NREL
Transforming ENERGY

Energy Storage Analysis

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DOE Hydrogen and Fuel Cells Program
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Project ID # SA173

Overview

Timeline	Barriers
Start: October, 2018 End: September, 2019* * Annual direction determined by DOE	4.5B Stove-piped/Siloed Analytical Capability 4.5C Inconsistent Data, Assumptions and Guidelines 4.5E Unplanned Studies and Analysis
Budget	**Partners**
FY19 Planned DOE Funding: $155K Funds Received to Date: $155K	**Collaborators** • DOE, Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Office • DOE, EERE, Vehicle Technologies Office • Xcel Energy • Southern Company Services • Argonne National Laboratory • National Renewable Energy Laboratory

Energy storage analysis assesses market relevance and competitiveness for hydrogen.

Relevance/Impact 1

Analysis assesses hydrogen system competitive space and valuation in the landscape of energy storage technologies.

- H2@Scale
- Additional external reviewers

- Fuel Cell Technologies Office
- H2@Scale

Analysis Framework

- H2FAST
- Cost estimation
- Competitive market analysis
- Financial analysis
- Data: HDSAM, MYRD&D, H2A, VTO targets, AMO targets

Models & Tools

- H2FAST
- RODeO

NREL: H2FAST

Studies & Analysis

- Competitive tech. assessment
- Grid support & co-products

Outputs & Deliverables

- Annual report
- Inputs to working groups
- Input to HTAC

Acronyms

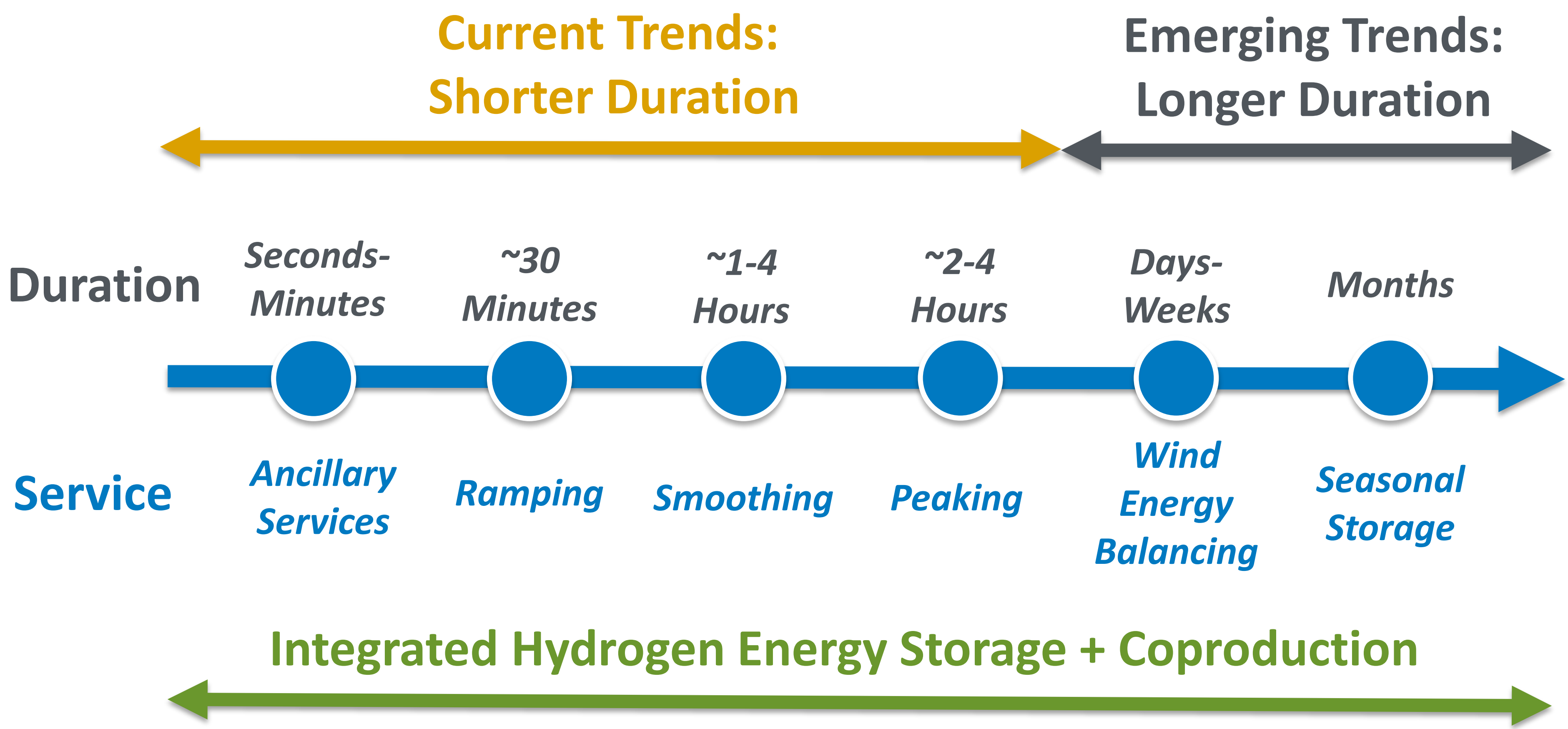
H2FAST: Hydrogen Financial Analysis Scenario Tool

