Grid Integration and Hydrogen Energy Generation: Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

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Project Start Date: October 1, 2017
Project End Date: September 30, 2020

Overall Objectives

- Validate electrolyzer network capability to support utility needs for stability with high penetration of renewables.

- Create control logic and communications for networked electrolyzer operation based on stability and economics.

- Quantify the benefit of electrolyzer operation to the power system stability and generalize its impact for multiple units connected in single- and multiple-distribution networks.

- Provide experimental data to H2@Scale modeling, simulation, and analysis team for performance, reliability, durability, and economic assumptions.

Fiscal Year (FY) 2018 Objectives

- Expand the grid modeling to accommodate futuristic hydrogen refueling stations (H2@Scale) providing energy storage for very high renewable energy penetration in digital real-time simulations. This platform will be used to assess the value of electrolyzers by providing hydrogen storage under varying renewable energy penetrations including solar and wind.

- Implement the "front end controller" (FEC) that interprets solar and wind profiles of varying penetration levels to make logical decisions to enable hydrogen-based storage. Additional capabilities of the FEC include the accurate interpretation of sample utility signals and safe control of the operation of the hydrogen refueling station. Ensure the control signals generated by FEC for the lower level controller respond to different utility signals and hence can participate in demand response and ancillary service programs.

- Perform real-time simulation within which the future hydrogen refueling station is controlled by the FEC to provide local fast loop support and macro grid-level slow loop support. The hydrogen refueling station hardware at NREL will be used as power-hardware-in-the-loop (HIL) to perform real-time simulation and extend the potential of H2@Scale support for renewable energy penetration.

- Test and validate the performance of single and multiple electrolyzers (MW scale) in providing local voltage and frequency support when integrated with the FEC.

- Test the performance of the FEC in driving the electrolyzer to account for the variability of varying penetration levels of wind and solar that is connected at diverse locations within the power grids.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

(B) Lack of Data on Stationary Fuel Cells in Real-World Operation

(G) Hydrogen from Renewable Resources

(H) Hydrogen and Electricity Co-Production.

Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE milestone from the Systems Analysis and Technology Validation sections of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Milestone 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)

FY 2018 Accomplishments

Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

- To accomplish the objectives of this project, Idaho National Laboratory (INL), the National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) utilized several core capabilities related to hydrogen and real-time simulations with HIL:
  - o Real-time connectivity between the real-time simulators and electrolyzer at the two labs
  - o Advanced grid modeling, hydrogen components and systems, control systems development, and optimization.

- The team completed the implementation of the FEC on a processor board and interfaced with the real-time simulator to develop a real-time test bed for rapid prototyping of the functionalities of the FEC. This platform serves as the verification and validation platform for the FEC development and testing.

- A paper related to electrolyzers and grid interaction assessment was published in *Energies MDPI*. Title: "Electrolyzers Enhancing Flexibility in Electric Grids,"

Manish Mohanpurkar, Yusheng Luo, Danny Terlip, Fernando Dias, Kevin Harrison, Joshua Eichman, Rob Hovsapian, and Jennifer Kurtz.

- An urban city model, within which hydrogen fuel cell electric vehicles (FCEVs) have a large-scale adoption and are used for public transportation, was built using the data provided by the New York Taxi and Limousine Commission. The study results and discussion were published as a peer-reviewed paper and presented at the IEEE conference, Probabilistic Methods Applied to Power Systems, Boise, Idaho, June 2018. Title: "Optimal Scheduling of Electrolyzer in Power Market with Dynamic Prices," Yusheng Luo, Min Xian, Manish Mohanpurkar, Bishnu P. Bhattarai, Anudeep Medam, Rahul Kadavil, and Rob Hovsapian.

- A "renewable energy module" was built and integrated into the FEC that was iteratively built in the past-funded project by the Fuel Cell Technologies Office. This renewable energy module can predict the renewable energy output of a desired plant and, in turn, provide control for the hydrogen electrolyzers. The outcome of this research direction enables a controllable and relatively predictable renewable energy output to the grid.

- Two power grid representations were utilized to understand the potential of H2@Scale to provide energy storage for renewable energy assimilation—San Diego Gas and Electric and Pacific Gas and Electric. IEEE models were also adopted for analysis.

- NREL, INL, and SNL had a technical interchange meeting in June 2018 to gauge the progress of the project and increase the effort on areas of testing and the development of the FEC in line with the optimization-based findings of the cost of hydrogen.

- The performance of multiple FECs that cohesively operate distributed electrolyzers in providing MW-level storage to renewable energy was tested and validated. Centralized and distributed electrolyzers connected to the test grids at different locations provide grid support based on FEC action.

