Techno-economic Analysis of the Cryogenic Flux Capacitor Compared to Other forms of Hydrogen Production and Storage

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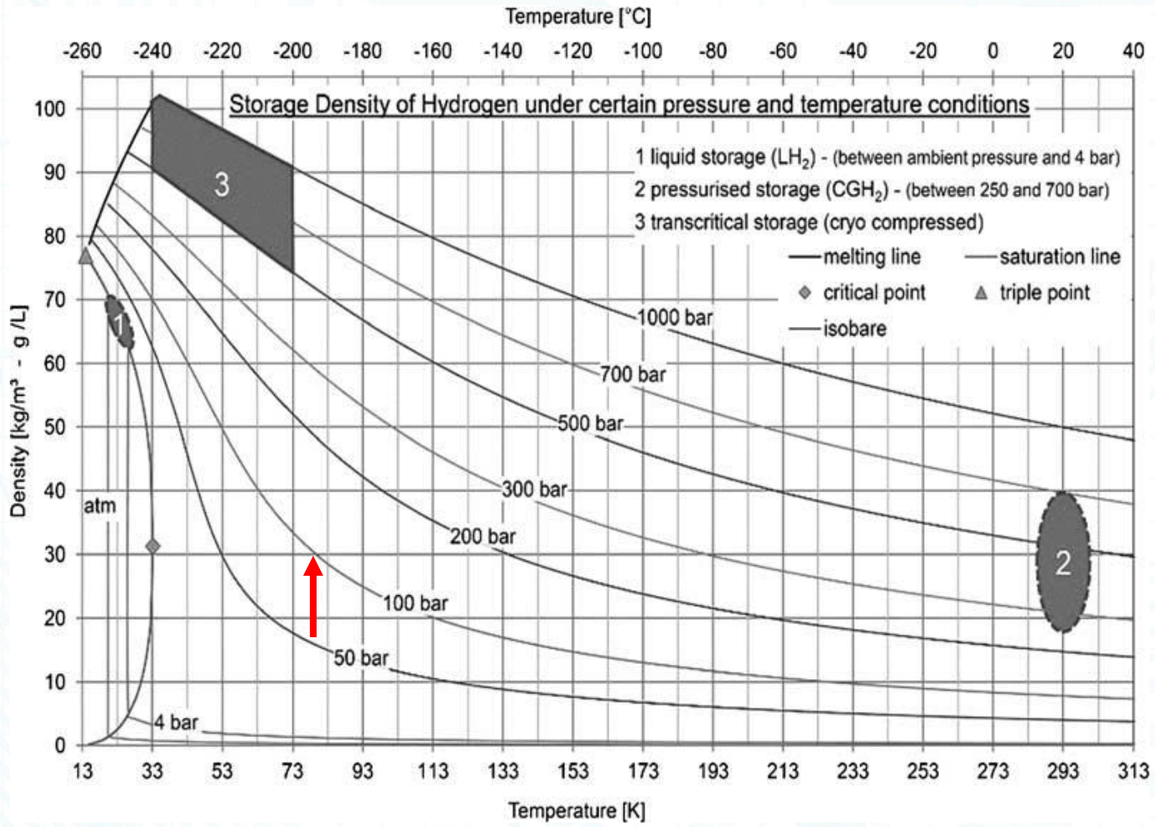
Background

- Physisorption of gas into nanoscale pores of aerogel
- NASA development of various aerogel packaging for containment in a pressure vessel
- Testing has been completed for nitrogen, air, oxygen, argon, and hydrogen
  - DOE grant lead by SwRI, working with UCF, NASA, and Air Liquide
- Mass uptake measurements to demonstrate aerogel performance
  - Testing at the 1g and 1kg of hydrogen scale
  - Tests showed 36-38% increased uptake over an empty vessel at T&P
- Continued testing for pressure up to 50 bar

Motivation

- Pair a storage system with its complimentary conditioning system
  - Improve cost and performance with CFC refrigeration
  - Refrigerate to 80K to improve vs liquification
- Analyze costs and performance of the system for green hydrogen vs SMR blue hydrogen
- Base commercial costs on limits of current testing, not hopes of future performance
  - Explore the 50 bar and 80K system



