Renewable Electrolysis System Development

Cooperative Research and Development Final Report

CRADA Number: CRD-16-00645

NREL Technical Contact: Kevin Harrison

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5900-87321
August 2023

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NOTICE

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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Cooperative Research and Development Final Report

Report Date: August 22, 2023

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Proton Energy Systems d/b/a Proton Onsite (Currently known as Nel ASA)

CRADA Number: CRD-16-00645

CRADA Title: Renewable Electrolysis System Development

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$200,000.00
TOTALS	$200,000.00

Executive Summary of CRADA Work:

Renewable hydrogen is becoming globally recognized as a key component required for de-carbonization of our energy system, both as a medium for capture of excess renewable energy sources, vehicle refueling, and as an intermediate for multiple industrial processes. Hydrogen production, via low-temperature electrolysis, is a flexible grid-friendly, clean energy carrying intermediate that enables fast ramp and de-ramp rates as naturally varying solar, wind, and storage systems become a larger percentage of the electricity mix. Analysis shows that by 2050, employing renewable hydrogen at scale can decrease total U.S. CO_2 emissions by about half relative to business as usual, critical to achieving >80% greenhouse gas reduction targets.

Energy storage systems help commercial customers reduce their electric bills by storing energy from the grid or from renewable electricity sources when energy is inexpensive, then using that stored energy when demand and prices are high. Proton exchange membrane (PEM) electrolysis is one of the few technologies that can produce hydrogen with zero carbon emissions at relevant scale (hundreds of MWs) in the near term. NREL's research has shown that electrolyzers are fast and flexible enough to participate in energy and ancillary service markets that can help stabilize the grid.

In 2015, Proton OnSite (now NEL Hydrogen) introduced the M-series electrolyzer platform, the world's first megawatt PEM electrolyzer for the global energy storage market, offering a carbon-free source of hydrogen fuel or process gas. In addition, the ability to sell the hydrogen into a high value application like vehicle (e.g., light–and heavy-duty and material handling) fueling allows for a layering of revenue streams that creates better business cases for hydrogen energy storage systems (HES). The ability to provide multiple value streams from the fast-responding controllable electrolyzer will have a direct impact on the net cost of hydrogen.

CRADA benefit to DOE, Participant, and US Taxpayer:

Uses the laboratory's core competencies.

Summary of Research Results:

Purpose

Although the market potential for renewable electrolysis is massive, systems must be optimized to hit cost targets for specific applications. Today, AC/DC power conversion accounts for about 20 – 30% of the capital cost of Proton's M-Series electrolyzer system. While capital costs of the M-series have dropped below $2/Watt, further cost reduction is required to increase market deployment opportunities.

The objective of this project includes the development of a design basis using advanced power converter components and architectures that are optimized for both regulated grid and varying renewable electricity sources to reduce the capital costs of an integrated system. The project will benchmark Proton's M-series electrolyzer (AC/DC - grid-connected) rectifier design with other mainstream MW-scale power converters, including low-cost PV inverters (DC/AC), that have prices roughly half of Proton's rectifiers. Benchmarking will help inform why large-scale power rectifiers remain a large percentage of the electrolyzer system capital cost and identify pathways to reduce that contribution closer to that of PV inverters.

NREL will utilize their Electrolyzer Stack Test Bed, strengths in systems integration, access to renewable electricity subject matter experts, and hardware validation capabilities at the Energy Systems Integration Facility to develop and design an advanced power converter to provide a pathway for reduced capital cost and improved efficiency of Proton's M-series electrolyzer.

Statement of Work

Power Conversion

Megawatt electrolyzer power conversion architectures will be studied in the context of state-of-the-art large-scale renewable power installations. The project will highlight opportunities to leverage DC aspects of renewable electricity sources to reduce the cost of PEM-based power-to-gas solutions. Next-generation power converters are expected to be lower cost, capable of higher voltage interconnection, and provide advanced grid support functionality (due to increasing variable renewable sources) without jeopardizing electrolyzer stack life and efficiency. This project will provide a design basis that coalesces Proton's requirements for advanced power converter architectures, DC stack specifications and optimized balance-of-plant sub-systems that are flexible in grid and renewable electricity applications. The net result will be an electrolyzer with lower capital cost and improved efficiency (e.g., lower power conversion losses, improved in/output voltage matching, and advanced functionality). These improvements will reduce the cost of hydrogen and enhance the value proposition around hydrogen energy storage (HES). In addition, it will provide a validation template for modeling the electrolyzer's application to ancillary services such as frequency regulation.