- Varying levels of renewable energy penetrations (20%, 30%, and 50%) for the

electric grids were investigated for the test grids to assess the energy storage potential of H2@Scale infrastructure.

Topic 1A. Experimental and Core Capability Related to H2@Scale

- A programmable high-power source for controlled AC and DC output and frequency conversion as well as product tests relative to high-temperature electrolysis stacks were procured.

INTRODUCTION

This project aims to quantify the value of hydrogen refueling stations from a grid integration perspective to provide energy storage for accommodating renewable energy. Significant emphasis is on assessing the potential of H2@Scale (MW level) to provide hydrogen energy-based storage to reduce the variability of renewable energy sources. The anticipated value of electrolyzers stems from the fact that they are a controllable load with fast response. They are typically coupled with hydrogen energy storage, dispensers, and compressor units to form hydrogen refueling stations. They provide the flexibility to meet hydrogen demand with stored hydrogen when responding to the grid demand and store more hydrogen when the grid power demand is low. In addition to this complementary approach, local energy storage potential from hydrogen infrastructure can be established. The input resource for electrolyzers is electricity, which allows flexible co-placement of electrolyzers with other distribution energy sources in a power system network, leading to an optimal value of the objective function. Real-time simulations of power systems that include renewable energy modeling with HIL of the electrolyzer and supplementary systems representing the hydrogen refueling station form the test setup of this project.

This project leverages the existing work at INL, NREL, and SNL in the areas of power systems, electrolyzers, power markets, optimization, and control systems. The 250-kW modular electrolyzer stack is utilized for performing real-time simulations and HIL to generate high-accuracy data and results. The FEC developed in this research helps integrate the operations of the electrolyzer with the grid management systems and adds stability as the variability in renewable energy is reduced. The flexibility on account of controllability is utilized to assimilate renewable energy, manage distribution loads, and provide grid support. The adoption of the FEC developed and tested in this project will drive down the cost of generating hydrogen while maintaining the requisite reserves to meet demands for power.

APPROACH

The team developed and worked on an optimization-based approach to create the "renewable energy module" that provides the FEC the necessary information related to renewable energy penetration on the grid. There are two ways to address renewable energy penetration at very high levels and accommodate renewable energy sources' variability and unpredictability. The first one is to let the utility or operator directly control and hence manage the output of the renewable energy plant. At very high penetration levels of renewable energy, the grid operators need significant flexibility to manage the variability and uncertainty.

The second approach includes coordinating the operation of the renewable energy plant and local hydrogen storage with the grid operator or utility to improve predictability and lessen uncertainty. This will ultimately reduce cost and stress as well as augment the stability of the electric grids. Numerous instances have been recorded in which the excess renewable energy is spilled and hence underutilized. For such instances, hydrogen operators can get electricity for free or even get paid to consume it to maintain stability. This ultimately adds to the revenue of the hydrogen station operators, reduces the costs of producing hydrogen, and makes the market more viable.

This project experimentally verified the response of the FEC controlling the operation of the electrolyzer in response to renewable energy-related information with the optimal location and sizing of the electrolyzer. Advanced optimization techniques are being utilized for assessing the feasibility of sizing of hydrogen infrastructure for a given level of renewable energy. Several other grid scenarios related to grid dynamics and transients were also simulated in real time to assess the coordinated operation of FECs and electrolyzers. For these cases, the FEC and electrolyzer demonstrated voltage and frequency support to the grid in addition to the renewable energy assimilation. Voltage support by the FEC and electrolyzer in providing grid services using the hardware stack was also demonstrated.

The key takeaway is the optimal location and sizing of electrolyzers can greatly affect the performance of electrolyzers in providing local support, so optimization plays a key role. From past Fuel Cell Technologies Office-funded projects, the FEC had two major functional modules represented by two control loops—slow

