Long Duration Energy Storage

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Short vs Long Duration Storage Technologies

Electrochemical storage

- Lithium-ion (Li-ion) batteries
- Redox flow batteries
- Metal-air batteries

Mechanical storage

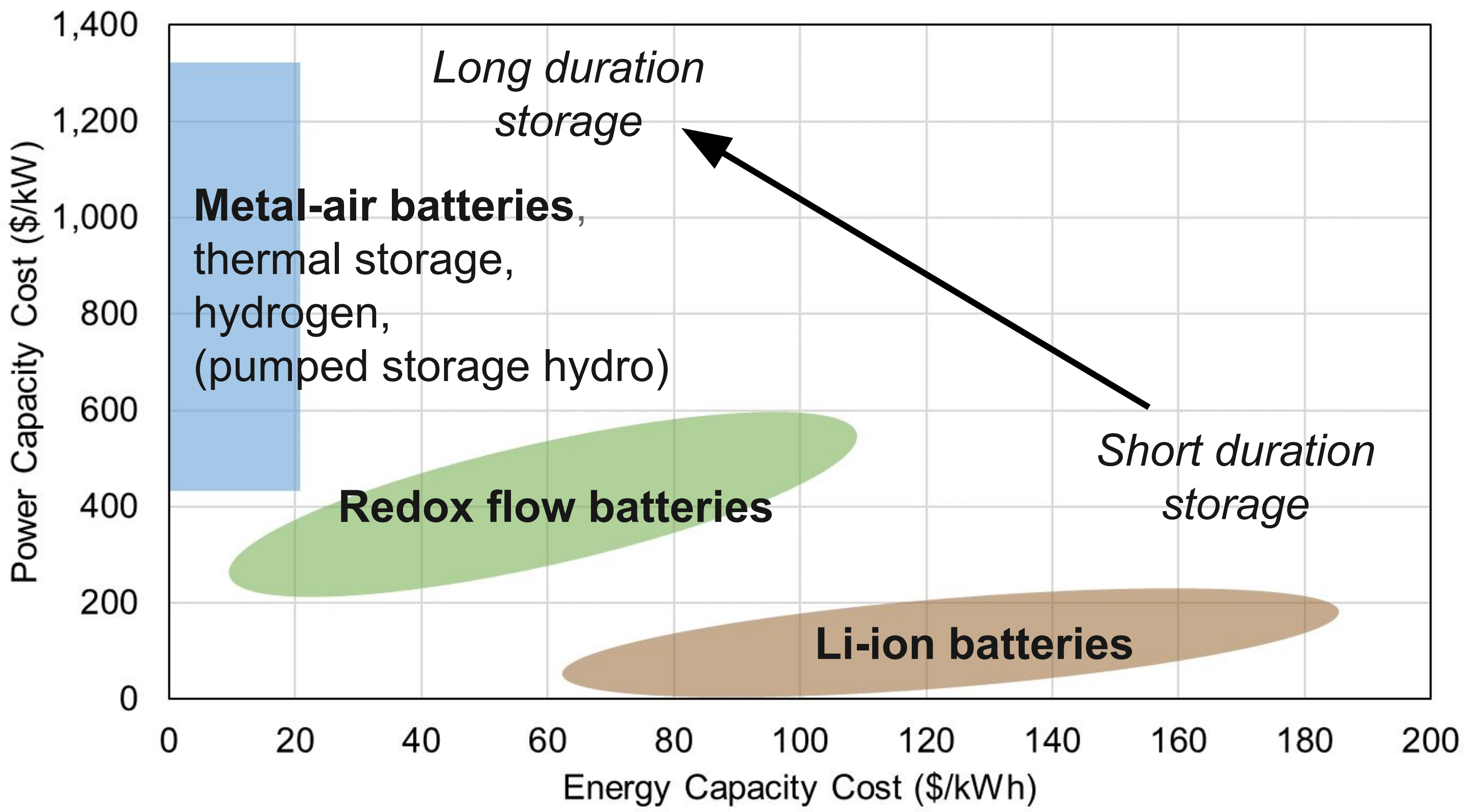
- Pumped storage hydro
- Compressed air storage