HDSAM: H2A Delivery Scenario Analysis Model

H2@Scale: Hydrogen at Scale

Market Segmentation of Energy Storage

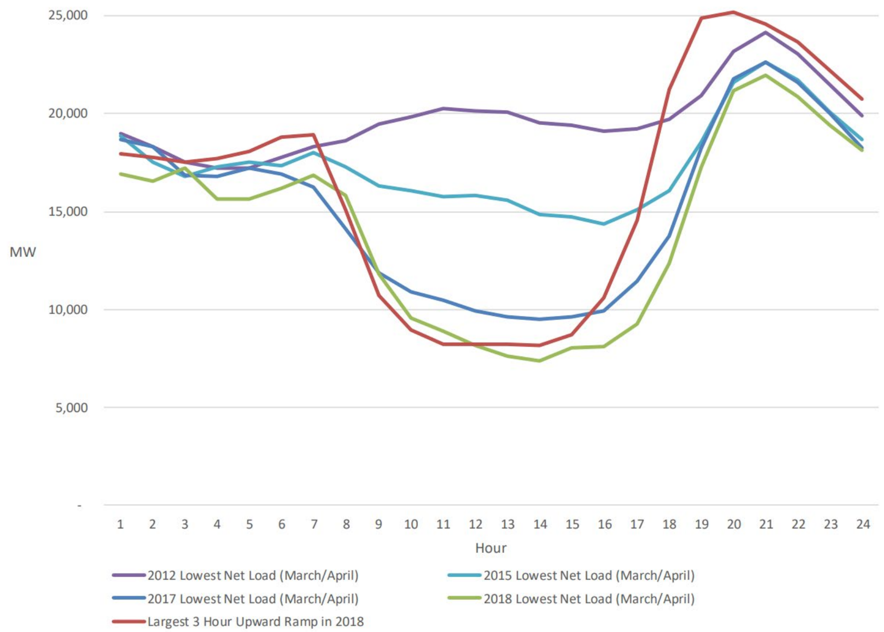
Relevance/Impact 2



Current and emerging energy market trends can be met using integrated hydrogen energy storage while also co-producing hydrogen for high value uses

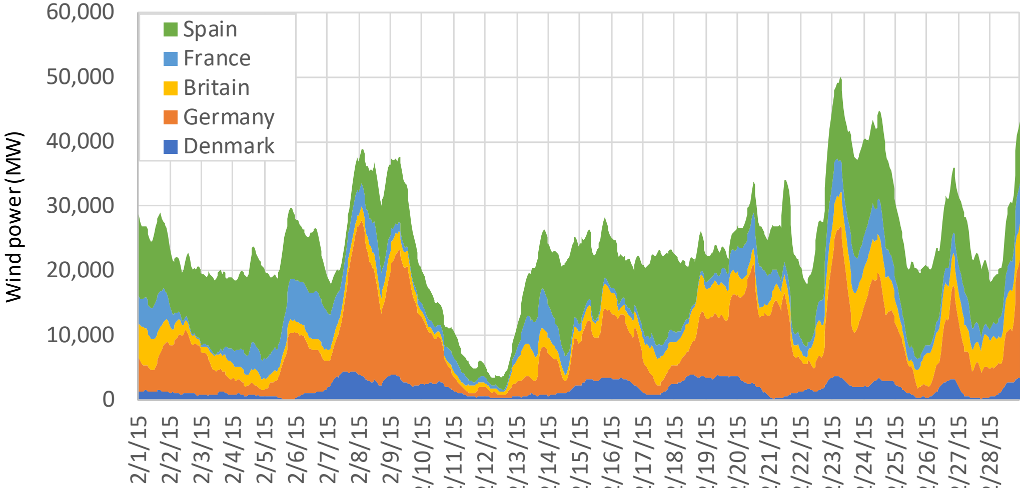
Energy Storage Needs Examples

Relevance/Impact 3



Diurnal "Duck Curve":