and fast loops. The slow loop is associated primarily with the cost optimization of hydrogen, whereas the fast loop deals with the provision of grid services by the stack. The "renewable energy module" was added to the existing two loops to provide the functionalities shown in Figure 1.
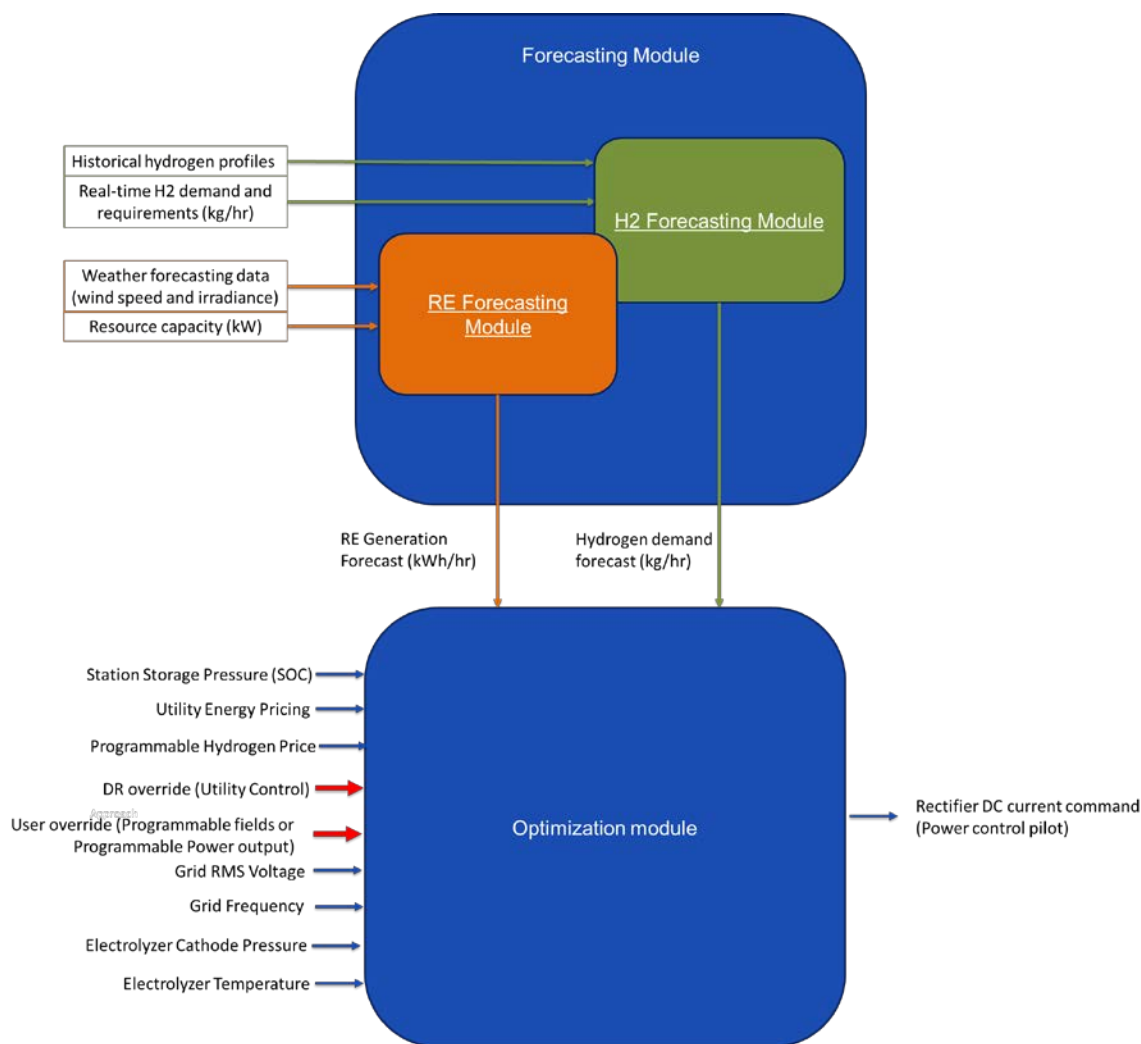
Figure 1. Data exchange between forecasting module and optimization module

Figure 2 provides detailed functionalities and expected data for all modules with inputs and outputs for the entire FEC. The regional power grid models, FEC, distributed real-time simulations, and connectivity between INL and NREL enabled the assessment of hydrogen-based energy storage for renewable energy. The selection and modeling of renewable energy penetration of diverse levels (20%, 30%, and 50 %) were integrated into the regional grids. Existing NREL databases related to renewable energy (solar and wind) were studied for the same penetration levels.
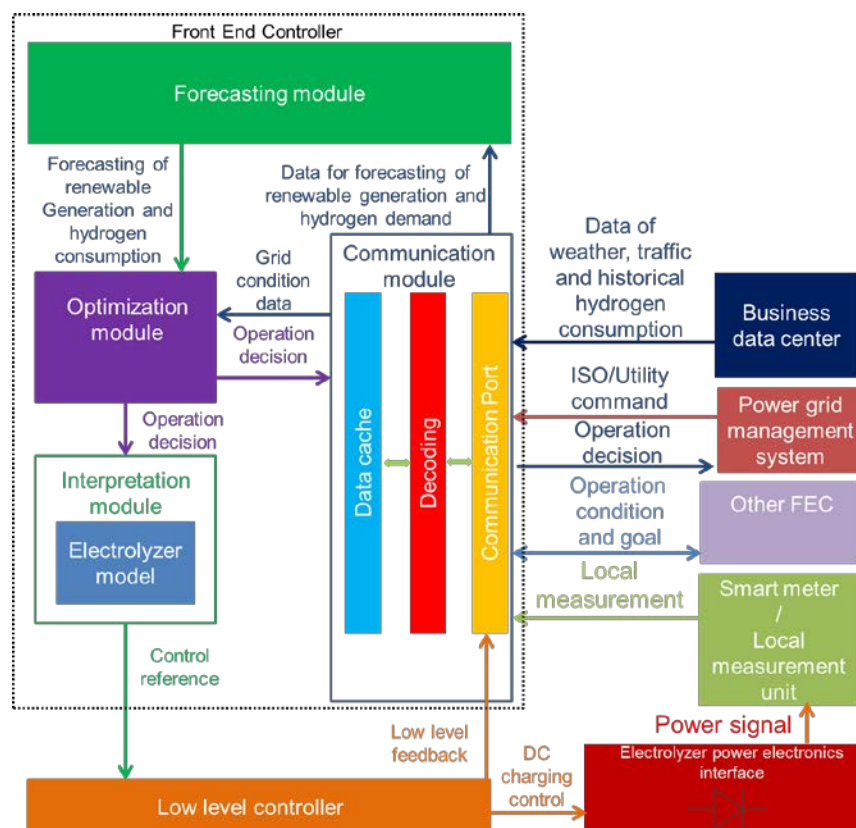
Figure 2. Updated FEC configuration with the integration of renewable energy module

