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Renewable Hydrogen for a Carbon-Free Data Center

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Hydrogen and Fuel Cell R&D for Datacenter Applications

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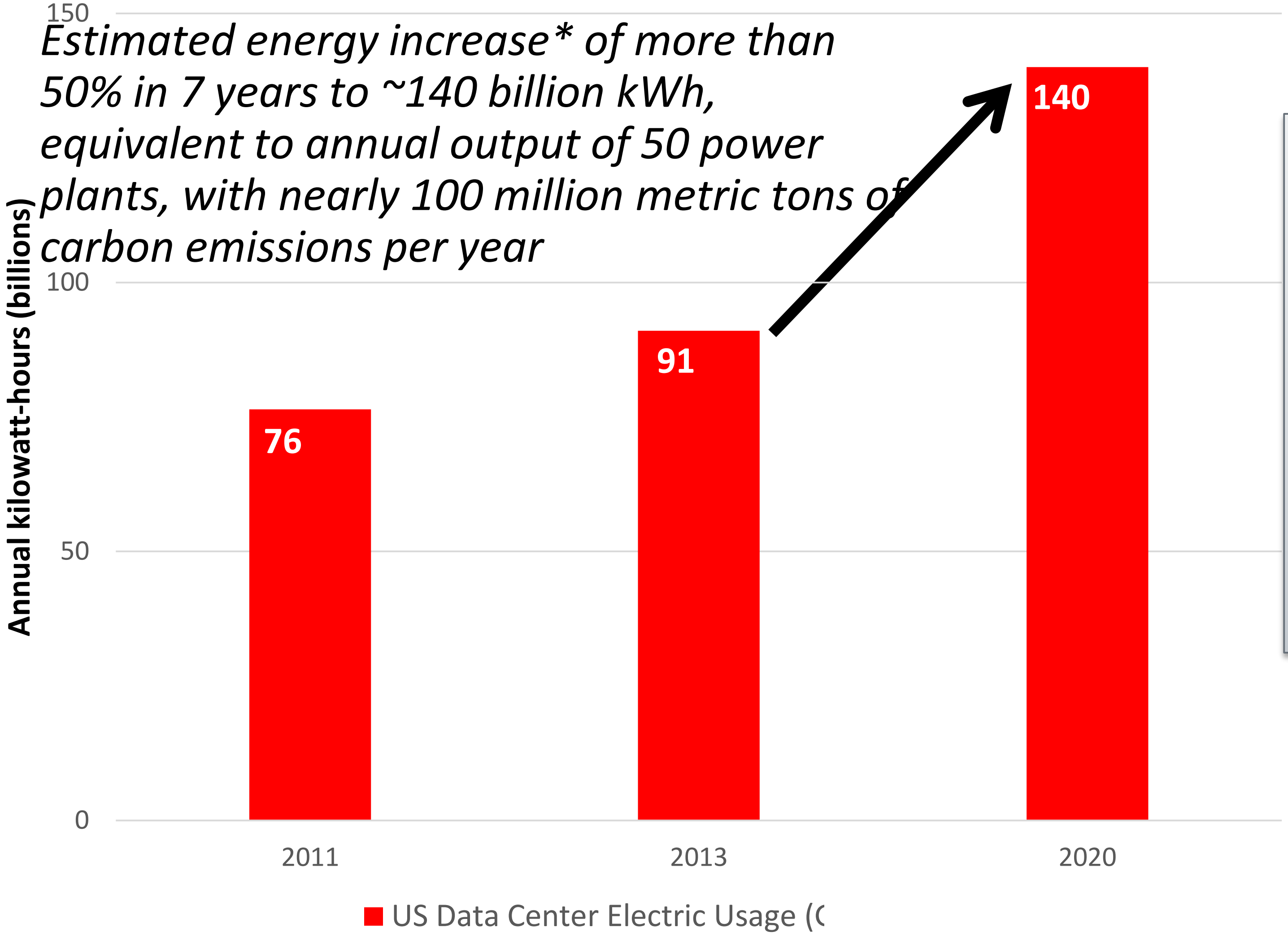
Data Center Energy Challenge –
High costs in power infrastructure, inefficiencies, and backup power required



* http://www.nrdc.org/energy/data-center-efficiency-assessment.asp

Data center electricity use would be 3.5% of total U.S. electricity use in 2020 according to projections.

Annual Energy Outlook 2019
Table: Electricity Supply, Disposition, Prices, and Emissions
Case: Reference case