- hours of storage is needed
- this happens daily



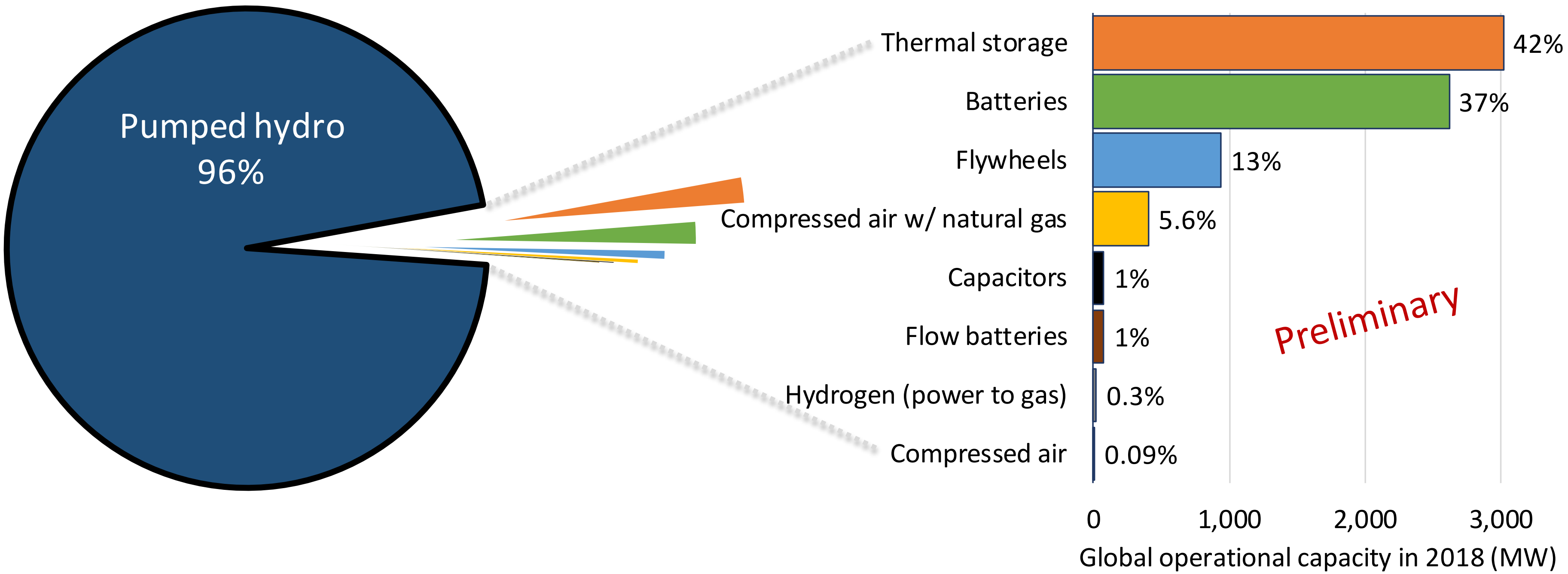
Wind gaps:

- days of storage is needed
- this happens few times a year
- long distance transmission does not address such gaps

Source: https://www.energy.ca.gov/renewables/tracking_progress/documents/resource_flexibility.pdf
http://www.pfbach.dk/

Global Energy Storage Market Inventory, 2018

Relevance/Impact 4



Global Energy Storage Inventory:

- 96% is pumped hydro serving diurnal operation
- Batteries typically provide few hours of storage
- Thermal storage is predominantly molten salt for concentrated solar
- Fly wheels provide very short duration storage (frequency regulation)

