Availability of the elements for scaling up batteries for grid and vehicle energy storage

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4th Symposium on Energy Storage: Beyond Lithium Ion
June 7, 2011

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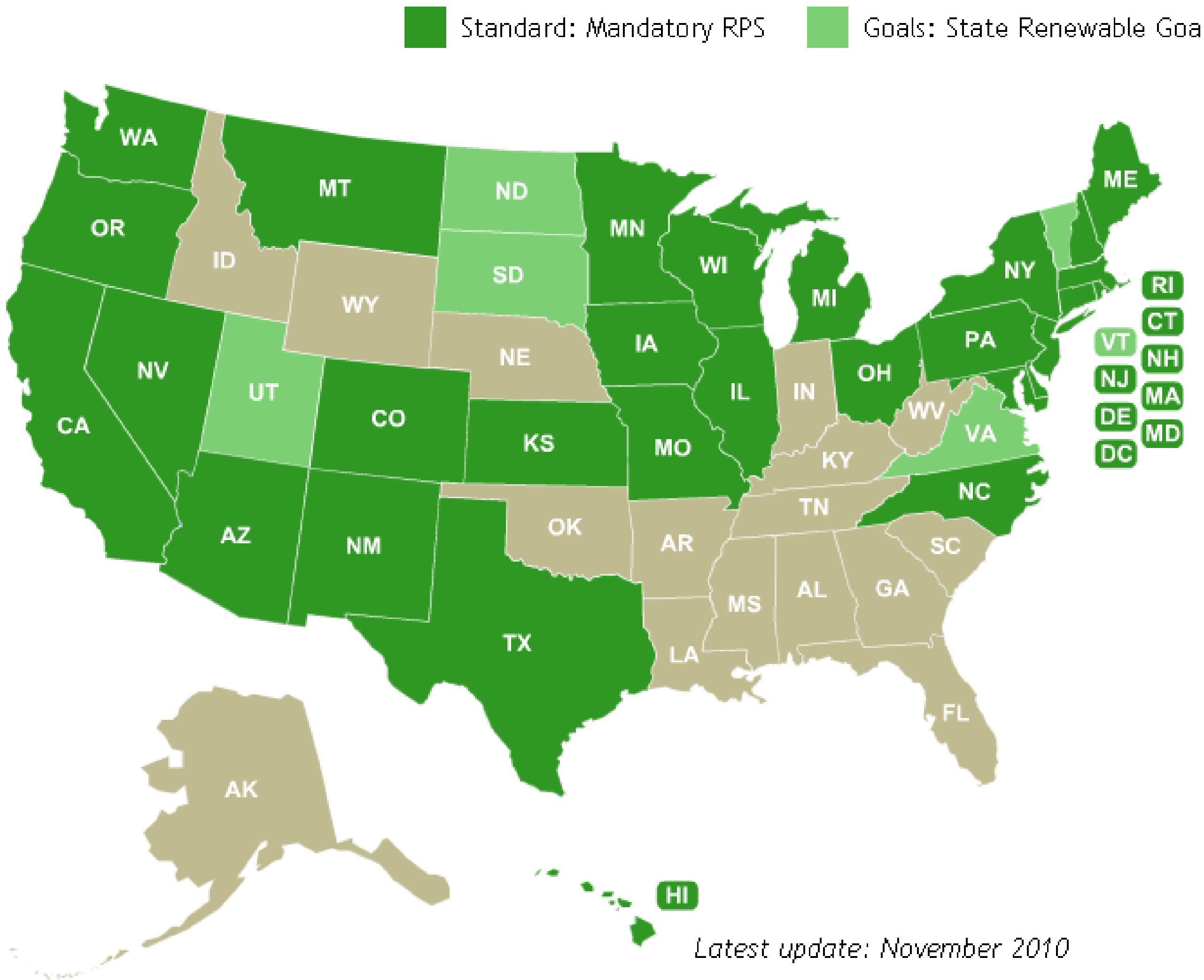
Outline of the talk

- **Research question and motivation**
- Couples, methods, and results
- Conclusions and further thoughts

Our research question

- **We asked**: in the short (10 to 15 year) and long (40 to 50 year) term, what is the availability of the elements for scaling up batteries for grid and vehicle energy storage?
- Proviso: given the long time frames and estimates involved our results are semi-quantitative.

