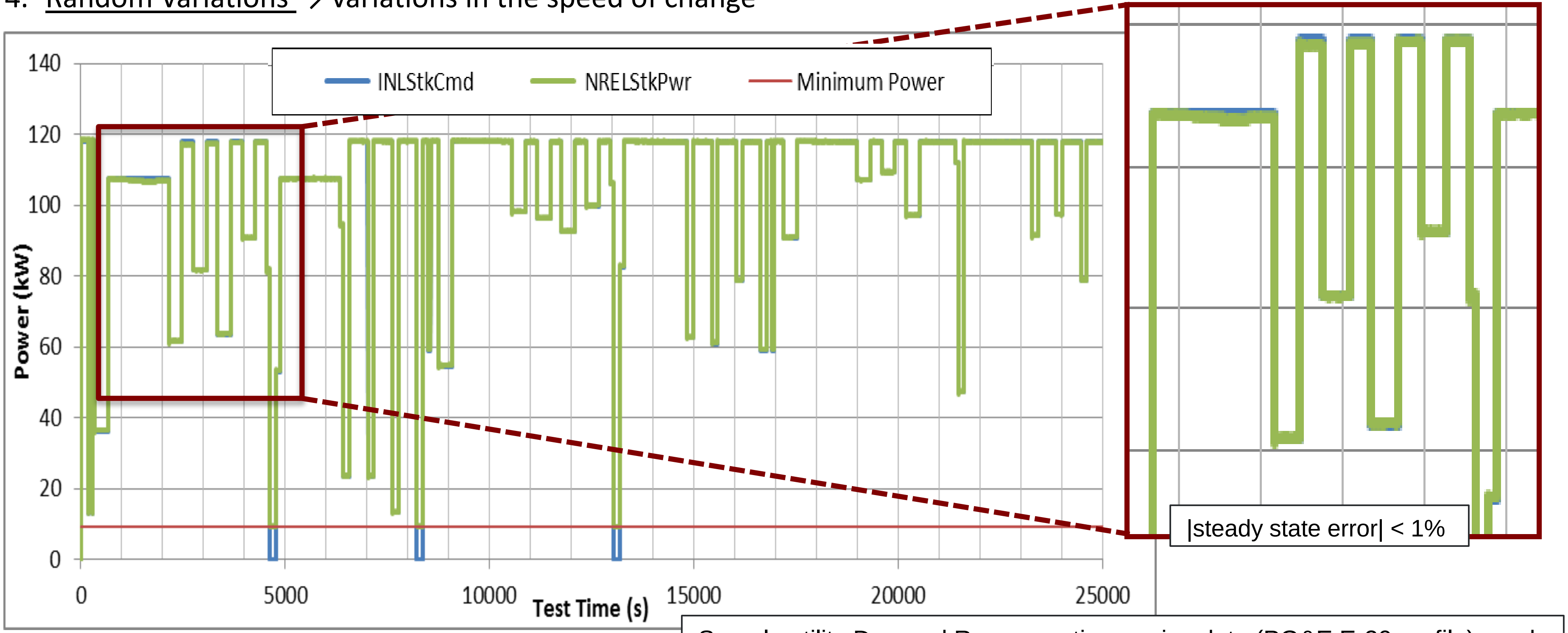
NREL

Demand Response Simulations

Remote electrolyzer operation over 200 hour test period shows electrolyzer's ability to participate in grid support market

Four distinct profiles were used to characterize the electrolyzer response to remote commands

1. Ramp Up, Ramp Down → variations in increasing or decreasing load steps
2. Load Steps → variations in the size of change
3. Utility Demand Response → expected performance of electrolyzer in grid application
4. Random Variations → variations in the speed of change

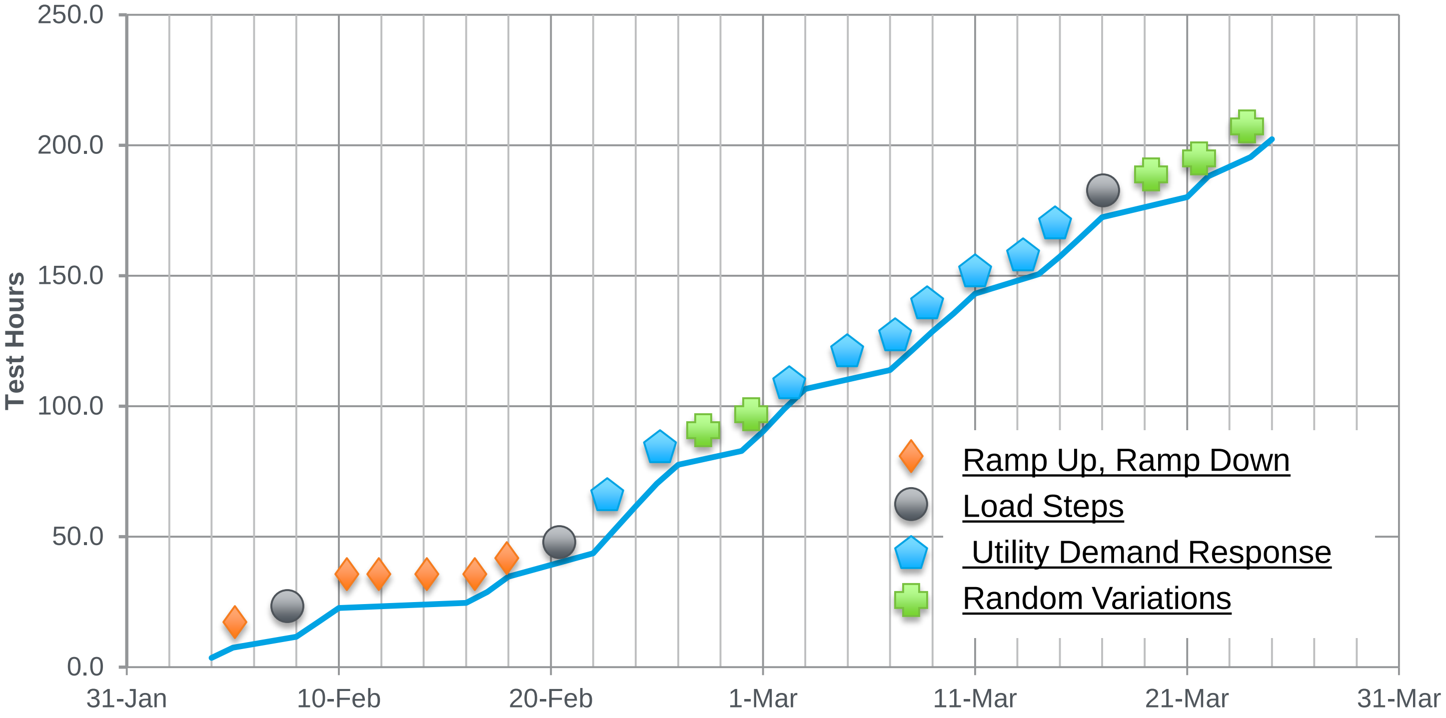


|steady state error| < 1%

Sample utility Demand Response time series data (PG&E E-20 profile) used to remotely control the electrolyzer over ~7 hour window 8 March 2016.

Electrolyzer Characterization Testing

Types of tests run to achieve 200 hours



Summary of Electrolyzer Characterization Testing

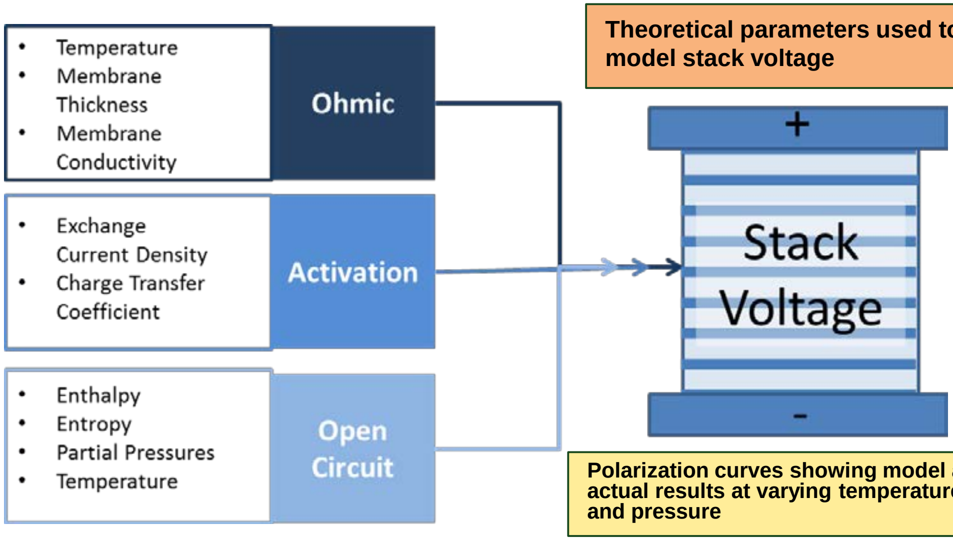
Fast response time & quick slew rate

Performance Metric	Ramp	Load	DR	Random
Response Time	< 1seconds	< 1seconds	< 1seconds	< 1seconds
Settling Time	< 1seconds	< 1seconds	< 1seconds	< 1seconds
Slew Rate	+1 kW/second -1 kW/second (Other rates were 0.5 and 2 kW/second)	Predetermined load values at variable times	10 kW, 20 kW, 30 kW, 40 kW, 50 kW, 118 kW, & E-20 DR (PG&E) at 2, 5, and 10 minutes interval	Random set-points between 13 & 118 kW per second
Operational Limits	13 kW to 118 kW	13 kW to 118 kW	13 kW to 118 kW	13 kW to 118 kW
Startup and Shutdown Time	30 seconds and < 1 second	30 seconds and < 1 second	30 seconds and < 1 second	30 seconds and < 1 second

