ENERGY TECHNOLOGIES AREA

LAWRENCE BERKELEY NATIONAL LABORATORY

Energy Analysis &
Environmental Impacts Division

Reversible Fuel Cell Cost Analysis and Megawatt PEM Cost Analysis for H2 Grid Storage Systems

FC332

DOE HFCTO 2022 AMR Poster

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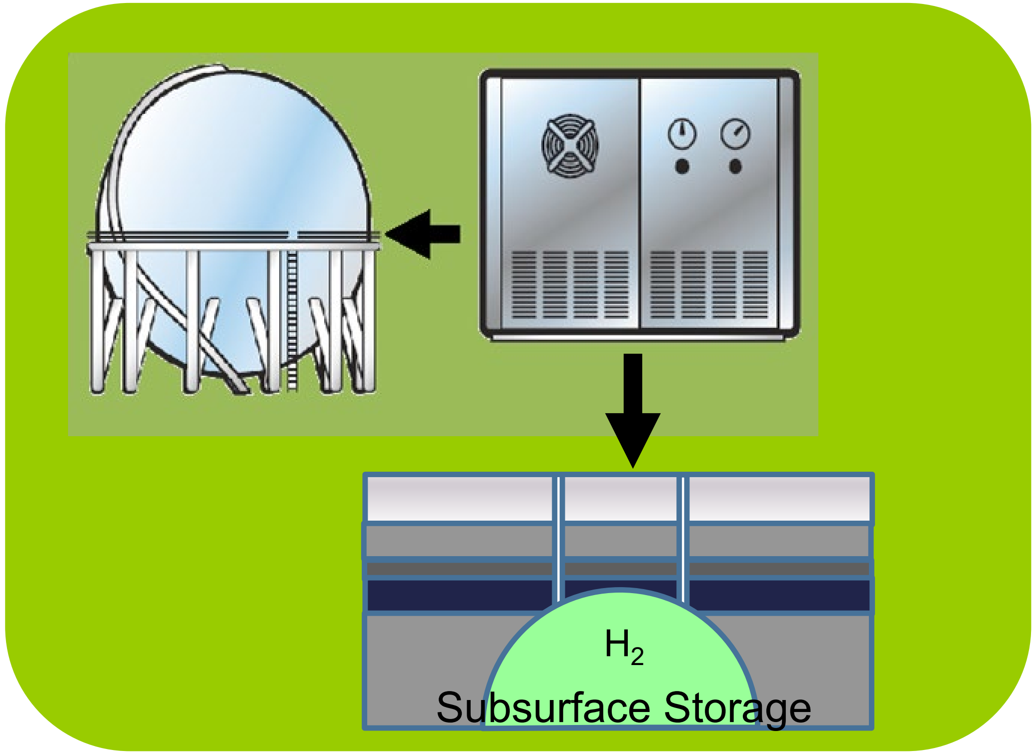
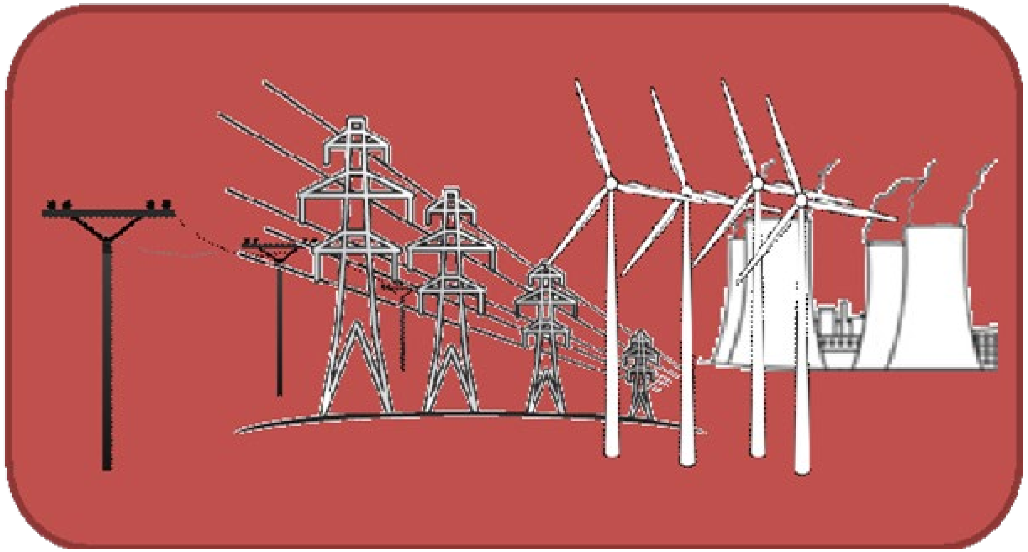
Project Goals

Determine the future potential cost reductions from unitized reversible fuel cells and megawatt-scale (MW) PEM fuel cell systems (FCS) for H2 grid storage systems



H2 stored above ground
or subsurface storage



H2 to electricity for grid support
from a H2 turbine, H2 FCS,
or unitized reversible fuel cell

Overview

Timeline

- Project Start Date: Nov 1, 2018
- Project End Date: May 30, 2022
- Percent complete: ~90%

Barriers Addressed

- The potential for greater cost reduction in **MW-PEM stationary systems (focus of this poster)**
- The extent to which hydrogen energy storage costs can be reduced by consolidating electrolyzers and fuel cell stacks in a unitized, reversible fuel cell.
- The role of hydrogen for long term energy storage to support greater fractions of variable renewable electricity

Budget

- FY19 DOE Funding: $ 200,000
- FY20 DOE Funding: $ 325,000
- FY21 DOE funding: $125,000k
- Total DOE Funds Received to Date: $650,000 [$250,000 for MW-PEM]

Partners

- NREL (Year 1)
- Ballard (Year 3)

Relevance and Milestones

- **Scaling up PEM systems to MW-scale** could result in substantial cost reductions for larger scale PEM stationary power systems to support high renewables electricity grid
- Alternatively, unitized reversible fuel cells (consolidated stack) with H2 storage, could form a cost-competitive long duration energy storage system
- BARRIERS FROM 2016 MYRDDP: **Reducing cost and increasing durability are the main challenges** for the implementation of MW-scale H2-PEM fuel cell systems and reversible fuel cells