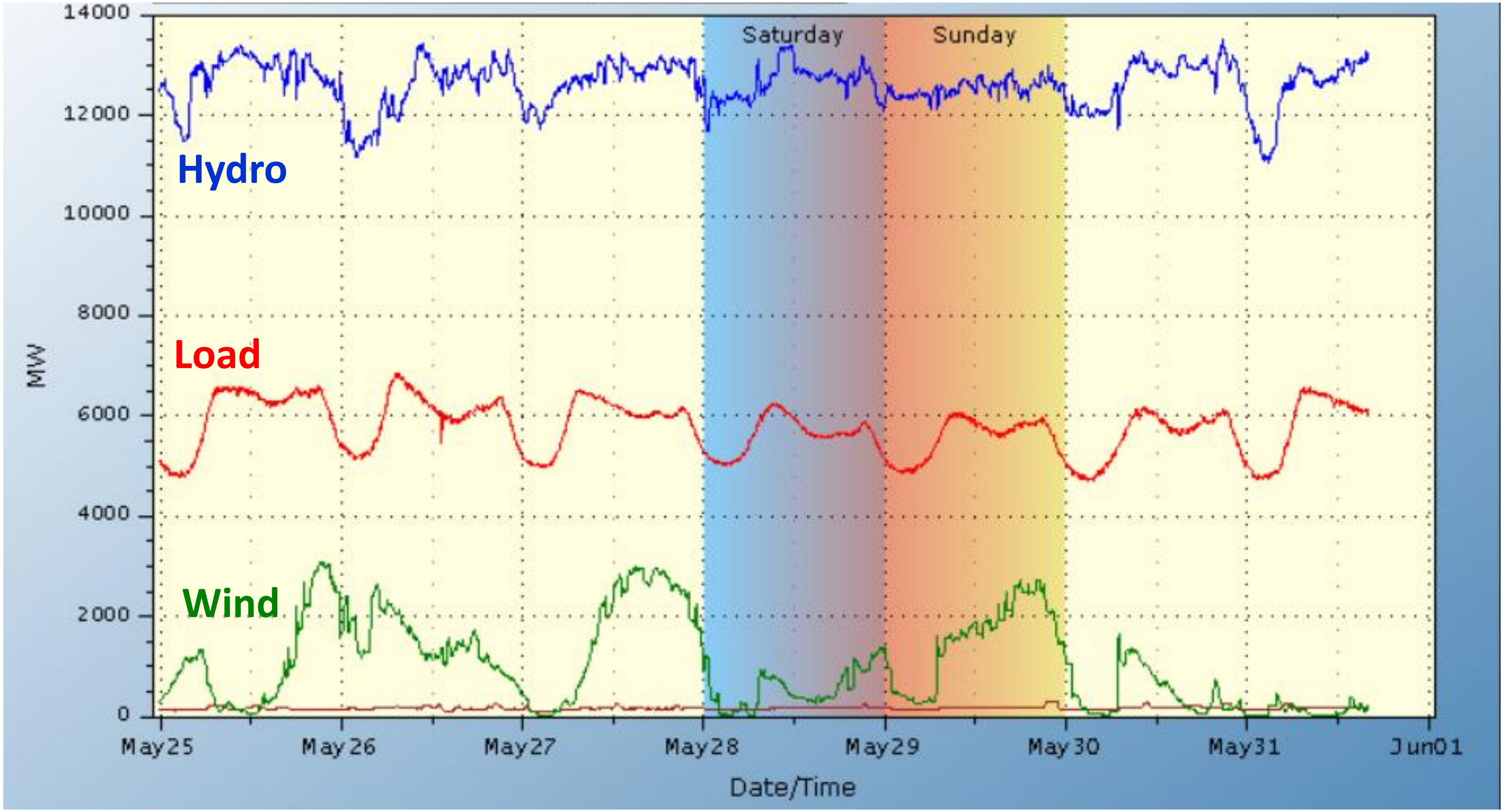
Many states and countries have a renewable portfolio standard



