Techno-Economic Analysis of Hydrogen Production and Compressed Air Energy Storage from Variable Renewable Energy

Troy Teel[1,2], Kyle Buchheit[1,2], Sandeep Pidaparti,[1,2], Bob Stevens[1]
[1]NETL
[2] NETL Support Contractor

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Overview and Objective

The Challenge

- Increased utilization of (unreliable and interruptible) variable renewable energy (VRE) causes instability to the nation's electrical grid.

Project Proposal

- Use excess VRE to generate hydrogen (H_2) and compressed air and store them until needed for grid stability through on-demand, H_2-fueled power generation.

Objectives

- Understand the value of integrating electrolysis hydrogen production, hydrogen gas turbines, and compressed air energy storage (CAES) in a high VRE environment.
- "Off-the-shelf" or near-future technology should be considered for the system, such as the commercial proton exchange membrane (PEM) electrolyzer Siemens Silyzer 300 and one of two variations of the CAES system from Siemens Energy.

Project Concept

Background

Green CAES by Bechtel [2]

- Existing CAES (Alabama, Germany) uses natural gas fuel (with carbon emissions)
- Utilize H_2-fueled turbine instead
- Turbine generates power and pre-heats compressed air
- Smaller scale: ~40 MWe

Siemens CAES system with H2 [1]

- Larger scale: ~160 MWe
- Equipment identified
- Air flow requirements provided

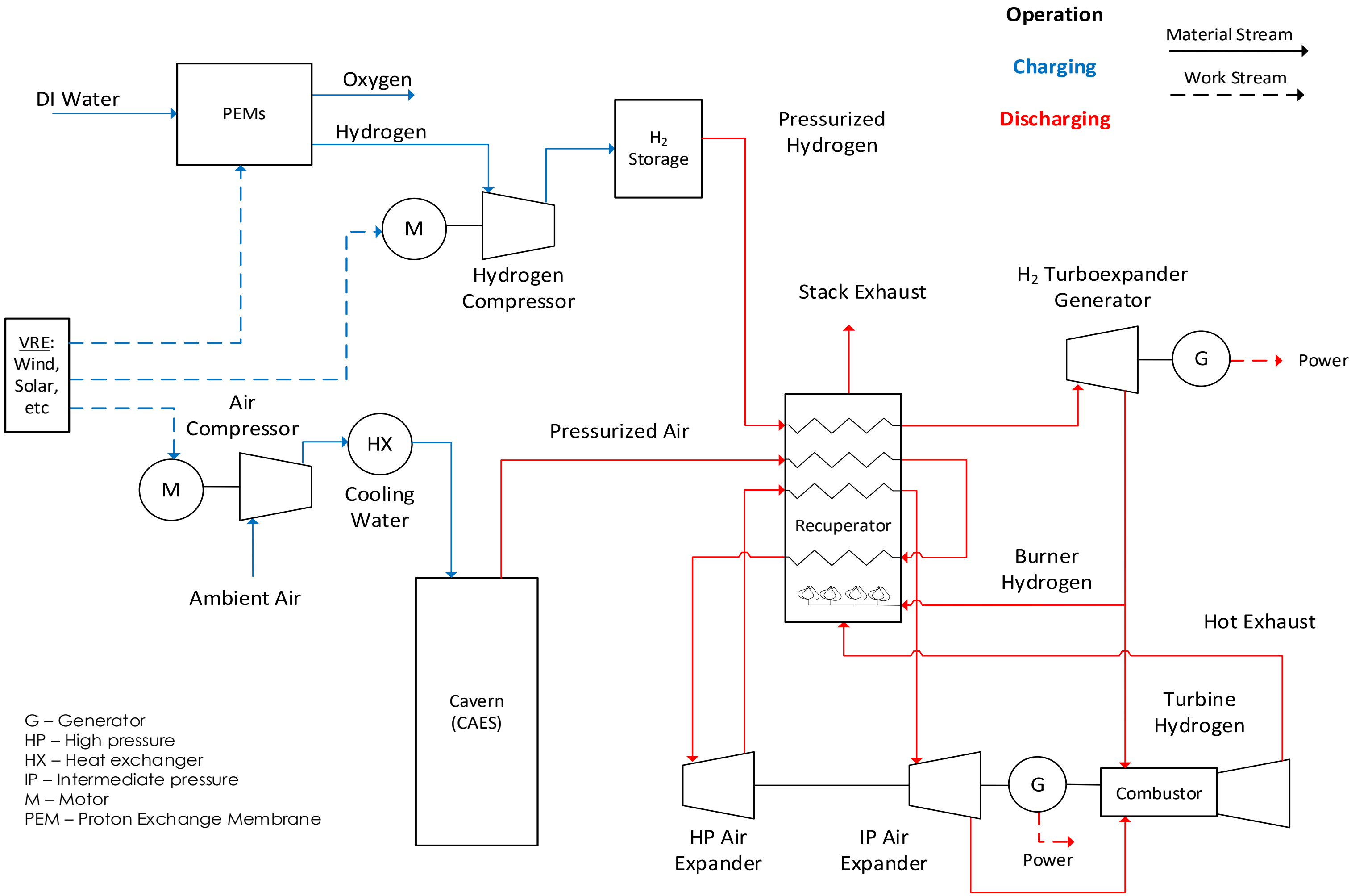
NETL System

- Added the PEM electrolyzer and H_2 turboexpander generator to the Siemens System
- PEM electrolyzer size based on required hydrogen (no excess for market sales)