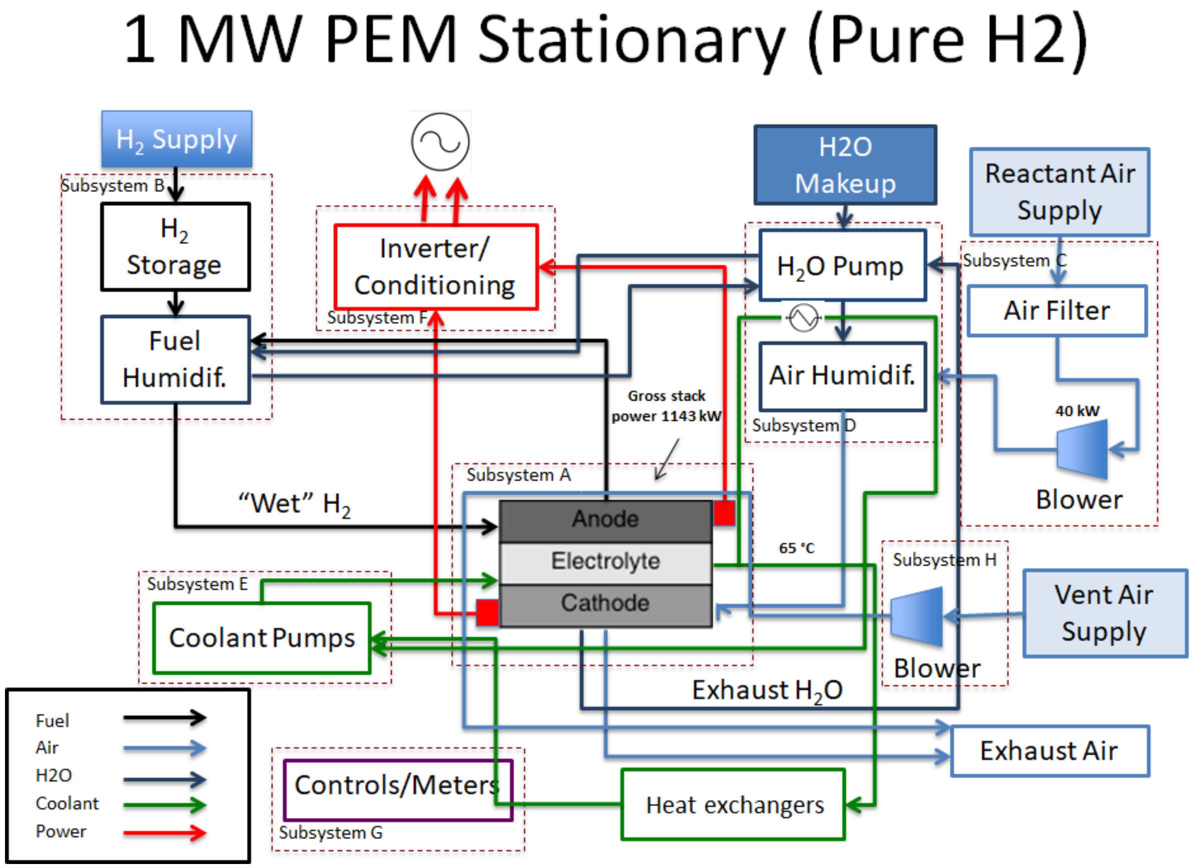
Milestone	Date
Cost analysis comparison and applicability of using mobile fuel cell cost estimates for stationary fuel cell systems for H2 storage system	FY 2021 Q3/Q4
Cost estimates for MW-scale H2 PEM stationary FCS for 5,000-25,000-hour lifetime vs 40,000-60,000-hour lifetime	FY 2022 Q1/Q2

Approach – MW-PEM H2 System costing

- Derive estimates for MW-scale PEM H2-fuel cell system cost and cost competitiveness for use in H2 storage systems for renewable electricity grid support
- Utilize literature from past stationary and vehicle cost studies
  - Adjust stack for lower lifetime case and power only (non- combined heat and power from three past studies for DOE: LBNL (Wei et al. 2014), Battelle (Contini et al. 2016), Strategic Analysis (James and DeSantis 2015) stationary studies:
  - Assess cost reduction available from potential use of vehicle-like stacks and systems for stationary applications: Strategic Analysis vehicles studies (James et al. 2012, 2017, 2018, 2019)
- For lower lifetime case below, scale stack to higher volumes and adjust cell PGM and membrane/GDL thickness for lower lifetime (25,000 hr from > 50,000hr)
- Characterize cost for major balance of plant components at MW-scale
- Update DOE HFCTO stationary target to include MW-PEM H2 fuel cell system target for grid support

Reference	HFCTO Stationary targets	This work
System type	Combined heat and powe	Power generation
Input fuel	Natural gas from utility	H2 from large scale H2 storage
System size	10-250kW	1-10 MW
System lifetime	60,000 - 80,000 hrs	25,000 hrs, > 50,000 hrs
Ann volume	0.1- 1.25 GW	Up to 12.5 GW per year