Source: RPS Edge database

Wind and solar often have a variable output

Bonneville Power Administration data, May 25 – June 1, 2011



Source: BPA website. The Bonneville Power Administration manages power throughout the US Pacific Northwest.

Scaling up renewables may require a major scale-up of battery production

- Without energy storage: grid expansion and demand management.
- With energy storage:
  - Pumped hydro and compressed air currently dominate.
  - Batteries (and other technologies) can be deployed anywhere.

Seneca pumped storage reservoir and the Kinzua dam on the Allegheny river, PA

A123 Systems battery storage in Chile

Scaling up electric vehicles may require a major scale-up of battery production

- Batteries have the highest energy per mass and volume of available electrical storage devices.

There is a Race for 21st Century Vehicle Fuels

Fossil fuels (fossil)

Improved efficiency (none)

Biofuels (sunlight)

Batteries (fossil, renewables)

Hydrogen (fossil, renewables)

Synthetic liquid fuels
(fossil, renewables)

Which pathway will win?

- Cost
- Technical readiness
- Infrastructure requirements
- Resources
- Environment
- Politics and regulation

Slide inspired by the late Alex Farrell, UC Berkeley

For each couple we looked at three questions

1) Based on the specific energy, is the couple suitable for electric vehicles or only for grid-scale batteries? Vehicle batteries should have high specific energy and energy density.

2) What is the energy storage potential (in TWh) based on annual production (“flow”) and reserve base (“stock”)?

3) What is the cost of the elements in the couple (in $/kWh)?

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- Research question and motivation
- **Couples, methods, and results**
  - **Specific energy of the couples**
  - Energy storage potential (ESP) of the couples
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Most couples are established and reversible; some are in the development or research stage

Li-ion / Li metal

$C_6/LiCoO_2$
$C_6/LiMn_2O_4$
$C_6/LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
$C_6/LiFePO_4$
$Li_4Ti_5O_{12}/LiCoO_2$

