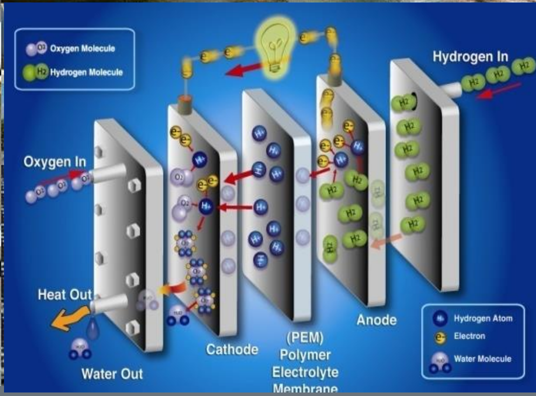
# U.S. Department of Energy Fuel Cell Technology Office

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy








## Role of Electrolyzers in Grid Services

05/23/2017

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Power and Energy Systems
Idaho National Laboratory

# Funding Acknowledgment


- DOE Grid Modernization Laboratory Consortium (GMLC) project 1.4.2 “Definitions, Standards and Test Procedures for Grid Services from Devices”

- DOE Fuel Cell Technologies Office (FCTO) project “Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation”

# Classes of Devices and Services

## Devices (DERs)

**Responsive, flexible end-use loads**

- Water heaters
- Refrigerators
- Air conditioners
- Commercial rooftop units (RTUs)
- Commercial refrigeration
- Commercial lighting
- Electric vehicles (charging only)
- Electrolyzers

**Storage**

- Battery / inverter systems
- Thermal storage systems
- Electric vehicles (full vehicle-to-grid)

**Distributed generation**

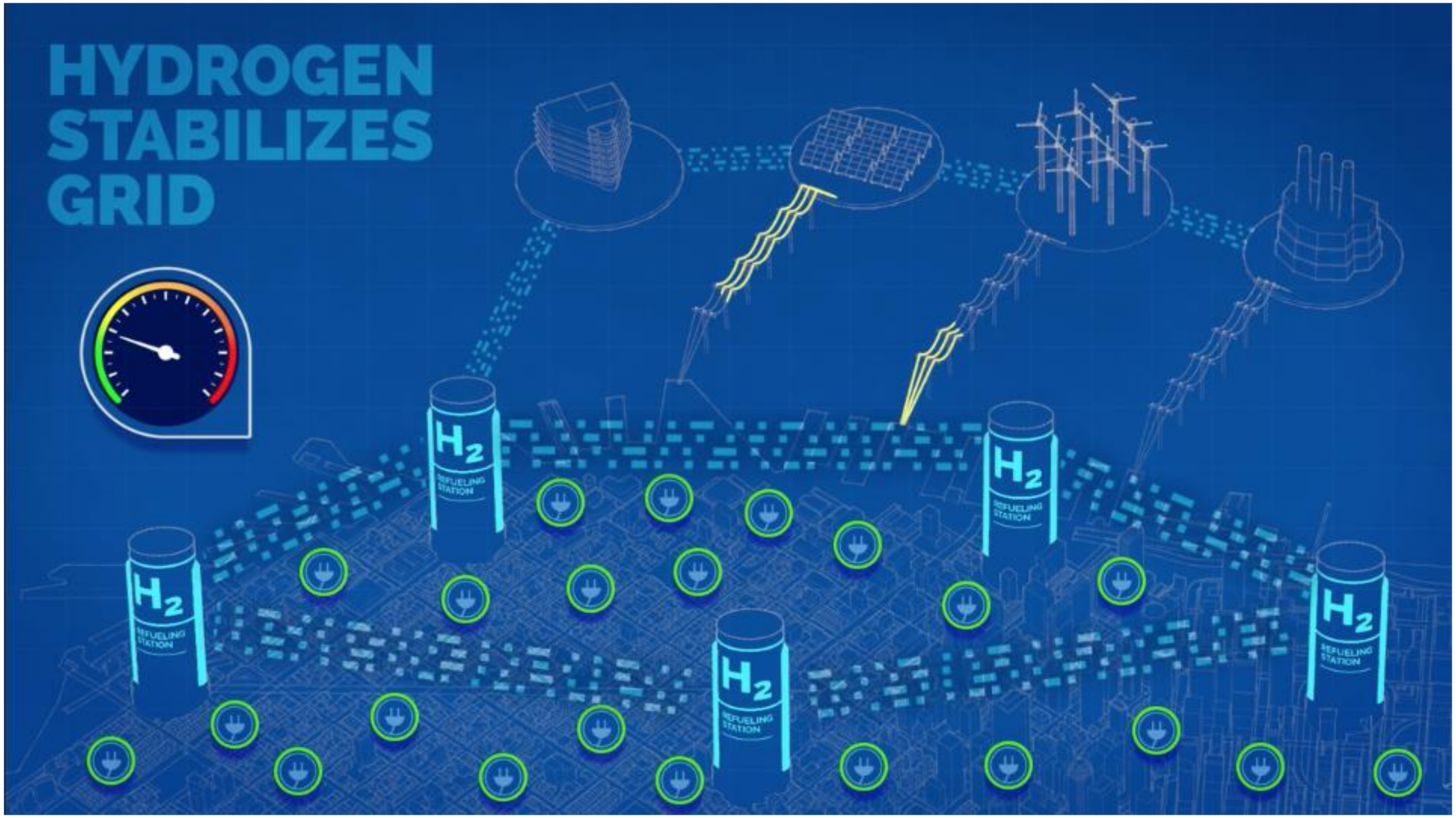
- Photovoltaic solar (PV) / inverter systems
- Fuel cells

## Grid Services

- Peak load management (capacity)
- Energy market price response (wholesale energy cost)
- Capacity market dispatch (market value)
- Frequency regulation (market value)
- Spinning reserve (market value)
- Ramping (new)
- Artificial inertia (new)
- Distribution voltage management (new; e.g., PV impacts management)

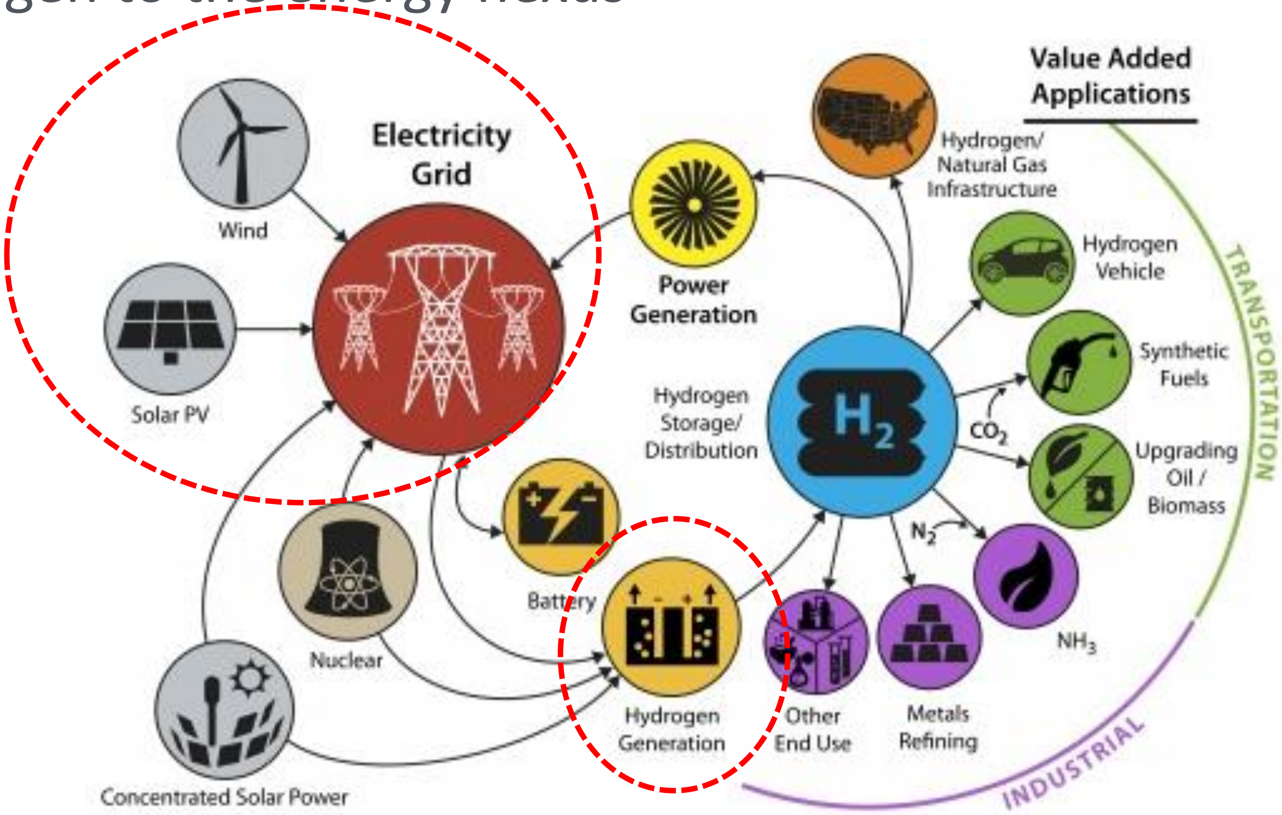
# Motivation

- Hydrogen production and storage during excess generation from renewables or traditional energy sources.
- Hydrogen can provide grid services



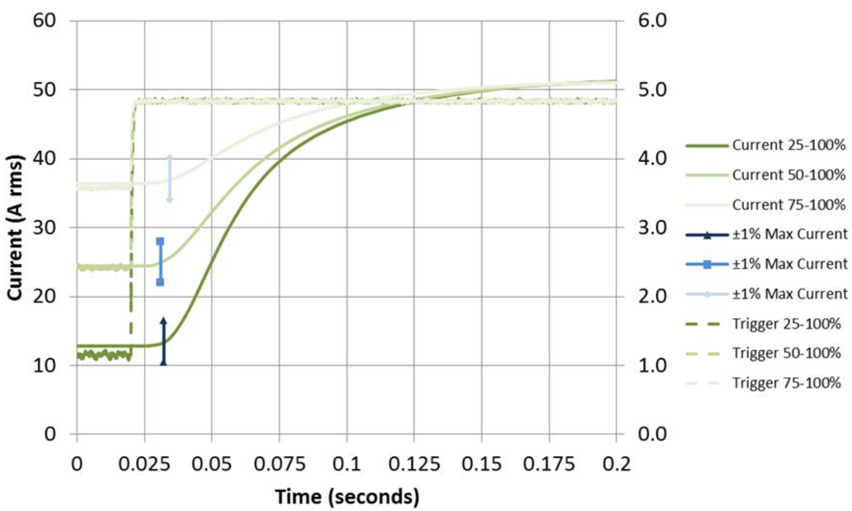
# H2@Scale Relevance

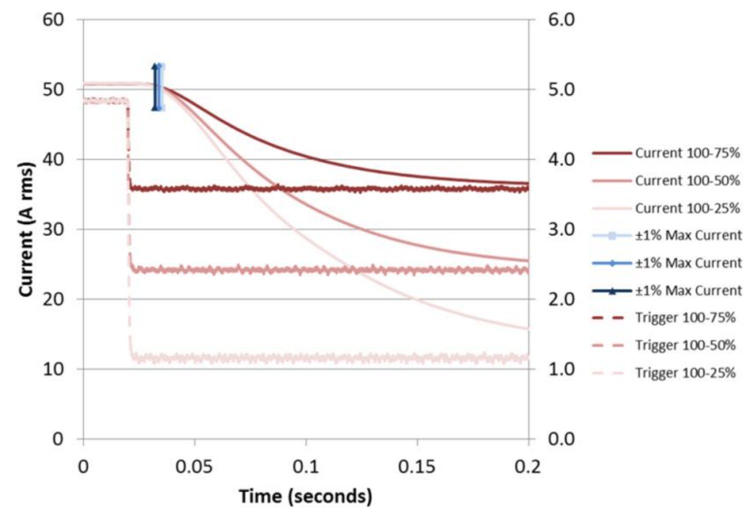
- Current activities - role of hydrogen refueling stations in the electricity grid and renewable energy assimilation
- H2@Scale has a longer term vision with potential benefits of hydrogen to the energy nexus