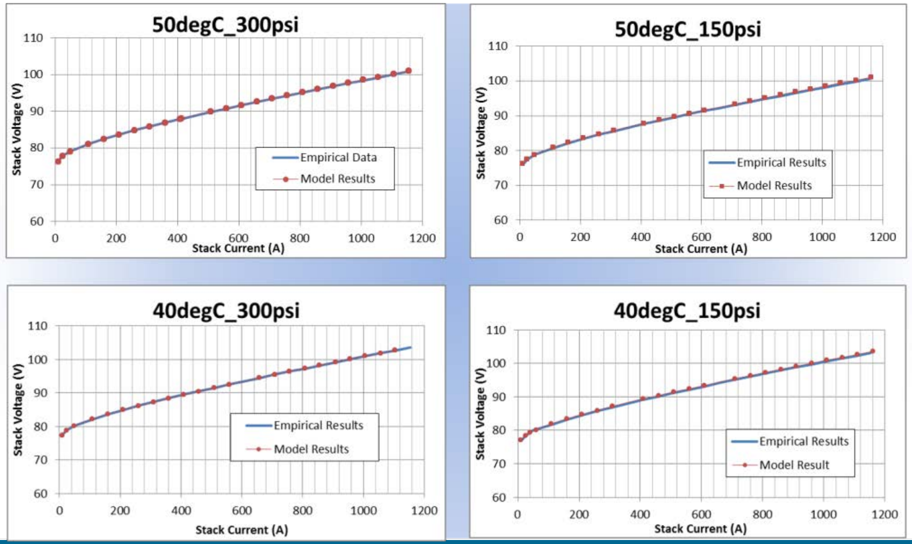
Electrolyzer Modeling

Electrolyzer model developed in RSCAD and validated against 120 kW stack using RTDS simulations

Theoretical parameters used to model stack voltage

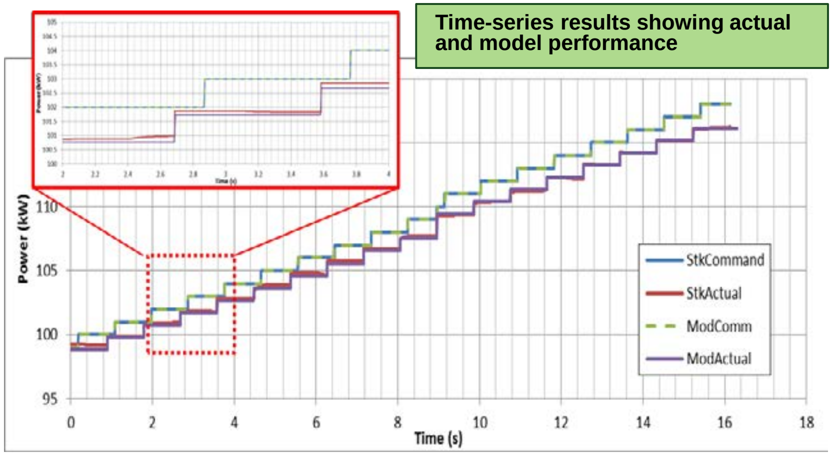


Polarization curves showing model and actual results at varying temperature and pressure



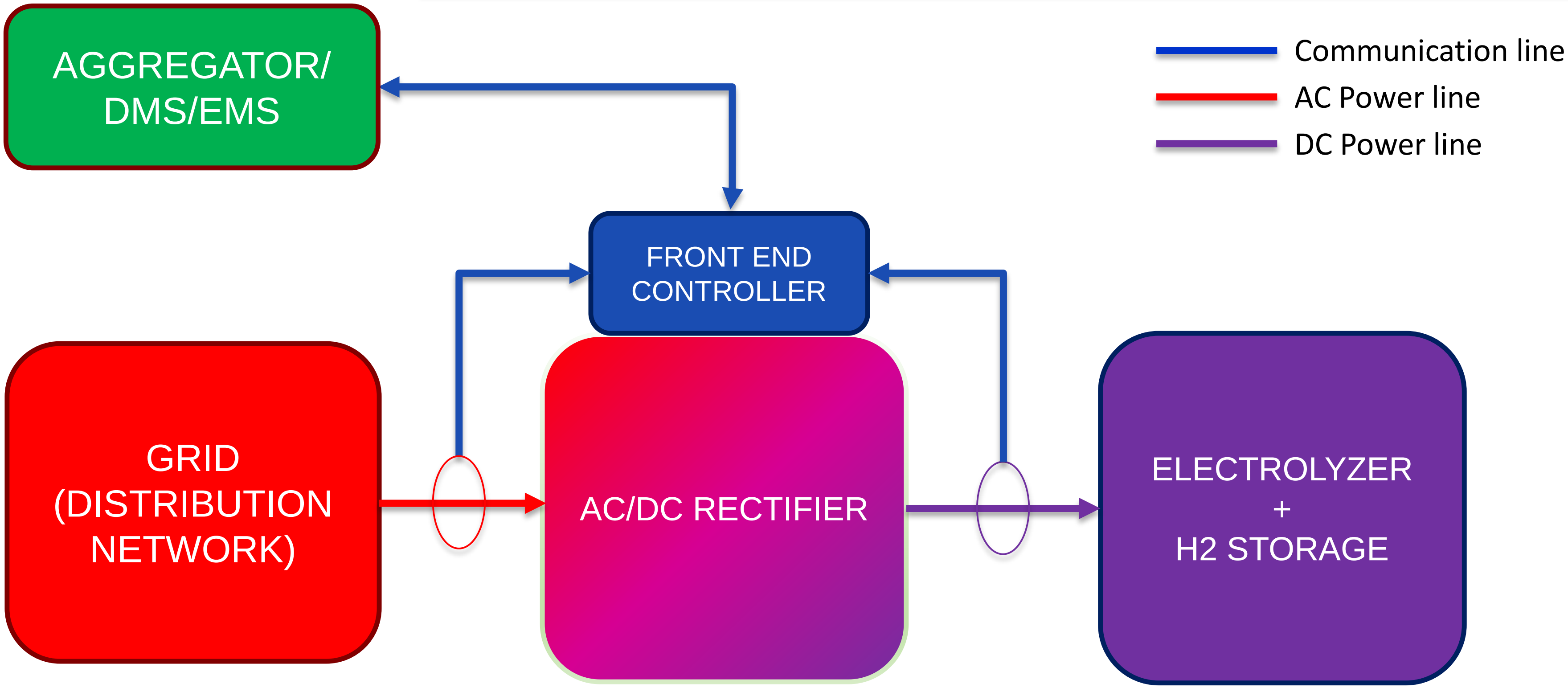
- Collect empirical data on 50-cell PEM stack
- Develop balance of plant model in RSCAD using theoretical equations
- Match empirical and theoretical results using curve fitting to derive parameters
- Compare time-series results from PEM stack and model using INL RTDS test protocol

Time-series results showing actual and model performance



Front End Controller & Electrolyzers

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.



AGGREGATOR/ DMS/EMS

FRONT END CONTROLLER

GRID (DISTRIBUTION NETWORK)

