LDES - LONG DURATION ENERGY STORAGE:
THIS GENERATION'S GRAND CHALLENGE

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LDES: LONG DURATION ENERGY STORAGE

HOURS OF ENERGY DISCHARGE – "DURATION" – HAS EMERGED AS A KEY GRID METRIC

why
how to
emerging tech roadmap

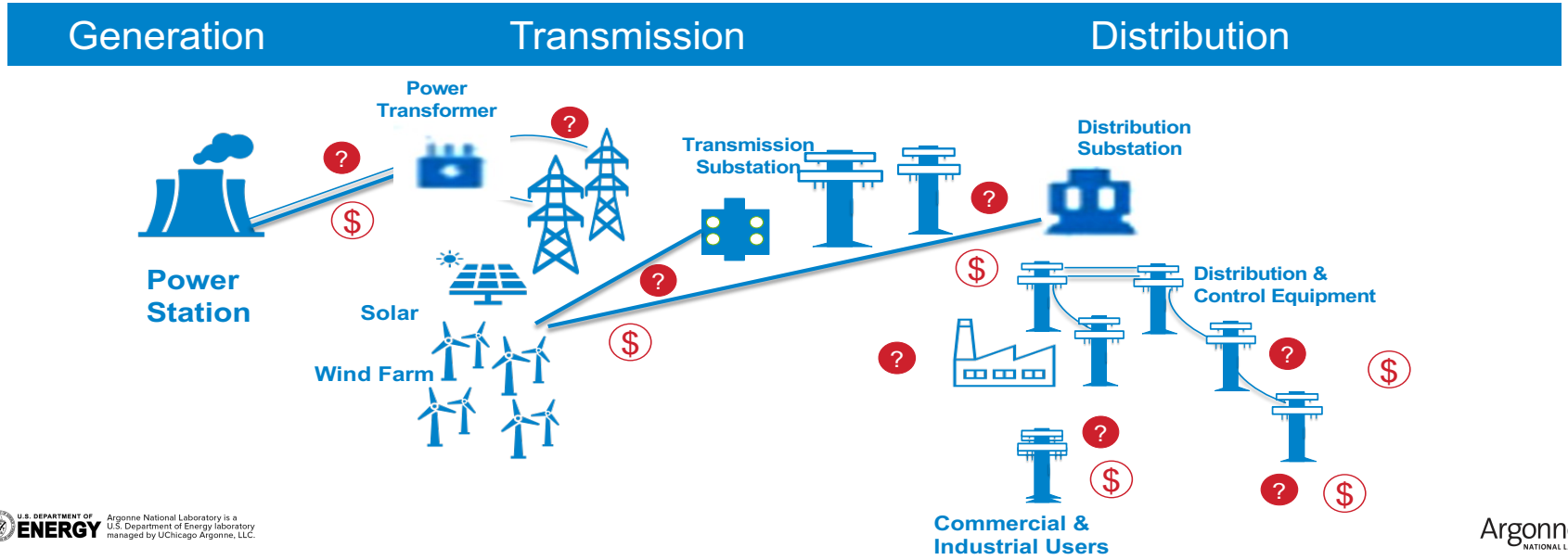
LDES: WHY

WHY/WHAT - IT'S COMPLICATED:

