Economically Viable Intermediate to Long Duration Hydrogen Energy Storage Solutions for Fossil Fueled Assets

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Project Team:
West Virginia University
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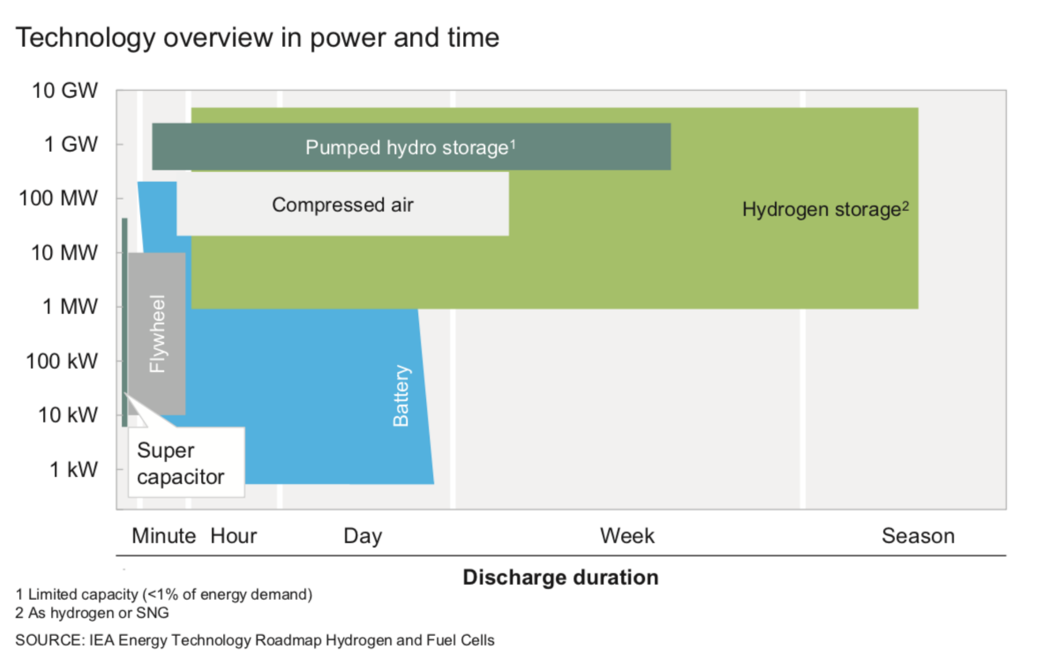
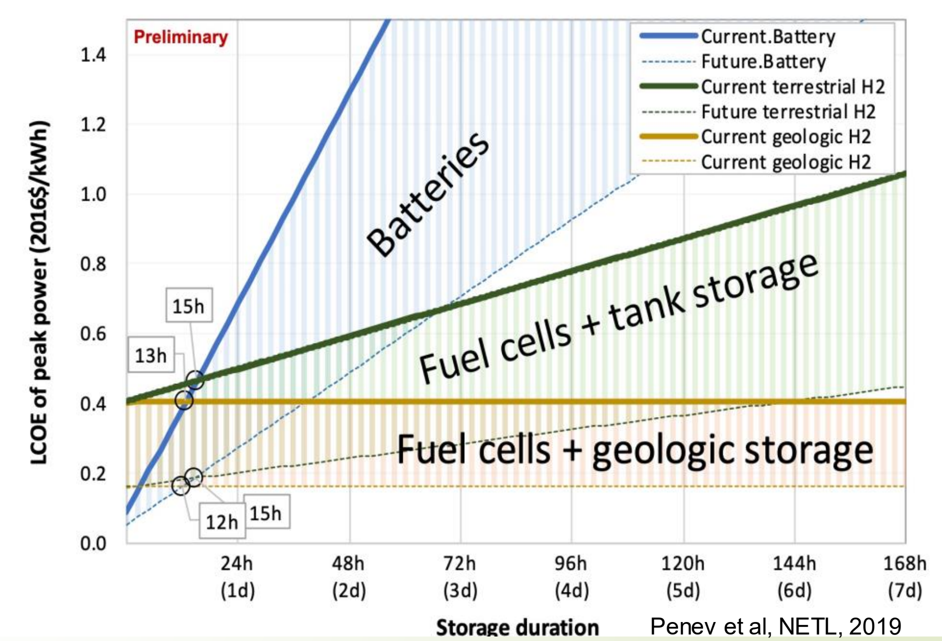
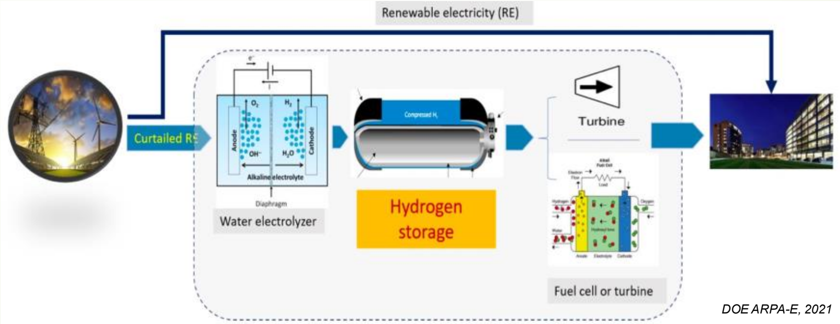
Hydrogen-based energy storage is considered as one of the most suitable solutions for long-duration storage needs







- On-going demonstrations at multi-megawatt to hundreds megawatt-hour energy level
- **Eeconomically better than batteries over 10-12 hrs**

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Today's H_2 based long duration energy storage still presents a significant cost premium, and may not be economically viable

Energy Plant Type	LCOE $ per MWh
Offshore Wind	130.40
Coal with 30% CCS	104.60
Coal with 90% CCS	98.60
Biomass	92.20
Advanced Nuclear	77.50
Nat Gas Combined Cycle with CCS	67.50
PV Solar	60.00
Hydro-electric	39.10
Land Based Wind	55.90
Natural Gas Combined Cycle	**41.20**
Geothermal	41.00
Energy Storage System	**Additional LCOE $ per MWh**
Li-ion Battery	100-300
Today H2 based	50-60

Added LCOE

Li-Battery: $100-300/MWh

H2 system: $50-60/WMh

Electricity cost not included

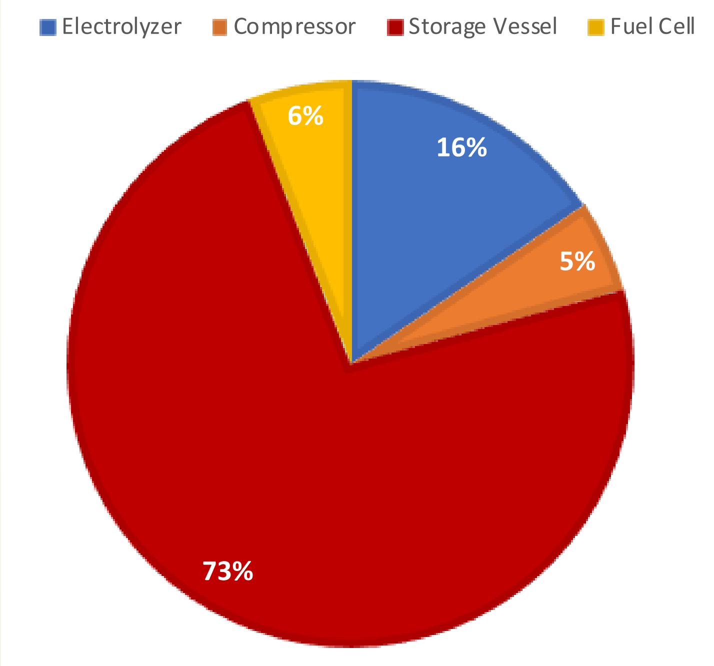
0% discount rate

Cost of storage vessel accounts for >70% of entire system cost

Proportional to storage duration

The longer the storage duration, the higher percentage of storage vessel sub-system in the entire capital cost

Cost breakdown of hydrogen storage system



Data source: EIA, NREL, solarcellcentral.com 7/2020

Basis for analysis:10MW, 7-day storage. 30-year operation life for hydrogen system, and 10 years for Li-ion battery

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Options for H_2 storage subsystem:

- High pressure H_2 vessel storage is one of the mature and cost-effective options, but **limited by volume**