Carbon-Free Data Center Scale Comparison – Megawatts Shipped

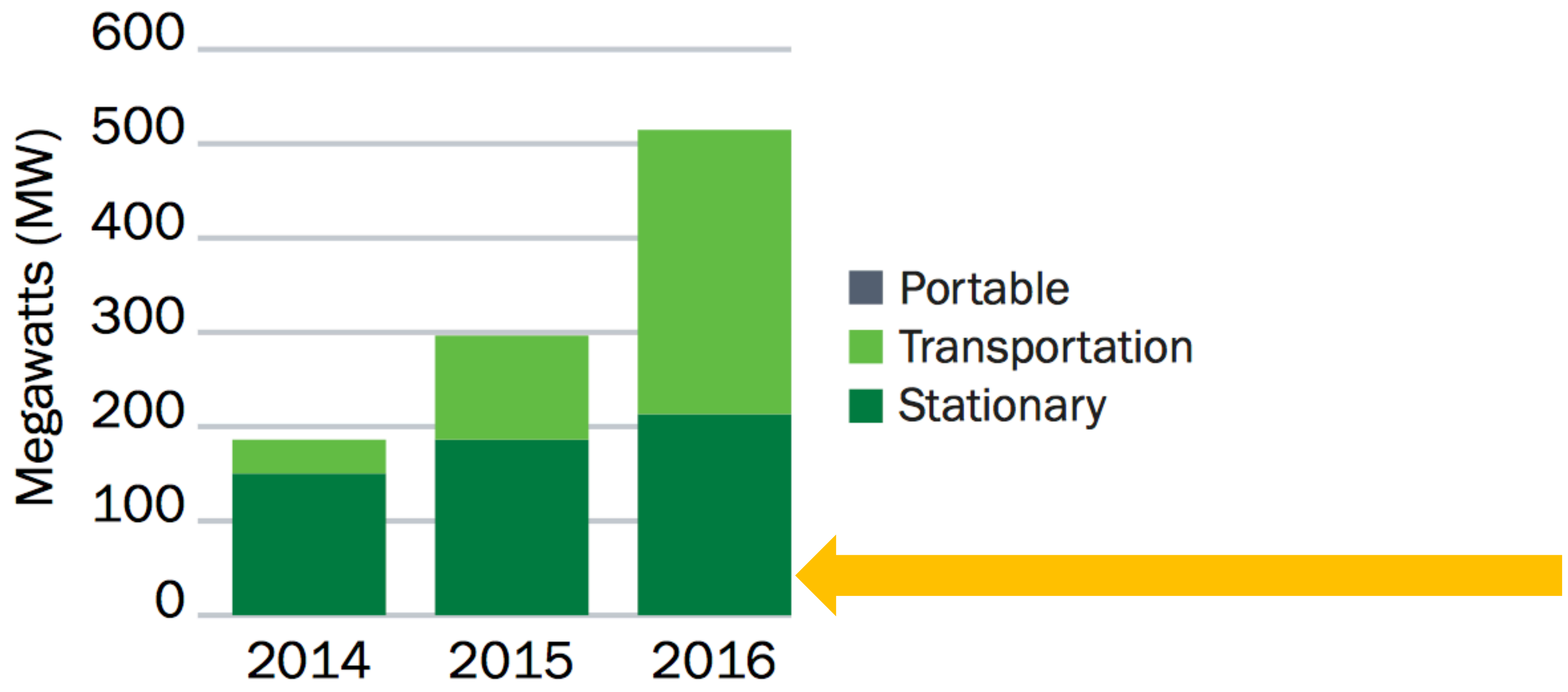


Figure 2: Megawatts of Fuel Cells Shipped Worldwide by Application
Source: U.S. Department of Energy
Fuel Cell Technologies Office, E4 Tech

https://energy.gov/sites/prod/files/2017/10/f37/fcto_2016_market_report.pdf

Just one large data center is ~25% of worldwide stationary shipments (MW) in 2016

Carbon-Free Data Center Vision

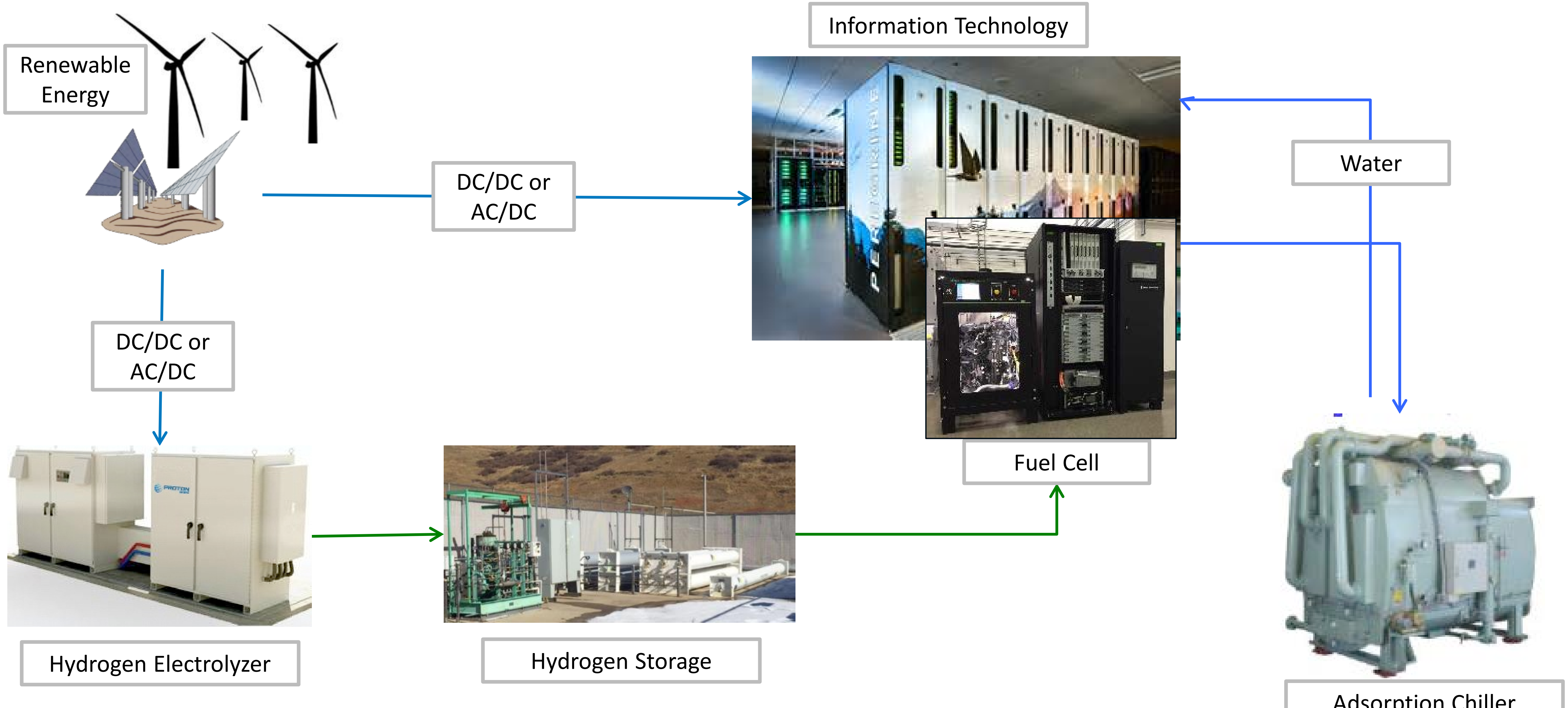


Photo credits (L to R): Proton Onsite; NREL; Power Innovations; NREL; HPE

Schematic illustrative of possible system

One concept : FC integrated racks

Integrated Fuel Cell Data Center	Comparison to Baseline, Air Cooled Data Center (traditional)
Hydrogen distribution inside data center	+ Lower cost than electrical distribution inside data center + Simplified mechanical system + Estimated lower operation and maintenance costs + CHP – waste heat capture and re-use - High capital costs
Fewer IT racks for data center load	+ Liquid cooled ~1.8x higher rack density than air cooled + Decreased data center footprint and decreased building shell cost
Resiliency	+ Individual racks can continue operation while maintaining other racks + External diesel generator backup and uninterruptible power supplies are not needed