$Si/LiCoO_2$
$C_6/0.3LiMn_2O_3 \cdot 0.7LiMn_{0.5}Ni_{0.5}O_2$
$C_6/LiMnPO_4$

$Li/LiCoO_2$
Li/S

Aqueous

Pb/PbO_2
Cd/NiOOH
$REE\text{-}Ni_5H_6/NiOOH$
$LaNi_5H_6/NiOOH$

Zn/NiOOH
Zn/MnO_2

High temperature

$Na/NiCl_2$
Na/S

Mg/Sb

Flow

$V(SO_4)/VO_2(HSO_4)$
Zn/Br_2
$Na_2S_2/NaBr_3$
$CrCl_2/FeCl_3$
$Zn/Ce(CO_3)_2$

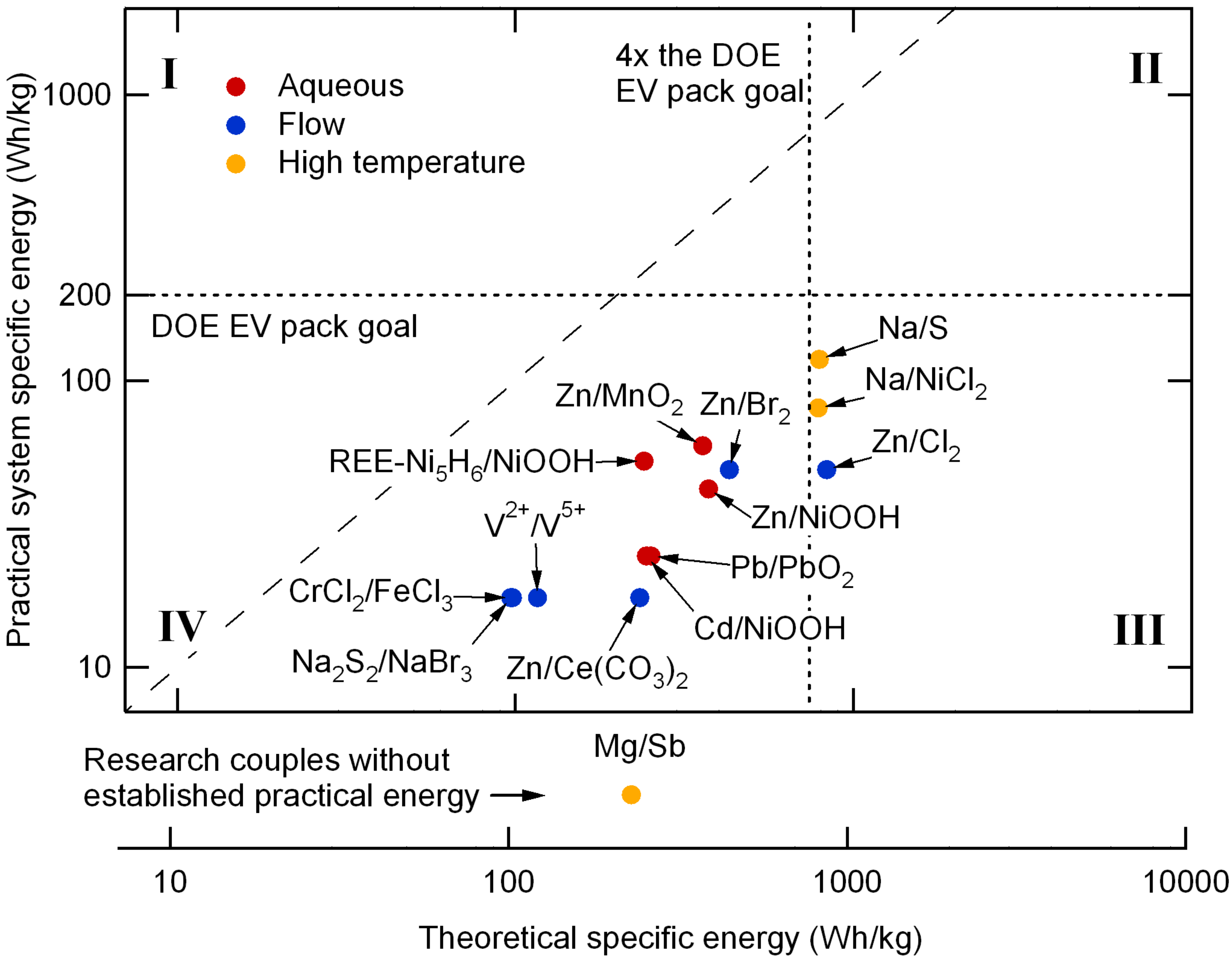
Zn/Cl_2

Metal air

Zn/O_2
Li/O_2

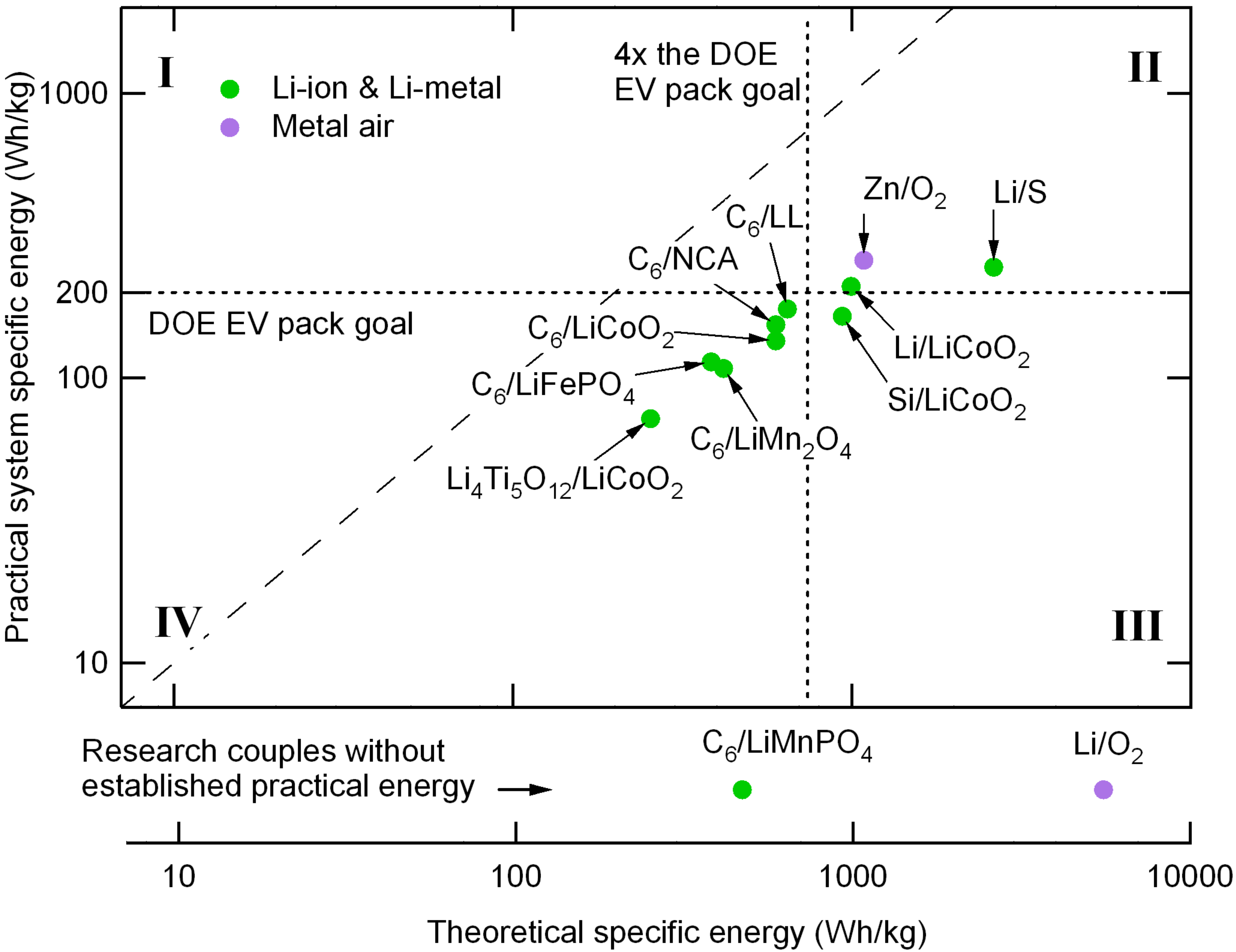
Bolded couples have established, good reversibility

Many couples are suited for grid applications



REE = Rare Earth Element

Li-based couples are best suited for vehicles



LL=layered-layered ($0.3LiMn_2O_3 \cdot 0.7LiMn_{0.5}Ni_{0.5}O_2$), NCA=$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

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Our analysis only includes the elements contained in battery active materials