Thermal storage

- Molten salt, hot rocks
- Heat pumps

Chemical storage

- Hydrogen

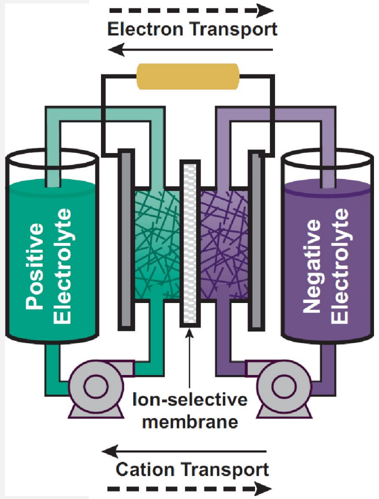


- Power capacity cost = cost per kW of maximum instantaneous power
- Energy capacity cost = cost per kWh of energy storage capacity
- Duration = energy capacity / power capacity

Long-duration energy storage options are developing

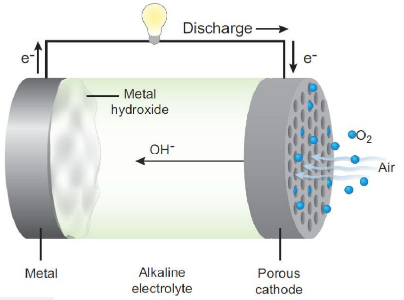
Redox Flow Batteries

- Independent scaling of power (stack) and energy (tanks) makes RFBs tunable for storage duration
- Vanadium redox is most technically advanced but cost and supply challenged
- Lower-cost highly stable chemistries for long-duration applications are in development



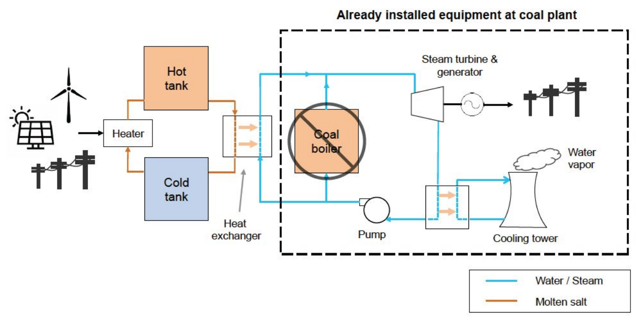
Metal-Air Batteries

- Very low energy cost makes metal-air attractive despite high power cost and low round-trip efficiency
- Best suited for long-duration storage applications
- Can use low-cost earth-abundant elements such as Zn and Fe with large existing supply chains



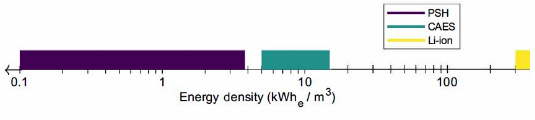
Thermal Energy Storage

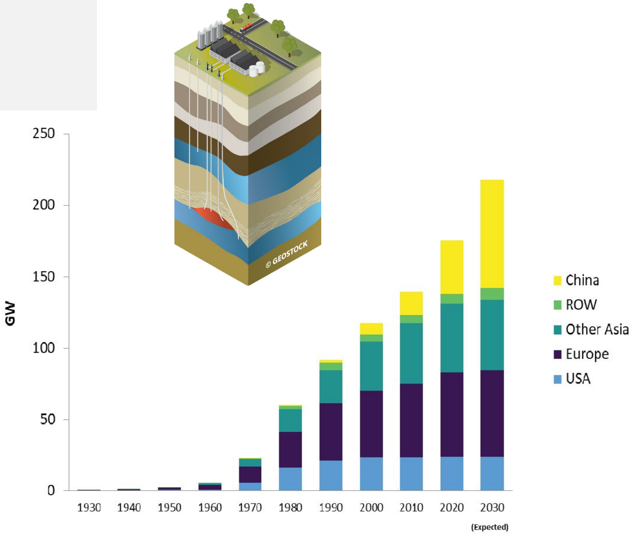
- Key cost challenge: conversion of heat to electricity
- Near-term low-cost option: Steam turbine retrofit with TES at existing coal plants