# Dynamic Characteristics: Ramp-up and Ramp-down Test

- Ramp-up Tests
  - from 25% to: 50%, 75% and 100% of rated power
- Ramp-down Tests
  - from 100% to: 75%, 50% and 25% of rated power



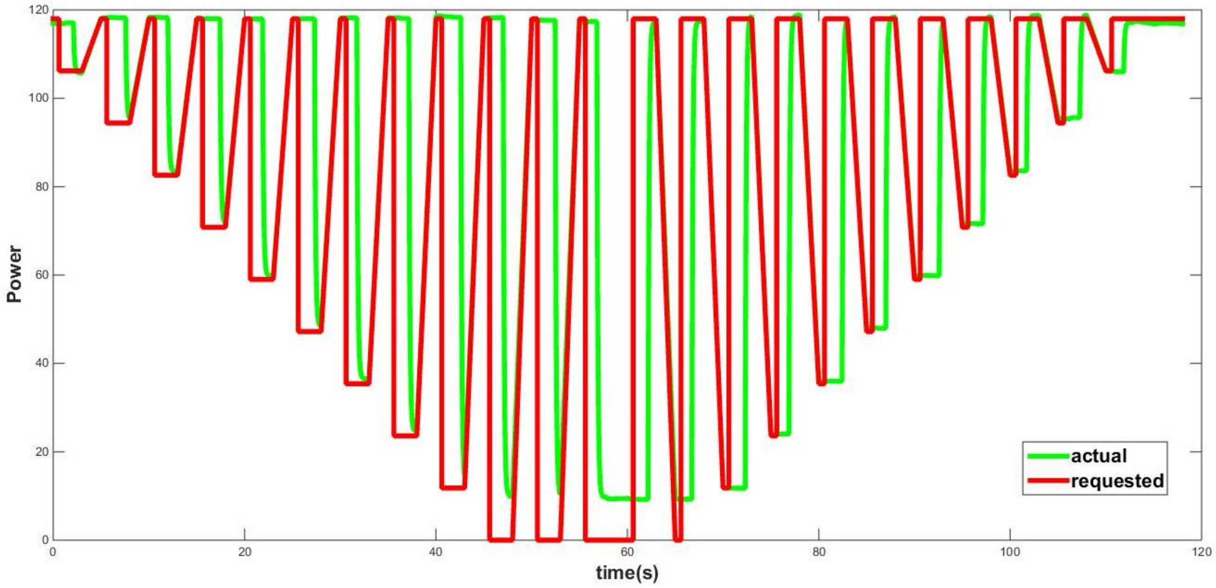




Ramp-up and ramp-down response of a PEM electrolyzer [Ref. 1]

| | PEM electrolyzer |
|---|---|
| Electrical Power | 40 kW |
| Rated Current | 155 A per stack |
| Stack Count | 3 |

# Dynamic characteristics – Power Variation

- Power set-point variation to examine Demand Response
  - quantification of rate of rapid load change and demand response
  - tested with SCADA system – inherent delay of 1 second




INL & NREL testing of a 120kW electrolyzer

# 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

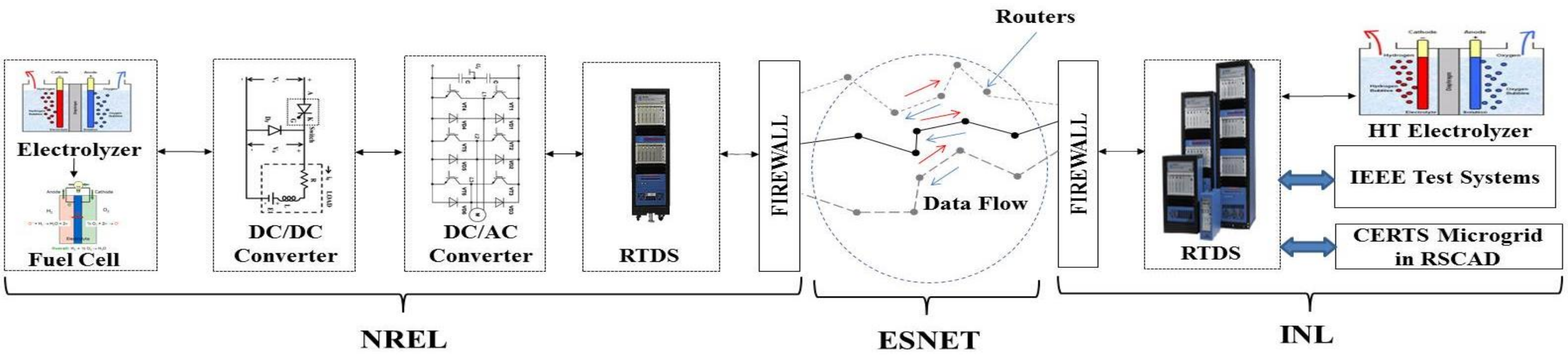


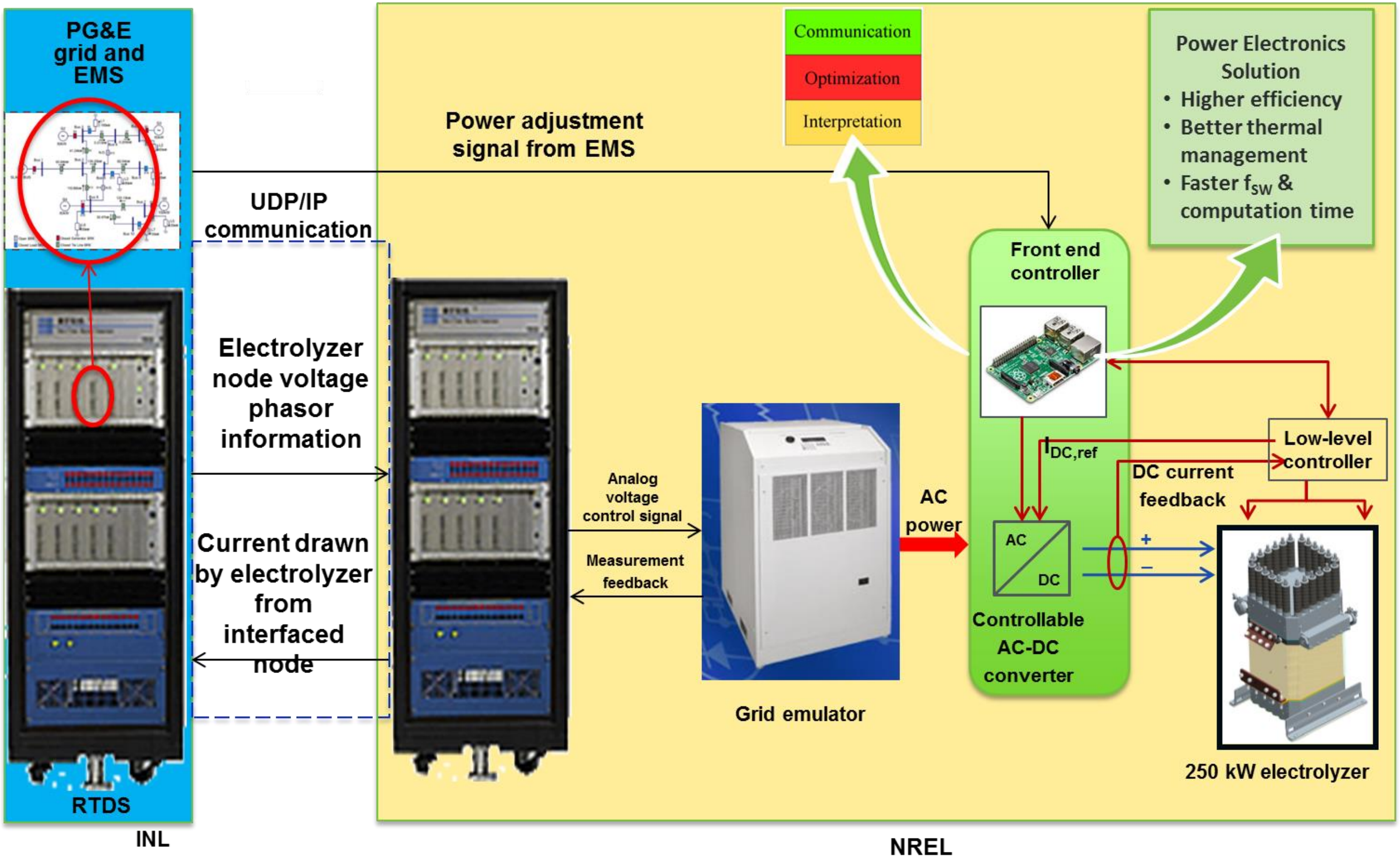
- Purely resistive load, supplied from a DC source (power converter)
- Very high rate of change and flexibility in setting power operating points
- Capable of sensing deviations in power systems, capable of adjusting their operating points to support the grid (fleets of electrolyzers)
- Frequency and voltage support by reducing/increasing power consumption