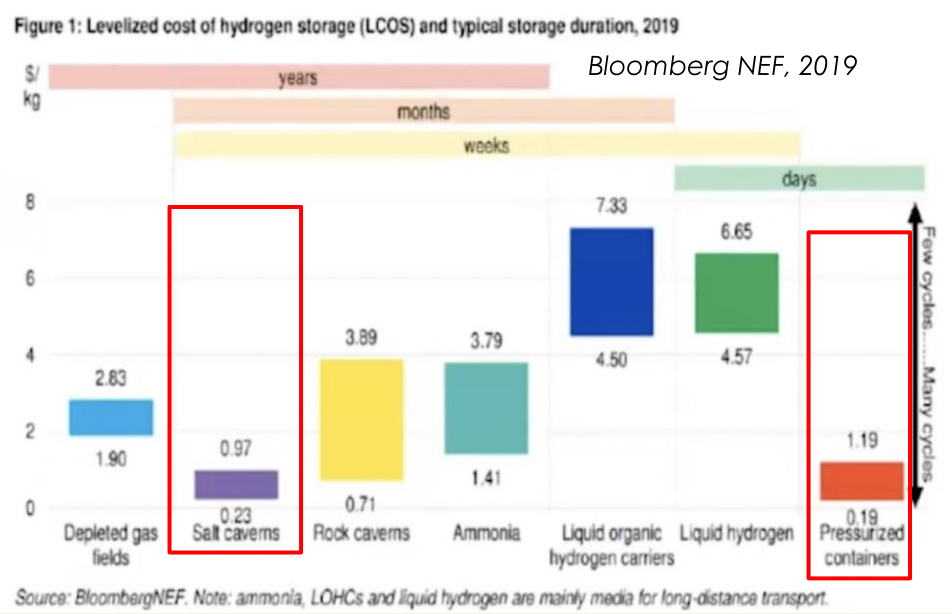

Table 1: Hydrogen storage options *BloombergNEF, Hydrogen Economy Outlook 2020*

	Gaseous state				Liquid state			Solid state
	Salt caverns	**Depleted gas fields**	**Rock caverns**	**Pressurized containers**	**Liquid hydrogen**	**Ammonia**	**LOHCs**	**Metal hydrides**
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

"Salt cavern and <u>high-pressure tank storages</u> are mature technologies, while the other options are, for the most part, at lab scale."

(Source: ARPA-E RFI "Stationary Hydrogen Storage Technology Development", Jan, 2021)

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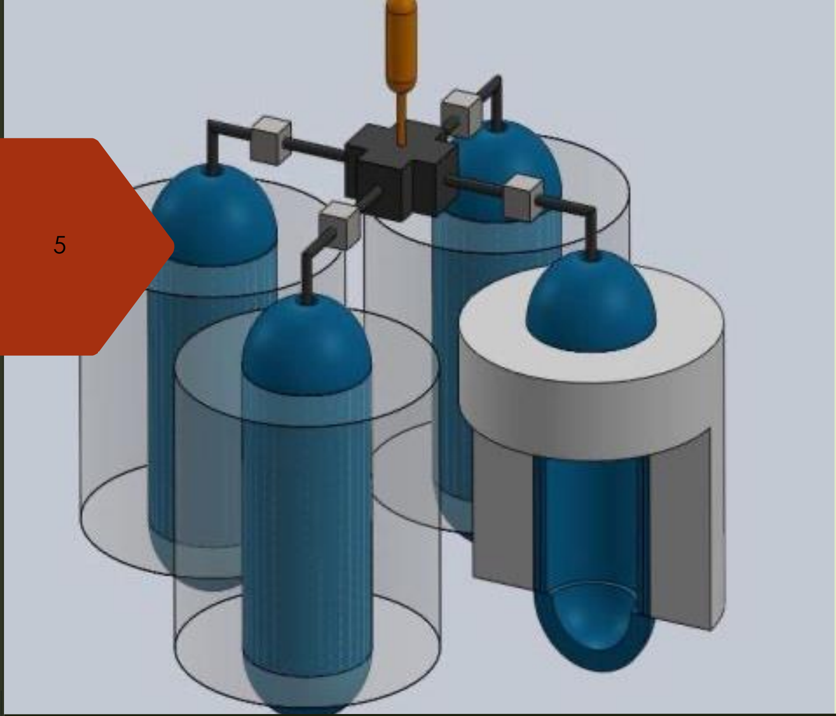
Our Key Technology: Steel-Concrete Composite Vessel

Overcoming the volume limit of pressurized H_2 storage for cost, scalability, durability, and safety

- SCCV is an innovative solution specifically designed and engineered for **large scale** stationary high-pressure gaseous **hydrogen** storage applications
  - Addressing two critical challenges: **high capital cost** and **safety** concerns of hydrogen embrittlement
  - US Patent 9,562,646 B2
  - **30%-60% cost of today's high-pressure hydrogen storage tubes**
- Novel design
  - Eliminate hydrogen embrittlement problem **by design**
  - Enable use of cost-effective commodity materials (concrete and steels)
- Scalability enabled by advanced manufacturing technologies
  - Advanced **welding**, proprietary pre-stress wire wrapping technology and sensor technologies for reduced cost and improved safety
  - 500 – 2000 kg H_2 vessels mass-produced in shop vs today's seamless tube at 20-50kg H_2
  - Even larger, super sized H_2 vessels by on-site construction
- Code/standard accepted fabrication practices
  - **ASME Pressure Vessel Code Case 2949**
  - Designed for >30 years cyclic operation life
  - Can be fabricated with today's commercially ready manufacturing technologies
- Modular design
  - Flexibility for scalability
  - Flexibility for cost optimization
  - System reliability and safety



Project Objective

- **Technical Viability**: Enables EGUs to operate at optimal baseload operation conditions through use of *sufficiently large* storage system to manage the dynamic changes in electric grid demand and electricity price over intermediate to long-durations (i.e., ***from 12 hours to weeks***).
- **Economic Viability**: Target *added* round-trip levelized cost of energy (LCOE) no greater than 10% of LCOE of today's fossil plant for 30 years operation.
- **Phase I Concept Feasibility Study**
  - Focus on a **site-specific** *conceptual design* for a fossil power plant, to demonstrate both the technical and economic feasibility of SIHES.
- **Phase II pre-FEED study for a specific fossil asset**
  - Pre-FEED, and eventual site demonstration and deployment of SIHES in fossil power generation.
- DOE FOA Requirement on H_2 Storage System: **>10MWh**

Initial Entry Point:

HyPeaker

Hydrogen based peaking power generation units

- **Augment or Replace Peakers (Peaking power generation units)**
  - TVA Johnsonville Combustion Turbine Plants (50-60MW/unit)
- Compared to baseload units
  - Peakers are much smaller – more manageable for **early adoption** from both technical and capital investment perspectives
  - More expensive and inefficient to run, on MWh basis, than the baseload plants
  - Emit higher rates of CO_2 and health-harming air pollutants
- Run infrequently during periods of high peak demand. Only used for a few hours at a time, with capacity factor of 0.1 or less
  - **Such low-capacity factor and intermittent operation allows a HyPeaker to generation H_2 when the electricity/fuel price is favorable, and supply the peak demand at a prime price**
- More than 1,000 natural gas- and oil-fired peaker plants in the US. A sizable market
  - Disproportionately located in disadvantaged communities, significant societal benefits
- Characteristics of HyPeaker Plants:
  - **Buy low. Sale High**

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Specific Site: TVA's Johnsonville Combustion Turbine Plant

The study will be based on new 60MW aeroderivative gas turbine to be installed at this site

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A 2-pronged approach to reduce the cost of H_2 energy storage system for HyPeakers

- Drastically reduce the cost of hydrogen storage subsystem
  - Low-Cost Steel Concrete Composite Vessel (SCCV) for Stationary High-Pressure Hydrogen Storage,
    - At the scale suitable for fossil power plants
    - 10 to 100s tons of H2, or hundreds MWh to GWh stored energy
- System level design optimization specific for fossil power plants
  - Determine sub-systems/components most appropriate for fossil power plants
    - Hydrogen production (E to H_2) sub-system
    - Hydrogen storage sub-system, at scale of MWh to GWh storage
    - Electricity generation (H_2 to E) sub-system
  - Sub-system capacity optimization and matching, assisted by TEA modeling

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R&D Activities

Drastically reduce the cost of hydrogen storage subsystem	Effectively integrating hydrogen energy storage system with fossil assets	Techno-economic optimization	Target level of performance

• Further develop our ultralow cost steel concrete composite vessel (SCCV) for tailored use in HyPeaker
• Scalability
  • 500-1000 kg H2 vessels mass-produced in shop (vs 30-50kg of today's vessels)
  • Tens to hundreds tons of H2 by on-site construction
	• Considerable room and **unique opportunities** exist in optimal integration of HyPeaker into fossil assets	• Optimization of both system design and operation of HyPeaker for the highly dynamic storage demands and electricity fluctuations	• Baseline design for a specific type fossil power plant selected by TVA
			• Expected hydrogen energy storage parameters
			  • Cost target: added round-trip E-H_2-E LCOE in the range of 10% of base LCOE of today's fossil plant (i.e. $5-10/MWh)
			  • 30-500MWh for 1-10 days for 30-year operation