Local Considerations + Economic Criteria → Complex Situations & Decisions

FUTURE GRID COMPLEXITY = STATIONARY ES COMPLEXITY

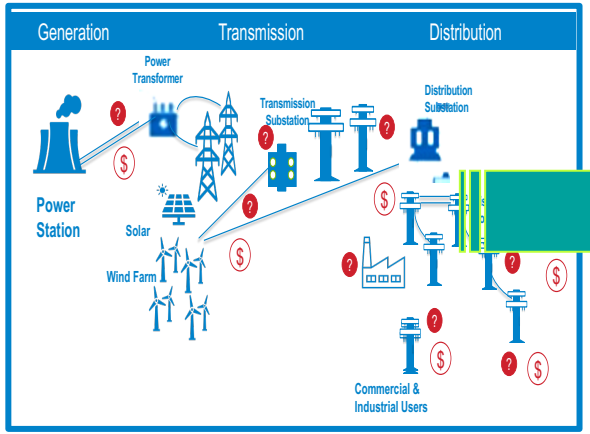
RENEWABLE GENERATION → DISTRIBUTED GENERATION

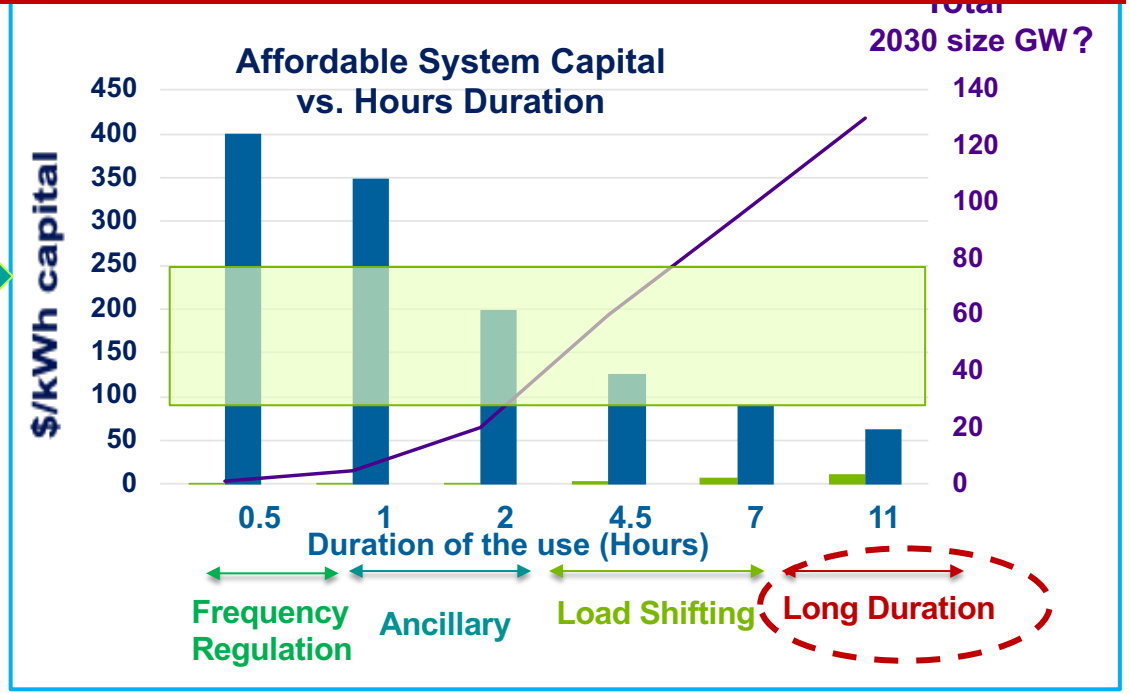


GENERALIZATONS: HOURS DISCHARGE

More renewables = more variability → Increased stabilizing duration → → less affordable cost

