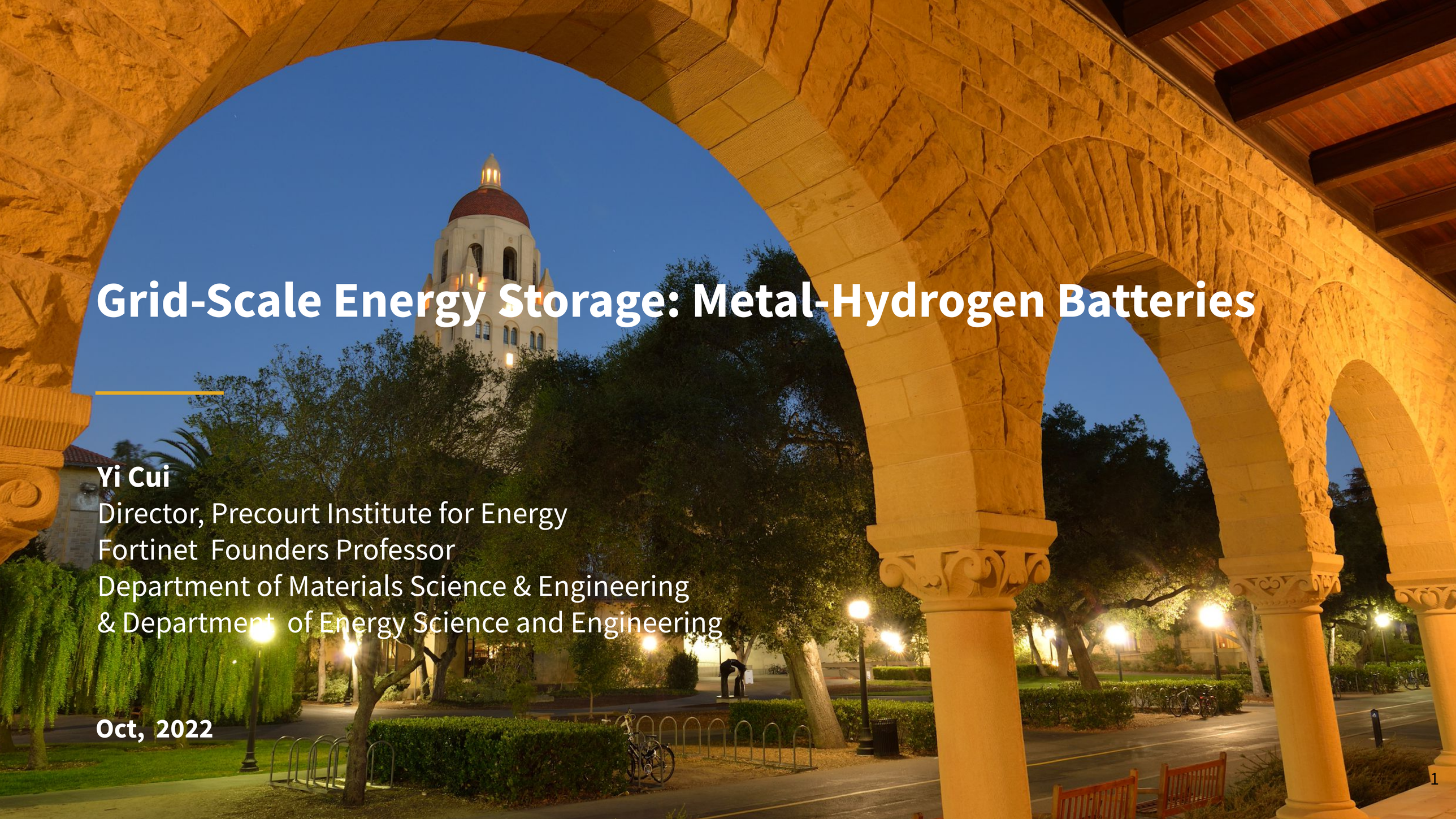

Grid-Scale Energy Storage: Metal-Hydrogen Batteries

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Scaling Challenge: Stationary Energy Storage

Renewable electricity cost: 1-3 cents/kWh in the long term

Technology gap: grid scale energy storage across multiple time scale

minute hour day week month season

World electricity (2019): 23,000 TWh

72hr storage

200 TWh batteries

$100/kWh

$20Trillion

Scaling Challenge: Mobile Applications

Electronics

Drone

Electrical Vehicles

1.4 billion cars/trucks
70kWh/car

→

100 TWh batteries

$100/kWh

→

$10Trillion total
$1Trillion/yr

Mobile + Stationary Applications:

300 TWh Battery

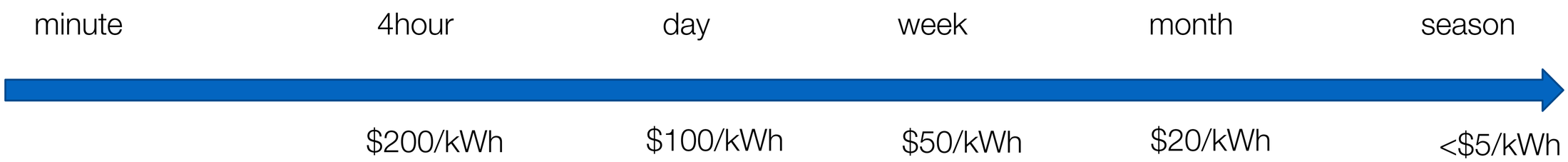
1 TWh/year production (included planned factories)

300 years needed

Need to scale up battery yearly production 10-30 times

Grand Challenges for Grid-scale Storage

1. Very low cost (time scale dependent): flexible across multiple time scales



2. Life (30 years, >11,000 cycles (1cycle/day), 33,000 (3 cycles/day)

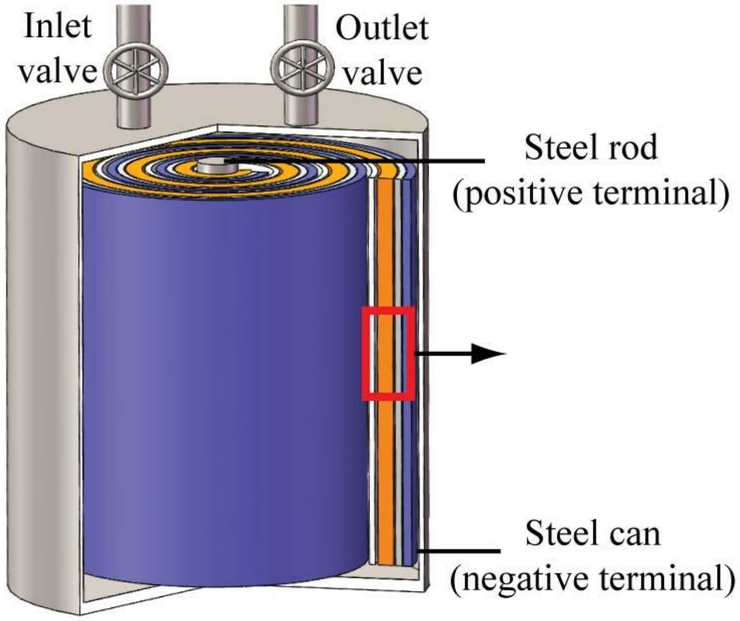
3. Maintenance-free in all climates (extreme heat +50C) or cold (-30C)