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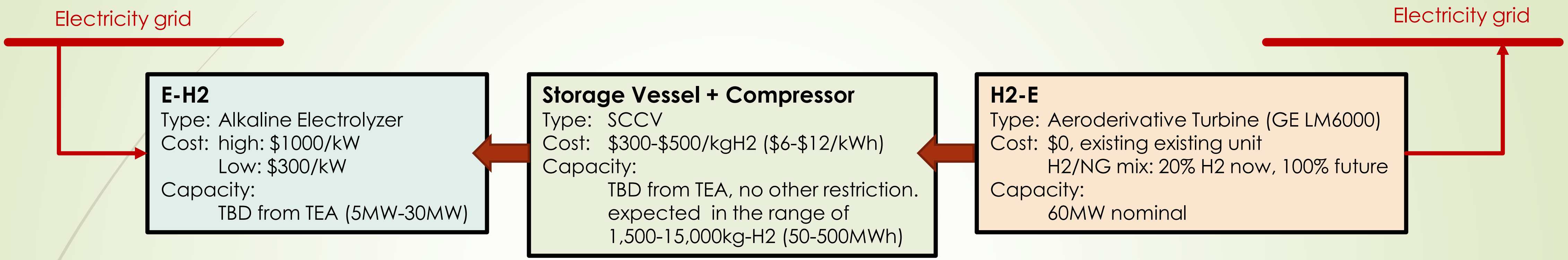
Flow of Phase II Key Activities



- System optimization for selected site, assisted by *TEA modeling*
  - Identify H2 to E sub-system requirements
    - Power, duration and capacity factor
    - TVA specific electricity and fuel cost structure
  - Determine and design H2 storage sub-system
    - Storage capacity (kg of H2, pressure, size, cost)
    - Compressor (pressure, throughput, cost)
  - Determine capacity of electrolyzer sub-system
    - Capacity, cost
- Initial system design
- Price and cost of major components/sub-systems from potential suppliers and vendors
- System optimization assisted by TEA
  - Level 1: System design optimization
  - Level 2: Operation optimization
- Review and refine system design and component specifications
  - Mostly likely drive by the cost
- Final Pre-FEED design and engineering results

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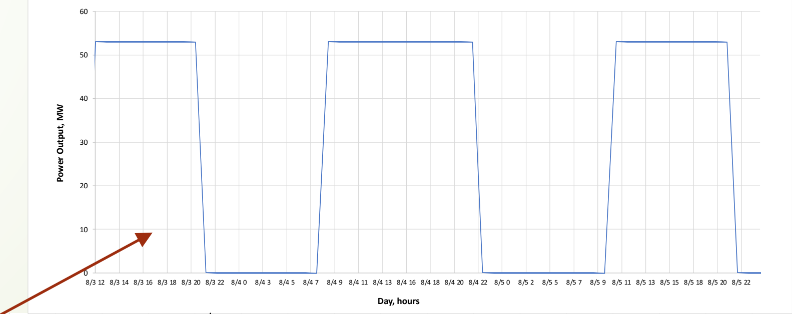
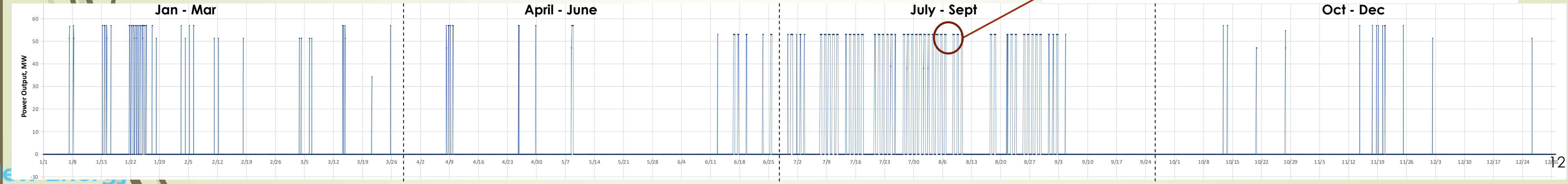
H2-E unit at Johnsonville CT plant site

- GE LM6000 aeroderivative gas turbine
  - Rated power: 60MW. Projected power generation range: 47-55MW
  - H2 and natural gas mixture: 20% volume initially, also need to consider 100% H2 for future
  - Thermal efficiency: 38.5%
- ***Projected*** operation profile
  - Summer: longest operation: 8-14 hours/day
  - Winter: shorter, 2-5 hrs/day
  - Spring and Fall: rarely
  - Optional: cover 80-95% of operation scenarios, for cost optimization. Remaining to be covered by 100% natural gas. (Beauty of H2/NG blend)
  - Capacity factor:
    - heavy years: ~10-12%, average years: 5-6%, light years: 1-2%. Consistent with typical Peaker operation CP
- ***Projected*** cost of electricity generation
  - Next 20 years (with uncertainties)
  - $20-30/MWh on low end, $40-80/MWh on high end

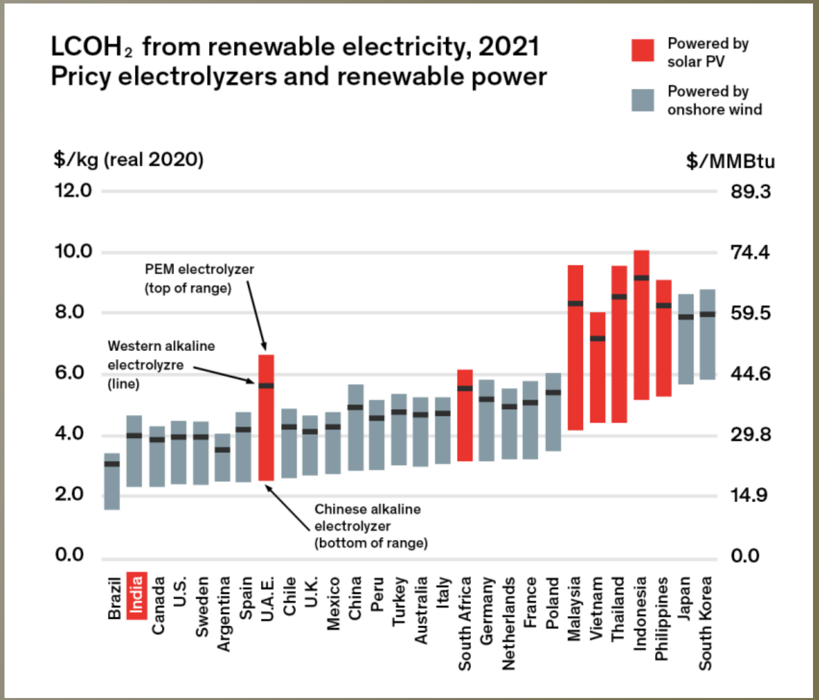


“average years”



Cost of major components/subsystems

- Quotes from multiple manufacturers and system provided
  - US domestic and international
- Alkaline electrolyzer
  - $300 to $1000/kWh for 5-30MW capacity range
  - Suitable for relatively stable electricity supply from fossil plant base load units
  - Low system cost
  - Relatively mature technology and scalability to MW/GW range
  - Slightly lower efficiency: ~60%
- High-pressure storage vessel
  - Today's tube on market: $1200-$1500/kg-H2
  - SCCV: $200-$800/kg-H2
- H_2 compressor
  - Compressing H2 from 150psi (typical alkaline electrolyzer output pressure) to 3000psi (storage pressure for H2), at rate of 150-350 kg-H2/hr total
  - $4,000-$10,000/kg-H2/hr for required pressure and flow rates



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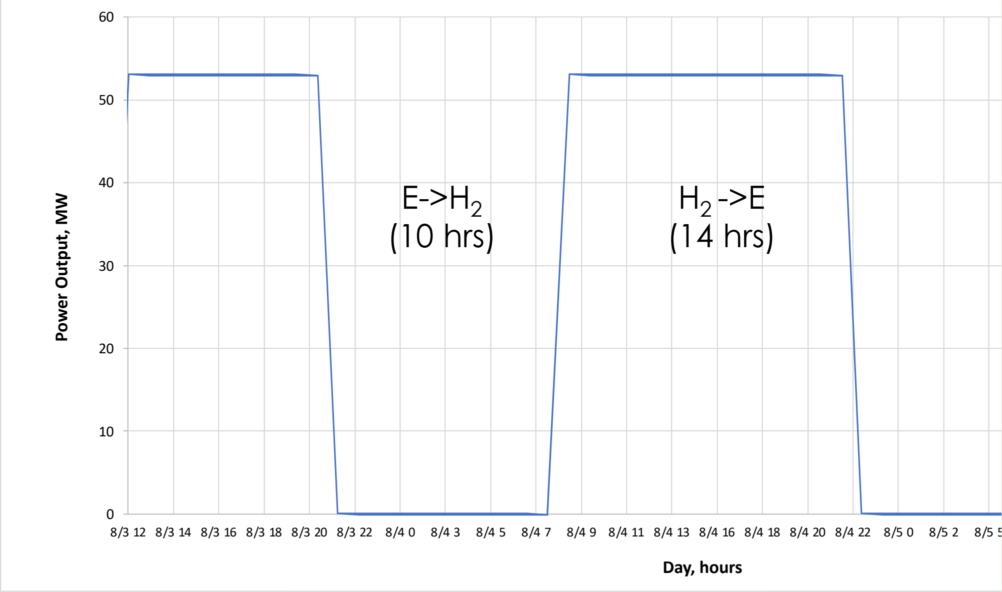
Baseline design of HyPeaker system