AC/DC RECTIFIER

ELECTROLYZER + H2 STORAGE

Communication line

AC Power line

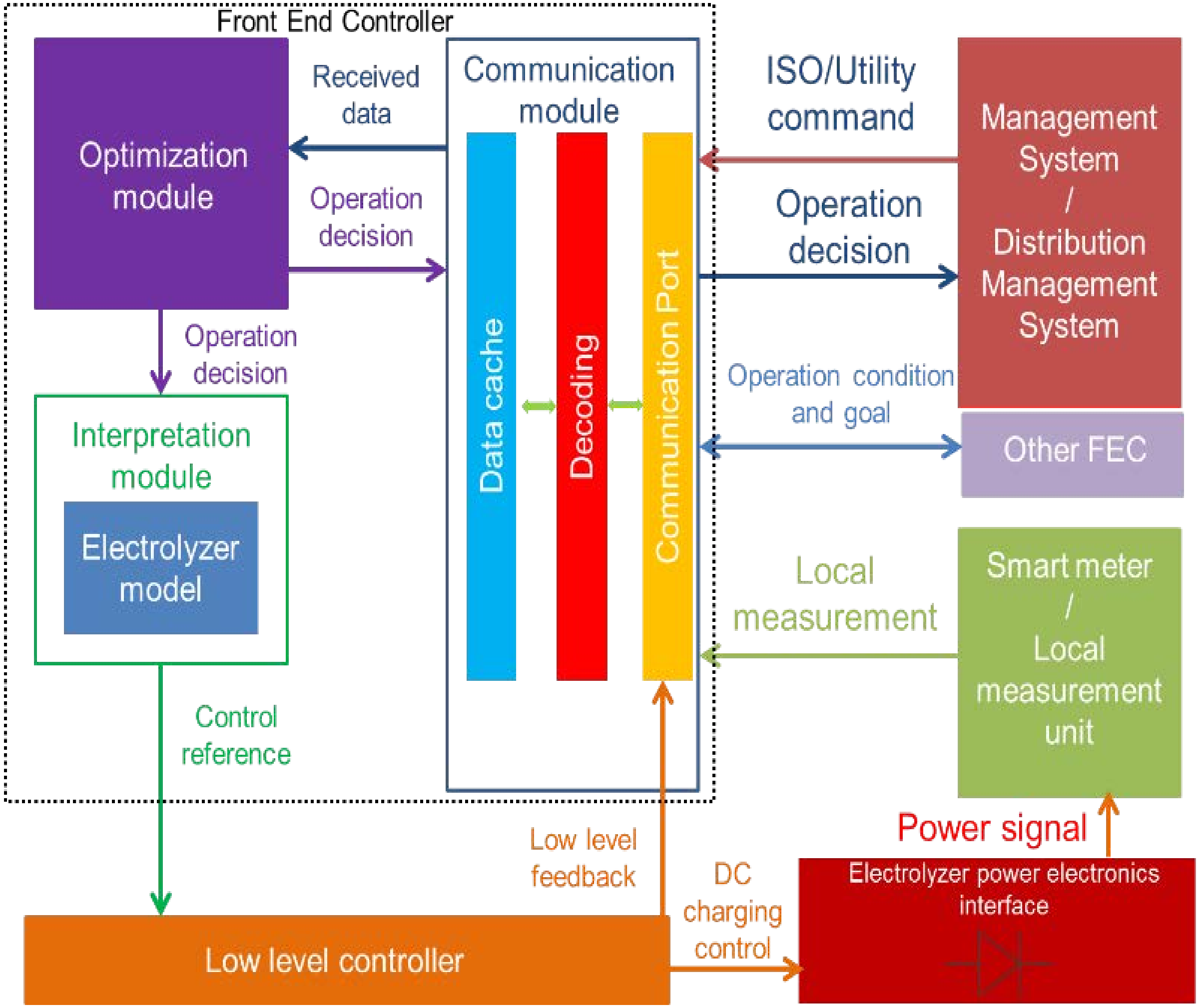
DC Power line

Front End Controller

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

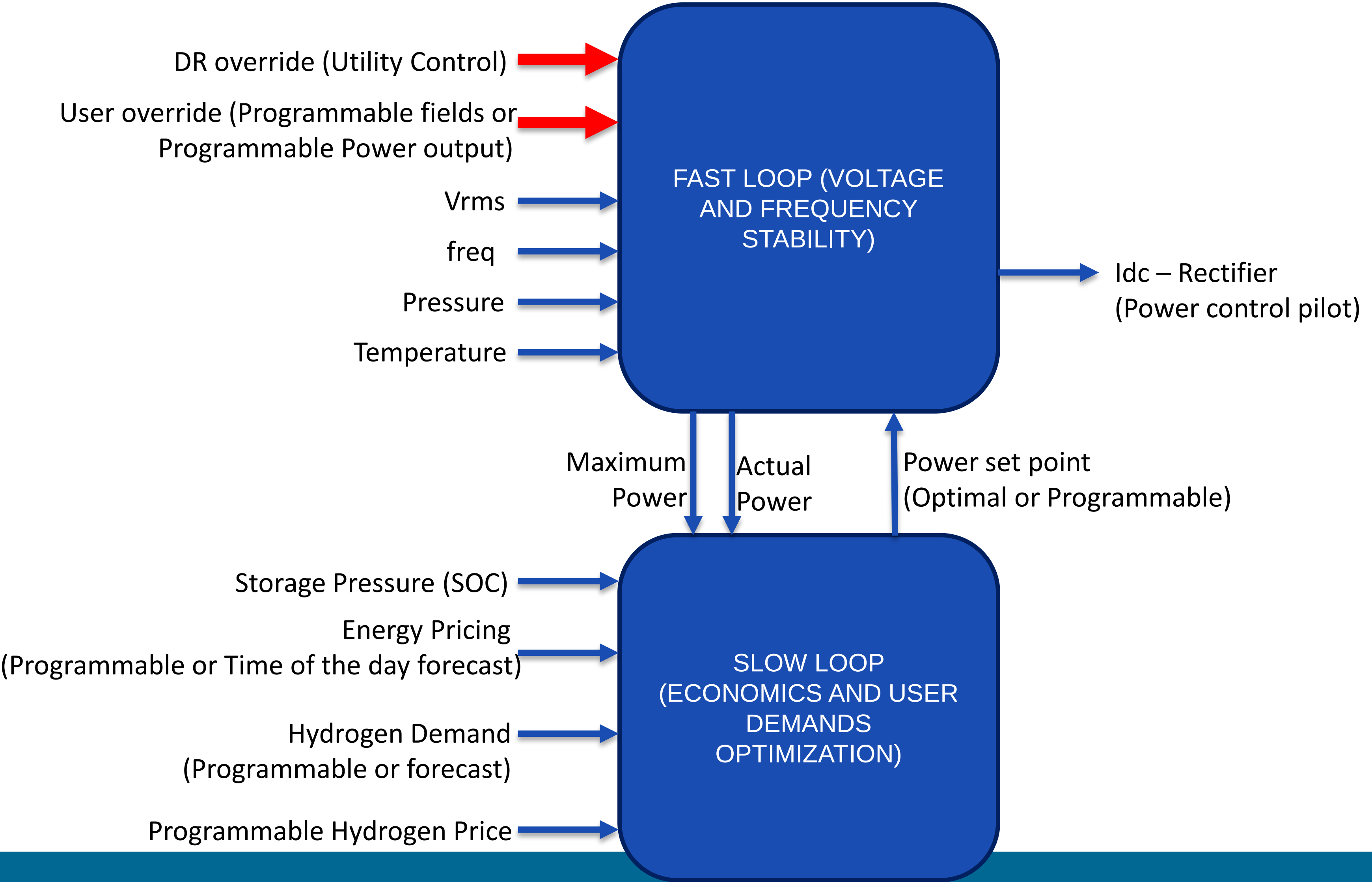
FEC consists of three modules:

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



FEC Inputs/Outputs

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



DR override (Utility Control)

User override (Programmable fields or Programmable Power output)

Vrms

freq

Pressure

Temperature

FAST LOOP (VOLTAGE AND FREQUENCY STABILITY)

Idc – Rectifier
(Power control pilot)

Maximum Power

Actual Power

Power set point
(Optimal or Programmable)

Storage Pressure (SOC)

Energy Pricing
(Programmable or Time of the day forecast)

Hydrogen Demand
(Programmable or forecast)

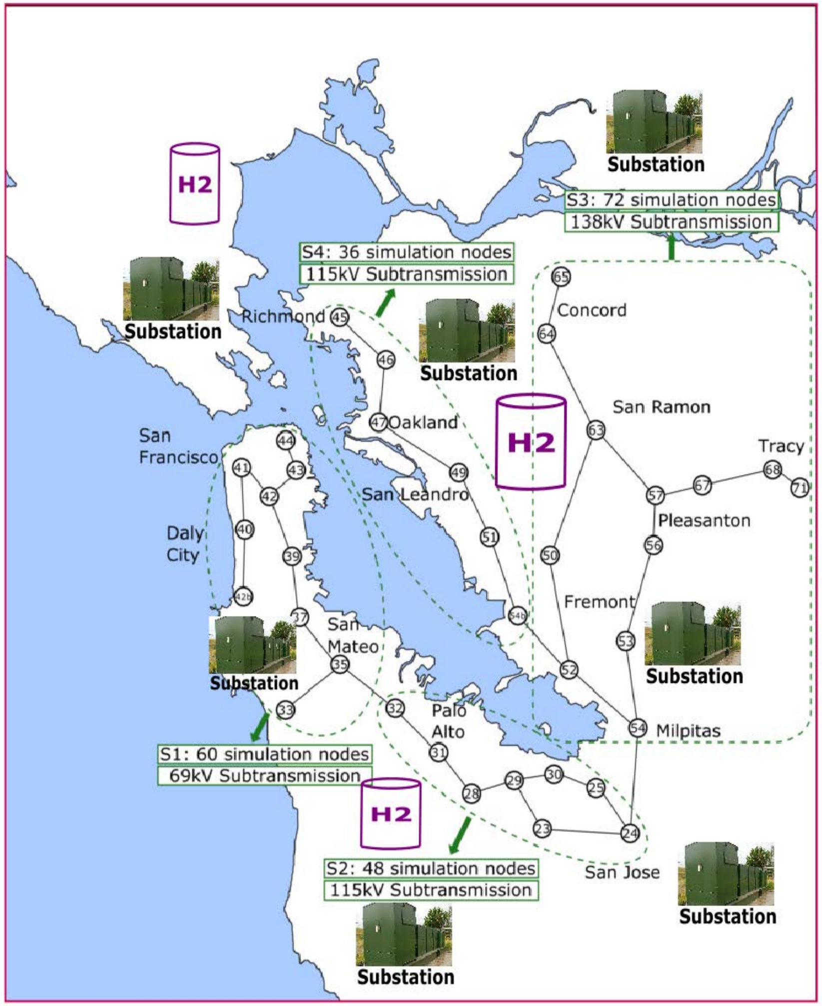
Programmable Hydrogen Price

SLOW LOOP (ECONOMICS AND USER DEMANDS OPTIMIZATION)

Grid Modeling, Real-Time PG&E Network

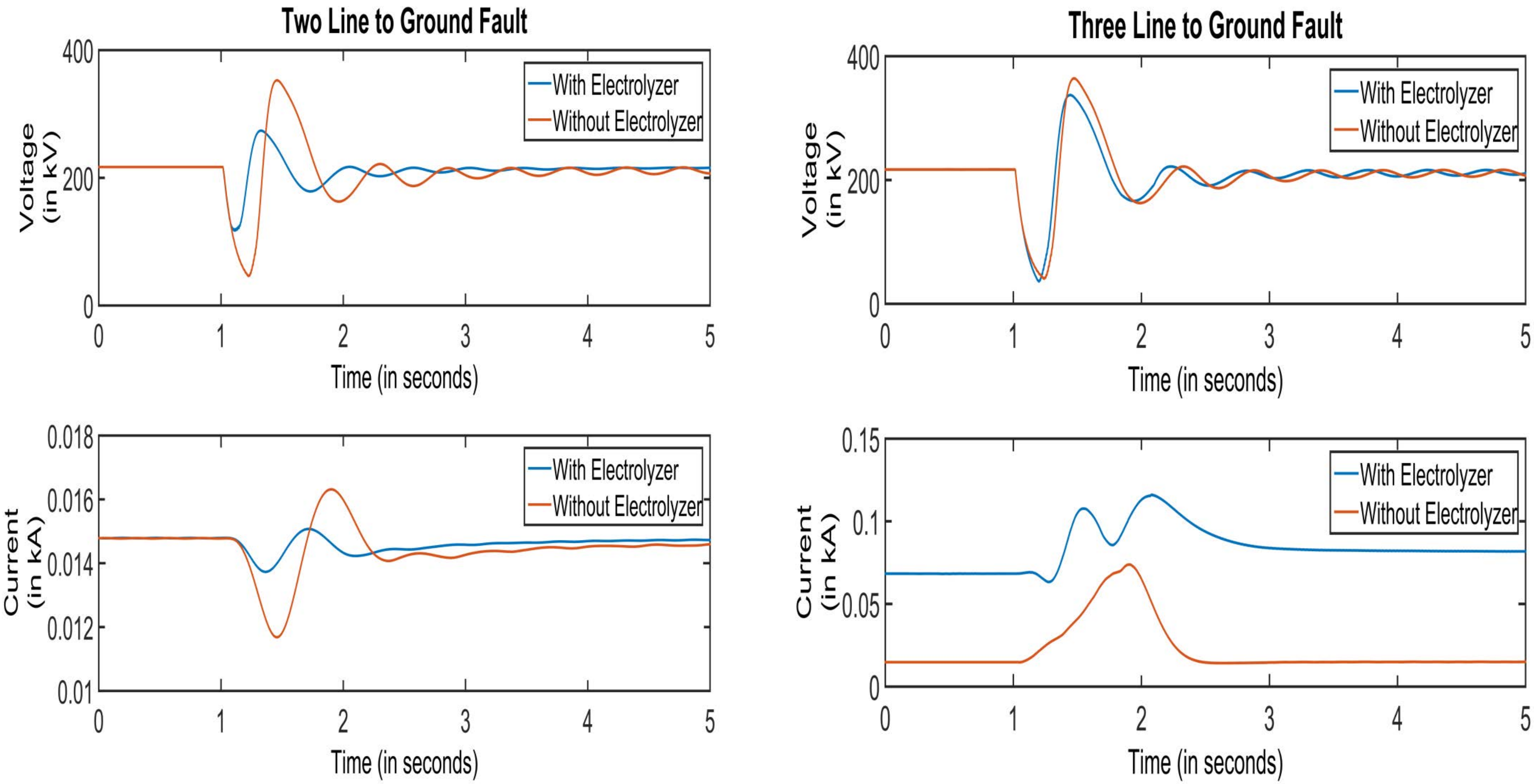
Real-time grid model of Pacific Gas & Electric that covers hydrogen refueling station interconnections