Source: DOE Global Energy Storage Database

Landscape of Energy Storage Technologies

Relevance/Impact 5

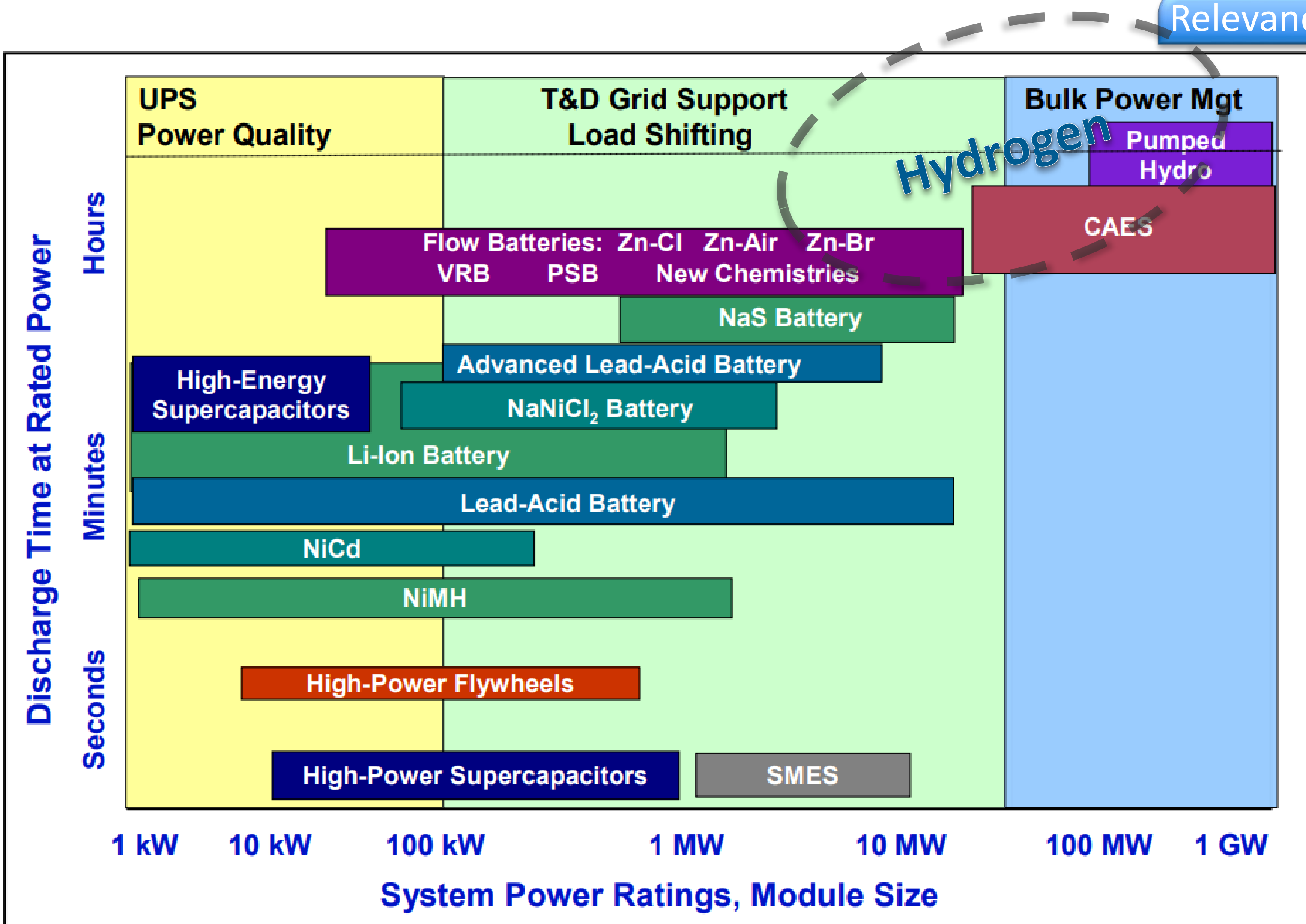
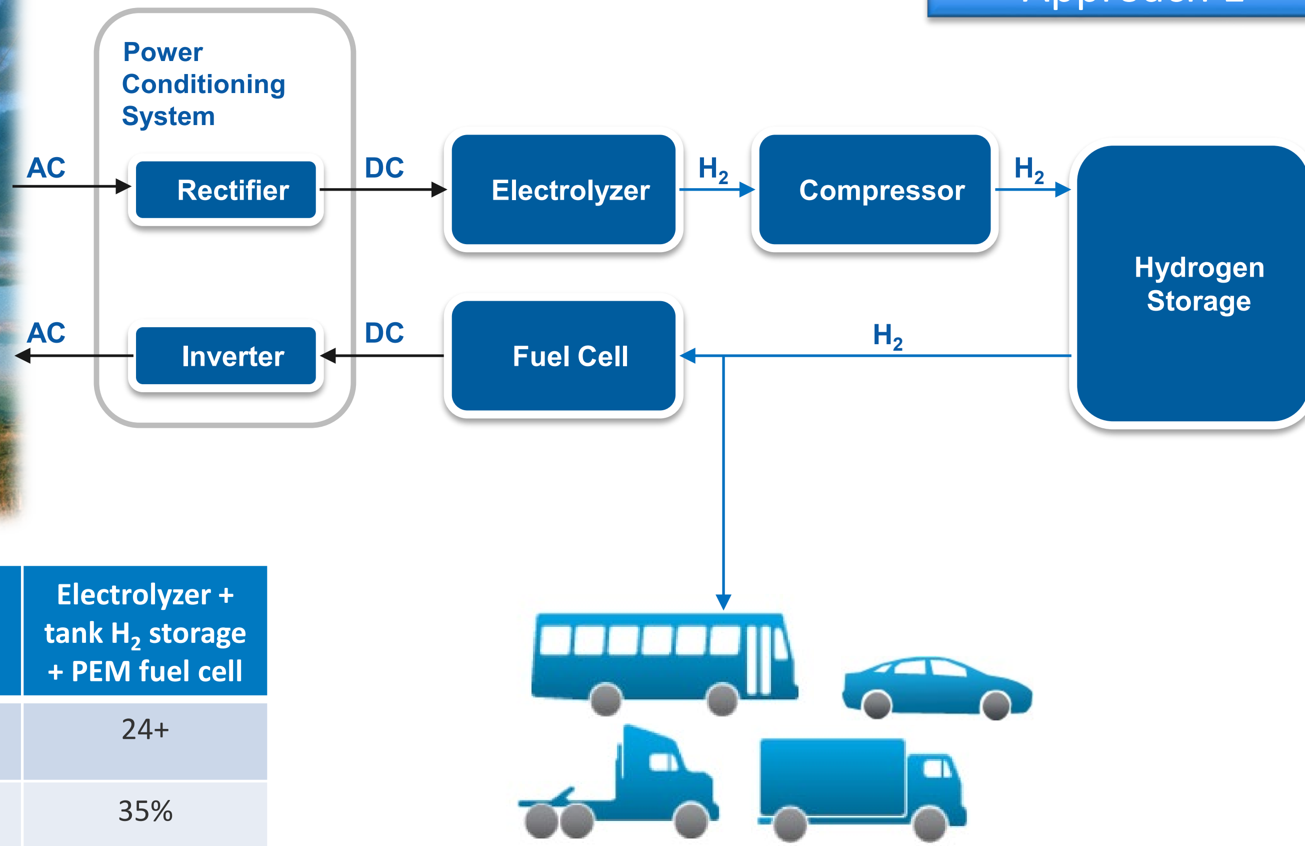