Project Concept

Diagram Overview – Dynamic Representation

- VRE generates the H_2 via PEM electrolysis and powers the air/H_2 storage compression
- Two storage components
  - Electrolyzer H_2
  - Compressed air
- H_2 burner to pre-heat stack air is needed
- Cycle time: 16 hr. charge and 8 hr. discharge



G – Generator
HP – High pressure
HX – Heat exchanger
IP – Intermediate pressure
M – Motor
PEM – Proton Exchange Membrane

Source: NETL

Equipment Specifications

Discharge Mode

- Air-expansion power generation [1]:
  - Siemens SST-800 Modified steam turbine generator
  - Required air flow rate of 320 lbm/s (145 kg/s)
  - Two-stage, HP/IP heated air expansion
  - Exhaust discharges to the low pressure H_2 combustion turbine generator

CAES Discharge	
Discharge Time, hrs	8
Maximum Cavern Pressure, bar (psia)	150 (2176)
Minimum Cavern Pressure, bar (psia)	100 (1450)
Isothermal Cavern Temperature, °C (°F)	50 (122)
Air Flow Rate, kg/s	145 [1]
Working Volume: Cycle Mass Flow, kg	4,176,000
1st Stage Expander Inlet, °C, bar (°F, psia)	540, 140 (1004, 2030) [1]
2nd Stage Expander Inlet, °C, bar (°F, psia)	530, 48 (986, 696) [1]
3rd Stage Expander Inlet to CGT, °C, bar (°F, psia)	410, 24 (770, 348) [1]

Equipment Specifications

Discharge Mode (continued)

- Combustion Turbine Generator
  - Siemens SGT-800
  - 45 – 62 MWe (simple cycle power generation) [3]
  - ❖ 90-124 MWe (without inlet air compression requirements)
  - Operating limits with hydrogen fuel [3]:
    - Currently 75 vol% H_2 capability with dry low emission burner
    - Aim to reach 100 vol% H_2 by 2030
    - 100 vol% H_2 with wet low emission burner
  - H_2 fuel requirement is 4,540 kg/hour
  - Turbine exhaust preheats compressed air and compressed hydrogen
- H_2 Turboexpander Generator
  - H_2 stream preheater required
  - H_2 outlet pressure is 24 bar (348 psia)
  - Set 98% mechanical efficiency with generator

Equipment Specifications

Charge Mode – Hydrogen

- H_2 Production
  - Siemens Silyzer 300 Electrolyzer [4]
  - 75.5% efficiency
  - 14 kg of H_2 per hour per module
  - 0.73 MW/hr. of electricity per module
  - Deionized water consumption ~10 liters per kg hydrogen
  - Required production is H_2 turbine generator 2,270 kg of H_2/hour [3] plus burner H_2
- H_2 Compression
  - Suction at 80°C (176°F) and atmospheric pressure
  - Discharge at 100–50 bar (1450–2175 psia)
- H_2 Storage
  - Options varied: cavern and above-ground tanks
  - Temperature depends on storage system

Equipment Specifications

Charge Mode – Air

- Charge Air Compression
  - Siemens STC-GV: one motor with 2 cases (LP/HP)
- Air Storage Cavern
  - CAES system is diabatic (no thermal storage system)
  - Maximum pressure of 150 bar (2176 psia)
  - Set minimum cavern pressure of 100 bar (1450 psia) – based on a similar operating ratio of the existing caverns
  - Max de-pressure rate of 10 bar/hr (145 psig/hr.) [5]
  - As such, the de-pressure rate is 6.25 bar/hr (91 psi/hr)

CAES Charge	
Charge Time, hours	16
Inlet Air Pressure, bar (psia)	1 (14.676)
Inlet Air Temperature, °C (°F)	15 (59)
Air Flow Rate (kg/s)	72.5*
Interstage Air Temperature, °C (°F)	38 (100)
Discharge Air Pressure, bar (psia)	100-150 (1450-2176)
Discharge Air Temperature, °C (°F)	38 (100)
Low Pressure Stages	6 [1]
LP Compression Isentropic Eff, %	87
High Pressure Stages	2 [1]
HP Compression Isentropic Eff, %	87

* Based on half of the Siemens discharge design rate [1]

Cavern Storage

Cavern Design

- The literature search reveals a range of pressure-depth design factors depending upon the application.
- The design factor for the H_2 cavern is at least 4.8% more conservative than air caverns.