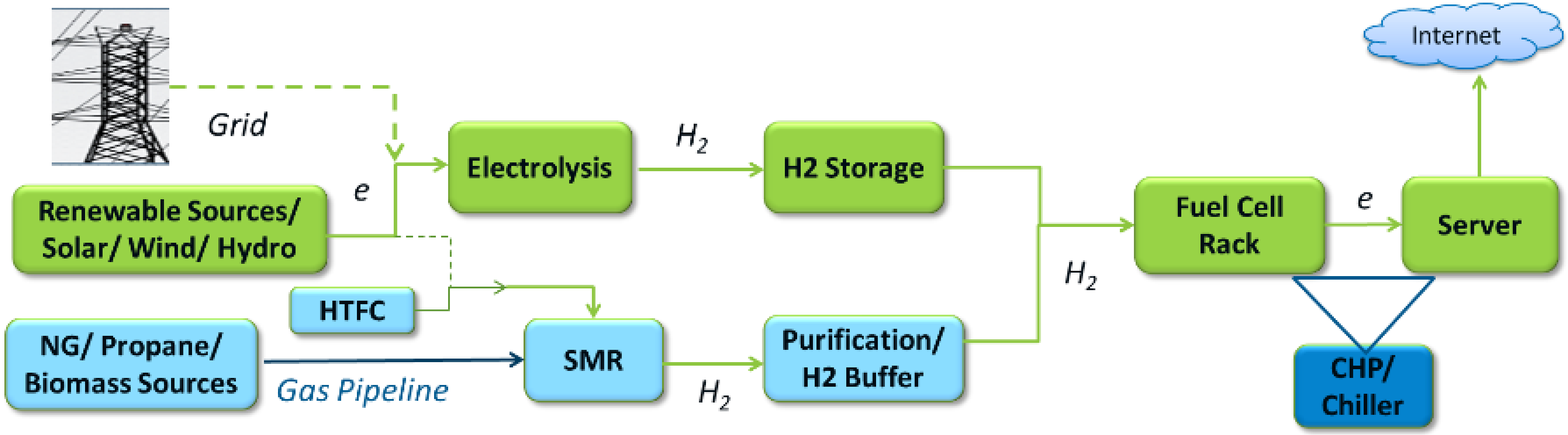
- ✓ Reduce long-term data center overall Total Cost of Ownership
- ✓ Increase reliability and resiliency
- ✓ Take advantage of inexpensive renewables in the future

	Standard Data Center	Fuel Cell Data Center
Critical IT load (MW)	50	50
Rack power (kW)	12	60
# of IT racks	4,167	833
IT cooling methodology	Air	Liquid
Fuel Cell Racks (130 kW per rack)	0	424
% IT rack load to air	100	30
% IT rack load to water	0	70
Central UPS?	Yes	No
Diesel generators?	Yes	No
Chiller types	Absorption	Adsorption
Chiller capacity (tons of refrigeration)	1,200	200
Cooling towers?	Yes	Yes

System Modeling for Hydrogen Infrastructure

Scenarios	Sizing	Economics

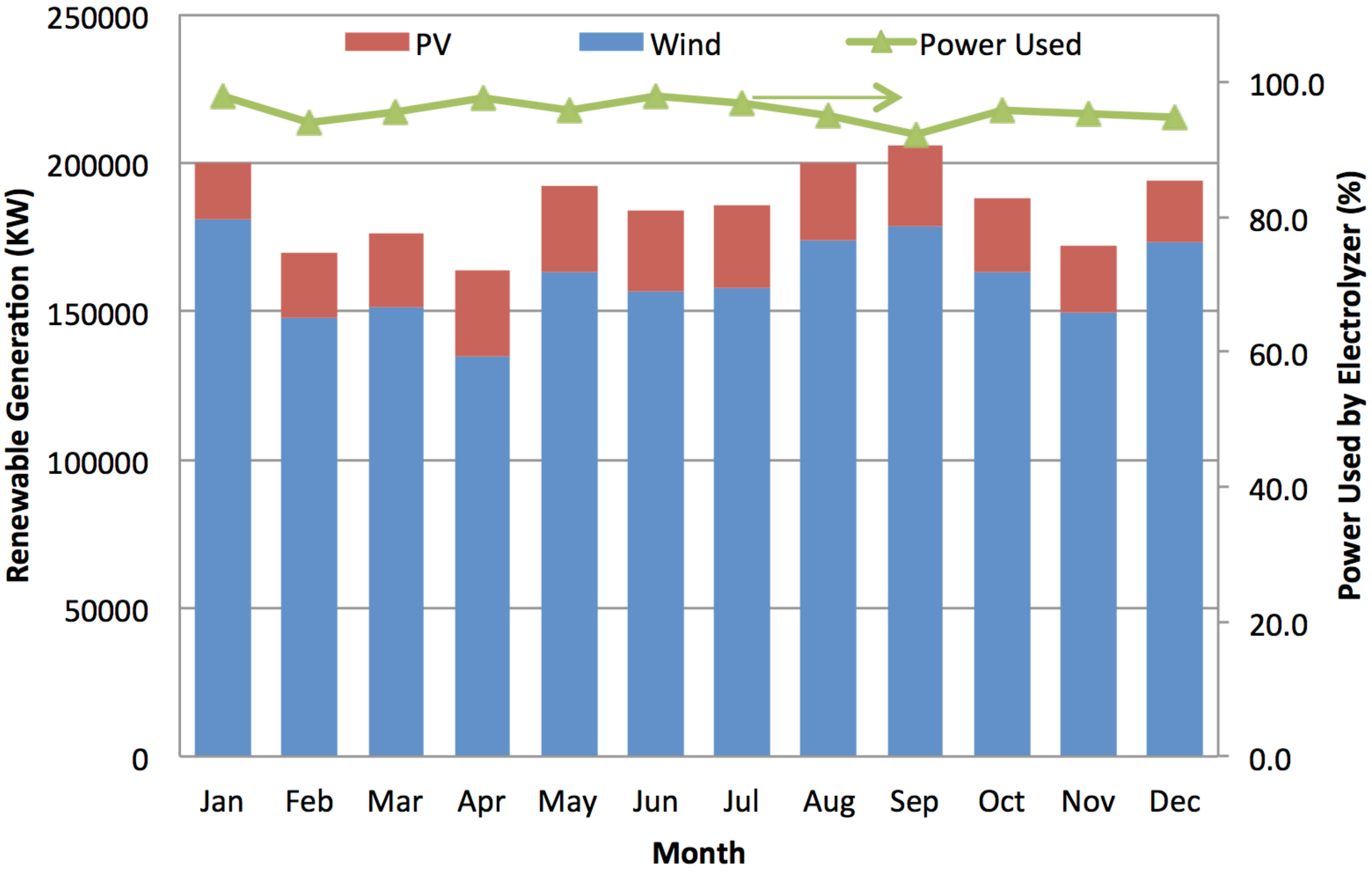
• Two Locations
  • Quincy, WA
  • San Antonio, TX
• Energy Sources
  • 100% renewable (PV and wind)
  • Natural gas to hydrogen
  • Grid independent and grid dependent
	• **50 MW 24/7 load demand**
	• Renewable generation name plate
	• Renewable generation output estimate
	• Electrolysis name plate
	• Hydrogen production estimate
	• Hydrogen storage
	• Equipment footprint
		• Renewable generation and hydrogen infrastructure
		• Data center total cost of ownership
		• Capital costs
		• Operation and maintenance costs
		• Cost estimates include current and projected