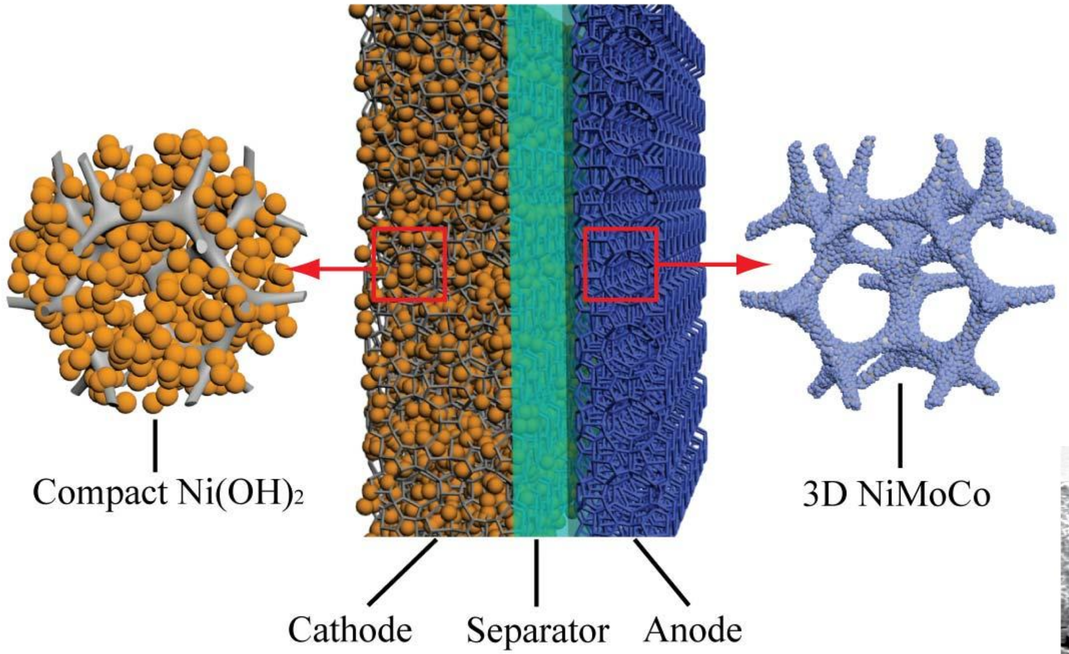
4. Very safe

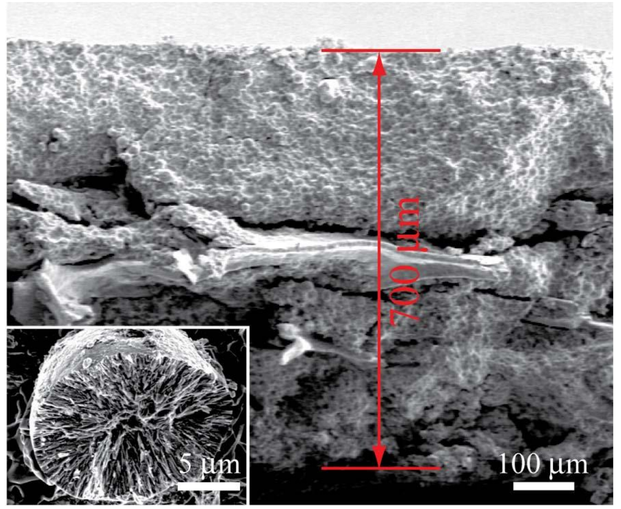
5. Cradle-to-cradle recyclability

Li-ion batteries	~$130/kWh	3000 cycles (10 years)	~170-250 Wh/kg	safety issue, hard to recycle

Ni-H_2 battery: design and principle







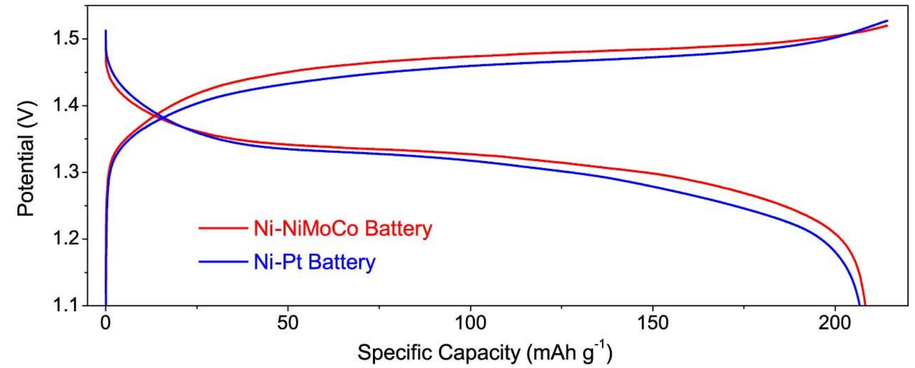
$$\text{Cathode: } Ni(OH)_2 + OH^- \underset{discharge}{\overset{charge}{\rightleftharpoons}} NiOOH + H_2O + e^-,$$

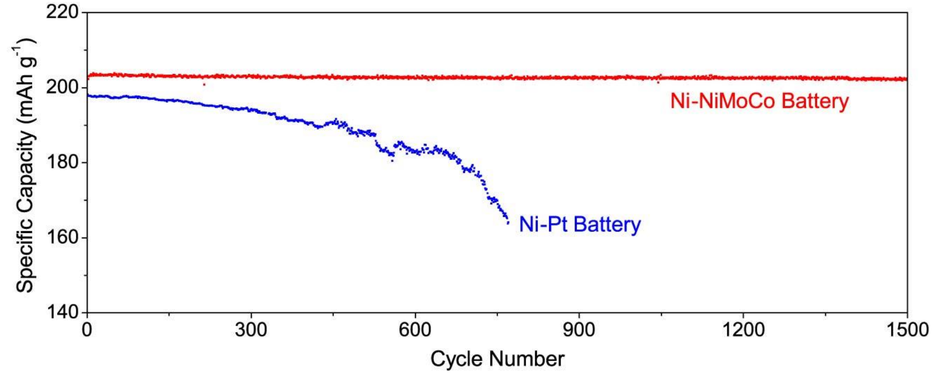
$$\text{Anode: } H_2O + e^- \underset{NiMoCo,discharge}{\overset{NiMoCo,charge}{\rightleftharpoons}} \frac{1}{2}H_2 + OH^-,$$