Application		Maximum Salt-Mined Cavern Design Factor (bar/m [psi/ft])
H_2 Cavern [6]	Murray et al. (SHASTA)	0.156 (0.69)
Air Cavern [5]	Pacific Northwest Laboratory, 1982	0.1639 (0.725)
Air Cavern [1]	Siemens Energy	0.181 (0.8)

Cavern Storage

Salt-Mined Cavern Sizing Results

Sizing Criteria	Air Cavern	H_2 Cavern
Maximum Air Operating Pressure, bar (psia)	150 (2176)	150 (2176)
Maximum Allowable Working Pressure, Assuming an Overdesign Factor Similar to Huntorf Plant, bar (psia)	215 (3108)	215 (3108)
Maximum Salt-mined Cavern Design Factor, bar/m depth	0.1639	0.156
Minimum Top of Cavern Depth, m (ft)	**1,457 (4,780)**	**1,524 (5,000)**
Calculated Cavern Diameter, m (ft)	22.6 (74)	12.5 (42)
Calculated Cavern Height, m (ft)	113 (370)	62.5 (210)
Calculated Cavern Volume, m^3 (ft^3)	47,040 (1,661,100)	8,220 (290,350)
Minimum Bottom of Cavern Depth, m (ft)	**1,570 (5,150)**	**1,588 (5,210)**

- Cavern depths range 4,800–5,200 ft.
- Air and H_2 salt-mined caverns are feasible. The calculated depth requirements are comparable to existing caverns.

Case Summary

H_2 Storage Options

❖ All cases are based on the H_2 storage

- Case 0 has H_2 salt-dome storage cavern at 150 bar (2,176 psi) charged
- Case 0A has H_2 above ground storage at 150 bar (2,176 psi) charged
- Case 1 has H_2 above ground storage at 500 bar (7,252 psi) charged
- Case 0B is an economic scenario based on Case 0 with no electrolyzer capital expense or calculated operation and maintenance (O&M); instead, H_2 is generated at a fixed O&M cost per kg.

Performance Highlights

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Major Rotating Equipment and Power Impacts

- HP air expander power declines during discharge.
- H_2 turboexpander power is constant with aboveground storage at 500 bar.

	Case 0 150 bar	Case 0 100 bar	Case 1 500 bar	Case 1 250 bar	Unit
Charging Mode					
CAES Air Compressor	38,600	35,440	38,600	35,440	kWe
PEM H_2 Production Unit	175,200	175,200	175,200	175,200	kWe
H_2 Compressor	8,080	7,370	10,350	8,980	kWe
Net Plant Power[A]	**-224,440**	**-220,490**	**-226,730**	**-222,130**	kWe
Discharging Mode					
HP Air Expander Power	29,700	20,900	29,700	20,900	kWe
IP Air Expander Power	18,800	18,800	18,800	18,800	kWe
H_2 Turboexpander Generator	3,800	2,800	4,700	4,700	kWe
Combustion Turbine Power	128,100	128,200	128,100	128,200	kWe
Total Gross Power	**180,400**	**170,700**	**181,300**	**172,600**	kWe
Total Auxiliary Load	3,000	2,970	3,010	2,980	kWe
Net Plant Power	**177,400**	**167,730**	**178,290**	**169,620**	kWe
Average Net Plant Power	**172,565**		**173,955**		kWe

[A] The net power is reduced for economic Case 0B by the PEM electrolyzer power (175.2 MWe)

Economic Analysis

Assumption Summary

- Capacity factor = 90%
- Financial factors
  - Same as natural gas combined cycle (NGCC) baseline cases
  - Fixed charge rate (FCR) = 0.0707
  - Ratio of total as-spent cost/total overnight cost (TASC/TOC) = 1.093
- Each case has start of discharge (end of charge) and end of discharge (start of charge). The power generation is averaged
- Equipment is sized for the largest demand (not the average)
- PEM membrane stack replacement is an O&M expense
  - Stack life of 7 years [7]
  - Replacement cost is 15% of the membrane total plant cost (TPC) [7]
- Assume no cost VRE in all cases
  - VRE cost sensitivity is analyzed

Economic Results

Capital Cost Comparison

- The H_2 system, mainly the H_2 storage option, is the primary difference.

Cost Account Description TPC ($/1,000)	Case 0 H_2 Salt-Dome Storage Cavern (150 bar)	Case 0A H_2 Aboveground Storage Vessels (150 bar)	Case 1 H_2 Aboveground Storage Vessels (500 bar)
Feedwater & Misc. Balance of Plant Systems	$11,188	$11,188	$11,401
CAES Air System	$116,468	$116,468	$116,547
H_2 System	$104,855	$126,676	$185,132
Combustion Turbine & Accessories	$15,192	$15,192	$15,192
Heat Recovery, Ductwork, & Stack	$20,197	$20,207	$20,249
Cooling Water System	$11,950	$11,950	$12,214
Accessory Electric Plant	$155,655	$155,655	$156,706
Instrumentation & Control	$32,533	$32,533	$32,620
Improvement & Site	$15,519	$15,519	$15,555
Buildings & Structure	$5,126	$5,126	$5,139
Total	**$488,682**	**$510,513**	**$570,755**

Economic Results – CAES same (all cases)

Capital Cost Breakdown

- CAES cavern is based on H_2 cavern cost (adjusted for depth and volume).
- Remainder of CAES system is based on steam generation equipment.