- Requirement
  - H_2 production and storage must meet maximum H_2 consumption during the longest hours (14 hrs) of HyPeaker operation in one day
- For 20% vol H_2 mix
  - 4000 kg-H_2 in the highest usage day
- Electrolyzer: 22.5MW
- Storage vessel:
  - 4 vessels with cascading operation at 500-1500kg-H2 per vessel
- Capital Cost
  - \$15-30M for 20% vol H_2 mix
    - Electrolyzer: 75%
    - Vessel: 15%
    - Compressor: 10%
  - Not including aero-derivative power generation unit



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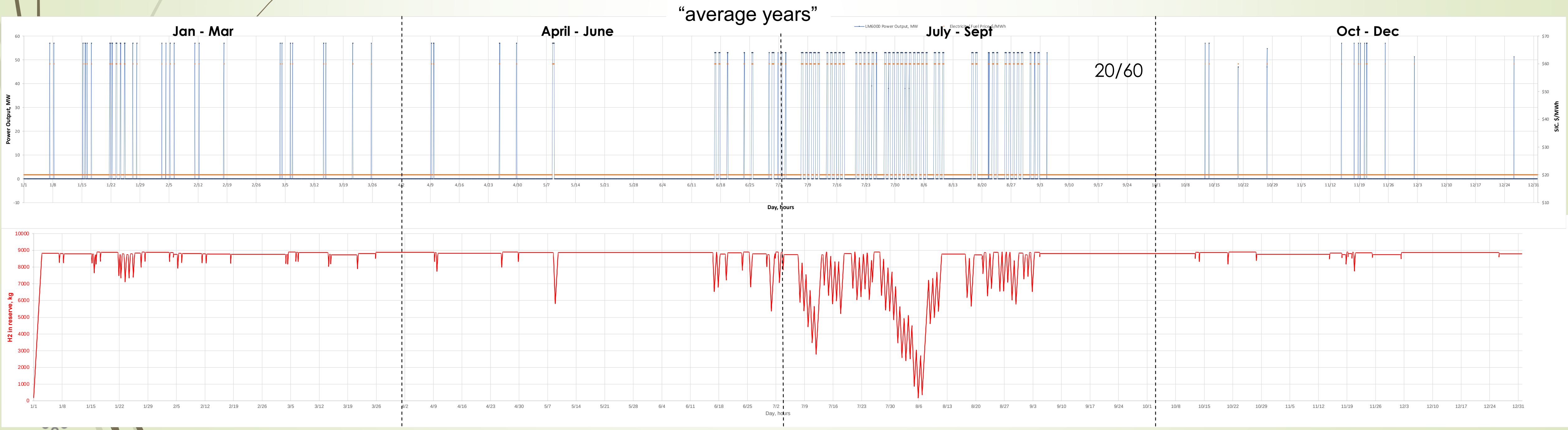
System design optimization through seasonal balance of H_2 production and usage (long duration storage scenario)

- WENE's system design analysis tool
- Principles
  - Run "smaller" electrolyzer for longer hours over week/month shift, when fuel/electricity cost is low
  - Use "oversized" storage vessel to store H2 over week/month
  - Ensure enough H2 for peak day usage
  - Include electricity/fuel cost variations (daily and seasonal)
  - Optimization target: total system cost minimum
- Example with simplified electricity/fuel cost profile: $20-60/MWh

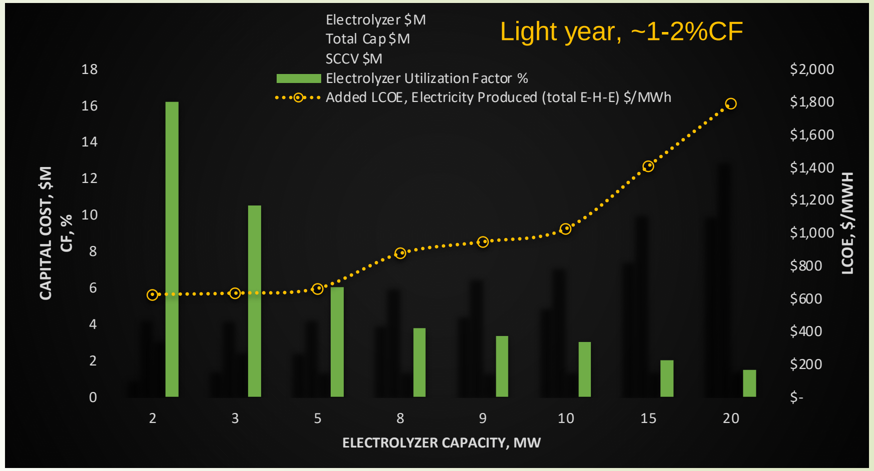


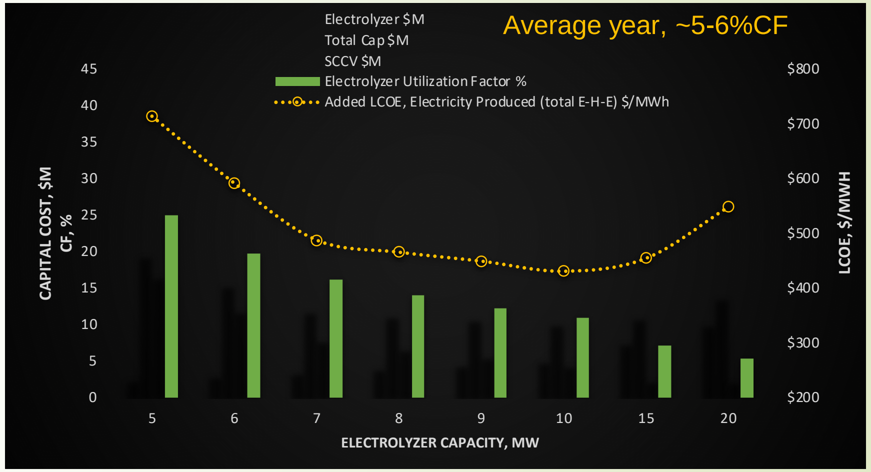
System Design Analysis

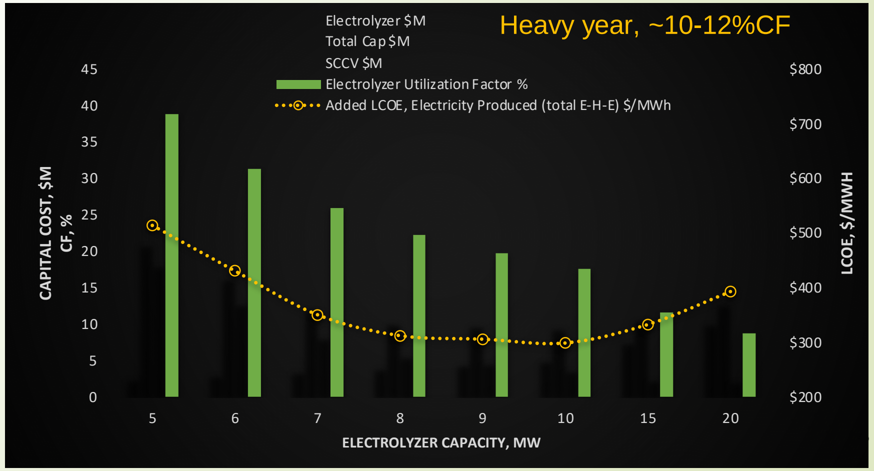
- **Basic Design Parameters**:
  - Actual projected fuel/electricity cost: $20-80/MWh
  - Alkaline electrolyzer: $500/kWh
  - Storage Vessel: $500/kg-H2
  - Compressor: $4000/kg-H2/hr
  - Gas turbine: existing peaker, cost not included
  - 7% discount rate
- **Optimal design to cover projected 20 years operation**
  - Electrolyzer: 9MW
  - Storage vessel: 11,000kg H2
  - Compressor: 160kg-H2/hr
  - Total capital cost:
    - **$10.68M**
    - **$6.67M** (best global supply)
    - **$21.7M** (today's tube storage)
- **Low electrolyzer utilization rate** is a major factor for LCOE
- Despite low round-trip efficiency (~23%), cost of electricity for E-H2-E is only a small fraction of LCOE
- Level 2 TEA: Opportunities to greatly reduce LCOE and improve profit margin through operation optimization