Accomplishment: Defined functional specs for MW-scale PEM

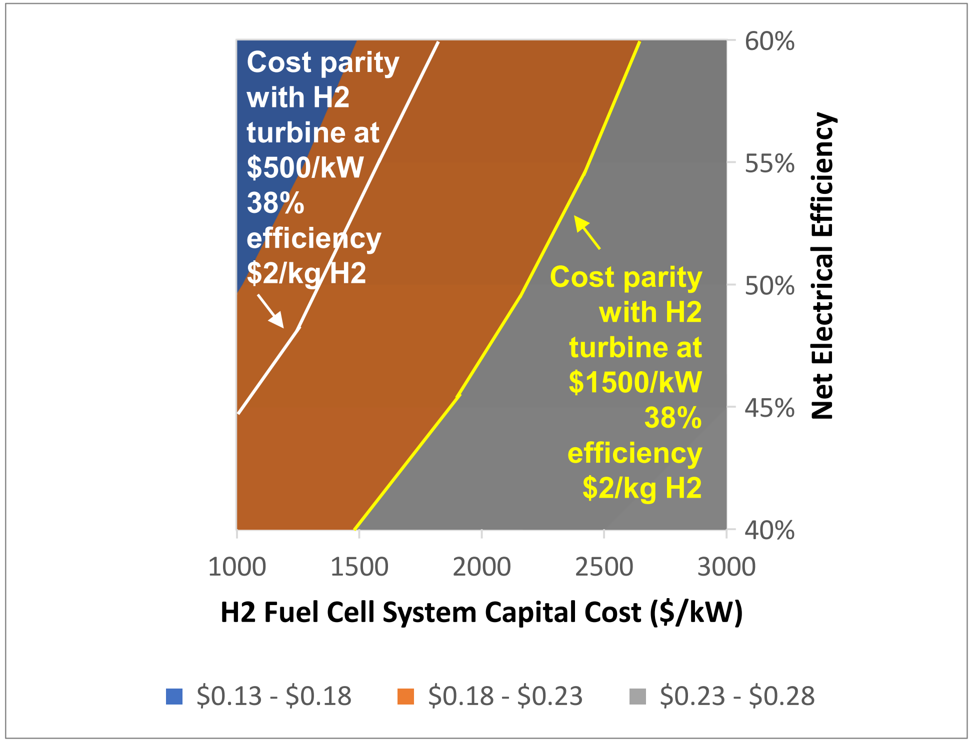


Benchmarked performance w/ Hydrogenics and DEMCOPEM published data

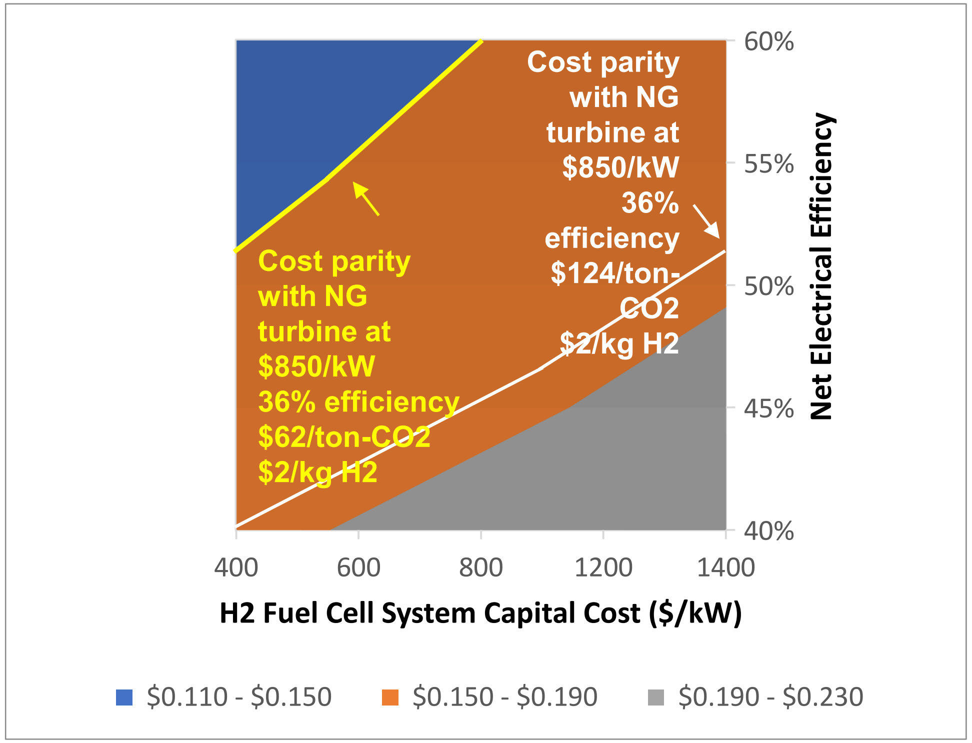
1 MW Size		Best. Ests.	
	Unique Properties:		Units:
System	Gross system power	1143	kW
	Net system power	1000	kW (AC)
	Physical size	2.9x 7.2 x 9	meter x meter x meter
	Physical weight	~50,000 kg	kg
	Electrical output	480V AC	Volts AC or DC
	DC/AC inverter effic.	95%	%
	Peak ramp rate	30	kW/sec - size dep
	Waste heat grade	N/A	Temp. °C
	Fuel utilization % (first pass)	95%	%
	Fuel utilization % (overall)	99%	%
	Fuel input power (LHV)	2028	kW
	Stack voltage effic.	57%	% LHV
	Gross system electr. effic.	56%	% LHV
	Avg. system net electr. effic.	49%	% LHV
	Thermal efficiency	N/A	% LHV
	Total efficiency	49%	Elect.+thermal (%)
Stack	stack power	23.80	kW
	total plate area	900	cm^2
	CCM coated area	630	cm^2
	single cell active area	567	cm^2
	gross cell inactive area	37	%
	cell amps	340	A
	current density	0.60	A/cm^2
	reference voltage	0.7	V/cell
	power density	0.420	W/cm^2
	single cell power	238	W
	cells per stack	100	cells
	percent active cells	100	%
	stacks per system	48	stacks
Addt'l Parasitics	Compressor/blower	40	kW
	Other paras. loads	50	kW
	Parasitic loss	90	kW