- Several current and future locations of the hydrogen refueling stations are generated from earlier NREL studies
- Network synthesis and modeling in real-time simulator at INL, represents the PG&E infrastructure
- It spans major distribution and coupling transmission lines (from 69 kV to 138 kV) associated with the hydrogen refueling infrastructure
- Serves as a testbed for testing grid services and stability of connecting electrolyzers in utility systems
- Centralized and distributed electrolysis is assessed under different grid and market conditions



Impacts of Electrolyzer on Power System Transient Stability

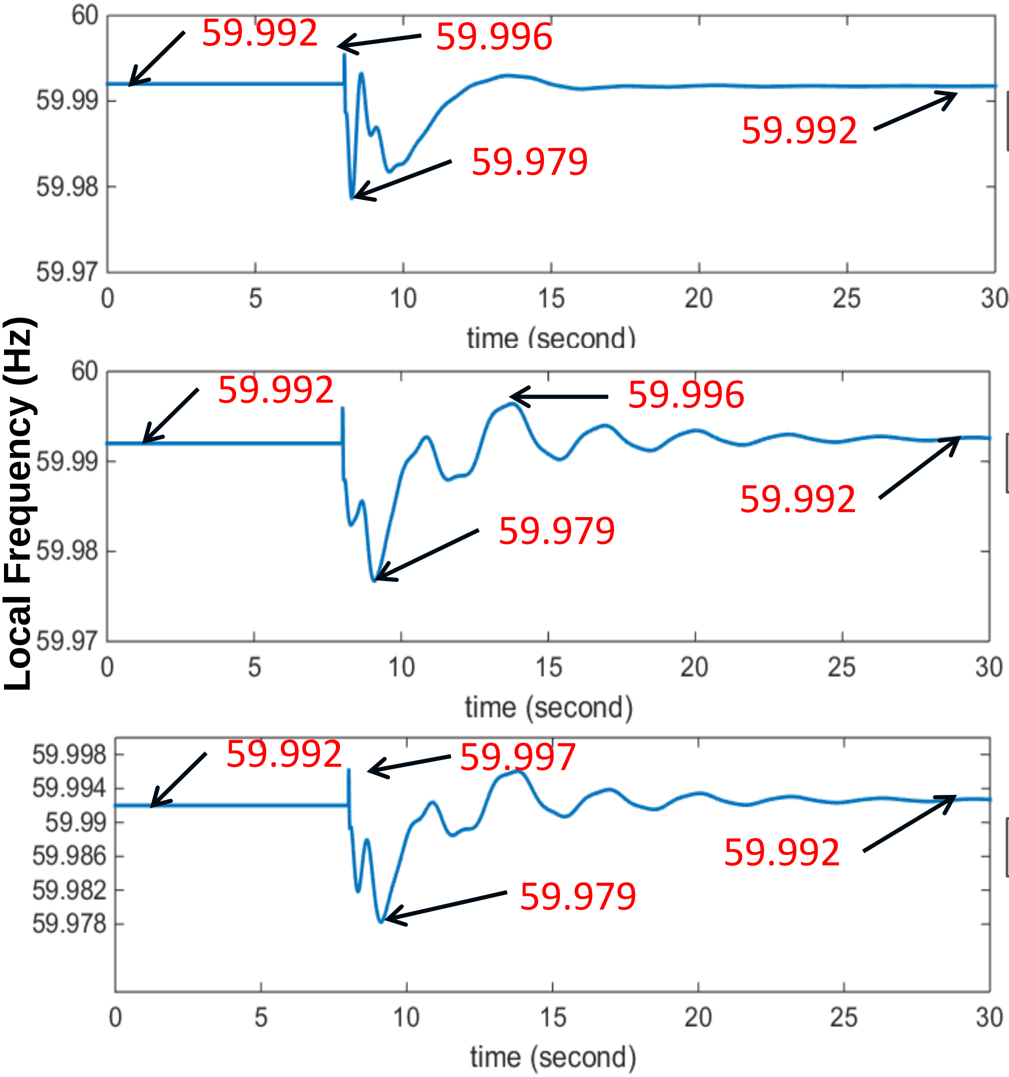
Demonstration of reduction in transients created from faults with electrolyzers in the grid