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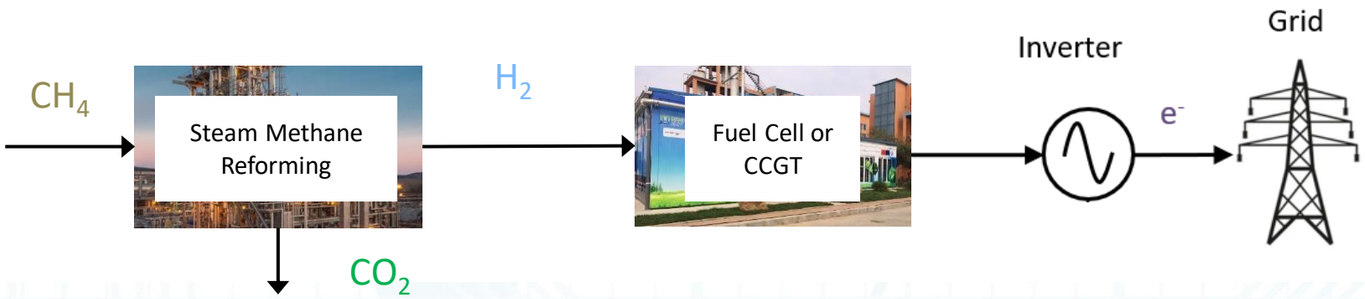
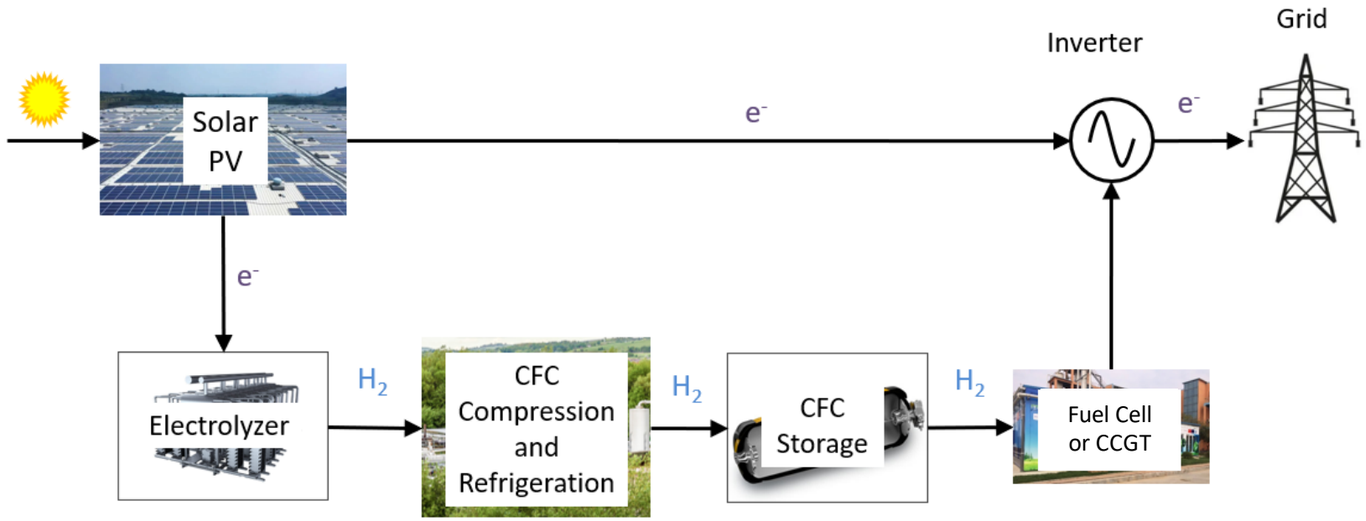
Techno-Economic System Approach

- Blue Hydrogen by SMR
- Green Hydrogen by PV with an Electrolyzer
- Storage:
  - Compressed GH_2 at 700 bar
  - Cryogenic LH_2
  - CFC at 80 K and 60 bar
- Looked at:
  - 25MW Fuel Cell
  - 650MW Fuel Cell or Combined Cycle Gas Turbine (CCGT)





Cost and Performance Sources and Methods

- Sources for costs and performance primarily NREL, NETL, DOE Grand Challenge Cost Analysis, and others
- Import/export of hydrogen into storage under a fixed purchase/sale price of $6/kg as fuel
- 10 hour duration was focus of current work
- CFC storage costs estimated using current BOM for 1kg unit, using 36% storage improvement at T&P, and scaling to 125 m^3
- A ratio of component cost to installed cost of 2.5 based on baselines

Source	Used for
NREL Solar Baseline	Solar PV
DOE Grand Challenge 2022 Report	Fuel Cell, Electrolyzer, GH_2 Compression, Cavern Storage
NETL Fossil Generation Baseline	Combined Cycle Gas Turbine (CCGT)
NETL Fossil Hydrogen Generation	SMR, GH_2 Compression
Amos, "Costs of Storing…"	GH_2 Storage, LH_2 Liquifying, LH_2 Storage
Green, "Cost of Coolers…"	CFC Refrigeration

Cost Factors and Analysis Overview

- LCOE is normalized to total electricity produced
- LCOS is normalized to electricity produced by storage
- LCOH is normalized to hydrogen generated
- 30 year cash flow analysis
  - Based on discount rates from NREL
  - 15 year financing at 6.8% APR

OPEX	
General O&M (%CAPEX/yr)	0.8-3.0%
Natural Gas ($/MMBTU)	4.42
CO2 Disposal Cost ($/tonne)	8.0