# Role of Electrolyzers in Grid Services



- 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

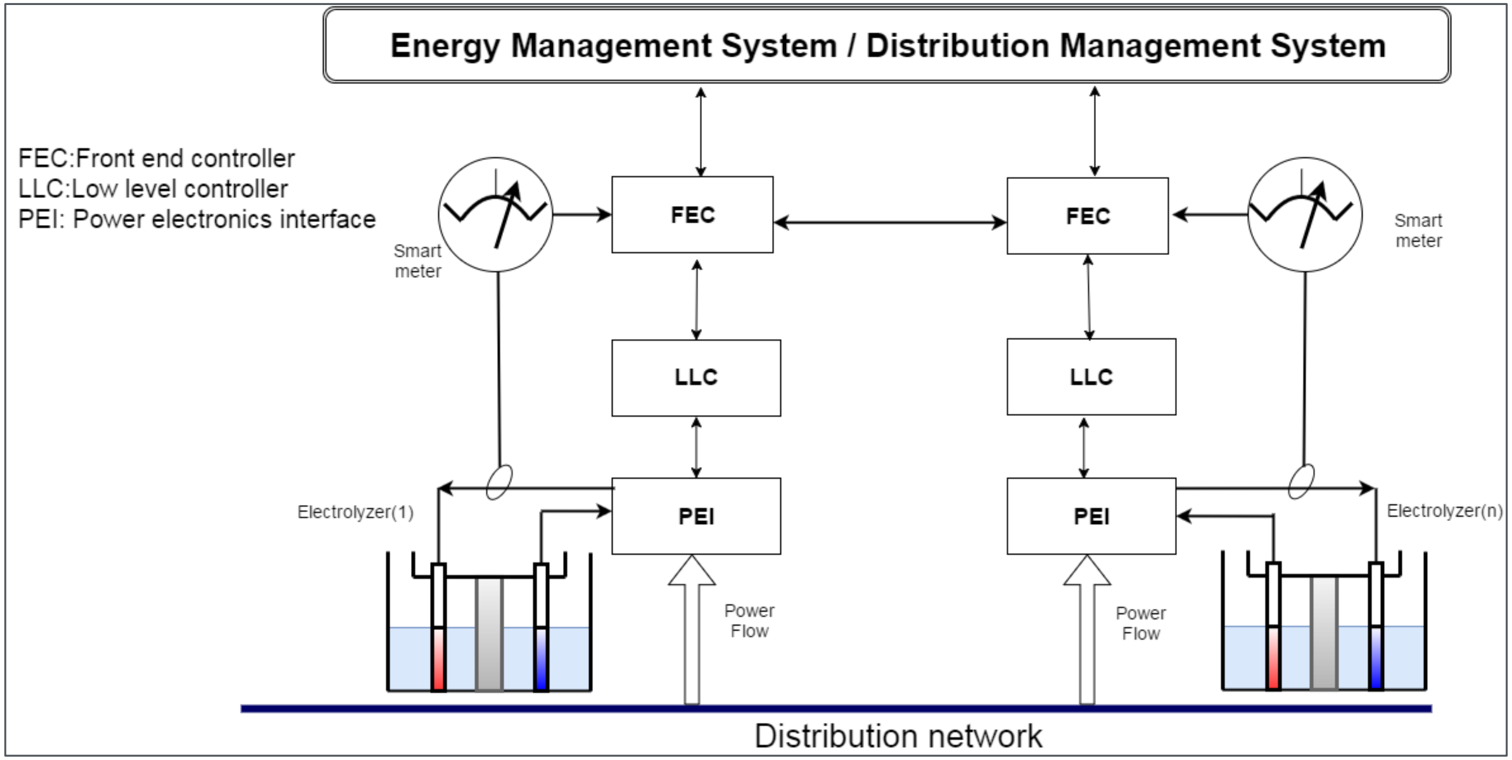




PG&E grid and EMS
RTDS
INL
Power adjustment signal from EMS
UDP/IP communication
Electrolyzer node voltage phasor information
Current drawn by electrolyzer from interfaced node
Communication
Optimization
Interpretation
Power Electronics Solution
• Higher efficiency
• Better thermal management
• Faster $f_{SW}$ & computation time
Front end controller
Analog voltage control signal
Measurement feedback
Grid emulator
AC power
$I_{DC,ref}$
AC
DC
Controllable AC-DC converter
DC current feedback
Low-level controller
+
−
250 kW electrolyzer
NREL

# Controller Requirements

- High-level controller (Front-end controller)
  - applies EMS requirements and supports power quality by varying the electrolyzer's operating point
  - communicates to other FECs to coordinate remedy actions

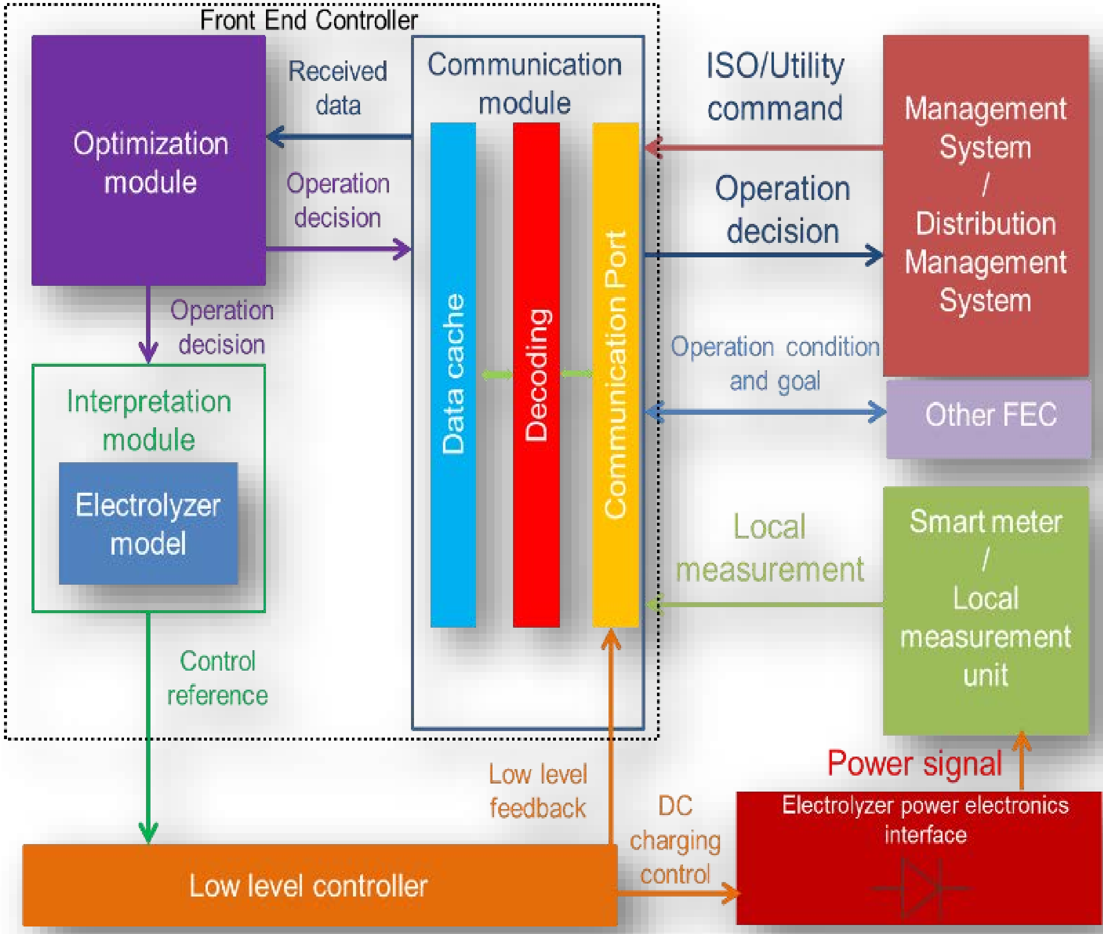


FEC consists of three modules:

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

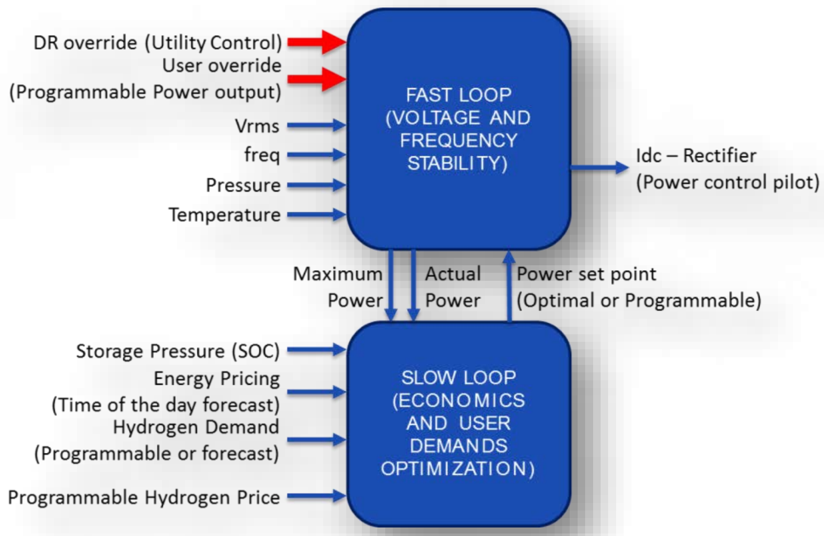
3. **Interpretation module**
   Generates the reference control signal in order to ensure that the low level controller properly integrates with the FEC

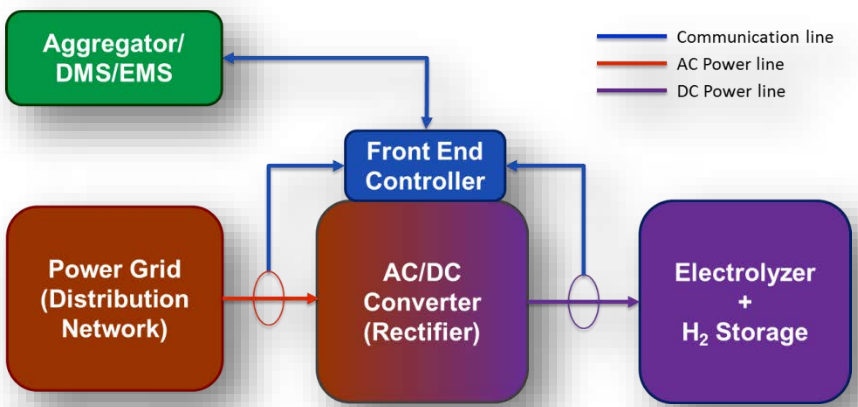


# Front-End Controller Architecture 2

- FEC receives numerous information at input, applies optimization algorithm, and generates reference DC current
- Reference is forwarded to the electrolyzer's low level controller

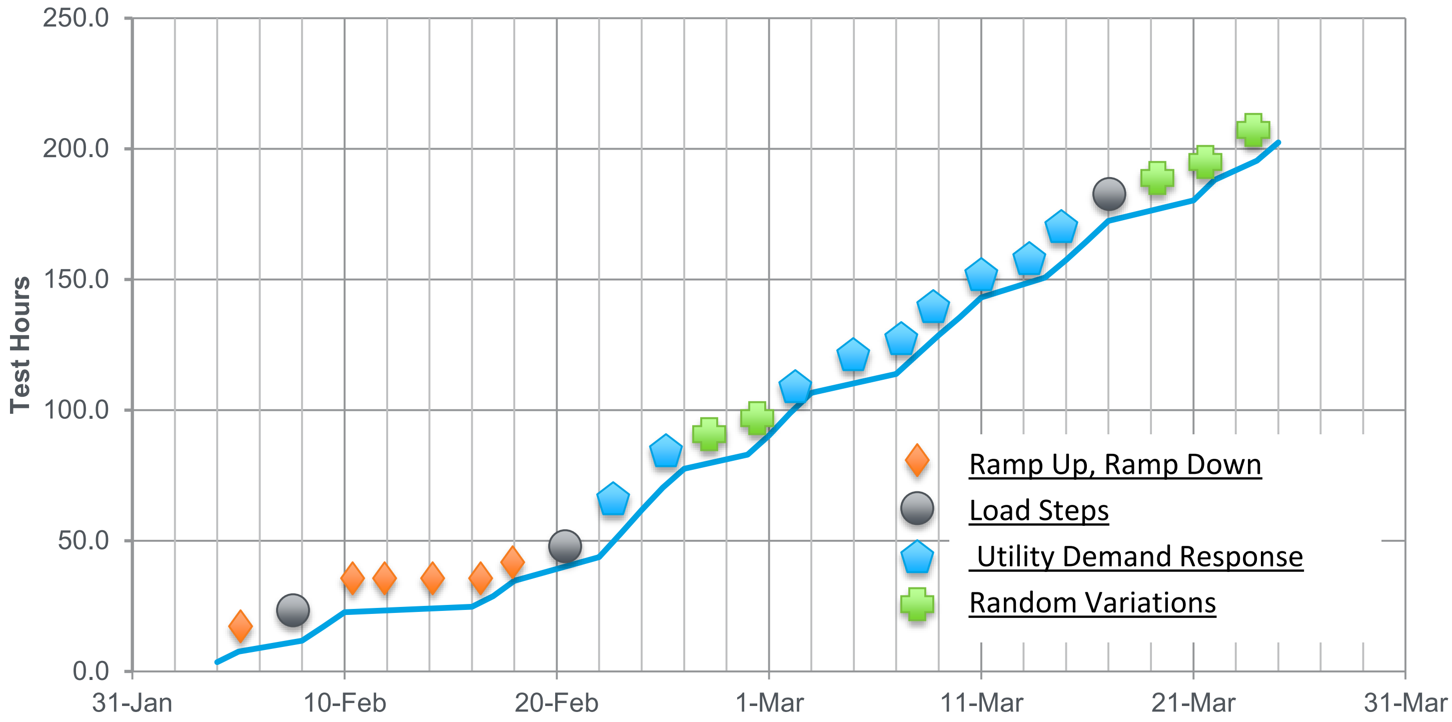
- FEC interfaced with Electrolyzer
- DR Signal received from higher level control (EMS/DMS/Aggregator)
- Local sensing of power quality
- Reference operating point (DC-current) sent to power converter