Distributed real-time simulations and HIL were performed utilizing the 250-kW electrolyzer stack and a hardware implementation of the FEC. The functionalities of the electrolyzer stack responding to control signals from the FEC were verified for applications including grid services within the required time resolutions. An IEEE 34-bus test system and Pacific Gas and Electric representation in a real-time environment was created to understand and assess the performance of the integrated FEC and electrolyzer stack. Regional power grid models, including Arizona, southwest California, and the Bay Area, leverage existing models from the IEEE standard systems library that are directly derived from existing power grids around the United States.

The test results demonstrated the capability of the electrolyzer to provide local grid services and the ability of the FEC as hardware to control the electrolyzer. Economic optimization in the FEC has also been developed and implemented. This allows the FEC to make optimal decisions under different market rates and structures to generate hydrogen at a low cost. The optimization developed for the electrolyzer and implemented in the FEC hardware serves the purpose of striking a balance between providing support to the grid operations and increasing the profit of the hydrogen producer. Economic results were discussed and presented last year and are not included here. The distributed real-time simulations between INL and NREL involved controlling the electrolyzer hardware stack using the FEC implemented on the PI-card (a processor card). The data transmission for controlling the stack power consumption was 100 Hertz. This testing was important to verify the communication between the FEC on the PI-card with the hardware stack. This integrated platform was utilized to test the controllability of electrolyzer stacks based on the functionalities defined in the FEC under dynamic grid conditions. The electrolyzer stack controlled via the FEC on the PI-card demonstrated voltage and frequency support to the grid based on varying grid conditions including renewable energy variations.

Solar Forecasting Module in the FEC

The solar photovoltaic (PV) time-series forecasting is based on a popular linear regression forecasting model that uses the SARIMAX (Seasonal Autoregressive Integrated Moving Averages with eXogenous regressors) process in order to account for the inherent seasonal effect of PV power output time series. The SARIMAX model allows for integration of exogenous variables such as weather data for temperature in the future to improve the forecasting accuracy. Real-world PV output time-series data for 1 year is used to perform the day-ahead prediction. The time-series data is split into two parts—the training part, which makes up about 90% of the input data and will be used to train the model, and the remaining 10%, the test part, which will be used to evaluate the accuracy of the trained SARIMAX model as shown in Figure 3.
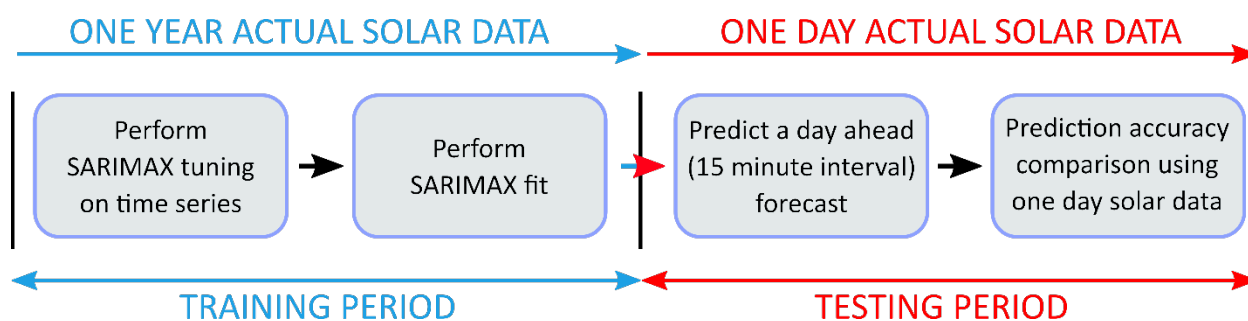