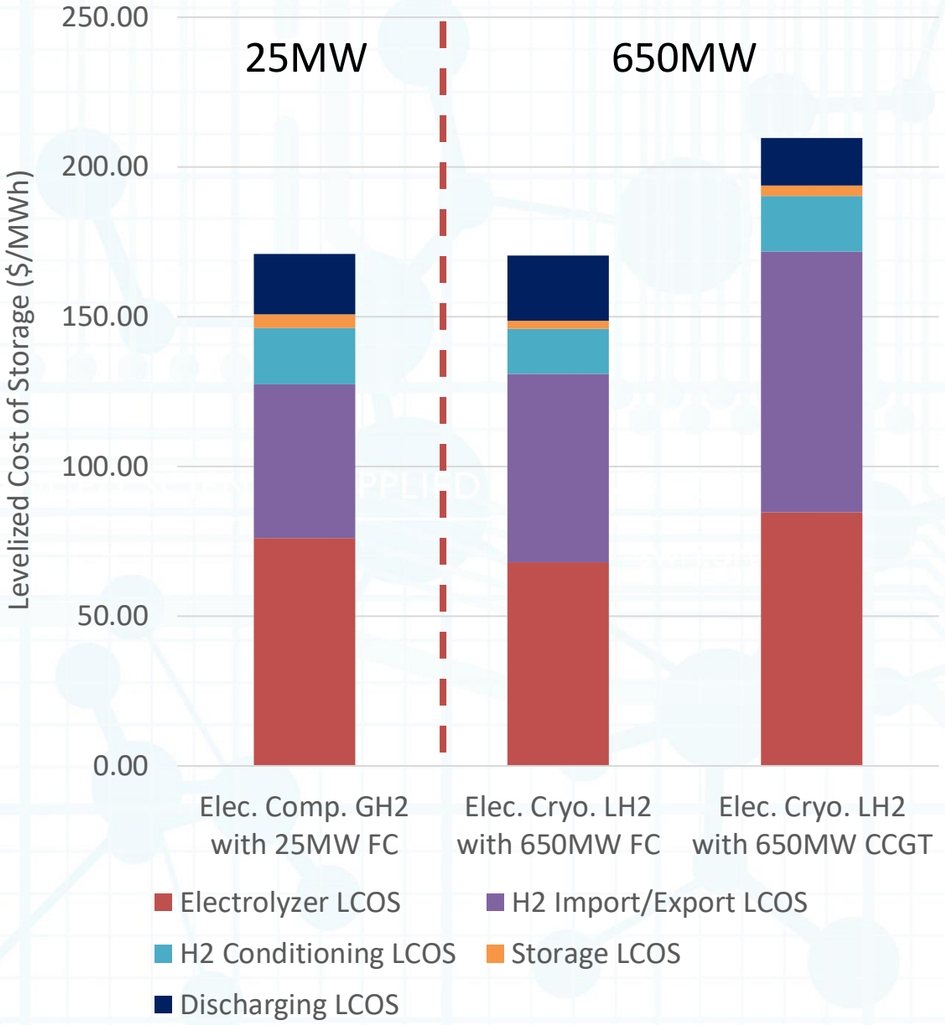
CAPEX	25 MW	650 MW
Solar PV ($/$kW_{DC}$)	1,000	990
Electrolyzer ($/$kW_{DC}$)	1,316	1,316
SMR ($/kg/hr)	109,537	37,982
GH_2 Compression ($/kg/hr)	15,606	-
H_2 Liquification ($/kg/hr)	-	13,833
GH_2 Refrigeration ($/kg/hr)	8,647	3,465
GH_2 Storage ($/tonne)	822,000	-
LH_2 Storage ($/tonne)	-	577,922
CFC Storage ($/tonne)	577,898	577,898
Fuel Cell ($/$kW_{AC}$)	1,320	1,320
CCGT ($/$kW_{AC}$)	-	952