	GT CF, %	LCOE, Electricity (Total E-H2-E) $/MWh	Electrolyzer Utilization Rate, %	LCOE, H2 (Total E-H2), $/kg-H2
Heavy Years	**10-12%**	**$306**	**20%**	**$3.93**
Average years	**5-6%**	**$449**	**12.3%**	**$5.76**
Light Years	**1-2%**	**$946**	**3.3%**	**$12.12**

LCOE of Li-Battery for average years: $800/MWh ($200/kWh, 80% RTE, 10 yr life)







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Techno-Economic Analysis of E-H_2-E System

Ijiwole Ijiyinka, Md Emdadul Haque, Debangsu Bhattacharyya
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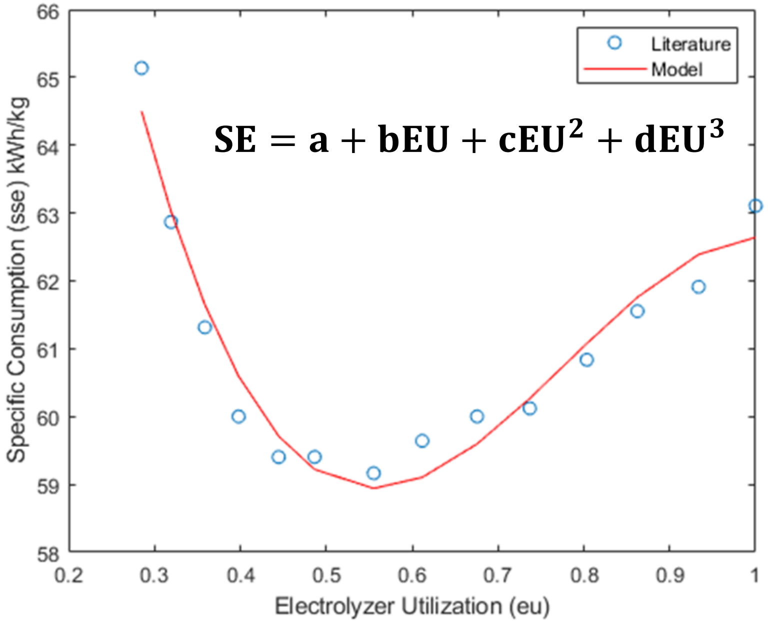
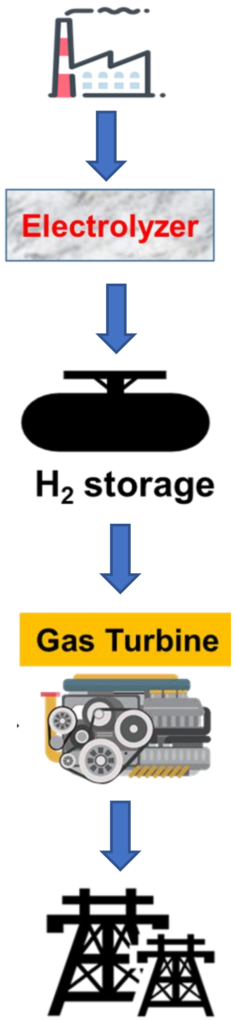
April 19, 2023

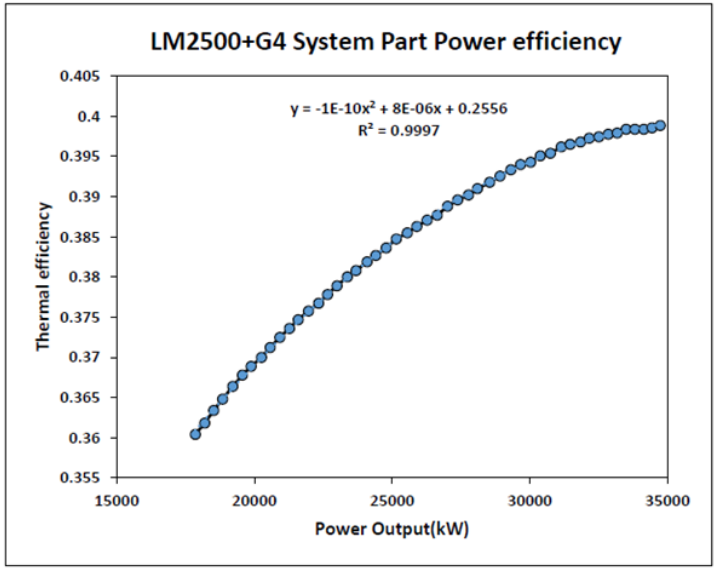
Electrolyzer and Aeroderivative Turbine Model



$$EU(x) = \frac{H_2\ Prod.Rate}{Design\ H_2\ Prod.Capacity}$$

- $CAPEX_{Elec} = 988 \times Capacity_{Elec}$
- $OPEX_{fixed,Elec} = 40 \times Capacity_{Elec}$
- $OPEX_{var,Elec} = 0.08 \times H_{2,production}$





$$Eff = 0.2556 + 8e^{-6}P_{output} + 1e^{-10}P^2_{output} + +0.2556$$

- $Thermal\ Efficiency = \frac{3600 \times P_{produced}}{LHV_{H_2} \times \dot{m}_{H_{2,injection}} + LHV_{NG} \times \dot{m}_{NG}}$
- $CAPEX_{AT} = 1000 \times Capacity_{AT}$
- $OPEX_{fixed,AT} = 0.0153 \times CAPEX_{AT}$
- $OPEX_{var,AT} = 0.695 \times P_{produced}$

Reference

[1] Roberta C., Enrico B. & Lucal D. Z. Techno-Economic Model for Scaling Up of Hydrogen Refueling Stations. *Energies* **2022,**15,7518

[2] Gas Turbine World (USPS 944760. ISSN 0746-4134

Optimal Design of Hydrogen Storage Vessel

Design Basis:

- Cylindrical Vessel with hemispherical end.
- Wall thickness includes corrosion allowance and stress.

Total Volume of material for Cylindrical Vessel: $V_t = V_m + 2 * V_{mh}$

$$log_{10} C_p^o = K_1 + K_2 \, log_{10} V_t + K_3 \, (log_{10} V_t)^2$$

$$C_{BM} = C_p^o \, F_{BM}$$

$$F_{BM} = B_1 + B_2 F_p F_M$$

$$CAPEX = 1.18 \sum C_{BM}$$

Where, V_m = Cylindrical Shell = $\pi L(Ro^2 - R^2)$ and V_{mh} = Hemispherical Head = $\frac{2\pi(R_o^3 - R^3)}{3}$

C_p^o = Purchased cost, K_1, K_2, K_3, B_1, B_2 = Factor, C_{BM} = Bare module cost

F_{BM} = Bare module factor, F_p = Pressure factor, F_M = Material Factor

WestVirginiaUniversity

NPV Optimization

$$maxNPV = \sum_{t \in T} REVENUE_t - CAPEX_t - OPEX\_fixed_t$$

$$REVENUE_t = LMP_t P_{grid,t} - LMP_t P_{consumed,t} - OPEX_{variable,t}$$

$$P_{grid,t} = GT\ power\ produced$$

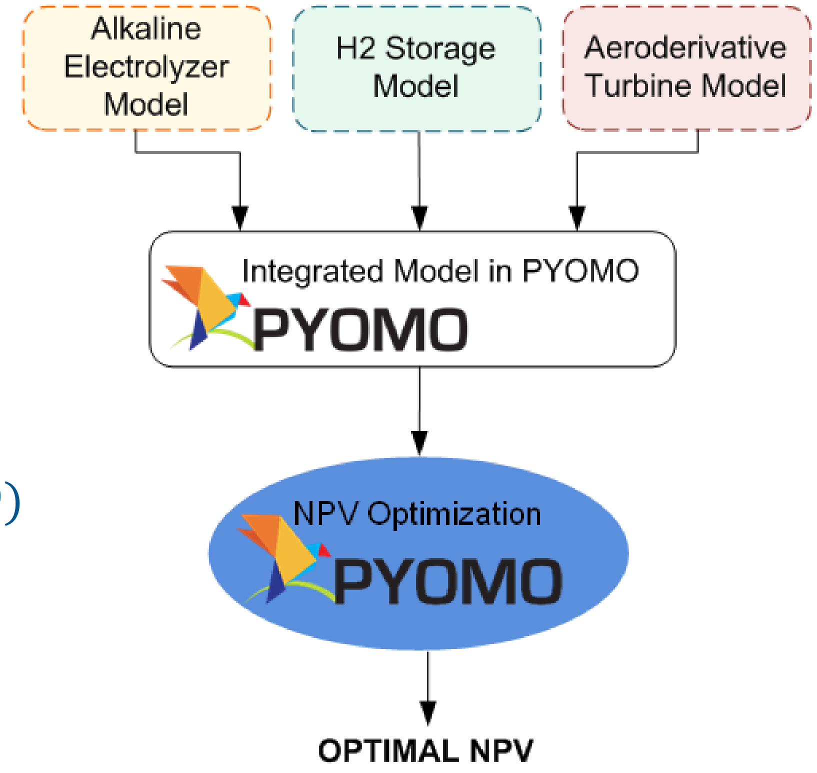
$$P_{consumed,t} = Electrolyzer\ + H_2\ Compressor$$