TPC Breakdown Cost Component ($1,000)	Case 0 H_2 Salt-Dome Storage Cavern (150 bar)	Case 0A H_2 Aboveground Storage Vessels (150 bar)	Case 1 H_2 Aboveground Storage Vessels (500 bar)	Case 0B H_2 Salt-Dome Storage Cavern (150 bar)
CAES – Air System				
CAES Air (Charge) Compressor	$83,341	$83,341	$83,341	$83,341
CAES Air Cavern [8]	$12,344	$12,344	$12,344	$12,344
HP/IP Air (Discharge) Expanders	$15,171	$15,171	$15,171	$15,171
HP/IP Air Expanders Accessories	$192	$192	$192	$192
CAES Air System Piping	$4,027	$4,027	$4,027	$4,027
Air Compression Foundations	$1,392	$1,392	$1,392	$1,392
Total CAES Air System	**$116,468**	**$116,468**	**$116,468**	**$116,468**

Economic Results

Capital Cost Breakdown (continued)

- H_2 storage option is the primary difference (except for Case 0B).

TPC Breakdown Cost Component ($1,000)	Case 0 H_2 Salt-Dome Storage Cavern (150 bar)	Case 0A H_2 Aboveground Storage Vessels (150 bar)	Case 1 H_2 Aboveground Storage Vessels (500 bar)	Case 0B H_2 Salt-Dome Storage Cavern (150 bar)
H_2 System				
PEM H_2 Production [7]	$82,433	$82,433	$82,433	-
H_2 (Charge) Compression	$8,142	$8,142	$9,925	$8,142
H_2 Storage Cavern [8]	$2,282	$0	$0	$2,282
H_2 Aboveground Storage	$0	$24,103	$80,343	$0
H_2 Turboexpander Generator	$1,978	$1,978	$2,345	$1,978
H_2 In-Line Stack Burner	$9,721	$9,721	$9,721	$9,721
H_2 Compression Foundations	$299	$299	$365	$299
Total H_2 System	**$104,855**	**$126,676**	**$185,132**	**$22,422**

Economic Results

Cost of Storage

- H_2 cavern cost is dependent upon pressure, depth, and storage mass
- CAES cavern is based on H_2 cavern cost (adjusted for depth and volume)
- Aboveground vessel cost is dependent upon pressure and storage mass

	Air Salt-Dome Storage Cavern	H_2 Salt-Dome Storage Cavern	H_2 Aboveground Storage Vessels	H_2 Aboveground Storage Vessels
Maximum Pressure, bar	150	150	150	500
Cavern Depth, m	1,457–1,570	1,524–1,588	–	–
Stored Mass, kg	8,355,378	100,802	100,802	100,802
Storage TPC, $1000	$12,344	$2,282	$24,103	$80,343
Cavern Cost, $/kg stored	**$1.48**	**$22.64**	–	–
Vessel Cost, $/kg H_2 stored	–	–	**$239**	**$797**

Economic Results

Levelized Cost Comparison

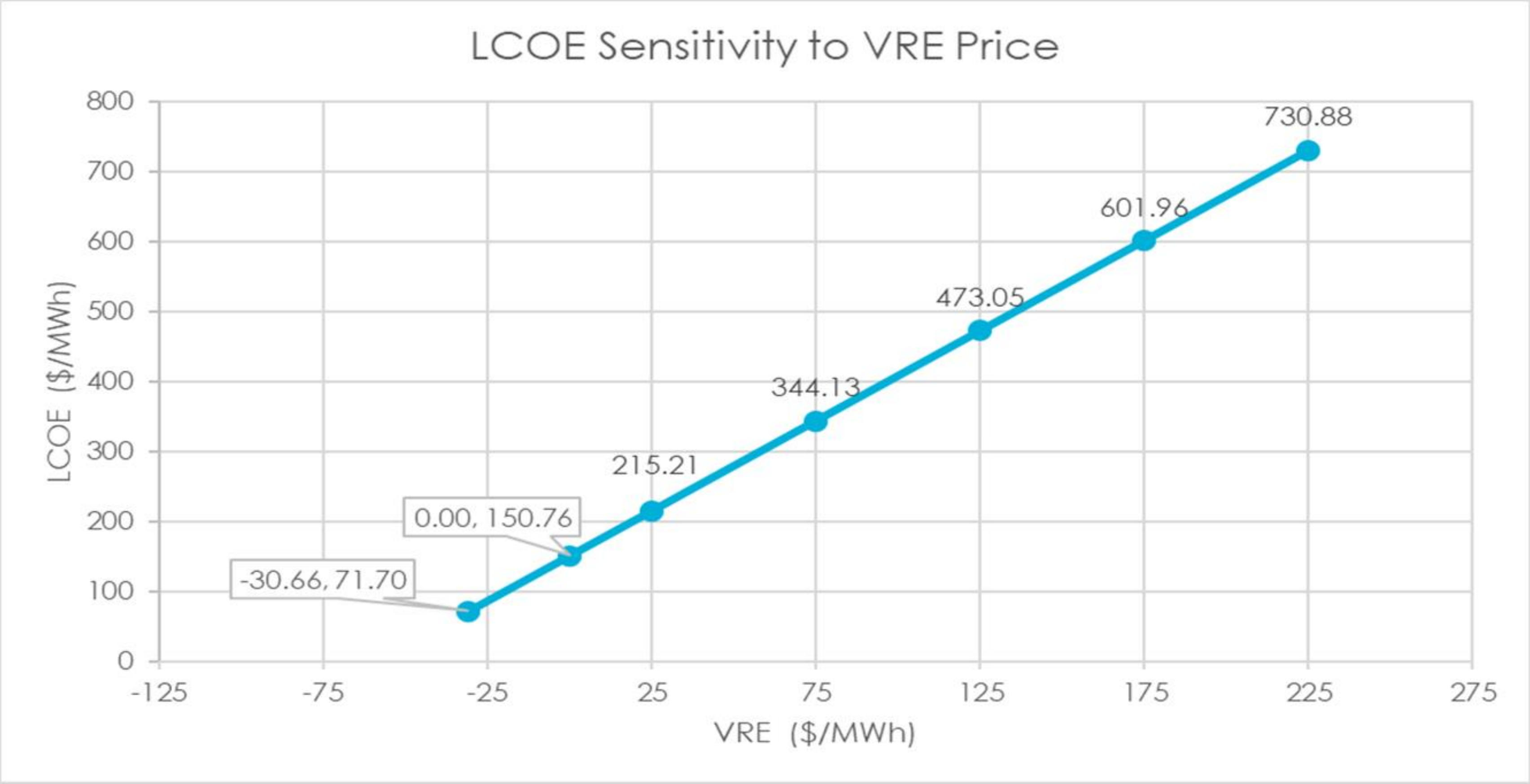
- Case 0B results are based on an H_2 generated cost of \$2/kg H_2.