DOE defines LDES as > 10-hour Discharge

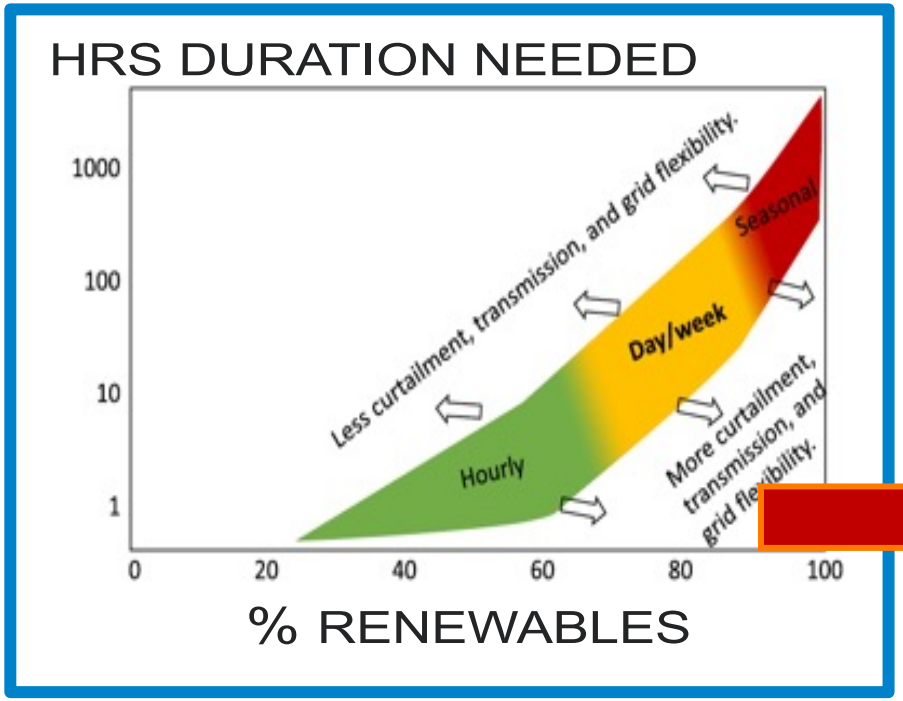




Li-Ion price range

LDES NEED - THIS IS ALL RELATIVELY NEW

Seminal LDES work: Albertus et. al. 2020



Albertus et al., Joule (2020)

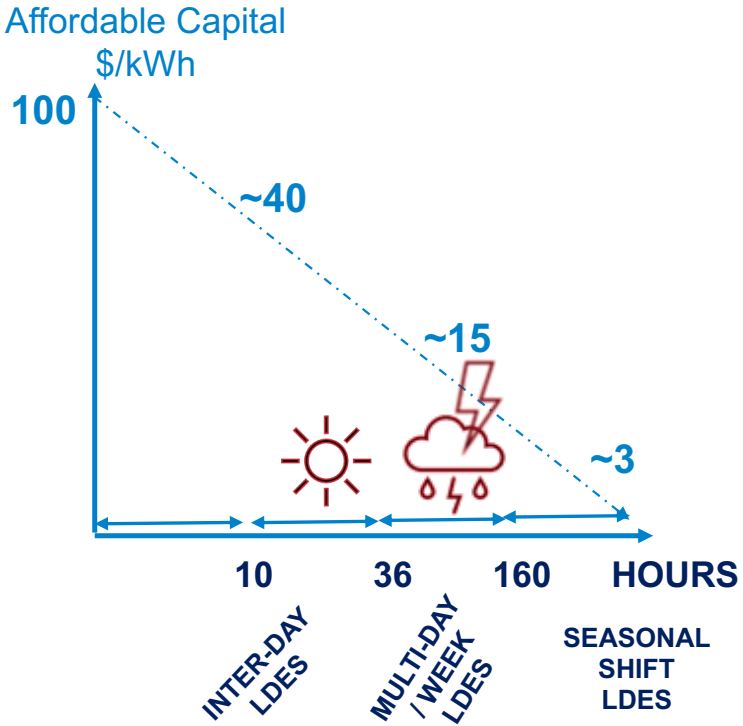
It quickly becomes very complicated

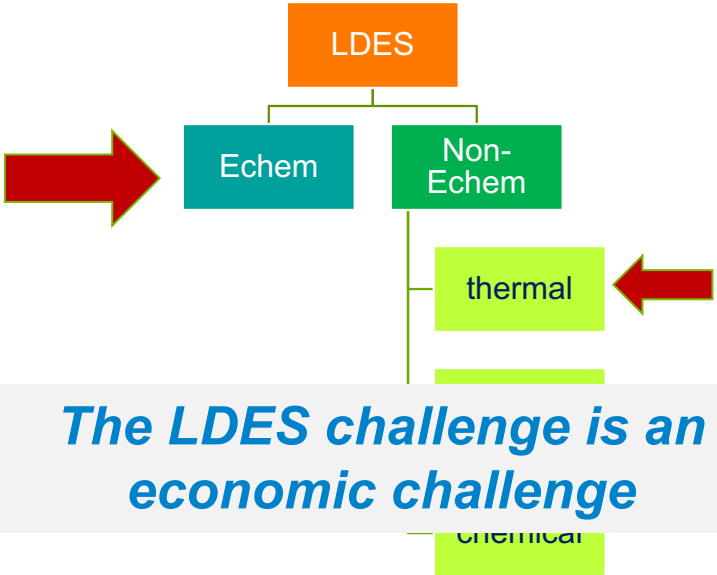
- renewable content ↑
- hours use/cycle ↑
- affordable cost ↓