Figure 3. Prediction process utilized in the FEC for interpreting PV

The seasonal ARIMAX model is generally referred to as SARIMAX (p, d, q) x (P, D, Q, s), where p, d, q and P, D, Q, s are non-negative integers that refer to the polynomial order of the autoregressive (AR), integrated (I), moving average (MA), and periodicity parts of the nonseasonal and seasonal components of the model. In the training phase, a grid-based search is performed to estimate the orders for (p, d, q) and (P, D, Q) that result in the best fit mainly based on the Akaike Information Criterion, which is an estimator of the relative quality of the fitted model for the given training data set. Comparison of the training data with the fitted data obtained from the SARIMAX (1, 0, 1) x (1, 1, 1, 12) model as shown in Figure 4 suggests that the SARIMAX model is able to obtain a good fit.
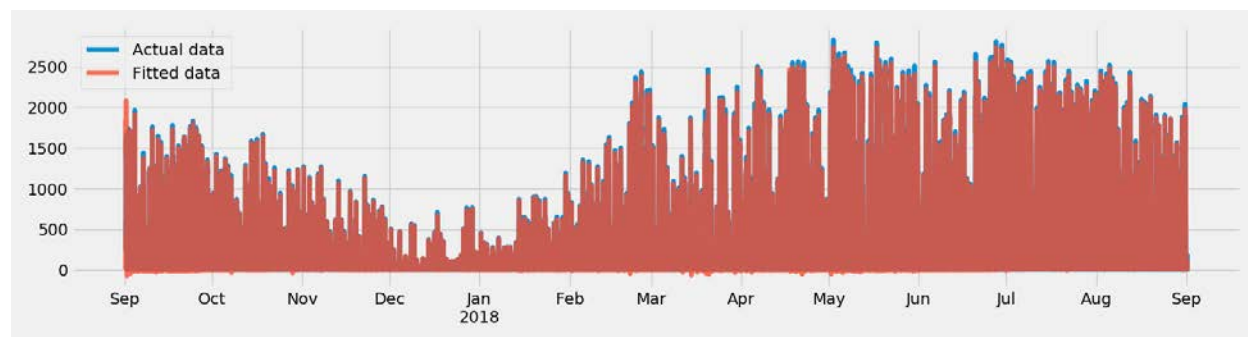

Figure 4. SARIMAX model fitted with training data

The trained model is then used to perform a day-ahead prediction with a time resolution of 15 minutes as the input data set. The day-ahead prediction is then compared against the test data set to measure the effectiveness of the PV prediction using root mean square error technique. To demonstrate the H2@Scale renewable energy penetration in a grid, the available power from the renewable energy source, "Pset," is obtained from the solar forecast module of the FEC and sent to the electrolyzer. The electrolyzer should then be able to consume the power as requested. The project ran several cases and combinations of 20%, 30%, and 50% PV penetration (concentrated and distributed) on the test systems with suitably scaled hydrogen infrastructure to support the storage. A sample case of 20% PV penetration is discussed here, in which the electrolyzer is centralized, but we have simulated an array of distributed PV cases as well.