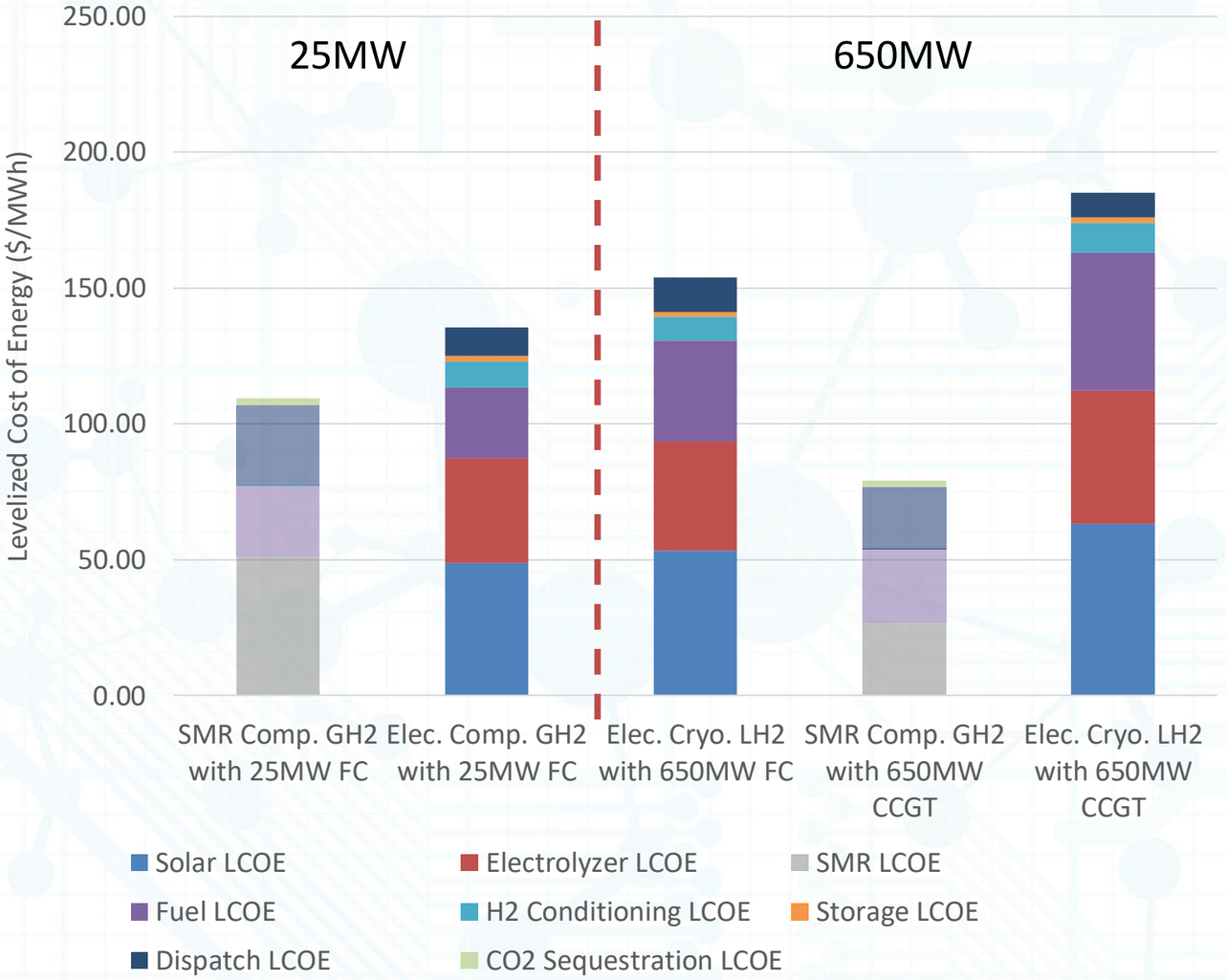
Commercial Systems Results

	SMR Comp. GH2 with 25MW FC	Elec. Comp. GH2 with 25MW FC	Elec. Cryo. LH2 with 650MW FC	SMR Comp. GH2 with 650MW CCGT	Elec. Cryo. LH2 with 650MW CCGT
Round Trip Efficiency (%)		43.8%	40.4%		30.8%
Total CAPEX	$139.3 M	$345.7 M	$9,387.3 M	$1,882.6 M	$10,896.6 M
Total OPEX	$4.0 M	$3.3 M	$109.4 M	$119.6 M	$119.2 M
Net Annual Cost of Fuel ($)	$5.9 M	$7.5 M	$277.5 M	$200.8 M	$379.6 M
Sequestration Cost	$0.5 M			$18.7 M	
Levelized Cost of Unconditioned H_2 ($/kg)	1.91	5.04	5.09	1.31	5.02