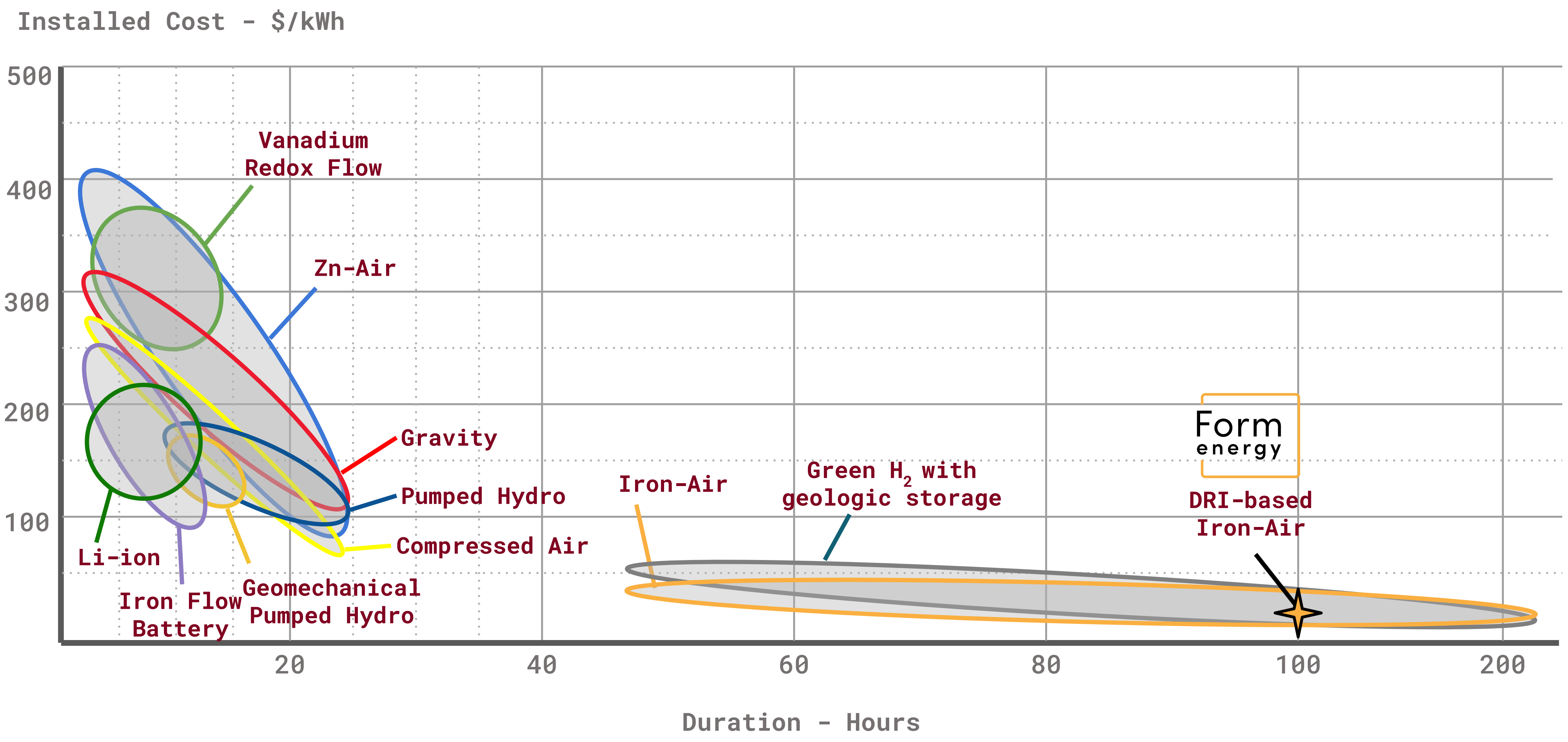
Mechanical Energy Storage

- Historically constrained by low energy density, geology
- Pumped storage hydropower is expanding rapidly in China but not U.S.