Summary of Options Considered

Scenarios	1. Wind/PV -> H2 -> IT	2. Wind/PV -> H2 -> IT & Wind/PV -> IT	3. Add grid to 2	4. Natural Gas (NG)->H2		
Description	All data center power comes from renewable produced hydrogen Includes San Antiono, TX & Quincy, WA locations	Data power is shared with direct renewables (highest efficiency, most intermittent) & renewably produced hydrogen Includes San Antiono, TX & Quincy, WA locations	Scenario 2 and Includes grid power purchase and sell cost Includes Quincy, WA location	Case 1. NG SMR with Grid	Case 2. NG SMR HT FC for auxiliary power	Case 3. NG SMR HTFC and renewable Power
Pros	Zero emissions (excluding component manufacturing) Electrolyzer handles renewable intermittenancy and variability FC deliver constant, high quality power	Best renewable round trip efficiency. Lower capital cost reduced renewable and hydrogen storage capacity.	Possible option for near-term	Low capital cost	Grid independent	Grid independent plus renewables, limit total capital around $0.2 billion
Cons	~35% round trip efficency requires large renewable size High runtime onFC and electrolyzer increases maintenance costs	Requires both electrical and hydrogen infrastructure in the data center. Need controlling coordination of renewable power supply and fuel cell ramping	Not zero emissions Requires grid connection	Carbon from NG	Carbon from NG, also HOMER is incapable to simulate HT FC and power FC at the same time.	Carbon from NG, beyond HOMER controler capability for power generation, storage, and consumption optimizaiton.

Renewable Hydrogen Production Modeling



- H2 to Power to supply 50 MW data center IT load.
- ~33% renewable generation capacity factor (location specific)
- Electrolyzer follows variable renewable generation
- Nameplate size to ensure sufficient storage during low or no renewable generation
- Example – 100% renewable, WA location has 635 MW generation (525 MW is wind) and 250 MW of electrolysis
- Smaller systems for other intermediate scenarios

Comparison of hydrogen production (electrolyzer) and consumption (fuel cell) Scenario 1 Quincy WA