# Electrolyzer Characterization Testing

**Types of tests run to achieve 200 hour test results**

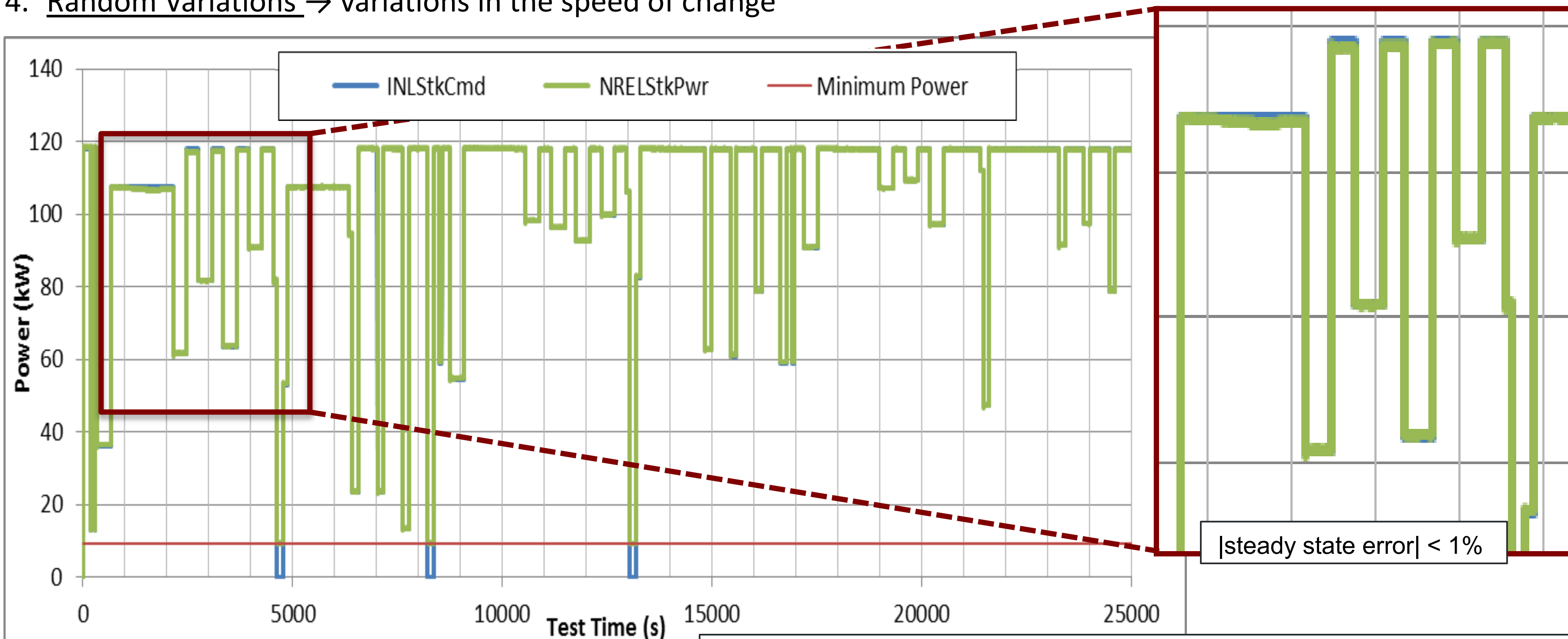


# Demand Response Testing

**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




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.

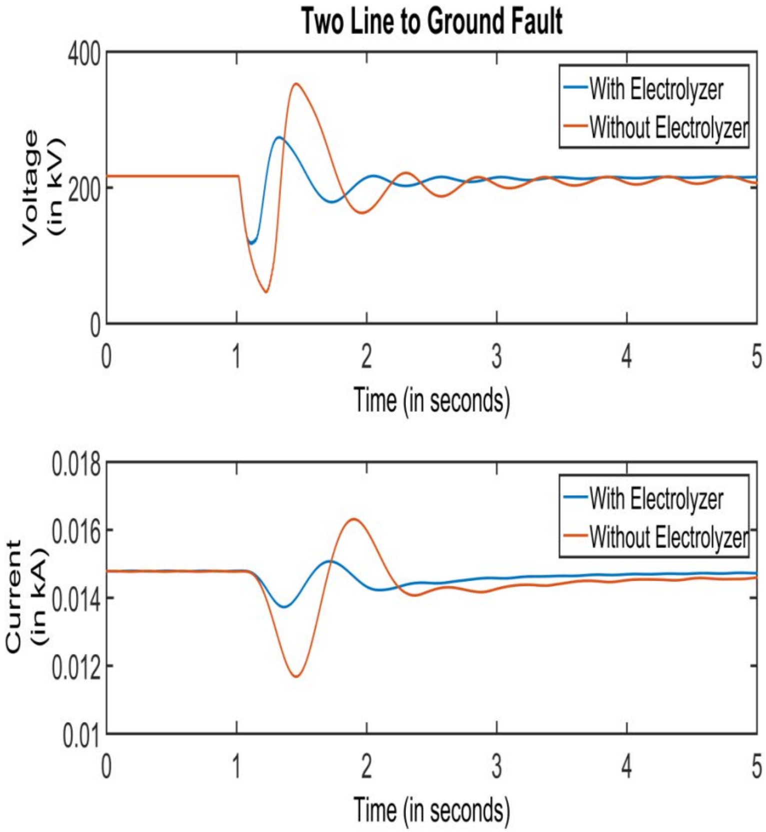
# Electrolyzer Characterization Testing: Summary



**Fast response time & quick slew rate**

| Performance Metric | Ramp-up & Ramp-down | Load Steps | DR | Random Variation in Load |
|---|---|---|---|---|
| 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 |

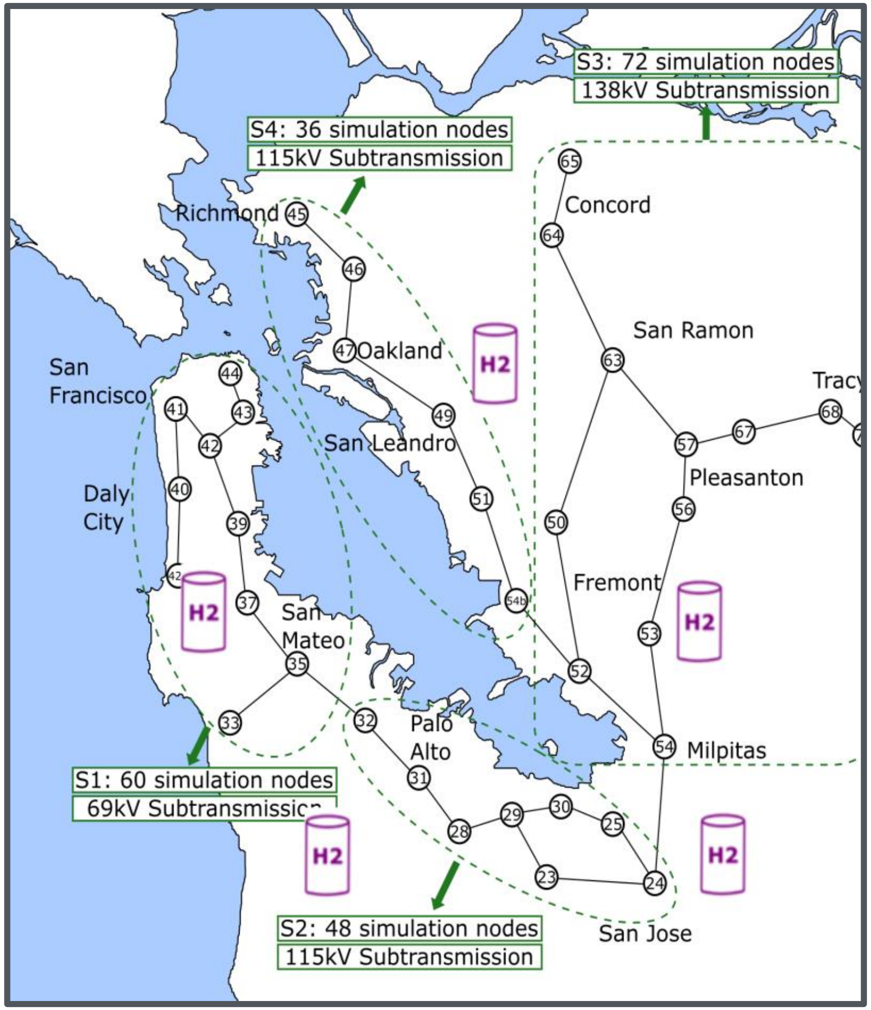
- Demonstration of reduction in transients created from faults with electrolyzers in the grid




**Resistive Capabilities and Impacts on the Grid**

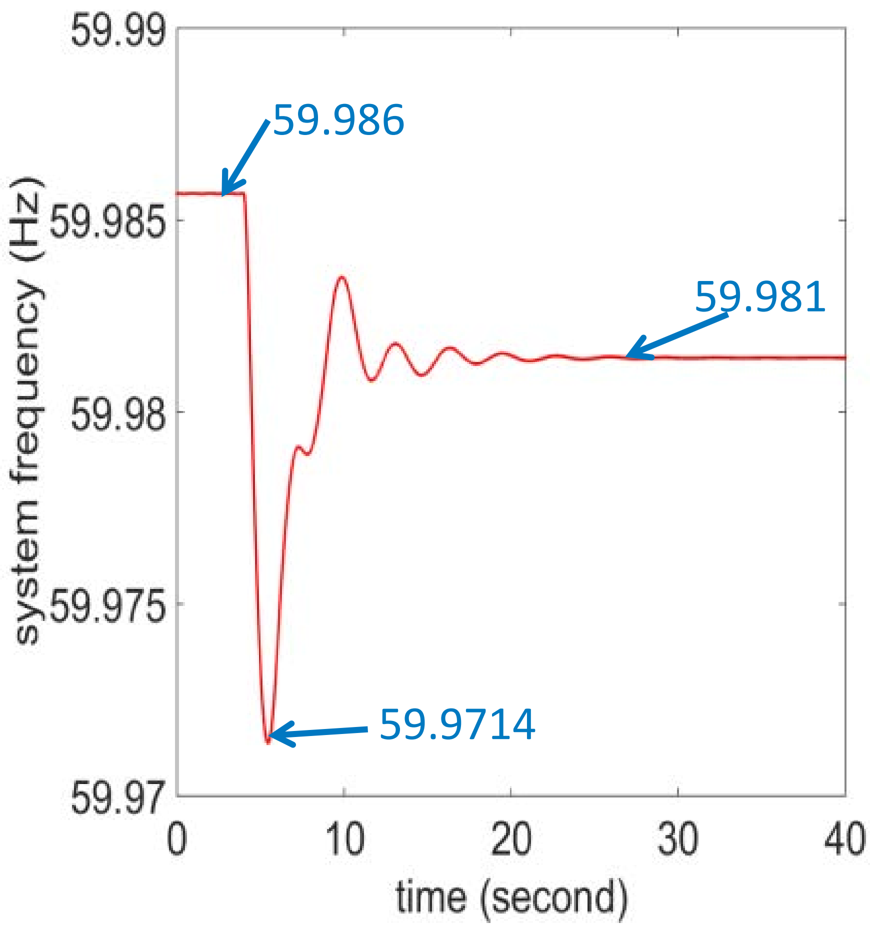
**Real-time grid model of Pacific Gas & Electric that covers hydrogen refueling station interconnections**