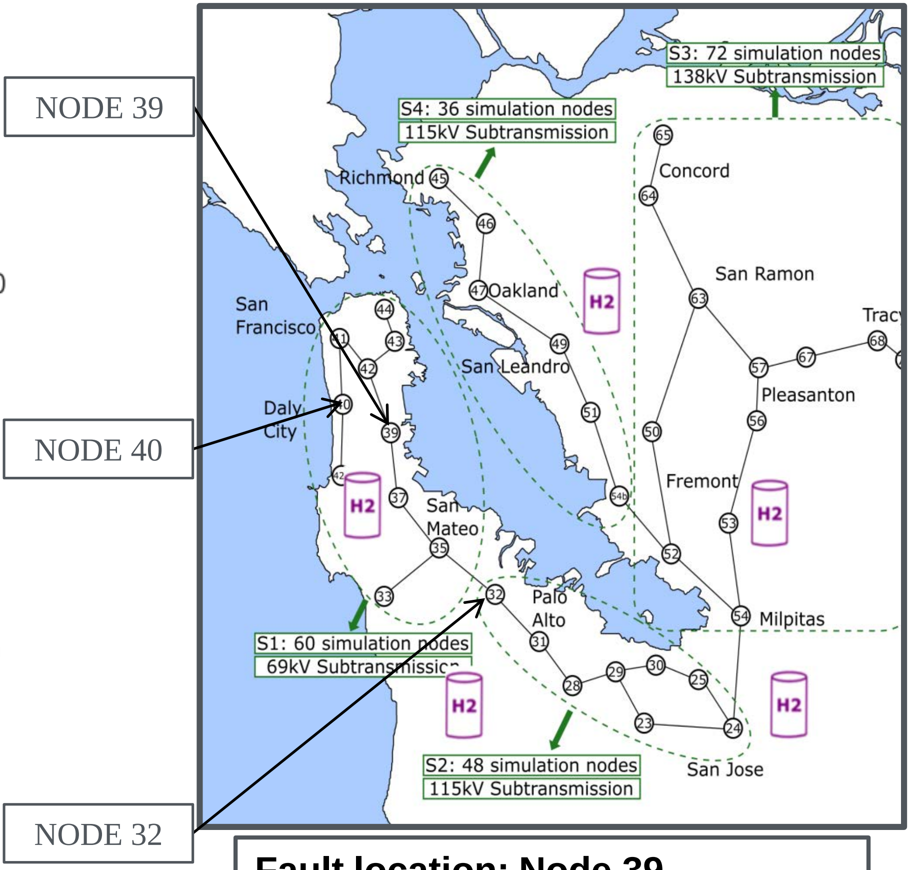


Resistive Capabilities and Impacts on the Grid

Frequency Support by Multiple Electrolyzers with FEC

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

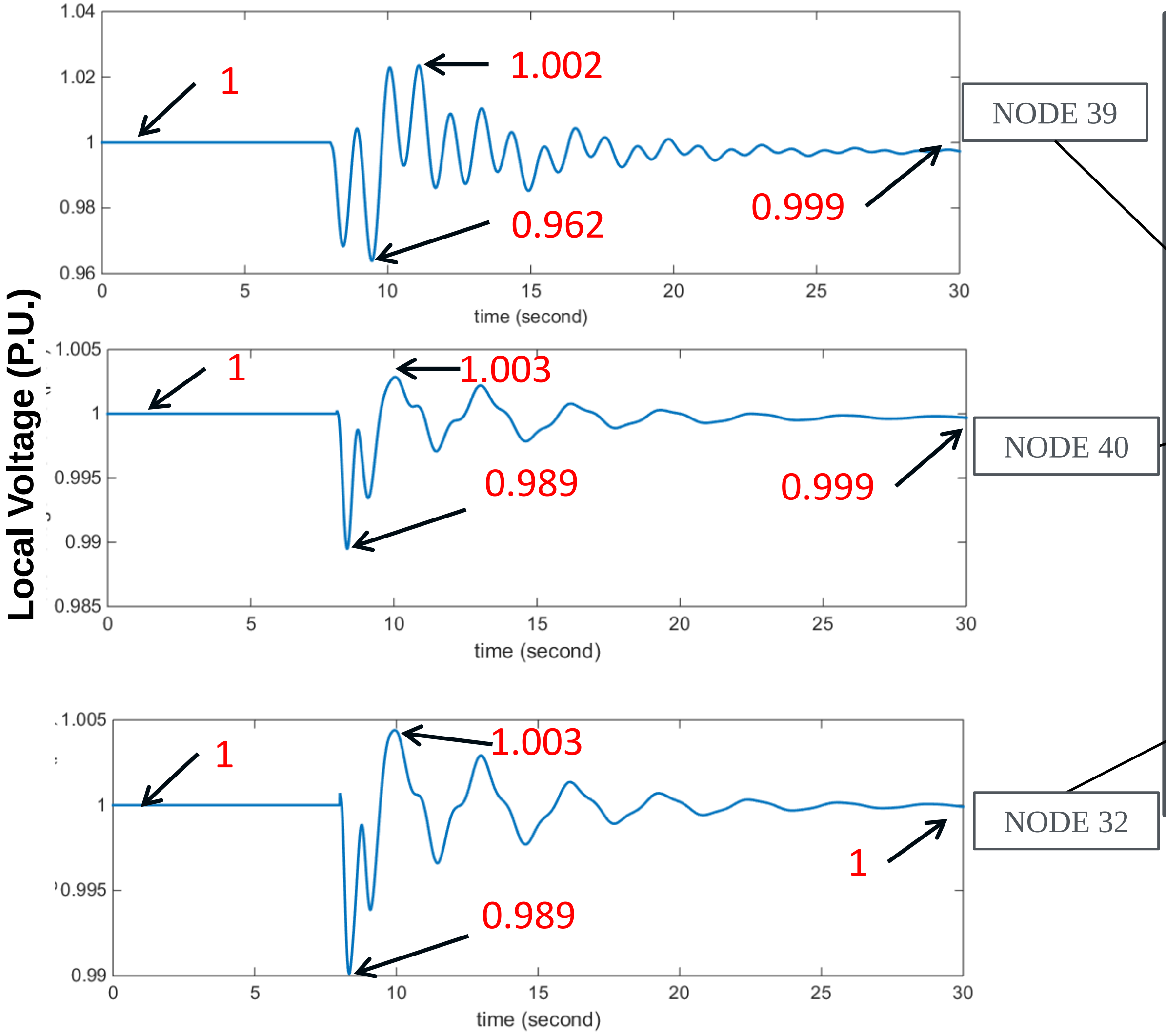


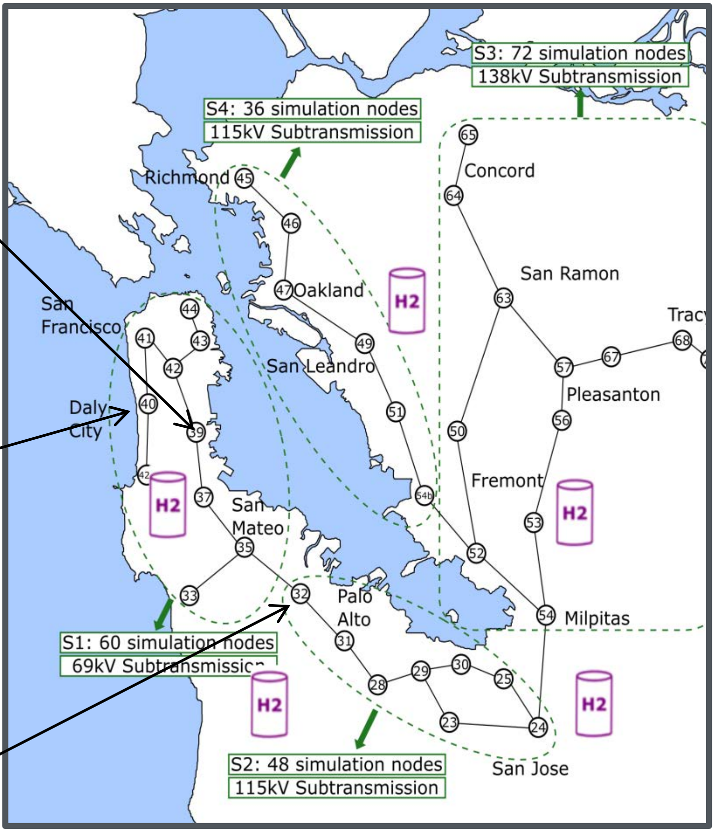


Fault location: Node 39
Fault type: Three phase balance
Fault duration: 0.1 seconds

Voltage Support by Multiple Electrolyzers with FEC

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





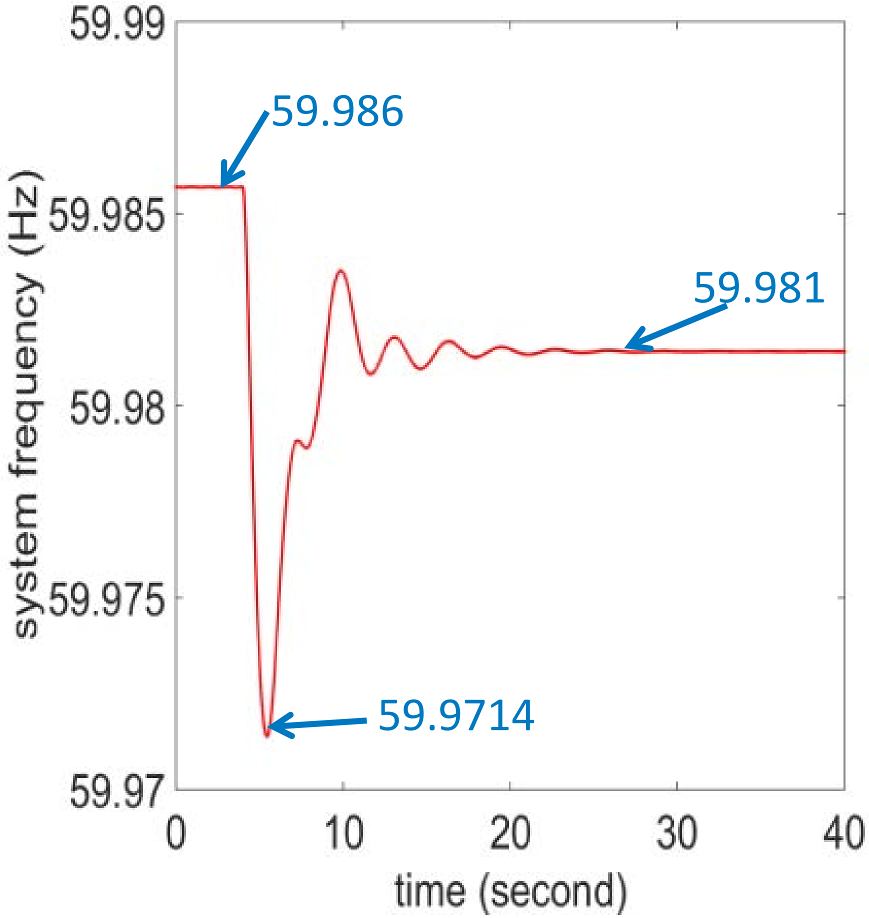
Fault location: Node 39

Fault type: Three phase balance

Fault duration: 0.1 seconds

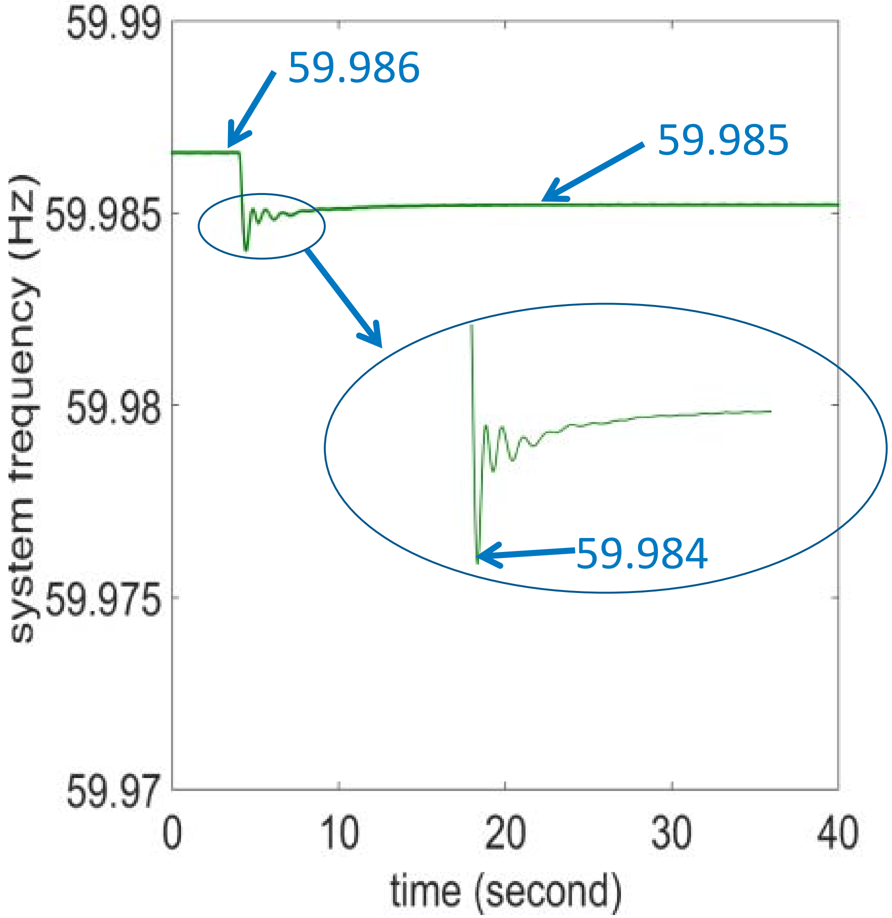
Frequency Support by Centralized Electrolysis