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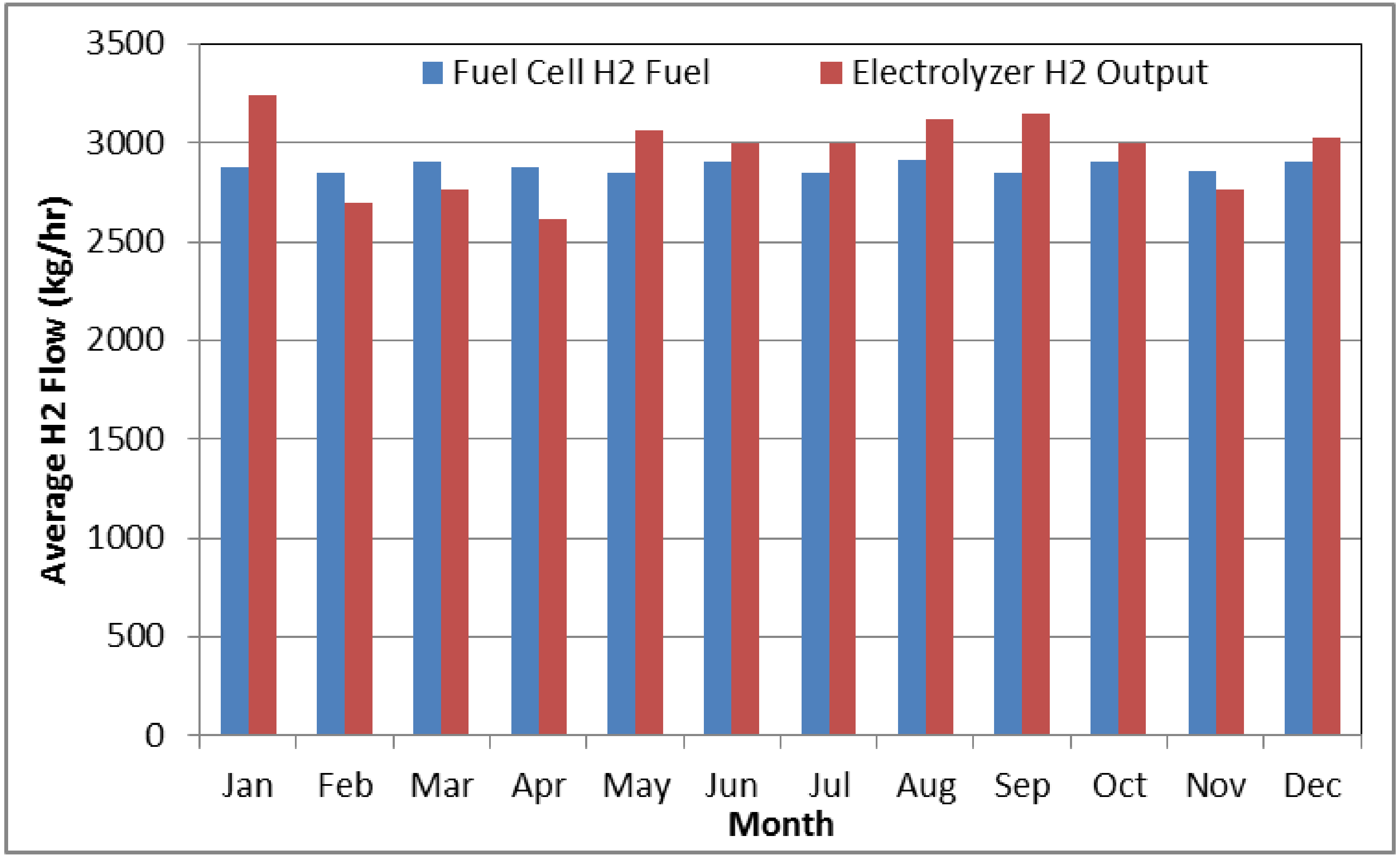
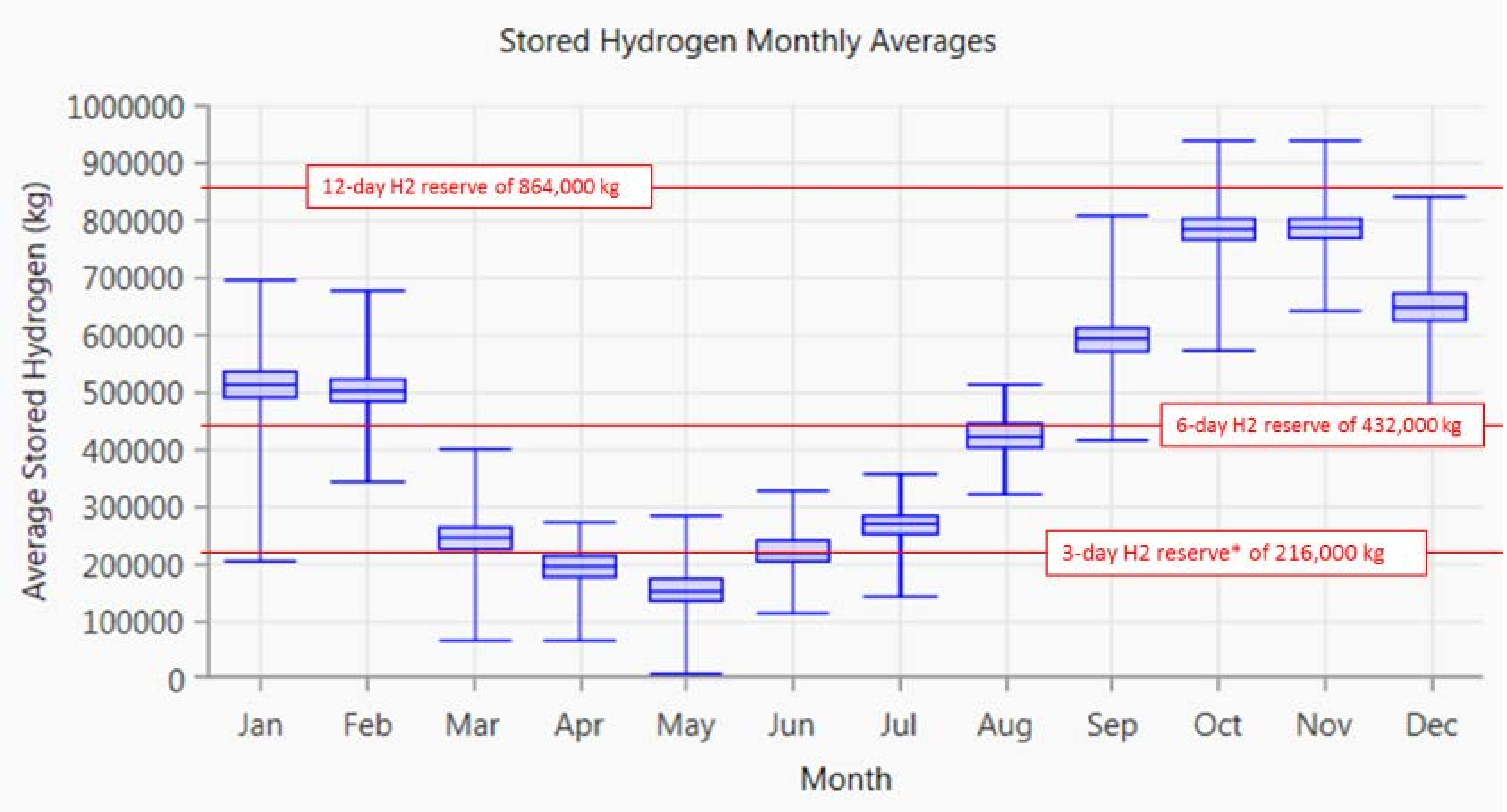


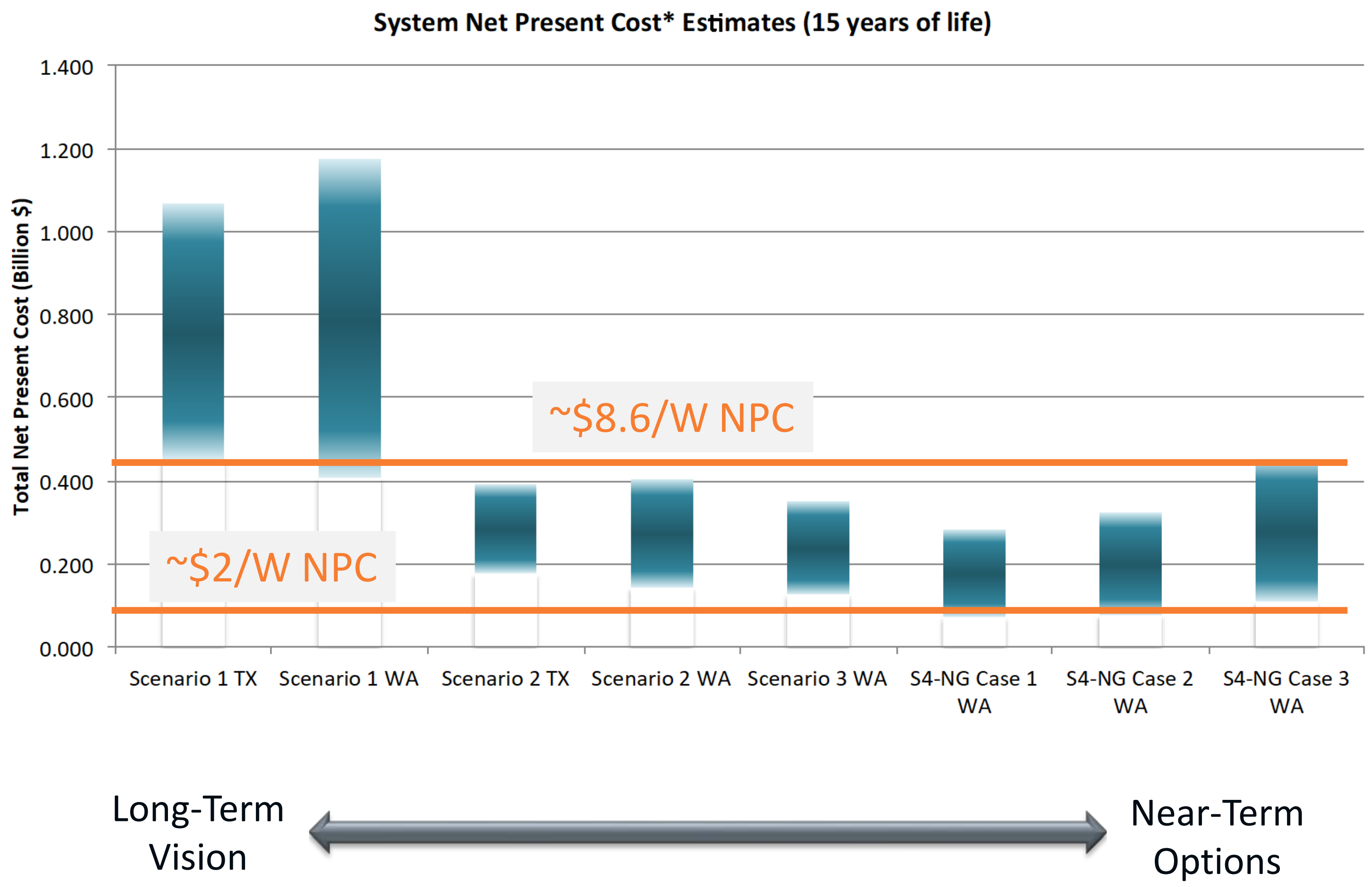
- Hydrogen production lower than consumption in February through April
- Lower generation times drives the renewable generation size