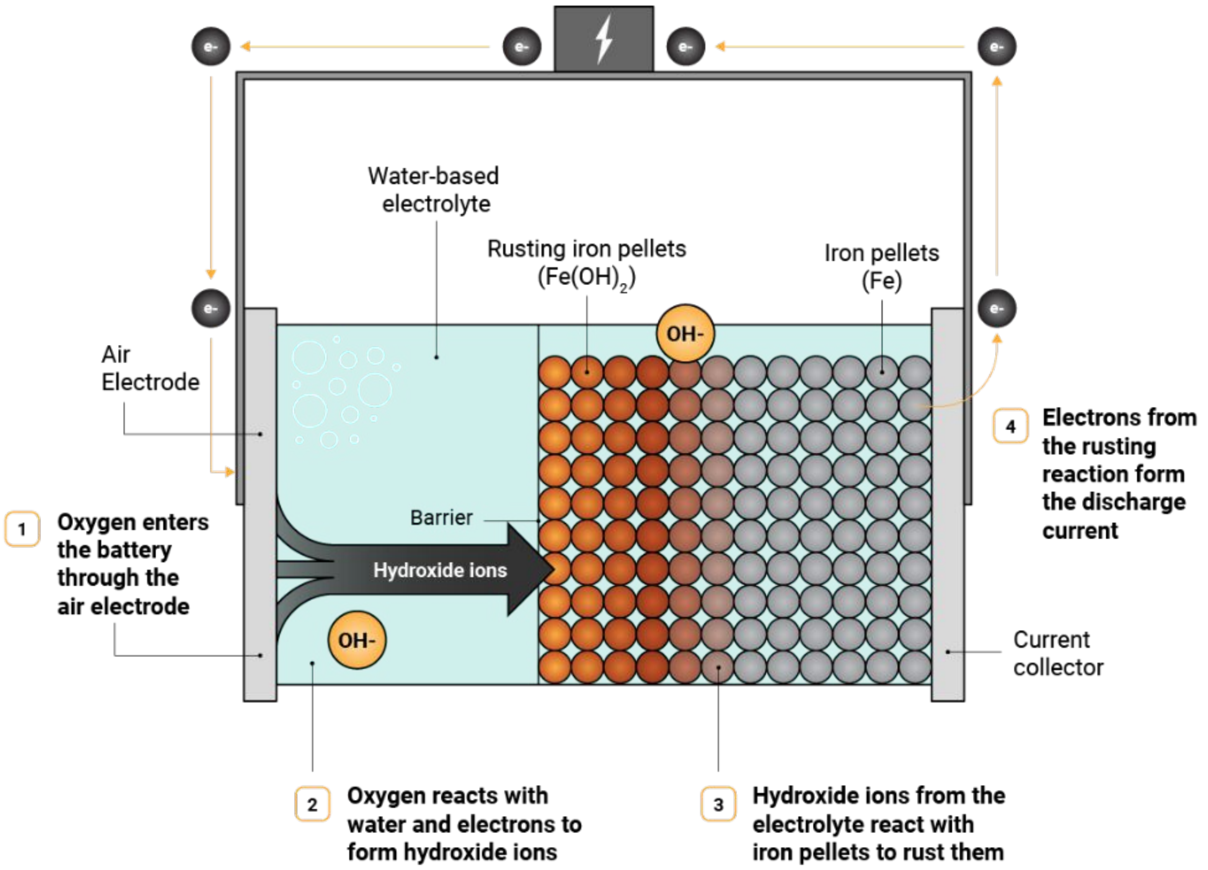


Fe-air batteries can enable cost-effective multi-day storage

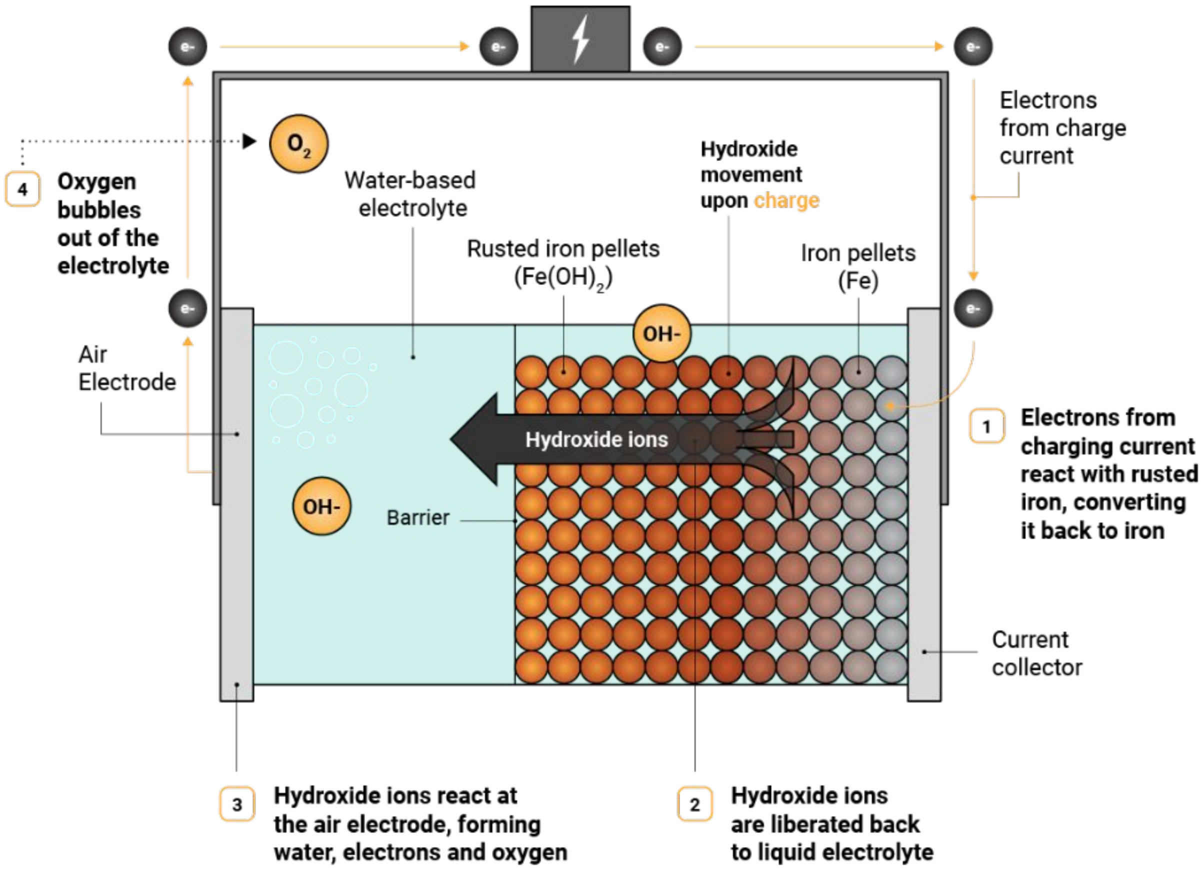


Iron-Air Batteries use Principle of “Reversible Rusting”

Discharge



Charge



Form energy

W.H. Woodford *et al.*, *One Earth*, 2022, https://doi.org/10.1016/j.oneear.2022.03.003

Leveraging the lowest-cost iron materials from the steelmaking supply chain

Iron Ore

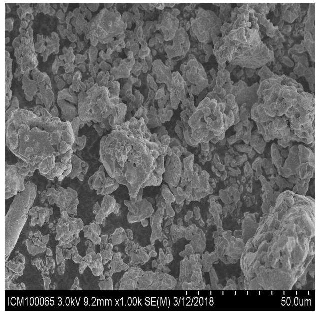
Iron Ore Pellets

Direct Reduced Iron (DRI)

Hot Briquetted Iron (HBI)

Pig Iron

Atomized / Sponge / Carbonyl Irons



More oxidized
Higher impurities
Lower cost

→

More metallic
Lower impurities
Higher cost

Direct Reduced Iron (DRI) is the lowest cost form of metallic iron

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Scalability of Fe-air Batteries

- Two iron barges = 1 GWh of Fe-air batteries
- One U.S. iron reduction plant today produces ~2 million tons of Fe/year → 0.5 TWh/yr of Fe-air
- Reaching 100 TWh (global) by 2050 requires <1% increase in current global iron production
- U.S. supply chain already exists