- 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

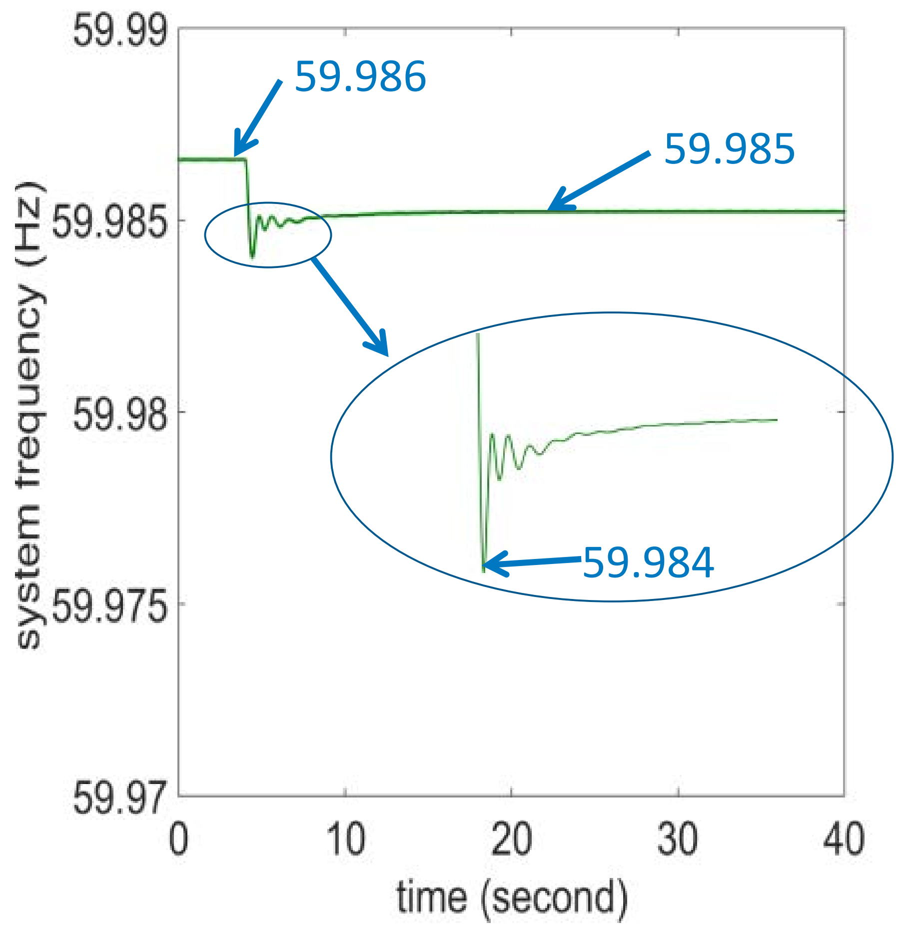


# Frequency Support by Centralized Electrolysis

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



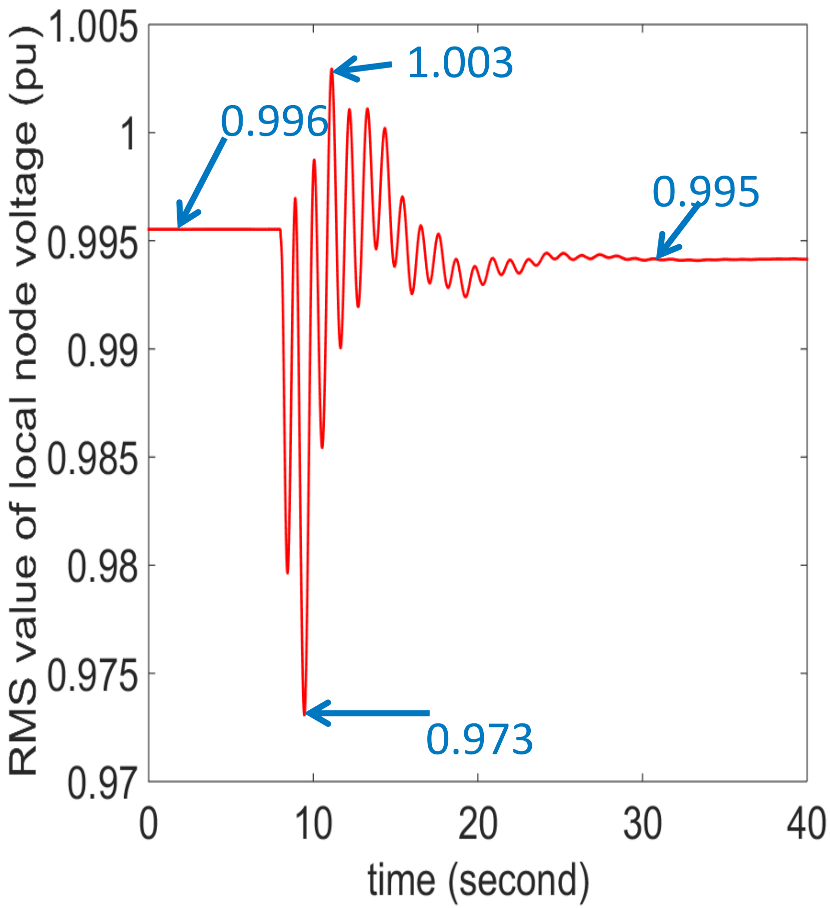

**Electrolyzer Response without FEC**



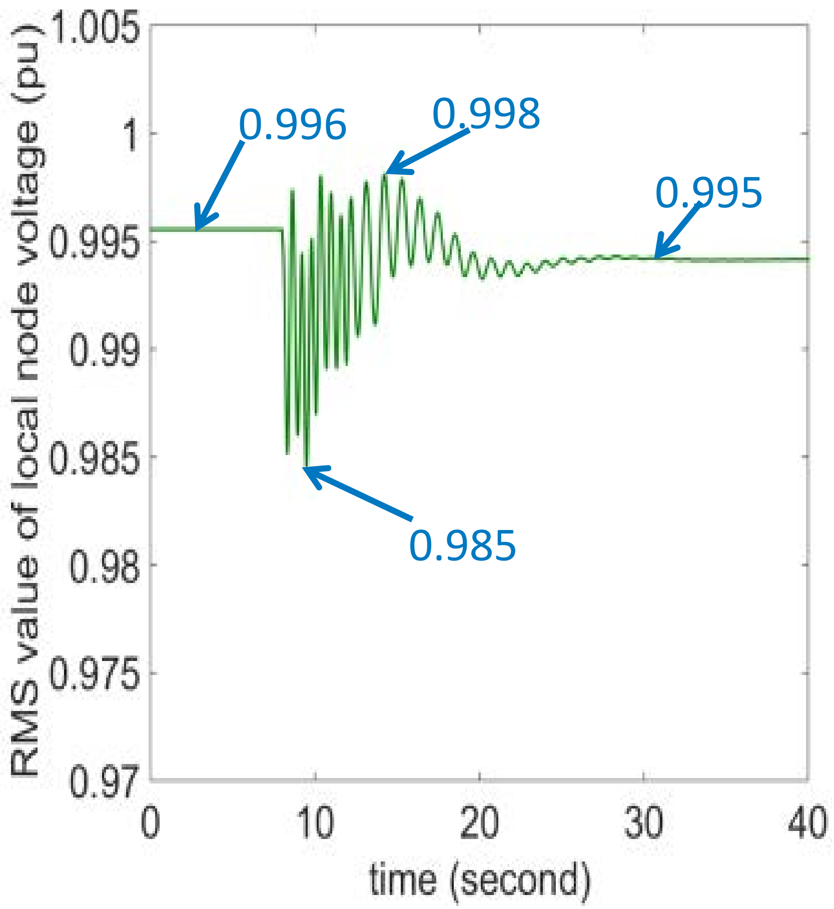

**Electrolyzer Response with FEC**

# Voltage Support by Centralized Electrolysis

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



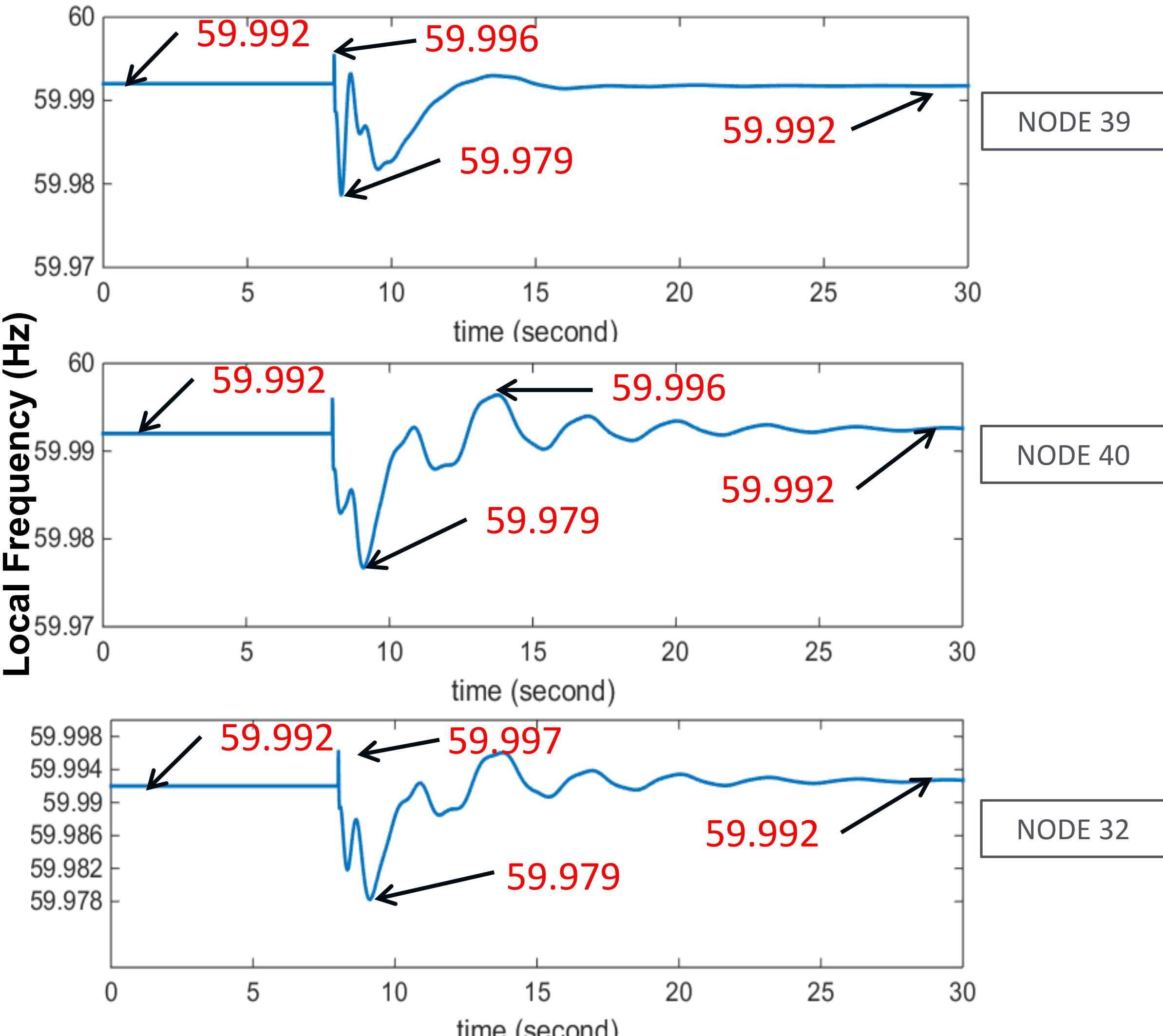

**Electrolyzer Response without FEC**

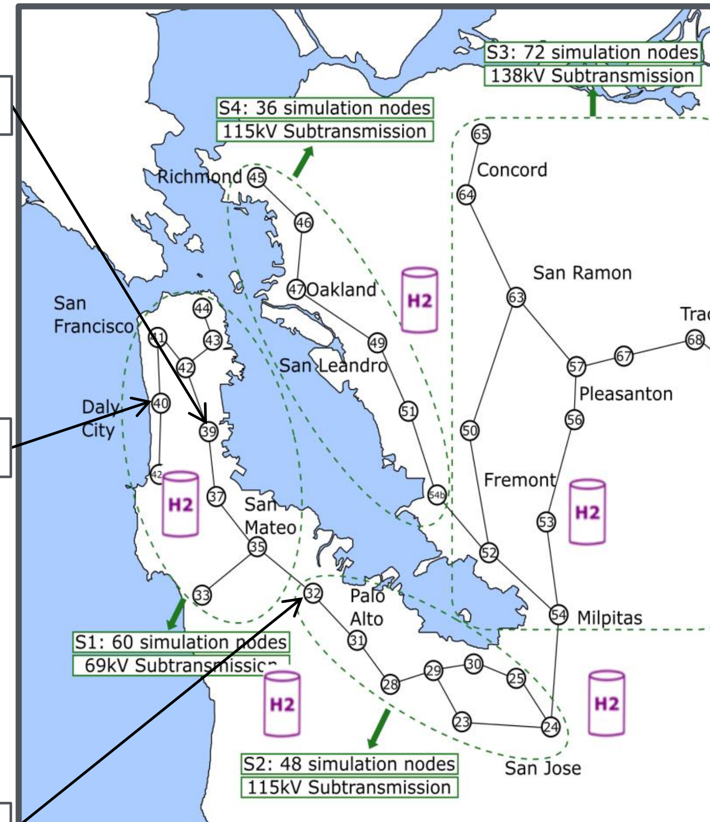



**Electrolyzer Response with FEC**

# Frequency Support by Multiple Electrolyzers with FEC

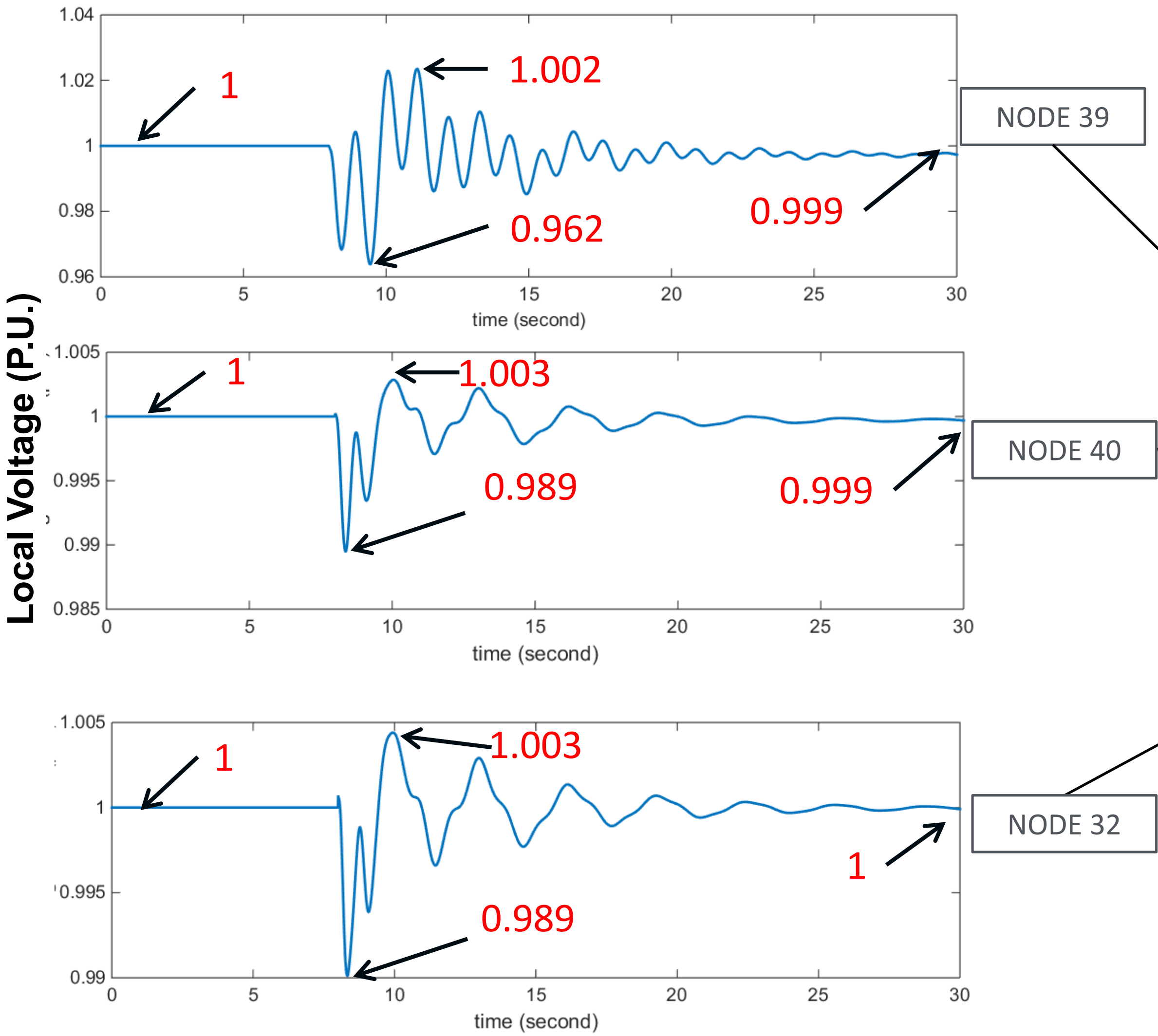
**Multiple electrolyzers controlled by FEC can enhance overall grid stability by limiting frequency excursions**