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



Electrolyzer Response

Without FEC



Electrolyzer Response

With FEC

Voltage Support by Centralized Electrolysis

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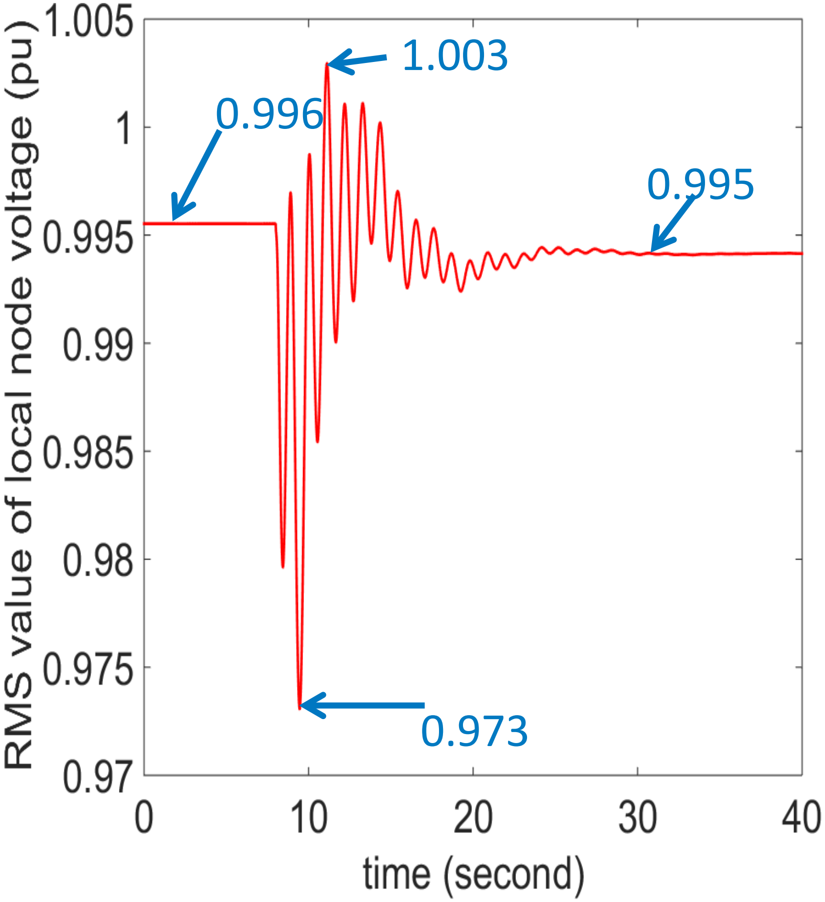
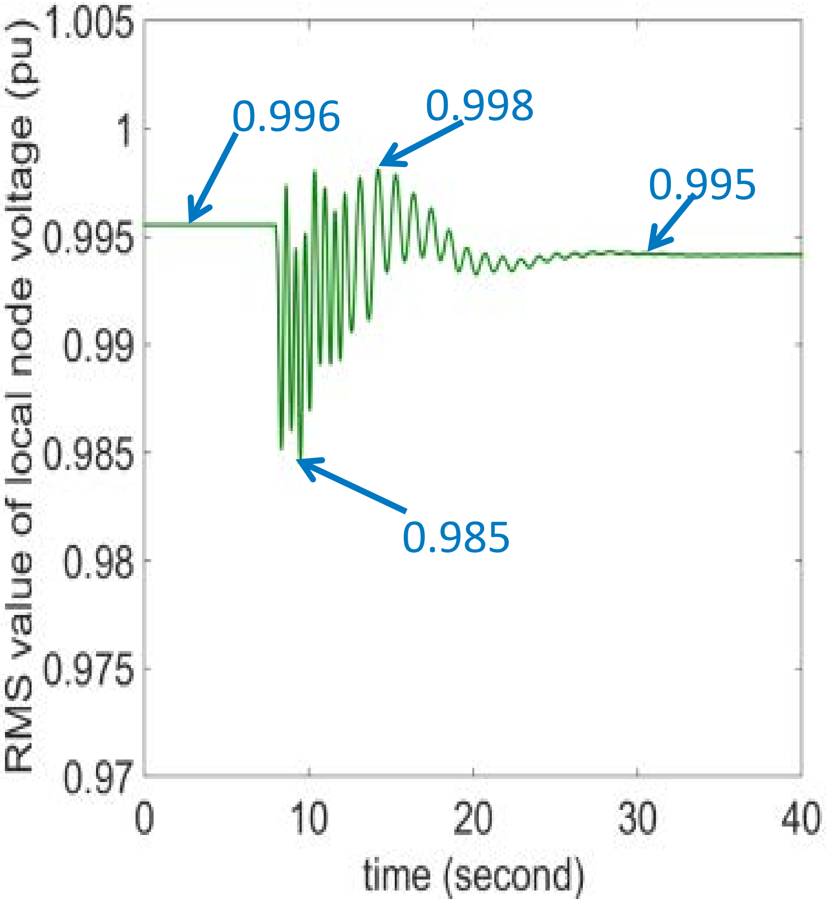


Electrolyzer response without FEC



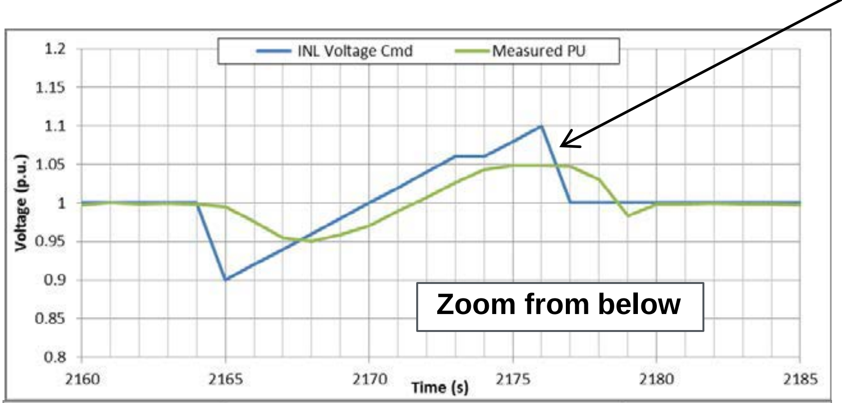
Electrolyzer response with FEC

Grid Simulator Based Control of Electrolyzer Stack

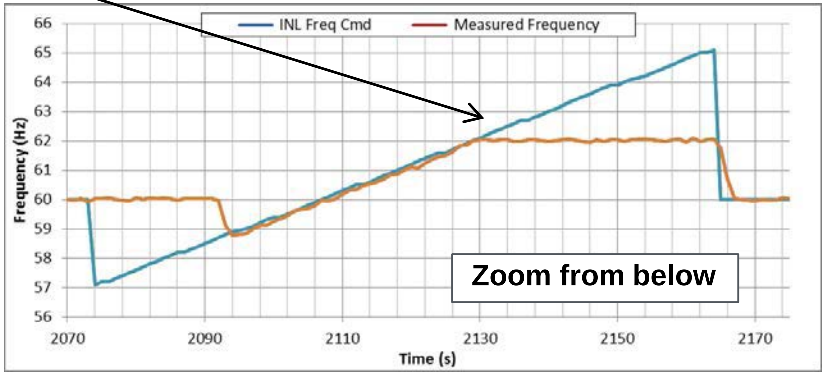
First use of grid simulator capability at ESIF to control the electrolyzer power supplies

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

Command outside of limitation



Zoom from below



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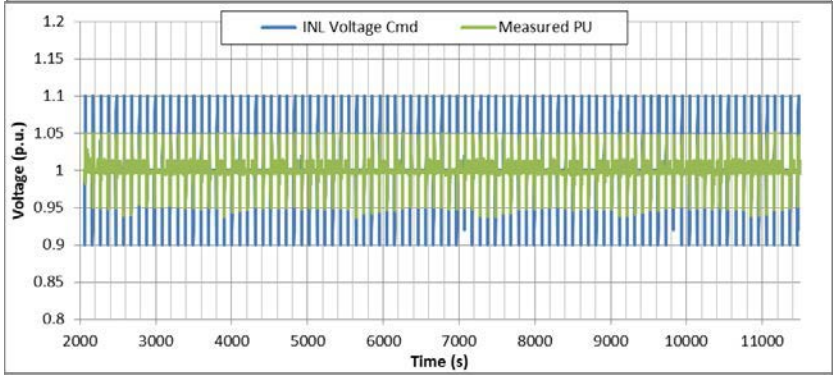
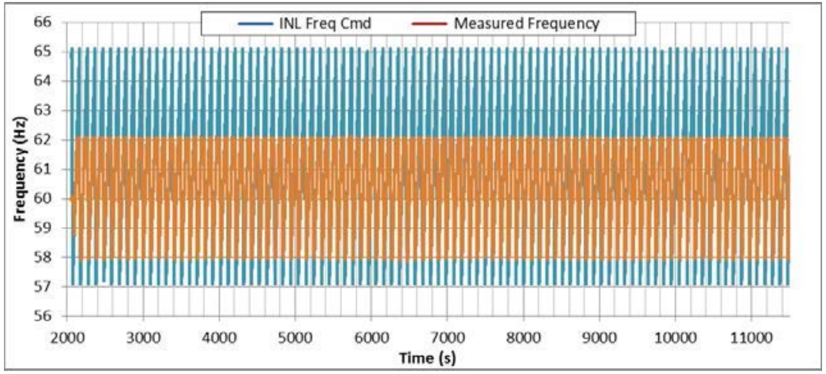
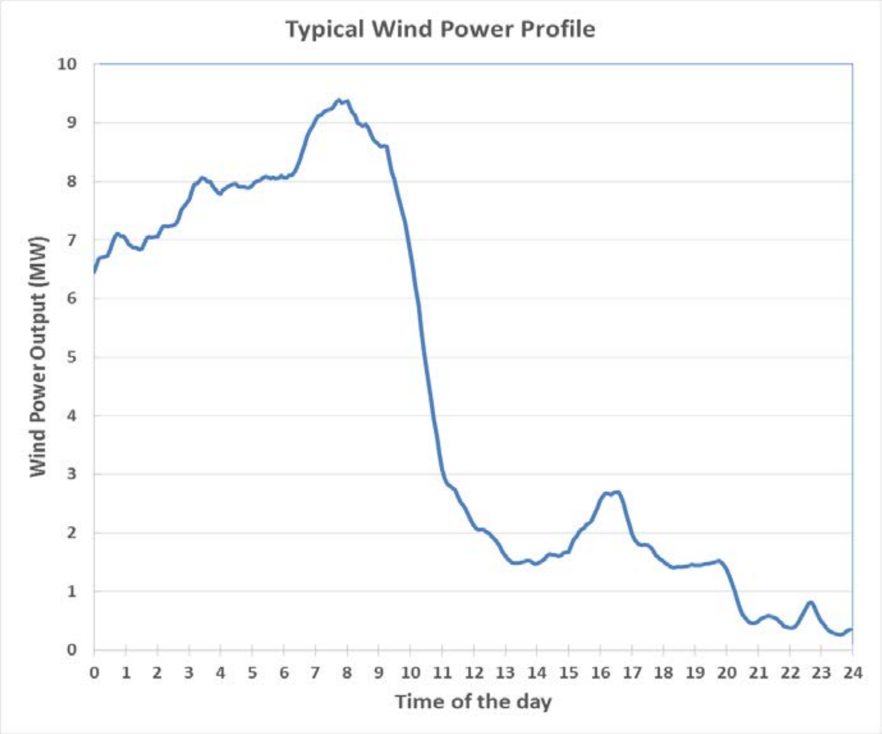
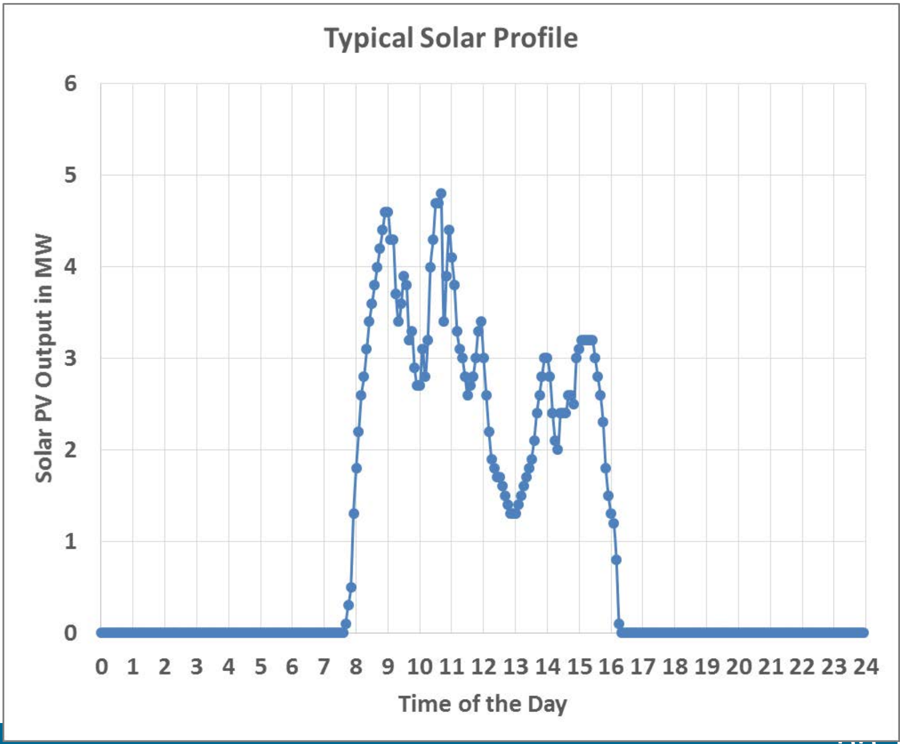