Form energy

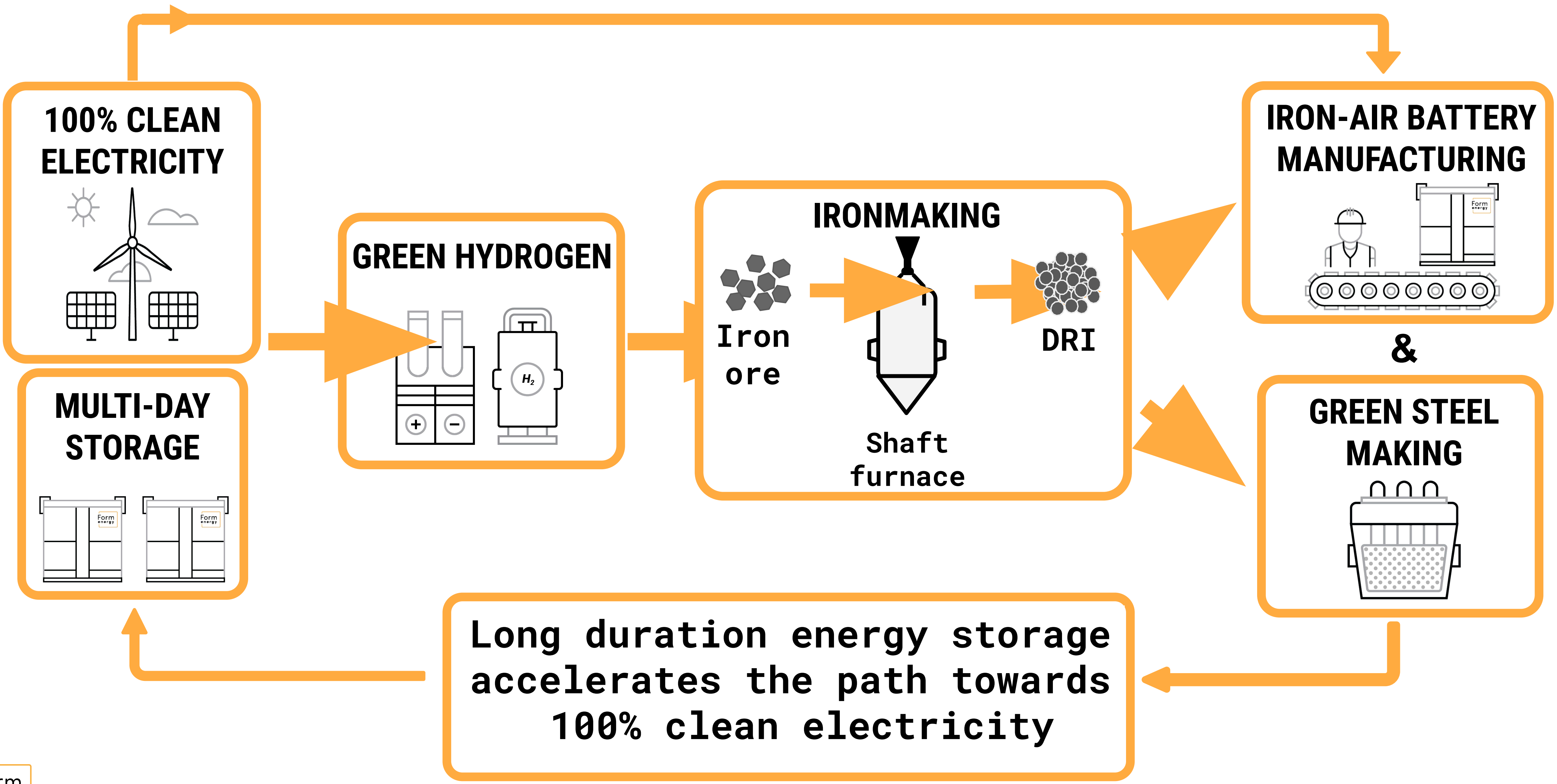
Iron-air multi-day storage commercial pilot projects

10 to 15 megawatts/1-1.5 gigawatt hours of energy storage systems to be located in the utility's service area

1.5 megawatt/0.15 gigawatt hour multi-day energy storage project in Cambridge, Minnesota

- **Site selection for first manufacturing plant underway**
- **Will be east of Mississippi, ideal location for Fe-air is coal and steel country – need water and rail access**
- **Ramp over three years to 500 MW, 50 GWh**
- **Multiple GW, 100's of GWh capacity by 2030**
- **Pathway to 10-20 TWh in U.S. by 2050**

The Iron-Energy Nexus: Long duration storage and clean steelmaking



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The Future of Energy Storage

An Interdisciplinary MIT Study

Message #1:

1. **Federal R&D policy should focus on long-duration storage technologies to support affordable, reliable future electricity systems.**
2. Storage can make regionally-tailored, net-zero electricity systems affordable.
3. Market designs and regulatory policies need to be reformed to enable equitable & efficient decarbonization.

Production challenge in reaching 100 TWh globally (10-20 TWh U.S.) by 2050

Materials Availability

- Li-ion battery critical elements (Li, Co, Ni) are production limited.
- Vanadium (redox flow batteries) is both production and resource limited.
- Requires production CAGR near or above historical maxima for next 28 yrs
- Typical time from prospecting to deployment of minerals is 5-15+ years.

	Historic CAGR	CAGR for 100 TWh through 2050	Resource limit (2020)
Lithium	**3%-15%**	**12% (50% mkt)**	**700 TWh**
Cobalt	**-2%-10%**	**6-15% (50% mkt)**	**125-280 TWh**
Nickel	**0%-5%**	**10% (50% mkt)**	**400 TWh**
Vanadium	**-5%-12%**	**25% (50% mkt)**	**70 TWh**

- Number in parentheses indicates % of new production used for batteries
- CAGR = compound annual growth rate (in production)
- Citation: MITEI Future of Energy Storage

Scaling Li-Ion Battery Production

- 20% CAGR projected through 2030
- Reaches 2.5 TWh/year by 2030
- Need 20% CAGR through 2050 to reach 100 TWh