Albertus et al., Joule (2020)

NOT ONE MARKET SEGMENT
NOT ONE TECHNOLOGY OPTION

No technology today can meet the targets today

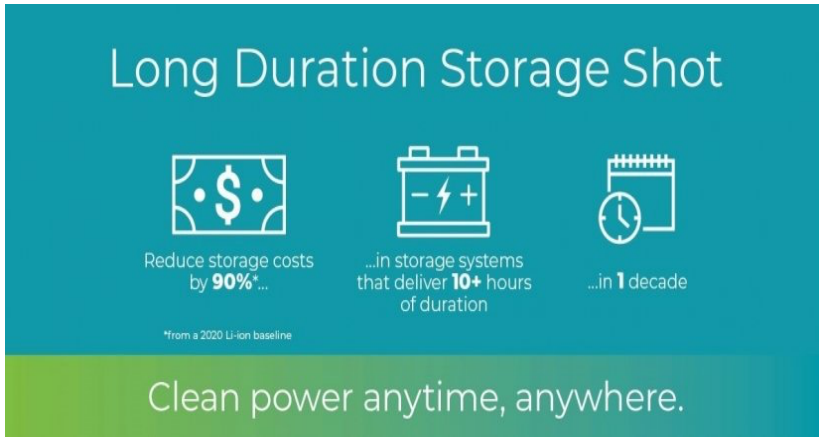




The LDES challenge is an economic challenge

DOE KNOWS THIS IS HARD: LDES EARTHSHOT

ENERGY earthshots | Storage™
U.S. DEPARTMENT OF ENERGY



Earth Shot Metrics	
LCOS	0.05 cents*/kWh-Cycle
Duration	10 hours
Cost	90% reduction vs. 2020 Li-Ion
Timeframe	10 years to success

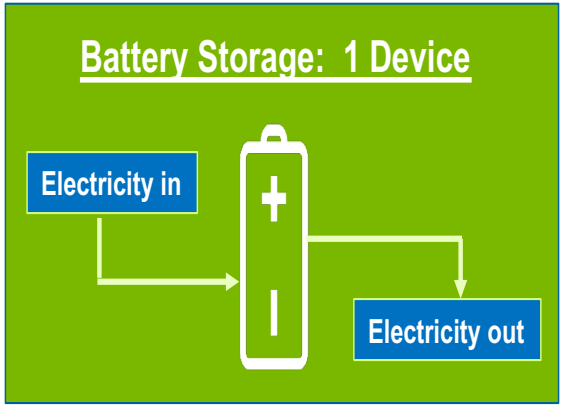
* Fully loaded system cost using power electronics & available/cycled energy

LDES: DESIGNING SOLUTIONS

ENERGY STORAGE OPTIONS: SHORT & LONG DURATION

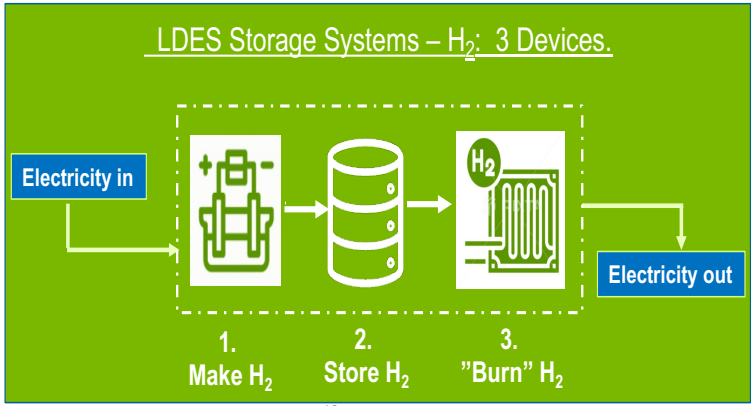
e^- in ⟺ e^- out: Two basic approaches

”Battery”