	Case 0 H_2 Salt-Dome Storage Cavern (150 bar)	Case 0A H_2 Aboveground Storage Vessels (150 bar)	Case 1 H_2 Aboveground Storage Vessels (500 bar)	Case 0B H_2 Salt-Dome Storage Cavern (150 bar)
Capacity Factor	90%	90%	90%	90%
Capital	\$50,812,301	\$53,076,989	\$59,326,492	\$50,220,219
Fixed	\$16,982,018	\$17,697,587	\$19,672,172	\$14,280,054
Variable	\$8,170,386	\$8,463,177	\$9,282,985	\$5,798,651
Fuel (H_2)	0	0	0	\$36,787,096
Annual Air Stored, kg	1,524,856,474	1,524,856,474	1,524,856,474	1,524,856,474
Air LCOS (\$/kg Air)	**\$0.05**	**\$0.05**	**\$0.06**	**\$0.07**
Annual H_2 Stored, kg	18,396,407	18,396,407	18,396,407	18,396,407
H_2 LCOS (\$/kg H_2)	**\$4.13**	**\$4.31**	**\$4.80**	**\$5.82**
Annual Net kWh (100%)	503,889,800	503,889,800	507,948,600	503,889,800
LCOE (\$/MWh)	**\$150.76**	**\$157.25**	**\$173.80**	**\$212.52**