Renewable Hydrogen Storage Modeling (Quincy, WA site)



- Hydrogen storage for minimum 3 day reserve (216,000 kg)
- 50 MW, 24/7 demand = 72,000 kg H_2/day (~50% efficient fuel cell)
- Some months hydrogen production is less than demand (e.g., February to April in WA)
- System footprint and hydrogen storage is largest for 100% renewable scenarios (e.g., ~650 acres in WA)

System Economic Estimates (excludes data center costs)



- High estimates based on current costs and low estimates based on projected costs
- Lower capital cost does not necessarily result in lower total cost of ownership

Installed Component	Current Cost (2016)	Projected Cost (2030)
Wind ($/kW)	1,397	1,200
Solar ($/kW)	1,500	1,000
Fuel cell ($/kW)	300 (eff. 50%)	50 (eff. 50%)
Electrolyzer ($/kW)	1200 (eff. 65%, 25 yrs)	800 (eff. 75%, 25 yrs)
Storage ($/kg)	500 (10 yrs)	7 (20 yrs) Cavern

Benefits of Fuel Cell-Powered Data Center

- Savings from grid independent operation
  - On-site generation with behind the meter electricity price
  - Avoid demand charges
  - FC electric power directly used by computer for low Power Usage Effectiveness (PUE)
  - Stable load and controlled environment favor higher fuel cell efficiency and longer servicer life.
- Energy savings:
  - Overall efficiency with heat recovery to drive chiller for building heating and equipment cooling needs
  - Data center of low cost and small foot print by FC racks
  - No H_2 distribution cost needed as H_2 is consumed locally
- Increase fuel cell production and accelerate its deployment.

Summary

Challenges

- High capital cost of several components
- Large scale storage options for hydrogen in carbon-free, renewable scenarios
- Conceptual change for data center design

Opportunities

- Hydrogen distribution less costly than electrical distribution
- Data center size, cost, and thermal load could be reduced
- CHP opportunities
- Synergies with large renewable deployments
- In near term natural gas options could be economic
- Increased resiliency and reliability

With the sustained drop of the cost for renewable power, long-term renewable hydrogen to supply fuel cells for powering a data center can realize both decarbonization and economic returns.

Backup

Modeling Objectives and Considerations

Carbon free computing – Utilize hydrogen as energy storage to integrate renewable solar and wind resources for a data center

- Model Scope: The hydrogen generation , storage, and consumption equipment will be defined in a conceptual block diagram. These components and subsystems will be included in a **conceptual** model to:
  - create equipment sizing (quantity and footprint)
  - annual renewable generation profile (based on Quincy, WA and San Antonio, TX locations)
  - annual renewable hydrogen generation profile
  - annual hydrogen demand profile
  - equipment cost estimates (based on current technology status, which are undersized for this full scale rollout)
- Model Setup
  - Two locations: San Antonio, TX and Quincy ,WA
  - Two cost inputs: current and projected values.
  - Four scenarios were considered:
    1. Grid-independent, renewable generation to hydrogen production to fuel cell power for data center (long-term vision)
    2. Grid-independent, renewable generation to hydrogen production to fuel cell power and renewable generation for data center
    3. Grid-dependent, renewable and fuel cell supply (basis for near-term vision)
    4. Natural gas reforming to hydrogen storage to fuel cell power for data center
  - No thermal load was considered yet.
- Model Results
  - Verified required capacity, load, and hydrogen storage.
  - Generated electricity and hydrogen generation profile.
  - Sized equipment.
  - Estimated electric and capital cost.