Accomplishment: MW PEM FCS vs H2/ Gas Turbine cost competitiveness

MW PEM vs H2 turbine



MW PEM vs gas turbine

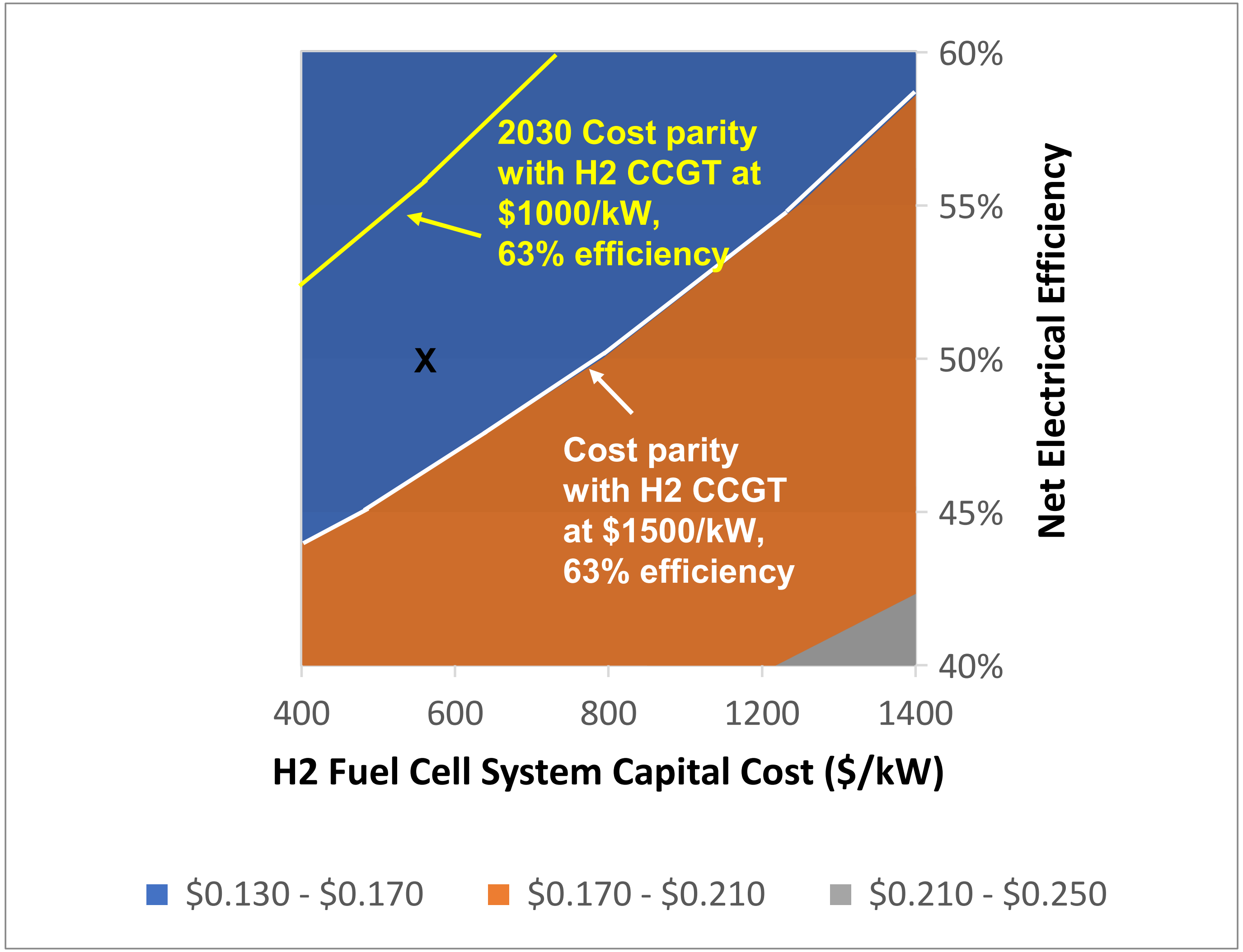


25% capacity factor for all cases assuming electricity grid with high renewable fraction (e.g., solar and wind)

Assumes natural gas 2030 price at high AEO case (67% higher price than 2021 at $0.83/therm)

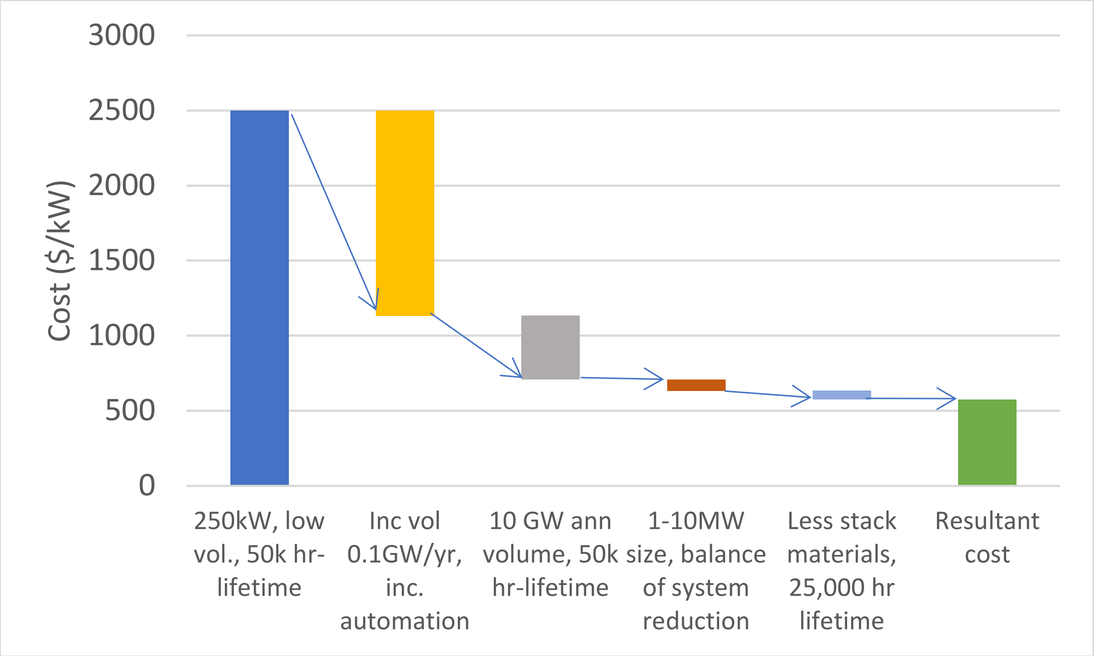
Yellow line also corresponds to gas at 2020 price ($.50/therm or 2030 Low AEO price), with $124/ton CO2 price