Levelized Cost of Conditioned H_2 ($/kg)	**1.92**	**5.43**	**5.40**	**1.32**	**5.33**
$LCOE_{DC}$ Solar Field ($/$MWh_{DC}$)		39.39	39.00		39.00
Total System LCOS ($/$MWh_{AC}$)		171.00	170.26		209.64
Combined System LCOE ($/$MWh_{AC}$)	**109.41**	**135.38**	**153.78**	**79.23**	**185.13**

- Solar storage system targeted less than $6/kg to ensure that production costs are less than sale cost
  - Results in small increases to LCOE

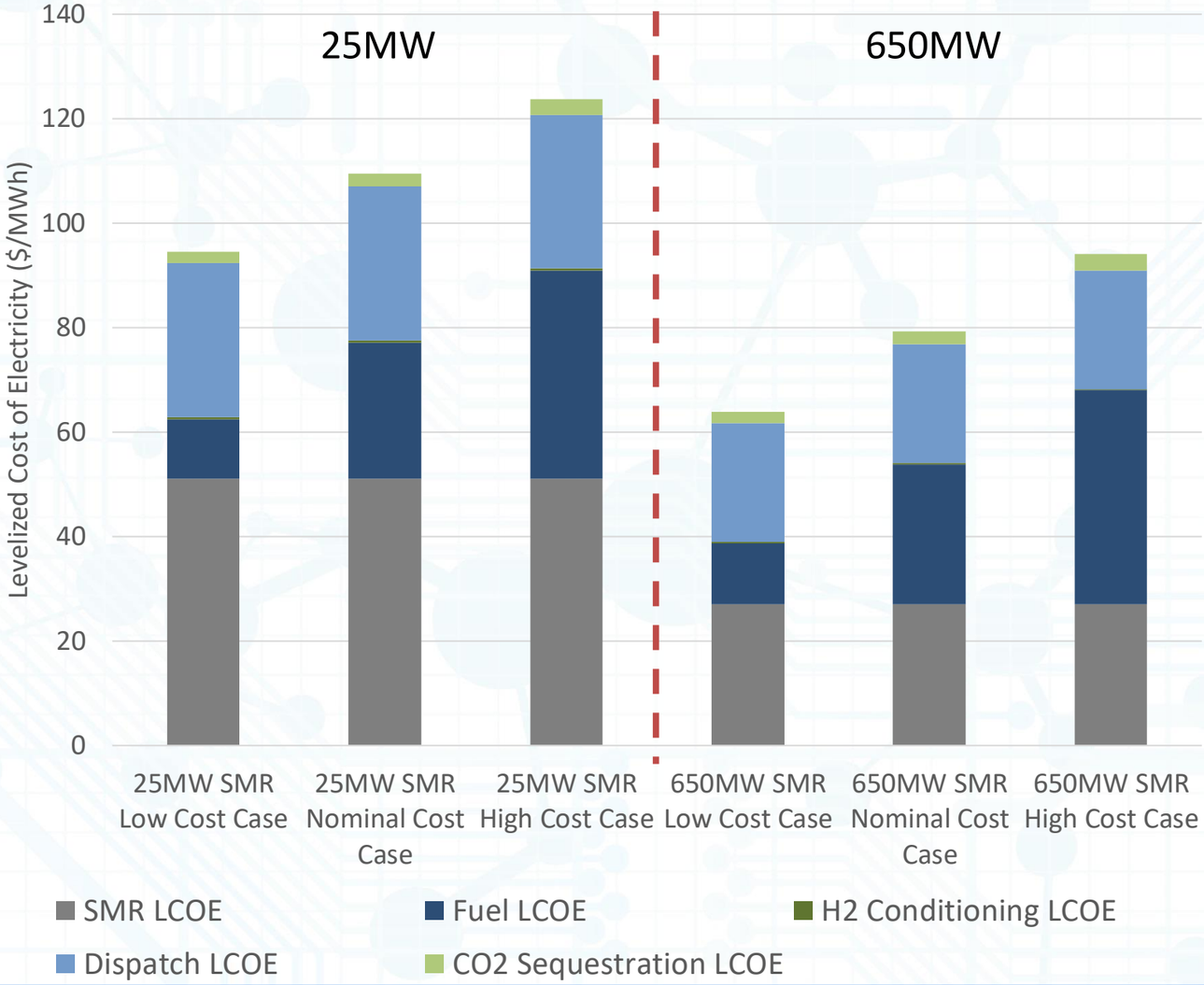
Commercial Systems LCOS and LCOE Breakdown