Sensitivity Analysis

LCOE Sensitivity to VRE Price

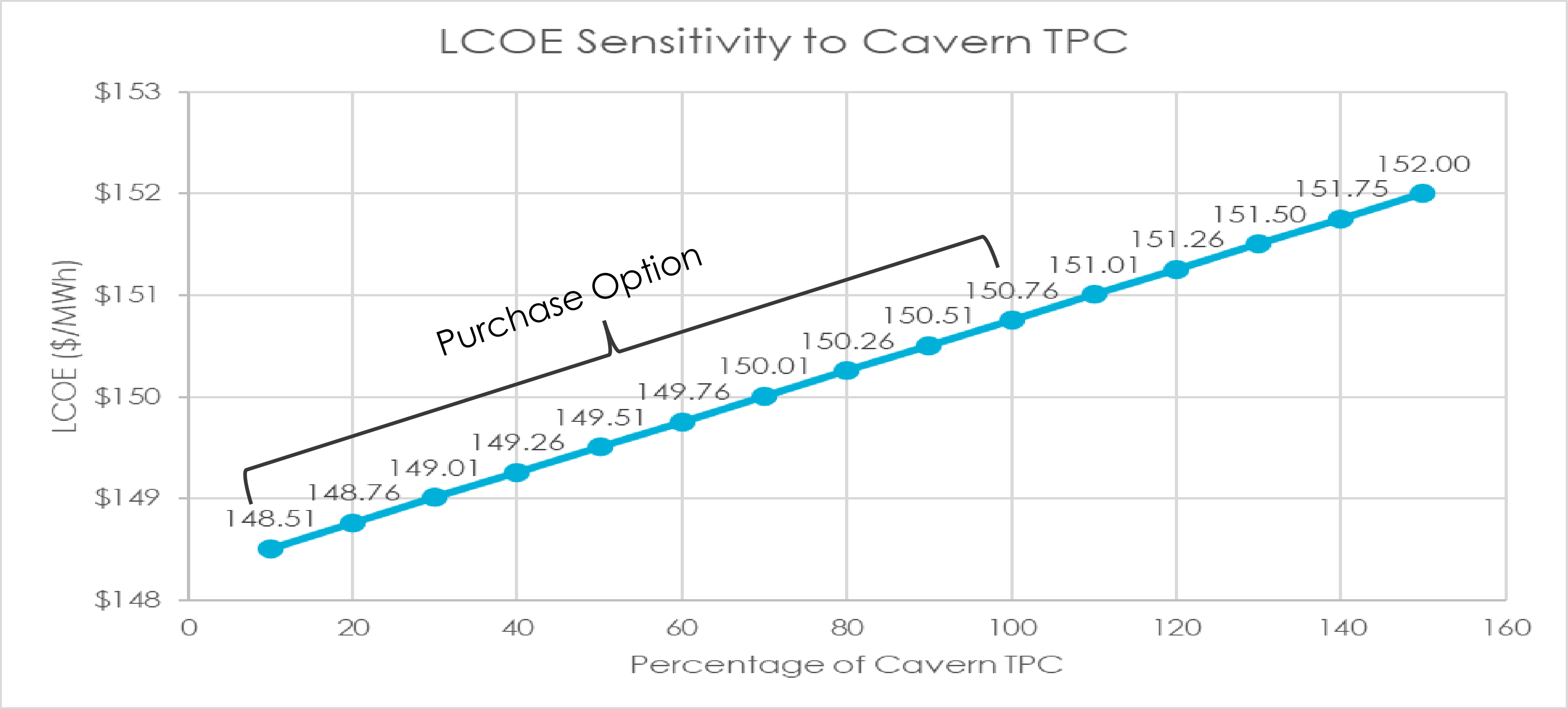
- Cases assume VRE is at no cost.
- VRE price varied $-30.66–225/MWh; LCOE varies $71.70–730.88/MWh



Sensitivity Analysis

LCOE Sensitivity to Cavern TPC

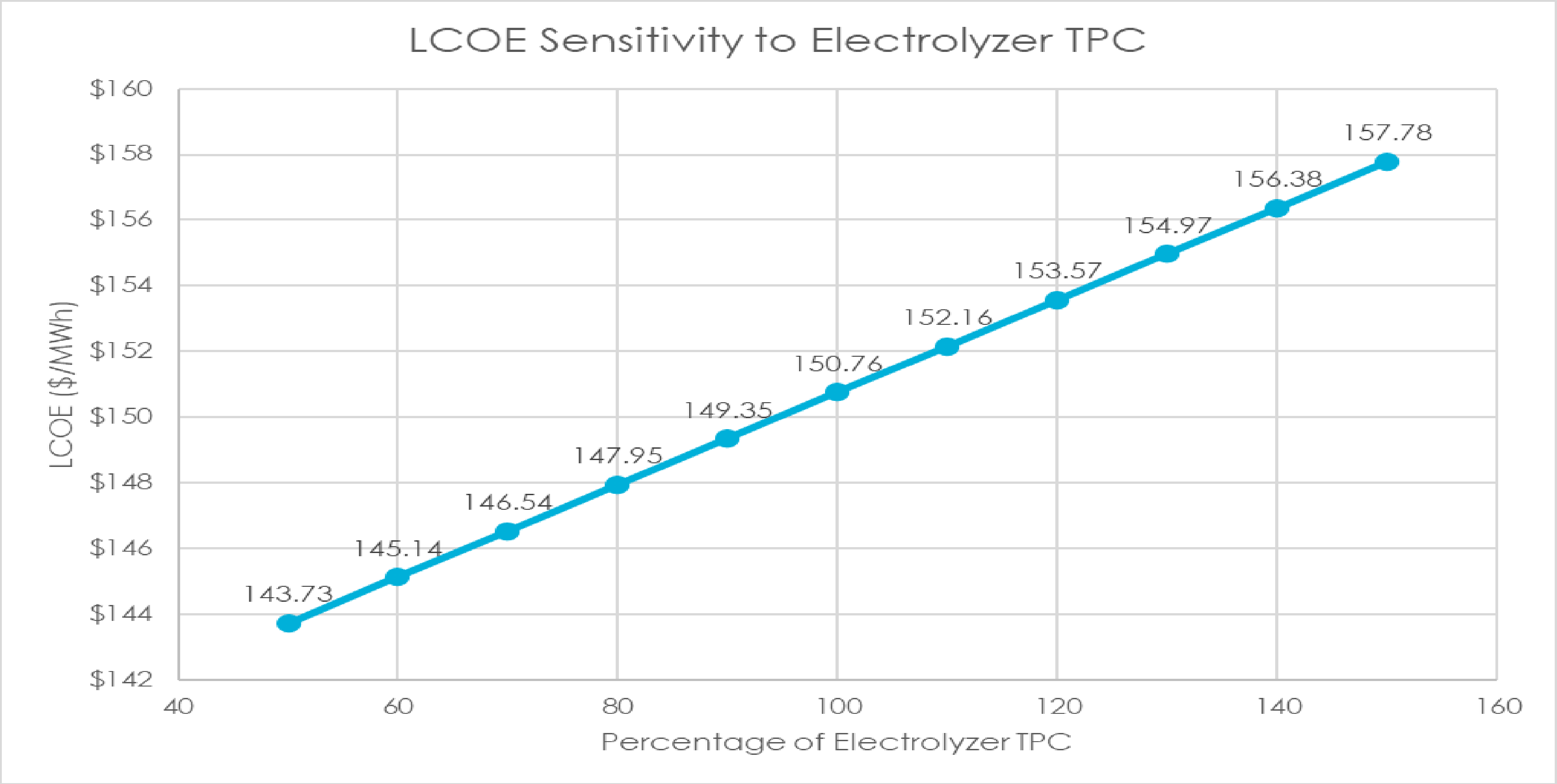
- Percentage of Cavern TPC varied 10–150%; LCOE varies $148.51–152.00
- Purchasing a suitable, existing cavern at a fraction of the new cavern cost is reflected by the line left of 100% Cavern TPC.