$$P_{A,f} = \frac{(1+i)^n - 1}{i(1+i)^n} \cdot \frac{1}{(1+i)^n}$$

← Assuming a lifetime of 30 years and an interest rate of 7.25% $(i = 7.25\%\ \ N = 29)$

$$CAPEX_t = \frac{CAPEX}{365 * 24 * P_{A,f}}$$

$$OPEX_{fixed_t} = \frac{OPEX_{fixed}}{365 * 24}$$



LMP Data*

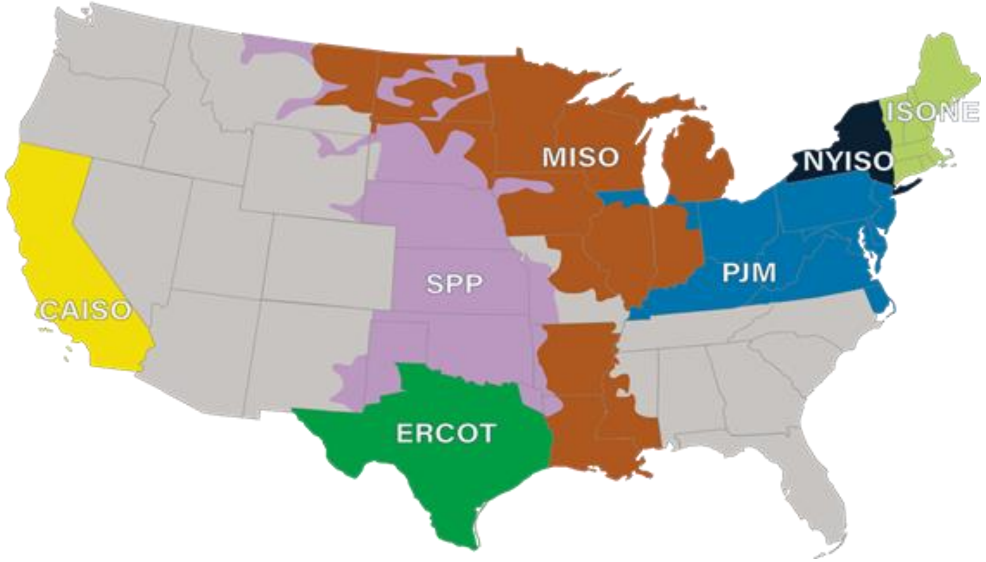
- Dynamic data spanned over a year at one hour sampling
- Two Sets of Data

❖**NREL** (Carbon tax of $150/ton and $100/ton)

- **CAISO-150, 100**
- **PJM-150, 100**
- **MISO-150, 100**
- **NYISO-150, 100**
- **ERCOT-150, 100**

❖**Princeton** (Carbon tax of $60/ton)

- **Base case**
- **High wind**
- **High solar**
- **Winter NY**



Reference

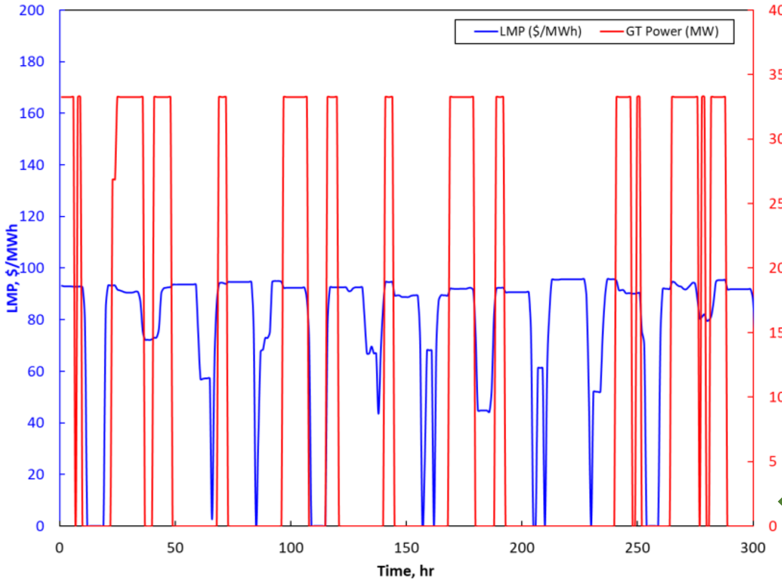
***[3]** Sun, Y., Wachche, S., Mills, A., Ma, O., Meshek, M., Buchanan, S., Hicks, A., Roberts, B., 2020. 2018 Renewable Energy Grid Integration Data Book. National Renewable Energy Laboratory, Golden, CO, USA.

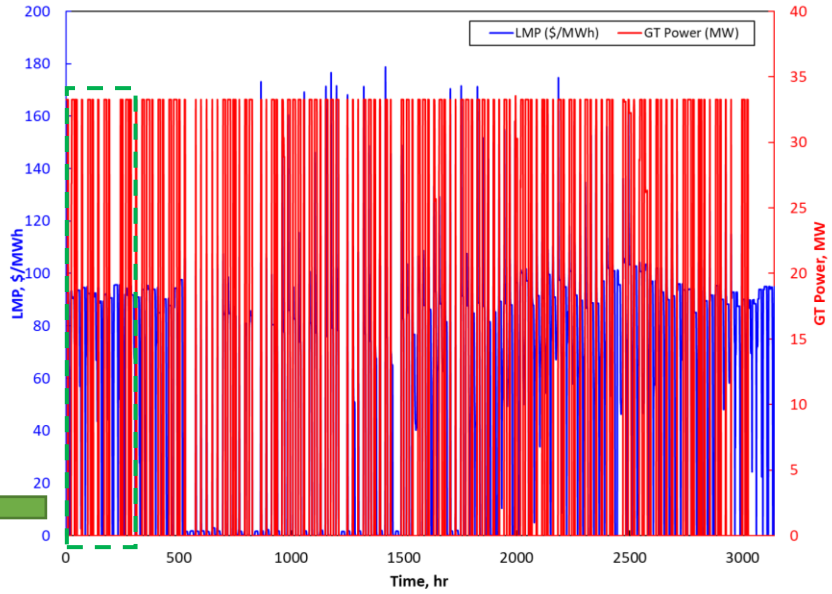
Case Study

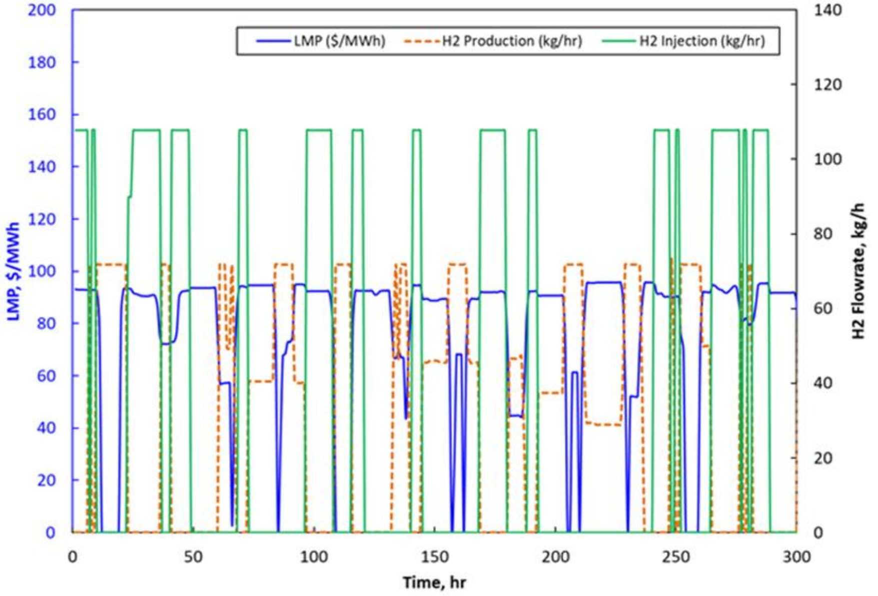
There are 4 cases studied based on CAISO-100 clustered LMP for a whole year. Total number of equivalent days are 131. Assumptions for case study are as follows:

	Case 1	Case 2	Case 3	Case 4
CO_2 Tax ($/ton)	**100**	**100**	**0**	**0**
H_2 as Fuel (Vol%)	**15%**	**0-15%**	**15%**	**0-15%**