Component Cost Estimates

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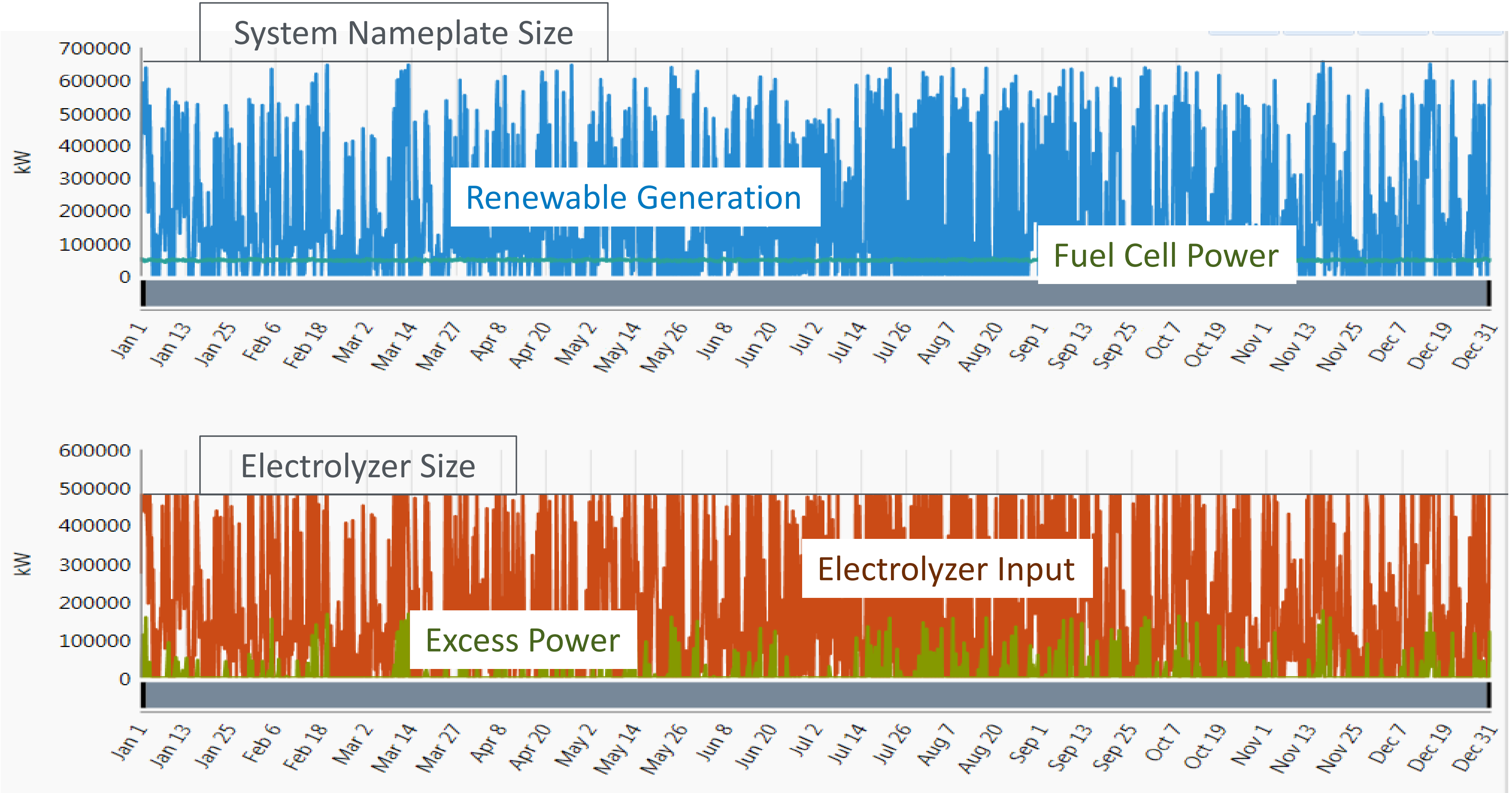
Installed Components	Current Cost (2016)	Projected Cost (2030?)	Reference Source
Wind ($/kW)	1,397	1,200	NREL report TP53045
Solar ($/kW)	1,500	1,000	GTM Research and DOE SunShot
Fuel cell ($/kW)	300 (eff. 50%)	50 (eff. 50%)	Industry and DOE Goal
Electrolyzer ($/kW)	1200 (eff. 65%, 25 yrs continuous)	800 (eff. 75%, 25 yrs)	NREL report TP53045 and internal discussion
Storage ($/kg)	500 (10 yrs)	7 (20 yrs) Cavern	Refer to DOE MYRDD and TP53045

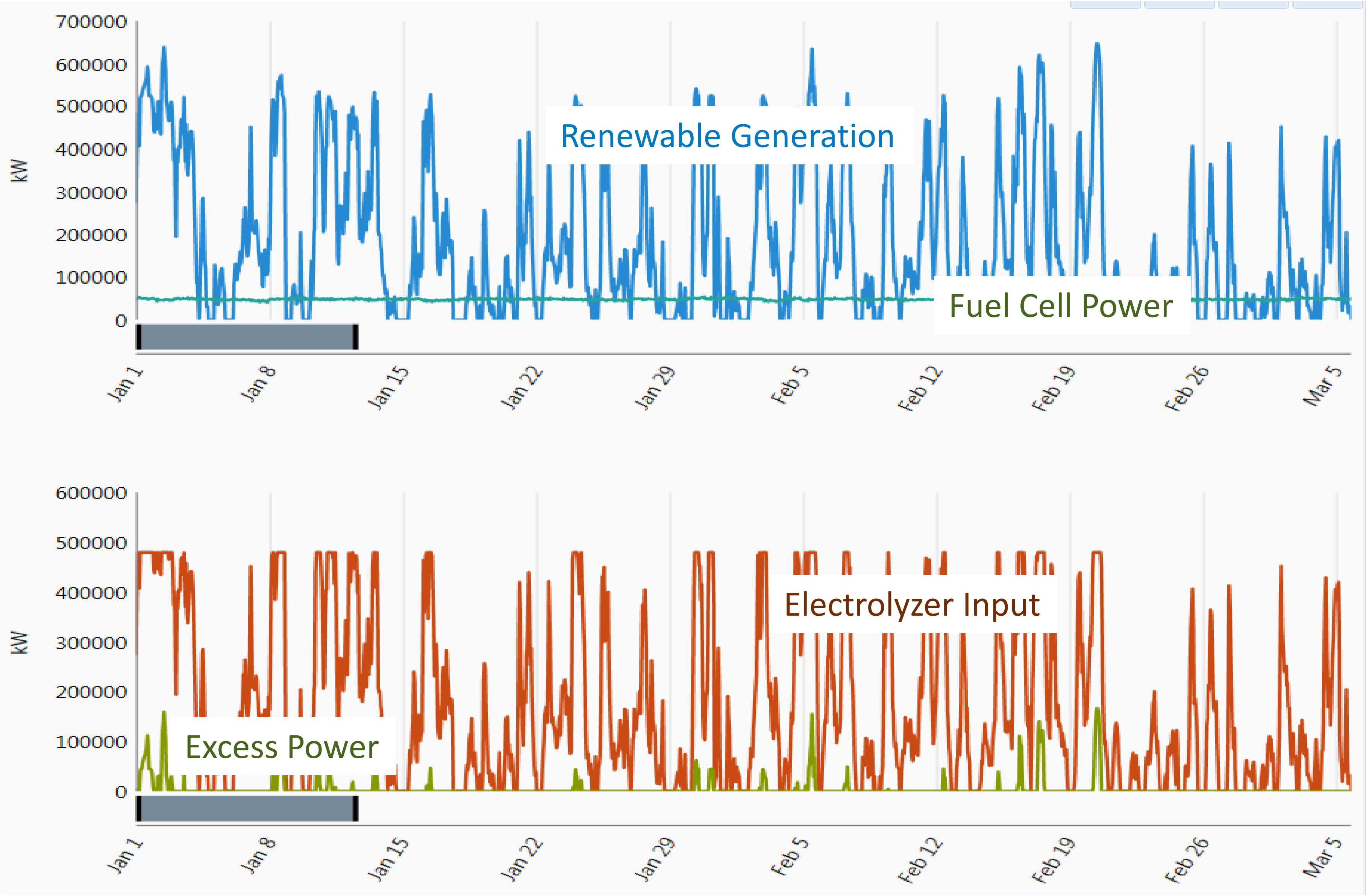
Note: No land cost were considered in COE numbers next.