- Example: Ni/MH battery

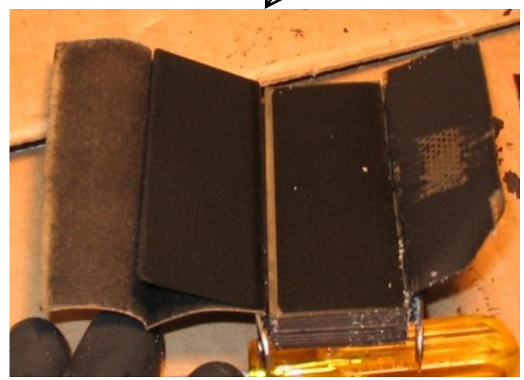
Elements used in battery active materials

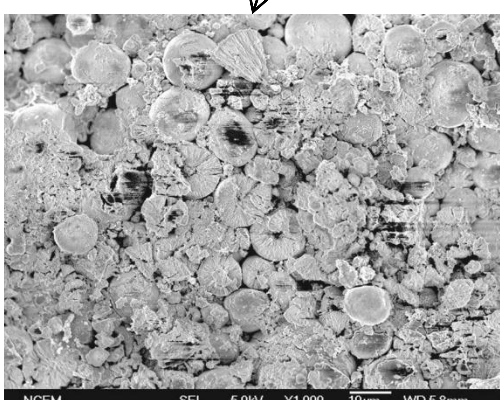
Ni, O, H, Rare earth elements

Battery electrode

Battery cell

Battery system





Images from the 2005 Prius Ni/MH battery

The energy storage potential is obtained from annual production and reserve base, and basic electrochemistry

- Resource availability is obtained from:
  - Annual production of the elements (metric tons): A “flow” that is known accurately.
  - Reserve base of the elements (metric tons): Includes amount of an element in the ground that be extracted at today’s prices *plus* some subeconomic reserves; a “stock” known with less accuracy.

- Each couple has a limiting element, the one that runs out first during scale up.

- The energy storage potential (ESP) (TWh) is obtained from the availability of the limiting element, and using couple stoichiometry and average cell potential.

- The couple cost ($/kWh) is obtained by summing the costs of all the elements. These values are uncertain because of the variety of forms of active material inputs.

Annual production and reserve base numbers are drawn from the USGS Mineral Commodity Surveys.

One example: the $C_6/LiCoO_2$ couple

	C_6 active material	$LiCoO_2$ active material
Annual production (metric tons):	C: "large"	Li: 25,400 Co: 75,900 O: "large"
Reserve base (metric tons):	C: "large"	Li: 11×10^6 Co: 13×10^6 O: "large"
Active-material limiting element:	C	Co
Practical specific capacity (mAh/g):	372	150