RESULTS

For the 20% penetration case: As shown in Figure 5, all the PV is located at 808, electrolyzers are located at 806, and the total power rating of the electrolyzer is 200 MW. Due to the spatiotemporal characteristics, variability, and uncertainty of renewable energy sources, their generation cannot be flexibly adjusted to match the demand from the load side. Excessive generation can even exert negative impact on the power grid when there is mismatch between generation and load. Hence localized storage in the form of hydrogen can play a significant role. Generating hydrogen with excess renewable energy generation is can help relieve certain stressful conditions. From this perspective, an observability of PV is created in the existing FEC in the form of a renewable energy module. This module enables the FEC to control the electrolyzer operations to complement the PV generation to soften the transients as shown in further results. The 20% PV penetration case along with the actual and forecast generation from the renewable energy module is shown in Figure 6. The load profile is shown in Figure 7. Figure 8 demonstrates the role of electrolyzers that are being controlled by the FEC with the renewable energy module.
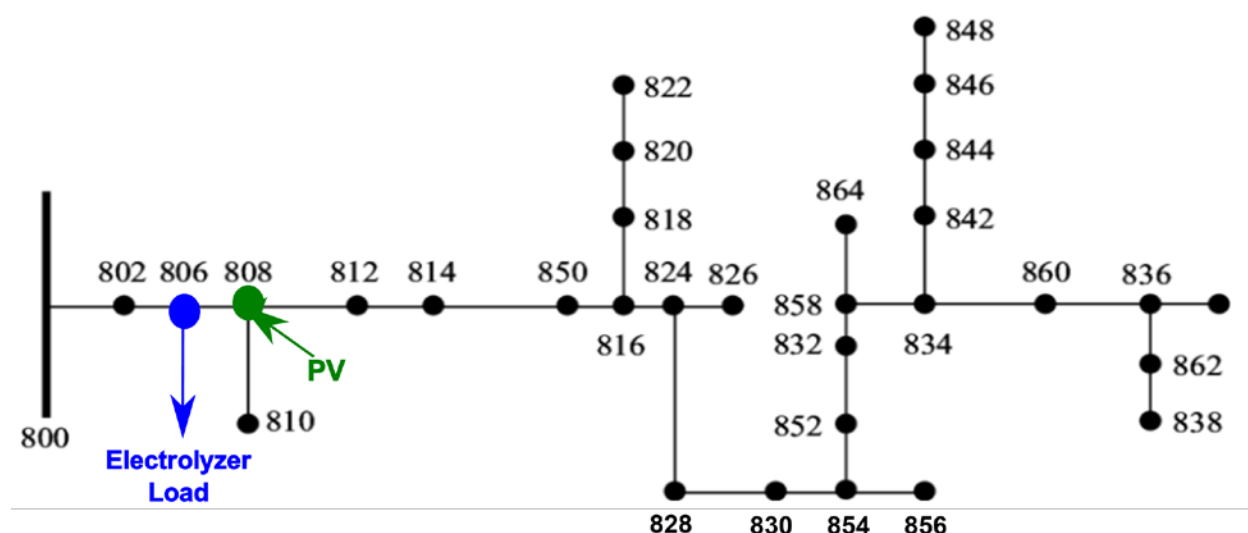

Figure 5. Test system for 20% penetration of PV and electrolyzers
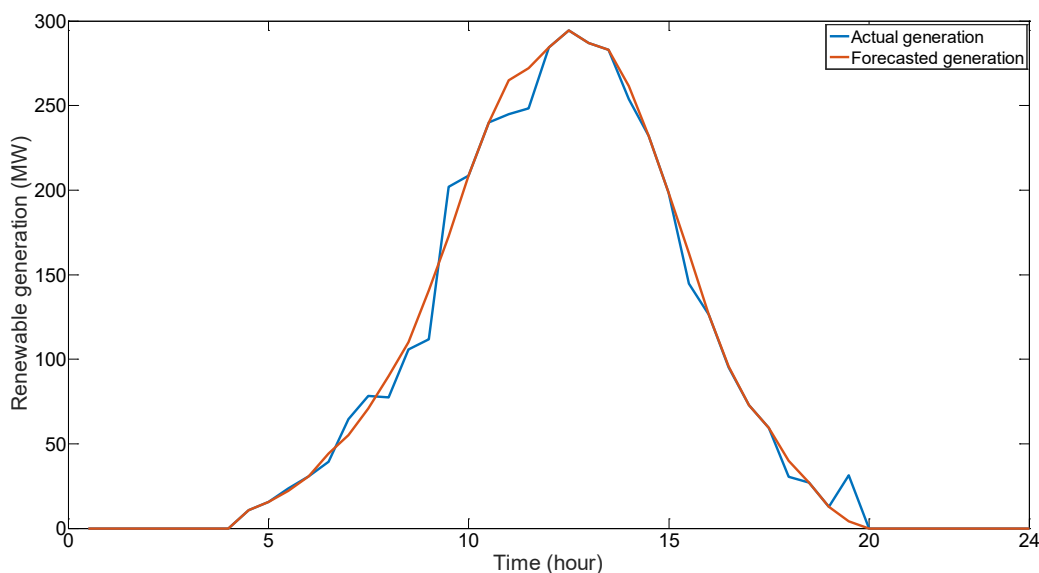