Annual Renewable Generation, Fuel Cell, Electrolyzer and Excess Power Estimate Scenario 1 Quincy WA



- Generation does peak at nameplate capacity
- FC Power constant for Data Center demand
- Electrolyzer size limited to 480 MW, which results in small amounts of excess renewable generation (< #%)

Jan-Mar Renewable Generation, Fuel Cell, Electrolyzer and Excess Power Estimate Scenario 1 Quincy WA



- Zoomed in to show highly variable operation
- Electrolyzer operation follows renewable generation profile
- Gaps in electrolyzer power indicate low renewable resources and depleting hydrogen storage
- Storage sizing dependent on renewable generation profile

Scenario Results Summary – PV & Wind

	Scenarios	1. Wind/PV -> H2 -> IT		2. Wind/PV -> H2 -> IT & Wind/PV -> IT		3. Add grid to 2	4. Natural Gas (NG)->H2		
		TX Site	WA Site	TX Site2	WA Site3	WA Site5	WA Site6	WA Site7	WA Site8
PV	Size (MW)	140	120	60	70	20	0	0	20
	Annual Generation (kWh/yr)	242,453,051	210,345,034	103,908,450	131,465,646	35,037,505			
	Footprint m^2 (acres)	903,000 (223)	774,000 (191)	387,000 (96)	594,000 (147)	129,000 (32)	0	0	32
	Initial Capital $M (current)	210	180	90	105	30	0	0	30
	Initial Capital $M (projected)								
	COE ($/kWh)	0.063	0.06	0.063	0.06	0.06			
	Capacity Factor	20%	20%	20%	20%	20%			
wind	Size (MW)	405	525	135	165	150	0	0	30
	Annual Generation (kWh/yr)	1,418,475,413	1,412,478,713	597,630,030	692,633,836	403,565,346			
	Footprint m^2 (acres)	1,458,000 (360)	1,890,000 (467)	486,000 (120)	451,500 (112)	540,000 (133)	0	0	27
	Initial Capital $M (current)	566	733	189	231	210	0	0	42
	Initial Capital $M (projected)								
	COE ($/kWh)	0.02	0.04	0.02	0.02	0.04			
	Capacity Factor	40%	31%	50%	48%	31%			

Scenario Results Summary – FC & H_2

	Scenarios	1. Wind/PV -> H2 -> IT		2. Wind/PV -> H2 -> IT & Wind/PV -> IT		3. Add grid to 2	4. Natural Gas (NG)->H2		
		TX Site	WA Site	TX Site2	WA Site3	WA Site5	WA Site6	WA Site7	WA Site8
FC	Size (MW)	60	60	60	60	50	60	60	60
FC	Annual Generation (kWh/yr)	419,750,000	419,750,000	102,908,450	215,187,945	20,141,200			
FC	Footprint m^2 (acres)	In Data Center	In Data Center	In Data Center	In Data Center	In Data Center			
FC	Initial Capital $M (current)	5	5	5.000	5	4	5	5	5
FC	Initial Capital $M (projected)								
FC	Efficiency	50%	50%	50%	50%	50%			
FC	Capacity Factory			23%	21%	80%			
Electrolyzer	Size (MW)	250	480	60	100	10	10	0	50
Electrolyzer	Power Consumption (kWh/yr)								
Electrolyzer	Water Consumption								
Electrolyzer	Annual H2 production (kg/yr)	25,820,120	25,740,828	4,400,394	6,711,857	1,204,779			
Electrolyzer	Initial Capital $M (current)	75	144	18	30	3	3	0	60
Electrolyzer	Initial Capital $M (projected)								
Electrolyzer	Efficiency	65%	65%	65%	65%	65%			
Electrolyzer	Capacity Factory	51%	37%	51%	47%	37%			
Electrolyzer	Footprint m^2 (acres)								
H2	Storage Amount (kg)	3,000,000	2,000,000	1,200,000	600,000	60,000	70,000	70,000	150,000
H2	Initial Capital $M (current)	375	250	150.00	75	8	9	9	19
H2	Initial Capital $M (projected)								
H2	Storage Footprint m^2 (acres)	305,400 (75)	203,600 (50)	122,160 (30)	61,080 (15)	6,108 (2)			

Scenario Results Summary – System

	Scenarios	1. Wind/PV -> H2 -> IT		2. Wind/PV -> H2 -> IT & Wind/PV -> IT		3. Add grid to 2	4. Natural Gas (NG)->H2		
		TX Site	WA Site	TX Site2	WA Site3	WA Site5	WA Site6	WA Site7	WA Site8
System	Total Generation (MW)	545	645	195	235	170	60	68	98
	Initial Capital $M (current)	1,230	1,312	451	445	254	45	79	223
	Initial Capital $M (projected)	682	850	236	290	203	31	58	165
	Estimated Net Present Cost (Billion $) Current Costs	1.069	1.176	0.392	0.405	0.351	0.283	0.324	0.454
	Estimated Net Present Cost (Billion $) Projected Costs (~2030)	0.618	0.769	0.215	0.262	0.225	0.211	0.247	0.345
	High cost for bar plot	0.451	0.407	0.177	0.143	0.126	0.072	0.077	0.109
	Total Footprint (acres)	360	467	126	147	133			32.000

Scenario Results Summary – Costs

Scenarios	1. Wind/PV -> H2 -> IT		2. Wind/PV -> H2 -> IT & Wind/PV -> IT		3. Add grid to 2	
	TX Site	WA Site	TX Site2	WA Site3	TX Site4	WA Site5
Estimated Capital Cost (Billion $) Current Costs	1.365	1.365	0.688	0.511	Not Run	0.611
Estimated Capital Cost (Billion $) Projected Costs (~2030)	0.775	0.964	0.270	0.330		0.547
Total Footprint (acres)	360	467	126	147	Not Run	133
Conclusions	Need to add	Need to add	Need to add	Need to add	Need to add	Need to add