Accomplishment: MW PEM FCS vs H2 Turbine CCGT cost competitiveness



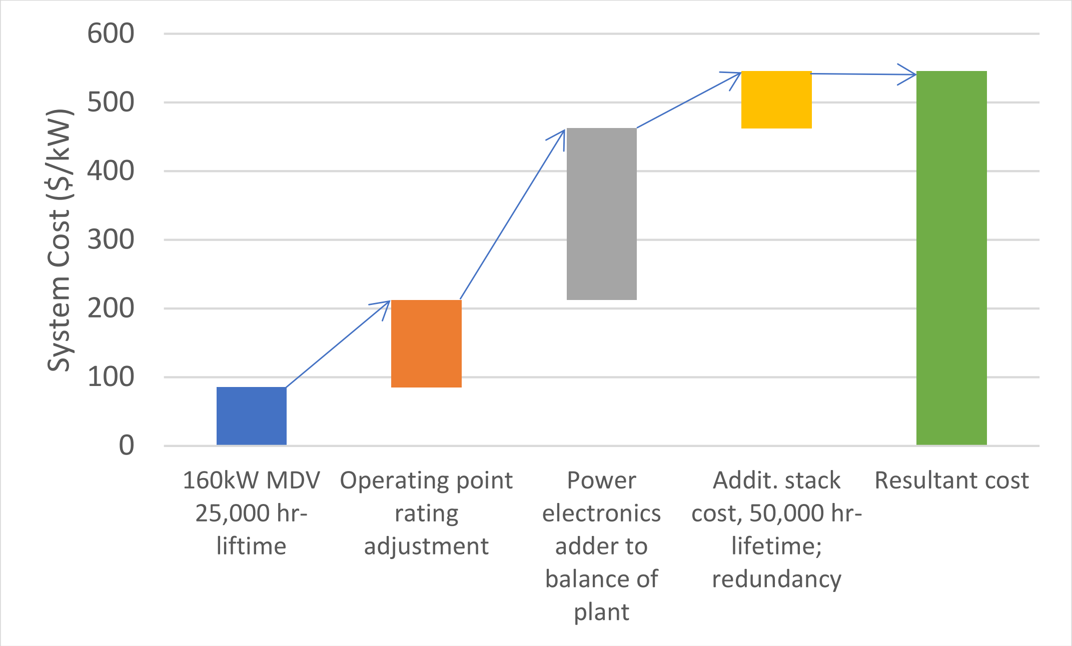
- At 50% efficiency, H2 PEM fuel cell system has cost parity at $400-800/kW with H2 CCGT at $1100-1500/kW ("X" denotes $550/kW, 50% efficiency for PEM fuel cell system)
- Assumes H2 CCGT at 63% efficiency and 25% capacity factor for both systems, $2/kg H2 delivery price

Accomplishment: Potential cost reduction from MW-PEM FCS for Long lifetime, shorter lifetime



- MW H2 PEM cost scaling based scaling up system size from low volume 250kW system size to high volume and to 1-10MW system size
- Estimated $1100/kW cap cost for 250kW, 0.1GW/yr vol.
- Estimated $650/kW cap cost for MW-scale, (50,000 hr. lifetime, 10 GW ann. volume) H2 PEM system, primarily from balance of plant cost reductions
- Estimated $550/kW cap cost for 25,000hr lifetime stack

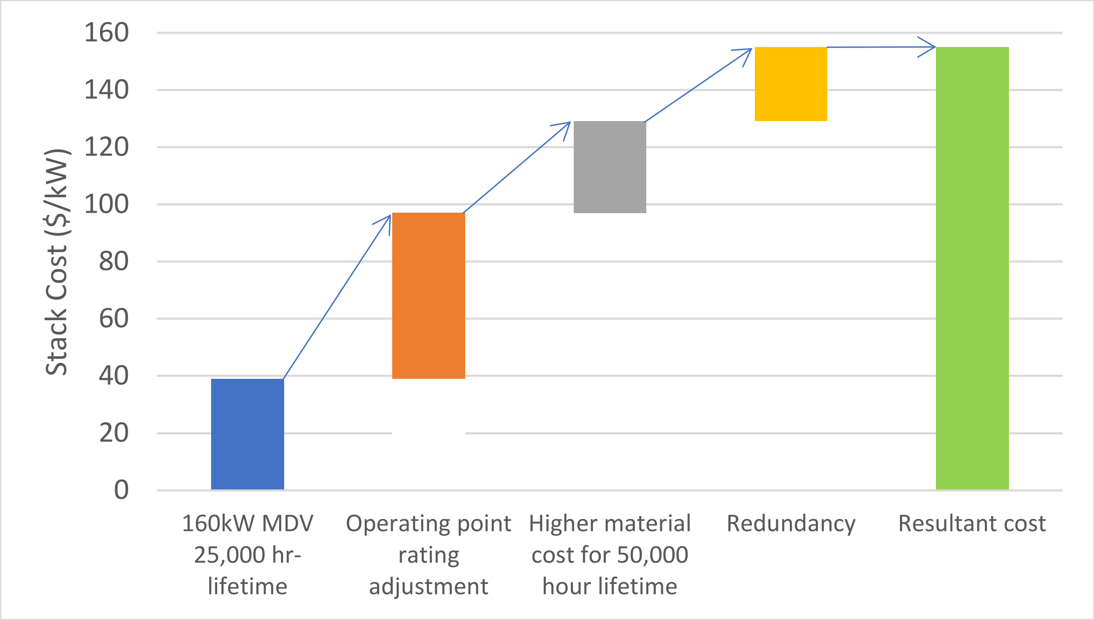
Accomplishment: Medium Duty Vehicle FCS cost compared to MW-PEM FCS cost



- Medium duty (MDV) system cost at $85 per kW[1] (16 GW/yr annual volume) is much lower than stationary costs due to several factors
- Accounting for these factors (manufacturing volume, operating point/power rating, power electronics, stack material loading, redundancy) bring it closer to stationary system cost ($550/kW at 50,000 hr. lifetime, 10 GW annual volume)

[1]*James et al. 2018*

Accomplishment: Medium Duty Vehicle stack cost compared to MW-PEM stack cost



- Medium duty (MDV) stack cost at $39 per kW[1] (16 GW/yr) is much lower than stationary costs due to several factors
- Accounting for these factors (manufacturing volume, operating point/power rating,, stack material loading, redundancy) stack cost to $155/kW for 50,000 hr. lifetime, 10 GW annual volume