Figure 6. Actual amount versus forecast amount of renewable generation (PV) for a given day
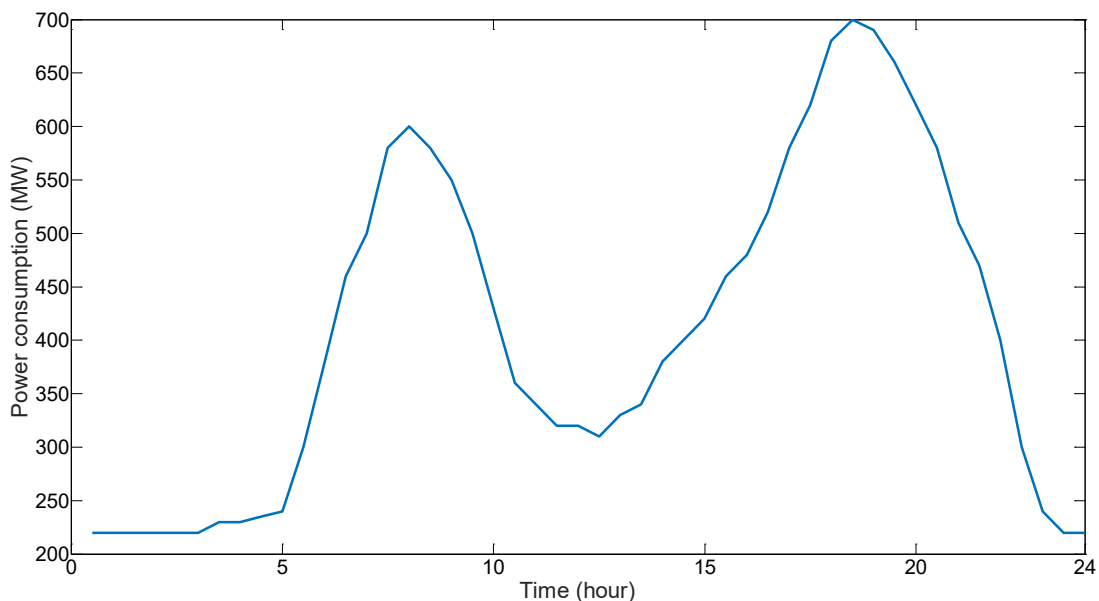
Figure 7. Load profile in test case of 20% renewable penetration

Observations for the 20% PV penetration case: Power consumed by electrolyzers can be leveraged as a balancing tool. As shown in Figure 8, the blue curve is the actual renewable generation for the 20% renewable penetration case. As the energy consumption of electrolyzers can be adjusted by FEC to the amount shown in the shadowed area, then the renewable generation injected to the grid will be shaped as the green curve, which is relatively flat. A flatter renewable energy generation is much easier to control and even dispatch for certain grid applications. The total hydrogen produced by the electrolyzer is directly a function of the energy consumed, and the FEC ensures typical hydrogen demand is satisfied. Figure 9 shows the comparison of impact to frequency stability during the transient noted in Figure 8. Without FEC-controlled electrolyzers, frequency can deviate up to 0.28 Hz. When electrolyzers are driven by FEC to offset the impact of excessive renewable generation, frequency deviation can be limited to within 0.006 Hz. Such a transient happens four times in this daily PV profile and is compensated for by the FEC-controlled electrolyzers.
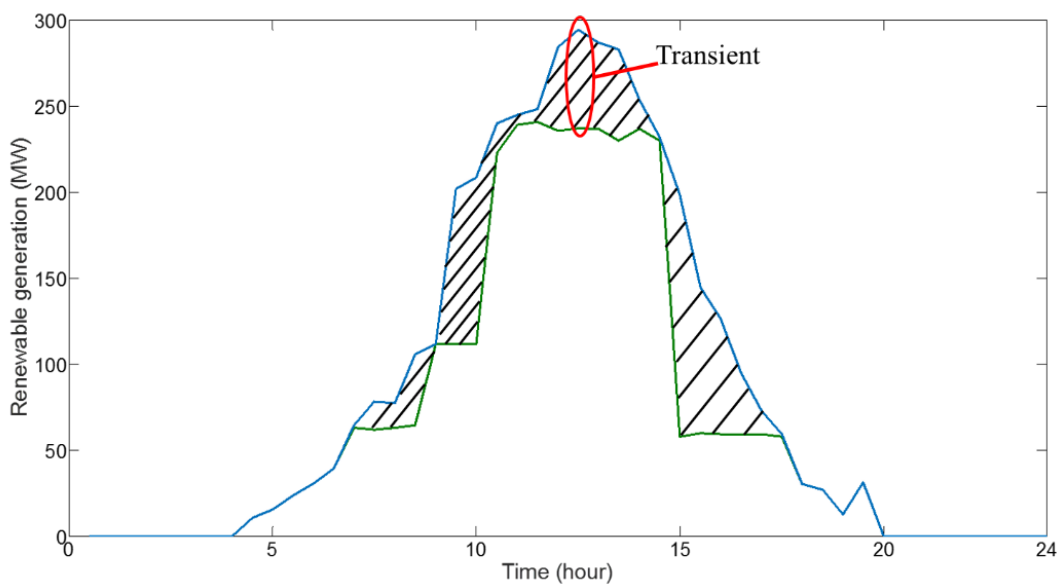