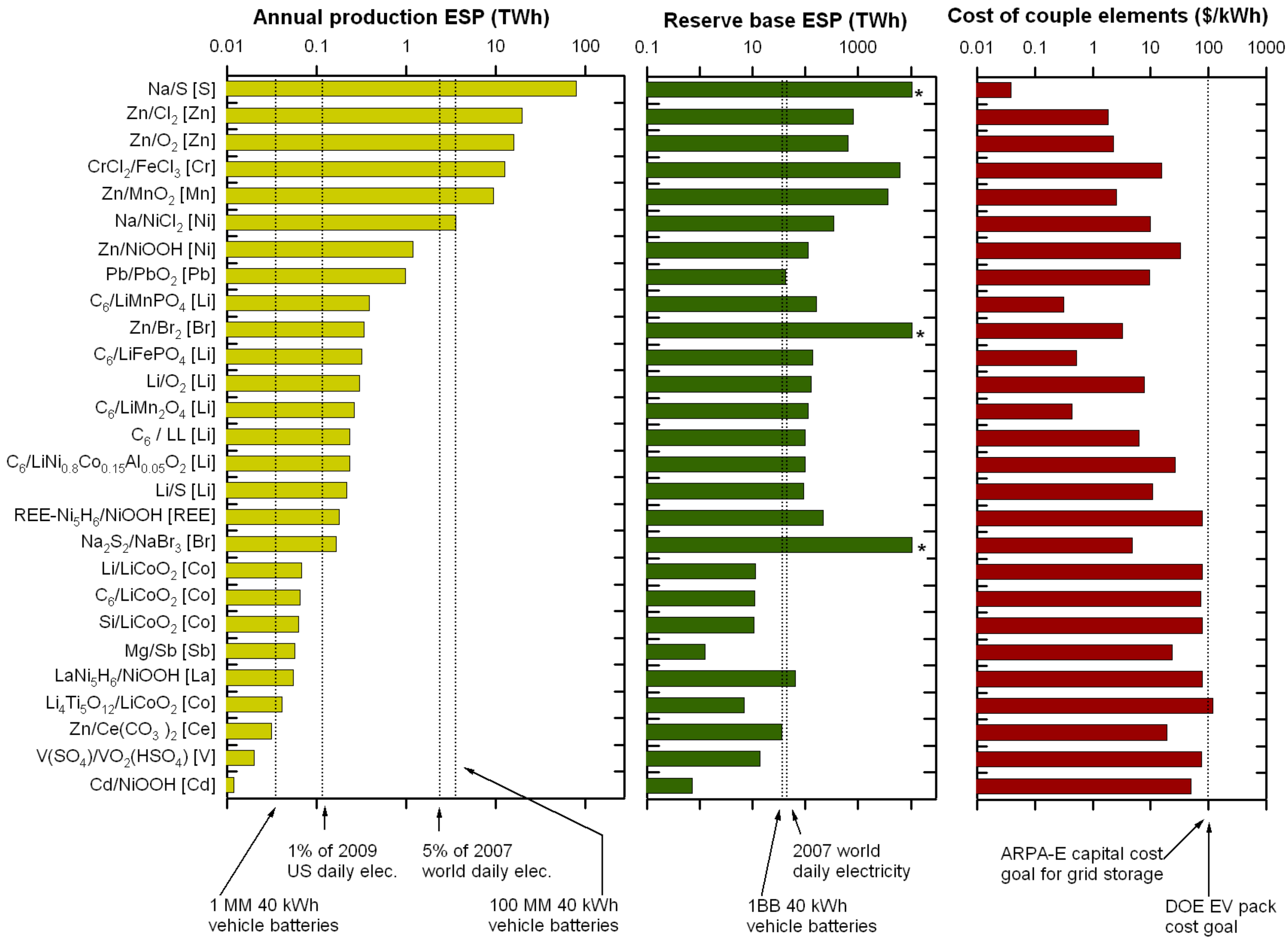
Couple limiting element: Co

Cell potential (V): 3.8

Annual production ESP (TWh): 0.07

Reserve base ESP (TWh): 11.43

Couple cost: 76.70 $/kWh



* Indicates a number beyond the limit of the plot

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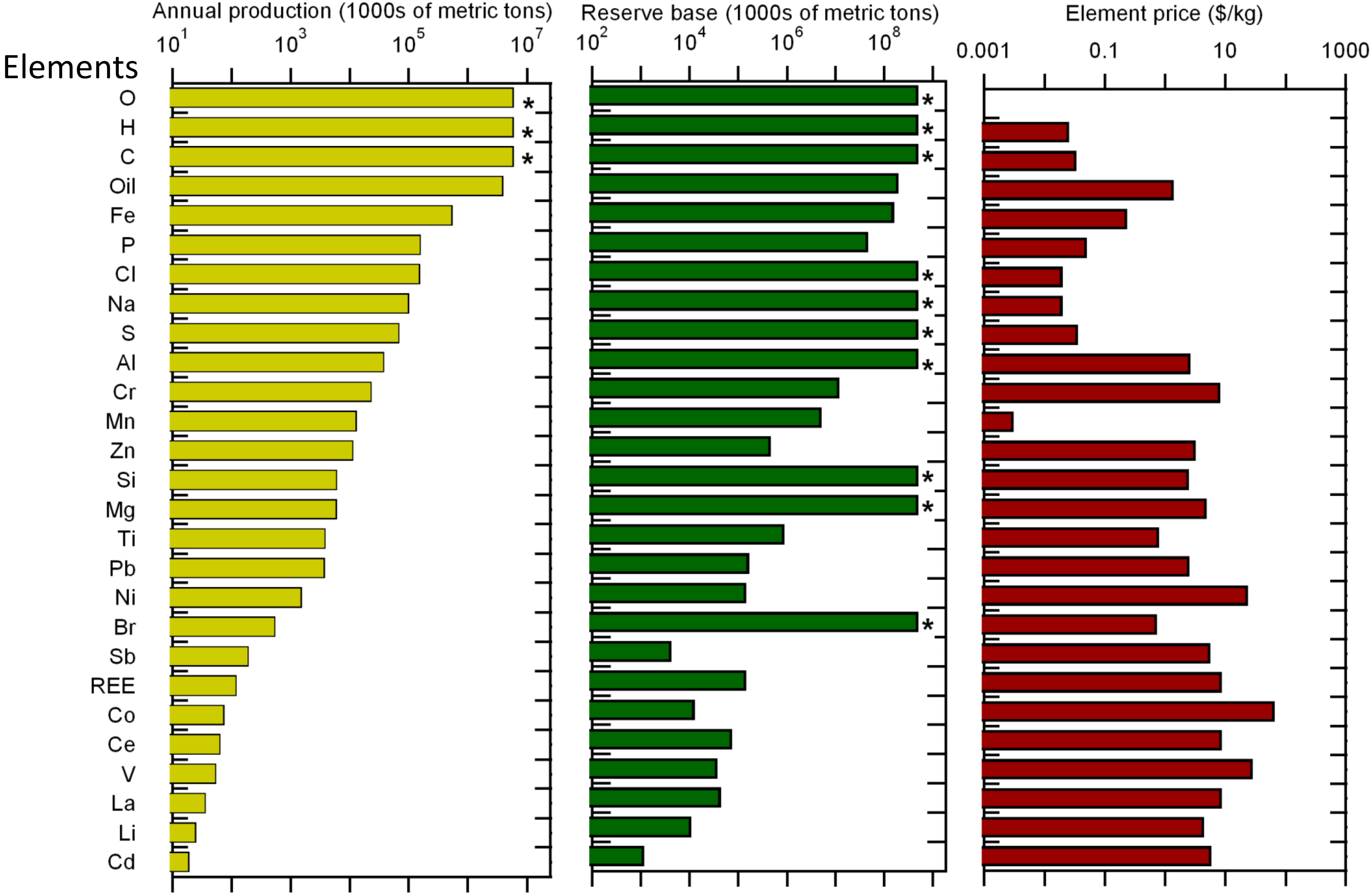
Conclusions

- **We asked**: in the short (10 to 15 year) and long (40 to 50 year) term, are there resource constraints on scaling up batteries for grid and vehicle energy storage?

- **The answers:**
- Several battery couples suitable for grid storage can scale without resource limits to short- and long-term goals: Na/S, Zn/Cl_2, $CrCl_2/FeCl_3$.
- For EVs, Li-based couples have the most suitable specific energy.
  - About 10 million 40 kWh Li-based EV batteries can be made with the annual production of Li.
  - About 1 billion 40 kWh Li-based EV batteries can be made with the Li reserve base.
- <u>Lifetime system cost, and other factors, will likely limit scale up more than resource constraints.</u>

Future battery chemistries: one example (Mg)



Other aspects to consider

- Increasing the production of an element by a factor of two requires investment and time.

- Recycling.

- Resource limits for other system components (not just the active materials). Catalysts may be particularly important (Pt, Pd, etc.).

- This work has been published:

Cyrus Wadia, Paul Albertus, Venkat Srinivasan, “Resource Constraints on the Battery Energy Storage Potential for Grid and Transportation Applications,” *Journal of Power Sources*, Volume 196, Issue 3, p. 1593-1598, 2011.

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