Figure 19. Positioning of Energy Storage Technologies

Source: DOE/EPRI Electricity Storage Handbook, 2015

Modeling Approach: Subsystem Boundaries

Approach 1



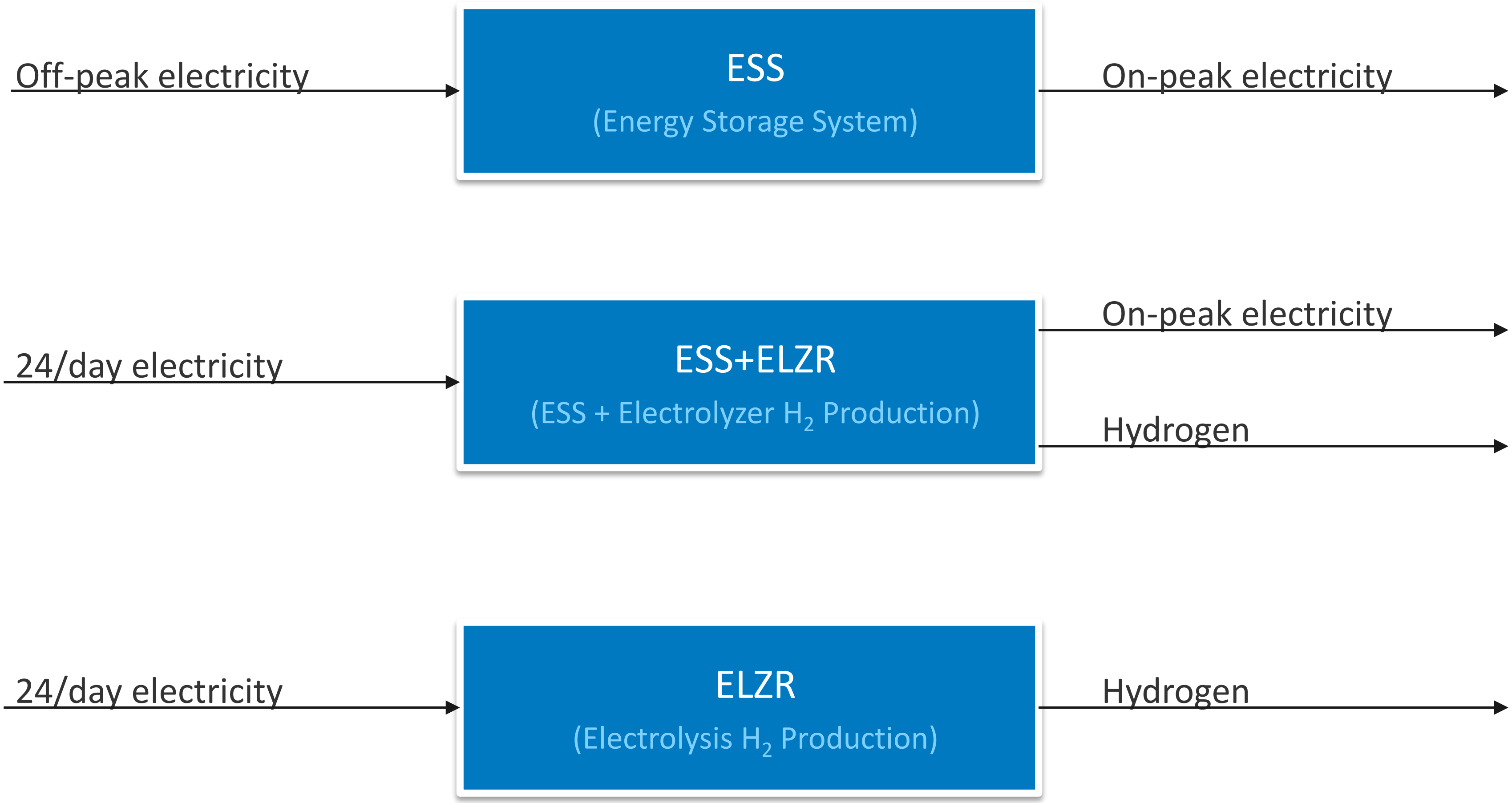
	Electrolyzer + tank H_2 storage + PEM fuel cell
Storage duration (h)	24+
Round trip efficiency	35%
Power capital ($/kW)	1,500
Storage capital ($/kWh-DC)	35
Stack life years (years)	8 – 10
Usable depth of discharge	~83%

Hydrogen systems also decouple power components (stacks, power conditioning) and energy components (hydrogen tanks), allowing more flexible design for storage duration.

Hydrogen systems also can co-produce hydrogen.