[1]*James et al. 2018*

Accomplishment: Preliminary MW-PEM technical targets

DOE HFCTO Technical Targets : 100 kW–3 MW Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas				Prelim. MW-PEM Fuel Cell System Targets, this work	
CHARACTERISTIC	UNITS	2015 STATUS	2020 TARGETS	2030 TARGETS	2030 TARGETS
Input fuel	Natural gas	Natural gas	Natural Gas	H2	H2
Electrical efficiency at rated power	% (LHV)	42–47	>50	50	50
CHP energy efficiency	% (LHV)	70–90	90	-	-
Equipment cost	$/kW	1,200	1,000	650	550
Annual manuf. volume (system size)	GW	0.1 (100kW)	1 (100kW)	10 (1 MW)	10 (1 MW)
Operating lifetime	h	40,000–80,000	80,000	> 50,000	25,000
System availability	%	95	99	99	99

Collaboration and Coordination

- Project collaborators:
  - Ballard Power Systems (sub-contractor)
- Describe the collaborative relationships and their importance in achieving the project's objectives.
  - Ballard is providing inputs and review of MW-PEM and system design, operational use cases and configurations, and cost modeling.

Remaining Challenges and Barriers

- Demonstration of MW-scale PEM in hydrogen storage system to provide integration, cost, and performance data
- Market adoption and manufacturing scale-up of MW-scale PEM systems
- Transition pathways for natural gas to H2 turbine compared to natural gas to H2 fuel cell systems

Proposed future work

- Equity impacts of large scale hydrogen storage systems including fuel cell system manufacturing
- Economic development / supply chain analysis of large-scale hydrogen storage systems including fuel cell system manufacturing
- Pursue technology demonstration projects and further techno-economic analysis
    - E.g., technology demonstration projects from California Energy Commission EPIC RD&D program and Southern California Gas Company’s clean distributed generation R&D program

Any proposed future work is subject to change based on funding levels.

Project Summary

- Competitive analysis for levelized cost of electricity from MW-scale fuel cell system compared to hydrogen-turbine based power for H2-storage systems
- Stationary H2-PEM fuel cell system cost estimated for MW-scale system sizes and potential for using vehicle-based fuel cell systems.
- Near term goal of $1000/kW cap cost for MW-scale FCS
- Longer term goal $600-700/kW capital cost for MW-scale H2 PEM FCS at >50,000 hours lifetime; $500-600/kW for 25,000 hour lifetime

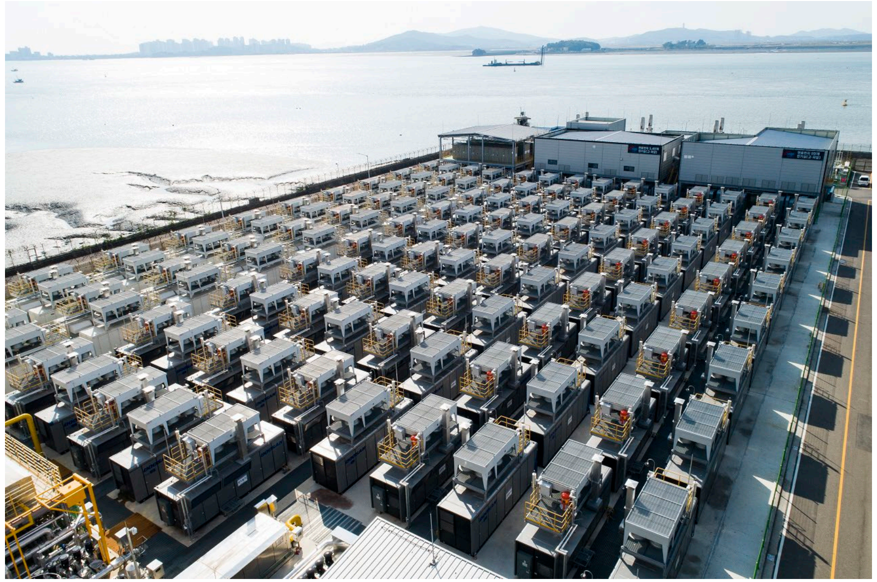
Technical Backup and Additional Information

Technology Transfer Activities

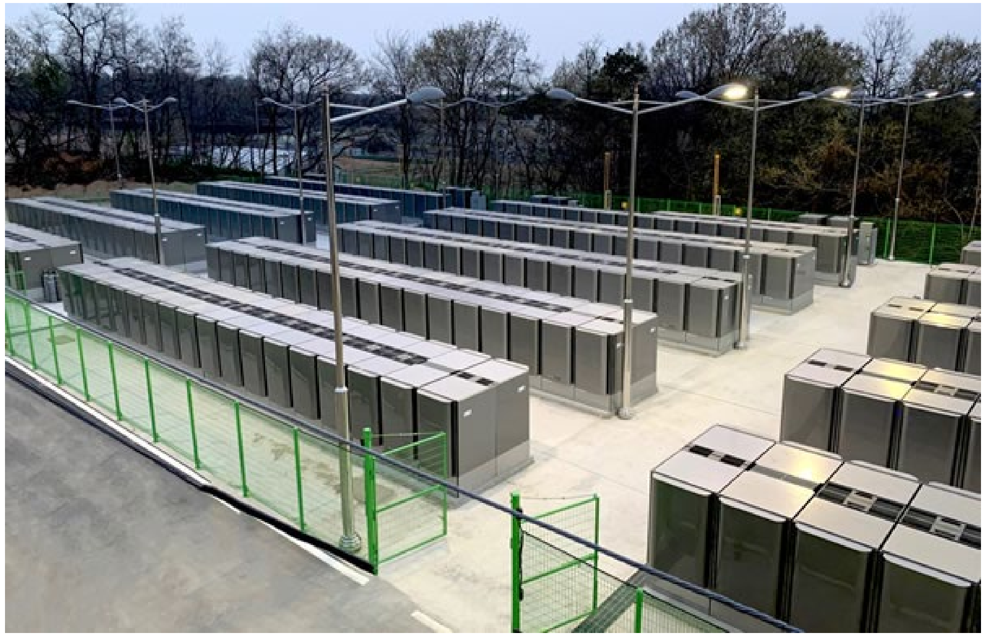
- Patent, licensing, or potential licensing information: none
- Technology-to-market or technology transfer plans or strategies:
  - Write up results from this project in two journal paper and disseminate in DOE Webinar
  - Updated DOE Record on URFC PEM targets
  - Plan to propose and update DOE HFCTO targets for MW PEM H2 stationary fuel cell systems