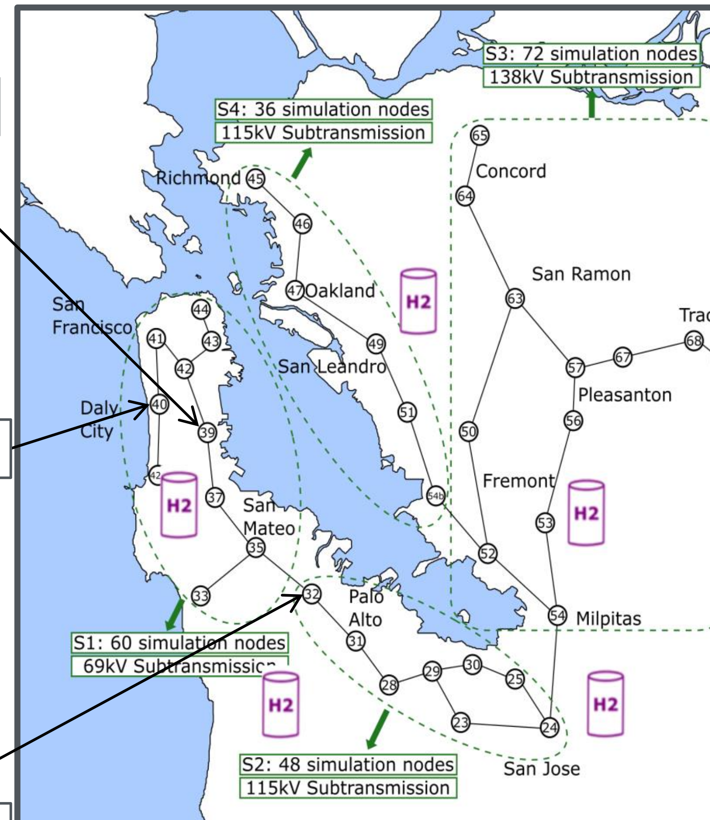



**Fault location: Node 39**
**Fault type: Three phase balance**
**Fault duration: 0.1 seconds**

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



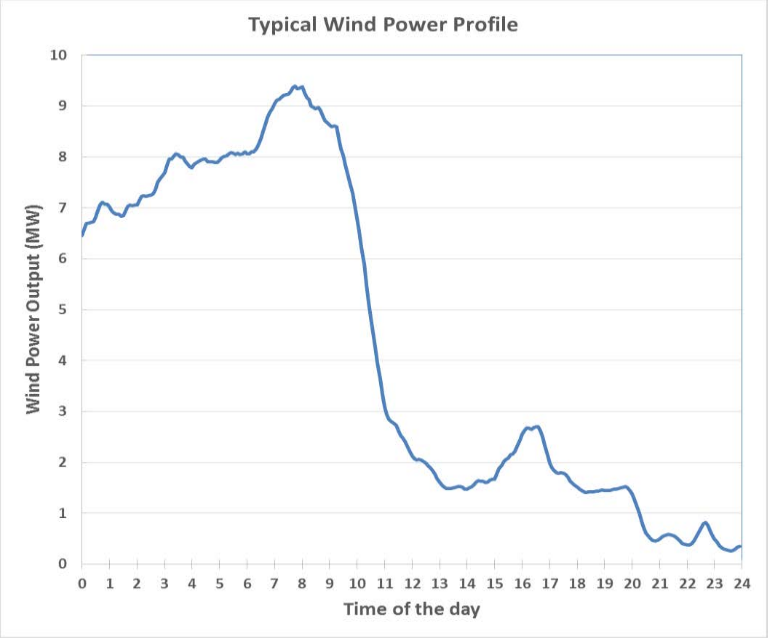

**Fault location: Node 39**

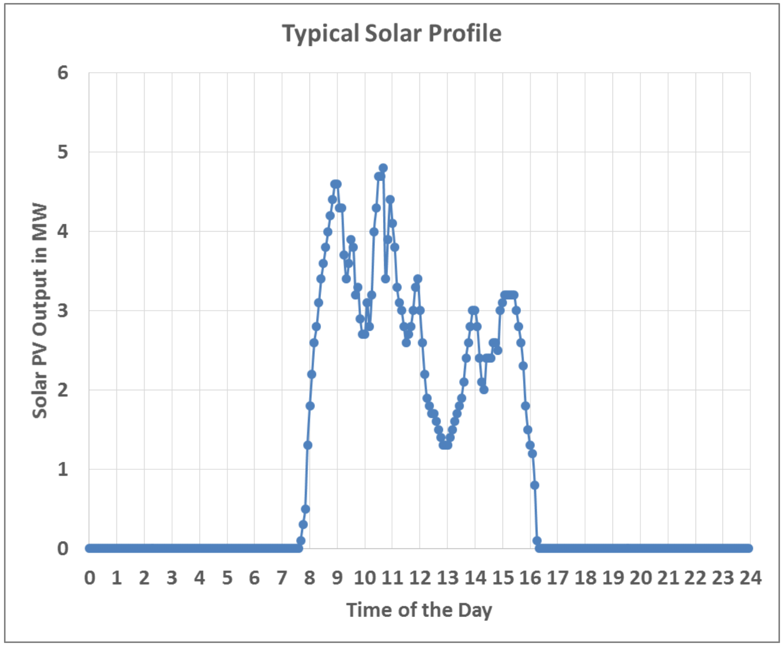
**Fault type: Three phase balance**

**Fault duration: 0.1 seconds**

# Variability of Renewable / Hydrogen Refueling Stations

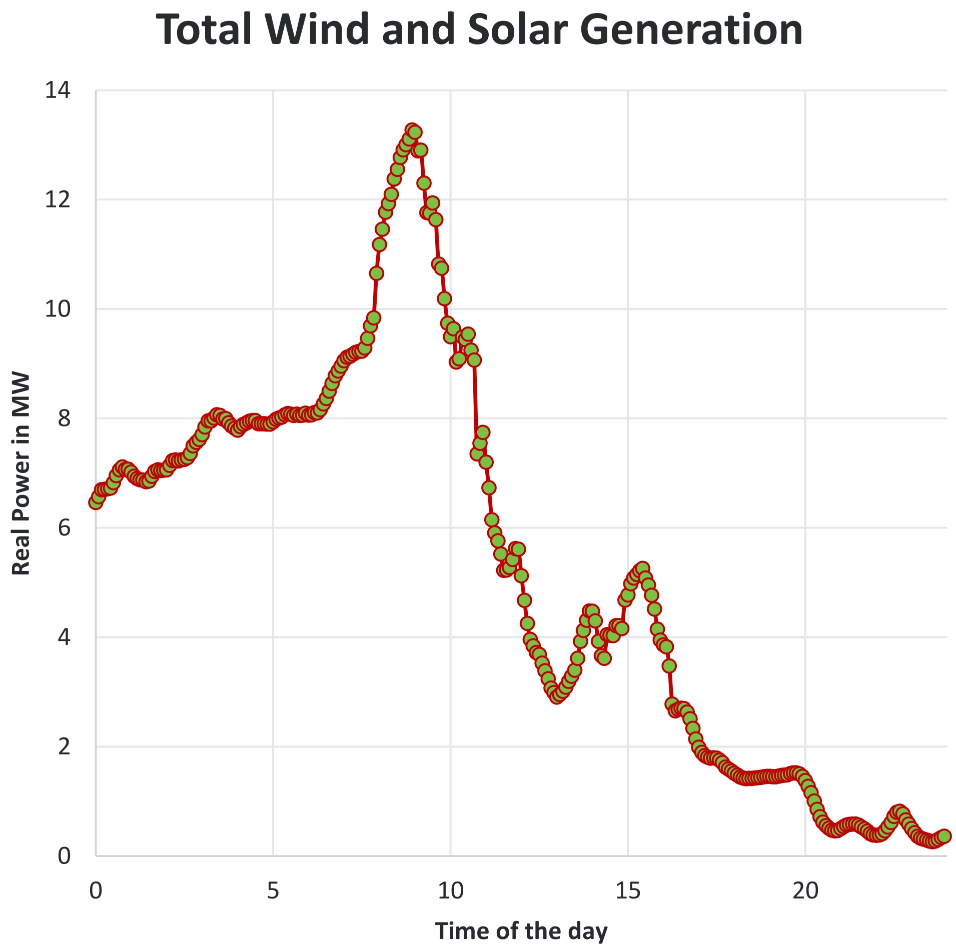
- Renewable Energy sources such as wind and solar demonstrate high degree of time dependent variability i.e., seconds to minutes to days…
- Electrolyzers have an innate capability to respond in seconds to follow control set points
- How can electrolyzers offset the variability observed by the power?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



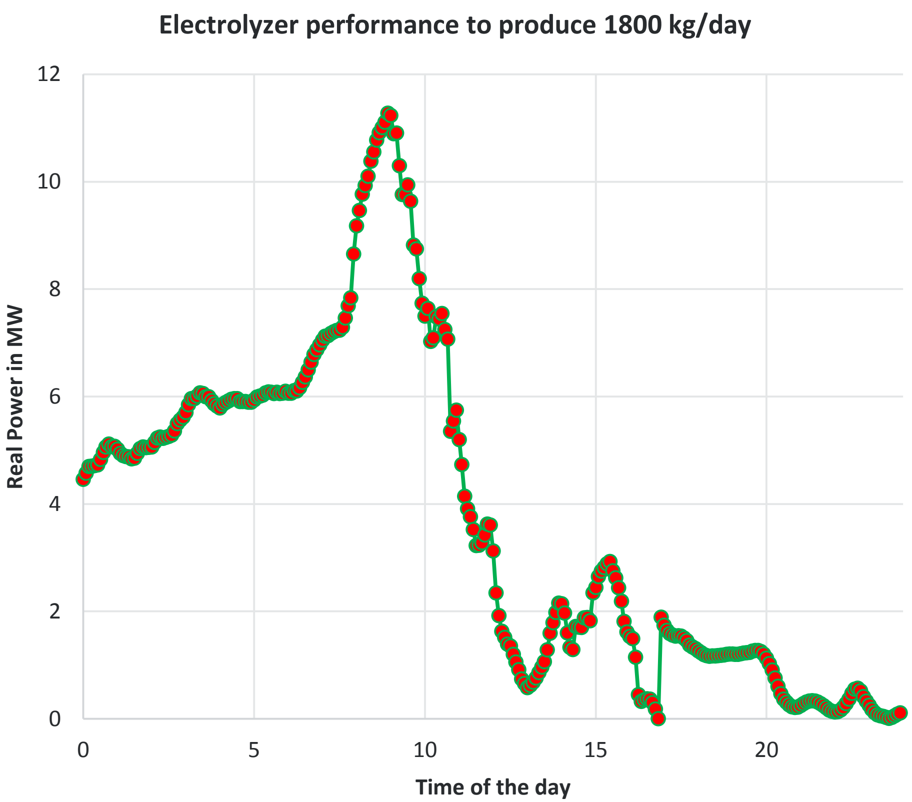
# 2018 Case with 7,200 FCEVs

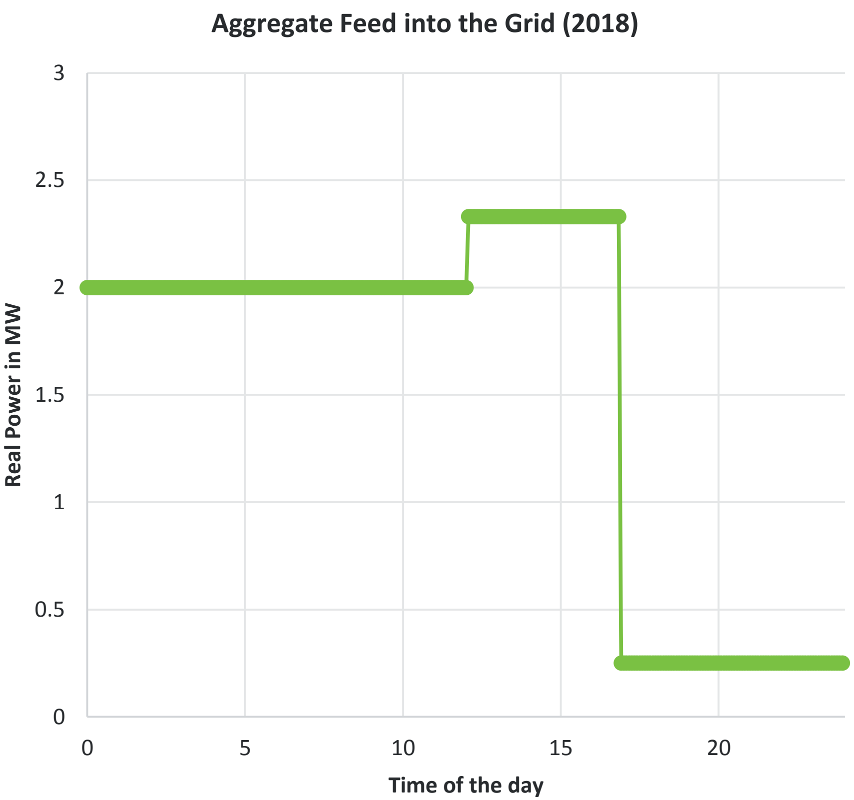
- Objective: Offset time-dependent, aggregated variability of solar and wind power using electrolysis