Other System Configurations

Approach 3

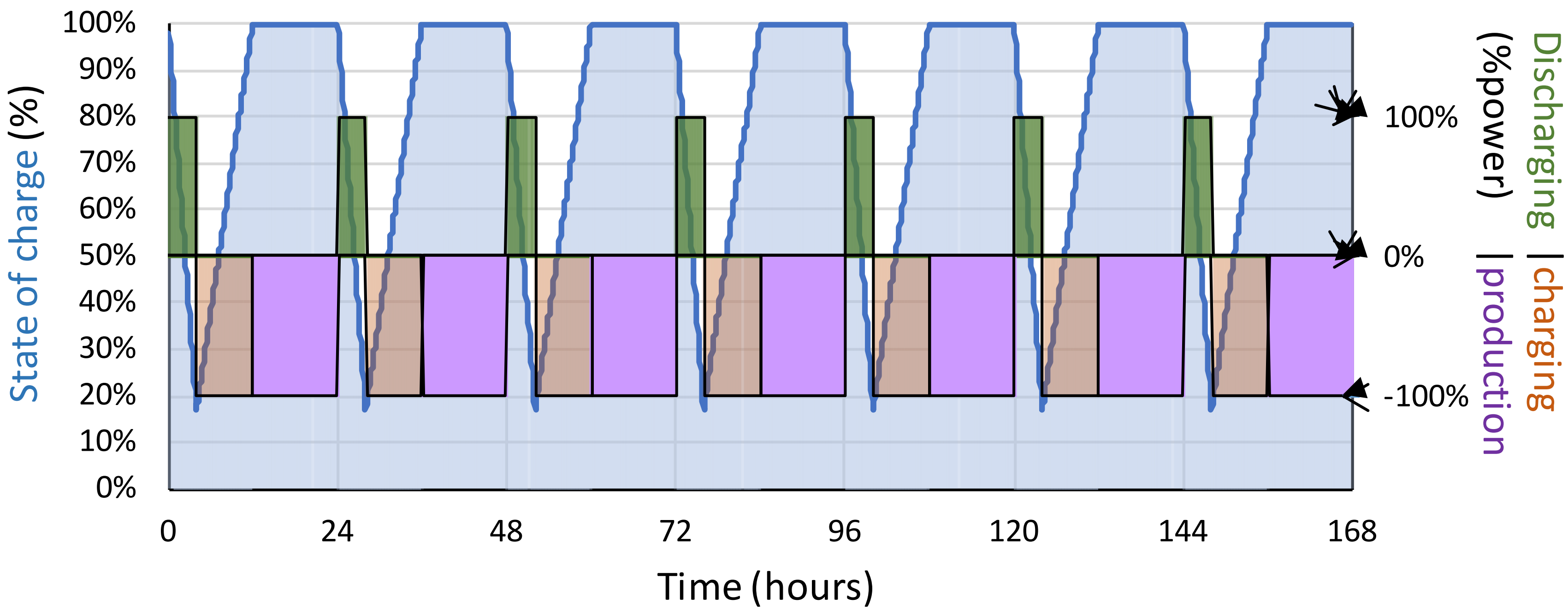


Three systems are evaluated in the same framework to assess integration of ESS and ELZR.

H2 storage technology can have other economic activity once storage is full.

Hydrogen Co-Production

Approach 4



Simple diurnal cycle:

- ✓ 4 hours power generation
- ✓ 8 hours storage recharge
- ✓ 12 hours hydrogen co-production

H_2 co-production would improve economics if H_2 price exceeds variable operating costs.

System Sizing Assumptions

Accomplishments 1

		ESS only	ESS+ELZR	ELZR only
Peak power production (h/day)	h/day	4	4	
Recharge time (h/day)	h/day	8	8	
H2 production (h/day)	h/day		12	24
Power generation (MW)	MW	10	10	
Power for recharging (MW)	MW	11.6	11.6	11.6
Power consumption (MWh/y)	MWh/y	33,977	84,943	101,932
Power production (MWh/y)	MWh/y	14,600	14,600	
H2 production (kg/day)	kg/day		2,530	5,061

ESS: Energy Storage System
ESS + ELZR: Energy Storage System + Electrolyzer Hydrogen Production
ELZR: Electrolyzer Hydrogen Production

Above system sizing allows meaningful unit capacity for grid support and hydrogen production volume. Approximately 2x installed capacity can provide sufficient hydrogen volume for large heavy duty stations.

Component Cost & Performance Assumptions

Accomplishments 2

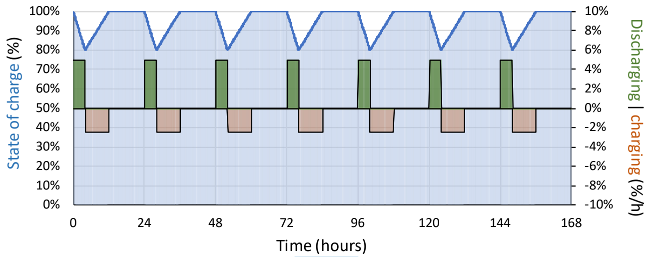
Subsystem	Technology Staus & Targets, all costs in 2016$	Current status
Rectifiers	Rectifier efficiency	98.4%
	Rectifier cost ($/kW AC)	$ 196
	Total installation cost factor (% of equipment capital)	57%
	System O&M (% of capital cost)	1.0%
Electrolyzers	Electrolyzer power use (kWh DC/kg)	54.3
	Electrolyzer cost ($/kW DC)	$ 737
	System life (years)	20
	Total installation cost factor (% of equipment capital)	57%
	System O&M (% of capital cost)	7.8%
Compressors	Power use (kWh AC/kg)	1.42
	Compressor cost factor A (equation form c=A*p^B; where p is power)	2290
	Compressor cost exponent B (equation form c=A*p^B; where p is power)	0.8225
	Cost factor for inclusion of oxygen compression	50%
	Total installation cost factor (% of equipment capital)	187%
	System O&M (% of capital cost)	4.0%
Storage	Terrestrial storage installed cost ($/kg)	1,168
	Terrestrial storage installed cost ($/kWh LHV)	35
	Terrestrial storage O&M (% of capital cost)	1.0%
	Cushion gas (%)	17.1%
Fuel cells	Fuel cell power production (kWh DC/kg)	20.0
	Fuel cell cost ($/kW DC)	507
	Total installation cost factor (% of equipment capital)	20%
	System O&M (% of capital cost)	6.0%
Inverters	Inverter efficiency (%)	98.6%
	Inverter cost ($/kW)	$ 384
	Total installation cost factor (% of equipment capital)	20%
	System O&M (% of capital cost)	1.0%
Feedstock	Electricity cost ($/kWh)	0.033

Cost and performance inputs have been peer reviewed by all stakeholders.