- Include plans for future funding from alternative sources as well as marketing strategies and options
  - Pursue technology demonstration and further techno-economic analysis in California through California funding agencies, e.g. technology demonstration projects from California Energy Commission EPIC RD&D program and Southern California Gas Company's clean distributed generation R&D program

Modular approach for MW-scale FC systems



Western Incheon Fuel Cell Power Plant, S. Korea, where Doosan Fuel Cell's **58.96 MW** are installed (440kW PAFC modules)

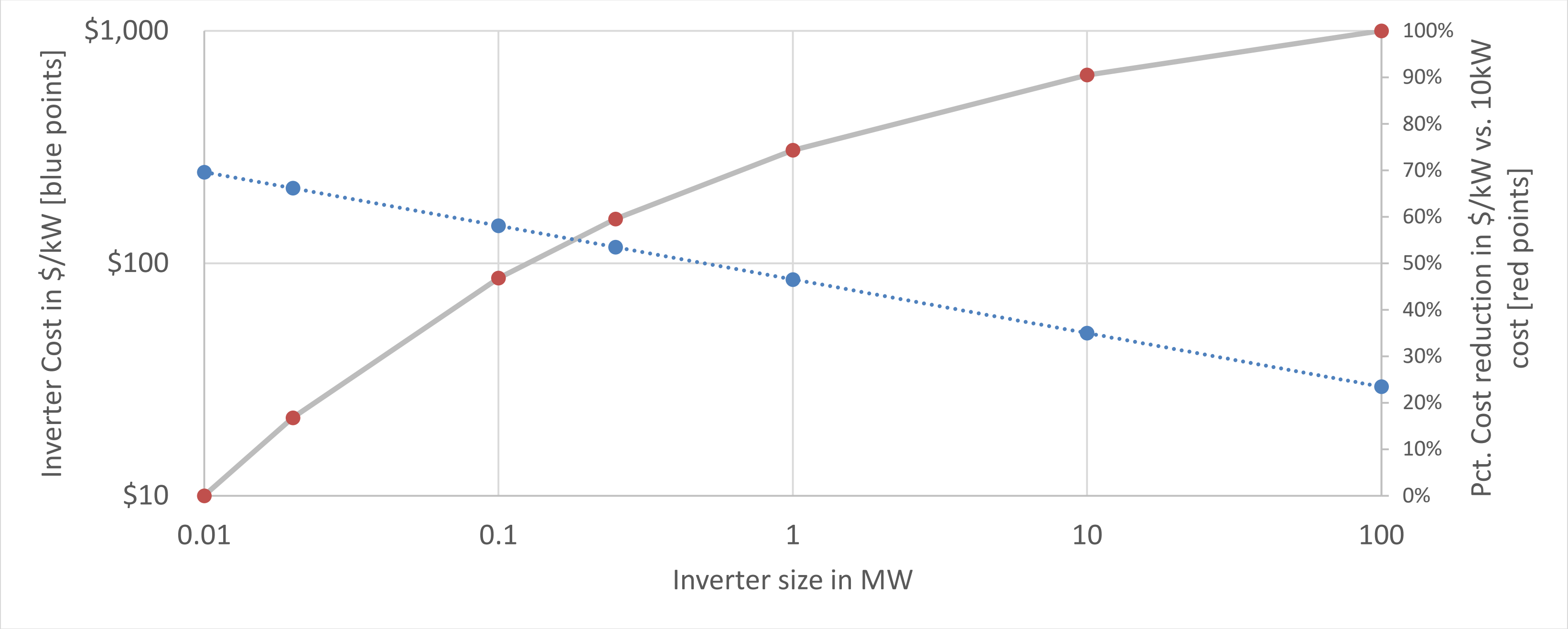


Bloom Energy **19.8 MW** fuel cell deployment of of Bloom Energy Servers, Hwasun, S. Korea (200kW SOFC modules)

- Modular design favored for consolidation of production units for design/capacity flexibility and market risk mitigation;
- Strategy employed by Doosan and Bloom Energy recent MW-scale fuel cell installation for PAFC, SOFC respectively, with unit sizes of 200-440 kW.

Cost reduction for inverter vs size (highest balance of system cost) slows down after 1MW size

- Plot of inverter cost vs size in kW from 10kW to 100MW
- Most of cost reduction (~75%) is achieved by 1MW
- 1MW inverter cost is about $100,000 or about $100/kW