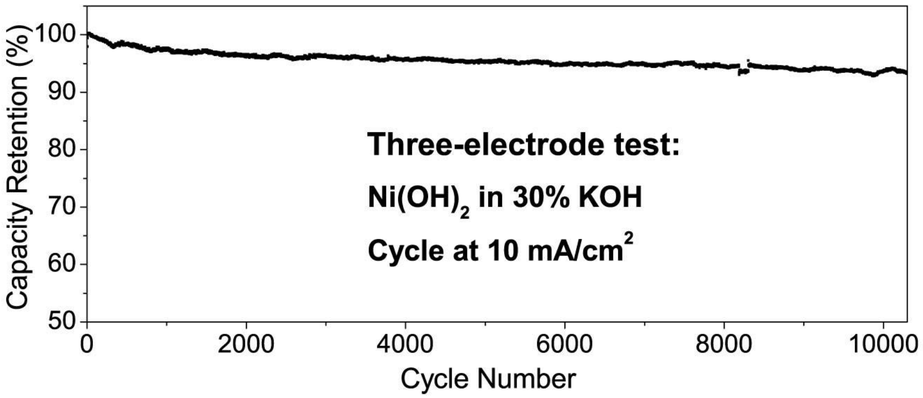
$$\text{Overall: } Ni(OH)_2 \underset{NiMoCo,discharge}{\overset{NiMoCo,charge}{\rightleftharpoons}} NiOOH + \frac{1}{2}H_2.$$

Wei Chen, Yi Cui*, *et al. Proc. Natl. Acad. Sci.* 2018, 115 (46), 11694-11699.

Ni-H_2 Battery Performance







- Energy density:

up to ~100 Wh/kg, ~400 Wh/l

- Battery Cost:

<$80/kWh at scale

- Life:

30,000 cycles

30 years

Wei Chen, Yi Cui*, *et al. Proc. Natl. Acad. Sci.* 2018, 115 (46), 11694-11699.