Feedstock electricity cost of 3.3¢/kWh is used.

H2FAST Model Used For Levelized Cost Analysis

Accomplishments 4

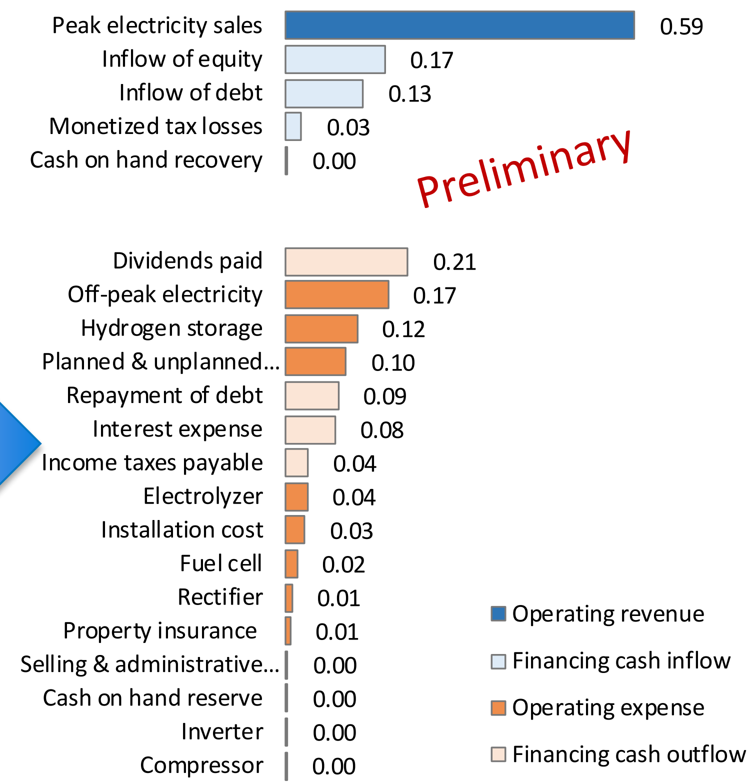


- Equipment sizing
- Cost estimation
- Efficiency estimation

- Energy Use
- Energy Costs
- Financial Assumptions

H2FAST

Real levelized value breakdown of peak electricity ($/kWh)



Techno-economic assessment is made based on minimal equipment sizing to achieve benchmark cycle. H2FAST model was used to evaluate financial performance of scenarios.