Shorter durations: 1 -100 hours

“Energy Storage System””



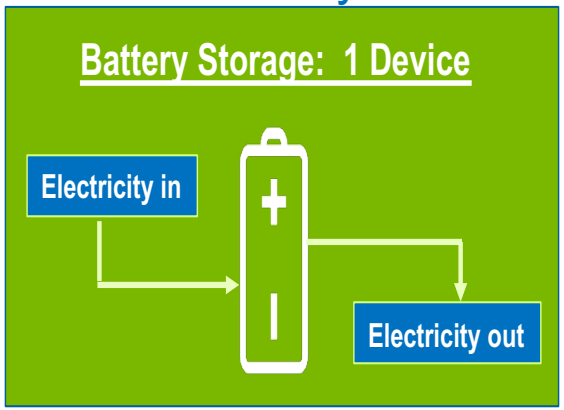
Long duration: 100 hours - ”seasonal”

INCREASING MATURITY with SHORTER DURATIONS

ENERGY STORAGE OPTIONS: SHORT & LONG DURATION

e^- in ⟺ e^- out: Two basic approaches

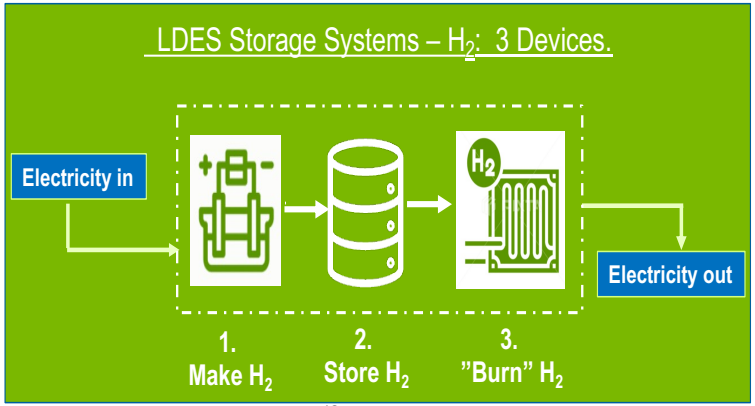
”Battery”



Shorter durations: 1 -100 hours

Nonflammable Li-ion
Flow cells
Fe/air battery
MgMnOx (thermal)
Liquid metal battery

“Energy Storage System””



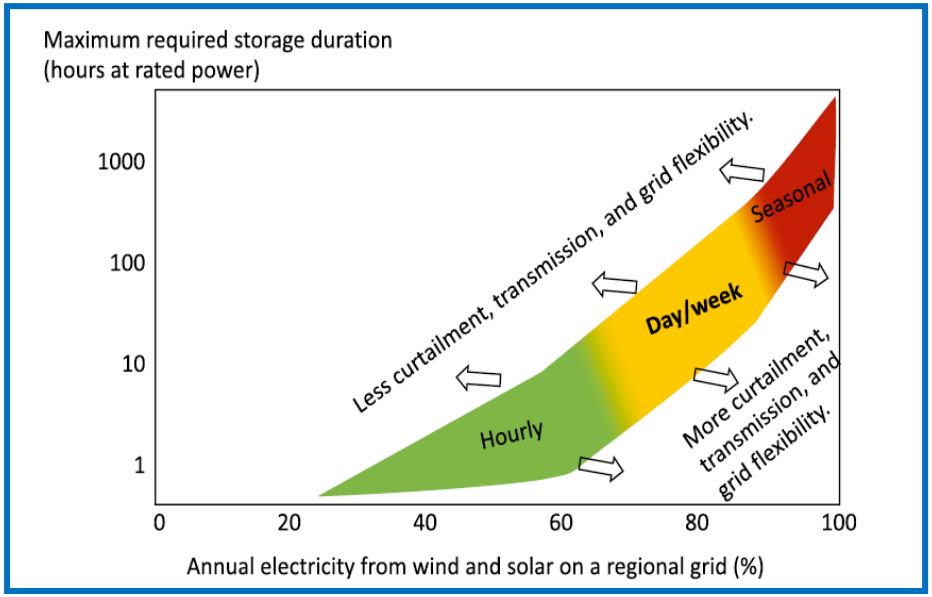
Long duration: 100 hours - ”seasonal”