NREL and Proton will focus on developing, integrating, and optimizing electrolyzer power supplies / interfaces and sub-systems for operation during: (1) Renewable electricity generator ramping, (2) Providing advanced grid services, and (3) Hydrogen curtailment due to high electricity pricing. These additional control features, for example, can keep demand charges, which are generally charged to commercial users based on their peak power level throughout the billing cycle, low.

The project will bring together subject matter experts from Proton and NREL to provide a technical basis to reduce the cost, increase the efficiency, and provide advanced functionality for the next generation of power conversion for Proton's M-Series (1.2 MW total, (4) 250 kW stacks, 432 kg/day) electrolyzer. Key aspects of the project include developing specifications for the DC output to the stack by understanding what level of ripple, can be tolerated. The goal is to provide optimized power conversion architectures that are lower in cost and more efficient in transforming AC and DC energy, which will result in a reduced capital cost of the system.

Tasks

1.1 Electrolyzer Stack and Power Supply Specification Development

1.1.1 Develop 250 kW stack specification document that includes acceptable ranges of parameters such as: DC ripple, over-current capability, response time, and voltage decay.

Results: NREL's approach to DC loads at power levels of 250 kW and above is to utilize multiple AC/DC rectifiers in a master/slave (from here on referred to as primary/secondary) configuration. This enables two or more power supplies to be placed in parallel for increased output current or in series for increased output voltage. With primary/secondary operation, power supplies operate at near equal current because they are operated in current control mode.

NREL has configured four (4) insulated gate bipolar transistors (IGBTs) based power supplies in parallel to reach 1 MW dc power level with current shared equally. The primary power supply is provided a DC current set point that is then shared equally across the other three (3) secondary power supplies. Each power supply is capable of 1000 Adc and will start limiting power if stack voltage reaches 250 Vdc, totaling 4000 Adc to achieve 1 MW. The upper voltage limits the number of cells in the stack to about 125 – assuming each cell voltage will slowly increase (i.e., decay) over a beginning of life value of about 1.9V per cell. End of life cell and stack voltage are monitored by the control system to determine when a stack requires replacement or if cell(s) are decaying faster than expected.

Overcurrent and voltage trip set points are configurable on the power supply but have an upper bound set by the manufacturer to 110% of maximum. Overvoltage alarm and fault levels follow the same formula providing operators to set a lower alarm level before reaching the hard limit of 110% of full-scale range of the power supply.

Figure 1. 500kW (out of 1MW) AC/DC power supplies at NREL power PEM electrolyzer system.

1.1.2 Benchmark electrolyzer rectifier costs and capabilities with other MW-scale power converters, such as, photovoltaic inverters (DC/AC) and chlor-alkali AC/DC power supplies.

Results: The chlor-alkali process is an industrial process for the electrolysis of sodium chloride solutions and use both thyristor- and IGBT-based high-power converters, where the IGBT system will have faster switching and lower resistance leading to higher efficiency. The chlor-alkali and water electrolysis processes have similar requirements in that both require high DC current at (relatively) low voltage while being connected to medium (10 – 20kV) AC voltage grids. However, low-temperature PEM-based water electrolysis has the additional requirement of achieving load following to enable interconnection with naturally varying renewable (e.g., wind and solar) electricity sources.

MW-scale active AC/DC rectifiers, based on thyristor and IGBT switching devices, cost between \$0.25 - 0.50 per watt and may also include a harmonic neutralizer. Harmonic neutralizers cancel lower order harmonics on the AC side of the power supply which eliminates power system noise problems at the source. MW-scale photovoltaic inverters (DC/AC), however, have a purchase price in the range of \$0.10 – 0.15 per watt. The significant difference in cost between multiple rectifier manufacturers and PV inverters was not completely identified during this work scope but it is suspected to be a function of the high DC current required for PEM electrolysis and the relatively low volume of production compared with solar photovoltaic inverters at this point in the technology maturity.

2.1 Perform a literature search and investigate advanced power converter components, architectures, and functionality for integration with grid and renewable electricity sources.