Case-1 (CO_2 Tax: \$100/ton, H_2: 15%) Results



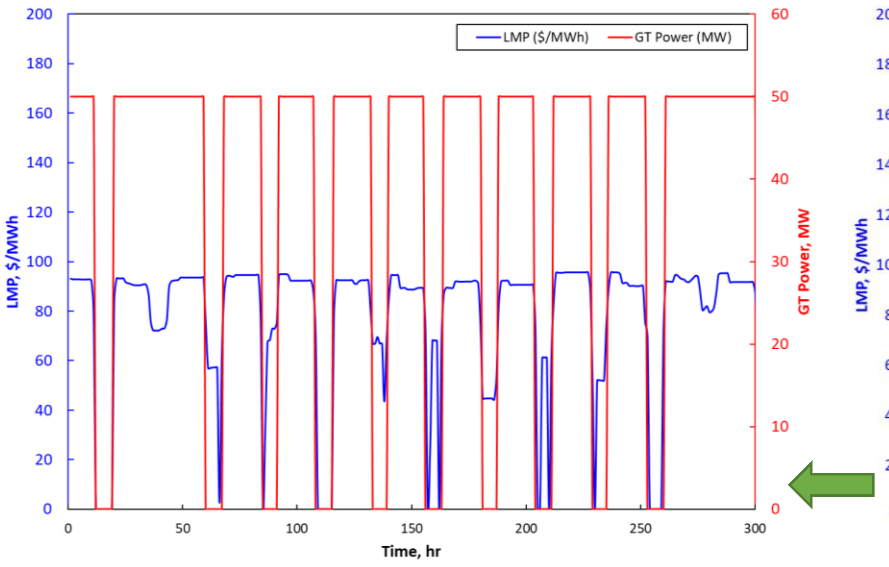


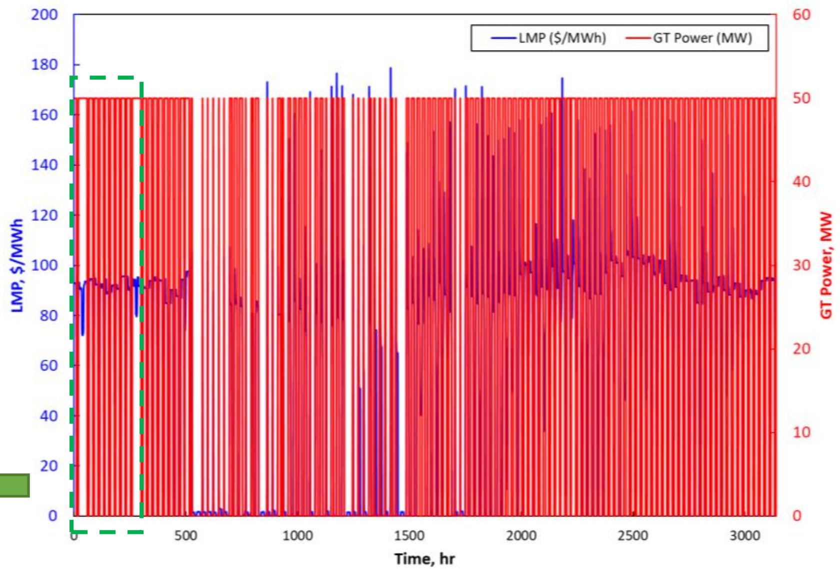


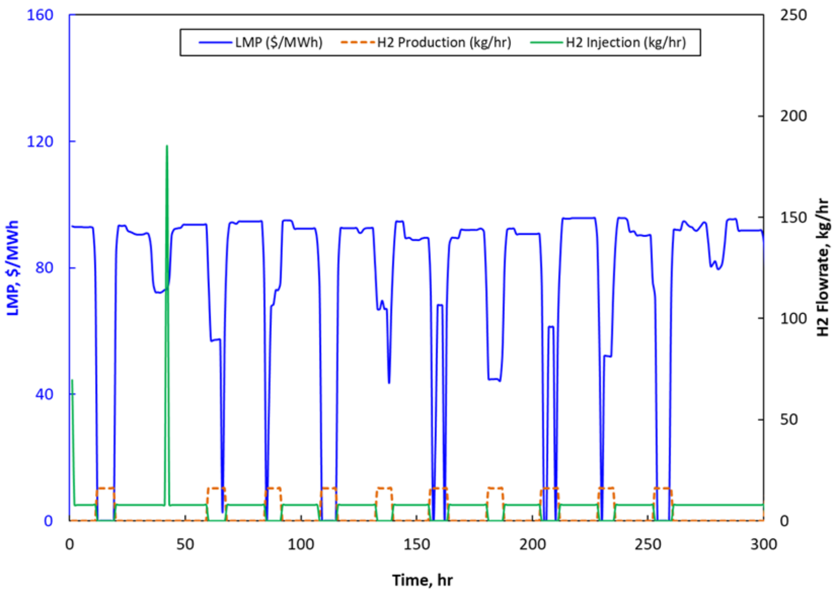
Design Variables	Value	Design Variables	Value
Max H_2 Production, kg/hr	71.86	H_2 Storage Pressure, bar	96.15
Max Electrolyzer Power, MW	4.5	GT Power Avg/Max, MW	9.09/33.25
H_2 Volume, m^3	409.38	NPV , \$MM	0.30

- H_2 production varies with LMP and max H_2 injection reaches to 108 kg/h.