Sensitivity Analysis

LCOE Sensitivity to Electrolyzer TPC

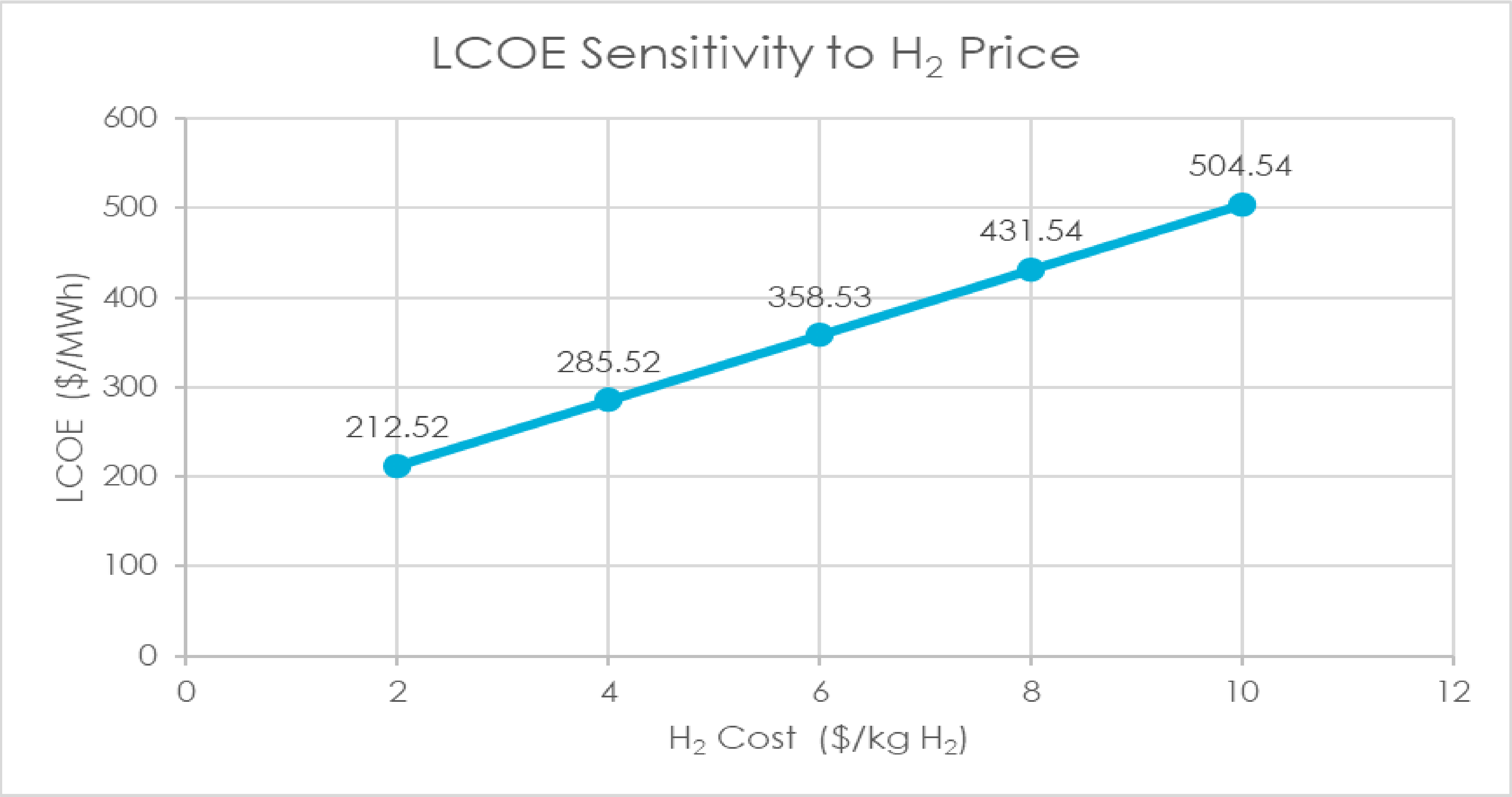
- Percentage of Electrolyzer TPC varied 50–150%; LCOE varies $143.73–157.78