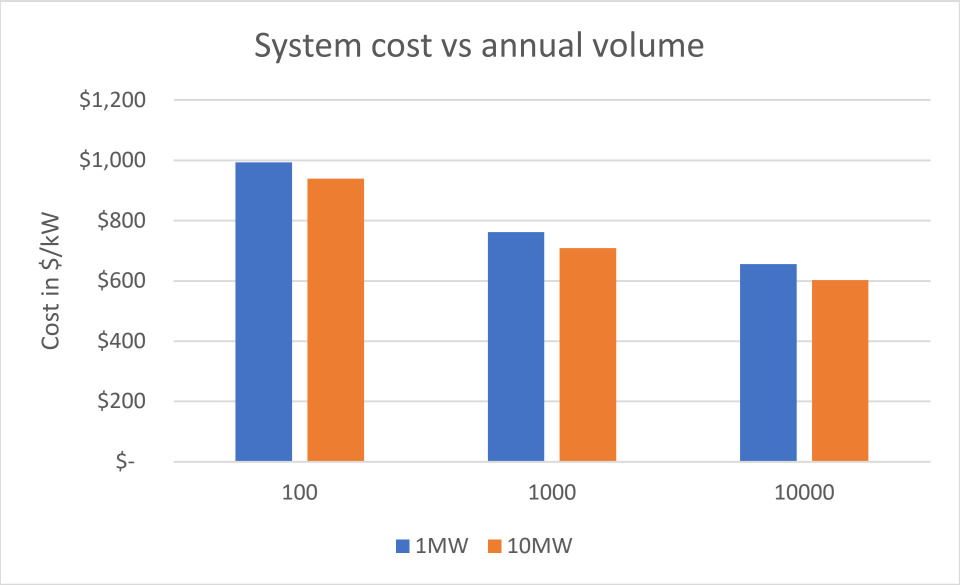
Ref: Vendor quotes; R. Fu 2018

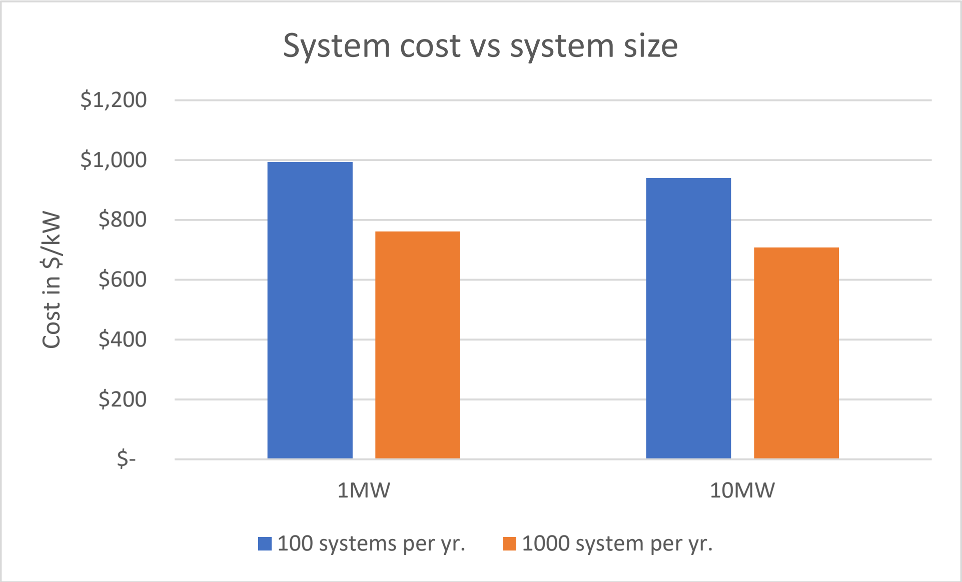
Stack differences for 25,000 hr vs >50,000 hr lifetime

Parameter	Units	25,000 hr lifetime	>50,000 hr lifetime
Membrane thickness	microns	14	25
Catalyst ink/application	mg/cm2	0.35	0.5
Gas diffusion layer (GDL)	microns	150	320
Reference		James et al. 2018	Wei et al. 2014

- Benchmarked 3 stationary studies' stack costs *[LBNL (Wei et al. 2014), Strategic Analysis (James and DeSantis 2015), Battelle (Contini et al. 2016)]*
- At high volume (5-10 GW annual volume) all 3 stationary studies have similar materials fraction of stack costs (63-68%) and 36-38% lower material costs for lower lifetime stack
- Estimate approximately 24% lower stack costs for lower lifetime stack at high volume

MW-PEM System cost vs system size and annual volume for >50,000 lifetime





DOE Hydrogen and Fuel Cells Program Record High-temperature unitized reversible fuel cells (based on this project)

Technical Targets for High-Temperature Unitized Reversible Fuel Cells (Cell/Stack level) for Electric Energy Storage Applications

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
Cell Performance/ Roundtrip Electric Efficiency at 0.5 A/cm2 FC; 1 A/cm2 EL	%	~ 80	85	90
Cell Durability/Degradation Rate	%/1000 hr	<1.5	0.25	0.125

Technical Targets for High-Temperature Unitized Reversible Fuel Cell Systems for Electric Energy Storage Applications

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
System Roundtrip Efficiency (includes thermal energy input)	%	37	60	65
Lifetime/Durability	hr [Cycles]	10,000 [unknown]	40,000 [daily]	80,000 [daily]
Levelized Cost of Storage	$/kWh	1.11	0.20	0.10
System Capital Cost by Power	$/kW	-	1,800	1,300
System Capital Cost by Energy	$/kWh	-	250	150

Reference: DOE Hydrogen and Fuel Cells Program Record, Reversible Fuel Cell Targets, Record 20001, April 16, 2020.

DOE Hydrogen and Fuel Cells Program Record: Low-temperature unitized reversible fuel cells (based on this project)

Technical Targets for Low-Temperature Unitized Reversible Fuel Cells (Cell/Stack level) for Electric Energy Storage Applications

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
Cell Performance/Roundtrip Electric Efficiency at 0.5 A/cm2 FC; 1 A/cm2 EL	%	52	55	65
Cell Durability/Degradation Rate	%/1000 hr	-	0.25	0.125
Total Cell PGM Loading	mg/cm2	1.3	1.0	0.5
Stack Capital Cost (Based on FC Power Output)	$/kW,	1,000	550	300

Technical Targets for Low-Temperature Unitized Reversible Fuel Cell Systems for Electric Energy Storage Applications

Characteristic	Units	2020 Status	2030 Targets	Ultimate Targets
System Roundtrip Efficiency	%	-	40	50
Lifetime/Durability	hr [Cycles]	-	40,000 [daily]	80,000 [daily]
Levelized Cost of Storage	$/kWh	1.60	0.20	0.10
System Capital Cost by Power	$/kW	-	1,800	1,300
System Capital Cost by Energy	$/kWh	-	250	150

Reference: DOE Hydrogen and Fuel Cells Program Record, Reversible Fuel Cell Targets, Record 20001, April 16, 2020.

Publications

- Y. N. Regmi, N. Danilovic, X. Peng, J.C. Fornaciari, M. Wei, et al. A low temperature unitized regenerative fuel cell realizing 60% round trip efficiency and 10 000 cycles of durability for energy storage applications, Energy & Environmental Science, 2020, Advance Article DOI: 10.1039/c9ee03626a

- In preparation:
  - Wei, M., Levis, G., Mayyas, A. Cost analysis of unitized reversible fuels cells for large scale H2 storage systems, manuscript to be submitted to International Journal of Hydrogen Energy
  - Wei, M., Cost analysis of megawatt polymer electrolyte membrane fuel cell systems for hydrogen storage and renewable electricity grid support, manuscript to be submitted to Energy Conversion and Management