- Total of 13 MW electrolyzer plant is used for this example
- 2018 test case projections from ARB on vehicle fuel use to generate 1,800 kg/day of hydrogen for 7,200 FCEVs
- Approximate fuel dispensed 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

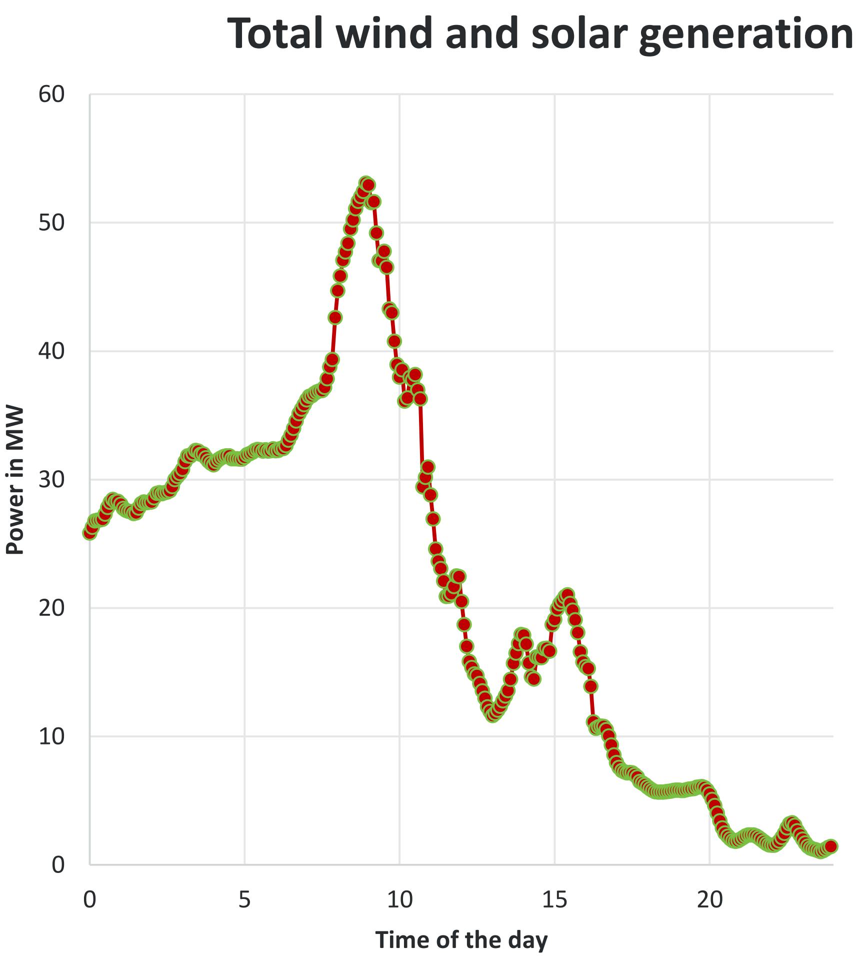
- Advanced control of a 13 MW electrolysis plant to offset variability of wind and solar power
- A fixed and predictable power injected into the grid from solar and wind plant due to coordinated operation with electrolyzers



# 2022 Case with 43,600 FCEVs

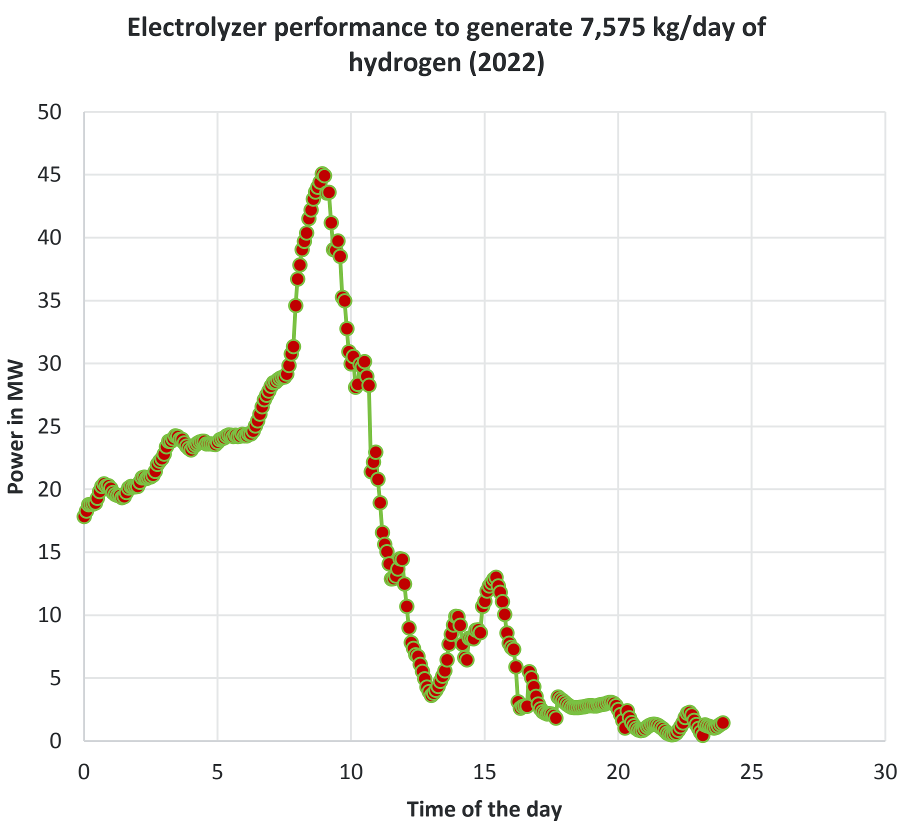
- Objective: Offset time-dependent, aggregated variability of solar and wind power using electrolysis
- Total of 45 MW electrolyzer plant is used for this example
- Typical efficiency of PV ~20-30%
- 2022 test case is used as reference to generate 7,575 kg/day of hydrogen for 43,600 FCEVs
- Approximate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