Figure 8. FEC-controlled electrolyzers modify the profile of renewable generation (20% renewable energy penetration)
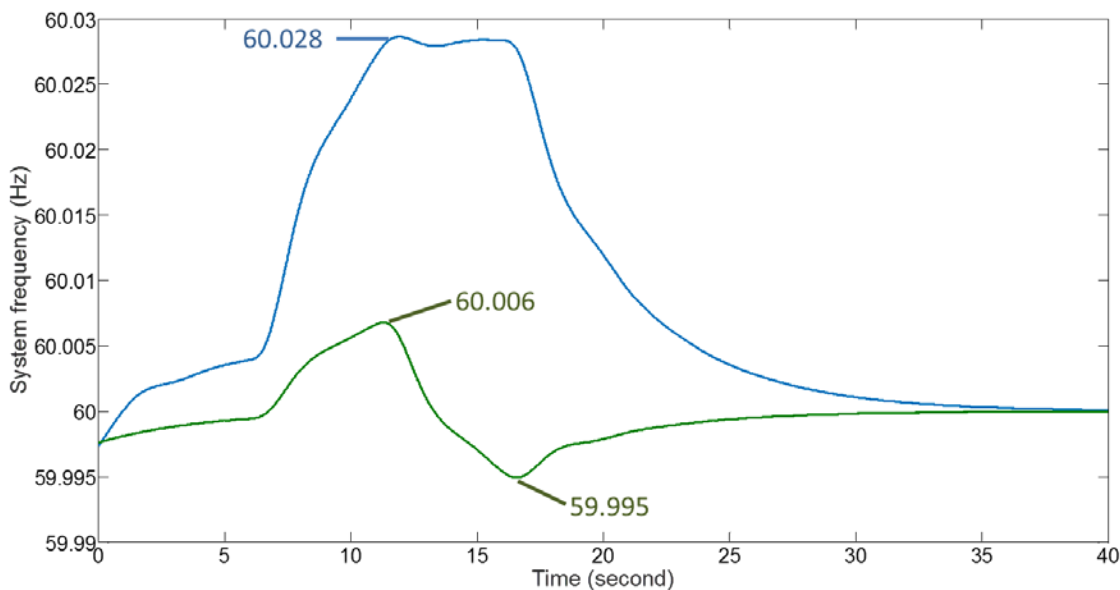
Figure 9. Comparison of system stability during transient with/without FEC-controlled electrolyzer (20% renewable energy penetration)

CONCLUSIONS AND UPCOMING ACTIVITIES

The capability of an electrolyzer as a controllable load and provider of grid services was demonstrated to be significant and was experimentally verified in a real-time environment. A special focus on the real-time simulations, inter-lab connectivity, HIL, and advanced grid modeling was used to assess the potential of H2@Scale infrastructure to provide energy storage for renewable energy.

The controllability of an electrolyzer was enabled by a vendor-neutral approach—the FEC. The FEC ensures an optimal response of the electrolyzer to provide essential grid support in the form of voltage and frequency support. An FEC is a set of generic controls that can be integrated with existing controllers of electrolyzers that are available in the market. The objective of developing FECs is to demonstrate the immense flexibility that electrolyzers can add to the power grid operations as well as to lower hydrogen costs. An FEC from a past-funded activity was leveraged to add a renewable energy module to enable the prediction and control of electrolyzers considering the physical constraints of electrolysis. The FEC tries to minimize the cost of production of hydrogen by participating in grid services and providing storage for the assimilation of renewable energy.

Integrated FEC configurations were tested in both large centralized electrolyzer plants and smaller distributed ones. Another combination of distributed and concentrated renewable energy was also explored. The 250-kW stack at NREL was used as the building block to extrapolate and assess the potential of H2@Scale to provide storage. Both configurations performed and provided essential flexibility and energy storage to the grid under dynamic renewable energy conditions. Additionally, the FEC can drive the hydrogen production cost lower by considering different utility rate structures, participating in demand response programs, and interfacing with market signals. Hardware-based testing in real time was used to infer and augment the understanding of the role electrolyzers can play in markets for additional revenue. The FEC is now implemented on a hardware controller card and its functionality testing with the electrolyzer stack (250 kW) is also completed.

Topic 1A. Experimental and Core Capability Related to H2@Scale

A vendor technical data sheet for the programmable high-power source purchased for installation in the INL Systems Integration Lab was developed. The power converter was purchased from AMETEK Programmable Power, California Instruments RS Series. This power conversion unit can connect the INL Digital Real-Time

Power and Energy Lab to a high-temperature steam electrolysis pilot plant ranging up to 250 kWe DC input. This enables INL to repeat the dynamic response testing performed using the NREL low-temperature electrolyzer. This activity was limited to specification of requirements, procurement, and delivery to INL. Testing will be completed in FY 2019 and the results will be compared to the low-temperature electrolyzer results measured in FY 2017 and FY 2018.