Sensitivity Analysis

LCOE Sensitivity to H_2 Price

- The cost of generated H_2 varied \$2–10/kg; LCOE varies \$212.52–504.54



Conclusions

- Air and H_2 salt-mined caverns are feasible (where salt domes exist with sufficient depths); calculated depth requirements are comparable to existing caverns.
- The proposed Siemens system (existing and near-future equipment) can meet the project's power generation objective.
- While facilities with above ground H_2 storage generate roughly 1% more power output than facilities with H_2 storage caverns, H_2 storage caverns are significantly more economical than above-ground vessels
- VRE price has a greater influence on LCOE than electrolyzer cost or cavern costs.

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Questions?

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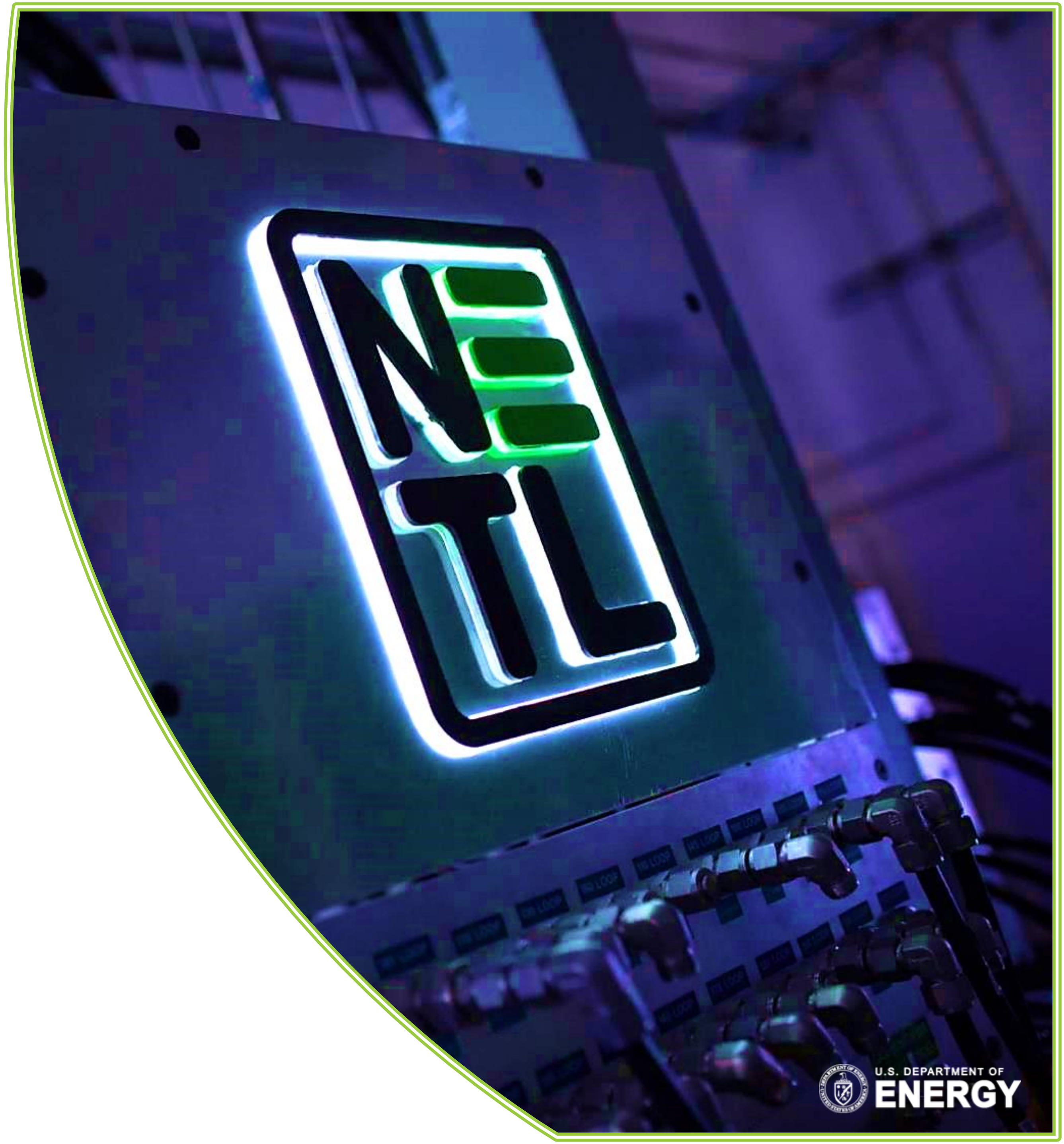
CONTACT:
Robert W. Stevens
Robert.Stevens@netl.doe.gov



Support Contractor Contacts

- Kyle Buchheit
  - Kyle.Buchheit@NETL.DOE.GOV
- Troy Teel
  - Troy.Teel@NETL.DOE.GOV
- Sandeep Pidaparti
  - Sandeep.Pidaparti@NETL.DOE.GOV

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