Sensitivity on Natural Gas and CO_2 Expense

- Nominal natural gas price $4.42/MMBTU
  - From DOE SMR Baseline
- Nominal CO_2 cost of sequestration is $8/tonne
- High and low natural gas price is $1.93/MMBTU to $6.75/MMBTU
- High and low CO_2 cost is $7/tonne to $10/tonne

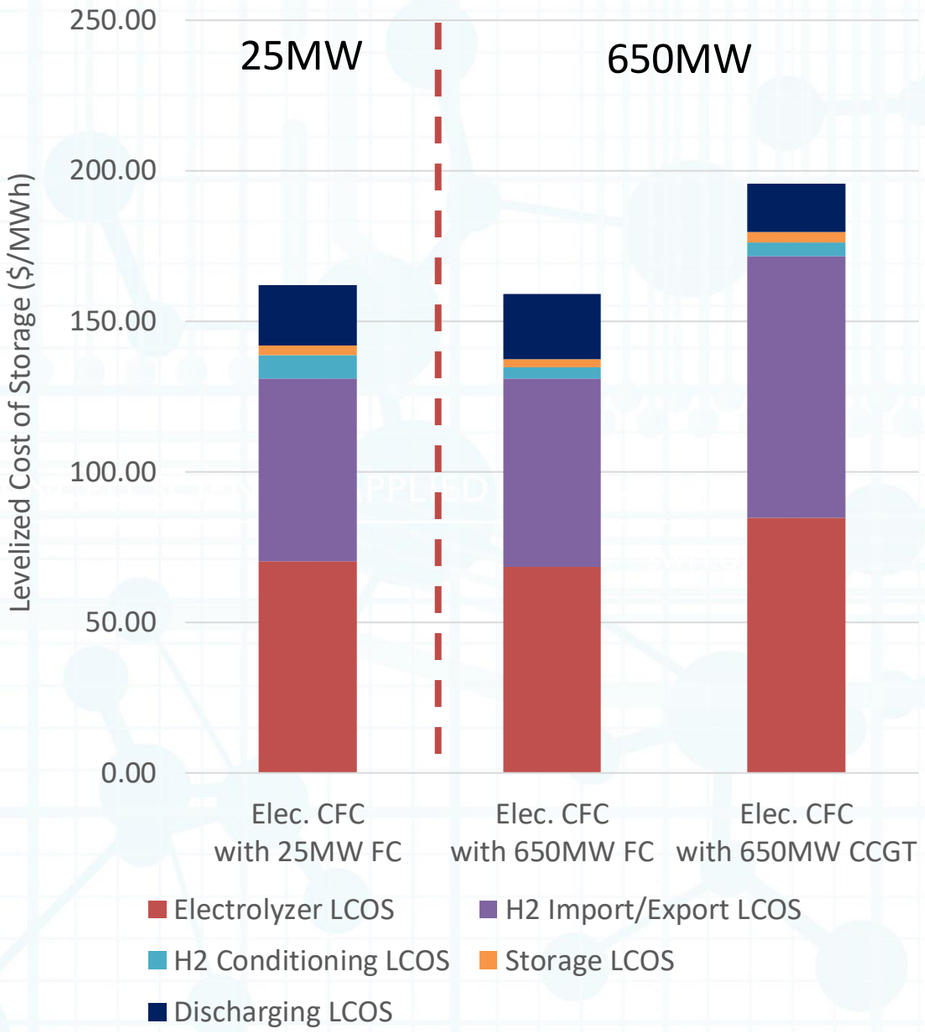


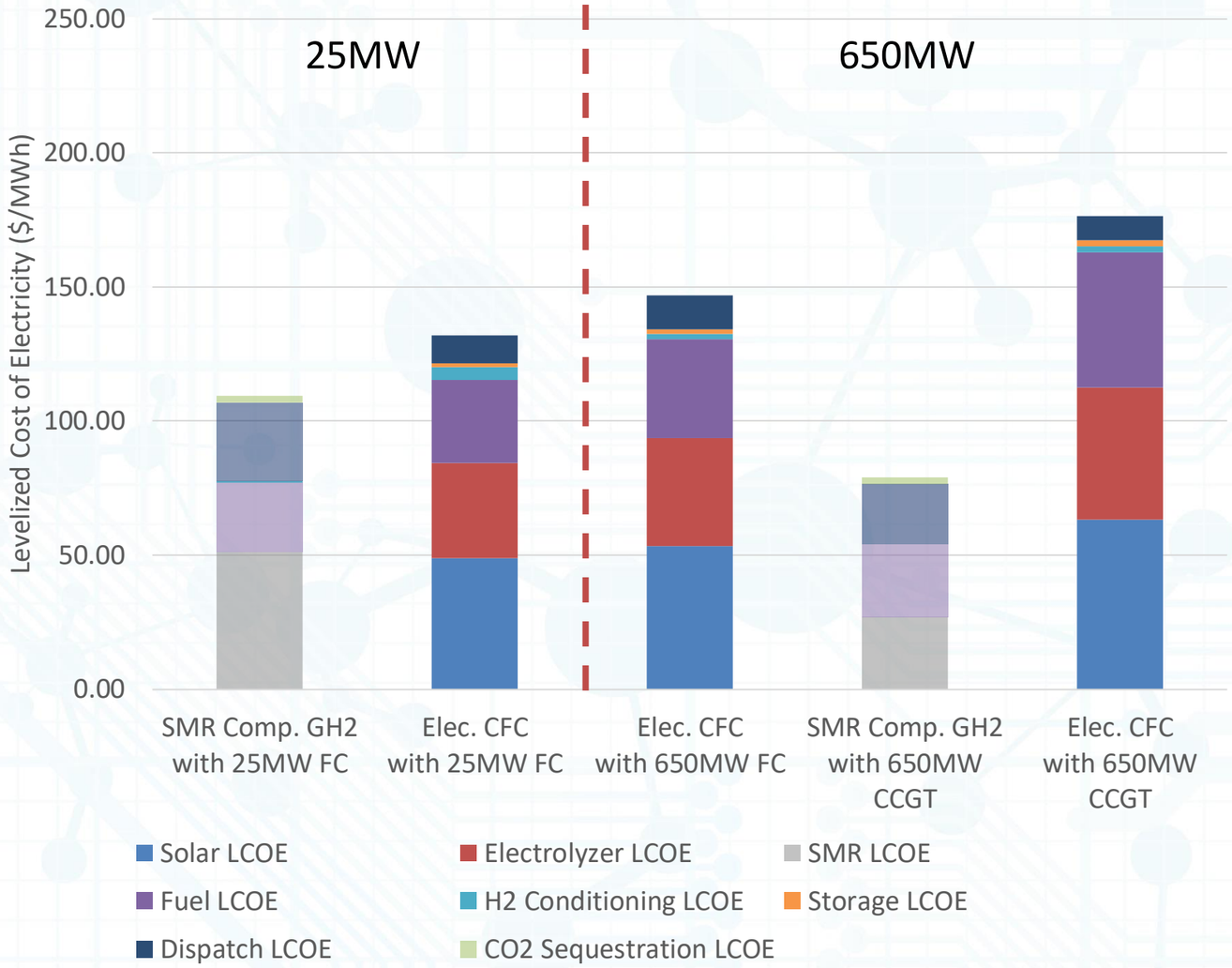
Cryogenic Flux Capacitor Systems Results

	SMR Comp. GH2 with 25MW FC	Elec. CFC with 25MW FC	Elec. CFC with 650MW FC	SMR Comp. GH2 with 650MW CCGT	Elec. CFC with 650MW CCGT
Round Trip Efficiency (%)		40.5%	40.5%		30.9%
Total CAPEX	$139.3 M	$320.8 M	$8,895.0 M	$1,865.7 M	$10,282.1 M
Total OPEX	$4.0 M	$3.0 M	$99.4 M	$119.3 M	$106.7 M
Net Annual Cost of Fuel ($)	$5.9 M	$8.9 M	$276.1 M	$200.8 M	$377.8 M
Sequestration Cost	$0.5 M			$18.7 M	
Levelized Cost of Unconditioned H_2 ($/kg)	1.91	5.36	5.08	1.31	5.01
Levelized Cost of Conditioned H_2 ($/kg)	**1.92**	**5.57**	**5.15**	**1.31**	**5.08**
$LCOE_{DC}$ Solar Field ($/$MWh_{DC}$)		39.39	39.00		39.00
Total System LCOS ($/$MWh_{AC}$)		164.09	158.58		194.87
Combined System LCOE ($/$MWh_{AC}$)	**109.41**	**131.88**	**146.90**	**78.96**	**176.54**

- 3-5% improvement of LCOE in storage cases
- High cost dominated by electrolyzer costs, low RTE and storage size limitation causing imports