Variability of Renewable Energy Sources

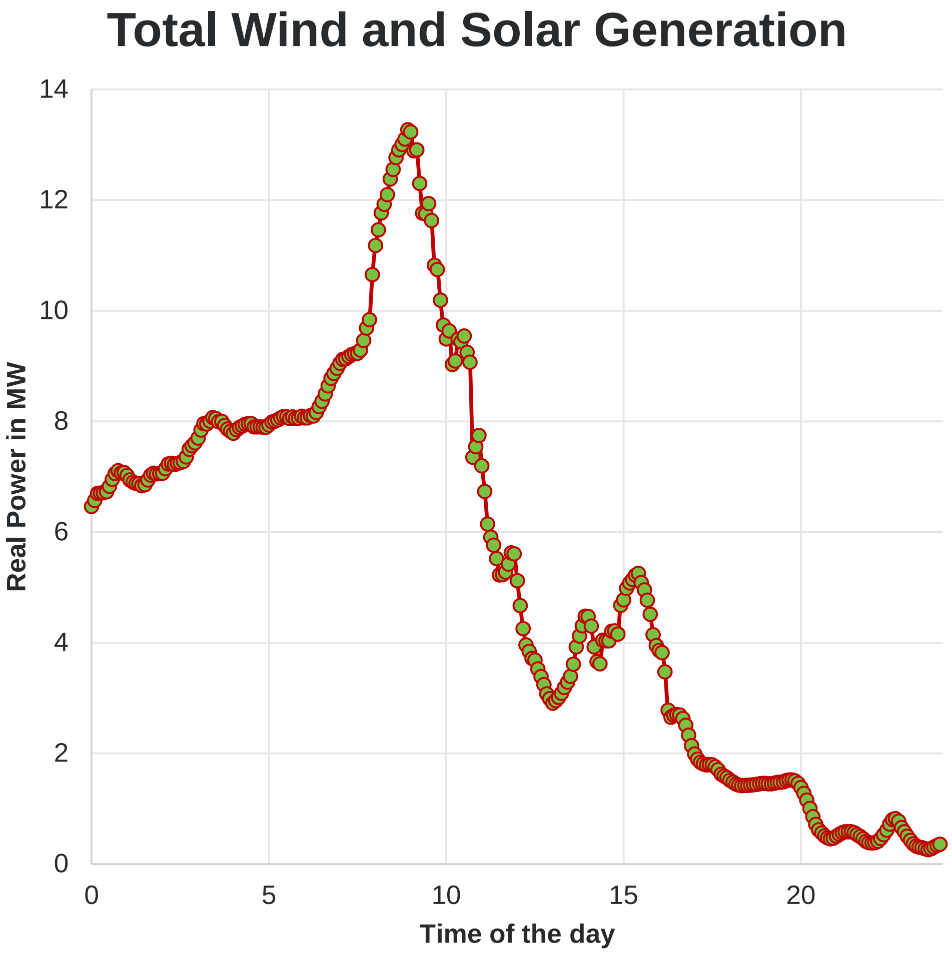
- Renewable Energy sources such as wind and solar demonstrate high degree of time dependent variability i.e., seconds to minutes to days…
- Electrolyzers have an innate capability to respond in seconds to follow control set points
- How can electrolyzers offset the variability observed by the power?
  - Grids expected predictable and non-varying generation sources
  - Hydrogen demands per day for different years are used as a constraint





2018 Case with 7,200 FCEVs

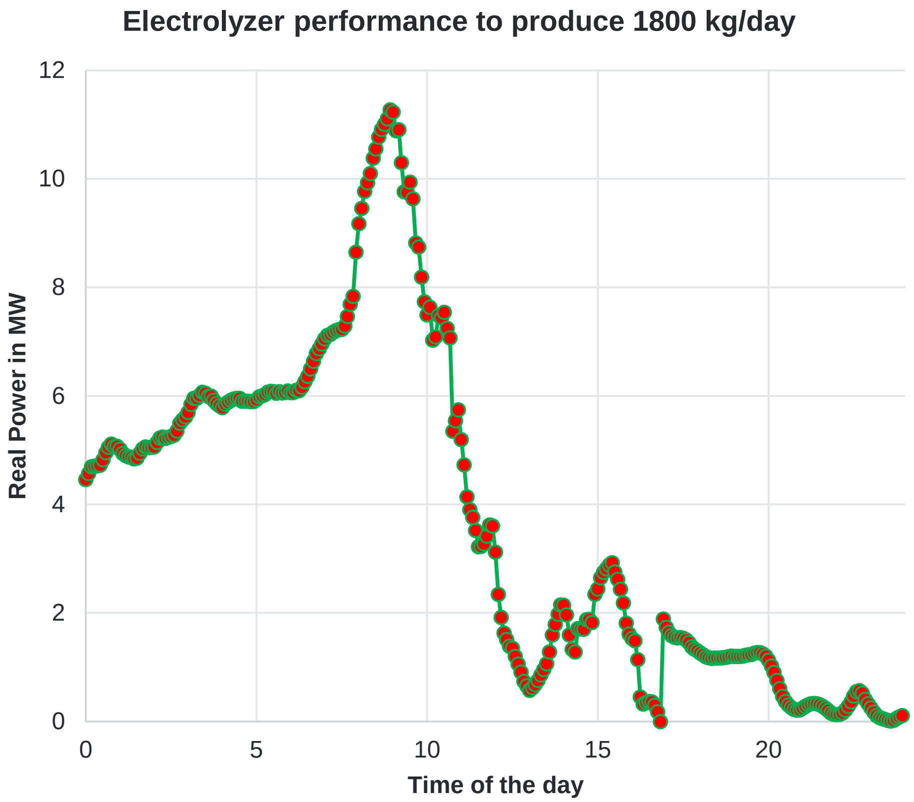
- Objective: Offset time-dependent, aggregated variability of solar and wind power using electrolysis
- Total of 13 MW electrolyzer plant is used for this example
- 2018 test case projections from ARB on vehicle fuel use to generate 1,800 kg/day of hydrogen for 7,200 FCEVs
- Approximate fuel dispensed in Santa Clara, Sacramento, San Francisco, Marin, Contra Cost and Alameda county
- Total energy consumed to generate this hydrogen demand 90.28 MWh/day

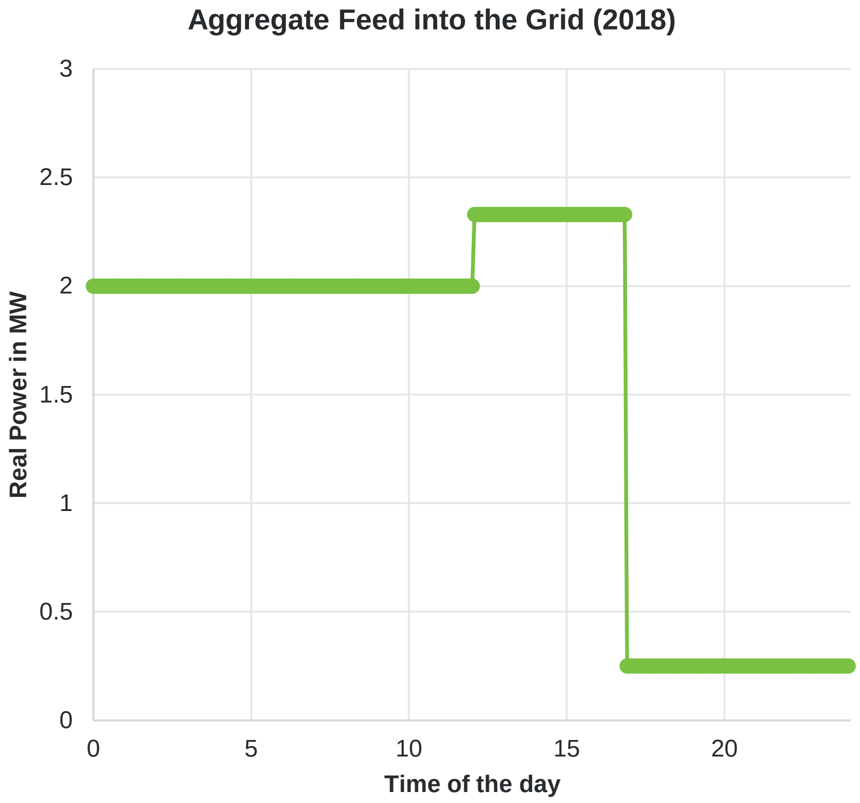


Wind, Solar, and Electrolysis

- Advanced control of a 13 MW electrolysis plant to offset variability of wind and solar power