Possible Cathode Chemistries for Metal Hydrogen Batteries

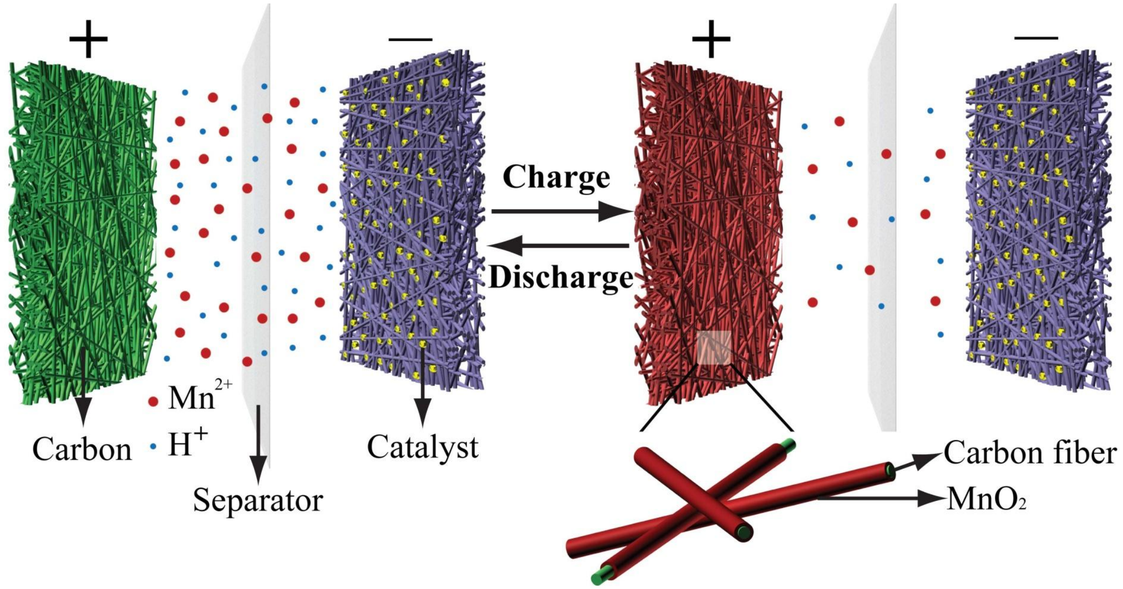
Ni: $23/kg

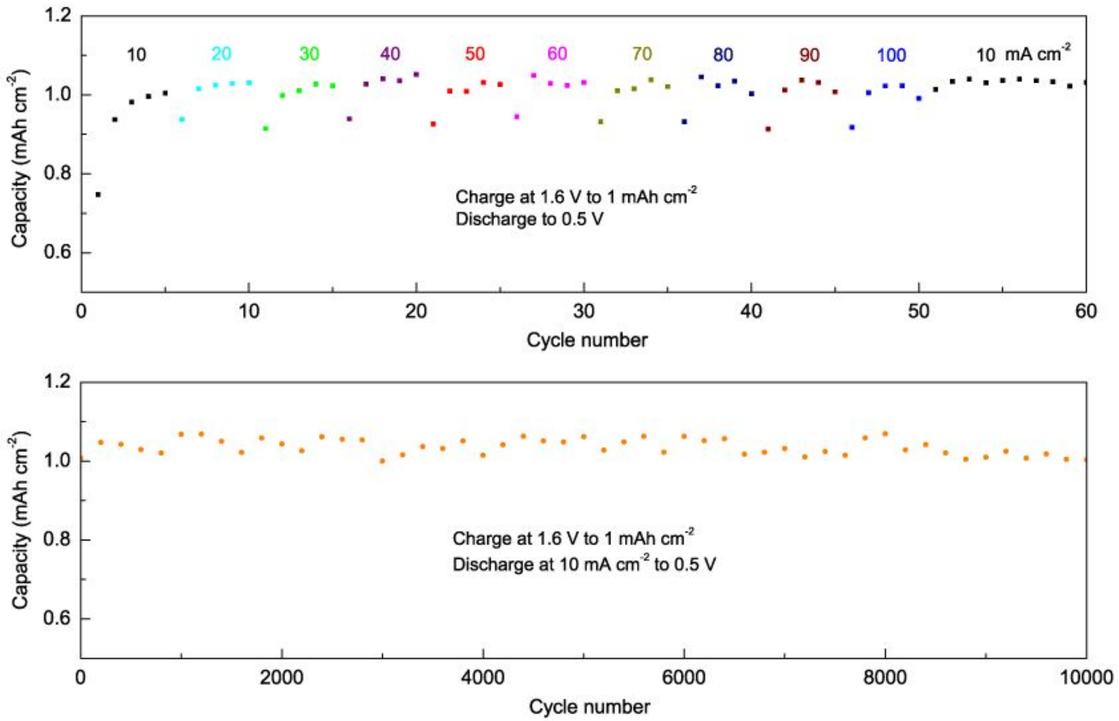
Mn: $2/kg

Pb: $2/kg

Fe: $ 0.09/kg

Mn-H_2 Batteries





Cathode $Mn^{2+} + 2H_2O \leftrightarrow MnO_2 + 4H^+ + 2e^-$

Anode $2H^+ + 2e^- \leftrightarrow H_2$

Overall $Mn^{2+} + 2H_2O \leftrightarrow MnO_2 + 2H^+ + H_2$

- Excellent rate capability: 100C
- No capacity decay after **10,000 cycles**.

W. Chen, G. Li, Yi Cui, et al. *Nature Energy*, 2018, 3, 428-435.

EnerVenue Inc: Metal-H_2 Batteries

Revolutionary stationary energy storage technology:

- **Long life：30 years，30,000 cycles**
- **Safe: zero accident**
- **Flexible storage：minutes-72 hours**
- **Zero maintainence**
- **Low cost**
- **Wide temperature range：-40 to +60C**

EnerVenue's Solution

- **Proven** *30+ years of use in space*
- **Durable** *30+ year lifespan; 30,000 cycles*
- **Safe** *No thermal runaway risk*
- **Flexible** *No use case limitations*
- **Maintenance-free**
- **Affordable** *Low-cost materials*

Summary

1). The scale of stationary storage is gigantic: 200TWh.
2). Energy storage is across multiple time scales (min to season) with a wide range of $/kWh.
3) There are some promising battery chemistries but we are not ready to pick winners. There are likely multiple winners for different time scales.
4) R & D and Innovations are urgently needed.