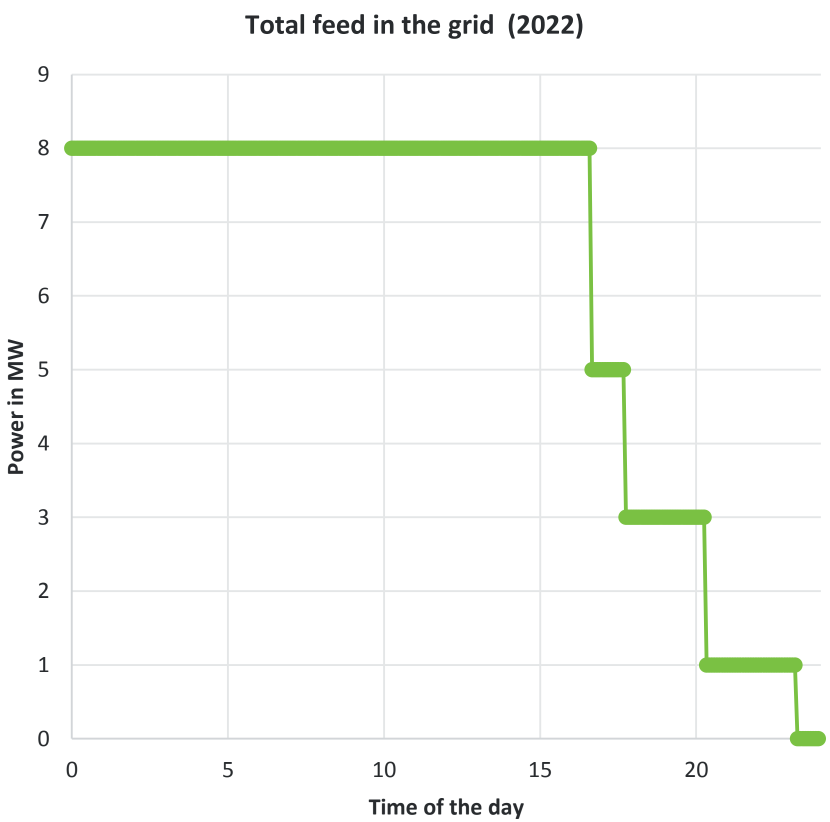


# Wind, Solar, and Electrolysis

- Advanced control of a 45 MW electrolysis plant to offset variability of wind and solar power

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



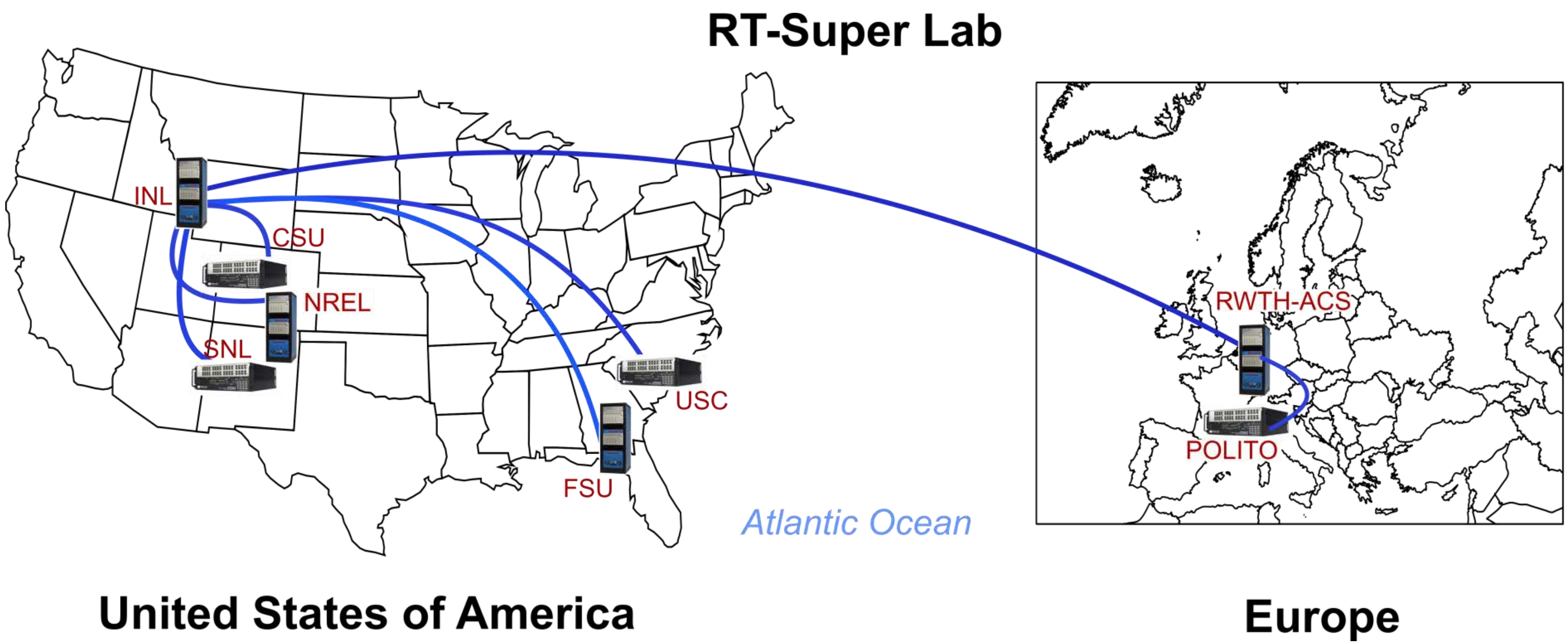
# Lessons learned

- Fleets of electrolyzers (hydrogen refueling stations)
  - grid support by reducing voltage and frequency excursions

- Enhanced revenue and reduced $H_2$ cost of production by participating in power grid services

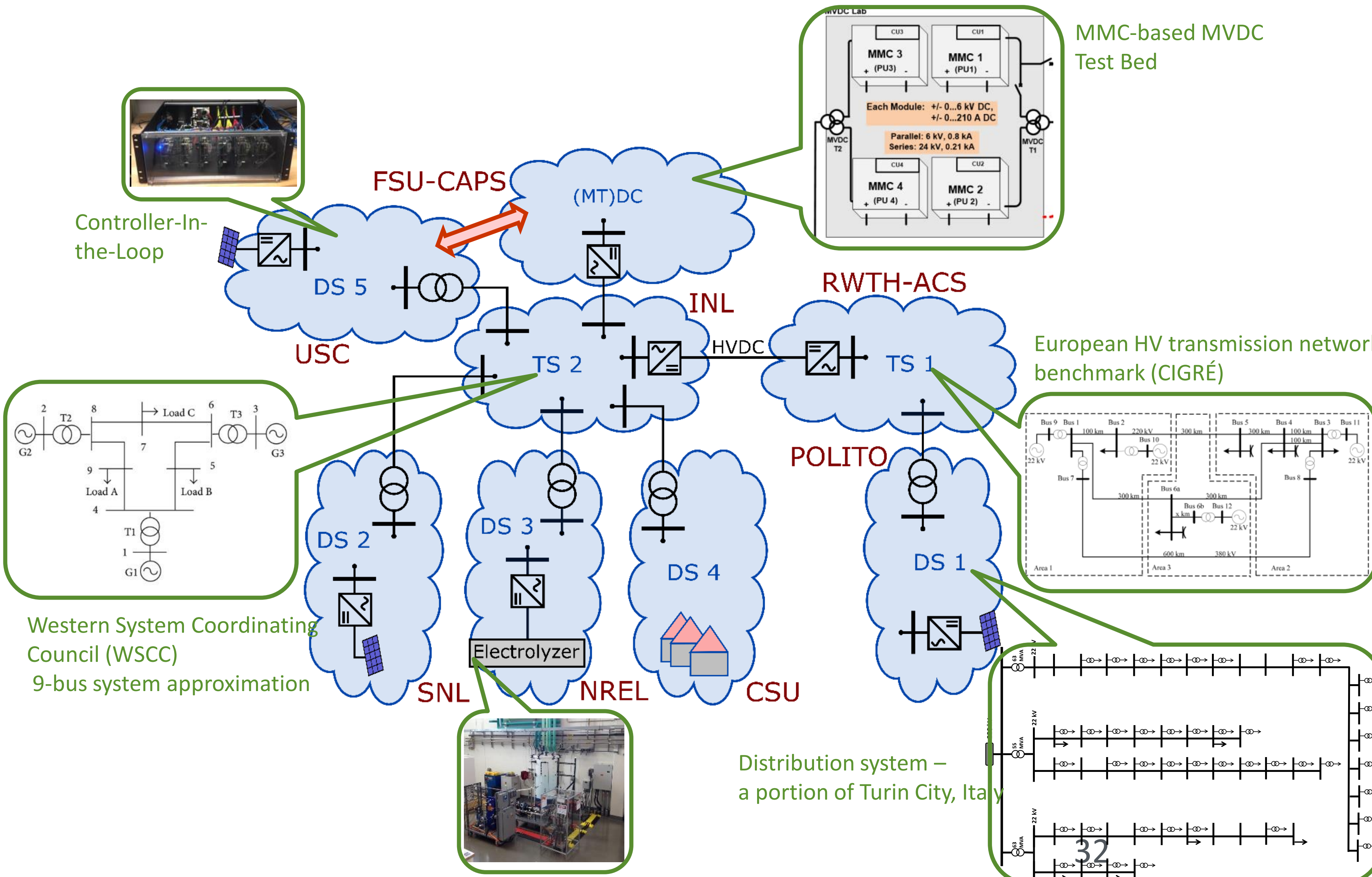
- FEC
  - is a vendor-neutral controller that is compatible with the existing electrolyzer's (low level) controllers
  - can receive and interpret communication signals coming from & going to EMS/DMS/Aggregator
  - enhances electrolyzer's basic purpose to produce hydrogen by providing grid services
  - allows cohesive response of fleets of electrolyzers
  - enables autonomous grid service responses
  - allows $H_2$ operator choice to participate in grid services (or not to)

# DoE – National Labs Real Time Super Lab connectivity




| Laboratory | | Location |
|---|---|---|
| Full Name | Acronym | |
| Idaho National Laboratory | **INL** | Idaho Falls, Idaho |
| National Renewable Energy Laboratory | **NREL** | Golden, Colorado |
| Sandia National Laboratory | **SNL** | Albuquerque, New Mexico |
| Colorado State University<br>Advanced Power Engineering Laboratory | **CSU-APEL** | Fort Collins, Colorado |
| Florida State University<br>Center for Advanced Power Systems | **FSU-CAPS** | Tallahassee, Florida |
| University of South Carolina | **USC** | Columbia, South Carolina |
| Polytechnic University of Turin | **POLITO** | Turin, Italy |
| RWTH Aachen University<br>Institute for Automation of Complex Power Systems | **RWTH-ACS** | Aachen, Germany |

# Multi-Lab Co-simulation and (P)HIL- Current Status



# Q&A



# References

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# Thank you

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