Case-2 (CO2 Tax: \$100/ton, H_2: 0-15%) Results



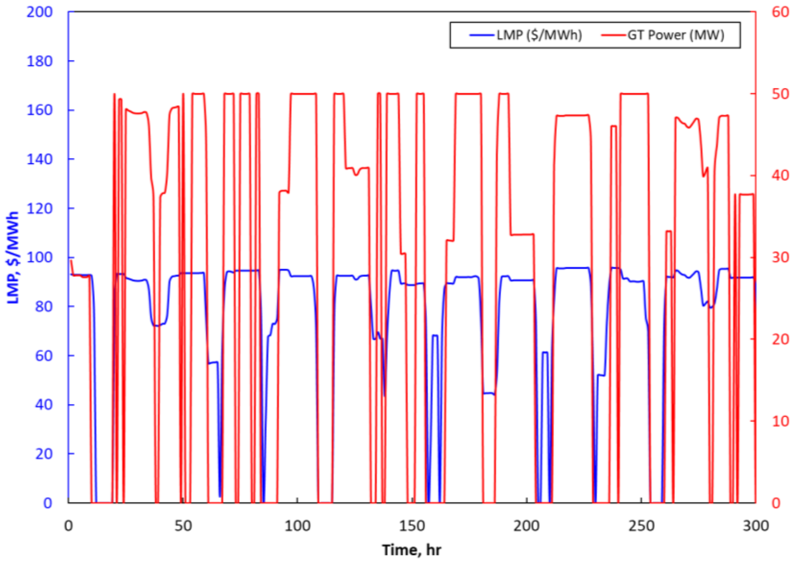


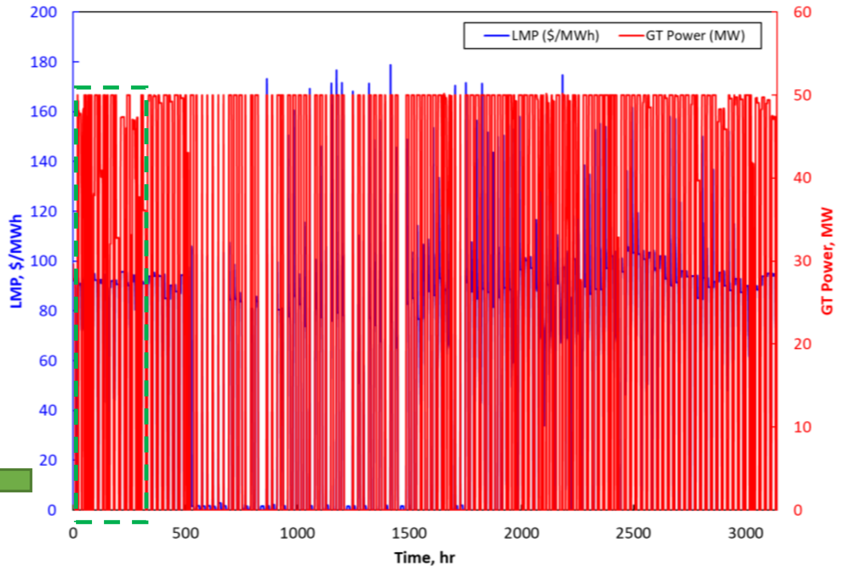


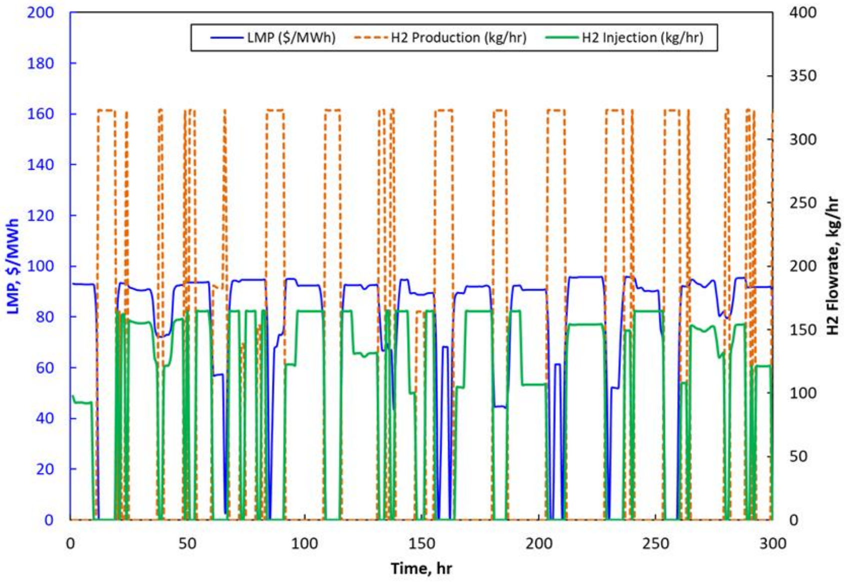
Design Variables	Value	Design Variables	Value
Max H_2 Production, kg/hr	15.96	H_2 Storage Pressure, bar	90
Max Electrolyzer Power, MW	1	GT Power Avg/Max, MW	24.91/50
H_2 Volume, m^3	171.5	NPV, \$MM	3.71

- Optimal solution found for low H_2 flowrate, and optimizer reaches to lower bound for electrolyzer.

Case-3 (CO_2 Tax: 0, H_2: 15%) Results



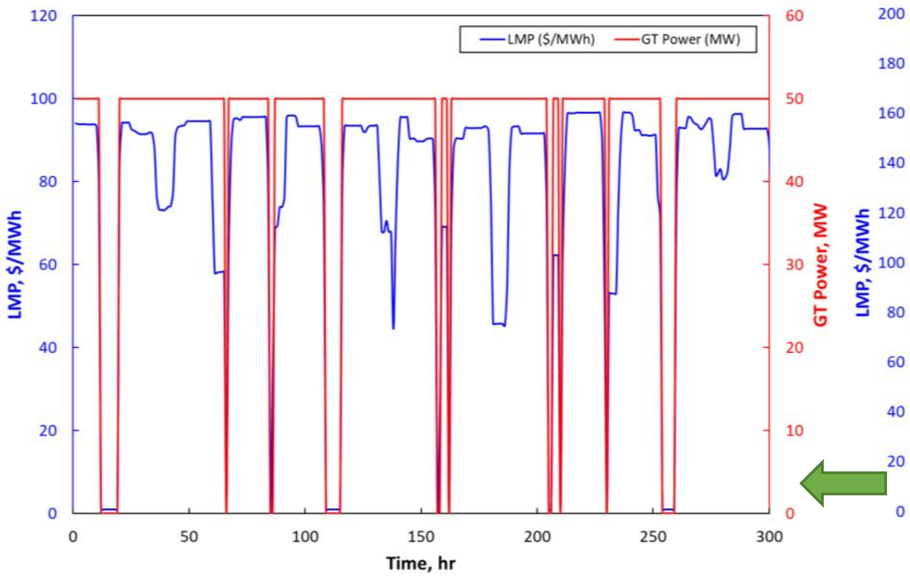


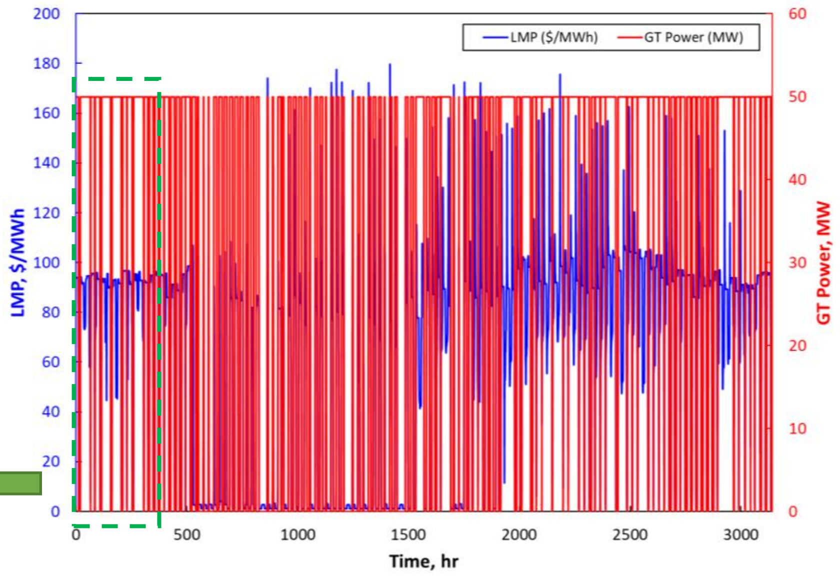


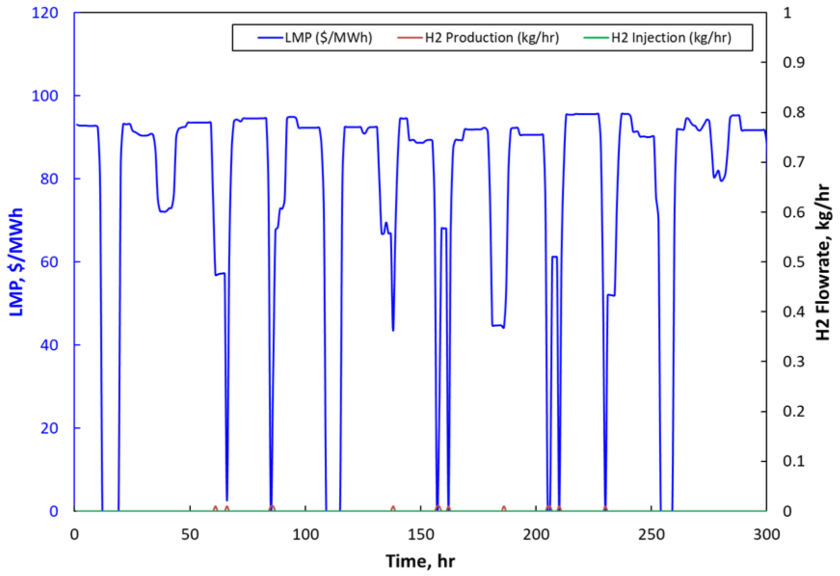
Design Variables	Value	Design Variables	Value
Max H_2 Production, kg/hr	322.76	H_2 Storage Pressure, bar	219.1
Max Electrolyzer Power, MW	20.22	GT Power Avg/Max, MW	25.71/50
H_2 Volume, m^3	179.7	NPV, $MM	9.0

- H_2 production and injection rate reaches to 323 kg/h and 164 kg/h respectively.

Case-4 (CO_2 Tax: 0, H_2: 0-15%) Results







Design Variables	Value	Design Variables	Value
Max H_2 Production, kg/hr	0	H_2 Storage Pressure, bar	------
Max Electrolyzer Power, MW	1.0	GT Power Avg/Max, MW	32.97/50
H_2 Volume, m^3	0	NPV, $MM	15.40

- Electrolyzer is not placed, i.e. H_2 production and Storage pressure 0, optimizer forcing the lower bound of 1 MW.

Conclusion & Future Work (WVU TEA)

- Model of an integrated system including electrolyzer, H_2 storage and aeroderivative turbine (AT) is developed in the Python platform for NPV optimization.
- The present work assumed that electricity consumed in the process is being purchased from the grid and produced electricity is sold to the grid and both of them are given by the LMP at that time instant.
- The electrolyzer produces H_2 at low LMP and injected at high LMP. The max capacity of the turbine is 50 MW for case 2, 3 and 4, while it is 33 MW for case 1.
- The NPV for case 4 is the highest because of no carbon tax and the flexibility of hydrogen usage. For Case 4, even though a small elecytrolyzer of 1 MW is forced (minimum), it was not optimal to use it; on the other hand, even though the electrolyzer design capacity is still at minimum for Case 2 similar to Case 4, electrolyzer was utilized to reduce the penalty from CO_2 tax.
- One key focus in the future will be to perform sensitivity studies to cost, results for LMP for other regions, and include other incentives such as from IRA.

Project Summary

- Deployment site selected, and identified early entry point for long duration hydrogen storage system:
  - Peaking power generation: HyPeakers
- Developed TEA model tool and completed system design optimization for HyPeaker
  - Based on projected operation profile and fuel/electricity price variations of the TVA site
  - Evaluated options of HyPeaker system design
- Completed the **site-specific concept** HyPeaker system design and operation metrices
  - HyPeaker is technically feasible and economically advantageous
  - Identified scenarios for HyPeaker operation to improve profit margin of fossil power plant integrated with H2 storage system
- Level 2 TEA optimization on-going
  - System and operation optimization based on economics

Thank you!