CFC Systems LCOS and LCOE Breakdown



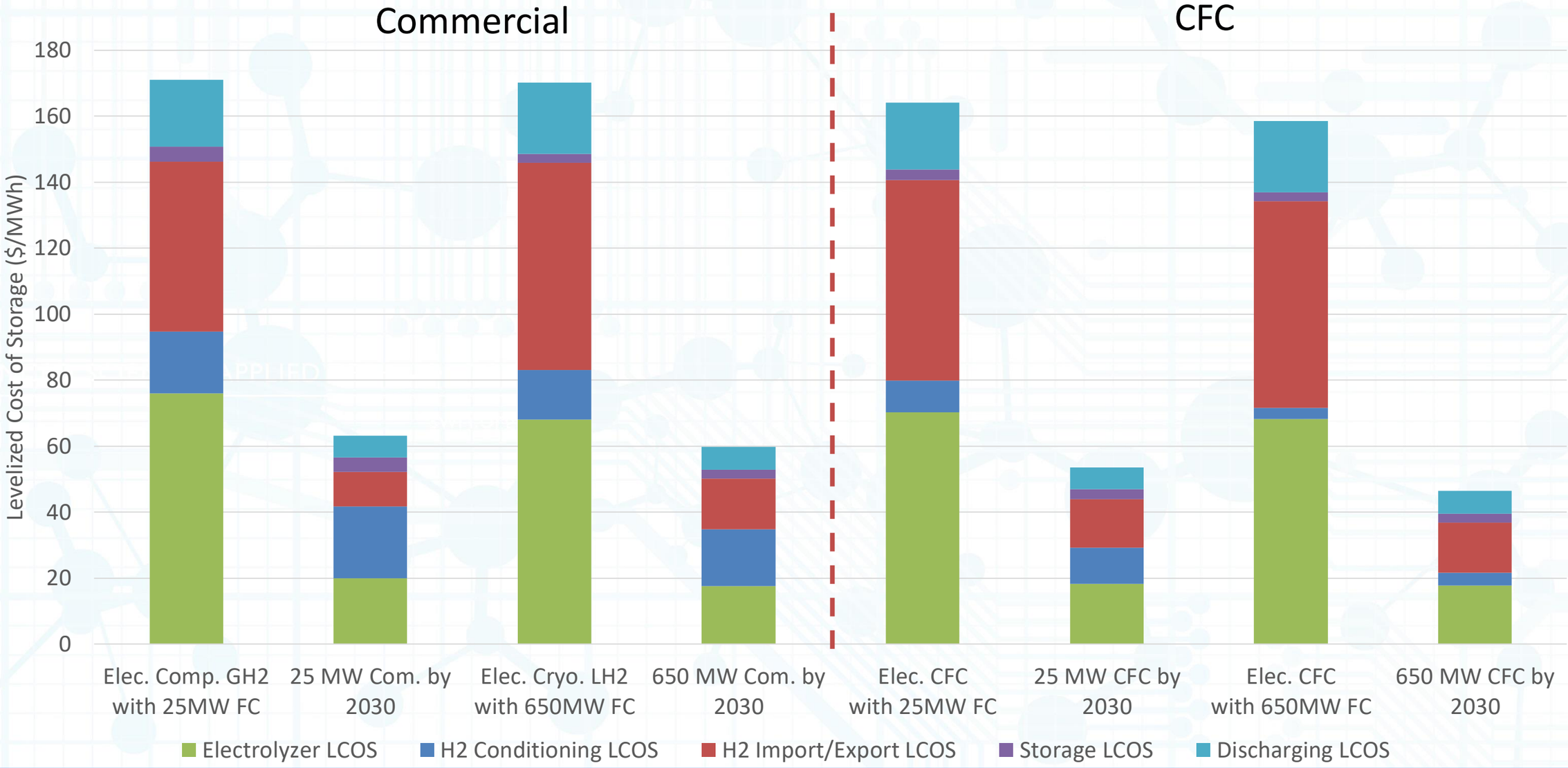


DOE Grand Challenge Goals for 2030

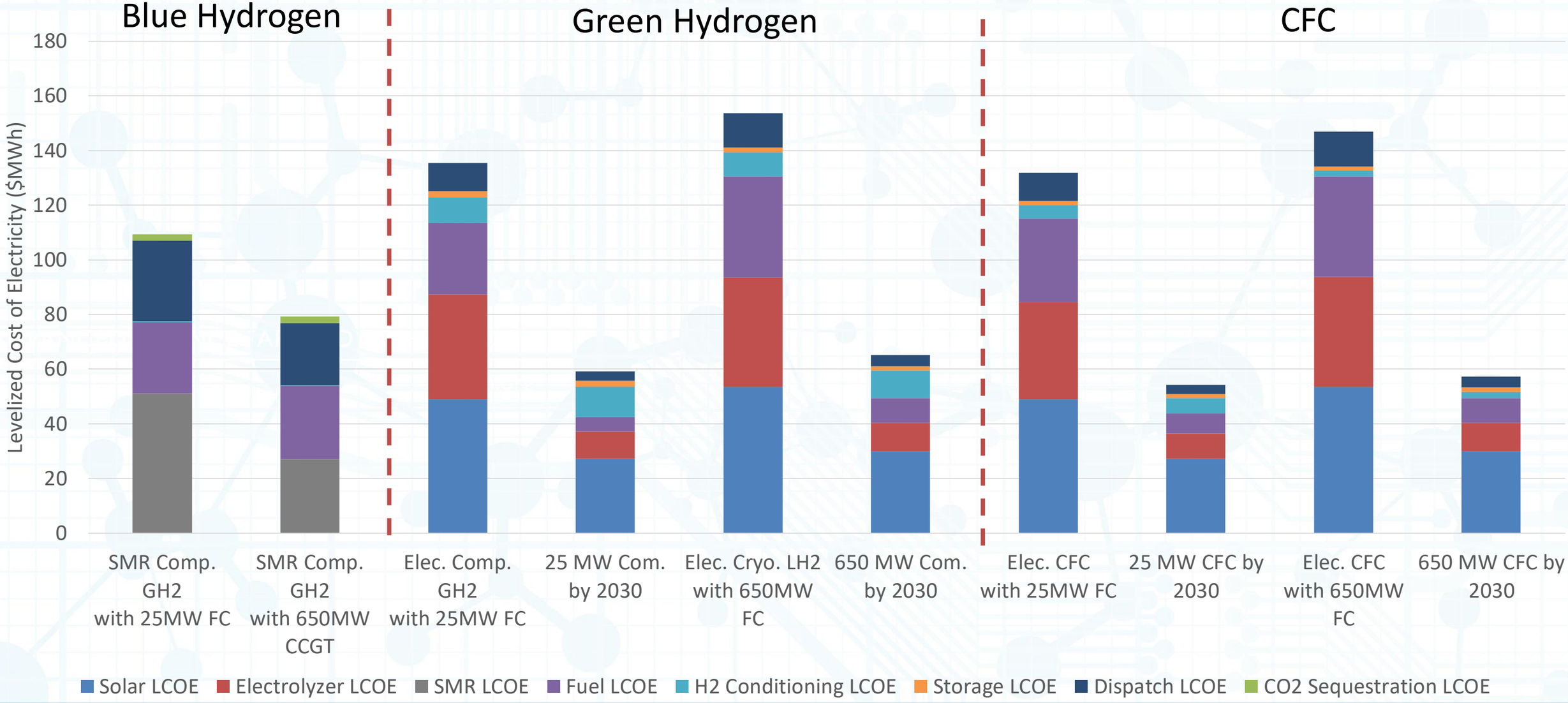
- DOE has established goals for improving the cost of green hydrogen
- DOE aspiring for $1/kg
  - DOE is assuming cavern storage
  - Fixed cost of buying and selling hydrogen changed to $2/kg for the analysis case
- Target costs by 2030 analyzed and applied to the cases