2.1.1 Document case studies of real-world installation topologies and configurations to inform state-of-the-art systems design, performance, and capabilities.

Results: There are internal capacitors across the output terminals of the power supply. A trade can be made between allowable DC ripple and response time. Reducing the DC output capacitor values will increase DC ripple but reduce response time. Maximum Slew Rate for standard models power supplies are typically around 100 ms for both current and voltage output changes to move from 0 to 63% of rated. [1]

However, to perform faster moving validation work on electrolyzer systems aimed at simulating ramp rates of renewable energy sources like wind and solar, a high-slew rate option is provided on the power supplies. Maximum Slew Rate for optional high-slew rate models are 4 ms for an output voltage change from 0 to 63%, and 8 ms for an output current change from 0 to 63%. However, real life response must also consider delays between the electrolyzer control system, the power supply interface, and what is measured at the stack. Figure 2 shows work NREL performed to show actual delay between the control system command and DC current measured at the stack of 50 ms. [2]

Part of the DC output stage consists of a bank of capacitors. These components require bleed resistors to discharge any voltage when the power supply has no load and is disabled. While the presence of these components and the resulting performance are normally industry accepted, there are applications where lower output capacitance and lower loss bleed resistors are extremely desirable if higher DC output ripple is acceptable. In this case, a high-slew rates would include a DC output stage consisting of lower capacitance and lower loss bleed resistors.

[1] Magna-Power Electronics MT Series Power Supply Manual, https://magna-power.com/products/magnadc/mt, Accessed July 10, 2023

[2] Katherine Ayers *et al* 2021 *Electrochem. Soc. Interface* **30** 67 **DOI** 10.1149/2.F16214IF

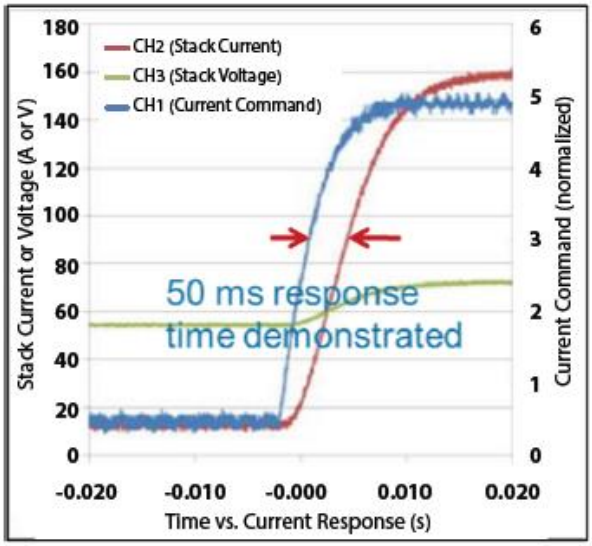

Figure 2. Response time of 50 ms between measured DC stack current (red) and current command (blue).

3.1 Working with Proton and power converter manufacturers, merge stack specifications (1.1) and advanced power converter design (1.2) to develop and design an advanced power converter for MW-scale water electrolysis.

3.1.1 Optimize efficient interfaces and power management of PEM electrolyzer systems (stack and balance of plant) and variable renewable electricity sources Results: The following summarizes numerous hardware and software approaches to efficiently connect (i.e., interface) a supervisory control system with the electrolyzer system to optimize integration with renewable electricity sources. Typical active AC/DC rectifiers are either operated as DC voltage or current sources for hydrogen production via electrolysis. However, for low-temperature water electrolysis, sourcing current is normally employed due to electrolyzer stack voltage dependence on reactant/product pressure, temperature, and stack life. In other words, stack voltage varies with those parameters so the power supply sourcing current will provide a known flow of hydrogen since the Faraday efficiency is assumed to be around 99% for PEM-based water electrolysis. For this reason, most manufacturers utilize current-sourced power supplies in state-of-the-art balance of plant design. Diagnostic functions of power supplies can be networked over Ethernet back to the control system and include; phase loss, excessive thermal conditions, overvoltage trip, overcurrent trip, and input fuse clearing or circuit breaker trip. In addition, ardware programming signals provide a flexible means of establishing control of the power supply as well as setting over current and voltage set points on the DC output.

<u>Subject Inventions Listing</u>: None

<u>ROI #</u>: None