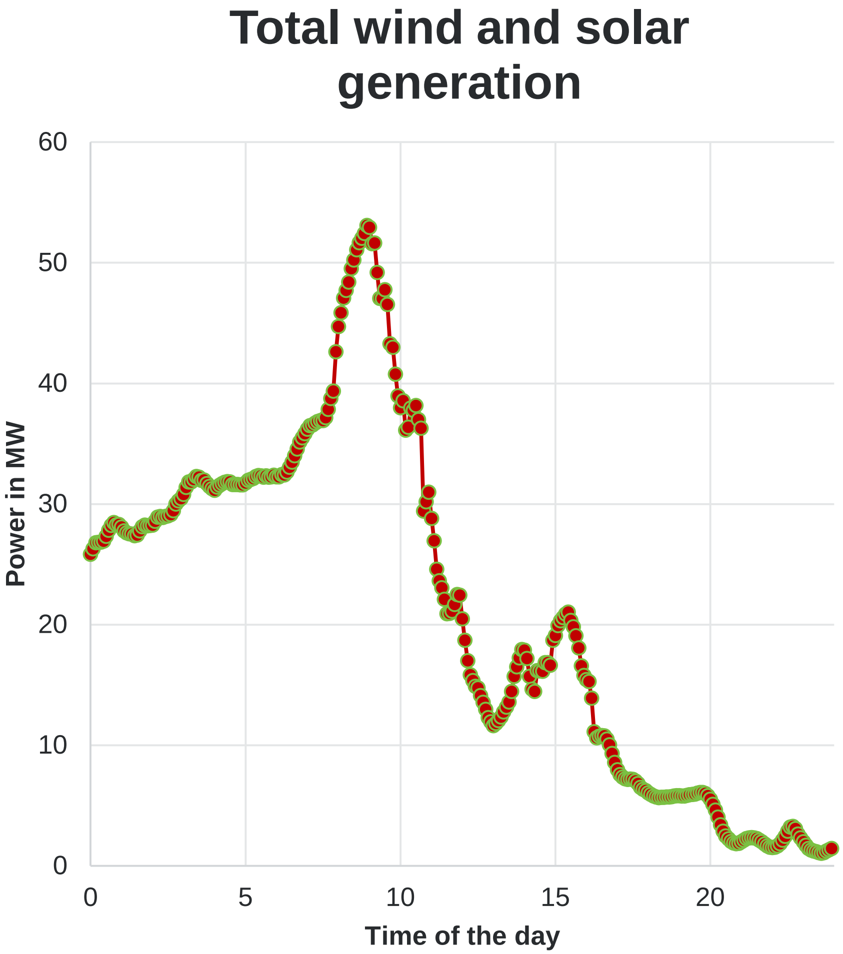
- A fixed and predictable power injected into the grid from solar and wind plant due to coordinated operation with electrolyzers





2022 Case with 43,600 FCEVs

- Objective: Offset time-dependent, aggregated variability of solar and wind power using electrolysis
- Total of 45 MW electrolyzer plant is used for this example
- Typical efficiency of PV ~20-30%
- 2022 test case is used as reference to generate 7,575 kg/day of hydrogen for 43,600 FCEVs
- Approximate fuel dispensed in Santa Clara, Sacramento, San Francisco, Marin, Contra Cost and Alameda county
- Total energy consumed to generate 330 MWh/day



Wind, Solar, and Electrolysis

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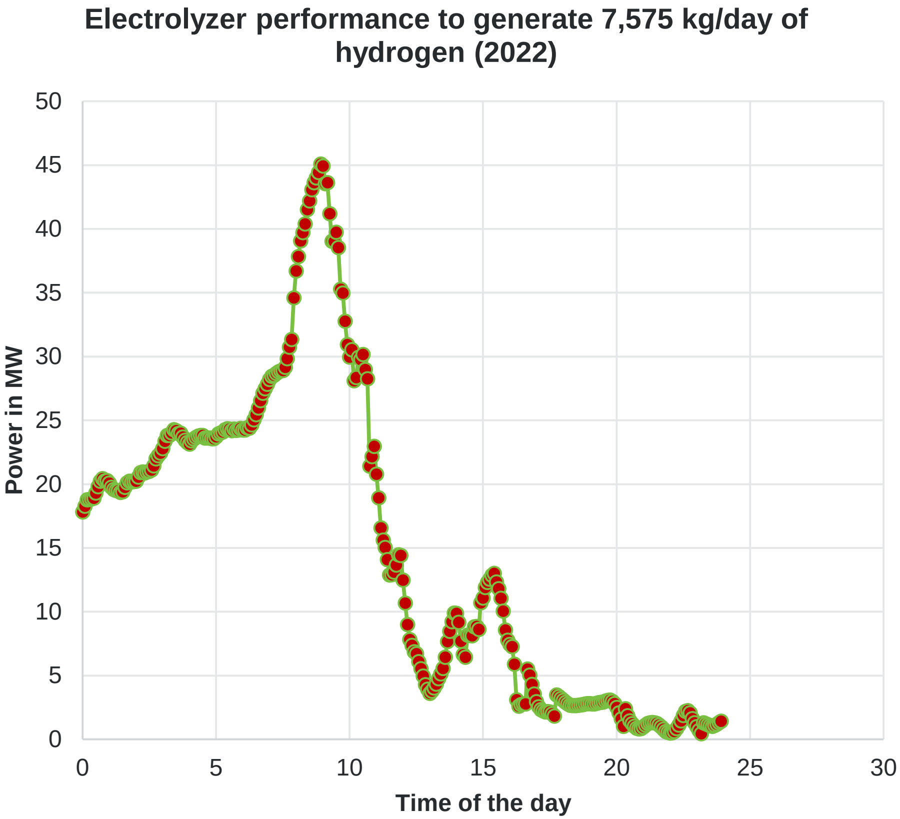

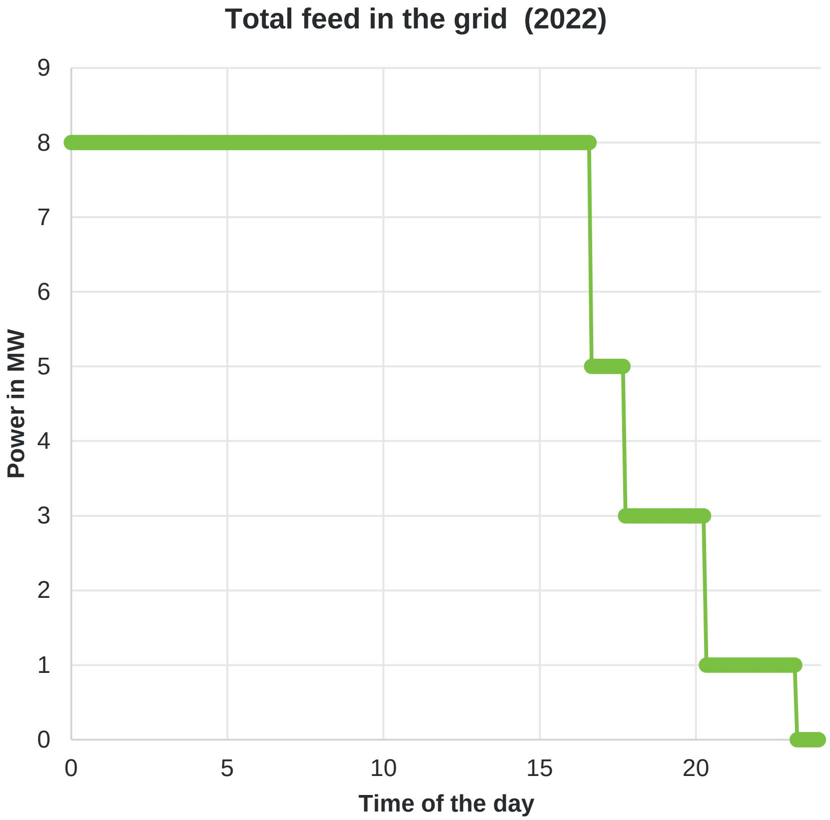

Future Work

- 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

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)*

Thank you

Backup Slides

Identified Grid Services 1

- Peak capacity management
  - deploying fleets of electrolyzers to consistently and reliably reduce critical peak loads within a defined region or location on the grid
- Energy market price response
  - fleets of electrolyzers consume energy when prices are low and defer consumption (set energy free) when prices are high
- Regulation
  - operating point adjustment counteracts short-term changes in electricity use that might affect the stability of the power system
- Spinning Reserve
  - by reducing its power consumption fleets of electrolyzers can support the event when loss of generation unit in the grid occurs

Identified Grid Services 2

- Ramping
  - analogue to generator, fleets of electrolyzers start and stop on command, while the "ramp rate" is the rate at which they can increase or decrease consumption
- Artificial inertia
  - fleets of electrolyzers regulate active power consumption in response rate of change of frequency
- Distribution voltage management
  - upon detecting the voltage deviations (self-sensing and/or receipt of external measurement signals) fleets of electrolyzers adjust the net load in the form of their reactive and/or real power components
- Autonomous grid service responses
  - additional (high-level) controller enables grid services in "stand-alone" mode

Key Capabilities of Electrolyzers

- Purely resistive load, supplied from a DC source (power converter)

- Very high rate of change and flexibility in setting power operating points

- Capable of sensing deviations in power systems, capable of adjusting their operating points to support the grid (fleets of electrolyzers)

- Frequency and voltage support by reducing/increasing power consumption

Controller Requirements

- High-level controller (Front-end controller)
  - applies EMS requirements and supports power quality by varying the electrolyzer's operating point