https://www.nrel.gov/hydrogen/h2fast.html

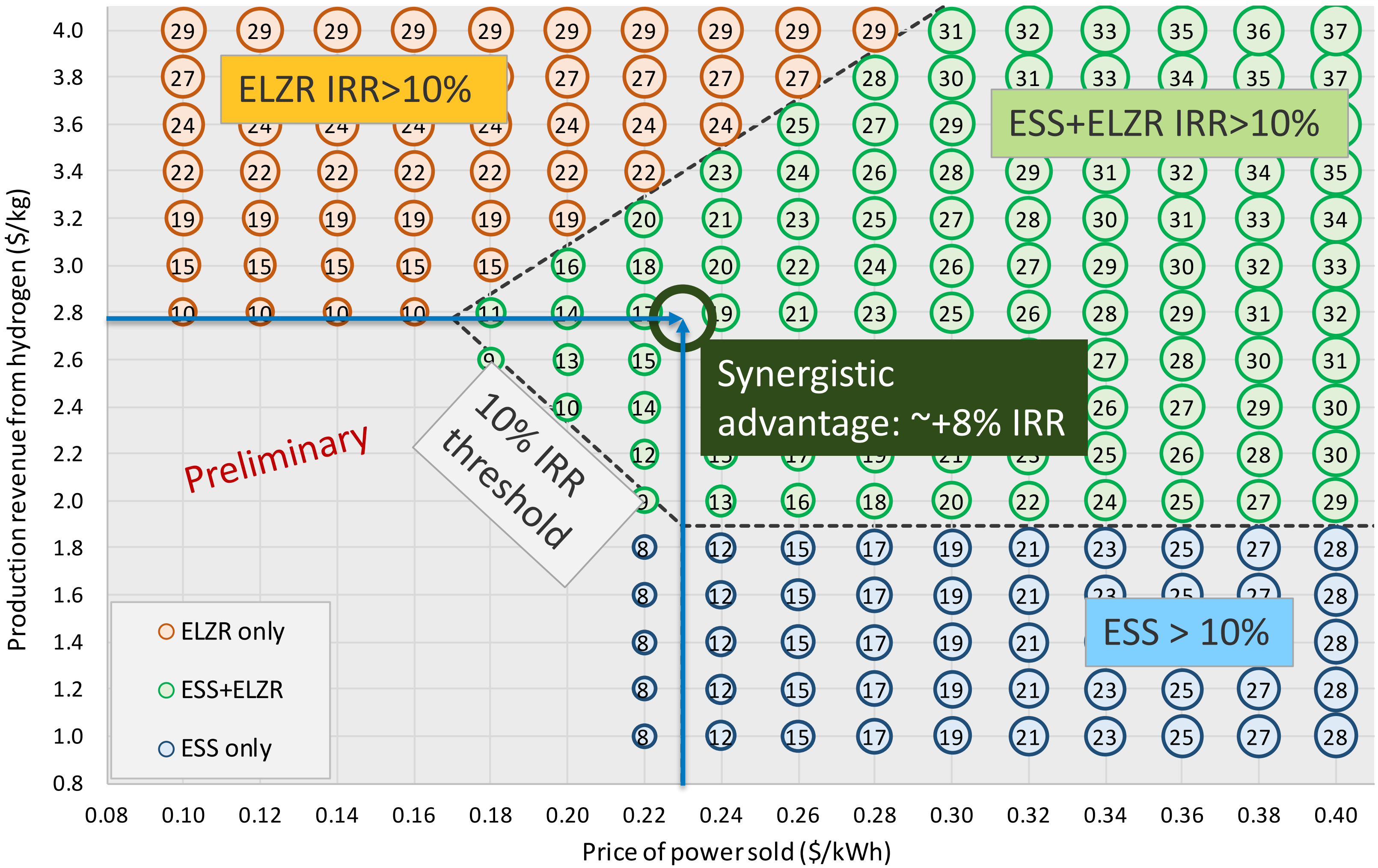
Financial Assumptions

Accomplishments 3

Financing Information	
Total tax rate (state, federal, local)	27.00%
Capital gains tax	15.00%
Are tax losses monetized (tax equity application)	Yes
Allowable tax loss carry-forward	7 year
General inflation rate	1.90%
Depreciation method	MACRS
Depreciation period	5 year
Leveraged after-tax nominal discount rate	10.0%
Debt/equity financing	1.50
Debt type	Revolving debt
Debt interest rate (compounded monthly)	4.00%
Cash on hand (% of monthly expenses)	100%

IRR% Sensitivity Vs. Co-Product Value

Accomplishments 5



- Bubble size is proportional to project internal rate of return IRR (%)
- Depending on value of electricity and hydrogen, ESS, ELZR or ESS+ELZR system yields highest IRR
- ESS +ELZR can lower the price of hydrogen from ~$3 to ~$2
- H_2 co-production reduces the cost of produced peak power.

Key Stakeholders

Collaboration

Reviewers

- DOE Fuel Cell Technologies Office
- DOE Vehicle Technologies Office
- Xcel Energy
- Southern Company Services, Inc.
- Argonne National Laboratory
- H2@Scale stakeholders

Remaining Challenges and Barriers

Challenges

Valuation of long duration storage is uncertain

- Most storage projects serve diurnal needs (<24h)
- Function of long-duration storage is currently served by fossil peaking plants

Limited operational data from existing energy storage projects for benchmarking

Inconsistent valuation of ancillary services by region in the US

Evaluate Means of Improving Round Trip Efficiency

Future Work 1

Increased efficiency can be traded for capital expenses

1. Increase electrolysis & fuel **cell active area**
2. Consider **solid oxide electrolysis** (SOEC)
3. Consider SOEC with **thermal storage** (store waste heat from power generation and use for thermal needs in electrolysis)
4. Consider **high pressure electrolysis** (reduce compression needs)
5. Consider compression energy recovery with **turbo expander**

Round trip efficiency is more important than capital cost.
Improving efficiency can be traded for increased capital cost.

Expand Peripheral Analysis

Future Work 2

Incorporation of portfolio of hydrogen technologies

- Reversible solid oxide fuel cell systems with thermal storage
- Use of spinning equipment for power generation
- Use of geologic and isostatic hydrogen storage (deep water) for larger scales

Extend analysis into larger systems in service of H2@Scale applications

Perform select system analysis using RODeO

- Detailed grid model
- Perform near-term simulation of ESS economic performance
- Feed into on-going work for valuation of long duration storage

Summary

- **NREL is performing integrated energy storage and hydrogen co-production analysis**
  - energy storage system operation can be enhanced with H2 co-production

- **Simple analysis framework was used to facilitate conception of integrated systems, and evaluate impact of technology tech. targets.**

- **Diverse stakeholder input is received**
  - DOE Vehicle Technology Office
  - DOE Fuel Cell Technology Office
  - Argonne National Laboratory
  - Xcel Energy
  - Southern Company Services, Inc.

- **Further exploration of technology options and grid services may expand the economic viability window of hydrogen technologies**

BACKUP SLIDES

List of Acronyms

AC	Alternating Current (electricity)
AMO	Advanced Manufacturing Office
DC	Direct Current (electricity)
DOE	United States Department of Energy
EERE	Energy Efficiency and Renewable Energy
ESS	Energy storage system
FCTO	Fuel Cell Technologies Office
H2	Hydrogen
H2@SCALE	Hydrogen at scale
H2A	Hydrogen Analysis model
H2FAST	Hydrogen Financial Analysis Scenario Tool
HDSAM	Hydrogen Delivery Scenario Analysis Model
HTAC	Hydrogen Technology Advisory Committee
kW	kilowatt (unit of power)
kWh	kilowatt hour (unit of energy)
LCOE	Levelized Cost of Energy
MACRS	Modified Accelerated Cost Recovery System (depreciation schedule)
MW	megawatt (unit of power)
O2	Oxygen
RODeO	Revenue Operation and Device Optimization Model
SOEC	Solid Oxide Electrolysis
VTO	Vehicle Technologies Office