System	DOE 2030 Goal	% Improvement from Current
Solar CAPEX	$555/kW	43.9%
Electrolyzer CAPEX	$350/kW	73.4%
Fuel Cell CAPEX	$435/kW	67.0%
Electrolyzer Efficiency	46 kWh/kg	15.3%
Price of Hydrogen	$1/kg	83.3%

Improvement in LCOS by 2030

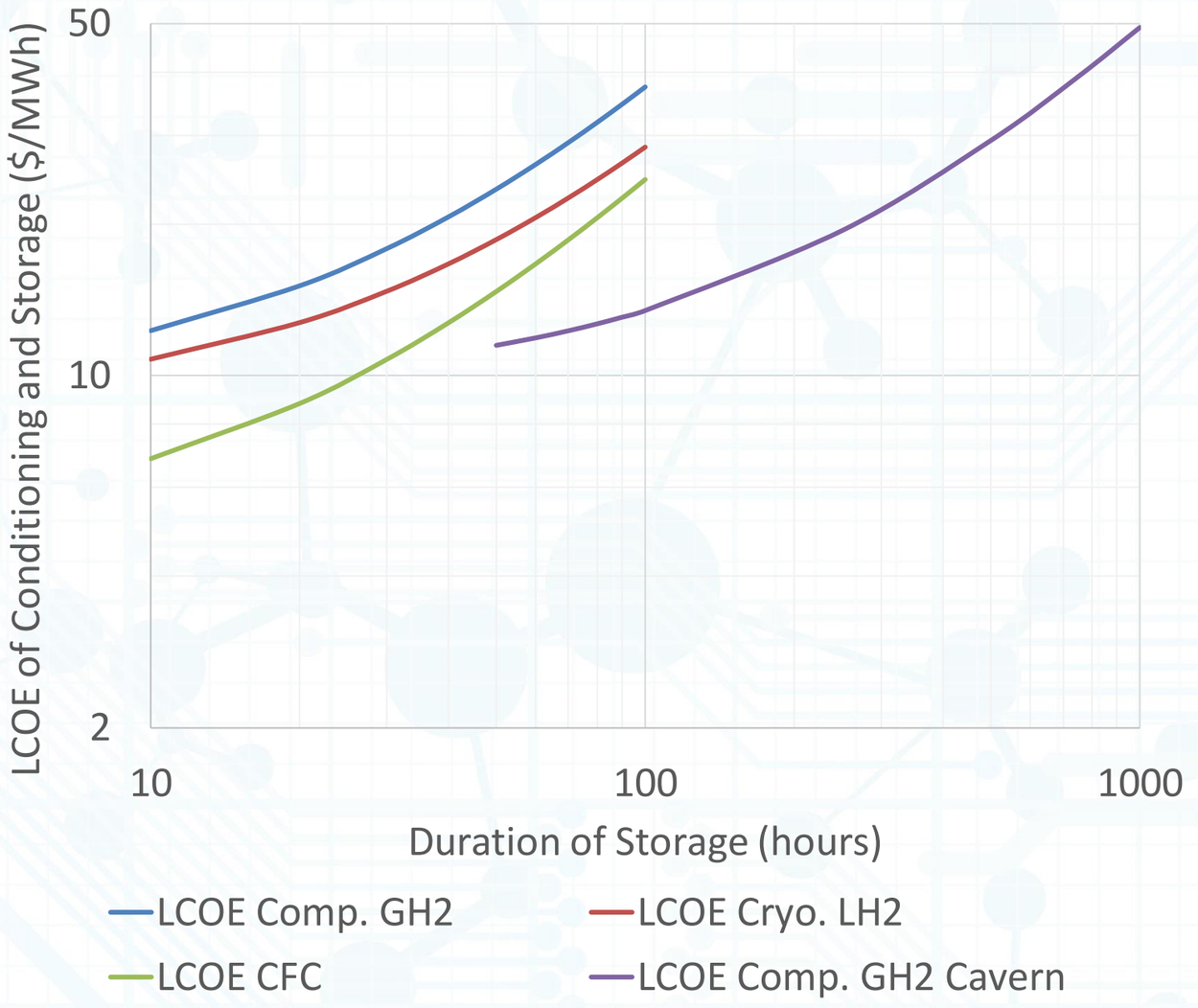


Improvement in LCOE by 2030



Storage in Caverns

- DOE grand challenge estimates caverns can be 116,000 $/tonne
- Caverns are analyzed as high-pressure 200 bar GH_2
  - Geographically limited
- Using LCOE for conditioning of GH_2, LH_2, and CFC, the values are added together
- Graph shows combined LCOE of only the conditioning systems and storage
- CFC shows a compelling cost case for10-40 hour duration range



Conclusions

- CFC when paired with a low-cost conditioning system, could provide improved costs for hydrogen energy storage
- Costs of green hydrogen higher than SMR in current costs
  - SMR provides between $1.3/kg blue hydrogen at all scales and 79 $/MWh at 650MW
  - Current commercial green hydrogen storage provides electricity at 135 $/MWh at 25MW and 154 $/MWh at 650MW
  - CCGT projected to be more expensive than fuel cell due to efficiency gap
- Cost and performance improvements in the DOE grand challenge by 2030
  - Hydrogen becomes much more closely competitive at 59 $/MWh at 25MW and 65 $/MWh at 650MW
  - CFC is projected to reduce hydrogen costs further to 53 $/MWh at 25MW and 58 $/MWh at 650MW
- Caverns are most cost effective for seasonal storage, but CFC is compelling at shorter durations

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Thank You

Questions?