H_2 system
MeOH system
NH_3 system

maturity

INCREASING MATURITY with SHORTER DURATIONS

LDES: ULTIMATELY AN ECONOMIC CHALLENGE



Hours	Affordable Capital ($/kWh)*	Examples
<6	<100	Li-ion
10-18	~40	Flow Cells, Earth abundant
50	7-20	Form Energy, Earth abundant
>100	3	Chemical: H2, NH3, etc.

Source: [51] P. Albertus, J. Manser, and S. Litzelman, "Long-Duration Electricity Storage Applications, Economics and Technologies," *Joule,* vol. 4,

* Paul Albertus – Joule 2020
Earth Abundant: Pb, Fe, S, Mn, S, Air, Na^+, H^+, K^+

THE LDES ECONOMIC CHALLENGE

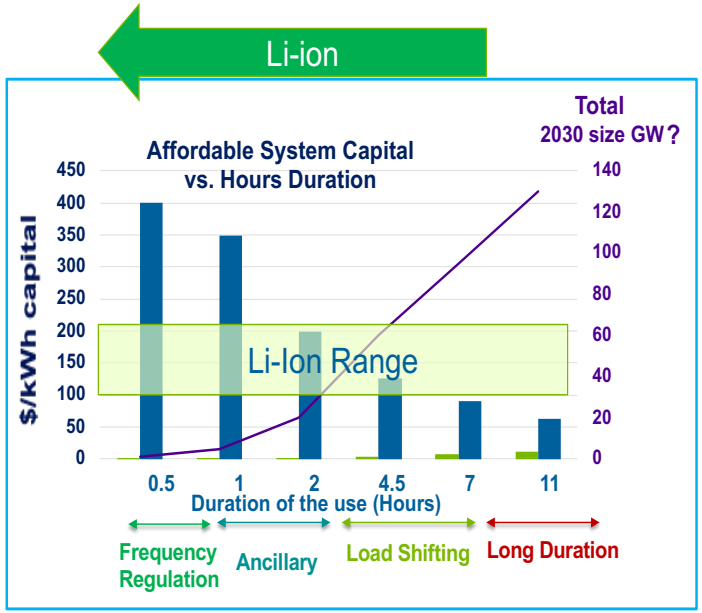
BRUTAL COST TARGETS: <<$100/kWh system capex, => “NEW” CHEMISTRIES

Targets: low cost, abundant raw materials = limited materials menu, typically aqueous

Brutal cost/performance requirements => full utilization of materials AND high cycle life

LDES: EMERGING TECH ROADMAP

LI-ION: CRITICAL TO MEET THE DEMAND IN NEXT 5+ YEARS

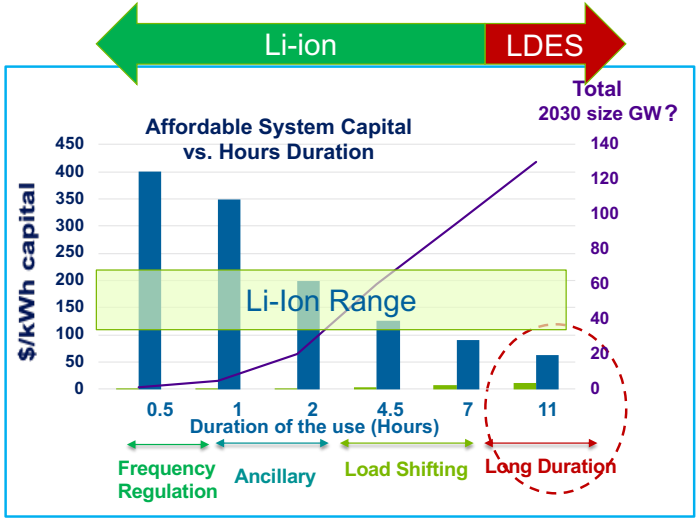


Li-Ion Improvements for 6-8 hour durations

- **TODAY:** Iron Phosphate cathodes (LFP)
- **SHORT TERM:**
  - No Co/High Ni NMC cathodes
  - Low Ni/No Co NMC cathodes
  - High cycle life – using AI/ML
- **MEDIUM TERM:**
  - Reduced flammability/better safety
  - Fe-oxide cathodes
- **LONG TERM:**
  - Na instead of Li
  - Fundamentally nonflammable

FLOW CELLS: >8 HOURS & ALREADY LARGE DEMOS TODAY

Today: majority of flow cell improvements are in type of chemistry/storage molecules
Future: improvements are in new cells designs for higher energy density



Flow Cells for > 8-hour durations

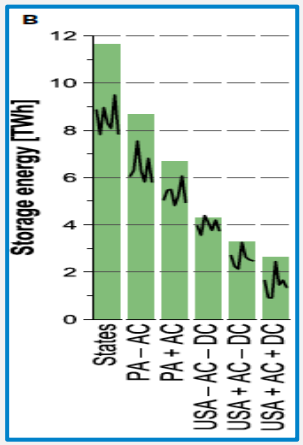
- **TODAY:**
  - ESS aq. Iron/Iron
  - EOS – Zn/Br_2
  - CMBlue – Organics/ High ED hybrid
  - Lockheed – metal chelates
- **SHORT TERM:**
  - Quino Energy - new organic actives
- **FUTURE:**
  - Higher energy density actives
  - Higher energy density cell designs

MORE OPTIONS EMERGING: >8 HOURS

- **FORM ENERGY:** Metal Air battery – “reversible rust”
  - > $600 million invested
- **LYTEN:** Li-S – actually making this work
  - > $100 million invested
- **AMBRI:** Liquid metal battery that uses material density differences instead of massive manufacturing
  - In generation 3 design
  - > $60 million
- **REDOXBLOX:** metal oxide/reduced metal – chemical/thermal storage
  - A round investments, but scaling up with ARPA-E
- **URBAN-ELECTRIC POWER:** age-old Zn/MnO2 primary battery made reversible

LDES FUTURE: EXACTLY HOW MUCH & *EXACTLY* WHAT KIND ARE A BIT UNCLEAR

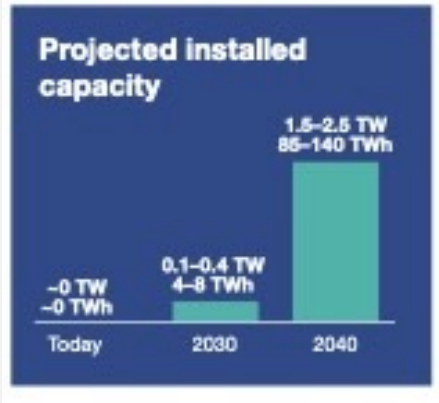
Full US
Grid Decarb:
2-6 TWh



Brown, Botterud, Joule (2020)

2020

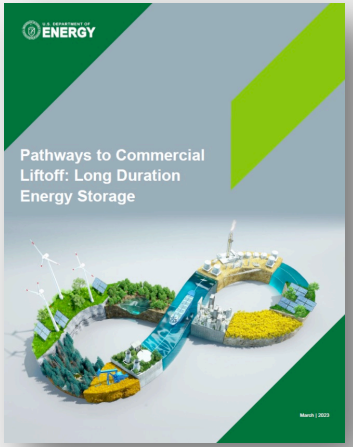
LDES Counsel*
Global
85-140 TWH cumulative



Cumulative capex
$1,500-3,000 US dBn

2021

2060 US Grid
-225-460 GW
-$330B Capital



2023

THANK YOU

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